Using a Structuredness Instrument to Characterize End of Course Projects

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Abstract

A course culminating project, a popular instructional activity in engineering and engineering technology courses, typically provides students with either a rewarding or a frustrating experience. Many times professors, in order to bring real industry practice into the classroom, ask students to solve problems based on complex cases. Depending on the student's familiarity with the project context, a student's problem solving skills, and the nature of the problem, student success in solving the problem can be limited.

Jonassen (1997) provides a foundational basis for defining a problem's nature using the attributes of structuredness, domain specificity, and complexity[1]. Recent research indicates that ill-structured or messy problems require different meta-cognitive processes and problem solving skills, when compared to well-structured problems. Houdeshell (2004) found that using ill-structured transfer activities produced significantly higher student learning than with well-structured transfer problems using an instructional design that supports a scaffolding environment[2]. Clearly then the use of ill-structured problems is desirable when combined within an appropriate instructional design. However, no instrument had been developed to measure problem structuredness.

This paper documents the process of developing and testing a structuredness instrument. The validation procedures utilized instructional materials developed within the scope of National Science Foundation DUE-ATE sponsored projects. The materials provide examples of well and ill-structured transfer activities for testing a proposed structuredness instrument. The instrument, based extensively on work done by Jonassen (1997, 2000), defines a structuredness index[1, 3]. An instrument reliability of 0.82 was demonstrated by the analysis of ten instructional transfer activities by three subject matter experts (SME). The activities evaluated included content materials from mathematics, science, business, and engineering technology. Additionally one of the SMEs applied the instrument to the analysis to twenty-two additional activities to determine the potential relationship between structuredness, and Jonassen's published problem taxonomy (rule, story, decision, troubleshooting, diagnosis-solution, and design). The data supports the relationship between the structuredness index and the problem taxonomy. The impact of this analysis is the verification of the relationship between problem structuredness and taxonomy, the publication of a structuredness instrument, and the reinforcement of the importance of instructional design to enhance student learning

Introduction

Ten years ago the National Center for Manufacturing Education (NCME) received funding from the National Science Foundation's Advanced Technological Education (NSF-ATE) program to develop, pilot test and publish curriculum materials for a competency-based Associate of Applied Science degree, using advanced manufacturing as the focus. This curriculum supports the broad NSF educational goal as stated by Neal Lane, former Director of the NSF, of ‘reaching all students at every level by promoting inquiry-based, hands-on learning experiences in science, mathematics and engineering’[4]. In order to accomplish the inquiry-based, hands-on learning goal, the Center’s Project Development Team (PDT) proposed a new instructional system design model during the summer of 1995[5-7]. An essential element of the design is the use of a summarizing activity that allows the students to reinforce and transfer competencies mastered in previous learning tasks to a new problem-solving context[8, 9] . The intent of the transfer activity is to stimulate students to make connections and generalizations about the competencies learned after applying them in a new way. The transfer activity reflects real world problems in order to provide student motivation and to enhance the student's ability to apply the learned skills to the workplace. Inherent in the proposed design is the ability to transfer the knowledge learned in one context to a new context.

The author observed that the student reaction to and success in solving end-of-course projects differed significantly among courses. In some courses the students were able to easily apply techniques learned in previous activities within the course, while other courses required significant support interventions to keep the students on the proper path to a correct solution. The author did not observe any apparent causal relationship among teams or course levels. This observation lead to the question: What was instructionally different among the transfer activities? Could a possible cause for the observed failure to transfer be Spiro’s level of cognitive load[10]?

Jonassen (1997) addresses Spiro’s potential cause by providing a foundational basis for load by defining the problem’s attributes of structuredness, domain specificity, and complexity[1]. Figure 1 illustrates the scope of a problem’s nature and relationship to cognitive load.

