Abstract Title Page

Title: Evaluating the Diagnostic Validity of the Facet-based Formative Assessment System

Author(s): Angela H. DeBarger, Louis DiBello, Jim Minstrell, William Stout, James Pellegrino, Geneva Haertel, and Mingyu Feng

Abstract Body

Background / Context:

We report on a rigorous, multidisciplinary investigation of the heavily utilized Physics Diagnoser formative assessment system. Our focus is on multiple aspects of diagnostic, instructional and content validity of the system and assessments relative to their use in science classrooms.

Facet-based assessments are one innovative approach to helping teachers diagnose students' science understanding (Minstrell, 2001; Minstrell, Anderson, Kraus, & Minstrell, 2008). The facets perspective assumes that students' understandings possess some strengths to build on, possibly in addition to problematic thinking that can be revised through additional learning opportunities. The term "facets" acknowledges that not all students' thinking can be considered "misconceptions" or errors. Facet clusters serve as the interpretive framework for analyzing student responses to questions and for designing instructional activities to promote learning.

Despite the designed-in multidimensionality of facet-based assessments, the preponderance of psychometric analyses performed so far have failed to capture the richness of the evidence about what students know and how they know it. Standard classical test theory or unidimensional approaches can be useful for capturing some critical measurement properties of items and instruments [such as gross item indices of "difficulty," biserial correlations with total score, and unidimensional indices of total score reliability including KR20 and Cronbach's alpha (Cronbach, 1951; Lord & Novick, 1968; Allen & Yen, 2002; van der Linden & Hambleton, 1997)], but are not designed to reflect the facet-based multidimensional richness of the data.

In light of the rich conceptual and cognitive model guiding item development and data collection, the failure to use more powerful measurement models means that the linkage from observation to interpretation and from interpretation back to cognition is only of the most rudimentary form. The work reported here provides a strong interpretive framework supported by sophisticated psychometric techniques as a way of capturing the diagnostic power of the instrument, and enhancing its usefulness as a formative assessment tool. Our approach provides insight about the potential of the facet-based approach to offer a clear and transparent articulation of the linkage between the assumptions about cognition and observed student performance.

Purpose / Objective / Research Question / Focus of Study:

The research design and team constitute a multidisciplinary attack on problems of educational and assessment design in physics instruction. Components of the research include: (a) an Evidence-Centered Design analysis of Diagnoser instructional materials and assessments that provides a view of the evidentiary coherence of the existing system; (b) an alignment study of the Diagnoser system with multiple standards frameworks that describes deep connections among existing standards frameworks and the Diagnoser system and illuminates how alignment approaches can simultaneously inform all aspects of a formative assessment system; (c) the application of sophisticated psychometric models to the existing data that provides statistical evidence for inferential claims that support classroom use of the Diagnoser system; and (d) the identification of cases in which new or improved Diagnoser question sets can be developed and tested with students. This paper focuses on methodologies associated with the psychometric analyses of the Diagnoser question sets and the alignment study.

Force and Motion content was targeted in this project for two reasons. First, extensive research has been conducted on misconceptions in force and motion (e.g., Driver et al., 1994; Hashweh, 1988; Lythcott, 1985; Wandersee et al., 1994) and by staff of several related

Diagnoser projects, providing a substantial research basis for the design of the instructional materials and assessments. Second, Force and Motion clusters are among the earliest developed as part of the online Physics Diagnoser and have been used continually since 2004 during which has been available via the internet, providing a large database of student performances for analysis.

Setting:

The study focuses on secondary school level physical science and physics instruction and assessment in Forces and Motion. The content is organized into three key concept strands (Description of Motion, Nature of Forces, and Forces to Explain Motion) and seventeen conceptual facet clusters, and includes more than thirty facet-based question sets. The list of facet clusters associated with each strand in Table 1 specifies the scope of the content. All instructional and assessment materials are available on the Diagnoser formative assessment system (www.Diagnoser.com).

