

¹ Text embedding models yield high-resolution insights
² into conceptual knowledge from short multiple-choice
³ quizzes

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⁵ **Abstract**

⁶ We develop a mathematical framework, based on natural language processing models, for track-
⁷ ing and characterizing the acquisition of conceptual knowledge. Our approach embeds each
⁸ concept in a high-dimensional representation space, where nearby coordinates reflect similar or
⁹ related concepts. We test our approach using behavioral data from participants who answered
¹⁰ small sets of multiple-choice quiz questions interleaved between watching two course videos
¹¹ from the Khan Academy platform. We apply our framework to the videos' transcripts and
¹² the text of the quiz questions to quantify the content of each moment of video and each quiz
¹³ question. We use these embeddings, along with participants' quiz responses, to track how the
¹⁴ learners' knowledge changed after watching each video. Our findings show how a small set of
¹⁵ quiz questions may be used to obtain rich and meaningful high-resolution insights into what
¹⁶ each learner knows, and how their knowledge changes over time as they learn.

¹⁷ **Keywords:** education, learning, knowledge, concepts, natural language processing

¹⁸ **Introduction**

¹⁹ Suppose that a teacher had access to a complete, tangible “map” of everything a student knows.
²⁰ Defining what such a map might even look like, let alone how it might be constructed or filled in, is
²¹ itself a non-trivial problem. But if a teacher *were* to gain access to such a map, how might it change
²² their ability to teach that student? Perhaps they might start by checking how well the student
²³ knows the to-be-learned information already, or how much they know about related concepts.
²⁴ For some students, they could potentially optimize their teaching efforts to maximize efficiency
²⁵ by focusing primarily on not-yet-known content. For other students (or other content areas), it
²⁶ might be more effective to optimize for direct connections between already known content and
²⁷ new material. Observing how the student’s knowledge changed over time, in response to their
²⁸ teaching, could also help to guide the teacher towards the most effective strategy for that individual
²⁹ student.

³⁰ A common approach to assessing a student’s knowledge is to present them with a set of quiz
³¹ questions, calculate the proportion they answer correctly, and provide them with feedback in the
³² form of a simple numeric or letter grade. While such a grade can provide *some* indication of whether
³³ the student has mastered the to-be-learned material, any univariate measure of performance on a
³⁴ complex task sacrifices certain relevant information, risks conflating underlying factors, and so on.
³⁵ For example, consider the relative utility of the theoretical map described above that characterizes
³⁶ a student’s knowledge in detail, versus a single annotation saying that the student answered 85%
³⁷ of their quiz questions correctly, or that they received a ‘B’. Here, we show that the same quiz data
³⁸ required to compute proportion-correct scores or letter grades can instead be used to obtain far
³⁹ more detailed insights into what a student knew at the time they took the quiz.

⁴⁰ Designing and building procedures and tools for mapping out knowledge touches on deep
⁴¹ questions about what it means to learn. For example, how do we acquire conceptual knowledge?
⁴² Memorizing course lectures or textbook chapters by rote can lead to the superficial *appearance*
⁴³ of understanding the underlying content, but achieving true conceptual understanding seems to
⁴⁴ require something deeper and richer. Does conceptual understanding entail connecting newly

45 acquired information to the scaffolding of one’s existing knowledge or experience [4, 9, 11, 12, 25,
46 57]? Or weaving a lecture’s atomic elements (e.g., its component words) into a structured network
47 that describes how those individual elements are related [35, 61]? Conceptual understanding
48 could also involve building a mental model that transcends the meanings of those individual
49 atomic elements by reflecting the deeper meaning underlying the gestalt whole [32, 36, 54, 60].

50 The difference between “understanding” and “memorizing,” as framed by researchers in ed-
51 ucation, cognitive psychology, and cognitive neuroscience [e.g., 20, 23, 28, 36, 54], has profound
52 analogs in the fields of natural language processing and natural language understanding. For
53 example, considering the raw contents of a document (e.g., its constituent symbols, letters, and
54 words) might provide some clues as to what the document is about, just as memorizing a passage
55 might provide some ability to answer simple questions about it. However, text embedding mod-
56 els [e.g., 5, 6, 8, 10, 13, 34, 44, 62] also attempt to capture the deeper meaning *underlying* those
57 atomic elements. These models consider not only the co-occurrences of those elements within and
58 across documents, but (in many cases) also patterns in how those elements appear across differ-
59 ent scales (e.g., sentences, paragraphs, chapters, etc.), the temporal and grammatical properties
60 of the elements, and other high-level characteristics of how they are used [37, 38]. According to
61 these models, the deep conceptual meaning of a document may be captured by a feature vector
62 in a high-dimensional representation space, wherein nearby vectors reflect conceptually related
63 documents. A model that succeeds at capturing an analogue of “understanding” is able to assign
64 nearby feature vectors to two conceptually related documents, *even when the specific words con-*
65 *tained in those documents do not fully overlap.* In this way, “concepts” are defined implicitly by the
66 model’s geometry [e.g., how the embedding coordinate of a given word or document relates to the
67 coordinates of other text embeddings; 49].

68 Given these insights, what form might a representation of the sum total of a person’s knowledge
69 take (speculatively)? First, we might require a means of systematically describing or representing
70 the nearly infinite set of possible things a person could know. Second, we might want to account
71 for potential associations between different concepts. For example, the concepts of “fish” and
72 “water” might be associated in the sense that fish live in water. Third, knowledge may have

73 a critical dependency structure, such that knowing about a particular concept might require first
74 knowing about a set of other concepts. For example, understanding the concept of a fish swimming
75 in water first requires understanding what fish and water *are*. Fourth, as we learn, our “current
76 state of knowledge” should change accordingly. Learning new concepts should both update our
77 characterizations of “what is known” and also unlock any now-satisfied dependencies of those
78 newly learned concepts so that they are “tagged” as available for future learning.

79 Here we develop a framework for modeling how conceptual knowledge is acquired during
80 learning. The central idea behind our framework is to use text embedding models to define the
81 coordinate systems of two maps: a *knowledge map* that describes the extent to which each concept is
82 currently known, and a *learning map* that describes changes in knowledge over time. Each location
83 on these maps represents a single concept, and the maps’ geometries are defined such that related
84 concepts are located nearby in space. We use this framework to analyze and interpret behavioral
85 data collected from an experiment that had participants answer sets of multiple-choice questions
86 about a series of recorded course lectures.

87 Our primary research goal is to advance our understanding of what it means to acquire deep,
88 real-world conceptual knowledge. Traditional laboratory approaches to studying learning and
89 memory (e.g., list-learning studies) often draw little distinction between memorization and under-
90 standing. Instead, these studies typically focus on whether information is effectively encoded or
91 retrieved, rather than whether the information is *understood*. Approaches to studying conceptual
92 learning, such as category learning experiments, can begin to investigate the distinction between
93 memorization and understanding, often by training participants to distinguish arbitrary or random
94 features in otherwise meaningless categorized stimuli [1, 17, 18, 21, 26, 52]. However the objective
95 of real-world training, or learning from life experiences more generally, is often to develop new
96 knowledge that may be applied in *useful* ways in the future. In this sense, the gap between modern
97 learning theories and modern pedagogical approaches that inform classroom learning strategies is
98 enormous: most of our theories about *how* people learn are inspired by experimental paradigms
99 and models that have only peripheral relevance to the kinds of learning that students and teachers
100 actually seek [23, 36]. To help bridge this gap, our study uses course materials from real on-

101 line courses to inform, fit, and test models of real-world conceptual learning. We also provide a
102 demonstration of how our models can be used to construct “maps” of what students know, and
103 how their knowledge changes with training. In addition to helping to visually capture knowledge
104 (and changes in knowledge), we hope that such maps might lead to real-world tools for improving
105 how we educate. Taken together, our work shows that existing course materials and evaluative
106 tools like short multiple-choice quizzes may be leveraged to gain highly detailed insights into what
107 students know and how they learn.