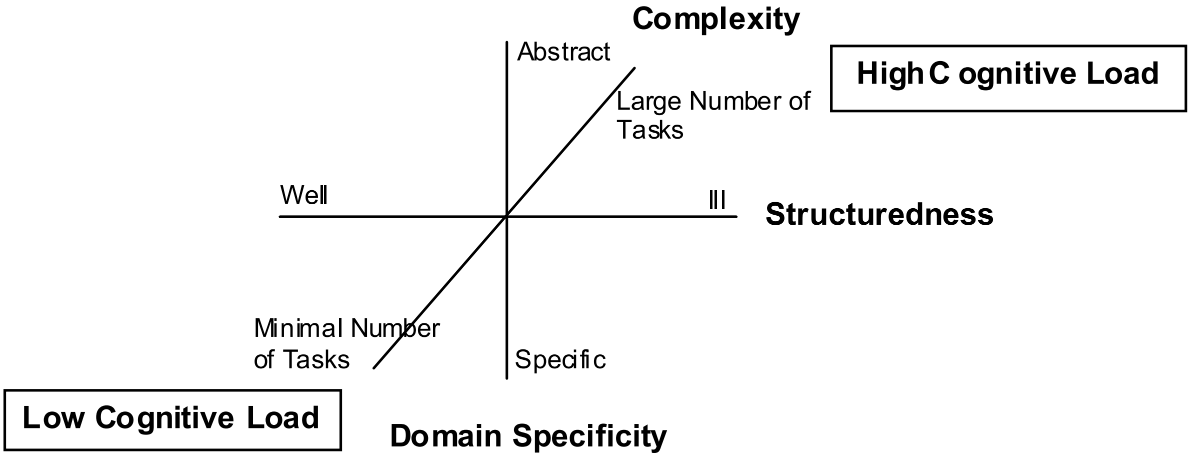

Figure 1. Problem Nature and Relationship to Cognitive Load[2].

Obviously, an abstract, complex, and ill-structured problem provides greater cognitive load to the student than a contextual, minimally complex, and well-structured problem. Cognitive load is defined as “the amount of effort-demanding, controlled processing that is imposed on a learner’s cognitive system”[11]. The greater the cognitive load the greater the likelihood of student frustration and failure; however, on successful completion the greater the developed skill in problem solving transfer. This study intends to discuss and quantify one of the problem characteristics—structuredness—by using instructional materials developed within the scope of National Science Foundation ATE sponsored projects. Examples of the range of problem structuredness, found within the project transfer activities, include well-structured story problems to ill-structured design problems. These examples in conjunction with discussed research help to answer the posed instructional design problem.

Research

Extensive study over the past century has been directed toward understanding the cognitive processes involved in transfer and instructional designs to support the transfer. Most of the research in the past focused on near transfer and more recently on far transfer. Practitioners currently support three positions on learning and transfer: behaviorism, cognitivism, and constructivism. The behaviorist approach to transfer is supported by the associationist principle; and the cognitivist and constructivist approaches by Gestalt principle with the constructivists asserting that knowledge is linked to the context in which it was learned[12]. The following table provides a summary of the relationship among the variables that affect transfer.

Table 1.

Relationships Among Learning Taxonomy, Knowledge Level, Cognitive Requirements and Cognitive Approach to Transfer

Learning Taxonomy[13]	Learner Knowledge Level of the Tasks	Cognitive Requirements of the Tasks	Cognitive Approach to Transfer
Memorizing information	Being able to recognize and apply the rules, facts and operations of a profession	Low degree of processing - behavioral outlook	Behaviorism
Applying skills	Thinking like a professional to extrapolate from general rules to particular, problematic cases (Near transfer)	Medium degree of processing - classification, rule, procedural - schematic organization, analogical reasoning and algorithmic problem solving (well-structured problem solving)	Cognitivism
Applying generic skills	Development and testing of new forms of understanding and actions when applying (Far transfer)	High degree of heuristic problem solving (ill-structured problem solving)[1]	Constructivism, use of situated learning, cognitive apprenticeships[14-16]

More recent research indicates that the students perform differently depending on the ill-structuredness of the problem. Jacobson and Spiro determined that participants using well-structured instructional design strategies demonstrated higher performance on declarative knowledge, while the ill-structured hypertext treatment promoted superior knowledge transfer[17]. In another example students using case-based lessons performed better than concept-based lessons in defining interrelationships and creating representations[18]. Hong demonstrated that for well-structured problem solving, domain-specific knowledge, structural knowledge, and justification skills were critical, and for ill-structured problems the skills for solving well-structured problems were needed, as well as metacognition and other non-cognitive variables[19]. This impact of structuredness was a key element for research reported by Houdeshell (2004). Houdeshell determined that using the Schwartz and Bransford protocols (concept maps with contrasting cases) with an ill-structured transfer problem produced a 32% increase in student performance versus a 17.6% increase with a moderately well-structured transfer activity[2, 20]. Clearly asking the student to apply skills learned within one context to a new ill-structured context required additional instructional support and scaffolding protocols. A secondary question is: Is there a relationship between problem type and structuredness? The next section reviews Jonassen's (2000) taxonomy of problems and the relationship to the practice of engineering and technology.

