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Free-Body Diagrams as a Foundational Basis for Development: Student FBD performance as an early indicator of success in a Fundamentals of Engineering Mechanics course

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Does Repeated Emphasis on Free Body Diagram Construction Correlate with Success in Introductory and Follow-On Mechanics Courses?

Abstract

Free Body Diagram (FBD) construction is one of the first and most important skills that students develop in engineering mechanics. Instructors often notice that students who struggle to draw correct FBDs early will continue to struggle throughout the course, and sometimes in later mechanics courses as well. Despite this observation, there is relatively little empirical research to determine whether assessment of FBD construction can be associated with broader academic performance. Beginning in Fall 2024, instructors in MC300: Fundamentals of Engineering Mechanics and Design introduced six short, graded, low-stakes FBD quizzes throughout the semester. These quizzes were designed to assess the students' ability to draw a Free Body Diagram while providing immediate feedback. This study examines whether performance on those quizzes correlates with overall performance in MC300 and with performance in a follow-on course, CE364: Mechanics of Materials.

Data from 666 students across three academic cohorts were analyzed using Pearson correlation. Across all cohorts, FBD quiz performance demonstrated a correlation with overall MC300 performance ($r = 0.273$, $p < 0.001$, $R^2 = 0.074$). Cohort-specific analysis revealed stronger relationships in later semesters (r ranging from 0.393 to 0.471). Among 145 Civil, Mechanical, and Nuclear Engineering majors who subsequently enrolled in CE364, FBD quiz performance demonstrated a correlation with CE364 performance ($r = 0.488$, $p < 0.001$, $R^2 = 0.238$), while overall MC300 performance demonstrated correlation ($r = 0.591$, $p < 0.001$, $R^2 = 0.350$). Considering Kraft's [1] research, these correlations might be stronger than they initially appear, due to uncontrolled factors commonly found in educational program evaluations.

Although causation cannot be inferred, the initial findings suggest that repeated, low-stakes assessment of student abilities and understanding may serve as an early indicator of broader mechanics performance. The results suggest the need for further study of the impact of student's ability to draw Free Body Diagrams (FBDs) upon their future engineering success,

Introduction

Introductory engineering mechanics courses serve as critical gateways within undergraduate engineering curriculum. These courses do more than introduce equilibrium equations and engineering notation; they also shape how students learn to represent and reason about physical systems. The habits developed in statics will often carry forward into mechanics of materials, structural analysis, and design courses.

Among the foundational skills introduced in statics, the construction of FBDs is arguably the most essential. A FBD is the bridge between the physical world and mathematical modeling. To correctly construct one, students must isolate a body of interest, choose consistent coordinate directions, identify applied forces, identify reaction forces, distinguish internal from external effects, and apply clear labeling. Errors in drawing a correct FBD will frequently propagate into incorrect equilibrium equations and flawed reasoning. The authors of this paper have often seen that students who struggle with properly drawing FBDs often struggle with general problem solving.

Faculty within the United States Military Academy's Civil and Environmental Engineering department have frequently observed that early difficulty with FBD construction appears to predict later performance challenges. The authors intend to examine the relationship between these early engineering skills and success in the deeper field of engineering. Much of the existing research on predictors of engineering success focuses on GPA, mathematics preparation, or demographic variables. There are not enough studies that isolate this foundational engineering skill and examine the statistical relationship with broader academic outcomes. We intend to contribute to this worthwhile area of study.

Beginning in Fall 2024, instructors in MC300: Fundamentals of Engineering Mechanics and Design implemented six graded, low-stakes FBD quizzes distributed throughout the semester. These short assessments were designed to analyze the students' representational reasoning while also minimizing student grade pressure and instructor grading burden. The present study investigates whether repeated assessment of FBD construction correlates with overall performance in MC300 and with performance in CE364: Mechanics of Materials.

MC300 is offered at the United States Military Academy as part of the Infrastructure Track within the Civil and Environmental Engineering Department. The course serves both Civil Engineering majors and non-majors and emphasizes equilibrium of particles and rigid bodies in two and three dimensions as well as truss and frame analysis. For engineering majors, MC300 precedes CE364 and therefore occupies a pivotal role in the curriculum as the initial course for several engineering majors.

Because MC300 functions as a gateway course, early indicators of poor student performance are of particular interest to instructors. If competence in FBD construction can demonstrate a meaningful correlation with later performance, it may provide instructors with a practical, low-cost mechanism for early identification and follow-on targeted support.

