# 2006-1653: IDENTIFYING AND INVESTIGATING DIFFICULT CONCEPTS IN ENGINEERING MECHANICS AND ELECTRIC CIRCUITS

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# Identifying and Investigating Difficult Concepts in Engineering Mechanics and Electric Circuits

## Abstract

Two research questions motivated this study: "What important concepts in electric circuits and engineering mechanics do students find difficult to learn?" and "How can we describe students' mental models of the concepts identified in question 1?" This paper discusses the process used to identify difficult concepts in engineering mechanics and electric circuits, the results of that identification process, and the results of interviews to uncover the mental models engineering students use to explain these concepts. This study, part of the Center for the Advancement in Engineering Education's "Scholarship of Learning Engineering" element, builds on previous work in thermal and transport science and allows comparisons among difficult concepts in chemical engineering, mechanical engineering, and electrical engineering.

## Introduction

The study described in this paper extends ongoing work to identify difficult concepts in thermal and transport science [12] and measure students' understanding of those concepts via a concept inventory [5, 6, 7]. The present work focuses on two fundamental areas of engineering: engineering mechanics (statics, strength of materials, and dynamics), and electric circuits, which are complementary to thermal and transport science. Thus the study was designed with the hope that commonalities might be found among difficult concepts in chemical engineering, mechanical engineering, and electrical engineering. Indeed, our results suggest that commonalities do exist at a very fundamental level.

The paper is organized into three sections. The first two sections will discuss the theoretical framework, methodology, and results of each of the two research questions. This is followed by a section which discusses implications of this work.

## What important concepts in electric circuits and engineering mechanics do students find difficult to learn?

### Theoretical framework

We chose to use Delphi methodology to gather expert opinions about which concepts in electric circuits and in engineering mechanics that were both important and difficult to learn. The Delphi method is a technique that elicits, refines, and draws upon the collective opinion and expertise of a panel of experts [4]. Delphi methodology has been used to elicit information and judgments from experts on anything from planning to problem-solving to decision making [2] and has been successfully used to in our prior work [12]. Four features characterize the Delphi method: anonymity, iteration, feedback, and statistical group response [10].

### Methodology

The Delphi participants were experienced practicing teachers in their respective engineering fields. There were two groups of participants: 10 faculty in circuits/electrical engineering participated in the electric circuits Delphi, and 13 faculty in mechanical/civil engineering participated in the engineering mechanics Delphi. Participants in the circuits/electrical engineering group had an average of 19 years of teaching at the college level and an average of 2.9 years of working in industry. One was a textbook author. Participants in the mechanical/civil engineering group had an average of 17 years of college teaching experience and an average of 3.4 years of working in industry. Six of the mechanical/civil experts were also textbook authors.

The Delphi method is based on a structured process for collecting and distilling knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback [1]. We followed the suggestion by Adler [1] that each Delphi begin with a generative round (which we called Round 0), followed by Rounds 1, 2, and 3, where participants ranked the items generated in Round 0. Convergence of ratings usually occurs within three rounds [3]. Information about each Round follows.

*Round 0*.

In Round 0, the Delphi participants generated lists of engineering concepts that were, in their opinion, most important and least understood by engineering students in their respective fields. Two researchers and one content expert coded the answers from the Mechanical/Civil Engineering experts and identified 28 engineering mechanics concepts that were reported by at least two people. Two researchers and a different content expert coded the Circuits responses and identified 27 concepts that were reported by at least two Circuits experts. These two lists of potentially important and difficult concepts were then used in Rounds 1, 2, and 3 of the Delphi study and are found in Table 1 and Table 2.

*Round 1*.

Each participant was given, via a web survey, their respective list of concepts and were to rate each concept on a scale from 1 to 10 on importance (1 = the concept is not important at all; 10 = the concept is extremely important) and on a scale from 1 to 10 on understanding (1 = students had no understanding of the concept; 10 = student have complete understanding of the concept). The median and the interquartile range for each concept were computed. See Table 1 and Table 2.

*Round 2*.

