ABSTRACT
Educational environments continue to rapidly evolve to address the needs of diverse, growing student populations, while embracing advances in pedagogy and technology. In this changing landscape, the design and delivery of high-quality assessments become even more challenging. In particular, ensuring that there is consistency among assessments of different offerings of a course, providing meaningful feedback about students’ achievements, and tracking students’ progression over time are all challenging tasks to be done at scale. In this paper, a collection of visual Topic Dependency Models (TDMs) is proposed that addresses three facets of the challenges noted above. It visualises the required topics and their dependencies at a course level (e.g., CS 100); visualises assessment data (material coverage and student achievements) at a classroom level (e.g., CS 100 Section 001) both at one point in time (static) and over time (dynamic). The models share a common, two-weighted graph foundation. The collection is illustrated using examples drawn from a high-enrollment introductory course in C programming for engineering students.

1. INTRODUCTION
Educational environments continue to rapidly evolve to address the needs of diverse, growing student populations while embracing advances in pedagogy and technology. This evolution has resulted in numerous environments such as traditional, e-learning, flipped, and MOOCs; these are supported by a wide range of tools and techniques. As the environments change assessment remains a core educational activity: the design and delivery of high quality assessments at scale becomes even more challenging.

The design of assessments can involve many forms of material. More traditional material includes homework assignments and examinations; more recently emerging material includes question repositories and games. The various forms provide more opportunities and possibilities for covering the required topics of a course (e.g., CS 100) in a particular offering (e.g., CS 100 Term 1 2016 Section 001); however, this rich variety also introduces new challenges to educational stakeholders (inside and outside of a classroom) with respect to assessment coverage and communication. Inside of a classroom, junior instructors or those teaching the course for the first time may find it challenging to evaluate the quality of assessment material in multiple forms with respect to a well-defined description of the course topics and their relationships (coverage). Instructors, junior and experienced, faces challenges to provide personalised feedback at scale to help students master the content (communicate achievements). Students may find it challenging to infer their strengths and weaknesses with respect to topics and their relationships, which can impede their studies (communicate achievements).

Outside of a classroom program administrators, course designers, and course co-ordinators also face challenges. Administrators find it challenging to compare the content and difficulty of formal assessments as well as students’ outcomes across different offerings of a course (coverage, achievements). Course designers and co-ordinators find it challenging to ensure the required topics and their relationships (e.g., questions with a combination of topics a, b and c) have been included in assessments (coverage).

The learning analytics community continues to actively investigate approaches that support the exploration of learning activities by different stakeholders. With the increase in the use of educational technologies and the advancements in the areas of learning analytics and educational data mining, a new field, commonly known as “Learning Dashboards” has emerged to help make sense of data sets in learning and education [6, 8, 5]. A variety of visualisations such as bar charts [3], pie charts [9], histograms [7], box plots, and skill meters [1] have been adopted to show the achievements of students for independent (stand-alone) topics; however, a search of the literature reveals the investigation and visualisation of students’ achievements in combining knowledge on multiple topics has not received any attention. Beyond the communication of achievement results the use of learning analytics for the design and delivery of assessment the area seems, as yet, to be under-developed and under-explored [4] offering many research opportunities.

In this work a collection of Topic Dependency Models (TDMs) is introduced to help reduce the research gap on assessment analytics described above. The collection addresses three facets of the problem. The first is the need for course level models to communicate the required topics and their relationships. The second is the need for classroom
level models to visualise assessment data within a class and support comparisons of assessment data between classes. The third is the need for models that visualise assessment’s trends over time. The collection of models shares a common graph foundation (two-weighted graph). Stakeholders can select the classroom level model and the assessment data to use. The collection is presented using illustrative examples drawn from a high-enrollment introductory course in C programming for engineering students at The University of British Columbia. The course has a hybrid educational environment that combines elements of a flipped classroom, traditional lecture and lab sessions, and a question repository, which results in a wide variety of assessment data. The course topics and dependencies span introduction (e.g., base conversions of integers), fundamentals (e.g., built-in data types), conditionals, loops, file I/O, arrays, and functions.

The remainder of this paper is organised as follows. Section 2 presents the underlying formal definition of the TDMs. Section 3 explores the stakeholders and their scenarios of use for assessment activities. Section 4 introduces the TDM collection. Finally, conclusion and future work are discussed in Section 5.