108 Results

109 At its core, our main modeling approach is based around a simple assumption that we sought to
110 test empirically: all else being equal, knowledge about a given concept is predictive of knowledge
111 about similar or related concepts. From a geometric perspective, this assumption implies that
112 knowledge is fundamentally “smooth.” In other words, as one moves through a space representing
113 an individual’s knowledge (where similar concepts occupy nearby coordinates), their “level of
114 knowledge” should change relatively gradually. To begin to test this smoothness assumption, we
115 sought to track participants’ knowledge and how it changed over time in response to training.
116 Two overarching goals guide our approach. First, we want to gain detailed insights into what
117 learners know at different points in their training. For example, rather than simply reporting on
118 the proportions of questions participants answer correctly (i.e., their overall performance), we seek
119 estimates of their knowledge about a variety of specific concepts. Second, we want our approach to
120 be potentially scalable to large numbers of diverse concepts, courses, and students. This requires
121 that the conceptual content of interest be discovered *automatically*, rather than relying on manually
122 produced ratings or labels.

123 We asked participants in our study to complete brief multiple-choice quizzes before, between,
124 and after watching two lecture videos from the Khan Academy [31] platform (Fig. 1). The first
125 lecture video, entitled *Four Fundamental Forces*, discussed the four fundamental forces in physics:
126 gravity, strong and weak interactions, and electromagnetism. The second, entitled *Birth of Stars*,



Figure 1: Experimental paradigm. Participants alternate between completing three 13-question multiple-choice quizzes and watching two Khan Academy lectures. Each quiz contains a mix of 5 questions about Lecture 1, 5 questions about Lecture 2, and 3 questions about general physics knowledge. The specific questions reflected on each quiz, and the orders of each quiz's questions, were randomized across participants.

127 provided an overview of our current understanding of how stars form. We selected these particular
 128 lectures to satisfy three general criteria. First, we wanted both lectures to be accessible to a broad
 129 audience (i.e., with minimal prerequisite knowledge) so as to limit the impact of prior training
 130 on participants' abilities to learn from the lectures. To this end, we selected two introductory
 131 videos that were intended to be viewed at the start of students' training in their respective content
 132 areas. Second, we wanted the two lectures to have some related content, so that we could test
 133 our approach's ability to distinguish similar conceptual content. To this end, we chose two videos
 134 from the same Khan Academy course domain, "Cosmology and Astronomy." Third, we sought to
 135 minimize dependencies and specific overlap between the videos. For example, we did not want
 136 participants' abilities to understand one video to (directly) influence their abilities to understand the
 137 other. To satisfy this last criterion, we chose videos from two different lecture series (Lectures 1 and
 138 2 were from the "Scale of the Universe" and "Stars, Black Holes, and Galaxies" series, respectively).

139 We also wrote a set of multiple-choice quiz questions that we hoped would enable us to
 140 evaluate participants' knowledge about each individual lecture, along with related knowledge
 141 about physics concepts not specifically presented in either video (see Supp. Tab. 1 for the full list
 142 of questions in our stimulus pool). Participants answered questions randomly drawn from each
 143 content area (Lecture 1, Lecture 2, and general physics knowledge) on each of the three quizzes.
 144 Quiz 1 was intended to assess participants' "baseline" knowledge before training, Quiz 2 assessed



Figure 2: Modeling course content. **A. Building a document pool from sliding windows of text.** We decompose each lecture’s transcript into a series of overlapping sliding windows. The full set of transcript snippets (across all windows) may be treated as a set of “documents” for training a text embedding model. **B. Constructing lecture content trajectories.** After training the model on the sliding windows from both lectures, we transform each lecture into a “trajectory” through text embedding space by joining the embedding coordinates of successive sliding windows parsed from its transcript. **C. Embedding multiple lectures and questions in a shared space.** We apply the same model (trained on the two lectures’ windows) to both lectures, along with the text of each question in our pool (Supp. Tab. 1), to project them into a shared text embedding space. This results in one trajectory per lecture and one coordinate for each question. Here, we have projected the 15-dimensional embeddings onto their first 3 principal components for visualization.

knowledge after watching the *Four Fundamental Forces* video (i.e., Lecture 1), and Quiz 3 assessed knowledge after watching the *Birth of Stars* video (i.e., Lecture 2).

To study in detail how participants’ conceptual knowledge changed over the course of the experiment, we first sought to model the conceptual content presented to them at each moment throughout each of the two lectures. We adapted an approach we developed in prior work [24] to identify the latent themes in the lectures using a topic model [6]. Briefly, topic models take as input a collection of text documents, and learn a set of “topics” (i.e., latent themes) from their contents. Once fit, a topic model can be used to transform arbitrary (potentially new) documents into sets of “topic proportions,” describing the weighted blend of learned topics reflected in their texts. We parsed automatically generated transcripts of the two lectures into overlapping sliding windows, where each window contained the text of the lecture transcript from a particular time span. We treated the set of text snippets (across all of these windows) as documents to fit the model (Fig. 2A; see *Constructing text embeddings of multiple lectures and questions*). Transforming the text from every sliding window with the model yielded a number-of-windows by number-of-topics (15) topic-proportions matrix describing the unique mixture of broad themes from both lectures

160 reflected in each window’s text. Each window’s “topic vector” (i.e., column of the topic-proportions
161 matrix) is analogous to a coordinate in a 15-dimensional space whose axes are topics discovered
162 by the model. Within this space, each lecture’s sequence of topic vectors (i.e., corresponding to its
163 transcript’s overlapping text snippets across sliding windows) forms a *trajectory* that captures how
164 its conceptual content unfolds over time (Fig. 2B). We resampled these trajectories to a resolution
165 of one topic vector for each second of video (i.e., 1 Hz).

166 We hypothesized that a topic model trained on transcripts of the two lectures should also
167 capture the conceptual knowledge probed by each quiz question. If indeed the topic model could
168 capture information about the deeper conceptual content of the lectures (i.e., beyond surface-level
169 details such as particular word choices), then we should be able to recover a correspondence
170 between each lecture and questions *about* each lecture. Importantly, such a correspondence could
171 not solely arise from superficial text matching between lecture transcripts and questions, since the
172 lectures and questions often used different words (Supp. Fig. 5) and phrasings. Simply comparing
173 the average topic weights from each lecture and question set (averaging across time and questions,
174 respectively) reveals a striking correspondence (Supp. Fig. 2). Specifically, the average topic
175 weights from Lecture 1 are strongly correlated with the average topic weights from Lecture 1
176 questions ($r(13) = 0.809, p < 0.001$, 95% confidence interval (CI) = [0.633, 0.962]), and the average
177 topic weights from Lecture 2 are strongly correlated with the average topic weights from Lecture 2
178 questions ($r(13) = 0.728, p = 0.002$, 95% CI = [0.456, 0.920]). At the same time, the average
179 topic weights from the two lectures are *negatively* correlated with their non-matching question sets
180 (Lecture 1 video vs. Lecture 2 questions: $r(13) = -0.547, p = 0.035$, 95% CI = [-0.812, -0.231];
181 Lecture 2 video vs. Lecture 1 questions: $r(13) = -0.612, p = 0.015$, 95% CI = [-0.874, -0.281]),
182 indicating that the topic model also exhibits some degree of specificity. The full set of pairwise
183 comparisons between average topic weights for the lectures and question sets is reported in
184 Supplementary Figure 2.

185 It is important to clarify that although we use topic model-derived embeddings to *characterize*
186 the conceptual content of the lectures and questions, we do not claim that the topic model itself
187 *understands* the conceptual content of the lectures or questions. Rather, we view the topic model as



Figure 3: Lecture and question topic overlap. A. Topic weight variability. The bar plots display the variance of each topic's weight across lecture timepoints (top row) and questions (bottom row); colors denote topics. The top-weighted words from the most “expressive” (i.e., variable across observations) topic from each lecture are displayed in the upper right (orange: topic 2; yellow-green: topic 4). The top-weighted words from the full set of topics may be found in Supplementary Table 2. **B. Relationships between topic weight variability.** Pairwise correlations between the distributions of topic weight variance for each lecture and question set. Each row and column corresponds to a bar plot in Panel A.