The participants were given a list of the concepts along with the medians and the interquartile ranges that were computed from Round 1. They were asked to rate each concept again, but this time, if their rating fell outside the interquartile range (the middle 50%), they were asked to provide a justification for their rating. New medians and interquartiles were computed from the Round 2 data.

*Round 3*.

The participants were then given the list of ratings from Round 2, along with justifications of those ratings outside the interquartile range. They were asked to rate the concepts for a final time, however, in this iteration, they did not have to justify ratings.

Delphi Results

Tables 1 and 2 track the change in the median ratings ratings over the 3 rounds. In most cases, the interquartile range of ratings decreases as the Rounds progress, and this is evidence of the convergence of opinions that one expects to see in a Delphi survey. Figures 1 and 2 are a graphical representation of the medians of the third round of each Delphi study. In the Circuits Delphi, all concepts had a median of 5 or more on importance and all but two concepts had a median of 5 of more on understanding. In the Mechanics Delphi all concepts were rated with a 5 or greater on importance and about two-thirds of the concepts were rated with a 5 or greater on understanding. In both cases, the concepts that eventually became concept questions are indicated with a square on Figures 1 and 2.

Although the results of the Delphi did converge as expected, neither the Electric Circuits and Engineering Mechanics Delphis indicated a group of concepts that were rated both as very important and very difficult to learn (i.e. poorly understood). This created some ambiguity about which concepts warranted further investigation. In order to gather additional input from experts, the results of the Delphi surveys were taken to an interactive workshop hosted at the Frontiers in Education conference [5]. Workshop participants were invited to gather according to discipline (chemical, mechanical, or electrical engineering) and then examine and comment on the Delphi results that most closely matched their expertise. They were asked to consider whether, based on their expertise, the results made sense. We also requested that they report which topics they considered "most difficult" and "most important." Session attendees were allowed to agree or disagree with the numerical findings of the Delphi surveys. The results of this session were taken into consideration when determining concepts of interest for the Circuits and Engineering Mechanics studies. The concepts that the FIE participants chose as difficult and important are indicated with a triangle shape in Figures 1 and 2.

Content experts met with the research team to determine which concepts in each field should be investigated. In addition to the Delphi results, data was provided from three other sources: input from faculty attending the FIE conference described above; theoretical "concepts of interest" from a distinguished cognitive psychologist; and practical input from the respective content experts themselves. Synthesis of the Delphi survey results, plus the three additional sources described above, resulted in lists of concepts in Engineering Mechanics and in Electric Circuits that were to be investigated further using students interviews.

It was determined that the Engineering Mechanics interviews should focus on the following concepts: *force* (including *internal and external force*, *free body diagrams*, *weight vs. mass*, and *distributed forces*), *stress and strain*, *friction* (both static and dynamic friction) and *moment of inertia*.

Electric Circuits interviews would focus on the following concepts: *AC steady-state circuit analysis* (including *AC power*), the *five fundamental electrical quantities* (charge, current, voltage, power, and energy), *Kirchhoff's Laws*, and *Thevenin/Norton* equivalent circuits.

Using these lists as guides, content experts created both calculation-based and open-ended questions that addressed these concepts. This now allowed us to begin to answer our second research question: *How can we describe students' mental models of these important and difficult concepts?*

**How can we describe students' mental models of these important and difficult concepts?**

Theoretical framework

As the conceptual framework to answer this question, we use the work of Reiner, Slotta, Chi, and Resnick [7] who posited that fundamental concepts like force, voltage, and current may be difficult for students to learn because students view those processes as if they were substances. Reiner et al. called this propensity to view processes as substances a "substance-based schema" and listed 11 attributes which are mistakenly applied to processes. Among these substance attributes is having a location, and being able to be consumed or contained. As we will discuss in the results section, we did found evidence that the student who were interviewed may have thought of *force* and *voltage* as substances.

Methodology

To begin the process of describing students' mental models of the concepts listed in the previous section, both content experts created questions to address each concept in their respective field. Questions were taken from exams or textbooks. In the case of the Engineering Mechanics interviews, three of a total of ten questions were adapted from the Statics Concepts Test (used with permission) [11]. Colorado School of Mines (CSM) seniors with a specialty in either electrical or civil or mechanical engineering were recruited via an email to the engineering seniors email list. Ten students (5 in electrical and 5 in civil/mechanical) were interviewed for one-hour each in March 2005. Student responses were transcribed and coded. Interpretation of results took place during the summer of 2005.