MC300 Approaches to Subject Mastery

Beginning in Fall 2025, students were presented with six Free Body Diagram quizzes during lessons spaced throughout the course. An object with various loads and supports was projected on a screen in the classroom, and students were given three minutes to draw a FBD on a sheet of paper. No calculations were required. The FBDs were then graded for clarity, completeness, and correctness according to a solution projected on the same screen. The grades were incorporated into the course scoring structure. These quizzes accounted for 30 of 2000 total course points (1.5%). Data were collected from 666 students across three academic cohorts.

FBDs covered a variety of conditions, with some in two-dimensions and some in three-dimensions. All FBD prompts were focused on non-concurrent force systems, with some depicting sections of trusses, one complete beam, one beam with a cut requiring understanding of beam internal forces, and two showing frame sections.

Literature Review

The construction of Free Body diagrams (FBDs) represents one of the most fundamental representational skills in engineering mechanics. In introductory statics courses, the FBD serves as the conceptual bridge between a physical system and its mathematical model. Students must identify system boundaries, distinguish between internal and external forces, represent reaction forces correctly, and impose equilibrium constraints. Errors in this process frequently propagate into incorrect equilibrium equations and flawed structural reasoning. Faculty experience consistently suggests that early difficulty with FBD construction often corresponds with broader struggles in statics and in follow-on mechanics coursework.

Despite these observations, relatively limited empirical research has examined whether early assessment of FBD construction correlates with follow-on academic performance.

Research examining student performance on Free Body Diagrams supports the claim that mastery of representational modeling is cognitively intensive. Sloboda et al. [2] investigated student performance on FBD problems presented at varying levels of abstraction and found that student success was strongly influenced by how the problem context was depicted. When abstraction increased or problem representation became less conventional, error rates increased substantially. These findings suggest that FBD construction is not merely procedural but also deeply tied to students' conceptual organization of force systems.

Structured assessment strategies in introductory mechanics have been studied extensively. Davis et al. [3] examined the effects of stimulating student preparation through structured, frequent assessments in introductory engineering mechanics. Their findings indicated that consistent low-stakes evaluations encouraged more regular preparation and participation, even when positive gains were minimal in final exam results. Similarly, Howard [4] evaluated the use of weekly quizzes in lieu of traditional homework in statics courses, and reported improved exam performance and increased student accountability. In large enrollment sections, Howard and Cole [5] found that weekly quizzes maintained student engagement while reducing grading burden, highlighting the efficiency of frequent, low-stakes assessment models.

The authors' present FBD assessment model aligns closely with these quiz-based engagement frameworks. While Davis et al. [3] and Howard [4][5] focus on overall course preparation, the current study isolates a single foundational representational skill of FBDs and evaluates whether its repeated assessment demonstrates measurable association with broader performance outcomes.

Additional research examining predictors of performance in statics courses provide context for interpreting such associations. Hu et al. [6] conducted a multivariate analysis of factors affecting student performance in statics and found that prior grade point average (GPA) and prerequisite mathematics performance were strong predictors of course outcomes. Their results suggest that early academic indicators show correlation with success in gateway engineering courses. However, prior work has largely focused on demographic and academic background variables rather than on mastery of specific disciplinary practices within the course itself.

The theoretical foundation for emphasizing FBD mastery can also be understood through the lens of cognitive representation and conceptual understanding. Engineering problem solving requires translation between physical systems and abstract models. The Free Body Diagram is not simply a procedural step; it is the mechanism through which Newtonian principles are translated into a mathematical form. When students fail to construct accurate FBDs, the issue is often more conceptual than computational. The ExCEEd teaching model, described by Estes, Welch, and Ressler [7], emphasizes structured board work, modeling clarity, and explicit diagrammatic reasoning as core components of effective engineering instruction. Within this framework, the accurate construction of diagrams is viewed as central to student learning rather than auxiliary.

Generally, research on instructional design supports the use of structured, deliberate practice for almost all foundational skills. Lowman [8] emphasizes that mastery in higher education develops through carefully sequenced practice opportunities combined with timely feedback. Fink [9] argues that significant learning experiences occur when students actively engage with foundational knowledge repeatedly and reflectively rather than passively receiving content over time. Cunningham and Lachapelle [10] further argue that thoughtfully designed engineering experiences must intentionally engage students in core disciplinary practices. Within mechanics education, the repeated construction of Free Body

Diagrams constitutes that disciplinary practice; requiring students to learn and apply equilibrium concepts rather than merely observe worked examples in class.