188 a tool for capturing the *structure* of the conceptual content of the lectures and questions in a way
 189 that enables us to capture, quantify, and track and predict participants' knowledge.
 190 Another, more sensitive, way of summarizing the conceptual content of the lectures and ques-
 191 tions is to look at *variability* in how topics are weighted over time and across different questions
 192 (Fig. 3). Intuitively, the variability in the expression of a given topic relates to how much “infor-
 193 mation” [19] the lecture (or question set) reflects about that topic. For example, suppose a given
 194 topic is weighted on heavily throughout a lecture. That topic might be characteristic of some
 195 aspect or property of the lecture *overall* (conceptual or otherwise), but unless the topic's weights
 196 changed in meaningful ways over time, the topic would be a poor indicator of any *specific* concep-
 197 tual content in the lecture. We therefore also compared the variances in topic weights (across time
 198 or questions) between the lectures and questions. The variability in topic expression (over time
 199 and across questions) was similar for the Lecture 1 video and questions ($r(13) = 0.824, p < 0.001$,
 200 95% CI = [0.696, 0.973]) and the Lecture 2 video and questions ($r(13) = 0.801, p < 0.001$, 95%
 201 CI = [0.539, 0.958]). Simultaneously, as reported in Figure 3B, the variability in topic expression

202 across *different* videos and lecture-specific questions (i.e., Lecture 1 video vs. Lecture 2 questions;
203 Lecture 2 video vs. Lecture 1 questions) were negatively correlated, and neither video’s topic
204 variability was reliably correlated with the topic variability across general physics knowledge
205 questions. Taken together, the analyses reported in Figure 3 and Supplementary Figure 2 indicate
206 that a topic model fit to the videos’ transcripts can also reveal correspondences (at a coarse scale)
207 between the lectures and questions.

208 While an individual lecture may be organized around a single broad theme at a coarse scale,
209 at a finer scale, each moment of a lecture typically covers a narrower range of content. Given
210 the correspondence we found between the variability in topic expression across moments of each
211 lecture and questions from its corresponding set (Fig. 3), we wondered whether the text embedding
212 model might additionally capture these conceptual relationships at a finer scale. For example, if a
213 particular question asks about the content from one small part of a lecture, we wondered whether
214 the text embeddings could be used to automatically identify the “matching” moment(s) in the
215 lecture. To explore this, we computed the correlation between each question’s topic weights
216 and the topic weights for each second of its corresponding lecture, and found that each question
217 appeared to be temporally specific (Fig. 4). In particular, most questions’ topic vectors were
218 maximally correlated with a well-defined (and relatively narrow) range of timepoints from their
219 corresponding lectures, and the correlations fell off sharply outside of that range (Supp. Figs. 3, 4).
220 We also qualitatively examined the best-matching intervals for each question by comparing the
221 question’s text to the text of the most-correlated parts of the lectures (Supp. Tab. 3). Despite that
222 the questions were excluded from the text embedding model’s training set, in general we found
223 (through manual inspection) a close correspondence between the conceptual content that each
224 question probed and the content covered by the best-matching moments of the lectures. Two
225 representative examples are shown at the bottom of Figure 4.

226 The ability to quantify how much each question is “asking about” the content from each moment
227 of the lectures could enable high-resolution insights into participants’ knowledge. Traditional
228 approaches to estimating how much a student “knows” about the content of a given lecture entail
229 computing the proportion of correctly answered questions. But if two students receive identical

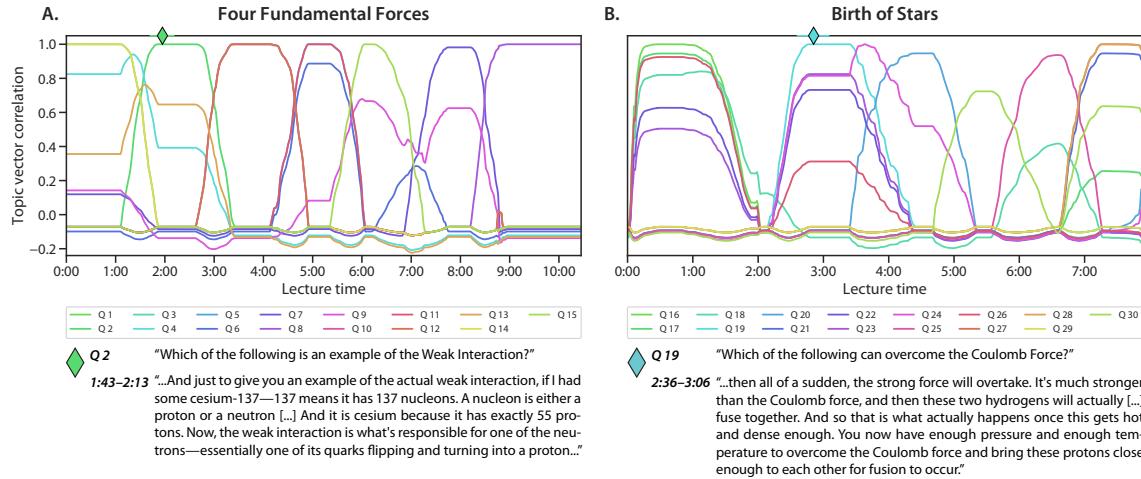


Figure 4: Which parts of each lecture are captured by each question? Each panel displays timeseries plots showing how each question’s topic vector correlates with each video timepoint’s topic vector (Panel A.: correlations for the *Four Fundamental Forces* lecture and associated questions; Panel B.: correlations for the *Birth of Stars* lecture and associated questions). The colors denote question identities. The diamonds in each panel denote the moment of peak correlation between the indicated question and the lecture trajectory. The associated questions’ text and snippets of the lectures’ transcripts from the surrounding 30 seconds, are displayed at the bottom of the figure.

230 scores on an exam, might our modeling framework help us to gain more nuanced insights into the
 231 *specific* content that each student has mastered (or failed to master)? For example, a student who
 232 misses three questions that were all about the same concept (e.g., concept *A*) will have gotten the
 233 same *proportion* of questions correct as another student who missed three questions about three
 234 different concepts (e.g., *A*, *B*, and *C*). But if we wanted to help these two students fill in the “gaps” in
 235 their understandings, we might do well to focus specifically on concept *A* for the first student, but
 236 to also add in materials pertaining to concepts *B* and *C* for the second student. In other words, raw
 237 “proportion-correct” measures may capture *how much* a student knows, but not *what* they know.
 238 We wondered whether our modeling framework might enable us to (formally and automatically)
 239 infer participants’ knowledge at the scale of individual concepts (e.g., as captured by a single
 240 moment of a lecture).

241 We developed a simple formula (Eqn. 1) for using a participant’s responses to a small set
 242 of multiple-choice questions to estimate how much the participant “knows” about the concept

reflected by any arbitrary coordinate, x , in text embedding space (e.g., the content reflected by any moment in a lecture they had watched; see *Estimating dynamic knowledge traces*). Essentially, the estimated knowledge at coordinate x is given by the weighted average proportion of quiz questions the participant answered correctly, where the weights reflect how much each question is “about” the content at x . When we apply this approach to estimate the participant’s knowledge about the content presented in each moment of each lecture, we can obtain a detailed time course describing how much “knowledge” the participant has about the content presented at any part of the lecture. As shown in Figure 5A and C, we can apply this approach separately for the questions from each quiz participants took throughout the experiment. From just a few questions per quiz (see *Estimating dynamic knowledge traces*), we obtain a high-resolution snapshot (at the time each quiz was taken) of what the participants knew about any moment’s content, from either of the two lectures they watched (comprising a total of 1,100 samples across the two lectures).