Population / Participants / Subjects:

Since the launch of the present version of Diagnoser in September 2004, about 4000 teachers have registered to use the system. Nearly 300,000 question sets (3 million items) have been completed by typical middle school and high school physical science and physics students during the period 2004-2009. Roughly half these data will be the focus of this study.

Intervention / Program / Practice:

Facet clusters are presented online to students and teachers via www.Diagnoser.com. Figure 1 shows the Forces as Interactions cluster as an example. Diagnoser includes questions to elicit student preconceptions (elicitation questions), lessons to allow students to test ideas and understandings (developmental lessons), sets of facet-based assessment items (question sets), and activities to address persistent problematic understandings (prescriptive activities). Each question set is composed of 6 to 12 items, and includes multiple-choice, numerical response, and open-ended text formats. Figure 2 presents one question set associated with the Forces as Interactions cluster. Teachers receive real-time results from question sets in reports describing the facets inferred for each student.

Research Design:

Psychometric analyses will include baseline unidimensional analyses, diagnostic modeling that includes new approaches for taking into account multiple choice distractors linked to specific facets, and direct statistical analyses of a students' patterns of inferred facets within a question set. We are computing a facet prevalence value for each student, each question set and each facet based on how many times that facet response was inferred for that student compared to the set of all inferred facets. We will compare students' facet prevalence values and their patterns to students' diagnostic model-computed facet profiles. We report on a comparison of students' performances at middle school and high school levels within and between clusters. To ensure that estimates of standard error, effect sizes, and statistical significance are not artificially inflated or deflated, we are accounting for clustering of students within classes by performing Hierarchical Linear Modeling (Raudenbush & Bryk, 2002) analyses.

The Alignment Study will evaluate the content and diagnostic validity of the Diagnoser system, with an emphasis on an analysis of facet clusters and question sets, as shown in Table 2.

Three panelists with expertise in physics content and science assessment will rate the alignment of facet clusters to standards frameworks and also rate the diagnostic capabilities of the question sets. All ratings will be completed independently.

Data Collection and Analysis:

Diagnostic Question Set Data. Existing Physics Diagnoser data available for analysis have been collected through the online website http://www.Diagnoser.com/. The primary student outcomes are the "facet scores" from a student's question set responses, which are a sequence of inferred facets derived from a student's multiple-choice responses. We summarize and represent students' facet scores for a given question set in three ways: (1) prevalence across the question set of inferred facets; which facets occurred and how often; (2) patterns of inferred facets; and (3) degree of consistency within a given student's facet pattern.

Advanced psychometric analyses focus on two main objectives: (1) to summarize the observed ranges and patterns of performance of a variety of groups of students in the question sets associated with each cluster; and (2) to provide a definitive evaluation of the diagnostic capacity of the question sets with respect to inferring students' facet profiles. Previous model-based psychometric studies of facet-based assessments have had limited success in capturing students' observed performance on items in ways that were aligned with the cluster and facets structure (Wilson 1992, 2008; Steedle & Shavelson, 2009; Steedle, 2008; Scalise, Madhyastha, Minstrell, and Wilson, 2010). We will report on a fresh set of approaches that take into account structural and design characteristics of the facets assessments using multidimensional diagnostic models. Highly promising diagnostic model-based analyses have been completed of another type of misconception-based assessment called concept inventories (Santiago-Román, 2009; Santiago-Román et. al., in preparation). In that work a set of "skills" for diagnostic measurement and reporting was shown to be highly predictive of student performance. We are carrying out similar diagnostic analyses for facet-based assessments, guided by findings from the alignment analyses and ECD analyses, and we are using a constrained latent class model for cognitive diagnosis called the Fusion Model and Markov Chain Monte Carlo model calibration methods (DiBello, Roussos & Stout, 2007; DiBello & Stout, 2003; DiBello & Stout 2007), as well as a partial credit model that allows for two possible responses to have the same ordered score level to scale the response data (Wilson 1992, 2008). New diagnostic models are being applied that take account of facet information linked to multiple choice options (DiBello, Stout & Henson, in press; also see de la Torre 2009).