The assessment model described in this study also draws upon principles of formative assessment. Shyr [11] documents the effectiveness of hands-on and active engagement techniques in enhancing classroom learning. Formative assessment, particularly when paired with immediate feedback, has been shown to improve student understanding and retention. In the present study, students completed FBD quizzes individually and then immediately graded them with projected solutions. This structure provided rapid feedback, enabling students to correct misconceptions before they became entrenched.

There is a social dimension of peer interaction that may also play a role in learning outcomes. Prabhu et al. [12] demonstrated that peer dynamics and study partnerships can affect inclusion and academic outcomes in engineering settings. While the FBD quizzes were individually completed, the immediate peer grading structure introduced a shared accountability that may reinforce precision and attention to detail.

While previous work has examined broad predictors of academic persistence in engineering, relatively few studies have isolated a specific foundational skill within a course and evaluated that skill's statistical association with broader academic outcomes. Building upon other authors' previous work, this study examined whether repeated, low-stakes assessment of Free Body Diagram construction, a single representational skill central to statics and mechanics, demonstrates correlation with overall course performance and with performance in a follow-on mechanics course.

This study does not attempt to establish causation. Rather, it seeks to determine whether a statistical association exists and whether such association is of sufficient magnitude to warrant further long-term and multivariable investigation. By grounding the assessment model within established pedagogical theory and connecting it to existing engineering education research, this work extends prior scholarship on active learning, structured assessment, and representational reasoning in mechanics.

Research Questions

This study addresses three primary research questions. First, is performance on repeated in-class FBD quizzes correlated with overall performance in MC300: Fundamentals of Engineering Mechanics and Design? Second, is there a relationship between FBD quiz performance and performance in CE364: Mechanics of Materials? Third, does overall performance in MC300 correlate with performance in CE364?

Methodology

Participants and Context

The dataset includes 666 students enrolled in MC300 across three academic cohorts: 2025-1, 2025-2, and 2026-1. MC300 serves as an introductory mechanics course emphasizing equilibrium of particles and rigid bodies in two and three dimensions. Course content also includes force systems, trusses, frames, centroids, and an introduction to axial stress and strain.

Among the 666 students, the authors matched 145 Civil, Mechanical, and Nuclear Engineering majors by an institutional identification number to CE364: Mechanics of Materials during the 2025-2 semester.

CE364 follows MC300 sequentially for most engineering majors and builds upon the equilibrium concepts introduced in the introductory course.

Assessment Model Design

Beginning in Fall 2025, MC300 administered six Free Body Diagram quizzes at intervals throughout the semester. Each quiz required students to construct a complete FBD for a given force system within a three-minute time limit. Students worked individually and immediately following completion, a solution was projected and students graded one another's work under instructor supervision. Each quiz was worth five points, yielding a total possible score of 30 points. Given the overall course total of 2000 points, the FBD quizzes constituted only 1.5% of the final grade.

An example of a representative FBD quiz prompt is shown in Figure 1, along with the corresponding instructor solution in Figure 2. The prompts were intentionally limited to foundational equilibrium scenarios, requiring students to isolate a body, identify all external forces and reactions, and represent forces and moments with consistent directional conventions. The goal of the exercise was not computational complexity but disciplined representational accuracy. Prior to Fall 2025, similar exercises were administered but not graded. Only graded quiz data were included in the current analysis.

Data Collection and Statistical Analysis

For each student, total FBD quiz points and overall MC300 course percentage were recorded. For matched students, CE364 overall course percentage was also collected. Pearson's product-moment correlation coefficient was used to evaluate linear relationships among these variables. Statistical significance was evaluated at $\alpha = 0.05$. Coefficient of determination (R^2) was calculated to interpret variance explained.

Results

Across all cohorts combined, FBD quiz performance demonstrated a positive correlation with overall MC300 course performance ($r = 0.273$, $p < 0.001$, $R^2 = 0.074$). This effect size appears typical in educational research, since outcomes reflect multiple interacting influences. Cohort-specific analysis revealed variability in effect size (see Table 2). In 2025-1, the relationship was weaker ($r = 0.152$, $p = 0.014$). In 2025-2, the correlation strengthened substantially ($r = 0.471$, $p < 0.001$). In 2026-1, a moderate positive correlation was observed ($r = 0.393$, $p < 0.001$). These differences may reflect individual cohort preparation, specific instructor emphasis, or grading variances.