Based on the results of the first round of interviews, content experts could make changes to the list of interview questions for a second round of interviews. Changes made to both the Engineering Mechanics questions and the Electric Circuit questions. The content of the electric circuit questions were changed to include only four open-ended questions that were designed to target the difficult circuit concepts of energy, charge, voltage, and current.

A different group of CSM seniors was recruited to answer these questions in October 2005. During the second round of one-hour interviews nine more students (5 electrical and 4 civil/mechanical) seniors were interviewed. Responses were again transcribed and coded. In both rounds of interviews each student was paid $20 for their participation, and standard protocols for human subjects research were followed.

Results

Results of the Delphi analysis suggest that concepts rated as important and well-understood by the Delphi participants are NOT understood by students. For example, as we will explain below, concepts such as *Charge vs. Voltage vs. Current* – which Delphi participants gave an understanding of 8 (with 10 meaning "everyone understands this") were very poorly understood when probed with open-ended questions. Why did the Delphi ratings not agree with the interview results? Because the Delphi results did converge and reach stability, we are confident that the Delphi results are representative of the collective opinion of the group of faculty who participated in the Delphi. So it does not seem that a flaw in the Delphi methodology itself resulted in this inconsistency. It is possible the students who were interviewed were not representative of the general population. Interviewees were self-selected, there was no grade point requirement, and came from only one institution, the Colorado School of Mines. Since the students who were interviewed were close to graduation, they were by default in good academic standing. They also volunteered to be interviewed knowing they would be asked to explain difficult concepts. Our speculation is that this circumstance would have skewed participants toward those who felt they understood the concepts well, as a $20 payment may not be worth the risk of being asked to answer questions you do not understand. Our best explanation for the mismatch between Delphi results and interviews is that the Delphi participants did not fully understand the degree to which their students did or did not understanding of the concepts they were rating. Although we invited experienced faculty to be part of the Delphi, we have found it is not uncommon for faculty to overestimate the degree to which students understand concepts [6, 7]. Replication of the interviews at another institution would help to determine if the mismatch in Delphi and interview results is an institutional effect, or more widespread.

Our interviews suggest that students do not fully understand fundamental concepts like *force* (in the case of Engineering Mechanics) and *voltage* (in the case of Electric Circuits). Analysis of interview results suggests that, as Reiner and her colleagues posited, students understand phenomenon like *voltage* and *force* to be substances. For example, students answering questions about free body diagrams may say that tension is a force inside a rope (so *force* is seen as a property of the rope, not the interaction between two or more bodies). Electrical engineering students talk about *voltage* as being the property of a particular location, not the charge difference between two locations.

## Implications

Our results agree with previous studies of engineering difficult concepts and misconceptions that suggest that engineering students who are academically successful often lack deep understanding of fundamental concepts in their field [6, 7]. Our results also support the work of Reiner et al. [9] who posited that fundamental concepts like *force*, *voltage*, and *current* may be difficult for students to learn because students view those processes as if they were substances. For students possessing a substance-based schema, the concept "force" (which is actually the *interaction* between two or more bodies) is thought to be a substance that is a property of a body. Likewise, voltage (the *charge difference* between two locations) is thought to be a substance that is the property of a particular location. Ongoing work in thermal science, particularly heat transfer, suggests that chemical and mechanical engineers may be misapplying the process vs. substance schema by confusing *rate* with *amount* [7]. Taken together, these studies suggest that evidence of substance-based models for processes may be present among students from chemical, mechanical and electrical engineering. If true, this suggests that helping students to create more accurate mental models, that represent emergent processes truly as processes, not substances, may be beneficial in many areas of engineering. Future work to create training modules to help students construct these accurate mental models will begin shortly.