Alignment Study. In contrast to typical alignment studies, this study will provide more substantial evidence about the diagnostic capabilities of the Diagnoser formative assessment system. Panelists will judge each facet cluster's alignment to three frameworks (AAAS Benchmarks for Scientific Literacy, College Board Science Standards, and the core and component ideas in the NRC's New Framework for Science Education Standards). Each panelist first will make a judgment about the degree to which the goal facets in each cluster address the content in the standards using a 4-point Likert scale (1 = Fully aligned to 4 = Not aligned). Particularly relevant to evaluating the diagnostic capabilities of the system, panelists also will: (a) judge the extent to which the problematic facets in each cluster reflect common misconceptions supported in the literature using a 5-point scale (1 = Very good coverage to 5 = Very poor coverage); and (b) confirm that problematic facets in each cluster are appropriately ranked from less to more problematic.

For each item in Diagnoser question sets, panelists will evaluate the extent to which response options exemplify the facets as they are coded. Panelists also will indicate which scientific practices (e.g., developing evidence-based models and explanations, reasoning about the relationships between variables) are elicited by associating questions with performance expectations in the College Board Standards. In addition, panelists will judge the degree to which the assessment tasks cover a range of representations and contexts needed to assess the content in the facet clusters. Because the data from question sets are critical for helping teachers make instructional decisions, panelists will indicate how effectively the reports: (a) communicate what students know and can do and (b) inform next instructional steps using a 4-point rating scales (Not at all effective/useful to Very effective/useful) and open-ended text responses.

Finally, for each question set panelists will review three common pathways through the question sets (based on actual student data), as not all students complete the same questions or questions in the same sequence. For each pathway panelists will evaluate whether questions are presented in a logical, conceptually appropriate for use by teachers to diagnose and remediate the misconceptions the students hold. Panelists will respond using a 4-point scale ranging from strongly agree to strongly disagree.

For each question in the alignment protocol, agreement will be calculated on judgments between panelists. If possible, discrepant ratings will be resolved by consensus.

Findings / Results:

Preliminary findings from analyses of diagnostic data and the alignment study are expected by August. Findings from psychometric analyses are expected to provide statistical evidence for degree of consistency between students' answer choices and inferred facet understandings. The analyses will include a comprehensive statistical description of facet patterns as they vary across groups of students and across clusters. A set of diagnostic inferential characteristics will be computed as measures of the diagnostic quality of the existing facets assessments. This first round of results from both studies will provide a basis for redesign or improvement of facet questions to be tested with new groups of students during the second half of the project.

Conclusions:

A key contribution of this project is its application of rigorous methods of psychometric and evidentiary analyses to the existing Physics Diagnoser system and its extensive existing database of student performance. These analyses will logically and statistically test the degree of concordance of the existing system and the substantial facets system developmental foundations and design which were based on pragmatic, subject area instructional and pedagogical expertise and early literature on physics teaching and learning and on misconception research. The Alignment Study implements a new approach for a comprehensive analysis of a formative assessment system. The psychometric analyses apply new diagnostic and statistical approaches to a very large database of existing data. In concert these approaches are assembling multiple strands of evidence to build a powerful, theoretically and empirically grounded validity argument that directly impacts the pragmatic successes of the Physics Diagnoser system, and that is expected to lead to methods for improving the questions to be tested with students in the second half of the project. In sum, this project applies a rigorous comprehensive approach to understanding the cognitive, instructional and inferential underpinnings of the Physics Diagnoser system in light of the Diagnoser's pragmatic classroom applications.