While the time courses in Figure 5A and C provide detailed *estimates* about participants’ knowledge, these estimates are of course only *useful* to the extent that they accurately reflect what participants actually know. As one sanity check, we anticipated that the knowledge estimates should reflect a content-specific “boost” in participants’ knowledge after watching each lecture. In other words, if participants learn about each lecture’s content when they watch each lecture, the knowledge estimates should capture that. After watching the *Four Fundamental Forces* lecture, participants should exhibit more knowledge for the content of that lecture than they had before, and that knowledge should persist for the remainder of the experiment. Specifically, knowledge about that lecture’s content should be relatively low when estimated using Quiz 1 responses, but should increase when estimated using Quiz 2 or 3 responses (Fig. 5B). Indeed, we found that participants’ estimated knowledge about the content of the *Four Fundamental Forces* was substantially higher on Quiz 2 versus Quiz 1 ($t(49) = 8.764$, $p < 0.001$) and on Quiz 3 versus Quiz 1 ($t(49) = 10.519$, $p < 0.001$). We found no reliable differences in estimated knowledge about that lecture’s content on Quiz 2 versus 3 ($t(49) = 0.160$, $p = 0.874$). Similarly, we hypothesized (and subsequently confirmed) that participants should show greater estimated knowledge about the content of the *Birth of Stars* lecture after (versus before) watching it (Fig. 5D). Specifically, since



Figure 5: Estimating knowledge about the content presented at each moment of each lecture. **A. Knowledge about the time-varying content of *Four Fundamental Forces*.** Each trace displays the weighted proportion of correctly answered questions about the content reflected in each moment of the lecture (see *Estimating dynamic knowledge traces*), using responses from a single quiz (color). The traces are averaged across participants. **B. Average estimated knowledge about *Four Fundamental Forces*.** Each bar displays the across-timepoint average knowledge, estimated using the responses to one quiz's questions. **C. Knowledge about the time-varying content of *Birth of Stars*.** The panel is in the same format as Panel A, but here the knowledge estimates are for the moment-by-moment content of the *Birth of Stars* lecture. **D. Average estimated knowledge about *Birth of Stars*.** The panel is in the same format as Panel B, but here the knowledge estimates are for the content of the *Birth of Stars* lecture. All panels: error ribbons and error bars denote 95% confidence intervals, estimated across participants.

271 participants watched that lecture after taking Quiz 2 (but before Quiz 3), we hypothesized that their
272 knowledge estimates should be relatively low on Quizzes 1 and 2, but should show a “boost” on
273 Quiz 3. Consistent with this prediction, we found no reliable differences in estimated knowledge
274 about the *Birth of Stars* lecture content on Quizzes 1 versus 2 ($t(49) = 1.013, p = 0.316$), but the
275 estimated knowledge was substantially higher on Quiz 3 versus 2 ($t(49) = 10.561, p < 0.001$) and
276 Quiz 3 versus 1 ($t(49) = 8.969, p < 0.001$).

277 If we are able to accurately estimate a participant’s knowledge about the content tested by a
278 given question, our estimates of their knowledge should carry some predictive information about
279 whether the participant is likely to answer that question correctly or incorrectly. We developed a
280 statistical approach to test this claim. For each question, in turn, we used Equation 1 to estimate
281 each participant’s knowledge at the given question’s embedding space coordinate, using all *other*
282 questions that participant answered on the same quiz. For each quiz, we grouped these estimates
283 into two distributions: one for the estimated knowledge at the coordinates of *correctly* answered
284 questions, and another for the estimated knowledge at the coordinates of *incorrectly* answered
285 questions (Fig. 6). We then used Mann-Whitney *U*-tests to compare the means of these distributions
286 of estimated knowledge.

287 For the initial quizzes participants took (prior to watching either lecture), participants’ estimated
288 knowledge tended to be low overall, and relatively unstructured (Fig. 6, left column). When we
289 held out individual questions and estimated their knowledge at the held-out questions’ embedding
290 coordinates, we found no reliable differences in the estimates when the held-out question had been
291 correctly versus incorrectly answered. This “null” effect persisted when we used *all* of the Quiz 1
292 questions from a given participant to predict a held-out question (“All questions”; $U = 50587, p =$
293 0.723), when we used questions from one lecture to predict knowledge at the embedding coordinate
294 of a held-out question about the *other* lecture (“Across-lecture”; predicting knowledge for held-out
295 *Four Fundamental Forces Questions* using *Birth of Stars* questions: $U = 8244, p = 0.184$; predicting
296 knowledge for held-out *Birth of Stars* questions: $U = 8202.5, p = 0.161$), and when we used questions
297 from one lecture to predict knowledge at the embedding coordinate of a held-out question about
298 the *same* lecture (“Within-lecture”; *Four Fundamental Forces*: $U = 7681.5, p = 0.746$; *Birth of Stars*:

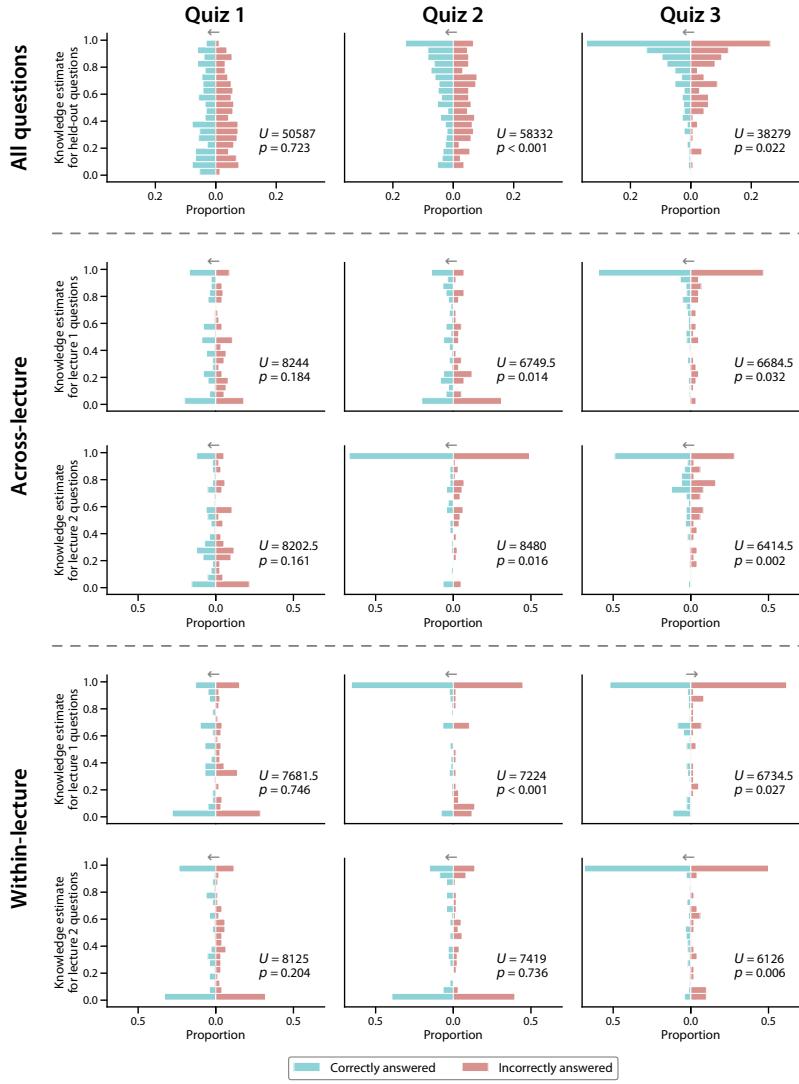


Figure 6: Estimating knowledge at the embedding coordinates of held-out questions. Separately for each quiz (panel), we plot the distributions of predicted knowledge at the embedding coordinates of each held-out correctly (blue) or incorrectly (red) answered question. The Mann-Whitney U -tests reported in each panel are between the distributions of estimated knowledge at the coordinates of correctly versus incorrectly answered held-out questions. In the top row (“All questions”), we used all quiz questions (from each quiz, for each participant) except one to estimate knowledge at the held-out question’s embedding coordinate. In the middle rows (“Across-lecture”), we used all questions about one lecture to estimate knowledge at the embedding coordinate of a held-out question about the *other* lecture. In the bottom row (“Within-lecture”), we used all but one question about one lecture to estimate knowledge at the embedding coordinate of a held-out question about the *same* lecture. We repeated each of these analyses using all possible held-out questions for each quiz and participant.