2. DEFINING TOPIC DEPENDENCY MODELS

The aim of the TDMs is to capture and communicate the coverage and achievements of a variety of forms of assessments with a range of stakeholders. Graphs and their visualisations are widely used to demonstrate the structure of complex data in a formal way, and they may be adopted for representing TDMs. Graphs can summarise a large amount of data in a compact form that is straightforward to understand by a broad audience, which makes them ideal for representing TDMs. Based on the formal definition of graphs presented in [10], the underlying structure of TDMs is defined as follows:

**Definition 1.** The topic dependency model (TDM) is represented using a two-weighted, undirected graph \( G = (V, E) \), where \( V \) is the set of vertices representing the topics, and \( E \) is the set of edges. An edge \( e \in E \) is represented as \( e = (v, w, c_1, c_2) \), where \( v \) and \( w \) are vertices (topics) being connected, \( c_1 \) represents the number of learning objects that are tagged with both topics \( v \) and \( w \) (coverage), and \( c_2 \) represents the performance on learning objects that are tagged with both topics \( v \) and \( w \) (achievements). An edge connecting a node \( v \) to itself (loop) contains information on learning objects that are only tagged with topic \( v \).

Use of two-weighted, undirected graphs as the formal underlying definition of the topic dependency model allows for visualisations that have simple interpretations, which are easy to understand by a broad audience. In the adopted visualisation (\( C_1 \)) is mapped to the thickness of an edge to represent coverage and (\( C_2 \)) is mapped to a colour of an edge to represent achievement. Figure 1 illustrates an example of a topic dependency model. Generally, these models can be generated manually or automatically from assessment scores. This example is demonstrating an assessment that spans four different topics. In this model edge thickness indicates coverage based on the number of questions, where a thicker line indicates a higher coverage. Edge colour spanning on a gradient from red to green indicates achievement, where a greener line indicates a higher achievement. The self-loop on Topic C indicates that there is one question on this topic and the average class score on the topic is quite high. The edge between Topic A and Topic B indicates that the combination of these topics has received a high coverage in the assessment and the average class score on these questions is very low. The structure of the graph reveals that Topic C is not covered in combination with any other topic.

![Figure 1: Example of a Topic Dependency Model](image)

A limitation of using two-weighted graphs as the underlying formal definition of the model is that two-weighted graphs are unable to visually represent the coverage of questions that are tagged with more than two topics (e.g., the graph is unable to show the coverage and achievement of questions that are tagged with \( a, b, \) and \( c \); instead questions that are tagged with these three topics would contribute to the coverage and achievement of three edges, (\( a,b \)), (\( a,c \)) and (\( b,c \)).

An alternative underlying foundation that could be considered for defining TDMs is a two-weighted hypergraph. This is a generalisation of ordinary graphs that allow hyper-edges, which can relate more than two nodes. Hypergraphs have the ability to visually present coverage of questions that are tagged with more than two topics; however, since they are not as commonly adopted, their visualisations may not be as easy to understand. The evaluation of the trade-off between the two alternative underlying foundations is left as future work; TDMs that use two-weighted graphs are adopted in this paper.

3. IDENTIFYING STAKEHOLDERS AND SCENARIOS

The educational stakeholders and their scenarios of use are introduced in this section, which are used to define a collection of visual TDMs.

A wide range of educational stakeholders including those in a classroom (students, instructors) and outside a classroom (course co-ordinator, course designer, program administrator, educational researcher) need to interacts with assessment data. Within a classroom students and instructors...
need to interact with assessment data in several ways. First, there is a need to share a common understanding of the educational goals for a class in terms of the required course content (topics, dependency relationships covered). This establishes a core, common foundation for all classes offered on a course.

Second, there is a need to analyze, create, compare, and select assessment material to ensure the course topics are covered. The assessment material can be analysed at one point in time (static) or over time (dynamic) to help identify trends in the coverage. For example, a collection of assessment material can be analyzed to identify the topics and dependencies that are richly or sparsely covered. Comparisons are useful to evaluate, for example, the coverage of an assessment currently being designed for a class (e.g., homework, quiz, lab, examination) with respect to one used in a previous class. This is valuable for instructors who do not have previous experience teaching the course, as the experience of previous instructors is embodied in their assessment material.

Third, there is a need to communicate the assessment achievements for both individual students and a cohort in a class; one or more assessments can be selected that span formative and summative material. For example, achievements on an examination or several assignments and a collection of questions from a peer-learning repository can be explored. The achievements can also be explored at one point in time (static) over time (dynamic) to help identify trends.

Outside a classroom program administrators and course designers need to establish and monitor the required content for each course, as part of a program curricula. Summaries of assessment material and achievements are needed to periodically analyze the coverage of the required course content in program and course level reviews (e.g., a program accreditation audit). Class co-ordinators may be responsible for monitoring multiple, large sections running concurrently and/or over multiple terms. The classes need to employ large teams of teaching assistants (undergraduate and graduate students) that change from term to term; different instructors are also assigned over time. A course co-ordinator can monitor the assessment material and achievements to help ensure the consistency of many sections running concurrently; in addition they can periodically analyse the coverage of the required course content, perhaps on a term or annual basis. From this broader perspective, the co-ordinator can identify, investigate, and address on-going problem areas in a course such as poor performance on particular topics. Here again, static and dynamic visualisations of assessment data would be valuable.

