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Pedagogy for Conceptual Thinking in the Digital Age: Enhancing Learning Outcomes with Meaning Equivalence Reusable Learning Objects (MERLO) Formative Assessments

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Abstract
The research presented in this paper is the fruit of an ongoing international collaboration with the goal of enhancing students learning outcomes by implementing and sharing a novel pedagogy for conceptual thinking, and use of an innovative didactical and methodological tool: Meaning Equivalence Reusable Learning Objects (MERLO) that provide student-centered, weekly formative assessments for exploring and discussing conceptual situations in small groups. It was developed, tested, and implemented in Canada at University of Toronto and Ryerson University, as well as in Israel, Italy, Russia, and Australia, in different knowledge domains, including: physics; biology; mathematics; mathematics teacher education; teacher training; developmental psychology; English as a second language; architecture; management; business; project management. Statistical analysis of MERLO data collected since 2002, shows that conceptual thinking enhance learning outcomes and deepens students' comprehension of the conceptual content of learned material. Conceptual thinking is learnable, and provide metrics to document continuous increase in higher-order thinking skills such as critical conceptual thinking, transfer of knowledge, and problem solving. Pedagogy for conceptual thinking is currently implemented with Brightspace (http://www.brightspace.com/), Integrated Learning Platform (ILP) offered by D2L (http://www.d2l.com/) that supports customizable online pedagogy.

Keywords: *pedagogy for conceptual thinking; meaning equivalence; MERLO; formative assessment; enhanced learning outcomes.*

1. Introduction

Traditional pedagogy focus on memory of facts and correct execution of problem solving procedures, and its learning assessments include structured items such as true/false and multiple-choice questions. In contrast, higher-order conceptual thinking skills is now recognized as a cornerstone of effective learning, ways of thinking that explore patterns of equivalence-of-meaning in ideas, relations, and underlying issues: 'understanding facts and ideas in the context of a conceptual framework' (Bransford, Brown, & Cocking. 2004). Meaning equivalence is a construct that denotes commonality of meaning across representations: a polymorphous - one-to-many - transformation of meaning. Learning assessments based on meaning equivalence with unstructured items capture this important aspect of conceptual thinking.

2. What is MERLO?

Meaning Equivalence Reusable Learning Object (MERLO) is a multi-dimensional database that allows the sorting and mapping of important concepts through exemplary target statements of particular conceptual situations, and relevant statements of shared meaning. Each node of MERLO database is an item family, anchored by a target statement that describes a conceptual situation and encodes different features of an important concept; and also include other statements that may – or may not – share equivalence-of-meaning with the target statement. Collectively, these item families encode the conceptual mapping that covers the full content of a course (a particular content area within a discipline).

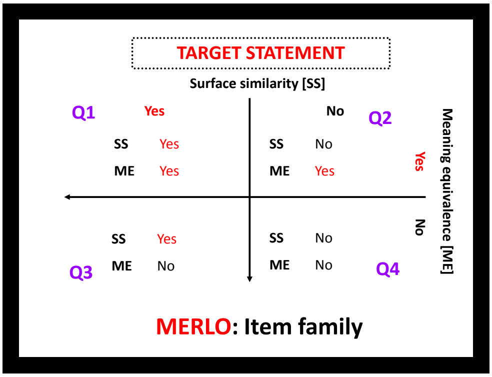

Figure 1: Template for constructing an item-family in MERLO

Statements in the four quadrants of the template, namely, Q1; Q2; Q3; and Q4; are thematically sorted by their relation to the target statement that anchors the particular node (item family); they are classified by two sorting criteria: *surface similarity* to the target, and *equivalence-of-meaning* with the target.