299 $U = 8125, p = 0.204$). We believe that this reflects a floor effect: when knowledge is low everywhere,
300 there is little signal to differentiate between what is known versus unknown.

301 After watching *Four Fundamental Forces*, estimated knowledge for held-out correctly answered
302 questions (from the second quiz; Fig. 6, middle column) exhibited a positive shift relative to held-
303 out incorrectly answered questions. This held when we included all questions in the analysis
304 ($U = 58332, p < 0.001$), when we predicted knowledge across-lectures (*Four Fundamental Forces*:
305 $U = 6749.5, p = 0.014$; *Birth of Stars*: $U = 8480, p = 0.016$), and when we predicted knowledge at the
306 embedding coordinates of held-out *Four Fundamental Forces* questions using other *Four Fundamental*
307 *Forces* questions from the same quiz and participant ($U = 7224, p < 0.001$). This difference did *not*
308 hold for within-lecture predictions of *Birth of Stars* knowledge ($U = 7419, p = 0.739$). Again, we
309 suggest that this might reflect a floor effect whereby knowledge about the content of the *Birth of*
310 *Stars* material is relatively low everywhere in that region of text embedding space.

311 Finally, after watching *Birth of Stars*, estimated knowledge for held-out correctly answered
312 questions (from the third quiz; Fig. 6, right column) was higher for held-out correctly answered
313 questions than for held-out incorrectly answered questions. This held when we included all
314 questions in the analysis ($U = 38279, p = 0.022$), when we carried out across-lecture predictions
315 (*Four Fundamental Forces*: $U = 6684.5, p = 0.032$; *Birth of Stars*: $U = 6414.5, p = 0.002$), and when
316 we carried out within-lecture predictions of held-out *Birth of Stars* questions using other *Birth of*
317 *Stars* questions from the same quiz and participant ($U = 6126, p = 0.006$). However, we found
318 the *opposite* effect when we carried out within-lecture predictions of held-out *Four Fundamental*
319 *Forces* questions using other *Four Fundamental Forces* questions from the same quiz and participant
320 ($U = 6734, p = 0.027$). Specifically, held-out correctly answered Quiz 3 questions about *Four*
321 *Fundamental Forces* had reliably *lower* estimated knowledge than held-out incorrectly answered
322 questions. Speculatively, we suggest that this may reflect participants forgetting some of the *Four*
323 *Fundamental Forces* content. If this forgetting happens in a relatively “random” way (with respect
324 to spatial distance within the text embedding space), then it could explain why some held-out
325 questions about *Four Fundamental Forces* were answered incorrectly, even if questions at nearby
326 coordinates (i.e., about similar content) were answered correctly. This might lead our approach

327 to over-estimate knowledge for held-out questions about “forgotten” knowledge that participants
328 answered incorrectly.

329 That the knowledge estimates derived from the text embedding space reliably distinguish
330 between held-out correctly versus incorrectly answered questions (Fig. 6) suggests that the text
331 embedding space bears at least some relationship to participants’ knowledge. But what does that
332 relationship look like as we move through the embedding space? For example, suppose we know
333 that a participant answers a question (at embedding coordinate X) correctly. As we move away
334 from X in the embedding space, how does quiz performance “fall off” with distance? Or, suppose
335 the participant instead answered that same question *incorrectly*. Again, as we move away from X
336 in the embedding space, how do the chances that the participant does *not* know about the content
337 change with distance? We reasoned that, assuming our space is capturing something about how
338 participants actually organize their knowledge, conceptual knowledge right around X should be
339 similar to the participant’s knowledge of the content at X . And at another extreme, at some distance
340 (after moving sufficiently far away from X), our guesses about what participants know (based on
341 their response to the question at location X) should be no better than guessing based on their
342 overall proportion of correctly answered questions—i.e., if Y is very far away from X , all we can
343 do with the participant’s response to X is guess that “their performance on quiz questions about Y
344 is about equal to their average performance on quiz questions about any material.”

345 With these ideas in mind, we asked: conditioned on answering a question correctly, what
346 proportion of all questions (within some radius, r , of that question’s embedding coordinate)
347 were answered correctly? We plotted this proportion as a function of r . Similarly, we could
348 ask, conditioned on answering a question incorrectly, how the proportion of correct responses
349 changed with r . As shown in Figure 7, we found that quiz performance falls off smoothly with
350 distance, and the “rate” of the falloff does not appear to change across the different quizzes, as
351 measured by the distance at which performance becomes statistically indistinguishable from a
352 simple proportion correct score (see *Estimating the “smoothness” of knowledge*). This suggests that,
353 at least within the region of text embedding space covered by the questions our participants
354 answered (and as characterized using our topic model), the rate at which knowledge changes

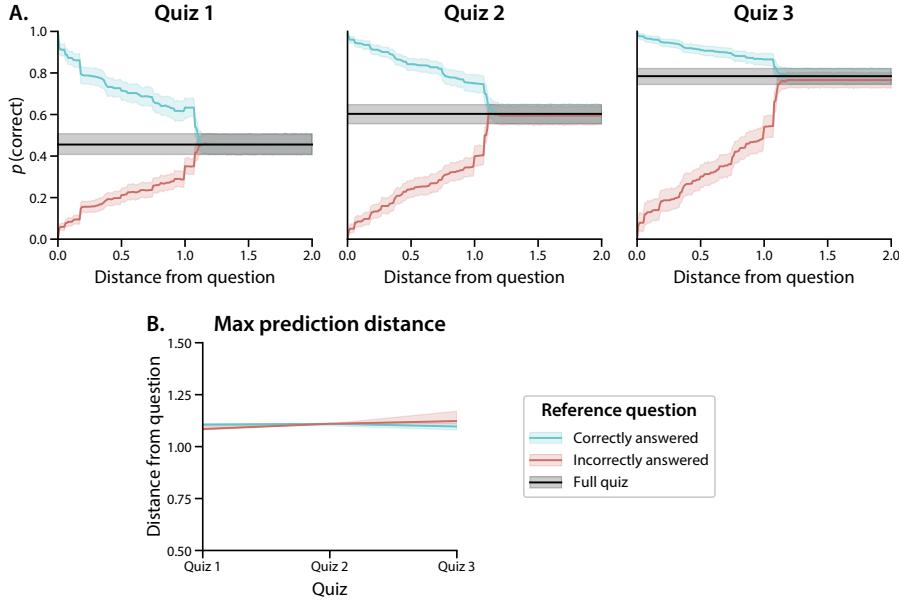


Figure 7: Quiz performance falls off gradually in text embedding space. A. Performance versus distance. For each participant, for each correctly answered question (blue) or incorrectly answered question (red), we computed the proportion of correctly answered questions within a given distance of that question’s embedding coordinate. We repeated this analysis for all questions and participants, and separately for each quiz (column). The black lines denote the average proportion correct across *all* questions included in the analysis at the given distance. **B. Maximum distance for which performance is reliably different from the average.** We used a bootstrap procedure (see *Estimating the “smoothness” of knowledge*) to estimate the point at which the blue and red lines in Panel A reliably diverged from the black line. We repeated this analysis separately for correctly and incorrectly answered questions from each quiz. **All panels.** Error ribbons denote bootstrap-estimated 95% confidence intervals.

355 with distance is relatively constant, even as participants’ overall level of knowledge varies across
 356 quizzes or regions of the embedding space.