Across all MC300 cohorts combined ($N = 666$), total FBD quiz performance demonstrated a positive correlation with overall MC300 course performance ($r = 0.273$, $p < 0.001$). The corresponding coefficient of determination ($R^2 = 0.074$) indicates that approximately 7.4 percent of the variance in overall course performance is associated with variance in FBD quiz performance. While this proportion of explained variance may appear modest, educational outcomes are inherently multivariate [1]. Research in engineering education frequently reports effect sizes in this range when examining single instructional interventions or isolated skill measures. Given that FBD quizzes accounted for only 1.5 percent of total course points, the presence of this degree of a relationship suggests that our measurement of student ability to depict FBDs captures meaningful variance in broader performance.

Table 1. Overall Correlation Between FBD Quiz Performance and MC300 Course Performance

Variable Comparison	N	r	p-value	R^2
FBD Total vs MC300 Overall %	666	0.273	< 0.001	0.074

Cohort-specific analysis revealed variability in effect size. In MC300 2025-1 ($N = 258$), the correlation was weaker ($r = 0.152$, $p = 0.014$). In MC300 2025-2 ($N = 126$), the relationship strengthened ($r = 0.471$, $p < 0.001$), explaining approximately 22 percent of variance. In MC300 2026-1 ($N = 282$), a relationship was observed ($r = 0.393$, $p < 0.001$). Such variability is not uncommon in educational research and may reflect differences in instructional emphasis, grading calibration, or cohort preparation. The strengthening of relationships in later cohorts may indicate improved alignment between instruction and assessment or increased emphasis on FBD clarity consistent with ExCEEd principles [7].

Table 2. Cohort-Specific Correlation Results for MC300

Cohort	N	r	p-value	R^2
2025-1	258	0.152	0.014	0.023
2025-2	126	0.471	< 0.001	0.222
2026-1	282	0.393	< 0.001	0.154

Among students matched between MC300 and CE364 ($N = 145$), FBD quiz performance demonstrated a positive association with CE364 course performance ($r = 0.488$, $p < 0.001$, $R^2 = 0.238$). Thus, nearly one quarter of the variance in follow-on course performance is statistically associated with FBD quiz performance in the introductory course (see Table 3).

Table 3. Correlation Between MC300 Metrics and CE364 Performance

Variable Comparison	N	r	p-value	R^2
CE364 % vs MC300 FBD Total	145	0.488	< 0.001	0.238
CE364 % vs MC300 Final Grade	145	0.591	< 0.001	0.350

An even stronger relationship was observed between overall MC300 performance and CE364 performance ($r = 0.591$, $p < 0.001$, $R^2 = 0.350$). Approximately 35 percent of the variance in CE364 performance is statistically associated with overall MC300 performance. This magnitude of association is especially substantial within educational research and seems to reinforce the perception of the role of MC300 as a foundational gateway course.

Discussion

The findings of this study seem to support the theoretical claim that student competence in drawing FBDs is central to success in engineering mechanics. The statistical relationship between FBD quiz performance and overall course outcomes reinforces the argument advanced by concept inventory research that diagrammatic reasoning reflects deeper conceptual understanding. Students who consistently construct accurate Free Body Diagrams may be demonstrating mastery of core equilibrium principles rather than just superficial familiarity with a set of steps they've been cajoled into memorizing.

The strengthening of correlations in later cohorts may reflect better instructor alignment with the ExCEEd model [7]. As instructors increasingly emphasize FBD construction, students may internalize the emphasis more effectively, resulting in stronger associations with overall performance.

The correlation between FBD quiz performance and CE364 outcomes further seems to support the concept of a continuity of competence across statics and mechanics courses. Mechanics of Materials is understood by CEE faculty to build upon the equilibrium reasoning introduced in statics, extending it into internal stress analysis and deformation modeling. Students who enter CE364 with strong FBD habits may be better positioned to analyze internal force distributions and stress transformations.

From a pedagogical standpoint, the assessment model aligns with Lowman's argument that mastery emerges from structured repetition combined with feedback [8]. The repeated, low-stakes design ensures that students encounter the foundational representational task multiple times without excessive anxiety. Fink's framework of significant learning experiences emphasizes active engagement with foundational knowledge [9]. The FBD quizzes operationalize this principle by requiring students to repeatedly model equilibrium in a variety of situations.