Jonassen ranked 11 taxonomy categories from well- to ill-structured[3]. Relating these problem types to real world problems clearly depends on the type of work and the level of the position that a student or graduate obtains. Most engineering and engineering technology graduates typically are required to perform a subset of Jonassen's 11 categories: design, diagnostic, decision, troubleshooting, rule, and algorithmic problems. These reflect a continuum of structuredness from ill to well; therefore, the instructional transfer activities should reflect this same continuum. This reinforces the need to develop an instrument that can quantify real world task structuredness and categorize currently developed instructional activities. Jonassen and others have researched and developed criteria for defining well and ill-structured problems[1]. These criteria summarized in Table 2 provide the theoretical basis for the author's structuredness instrument.

Table 2.

Structuredness Characteristics of Well and Ill-Structured Problems

Well-Structured Problems	Ill-Structured Problems
1. Present all elements of the problem"[1]	1. Lack definition of one or more of the problem elements[21]
2. Have clearly stated goals or outcomes	2. Possess vaguely defined or unclear goals and constraints[22]
3. Have a probable solution	3. Possess multiple solutions, or no solution[23]
4. Has defined evaluative solution criteria	4. "Possesses multiple criteria for evaluating solutions"[1]
5. Require only a limited number of regular procedural rules and principles	5. "Present uncertainty about the organization or use of the possible procedural rules and principles"[1]
6. Possess consist relationships between concepts, rules and relationships	6. Possess inconsistent relationships between concepts, rules and relationships
7. Fall within well-structured and predicable domains of knowledge	7. Fall within unstructured or unpredictable domains of knowledge
8. Possess correct, convergent answers	8. Possess more than one answer, perhaps divergent
9. Possess knowable solutions where all the problem states are known[21]	9. Possess no general rules or principles for describing or predicting most of the problem's solutions
10. Have a prescribed solution process.	10. Possess no explicit means for determining appropriate solution process
	11. "Require learners to make judgments about the problems and defend them"[1]

The stated research objective is to develop, test, and apply a structuredness instrument. The structuredness index of a sample activity is created based on the evaluator's answers to 13 questions. The instrument provides researchers, professors and instructional designers with a method to quantify problems related to structuredness. The methodology used validate the instrument is reported in the next section.

Methods

The author, using the well- and ill-structured problem characteristics found in Table 2, created an evaluation rubric, selected ten transfer activities for the instrument validation, and recruited four subject matter experts familiar with the content. These four engineering experts, all with graduate degrees, represented both industry and academic perspectives. The instrument found in the appendix at the end of the paper uses a five point Likert scale for each of the answers to 13 questions. This scale creates a theoretical range of the index from 13 to 65.

The evaluators independently read ten transfer activities and scored their answers using the Likert scale. The total score for each activity by evaluator was calculated by summing the 13 scale values. The resulting structuredness indexes (ten sets of four values each) were tested using a two factor ANOVA. A least significant difference calculation, based on an α risk of 0.05 was completed and used to compare average index ratings. Duncan (1974) advocated the use of Equation 1 to calculate the least significant difference between means[24].

$$\text{Least Significant Difference} = t_{a/2,\ MSE\ df}\sqrt{\frac{2MSE}{n}} \qquad (1)$$

Finally, the instrument reliability calculation used the ANOVA table results to determine the treatment variance to the total variance. Equation 2 illustrates the mathematical relationship.

$$\text{Instrument Reliability} = \sigma^2_{\text{Transfer Activity}} / \sigma^2_{\text{Total Variability}} \qquad (2)$$

A sample of ten transfer activities (*in Table 3) from the available 32 was selected for use in the creation of the instrument. The author chose modules that represented not only technology related content areas, but also mathematics, science, and business. Table 3 provides a description of the 32 transfer activities used in this study. The results of the applied methodology are found in the following section.

Table 3.