Appendix A. References

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Appendix B. Tables and Figures

Table 1
Strands and Clusters in Diagnoser

Strands	Clusters
Description of Motion	1. Position and Distance 2. Change in Direction 3. Determining Speed 4. Average Speed 5. Change in Speed 6. Acceleration
Nature of Forces	1. Identifying Forces 2. Forces Acting at a Distance 3. Forces as Interactions 4. Gravitational Forces 5. Magnetic Forces 6. Electric Forces 7. Electromagnetic
Forces to Explain Motion	1. Effects of Pushes and Pulls 2. Explaining Constant Speed 3. Explaining Changes in 1D Motion 4. Explaining Changes in 2D Motion

Source. www.Diagnoser.com

Table 2

Research Questions and Approach for Alignment Study

Research Questions	**Alignment to Internal or External Criteria or Other**	**Type of Validity**
RQ1: To what degree do standards and facet clusters address the same content categories?	**External:** Alignment of goal facets to 3 standards frameworks (Benchmarks for Scientific Literacy, College Board Standards objectives, and New Framework for Science Education core and component ideas	Content
RQ2: Do problematic facets represent the range of frequent 'misconceptions' and problematic ways of thinking?	**External:** Alignment of problematic facets to misconceptions reflected in research	Diagnostic; Cognitive
RQ3: Does the ranking of problematic facets reflect an order of less to more problematic?	**Other:** Judgment of the degree to which the ranking of the problematic facts reflect an order of less to more problematical	Diagnostic; Cognitive
RQ4: To what degree do Diagnoser questions align to facet clusters? (To what degree does the correct answer align to the goal facet? To what degree do the incorrect answers align to the problematic facets?)	**Internal:** Alignment of each question to facet cluster	Diagnostic; Cognitive; Indirect content validity*
RQ5: How well do the Diagnoser questions align with the scientific practices identified in the College Board Standards?	**External:** Alignment of each question to performance expectations in the College Board Standards for physical science and physics. (Performance expectations reflect the integration of practice with content specified in the associated objective.)	Content
RQ6: What degree of depth or complexity of knowledge do Diagnoser questions address?	**External:** Alignment of each question to components reflecting depth of knowledge (declarative, procedural, schematic, or strategic)	Cognitive
RQ7: Do the questions for each facet cluster provide opportunities for students to demonstrate knowledge of the facets using a range of representations and different contexts?	**Other:** Degree to which the assessment tasks cover a range of representations and different contexts	Diagnostic
RQ8: How well do the reports communicate student performance in ways that teachers understand and inform next instructional steps?	**Other:** Judgment of the effectiveness of the Diagnoser question set reporting functionality for supporting formative use of the question sets	Diagnostic
RQ9: To what extent do the pathways through the questions in each Diagnoser Question Set represent a logical, conceptually appropriate sequence?	**Other:** Judgment of the degree to which questions are presented in a logical, conceptually appropriate sequence in order to diagnose the misconceptions the students hold and remediate the misconceptions the students hold.	Diagnostic

*Indirect content validity signifies that if questions are aligned to facet cluster and facet clusters are aligned to content standards, we can infer that questions are aligned to content standards.

Facet Cluster - Forces as Interactions

Facets and facet clusters are a framework for organizing the research on student conceptions so that it is understandable to both discipline experts and teachers. Facet clusters include the explicit learning goals in addition to various sorts of reasoning, conceptual, and procedural difficulties. Each cluster contains the intuitive ideas students have as they move toward scientifically accurate learning targets.

Facets are arranged with the Goal Facets at the top of the page followed by the more problematic facets. Each facet has a two-digit number. The 0X and 1X facets are the learning targets. The facets that begin with the numbers 2X through 9X indicate ideas that have more problematic aspects. In general, the higher facet numbers (e.g., 9X, 8X, 7X) are the more problematic facets. The X0's indicate more general statements of student ideas. Often these are followed by more specific examples, which are coded X1 through X9.

Forces as Interactions Facet Cluster

00 The student understands that all forces arise out of an interaction between two objects and that these forces are equal in magnitude and opposite in direction.

- 01 All forces arise out of an interaction between two objects.
- 02 The force pairs are equal in magnitude.
- 03 The force pairs are opposite in direction.