For example, if the statements contain text in natural language, then by ‘surface similarity’ we mean same/similar words appearing in the same/similar order as in the target statement; and by ‘meaning equivalence’ we mean that a majority in a community that shares a sublanguage (Kittredge, 1983) with a controlled vocabulary (e.g., statistics) would likely agree that the meaning of the statement being sorted is equivalent to the meaning of the target statement. A typical MERLO assessment item contains 5 unmarked statements: an unmarked target statement plus four additional (unmarked) statements from quadrants Q2; Q3; and Q4. Our experience has shown that inclusion of statements from quadrant Q1 makes a MERLO item too easy, because it gives away the shared meaning due to the valence-match between surface similarity and meaning equivalence, a strong indicator of shared meaning between a Q1 and the target statement. Therefore, Q1 statements are excluded from MERLO assessment items.

Task instructions for MERLO assessment are: At least two out of these five statements – **but possibly more than two** – share equivalence-of- meaning. (1) Mark all statements – **but only those** – that share equivalence-of-meaning. (2). Write down briefly the reasons for making these decisions (Etkind, Kenett, & Shafrir, 2015).

The learner is first asked to carry out a recognition task in situations where the particular target statement is not marked, namely, features of the concept to be compared are not made explicit. In order to perform this task, a learner needs to begin by decoding and recognizing the meaning of each of the 5 statements in the set. This decoding process is carried out, typically, by analyzing concepts that define the ‘meaning’ of each statement. Successful analysis of all the statements requires deep understanding of the conceptual content of the specific domain. MERLO item format requires both rule inference and rule application in a similar way to the solution of analogical reasoning items. Once the learner marked those statements that – in her opinion – share equivalence-of-meaning, she formulates and briefly describes in writing the concept/idea/criteria she had in mind when making these decisions.

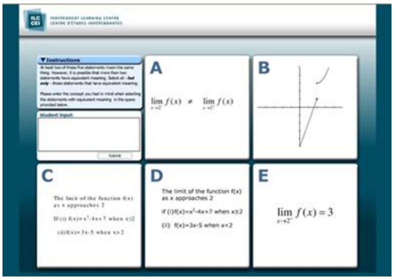

Figure 2: Example of MERLO item (mathematics/functions)

Figure 2 is an example of MERLO assessment item (mathematics/functions); it contains 5 representations that include text, equations, and diagrams; at least 2 two of these representations share equivalence-of-meaning.

Fig. 3 shows mean recognition scores of MERLO assessment in physics grade 11 students; the U-shape pattern, signifying depressed Q2 and Q3 scores, is a typical example of deficient conceptual comprehension. This type of U-shape pattern of mean ***recognition scores*** was observed in all MERLO assessments results for conceptual thinking across all types of learners (secondary; post-secondary; professional learning), in all knowledge domains, including: mathematics; physics; biology; psychology; education; architecture; project management; and business.

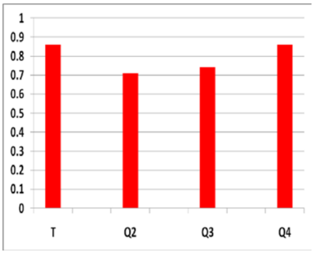

Figure 3: MERLO test results (mean recognition scores; physics/magnetism); Russian Academy of Science (2003).

3. MERLO metrics for diagnostics of misconceptions

The construct 'Boundary of Meaning' **(**BoM) is defined as: Given a community of specialists that share a sublanguage, and a Target Statement that encodes a particular conceptual situation; then BoM is defined as the boundary between two mutually exclusive semantic spaces in the sublanguage:

- a semantic space that contains only representations that do share equivalence- of-meaning with the Target Statement
- a semantic space that contains only representations that do not share equivalence-of-meaning with the Target Statement

What is the meaning of the U pattern of mean recognition scores with **consistently lower Q2 and Q3 scores across different knowledge domains?**

Specific comprehension deficits can be traced as **depressed recognition scores on quadrants Q2 and Q3**, due to the mismatch between the valence of surface similarity and meaning equivalence (Fig. 1). However, the interpretations of Q2 and Q3 scores are very different:

- A ***reduced score on Q2*** indicates that the learner fails to include in the Boundary of Meaning (BoM) of the concept certain statements that share equivalence-of-meaning (but do not share surface similarity) with the target; ***such depressed Q2 score signals an over-restrictive (too exclusive) understanding of the meaning underlying the concept.***
- A ***reduced score on Q3*** indicates that the learner fails to exclude from the Boundary of Meaning (BoM) of the concept certain statements that do not share equivalence of-meaning (but that do share surface similarity) with the target; ***this depressed Q3 score signals an under-restrictive (too inclusive) understanding of the meaning of the concept.***

Production score of MERLO test items is based on the clarity and accuracy of the learner's written description of the conceptual situation described in the item, and the explicit inclusion in that description of lexical labels of relevant and important concepts and relations. Thus, recognition and production scores provides teachers and learners with clear and reliable evidence for diagnosing misconceptions, and provide clues for remediation.

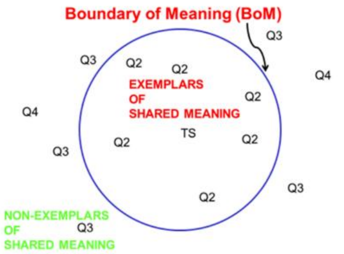

Figure 4: Boundary of Meaning (BoM) of TS include Target and Q2; exclude Q3 and Q4

Figure 4 illustrates a practical way to demarcate BoM for a particular Target Statement in a knowledge domain. Specific conceptual comprehension deficits are traced as depressed (lower) recognition scores on quadrants Q2 and Q3, due to the mismatch between the valence of surface similarity and meaning equivalence in these quadrants (Figure 1).

Pedagogy of conceptual thinking was designed to motivate and engage learners, and encourage cooperation. It includes weekly classroom formative assesments with MERLO items, as well as inclusion of MERLO items as part of mid-term tests and final exams.

MERLO formative assessment provides learners with opportunities to cooperate through discussions in small groups; then make their own decisions and send their individual responses to the instructor's computer via mobile communication devices; followed by class discussion. It takes about 20 minutes, and includes the following 4 steps: **Peer Cooperation and Small Group Discussion** (approx. 3-5 minutes); PowerPoint projection of a MERLO item; students cooperate in discussing the item in small groups (turn back/sideways to discuss with those seating next to them). **Individual Response** (3 min); each student sends her own individual ***recognition response*** through a personal communication device (smartphone/tablet/clicker), marking at least 2 out of 5 statements (A; B; C; D; E) in the multi-semiotic MERLO item that, in her opinion, share equivalence-of-meaning; then sends her ***production response***, briefly describing the reasons/concept she had in mind when making the above recognition decisions. **Feedback and Class Discussion of Students' *productive response*** (3-5 min); projection of the MERLO item, including several production responses sent by the students, and instructor's description of the MERLO conceptual context; class discussion and comparison of the various individual production responses.

Feedback and Class Discussion of Students' *Recognition Response* (3-5 min); projection of the MERLO item, showing the *correct recognition response* of the MERLO item (i.e., correctly marked/unmarked statements); class discussion and comparison of the various individual recognition responses.

4. Interactive Concept Discovery (InCoD)

Interactive Concept Discovery (InCoD) is a novel semantic search learning tool. It is an intuitive, interactive procedure that allows a learner to search large digital databases (eJournals; eBooks; databases; eArchives), and to discover the building blocks of a concept within a particular context of the knowledge domain, namely, co-occurring subordinate concepts and relations. InCoD construct concept maps that clearly identify not only the conceptual content of important concepts in course material, but also its internal conceptual structure - hierarchical and lateral relations among concepts and their building blocks.

The learner begins by conducting semantic search of *Key Word In Context (KWIC) – concordance;* read/save documents online; annotate and evaluate the degree of relevance of a particular document to the specific conceptual content under consideration; and construct graphical representations of links between concepts. InCoD data reveal the learner's consistency of 'drilling-down' for discovering deeper building blocks of the particular concept, as well as the temporal evolution of outcomes of the learning sequence. This digital record is an authentic, evidence-based demonstration of mastery of knowledge that can be used as a springboard for follow-up class and chat room discussions. It provides a credible record to the individual's learning process and learning outcomes (Shafrir, Etkind, & Treviranus, 2006).