Description of Selected Transfer Activities

Content Domain	Module Title	Transfer Activity Title	Taxonomy/ Structuredness Index Value
Principles of Mathematics	*Basic Statistical Variation*	A Handful of Beans*	Diagnosis (54)
	Statistical Distributions	Product Life Cycle Analysis for Warranty Determination*	Rule (63)
	College Algebra	Resource Allocation*	Story (65)
Principles of Science	*Describing Position, Velocity, and Acceleration*	Packaging to Survive a Drop*	Design (51)
	Basic DC Circuits	Industrial Application of Series and Parallel Circuit Concepts	Story (63)
	Precision, Accuracy, and Tolerance	Instruments for RGI	Decision (53)
	Forces and Their Effects	Truck Mileage	Diagnosis (30)
Humanities, Communications and Teamwork	*Professional Development*	Applying for an Internship at Robotic Grippers, Inc.*	Diagnosis (53)
Enterprise Integration	*Customer Satisfaction*	Expanding a Product Line*	Decision (52)
	Performance Measures	Cost Control at RGI	Rule (57)
Design for Manufacturing	*Conceptual Design*	Modifying the Robotic Gripper to Meet Customer Needs*	Design (48)
	Geometric Dimensioning and Tolerancing	GD&T at Robotic Grippers, Inc.	Diagnosis (55)
	Drawing and Sketching	Sketching and Drawing Concepts	Design (52)

		for a Robotic Gripper	
Quality Management	*Quality Foundations*	Quality Problems at RGI*	Diagnosis (38)
	Process Control	Are We Capable at RGI?*	Diagnosis (47)
	Continuous Process Improvement	Does the Change Process at RGI Need to be Changed?*	Diagnosis (33)
Manufacturing Processes and Materials	*Introduction to World Class Manufacturing*	The Total Manufacturing Enterprise	Case (57)
	Principles of Manufacturing Processes	New Product Planning at RGI	Decision (56)
	Basic Material Removal	Making Parts for the Robotic Gripper	Rule (57)
	Metallic Materials	Determining Alternative Materials and Potential Cost Savings	Decision (52)
	Non-Metallic Materials	Which Material Would You Use? Building a Better Bicycle	Decision (53)
	Metal Forming and Joining	Changing from Metals to Plastics	Rule (63)
	Plastics Manufacturing Processes and Materials	An Inventory Problem Real-World Production	Decision (55)
Production and Inventory Control	*Principles of PIC*	Process Improvement	Story (62)
	Introduction to JIT		Design (51)
	Process Flow and Lead Time Reduction	A Cellular Solution	Design (55)
	Consistent Work Methods and Build to Demand	An Assembly Challenge	Design (50)
	Kanban and Pull Systems	Cells Rock	Design (43)
Manufacturing Systems and Automation	*Manufacturing Work Cell Design*	Relays and Single-Phase	Design (48)
	Electrical and Electronic Controls	AC Motor-Starting Circuit	Trouble-shooting (56)
	Computer Numerical Control	CNC Operations at RGI	Design (53)
	Robots and Programmable Logic Controllers	Controlling Three Independent Sequential Conveyors	Design (47)

Results

Upon completion of the evaluations, a preliminary analysis tested the Pearson correlation of each question with the overall index score. The correlation, using the results from the four evaluators provided significant positive correlation coefficients ranged from 0.349 to 0.724 with significance $p < 0.01$. Consequently, all 13 questions remained as part of the study. A review of the initial descriptive statistics indicated two problems with the data, the evaluator transfer activities indicates significant variation occurred in the *Quality Foundations* and *Professional Development* transfer activities and an apparent significantly lower comparative variance between Evaluator Four and the other three evaluators. After a discussion with Evaluator Two one score was modified; however no changes were made on the second. A F test comparing evaluator four's rating variance (11.21) with the other three evaluator's pooled variances (48.86) indicate a F ratio of 4.36 with a corresponding probability of $p = 0.01$. A comparison of the other three evaluators did not produce a significant difference when tested at the 5% risk level. Given the ANOVA assumption of homogeneity of variation, Evaluator Four's data was removed from further consideration. Table 4 provides the revised summary results for the ANOVA and descriptive statistics. The ANOVA transfer activities results indicate a significance difference among the activities with a $p < 0.01$. The least significant difference test of sample means using the mean squared error term (MSE) with a 5 %; two tailed alpha risk and 18 degrees of freedom difference test produced a significance value of 6.22 index points. Applying the test to other combinations of the ten activities allows the defining of three cells of structuredness, a moderately ill-structured, moderately well-structured, and well-structured. The overall calculated instrument reliability applying the ANOVA data to Equation 2 yields instrument reliability equal to 0.82.