Also outside the classroom, educational researchers need to the results between control and experimental groups. Dynamic models can provide valuable insights with respect to pre- and post-test analysis [2] on the identification of trends.

Based on these stakeholders’ needs, a collection of TDMs for exploring assessment data is needed that spans course and class levels. An overview of the collection is illustrated in Figure 2. The stakeholders are shown at the top, the TDMs in the middle, and the assessment data sources to the left. A reference model is proposed as part of the collection, which captures the required assessment topics and dependencies at the course level. Both static and dynamic TDMs are needed at the class level, which can utilize a wide variety of assessment data to explore data within one class and comparisons across two classes. A stakeholder can se-
lect the TDM and the assessment data to use, providing a flexible solution. The Course Reference TDM is included as a grayed out backdrop in class models; this helps to conceptualize the bigger picture for the course in terms of prior, current, and future topics.

4. THE TOPIC DEPENDENCY MODEL COLLECTION

The TDM collection is presented in this section. The discussion is organized around the three main components introduced in Figure 2: course assessment reference; static class level visualisations, and dynamic class level visualisations.

4.1 Course Assessment Reference Model

The Course Assessment Reference TDM establishes a standard for a course by defining the course assessment material in terms of topics, dependency relationships, and the historical level of achievement obtained. The model specifies what needs to be assessed in a course, but does not constrain how this is accomplished in the classroom. For example, instructors have the flexibility to design their assessments to achieve the course requirements by using their preferred combination of summative and formative material (homework, labs, quizzes, examinations, and/or repository discussion is organized around the three main components in-

troduced in Figure 2: course assessment reference; static class level visualisations, and dynamic class level visualisations). This model provides a common assessment foundation for all classes on a course.

![Course Assessment Reference Model](image)

Figure 3: Illustrative Example: Course Assessment Reference Model

The Course Assessment Reference Topic Dependency Model is illustrated in Figure 3. In the illustrated model assessments on required topics and their dependencies are represented with coloured edges reflecting historical coverage and achievements. For example, assessment material on the Introduction topic is required (the edge is a self-loop). The dark green colour of this edge indicates classes have historically performed very well on this topic. A number of assessments related to Functions are required. For example, Functions, Functions and File I/O, Functions and Arrays, Functions and Loops, and Functions and Conditions are required for this course. These edges are in shades of orange, indicating students have historically performed adequately on these topics and dependencies. Assessments on File I/O and Arrays are also required for this course; this dependency is in red indicating students have historically performed poorly on this. Orange or red edges highlight ongoing issues in the course, which could be explored by course designers, class co-ordinators, and instructors.

4.2 Static Class Level Visualisation Models

The static class level TDMs support visualisations of assessment data (achievements and material) both within a classroom and across classrooms for comparison purposes. Achievement data from alternative sources (e.g., Homework assignments, question repositories) can be selected, either for individual students or a cohort.

4.2.1 Visualising Assessment Data Within a Class

The Assessment Material Availability Topic Dependency Model is illustrated in Figure 4. In the illustrated model the selected assessment material (three assignments and a question repository) is visualised, revealing variable coverage. For example, more material is available covering the Introduction, Fundamentals, Conditionals, and Loops topics, indicated by a wider blue edge. Less material is available covering Conditionals and Fundamentals, Conditionals and Loops, indicated by a thinner blue edge. The topics and edges with gray colour indicate the material on these are missing. Assessment material on these topics and their dependencies needs to be added, either by the instructor (e.g., designing an Assignment) or students (designing questions and contributing them to a peer-learning repository).

The Class Achievement TDM is illustrated in Figure 5. In the illustrated models the achievement results for Assignment #3 are presented for one student (Taylor) on the left and the entire cohort on the right. Taylor’s performance on questions spanning Fundamentals and Conditionals is very good indicated by the green coloured edge. However, Taylor’s performance on Conditionals is lower (orange edge) and
poor on Loops, Conditionals and Loops (red edge). This visualisation can help direct Taylor to focus on additional problems covering Conditionals and Loops. The cohort, in contrast, has performed very well on average across multiple topics indicated by green edges: Fundamentals; Fundamentals and Conditionals; and Loops. However, the class on average has performed poorly on Conditionals and Loops (red edges). This visualisation can help direct the class in general to focus on additional problems covering Conditionals and Loops.