357 Knowledge estimates need not be limited to the content of the lectures. As illustrated in
 358 Figure 8, our general approach to estimating knowledge from a small number of quiz questions
 359 may be extended to *any* content, given its text embedding coordinate. To visualize how knowledge
 360 “spreads” through text embedding space to content beyond the lectures participants watched, we
 361 first fit a new topic model to the lectures’ sliding windows with (up to) $k = 100$ topics. Conceptually,
 362 increasing the number of topics used by the model functions to increase the “resolution” of the
 363 embedding space, providing a greater ability to estimate knowledge for content that is highly

364 similar to (but not precisely the same as) that contained in the two lectures. This change in the
365 number of topics overcame an undesirable behavior in the UMAP embedding procedure [40],
366 whereby embedding coordinates for the 15-topic model tended to be “clumped” into separated
367 clusters, rather than forming a smooth trajectory through the 2D space. When we increased the
368 number of topics to 100, the embedding coordinates in the 2D space formed a smooth trajectory
369 through the space, with substantially less clumping (Fig. 8). We note that we used these 2D maps
370 solely for visualization; all relevant comparisons, distance computations, and statistical tests we
371 report above were carried out in the original 15-dimensional space, using the 15-topic model. Aside
372 from increasing the number of topics from 15 to 100, all other procedures and model parameters
373 were carried over from the preceding analyses. As in our other analyses, we resampled each
374 lecture’s topic trajectory to 1 Hz and projected each question into a shared text embedding space.

375 We projected the resulting 100-dimensional topic vectors (for each second of video and each quiz
376 question) onto a shared 2-dimensional plane (see *Creating knowledge and learning map visualizations*).
377 Next, we sampled points from a 100×100 grid of coordinates that evenly tiled a rectangle enclos-
378 ing the 2D projections of the videos and questions. We used Equation 4 to estimate participants’
379 knowledge at each of these 10,000 sampled locations, and averaged these estimates across par-
380 ticipants to obtain an estimated average *knowledge map* (Fig. 8A). Intuitively, the knowledge map
381 constructed from a given quiz’s responses provides a visualization of how “much” participants
382 knew about any content expressible by the fitted text embedding model at the point in time when
383 they completed that quiz.

384 Several features of the resulting knowledge maps are worth noting. The average knowledge
385 map estimated from Quiz 1 responses (Fig. 8A, leftmost map) shows that participants tended to
386 have relatively little knowledge about any parts of the text embedding space (i.e., the shading is
387 relatively dark everywhere). The knowledge map estimated from Quiz 2 responses shows a marked
388 increase in knowledge on the left side of the map (around roughly the same range of coordinates
389 traversed by the *Four Fundamental Forces* lecture, indicated by the dotted blue line). In other words,
390 participants’ estimated increase in knowledge is localized to conceptual content that is nearby (i.e.,
391 related to) the content from the lecture they watched prior to taking Quiz 2. This localization is

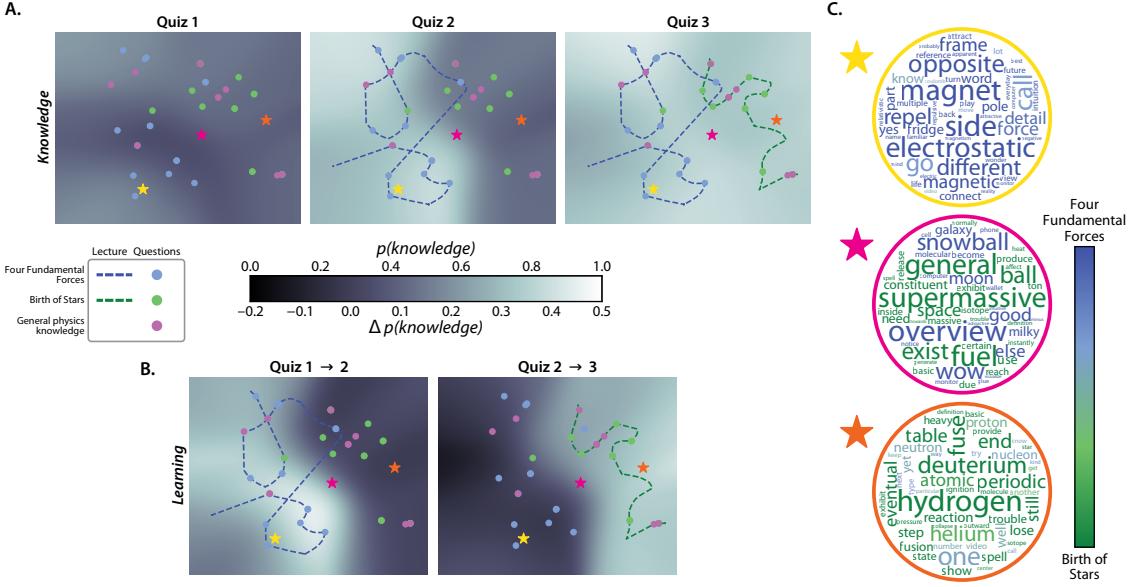


Figure 8: Mapping out the geometry of knowledge and learning. **A.** Average “knowledge maps” estimated using each quiz. Each map displays a 2D projection of the estimated knowledge about the content reflected by *all* regions of topic space (see *Creating knowledge and learning map visualizations*). The topic trajectories of the two lectures are indicated by dotted lines (blue: Lecture 1; green: Lecture 2), and the coordinates of each question are indicated by dots (light blue: Lecture 1-related; light green: Lecture 2-related; purple: general physics knowledge). Each map reflects an average across all participants. For individual participants’ maps, see Supplementary Figures 7, 8, and 9. **B.** Average “learning maps” estimated between each successive pair of quizzes. The learning maps follow the same general format as the knowledge maps in Panel A, but here the shading at each coordinate indicates the *difference* between the corresponding coordinates in the indicated pair of knowledge maps—i.e., how much the estimated knowledge “changed” between the two quizzes. Each map reflects an average across all participants. For individual participants’ maps, see Supplementary Figures 10 and 11. **C.** Word clouds for sampled points in topic space. Each word cloud displays the weighted blend of words underlying the topic proportions represented at the corresponding colored star’s location on the maps. In each word cloud, the words’ relative sizes correspond to their relative weights at the starred location, and their colors indicate their relative weights in the *Four Fundamental Forces* (blue) versus *Birth of Stars* (green) lectures, on average, across all timepoints’ topic vectors.

392 non-trivial: these knowledge estimates are informed only by the embedded coordinates of the
393 *quiz questions*, not by the embeddings of either lecture (see Eqn. 4). Finally, the knowledge map
394 estimated from Quiz 3 responses shows a second increase in knowledge, localized to the region
395 surrounding the embedding of the *Birth of Stars* lecture participants watched immediately prior to
396 taking Quiz 3.

397 Another way of visualizing these content-specific increases in knowledge after participants
398 viewed each lecture is displayed in Figure 8B. Taking the point-by-point difference between the
399 knowledge maps estimated from responses to a successive pair of quizzes yields a *learning map*
400 that describes the *change* in knowledge estimates from one quiz to the next. These learning maps
401 highlight that the estimated knowledge increases we observed across maps were specific to the
402 regions around the embeddings of each lecture, in turn.

403 Because the 2D projection we used to construct the knowledge and learning maps is invertible,
404 we may gain additional insights into these maps' meanings by reconstructing the original high-
405 dimensional topic vector for any location on the map we are interested in. For example, this could
406 serve as a useful tool for an instructor looking to better understand which content areas a student
407 (or a group of students) knows well (or poorly). As a demonstration, we show the top-weighted
408 words from the blends of topics reconstructed from three example locations on the maps (Fig. 8C):
409 one point near the *Four Fundamental Forces* embedding (yellow), a second point near the *Birth of*
410 *Stars* embedding (orange), and a third point between the two lectures' embeddings (pink). As
411 shown in the word clouds in the panel, the top-weighted words at the example coordinate near the
412 *Four Fundamental Forces* embedding tended to be weighted more heavily by the topics expressed
413 in that lecture. Similarly, the top-weighted words at the example coordinate near the *Birth of Stars*
414 embedding tended to be weighted more heavily by the topics expressed in *that* lecture. And the
415 top-weighted words at the example coordinate between the two lectures' embeddings show a
416 roughly even mix of words most strongly associated with each lecture.