Table 4.
Problem Characteristics Descriptive Statistics and ANOVA

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Evaluator 1	10	499	49.90	58.77
Evaluator 2	10	517	51.70	24.46
Evaluator 3	10	513	51.30	72.23
Basic Statistical Variation	3	172	57.33	8.33
College Algebra	3	186	62.00	27.00
Conceptual Design	3	143	47.67	0.33
Cont. Process Improvement	3	140	46.67	25.33
Customer Satisfaction	3	134	44.67	8.33
Position, Velocity and Accel.	3	147	49.00	4.00
Process Control	3	172	57.33	8.33
Professional Development	3	160	53.33	6.33
Quality Foundations	3	122	40.67	30.33
Statistical Distributions	3	153	51.00	9.00

ANOVA: Problem Characteristics Instrument

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Evaluators	17.87	2	8.93	0.68	0.52	3.55
Transfer Activities	1162.30	9	129.14	9.82	< 0.01	2.46
Error	236.80	18	13.16			
Total	1416.97	29				

Evaluator One applied the instrument to the remaining 22 cases and with the original ten cases obtained an overall summary distribution. The distribution with a mean of 52.1 and a standard deviation of 7.3, shown in Figure 3 exhibits a truncated normal distribution, with 20 out of the 32 exhibiting index values of 52 or higher. Further analysis assesses the theoretical link between the structural index number and the taxonomy. Jonassen's taxonomy would predict that the most ill-structured problems would be dilemmas, design, case, and diagnosis problems, while the algorithms, rule, and story problems the most well-structured. The same three evaluators categorized the ten transfer activities according to Jonassen's taxonomy. The author combined those activities for purpose of analysis into three taxonomy groups: ill-structured, moderately well-structured, and well-structured. The calculated reliability was 0.86, based on the data provided in Table 5 using the approach presented in Equation 2.