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Table 1. Ranking Results from Electric Circuits Delphi Study Rounds 1, 2, and 3

| Concept | Understood? | | | Importance? | | |
|---|---|---|---|---|---|---|
| | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 |
| 1. AC Power Concepts | 6 (4.25, 6.25) | 5 (4, 6) | 5 (4, 6) | 8 (6, 8) | 7 (7, 8) | 8 (7, 8) |
| 2. AC Steady-State Circuit Analysis (Phasors and Impedance) | 6 (4.75, 8) | 6 (4, 7) | 5.5 (5, 6.25) | 9 (7.5, 10) | 9 (8, 10) | 9.5 (8, 10) |
| 3. Active-Passive Power Sign Convention | 8 (8, 9) | 9 (8, 9) | 9 (9, 9) | 8 (5, 10) | 10 (7, 10) | 10 (9, 10) |
| 4. Charge vs. Voltage vs. Current | 7 (7, 9) | 8 (7, 9) | 8 (7, 8.25) | 10 (5, 10) | 10 (6, 10) | 8 (7.5, 10) |
| 5. Complex Numbers | 8 (5, 9) | 8 (5, 9) | 7 (5, 8.25) | 9 (5.75, 10) | 9 (9, 10) | 9 (8, 10) |
| 6. Current Divider | 6 (5, 8) | 7 (5, 8) | 6 (5, 7.25) | 8 (7, 10) | 8 (6, 10) | 8 (6.75, 8.25) |
| 7. Dependent Sources | 5 (4, 8) | 6 (4, 7) | 5.5 (4, 7) | 9 (7.75, 10) | 9 (8, 10) | 9 (7.75, 9) |
| 8. Energy Storage Elements (Inductance and Capacitance) | 7 (6, 9) | 7 (6, 8) | 7 (6.75, 8) | 10 (8, 10) | 10 (10, 10) | 10 (9.75, 10) |
| 9. Energy vs. Power | 7 (4, 8) | 7 (6, 7) | 6 (6, 7) | 10 (5, 10) | 10 (7, 10) | 9 (7.75, 10) |
| 10. Equivalent Resistance | 7 (4.5, 10) | 7 (5, 8) | 7 (5.75, 8) | 8 (6.5, 9.25) | 9 (8, 9.25) | 9 (8, 9.25) |
| 11. Frequency Response | 6.5 (2.25, 8) | 6 (4.5, 7) | 5 (4.5, 6) | 9 (7, 10) | 9.5 (8, 10) | 9 (8.5, 10) |
| 12. Interpretation of Circuit Diagrams | 6 (5, 8) | 6 (5, 7) | 6 (5.75, 6) | 8 (6, 10) | 10 (8, 10) | 9 (8.75, 10) |
| 13. I-V Characteristics of Current & Voltage Sources | 6 (5, 8) | 5 (5, 6) | 5 (5, 6) | 7 (5, 10) | 7 (6, 9) | 8.5 (6, 9) |
| 14. Kirchhoff's Laws | 9 (8, 10) | 9 (8, 10) | 8 (8, 9) | 10 (10, 10) | 10 (10, 10) | 10 (10, 10) |
| 15. Mesh vs. Node Method | 5 (3, 7) | 5 (5, 6) | 5 (4, 5) | 6 (5, 9) | 6 (5, 7) | 6 (5, 7) |
| 16. Mess-Current Method | 5 (4, 8) | 6 (5, 7) | 6 (5.75, 7) | 7 (3, 9) | 8 (5, 8) | 7 (5, 8) |
| 17. Node-Voltage Method | 8 (6, 8) | 7 (6, 8) | 7.5 (6, 8) | 9 (6, 10) | 10 (8, 10) | 9.5 (8, 10) |
| 18. Operational Amplifiers | 6 (6, 8) | 6 (6, 7) | 6 (6, 7) | 8 (7, 10) | 8.5 (8, 9) | 9 (8, 9) |
| 19. Reactive Power | 4 (2, 5) | 4 (2, 4) | 3 (2, 4.5) | 7 (6, 7) | 6 (6, 7) | 6 (5, 6.5) |
| 20. RLC Circuits | 6 (4, 7) | 5 (5, 6) | 5.5 (5, 6) | 7 (6, 9) | 8 (7, 9) | 8.5 (8, 9) |
| 21. Series and Parallel Circuit Elements | 8 (6, 10) | 9 (7, 9) | 9 (7, 9) | 9 (8, 10) | 10 (8, 10) | 9.5 (8.75, 10) |
| 22. Superposition Method of Circuit Analysis | 7 (4, 8) | 8 (6, 8) | 7 (6, 8) | 5 (5, 8) | 8 (5, 8) | 7.5 (7, 8) |
| 23. Thevenin/Norton Equivalent Circuits | 4 (3, 8) | 6 (4, 7) | 6 (4.75, 6.2) | 8 (7, 10) | 10 (8, 10) | 10 (9, 10) |
| 24. Three Phase System | 4 (3, 7) | 5 (2.75, 5.2) | 5 (2.5, 5) | 5 (3.75, 6) | 5 (4, 5.25) | 5 (4, 5) |
| 25. Transient Analysis (RC & RL Circuits) | 5 (4, 7) | 5 (5, 7) | 5.5 (5, 6) | 8(5, 9) | 9 (8, 9) | 9 (8, 9) |
| 26. Two Port Networks | 3 (3, 7) | 3 (2.75, 4.2) | 3 (2, 3) | 5 (2, 6.5) | 5 (3.75, 5.25) | 5 (3.5, 5) |
| 27. Voltage Divider | 7 (5, 9) | 8 (7, 8) | 8 (7, 8) | 10 (7, 10) | 10 (9, 10) | 10 (8, 10) |