4.2.2 Visualising Assessment Data Across Classes

The Compare Assessment Material TDM is illustrated in Figure 6. In the illustrated model two final examinations are presented for comparison. The examination on the left is from a previous class held Term 2 2015, authored by A. Archer. The examination on the right is from a current class held Term 1 2016, jointly authored by B. Baker and C. Cooper. The examination on the left has substantially more emphasis on assessment material that spans two topics. In particular, the visualisation indicates questions involving Functions and Conditionals, Functions and Loops, Functions and Arrays, and Functions and File I/O are included. In contrast, the examination on the right has more emphasis on assessing material on a topic by topic basis. Question are included that cover only Functions, but not Functions and another topic. This comparative visualisation can highlight inconsistencies in the topic coverage on examinations designed in different classes, which the instructors can explore.

The Assessment Achievement TDM is illustrated in Figure 7. In the illustrated models the achievement results for Assignment #3 are presented for two classes. The assignment achievement results on the left are for a current instructor, Class 1 (Term 1 2016 Section 001). The assignment achievement results on the right are from Class 2 held the previous year (Term 2 2015 Section 002). The visualisations indicate the assessments do not cover the same topics (different nodes, edges involved). For example, Class 1’s assignment includes questions on the Introduction topic and the Fundamentals topic, whereas Class 2’s assignment does not. Class 1’s assignment does not include questions on Loops, whereas Class 2’s assignment includes questions on Loops in addition to Loops and Conditionals. Class 1 has performed adequately on the Conditionals topic (orange edge); Class 2 has performed very well (green edge). Based on the assessment coverage, Class 2 appears to be further ahead in the course compared to Class 1, as Loops are typically covered after Conditionals in introductory programming courses. This visualisation can help direct the current instructor to investigate the underlying reasons for the distinct coverage and achievements.
4.3 Dynamic Class Level Visualisation Models

The dynamic class level TDMs support visualisations of assessment data (achievements and material) both within a classroom and across classrooms for comparison purposes, helping to identify trends over time. As with the static models, achievement data from alternative sources (e.g., homework assignments, question repositories) can be selected, either for individual students or a cohort.

4.3.1 Assessment Material Availability Over Time

The Assessment Material Progression TDM is illustrated in Figure 8 (top). In the illustrated model the evolution is seen as assessment material is added from alternative sources (e.g., Assignments, Peer-learning environment) over time. Material on few topics is initially available (e.g., Introduction). Later in the course, most of the topics have some coverage; however, some are easily seen to be missing (e.g., File I/O, File I/O and Arrays, File I/O and Functions) as their edges remain gray. The visualisation highlights the need to provide assessment material on these topics and their dependencies, either by the instructor (e.g., designing an Assignment) or students (designing questions and contributing them to a question repository).

4.3.2 Achievements Over Time

The Class Achievement Progression TDM is illustrated in Figure 8 (bottom). In the illustrated model achievement results on few topics are initially available (e.g., Introduction, Fundamentals); the light green colour indicates the class is performing well on the Introduction topic (green edge), but only adequately on the Fundamentals topic (orange edge). Later in the course, achievement data on additional topics are available and the visualisation indicates an improving trend on achievements in earlier topics. The last visualisation in time (Tn) indicates the students are performing very well on the many topics (Introduction, Fundamentals, Conditionals, Loops, and Functions). The achievements for questions on Arrays and those spanning Functions and Conditionals as well as Arrays and Loops are adequate (orange edge); however, questions on Functions and Loops as well as Functions and Arrays are poor (edges in red). Some topics are easily seen to be missing (e.g., File I/O, File I/O and Functions, File I/O and Arrays) as they remain gray. Achievement data on these topics and their dependencies needs to be added, either by the instructor (e.g., designing/grading an Assignment) or students (designing, contributing, and answering questions in a peer-learning repository).

5. CONCLUSION AND FUTURE WORK

The rapidly changing landscape of educational environments presents new challenges on the design and delivery of high-quality assessments at scale. In particular, ensuring that there is consistency among assessments of different offerings of a course, providing meaningful feedback about students’ achievements, and tracking students’ progression over time are all challenging tasks. In this preliminary work a collection of Topic Dependency Models (TDMs) is introduced to address three facets of the problem. The first is the need for course level models to communicate the required topics and their relationships. The second is the
need for classroom level models to visualise assessment data within a class and support comparisons of assessment data between classes (static); the third is the need for classroom level models that visualise assessment data trends over time. Stakeholders can select the TDM and the assessment data of interest to use, which may be available from a wide variety of sources.

In the next steps of the research a prototype is planned to implement the TDM collection in a Learning Dashboard. The prototype will be used to explore additional research questions such as the trade-offs in adopting alternative graph definitions and how to consider additional characteristics of assessment data including the difficulty of questions and the levels of knowledge addressed based on a cognitive taxonomy such as the revised Bloom’s taxonomy.

6. REFERENCES