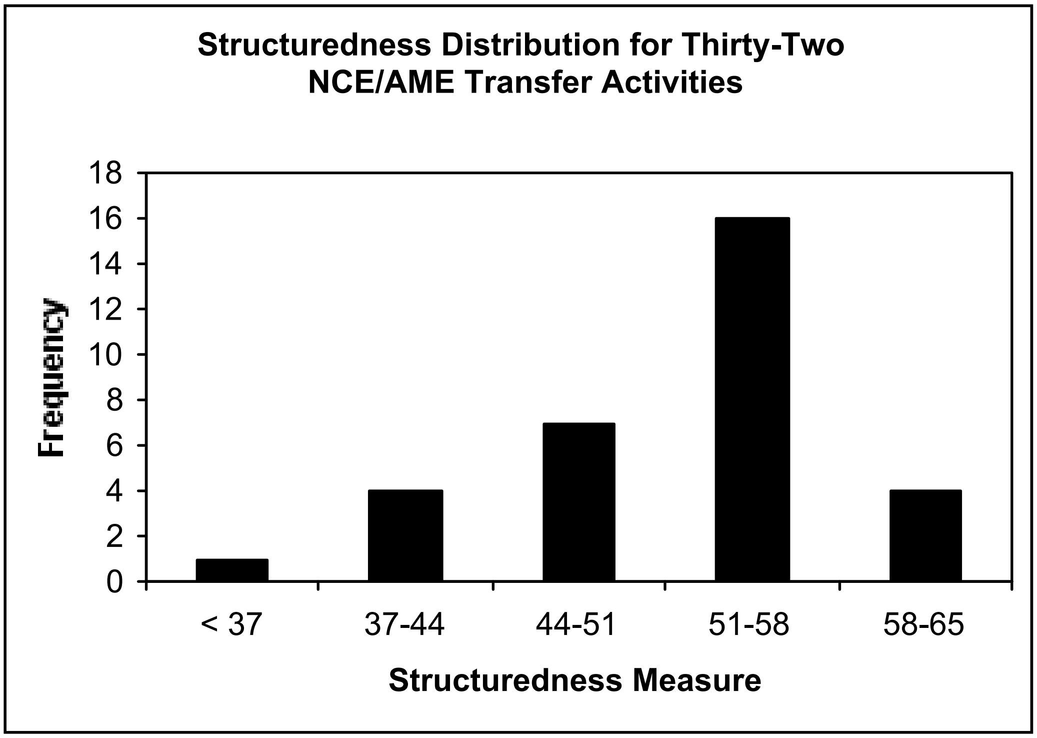

Figure 3. Structuredness Distribution for Thirty-two NCME Transfer Activities

Table 5.
ANOVA Summary for Taxonomy Characterization

Source of Variation	SS	df	MS	F	P-value	F crit
Between Activities	4.97	9	0.55	7.36	0.000	2.39
Between Evaluators	1.50	20	0.08			
Total	6.47	29				

The 32 activities were categorized by Evaluator One with the following results: 42% classified as ill-structured, design, case or diagnosis oriented, with an average structuredness index of 47.7; 22% classified as moderately well-structured, troubleshooting or decision making, with an index number of 53.8; and 25% classified as well-structured, story or rule based, with an average index number of 60.5. A Chi-squared test of the predicted versus actual results indicated no significant difference between the predicted distribution by taxonomy and the distribution predicted by the structuredness index $p > 0.10$. The results confirm the relationship between the structuredness instrument and Jonassen's taxonomy.

Discussion

The stated research objective was to develop, test, and apply a structuredness instrument. A theory-based instrument was developed and tested with reliability sufficient to distinguish between well and ill-structured problems. The evaluators were asked to use the instruments without any training and minimal initial guidance. This lack of direction or training contributed to the inconsistency among evaluators. A follow-up study using examples is planned in order to reduce evaluator variability. The Chi-squared test indicated that there was no significant difference between the predicted and actual distributions of activities. The structuredness evaluations were consistent in scoring except for the diagnosis category, which exhibited a significantly higher variability, $p < 0.05$. This could reflect the disposition of the writing teams towards more or less structured problems. This will require additional investigation.

The instructional materials evaluated within this study were written for an audience of first and second year college students majoring in a field of engineering technology. While the author feels that the instrument can be applied to a variety of disciplines based on the college level content mix of the initial ten samples, the potential application of the instrument to problem-based curriculums designed for K-12 would require additional research. A more important consideration is the potential use of a structuredness index in defining instructional design strategies.

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Appendix

Problem Characteristics Instrument

			Circle the most appropriate numerical representation		
1. Are all the elements of the problem present, and defined?	1	2	3	4	5
	Missing and not defined		Not defined		Present and defined
2. Does the problem have clearly stated goals or outcomes, and constraints?	1	2	3	4	5
	No stated goals and constraints		50/50 mix		Clearly stated goals and constraints
3. Does the problem have clearly defined criteria for a successful solution?	1	2	3	4	5
	Multiple and vague criteria		Multiple criteria		Clearly defined
4. Are their multiple representations or descriptions of the problem?	1	2	3	4	5
	Multiple		Few		Single
5. Does the problem have a solution?	1	2	3	4	5
	Has no consensus solution		Has multiple solution		Has a solution
6. Does the problem possess a correct, convergent answer?	1	2	3	4	5
	More than one correct divergent answer		More than one correc answer		Correct and convergent

7. Does the problem possess a solution(s) where the relationship between decision choices and the corresponding problem states are known?	1	2	3	4	5
	No general rules for predicting the problem state		Some problem states known		Solutions where all the problem states are known
8. Does the problem have a prescribed solution process?	1	2	3	4	5
	No explicit means for determining the appropriate solution processes		Some prescribed solution processes		Prescribed solution process
9. Does the problem require the solver to make judgements about the problem and then defend the answer?	1	2	3	4	5
	Judgements and defense		Judgements or defense		No judgements or defense needed
10. Does the problem fall within a well-structured and predicable domain of knowledge?	1	2	3	4	5
	Unstructured and unpredictable		Unstructured or unpredictable		Well-structured and predicable
11. Does the problem exhibit consist relationships between concepts, rules, and relationships when presented in different contexts?	1	2	3	4	5
	Inconsistent relationships		50/50 Mix		Consistent relationships
12. Is the problem solution product oriented or process oriented?	1	2	3	4	5
	Product		Mix		Process
13. What portion of the problem solution skills would be considered simple? (concepts, plans, and procedures)	1	2	3	4	5
	0%		50%		100%

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