| **Understanding Scale** | **Importance Scale** |
|---|---|
| 1 = no one understands the concept | 1 = not at all important to understand the concept |
| 10 = everyone understands the concept | 10 = extremely important to understand the concept |

Table 2. Ranking Results from Engineering Mechanics Delphi Study Rounds 1, 2, and 3

| Concept | Understood? | | | Importance? | | |
|---|---|---|---|---|---|---|
| | Round 1 | Round 2 | Round 3 | Round 1 | Round 2 | Round 3 |
| 1. 3-D Visualization | 3 (2.25, 5) | 4 (3, 5) | 4 (3.5, 5) | 8 (7, 9) | 8 (7.25, 9) | 8 (7.5, 9) |
| 2. Beam Deflection | 6 (4, 7) | 5.5 (5, 7) | 6 (5, 6) | 8 (7, 10) | 9 (8, 9) | 8 (7, 9) |
| 3. Beam Shear Stress | 5 (3, 6.5) | 4 (3, 5) | 4 (3, 5) | 8 (5.75, 10) | 6 (5, 9) | 7 (6, 8) |
| 4. Beams- Normal Stress | 7 (6, 8) | 7 (6, 8) | 7 (6, 8) | 10 (8, 10) | 9 (8, 10) | 9 (8.25, 10) |
| 5. Combined Loading /Column Buckling | 5 (4, 7) | 5 (4.5, 6) | 5 (4, 5) | 9 (7.25, 9.75) | 8.5 (7.75, 9) | 8 (8, 9) |
| 6. Conservation of Energy Thru Impact | 3 (3, 5.75) | 3 (3, 4.5) | 3 (3, 4) | 7.5 (3, 9.75) | 8 (5.5, 8.5) | 7 (7, 7.75) |
| 7. Couple | 5 (4, 7) | 5 (3.25, 7) | 5 (4.5, 7) | 8 (4, 10) | 8 (6.25, 9) | 7 (6.5, 9) |
| 8. Distributed Forces | 7 (4, 8) | 5 (5, 6.75) | 5 (5, 6) | 9 (8, 10) | 9 (8.25, 9.75) | 9 (8.5, 9) |
| 9. Equilibrium – sum of forces = 0, sum of moments = 0 (Newton's 3rd Law) | 7 (6, 8) | 7.5 (6.25, 8) | 7 (6.5, 8) | 10 (10, 10) | 10 (10, 10) | 10 (10, 10) |
| 10. External vs. Internal Forces | 5 (4, 6.5) | 5 (4, 6.75) | 5 (4.5, 6) | 9 (8, 10) | 10 (9, 10) | 10 (9, 10) |
| 11. Importance of signs on forces | 5 (4.25, 7.75) | 6.5 (5, 7) | 5 (5, 7) | 7.5 (6, 10) | 8.5 (7, 9.75) | 8 (7, 9) |
| 12. Isolating a body from surroundings | 5 (4, 6.75) | 5 (4, 6) | 5 (4.5, 6.5) | 9 (9, 10) | 10 (9, 10) | 10 (9, 10) |