The peer grading element may contribute to metacognitive calibration. Immediate feedback enables students to identify errors early, reducing the likelihood of entrenched misconceptions. The social accountability embedded in the grading structure may also reinforce careful work habits, consistent with research on peer influence in engineering education [12].

Importantly, the study does not establish causation. It is plausible that FBD quiz performance serves as a proxy for broader traits such as diligence, preparation, or mathematical maturity. However, even as a proxy measure, the ability to identify statistically meaningful associations early in a semester and early in engineering education has practical value in instruction and in professional development of future engineers. Early identification of students who struggle with representational tasks may allow targeted remediation before difficulties compound.

Conclusions

The findings seem to indicate that repeated, low-stakes assessment of Free Body Diagram construction demonstrates statistically significant association with broader academic performance in introductory mechanics and in a follow-on course. While explanatory power within MC300 is modest, cross-course associations are stronger.

These results do not establish causation; however, they suggest that representational competence may function as an early statistical indicator of broader academic outcomes. Given the minimal instructional burden required to implement repeated FBD assessment, this approach may provide instructors with an efficient and practical mechanism for early identification of students who may benefit from targeted support. In a course with hundreds of students, identifying the 10% of students who are struggling most could allow instructors to target those students with additional instruction that would be impractical or ineffective if aimed at the entire group of students. Future research incorporating longitudinal tracking and multivariate modeling is warranted to evaluate incremental predictive value.

Implications for Practice

The findings of this study carry several practical implications for instructors of introductory engineering mechanics and for departments concerned with early identification of students at risk of difficulty in foundational coursework.

First, the correlation between FBD quiz performance and overall course performance suggests that repeated assessment of foundational representational skills can serve as a low-cost diagnostic signal. Because the quizzes in this assessment model constituted only 1.5% of the overall course grade, the strength of their association with broader outcomes is worth noting. Instructors seeking early indicators of student difficulty may consider implementing short, structured FBD assessments within the first several weeks of a course. Even modest explanatory power may justify using an assessment model when the cost of implementation is minimal.

Second, the relationship between FBD quiz performance and performance in a follow-on course underscores the long-term value of frequent challenging and testing of students. Introductory mechanics courses frequently function as gateways within engineering curricula. If early fluency in FBDs correlates with later success, then departments may consider using such assessments not only for grading but also for formative advising. Students who consistently struggle with FBD construction might benefit from targeted remediation sessions, structured Additional Instruction interventions, or supplemental instruction focused explicitly on diagrammatic reasoning rather than solely on algebraic manipulation.

Third, the low-stakes structure of the quizzes appears pedagogically advantageous. By maintaining minimal grade weight, the assessment model reinforces accountability without introducing high-stakes pressure. This design aligns with research on formative assessment and retrieval practice, suggesting that frequent, low-pressure engagement promotes durable learning. Institutions concerned about grade anxiety or student overload may find this model scalable because it requires minimal grading infrastructure.

Fourth, the peer grading mechanism deserves attention. Immediate feedback appears to be a key feature of the intervention. Traditional homework grading often returns feedback days later, reducing its corrective impact. In contrast, the in-class grading model provides nearly instantaneous comparison between student work and the official solution. While concerns may arise regarding grading leniency among peers, the structured projection of solutions and instructor oversight mitigates these risks. Instructors adopting this approach should establish clear grading criteria and maintain visible calibration to preserve fairness.

Fifth, the assessment model is logistically scalable. The quizzes require no specialized technology, no additional software, and no complex data systems. They can be implemented in large lecture halls or small classrooms. Because each quiz requires only three minutes of student work and a brief grading interval, the instructional time investment is modest. Faculty who are hesitant to adopt large-scale pedagogical reforms may find this approach accessible and manageable.

Sixth and finally, the findings invite reconsideration of how foundational skills are framed within introductory courses. Free Body Diagrams are often treated as a preliminary step before the real problem-solving starts. The results of this study suggest that the reasoning required in drawing FBDs may be more deeply intertwined with broader academic performance than might be commonly assumed. Emphasizing skill in drawing FBDs and repeatedly assessing it may not only improve statics outcomes but also contribute to long-term success in engineering programs.

It is of course important to interpret these implications cautiously. The present study establishes a degree of statistical correlation, not causal influence. It remains likely that FBD performance reflects underlying academic behaviors in addition to directly causing improved outcomes. Nevertheless, from an instructional standpoint, the cost of implementing repeated FBD assessment is low, while the potential diagnostic and pedagogical benefits appear meaningful.