417 **Discussion**

418 We developed a computational framework that uses short multiple-choice quizzes to gain nuanced
419 insights into what learners know and how their knowledge changes with training. First, we show
420 that our approach can automatically match the conceptual knowledge probed by individual quiz
421 questions to the corresponding moments in lecture videos when those concepts were presented
422 (Fig. 4). Next, we demonstrate how we can estimate moment-by-moment “knowledge traces”
423 that reflect the degree of knowledge participants have about each video’s time-varying content,
424 and capture temporally specific increases in knowledge after viewing each lecture (Fig. 5). We
425 also show that these knowledge estimates can generalize to held-out questions (Fig. 6). Finally,
426 we use our framework to construct visual maps that provide snapshot estimates of how much
427 participants know about any concept within the scope of our text embedding model, and how
428 much their knowledge of those concepts changes with training (Fig. 8).

429 We view our work as making several contributions to the study of how people acquire con-
430 ceptual knowledge. First, from a methodological standpoint, our modeling framework provides
431 a systematic means of mapping out and characterizing knowledge in maps that have infinite (ar-
432 bitrarily many) numbers of coordinates, and of “filling out” those maps using relatively small
433 numbers of multiple choice quiz questions. Our experimental finding that we can use these maps
434 to predict responses to held-out questions has several psychological implications as well. For ex-
435 ample, concepts that are assigned to nearby coordinates by the text embedding model also appear
436 to be “known to a similar extent” (as reflected by participants’ responses to held-out questions;
437 Fig. 6). This suggests that participants also *conceptualize* similarly the content reflected by nearby
438 embedding coordinates. The “spatial smoothness” of participants’ knowledge (as estimated using
439 quiz performance) is being captured by the knowledge maps we are inferring from their quiz
440 responses (e.g., Figs. 7, 8). In other words, our study shows that knowledge about a given concept
441 implies knowledge about related concepts, and we also show how estimated knowledge falls off
442 with distance in text embedding space.

443 In our study, we characterize the “coordinates” of participants’ knowledge using a relatively

444 simple “bag of words” text embedding model [LDA; 6]. More sophisticated text embedding mod-
445 els, such as transformer-based models [15, 48, 59, 62] can learn complex grammatical and semantic
446 relationships between words, higher-order syntactic structures, stylistic features, and more. We
447 considered using transformer-based models in our study, but we found that the text embeddings
448 derived from these models were surprisingly uninformative with respect to differentiating or oth-
449 erwise characterizing the conceptual content of the lectures and questions we used. We suspect
450 that this reflects a broader challenge in constructing models that are high-resolution within a given
451 domain (e.g., the domain of physics lectures and questions) *and* sufficiently broad so as to enable
452 them to cover a wide range of domains. For example, we found that the embeddings derived even
453 from much larger and more modern models like BERT [15], GPT [62], LLaMa [59], and others that
454 are trained on enormous text corpora, end up yielding poor resolution within the content space
455 spanned by individual course videos (Supp. Fig. 6). Whereas the LDA embeddings of the lectures
456 and questions are “near” each other (i.e., the convex hull enclosing the two lectures’ trajectories is
457 highly overlapping with the convex hull enclosing the questions’ embeddings), the BERT embed-
458 dings of the lectures and questions are instead largely distinct (top row of Supp. Fig. 6). The LDA
459 embeddings of the questions for each lecture and the corresponding lecture’s trajectory are also
460 similar. For example, as shown in Fig. 2C, the LDA embeddings for *Four Fundamental Forces* ques-
461 tions (blue dots) appear closer to the *Four Fundamental Forces* lecture trajectory (blue line), whereas
462 the LDA embeddings for *Birth of Stars* questions (green dots) appear closer to the *Birth of Stars*
463 lecture trajectory (green line). The BERT embeddings of the lectures and questions do not show
464 this property (Supp. Fig. 6). We also examined per-question “content matches” between individual
465 questions and individual moments of each lecture (Figs. 4, 6). The timeseries plot of individual
466 questions’ correlations are different from each other when computed using LDA (e.g., the traces
467 can be clearly visually separated), whereas the correlations computed from BERT embeddings of
468 different questions all look very similar. This tells us that LDA is capturing some differences in
469 content between the questions, whereas BERT is not. The timeseries plots of individual questions’
470 correlations have clear “peaks” when computed using LDA, but not when computed using BERT.
471 This tells us that LDA is capturing a “match” between the content of each question and a relatively

472 well-defined time window of the corresponding lectures. The BERT embeddings appear to blur
473 together the content of the questions versus specific moments of each lecture. Finally, we also
474 compared the pairwise correlations between embeddings of questions within versus across con-
475 tent areas (i.e., content covered by the individual lectures, lecture-specific questions, and by the
476 “general physics knowledge” questions). The LDA embeddings show a strong contrast between
477 same-content embeddings versus across-content embeddings. In other words, the embeddings of
478 questions about the *Four Fundamental Forces* material are highly correlated with the embeddings of
479 the *Four Fundamental Forces* lecture, but not with the embeddings of *Birth of Stars*, questions about
480 *Birth of Stars*, or general physics knowledge questions. We see a similar pattern with the LDA
481 embeddings of the *Birth of Stars* questions (Fig. 3, Supp. Fig. 2). In contrast, the BERT embeddings
482 are all highly correlated with each other (Supp. Fig. 6). Taken together, these comparisons illus-
483 trate how LDA (trained on the specific content in question) provides both coverage of the requisite
484 material and specificity at the level of the content covered by individual questions. BERT, on the
485 other hand, essentially assigns both lectures and all of the questions (which are all broadly about
486 “physics”) into a tiny region of its embedding space, thereby blurring out meaningful distinctions
487 between different specific concepts covered by the lectures and questions. We note that these are
488 not criticisms of BERT (or other large language models trained on large and diverse corpora).
489 Rather, our point is that simple fine-tuned models trained on a relatively small but specialized
490 corpus can outperform much more complicated models trained on much larger corpora, when we
491 are specifically interested in capturing subtle conceptual differences at the level of a single course
492 lecture or question. Of course if our goal had been to find a model that generalized to many
493 different content areas, we would expect our approach to perform comparatively poorly relative to
494 BERT or other much larger models. We suggest that bridging the tradeoff between high resolution
495 within each content area versus the ability to generalize to many different content areas will be an
496 important challenge for future work in this domain.

497 Another application for large language models that does *not* require explicitly modeling the
498 content of individual lectures or questions is to leverage the models’ ability to generate text. For
499 example, generative text models like ChatGPT [48] and LLaMa [59] are already being used to build

500 a new generation of interactive tutoring systems [e.g., 39]. Unlike the approach we have taken here,
501 these generative text model-based systems do not explicitly model what learners know, or how
502 their knowledge changes over time with training. One could imagine building a hybrid system
503 that combines the best of both worlds: a large language model that can *generate* text, combined
504 with a smaller model that can *infer* what learners know and how their knowledge changes over
505 time. Such a hybrid system could potentially be used to build the next generation of interactive
506 tutoring systems that are able to adapt to learners' needs in real time, and that are able to provide
507 more nuanced feedback about what learners know and what they do not know.

508 At the opposite end of the spectrum from large language models, one could also imagine
509 *simplifying* some aspects of our LDA-based approach by computing simple word overlap metrics.
510 For example, the Jaccard similarity between text *A* and *B* is computed as the number of unique
511 words in the intersection of words from *A* and *B* divided by the number of unique words in
512 the union of words from *A* and *B*. In a supplemental analysis (Supp. Fig. 5), we compared the
513 LDA-based question-lecture matches we reported in Figure 4 with the Jaccard similarities between
514 each question and each sliding window of text from the corresponding lecture. As shown in
515 Supplementary Figure 5, this simple word-matching approach does not appear to capture the same
516 level of specificity as the LDA-based approach. Whereas the LDA-based approach often yields a
517 clear peak in the timeseries of correlations between each question and the corresponding lecture,
518 the Jaccard similarity-based approach does not. Furthermore, these LDA-based matches appear
519 to capture conceptual overlaps between the questions and lectures (Supp. Tab. 3), whereas simple
520 word matching does not. For example, one of the example questions examined in Supplementary
521 Figure 5 asks “Which of the following occurs as a cloud of atoms gets more dense?”. The LDA-
522 based matches identify lecture timepoints where the relevant *topics* are discussed (e.g., when words
523 like “cloud,” “atom,” “dense,” etc., are mentioned *together*). The Jaccard similarity-based matches,
524 on the other hand, are strong when *any* of these words are mentioned, even if they do not occur
525 together.