| 13. Linear vs. Circular Velocity and Acceleration | 4.5 (3, 6) | 5 (3, 5.5) | 5 (3.5, 5) | 7.5 (3.75, 10) | 8 (7, 9) | 8 (8, 8) |
| 14. Mohr's Circle | 6 (3. 7.5) | 6 (5, 6.5) | 5.5 (5, 6) | 7 (6, 10) | 6 (4, 8) | 5.5 (2.75, 8) |
| 15. Moment of Inertia | 4 (3, 7) | 4 (3, 7) | 4 (4, 5) | 9 (7, 10) | 8 (8, 9) | 9 (8, 9) |
| 16. Moments | 7 (5, 8) | 7 (6, 7.75) | 6 (6, 6.75) | 10 (9, 10) | 10 (9.25, 10) | 10 (10, 10) |
| 17. Momentum | 7 (2, 8) | 5 (3.5, 6.5) | 5 (3.5, 5.5) | 8.5 (6.75, 9.25) | 9 (8, 9) | 9 (8.5, 9.5) |
| 18. Rolling/Kinetic Friction | 3 (2, 6) | 4 (2.75, 6) | 4 (3, 4) | 9 (5.25, 9.75) | 8 (7, 9) | 7.5 (7, 8) |
| 19. Shear Force | 5 (3.5, 7.5) | 5 (4.5, 6) | 5.5 (5, 6) | 9 (7, 10) | 9 (8, 9) | 8 (7.25, 9) |
| 20. Static Friction | 5 (3, 6) | 5.5 (4, 6) | 5 (4.5, 6) | 8 (7, 9) | 8 (7.25, 9) | 8 (8, 9) |
| 21. Statically Indeterminant Members | 3 (2, 5) | 3.5 (2, 4.25) | 3.5 (3, 4) | 9 (8, 10) | 10 (8, 10) | 9 (8.5, 10) |
| 22. Stress vs. Strain | 6 (4.5, 7.5) | 7 (5, 7) | 6 (6, 7) | 10 (9, 10) | 10 (9, 10) | 10 (9, 10) |
| 23. Sum of Forces not equal to 0 in dynamics | 6 (3, 8) | 6 (4, 7) | 5.5 (4, 6) | 10 (9, 10) | 10 (9, 10) | 10 (9, 10) |
| 24. Torsion | 5 (4, 8) | 6 (5, 7) | 6 (5.5, 7) | 9 (8, 10) | 9 (8.75, 10) | 9 (9, 9) |
| 25. Translational & Rotational Motion | 5.5 (3, 6) | 4.5 (3.25, 5) | 4 (3, 5) | 9 (7.75, 10) | 8.5 (8, 9) | 8 (8, 9) |
| 26. Truss Analysis | 5.5 (5, 8) | 6 (5, 7) | 6 (5.5, 7) | 8 (5.75, 10) | 9 (5, 9) | 9 (6, 9) |
| 27. Two Force Members | 5 (5, 8) | 6 (5, 7) | 6 (5, 6.5) | 8 (6, 10) | 8 (6, 9) | 7 (6.5, 8.5) |
| 28. Weight vs. Mass | 7 (5, 8) | 7 (6, 7) | 7 (6, 7) | 10 (6.5, 10) | 9.5 (9, 10) | 10 (9, 10) |

| **Understanding Scale** | **Importance Scale** |
|---|---|
| 1 = no one understands the concept | 1 = not at all important to understand the concept |
| 10 = everyone understands the concept | 10 = extremely important to understand the concept |