Interactive Concept Discovery (InCoD) makes available to the learner all the different locations of sentences in the digital documents in the course Knowledge Repository (KR), likely written by different authors with different points-of-views and different examples, that contain a searched concept. Clicking on a found sentence provides access to the document where the sentence appears, so that the learner can examine the context in which the concept is discussed. Following the initial concordance/search, the learner may notice that in several locations/sentences, another concept consistently appears in close proximity to the searched concept. By clicking on the second concept, the learner activates a subsequence search of co-occurrence of both the initial concept and second concept, aimed at discovering consistent co-occurrence with the initial concept.

A Learner Individual Index collects data from each of the learner’s activities, including:

- Alphabetic indexing by name of concept
- Document/page
- Ranking (on scale of 1 to 5) in terms of degree of relevance to course content
- Annotations: brief summary of the specific conceptual context, followed by learner’s comments, tags, and links

Clicking on a particular entry in the Individual Index provides the date of creation of the entry by the learner, plus complete details of content. A Learner Individual Index is also available to the the instructor; it tracks the learner’s progress in mastering the conceptual understanding of the documents in the Knowledge Repository, and the specific learning outcomes accumulated throughout the course.

Concepedia (Conceptual Encyclopedia) is a weekly aggregation of all Individual Indexes of all learners in the class, in the context of the course knowledge domain, and is accessible to the instructor and to all students in the course. It also include learners’ commentaries on other learners’ annotations. A Concepedia enhances individuals’ reputations as cooperators who contribute to the public good, and reflects the cumulative process-learning-curve of the class.

5. Concept Science Evidence-Based MERLO Learning Analytics

Detailed data of learning processes and outcomes are collected, analyzed and available to the learners and to the teachers through learning analytics (Shafrir and Kenett, 2015).

Individual student’s data profile shows student’s Individual Index of InCoD, and scores of MERLO weekly formative assessments, mid-term tests, and final exams in individual courses. These scores identify specific deficits in conceptual understanding of course content, expressed as lower individual Q2 and Q3 scores, and document corrective interventions with individual learners.

Class data profiles show mean MERLO scores in weekly formative assessments, as well as mid-term tests, and final exams, as well as Concepedias for different courses. This data indicates class specific deficits, expressed as lower mean Q2 and Q3 class scores in conceptual understanding of particular course content, and may prompt the instructor to revisit this content in future lectures or other class activities. These inter-related learning-process data are collected continuously, not just in a particular class, but across all learning and teaching activities throughout the semester and the academic year. Eventually, and subject to strict privacy procedures that protect individual student identity and privacy, the learning analytics is available to the administration of the academic institutions.

6. Conclusions

A recent OECD review provides strong evidence for the important role of formative assessment in enhancing students' learning outcomes (Nusche, 2013, p. 145). This paper is about enhancing learning outcomes and deep understanding of concepts through interactive learning and methods for assessing such understanding. In the digital age, when data is abundant and technology is within reach of everyone, the focus on depth of understanding is gaining importance and urgency. This paper foster learning in the context of modern information technologies. The wide range of application areas where experience in these tools and techniques has been gained, demonstrates their universality and reflects on their large potential in future research and implementation initiatives.

Implementation, testing, and validation, since 2002, of pedagogy for conceptual thinking, lend support to the following conclusions:

- Weekly multi-semiotic MERLO formative assessments enhance peer cooperation, conceptual thinking, and learning outcomes.
- Pedagogy for conceptual thinking motivate and engage students. This is particularly evident - and important - in large undergraduate classes.
- Conceptual thinking is learnable.
- Good vs. poor conceptual thinkers score high (low) on deep comprehension of the content of other courses.
- Pedagogy for conceptual thinking, when implemented as a regular part of the instructional methodology, replicates the above pattern of results.

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