Future research should examine whether early-semester FBD performance can predict end-of-semester outcomes with sufficient sensitivity to guide targeted intervention. Additionally, multivariate modeling incorporating homework, exam performance, and prior academic metrics could be useful in clarifying whether FBD assessment contributes unique predictive value beyond other measures.

FBD Quiz Prompts and Solutions

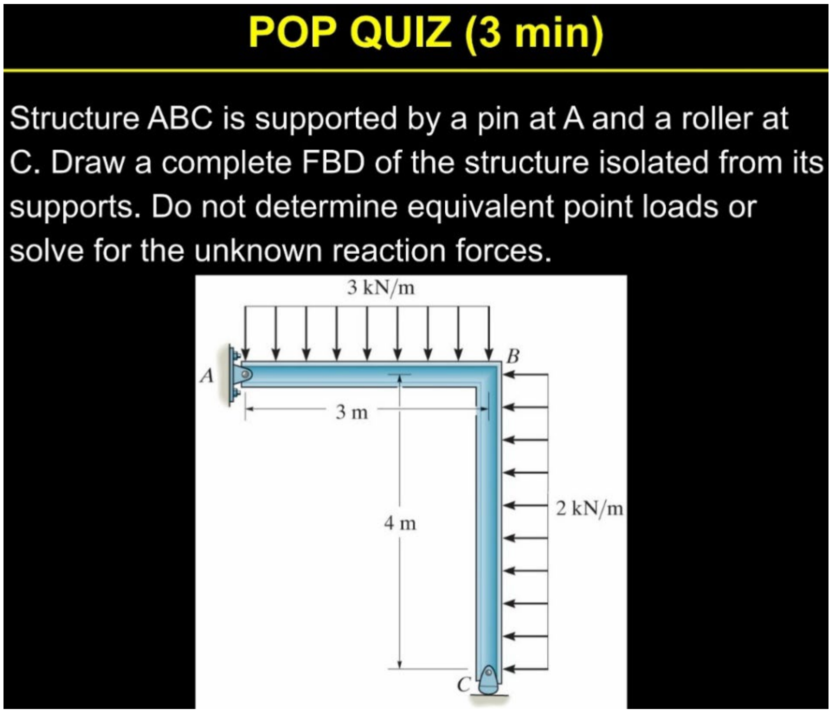

Figure 1: FBD Quiz 1

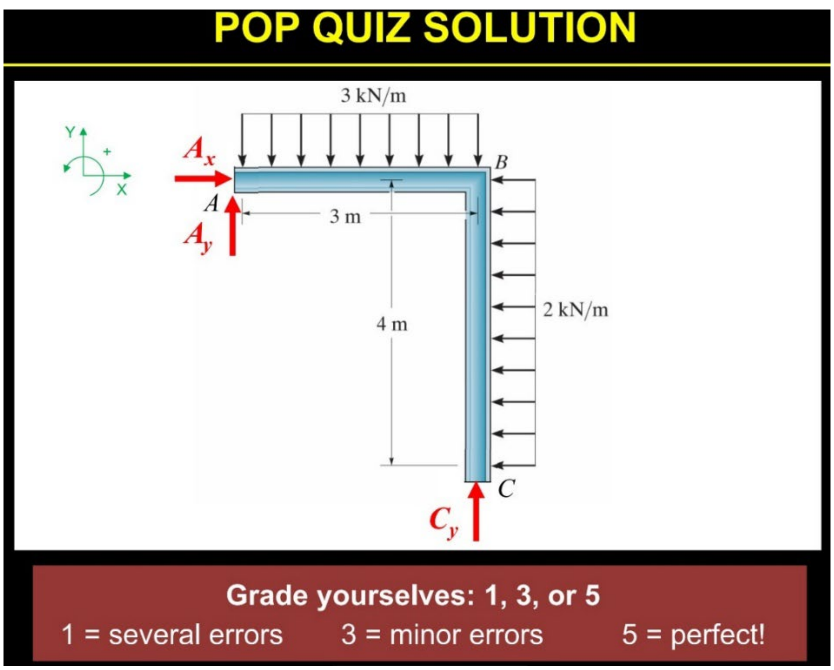

Figure 2: FBD Quiz 1 Solution

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Disclaimer

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