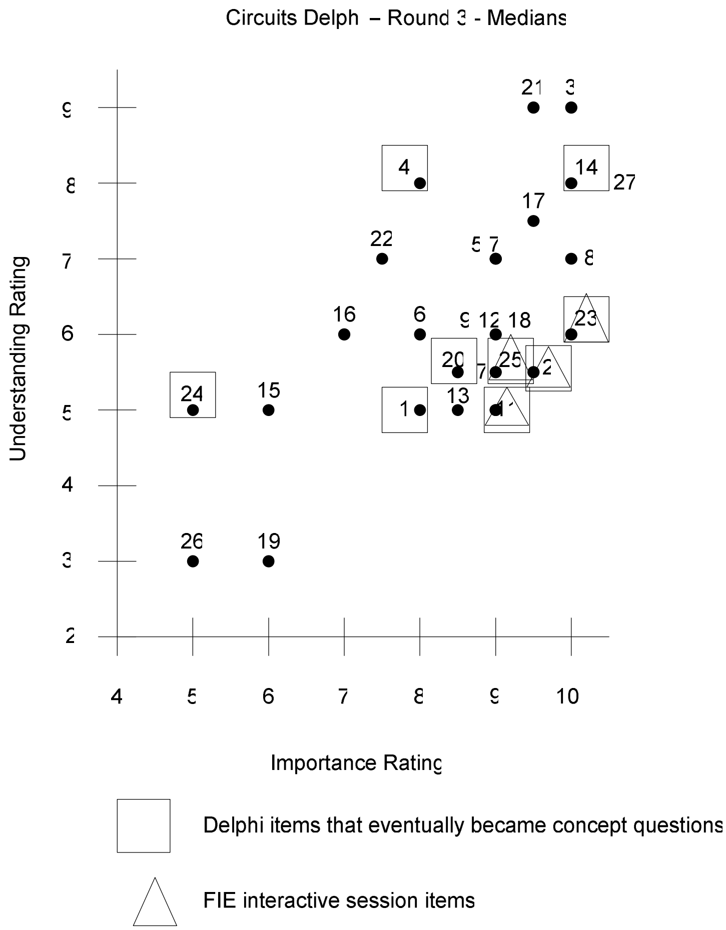


Figure 1 – Relationship between Delphi result on importance and understanding. Numbers shown refer to concept numbers listed in Table 1.

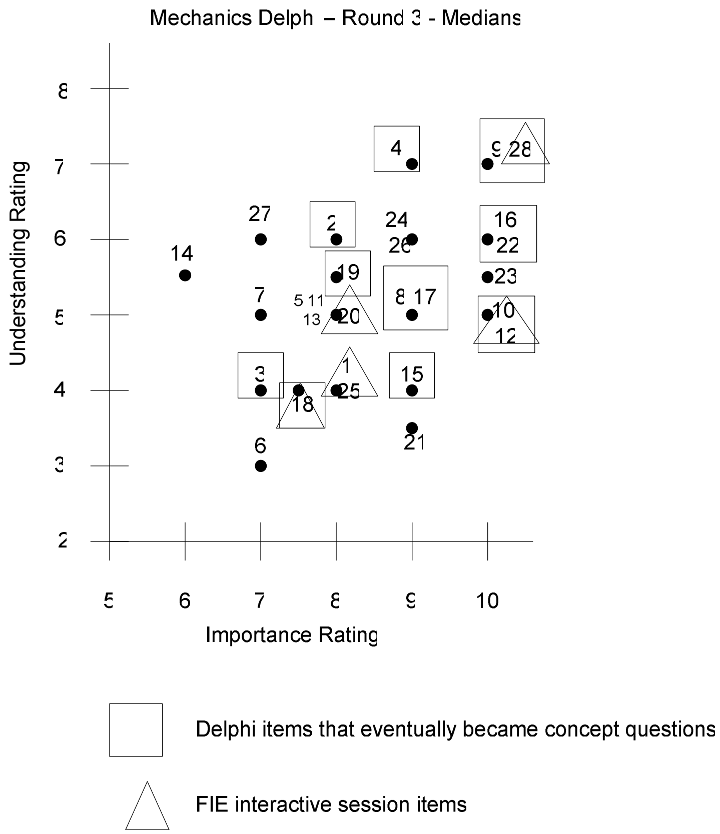


Figure 2 – Relationship between Delphi result on importance and understanding. Numbers shown refer to concept numbers listed in Table 2.