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40 The student identifies equal force pairs, but indicates that both forces act on the same object. (For the example of a book at rest on a table, the gravitational force down on the book and the normal force up by the table on the book are identified as an action-reaction pair.)

50 The student uses the effects of a force as an indication of the relative magnitudes of the forces in an interaction.

- 51 More damage indicates one of the interacting objects exerted a larger force.
- 52 If an object is at rest, the interaction forces must be balanced.
- 53 If an object moves, the interaction forces must be unbalanced.
- 54 If an object accelerates, the interaction forces must be unbalanced.

60 The student indicates that the forces in a force pair do not have equal magnitude because the objects are dissimilar in some property (e.g., bigger, stronger, faster).

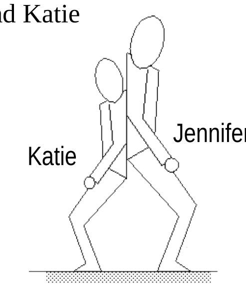
- 61 The 'stronger' object exerts a greater force.
- 62 The moving object or a faster moving object exerts a greater force.
- 63 The more active or energetic object exerts more force.
- 64 The bigger or heavier object exerts more force.

90 The student believes that inanimate/passive objects cannot exert a force.

Source. www.Diagnoser.com

Figure 1. Forces as Interactions Cluster

Question 1. Jennifer and Katie stand and lean on each other. Jennifer weighs 150 pounds and Katie weighs 120 pounds. Which one pushes harder on the other?



(a) Katie must push harder because she weighs less and has to compensate for having less weight. **[Facet 63]***

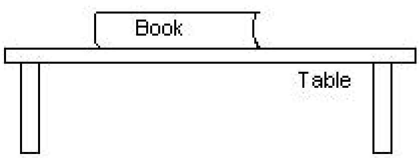
(b) Jennifer and Katie push on each other with the same size force because force pairs are always equal. **[Facet 02]**

(c) Jennifer pushes harder because she weighs more. **[Facet 64]**

(d) It depends on whether Jennifer or Katie moves. **[Facet 50]**

Question 2. In the text box below, describe who exerts the greater force in each of the following conditions AND why.
1. If Katie moves
2. If Jennifer moves
3. If neither moves

Question 3. In the picture, the book is at rest on the table. Which statement best describes the forces resulting from an interaction between objects?



(a) The book pushes down on the table with the same force that the table pushes up on the book. **[Facet 01]**

(b) The force by the table is equal and opposite to the force of gravity. **[Facet 40]**

(c) The gravitational force is equal to the weight of the book. **[Facet Unknown]**

(d) There are no forces due to an interaction in this situation since gravity is the only force acting on the book. **[Facet 90]**

Question 4. Jared is trying to decide if he will be able to push his car home after it runs out of gas. Which of the following conclusions is most likely to be true?

(a) If the car does move it is because Jared pushed harder on the car than the car pushed on him. **[Facet 53]**

(b) The car will NOT move because it is heavier than Jared so the car pushes back on him harder than he can push on the car. **[Facet 64]**

(c) The car will NOT move because the forces on the car are equal and opposite, so there is no net force. **[Facet 40]**

(d) The car may move. The motion of the car depends only on the forces acting on the car, not the force of the car pushing back on Jared. **[Facet 00]**

(e) Only if Jared is strong enough will he be able to push harder on the car than the car can push on him. **[Facet 63]**

Question 5. Bob weighs 150 pounds (667 newtons). Which of the following statements best explains the gravitational force affecting Bob?

(a) The Earth pulls on Bob with 150 pounds of gravitational force, but Bob pulls with less gravitational force on the earth since he has less mass. **[Facet 64]**

(b) The Earth pulls on Bob with 150 pounds of gravitational force, and Bob pulls on the Earth with equal gravitational force since force pairs are equal. **[Facet 02]**

(c) Since Bob will fall "toward the Earth" if he steps off a chair, the Earth's gravity must pull on him more than he pulls on the Earth. **[Facet 53]**

(d) The gravitational force acting on Bob must be more than the gravitational force he exerts on the Earth since Bob is the one who accelerates as he falls. **[54]**

Figure 2. Forces as Interactions Question Set 1

Question 6. Sarah plays defensive back on her school's soccer team. At practice she kicks the ball that was rolling toward her to the other end of the field. Which statement describes the force by the ball acting on Sarah's foot <u>during the kick?</u>

(a) The ball does not exert a force on Sarah's foot. **[Paired]** with question: 7
(b) The force by the ball is less than the force of Sarah's kick. **[Paired]** with question: 7
(c) The force by the ball is equal to the force of Sarah's kick. **[Paired]** with question: 7
(d) The force by the ball is greater than the force of Sarah's kick. **[Paired]** with question: 7

Question 7. Which reason best fits your answer to the previous question?

(a) Sarah is stronger than the ball.
(b) Sarah's kick made the ball move, but the ball did not move Sarah.
(c) Only Sarah can exert a force; the ball is not alive.
(d) All interacting objects exert equal forces on each other.

Combination of responses to Questions 6 and 7 linked to facets as follows:

(a:a) Sarah is stronger than the ball. **[Facet 90][Facet 61]**
(a:b) Sarah's kick made the ball move, but the ball did not move Sarah. **[Facet 90][Facet 53]**
(a:c) Only Sarah can exert a force; the ball is not alive. **[Facet 90][Facet 90]**
(a:d) All interacting objects exert equal forces on each other. **[Facet 90][Facet 01]**
(a:e) The ball hurt Sarah's foot more than she hurt the ball. **[Facet 90][Facet 51]**
(b:a) Sarah is stronger than the ball. **[Facet 61][Facet 61]**
(b:b) Sarah's kick made the ball move, but the ball did not move Sarah. **[Facet 53][Facet 53]**
(b:c) Only Sarah can exert a force; the ball is not alive. **[Facet 60][Facet 90]**
(b:d) All interacting objects exert equal forces on each other. **[Facet 60][Facet 01]**
(b:e) The ball hurt Sarah's foot more than she hurt the ball. **[Facet 60][Facet 51]**
(c:a) Sarah is stronger than the ball. **[Facet Unknown][Facet 61]**
(c:b) Sarah's kick made the ball move, but the ball did not move Sarah. **[Facet Unknown][Facet 53]**
(c:c) Only Sarah can exert a force; the ball is not alive. **[Unknown][Facet 90]**
(c:d) All interacting objects exert equal forces on each other. **[Facet 02][Facet 01]**
(c:e) The ball hurt Sarah's foot more than she hurt the ball. **[Facet Unknown][Facet 51]**
(d:a) Sarah is stronger than the ball. **[Facet 50][Facet 61]**
(d:b) Sarah's kick made the ball move, but the ball did not move Sarah. **[Facet 50][Facet 53]**
(d:c) Only Sarah can exert a force; the ball is not alive. **[Facet 50][Facet 90]**
(d:d) All interacting objects exert equal forces on each other. **[Facet 50][Facet 01]**
(d:e) The ball hurt Sarah's foot more than she hurt the ball. **[Facet 50][Facet 51]**
(a:f) The ball was moving when Sarah kicked the ball. **[Facet 90][Facet 62]**
(b:f) The ball was moving when Sarah kicked the ball. **[Facet Unknown][Facet 62]**
(c:f) The ball was moving when Sarah kicked the ball. **[Facet Unknown][Facet 62]**
(d:f) The ball was moving when Sarah kicked the ball. **[Facet 62][Facet 62]**

Question 8. When two objects interact and exert forces on each other, how can you tell which object exerts more force? Explain your answer in the space below.

Source. www.Diagnoser.com

* The facet codes do not appear in the questions shown to students, but are the facets diagnosed for the teacher for each response. See Figure 1 for Forces as Interactions facet cluster.

Figure 2. Forces as Interactions Question Set 1 (continued)