526 We view our approach as occupying a sort of “sweet spot,” between much larger language
527 models and simple word matching-based approaches, that enables us to capture the relevant

528 conceptual content of course materials at an appropriate semantic scale. Our approach enables us
529 to accurately and consistently identify each question’s content in a way that also matches up with
530 what is presented in the lectures. In turn, this enables us to construct accurate predictions about
531 participants’ knowledge of the conceptual content tested by held-out questions (Fig. 6).

532 One limitation of our approach is that topic models contain no explicit internal representations
533 of more complex aspects of “knowledge,” like knowledge graphs, dependencies or associations
534 between concepts, causality, and so on. These representations might (in principle) be added
535 as extensions to our approach to more accurately and precisely capture, characterize, and track
536 learners’ knowledge. However, modeling these aspects of knowledge will likely require substantial
537 additional research effort.

538 Within the past several years, the global pandemic forced many educators to suddenly adapt to
539 teaching remotely [30, 45, 56, 63]. This change in world circumstances is happening alongside (and
540 perhaps accelerating) geometric growth in the availability of high-quality online courses from plat-
541 forms such as Khan Academy [31], Coursera [64], EdX [33], and others [53]. Continued expansion
542 of the global internet backbone and improvements in computing hardware have also facilitated
543 improvements in video streaming, enabling videos to be easily shared and viewed by increasingly
544 large segments of the world’s population. This exciting time for online course instruction provides
545 an opportunity to re-evaluate how we, as a global community, educate ourselves and each other.
546 For example, we can ask: what defines an effective course or training program? Which aspects of
547 teaching might be optimized and/or augmented by automated tools? How and why do learning
548 needs and goals vary across people? How might we lower barriers of access to a high-quality
549 education?

550 Alongside these questions, there is a growing desire to extend existing theories beyond the
551 domain of lab testing rooms and into real classrooms [29]. In part, this has led to a recent
552 resurgence of “naturalistic” or “observational” experimental paradigms that attempt to better
553 reflect more ethologically valid phenomena that are more directly relevant to real-world situations
554 and behaviors [46]. In turn, this has brought new challenges in data analysis and interpretation. A
555 key step towards solving these challenges will be to build explicit models of real-world scenarios

556 and how people behave in them (e.g., models of how people learn conceptual content from real-
557 world courses, as in our current study). A second key step will be to understand which sorts
558 of signals derived from behaviors and/or other measurements [e.g., neurophysiological data; 2,
559 16, 43, 47, 50] might help to inform these models. A third major step will be to develop and
560 employ reliable ways of evaluating the complex models and data that are a hallmark of naturalistic
561 paradigms.

562 Beyond specifically predicting what people *know*, the fundamental ideas we develop here also
563 relate to the notion of “theory of mind” of other individuals [22, 27, 42]. Considering others’ unique
564 perspectives, prior experiences, knowledge, goals, etc., can help us to more effectively interact and
565 communicate [51, 55, 58]. One could imagine future extensions of our work (e.g., analogous to
566 the knowledge and learning maps shown in Fig. 8), that attempt to characterize how well-aligned
567 different people’s knowledge bases or backgrounds are. In turn, this might be used to model how
568 knowledge (or other forms of communicable information) flows not just between teachers and
569 students, but between friends having a conversation, individuals on a first date, participants at
570 a business meeting, doctors and patients, experts and non-experts, political allies or adversaries,
571 and more. For example, the extent to which two people’s knowledge maps “match” or “align” in
572 a given region of text embedding space might serve as a predictor of how effectively they will be
573 able to communicate about the corresponding conceptual content.

574 Ultimately, our work suggests a rich new line of questions about the geometric “form” of
575 knowledge, how knowledge changes over time, and how we might map out the full space of
576 what an individual knows. Our finding that detailed estimates about knowledge may be obtained
577 from short quizzes shows one way that traditional approaches to evaluation in education may be
578 extended. We hope that these advances might help pave the way for new approaches to teaching
579 or delivering educational content that are tailored to individual students’ learning needs and goals.

580 **Materials and methods**

581 **Participants**

582 We enrolled a total of 50 Dartmouth undergraduate students in our study. Participants received
583 optional course credit for enrolling. We asked each participant to complete a demographic survey
584 that included questions about their age, gender, native spoken language, ethnicity, race, hearing,
585 color vision, sleep, coffee consumption, level of alertness, and several aspects of their educational
586 background and prior coursework.

587 Participants' ages ranged from 18 to 22 years (mean: 19.52 years; standard deviation: 1.09
588 years). A total of 15 participants reported their gender as male and 35 participants reported their
589 gender as female. A total of 49 participants reported their native language as "English" and 1
590 reported having another native language. A total of 47 participants reported their ethnicity as
591 "Not Hispanic or Latino" and three reported their ethnicity as "Hispanic or Latino." Participants
592 reported their races as White (32 participants), Asian (14 participants), Black or African American
593 (5 participants), American Indian or Alaska Native (1 participant), and Native Hawaiian or Other
594 Pacific Islander (1 participant). (Note that some participants selected multiple racial categories.)

595 A total of 49 participants reporting having normal hearing and 1 participant reported having
596 some hearing impairment. A total of 49 participants reported having normal color vision and 1
597 participant reported being color blind. Participants reported having had, on the night prior to
598 testing, 2–4 hours of sleep (1 participant), 4–6 hours of sleep (9 participants), 6–8 hours of sleep (35
599 participants), or 8+ hours of sleep (5 participants). They reported having consumed, on the same
600 day and leading up to their testing session, 0 cups of coffee (38 participants), 1 cup of coffee (10
601 participants), 3 cups of coffee (1 participant), or 4+ cups of coffee (1 participant).

602 No participants reported that their focus was currently impaired (e.g., by drugs or alcohol).
603 Participants reported their current level of alertness, and we converted their responses to numerical
604 scores as follows: "very sluggish" (-2), "a little sluggish" (-1), "neutral" (0), "fairly alert" (1), and
605 "very alert" (2). Across all participants, a range of alertness levels were reported (range: -2–1;
606 mean: -0.10; standard deviation: 0.84).

607 Participants reported their undergraduate major(s) as “social sciences” (28 participants), “nat-
608 ural sciences” (16 participants), “professional” (e.g., pre-med or pre-law; 8 participants), “mathe-
609 matics and engineering” (7 participants), “humanities” (4 participants), or “undecided” (3 partici-
610 pants). Note that some participants selected multiple categories for their undergraduate major(s).
611 We also asked participants about the courses they had taken. In total, 45 participants reported hav-
612 ing taken at least one Khan Academy course in the past, and 5 reported not having taken any Khan
613 Academy courses. Of those who reported having watched at least one Khan Academy course,
614 7 participants reported having watched 1–2 courses, 11 reported having watched 3–5 courses, 8
615 reported having watched 5–10 courses, and 19 reported having watched 10 or more courses. We
616 also asked participants about the specific courses they had watched, categorized under different
617 subject areas. In the “Mathematics” area, participants reported having watched videos on AP
618 Calculus AB (21 participants), Precalculus (17 participants), Algebra 2 (14 participants), AP Cal-
619 culus BC (12 participants), Trigonometry (11 participants), Algebra 1 (10 participants), Geometry
620 (8 participants), Pre-algebra (7 participants), Multivariable Calculus (5 participants), Differential
621 Equations (5 participants), Statistics and Probability (4 participants), AP Statistics (2 participants),
622 Linear Algebra (2 participants), Early Math (1 participant), Arithmetic (1 participant), and other
623 videos not listed in our survey (5 participants). In the “Science and engineering” area, participants
624 reported having watched videos on Chemistry, AP Chemistry, or Organic Chemistry (21 partic-
625 ipants); Physics, AP Physics I, or AP Physics II (18 participants); Biology, AP Biology; or High
626 school Biology (15 participants); Health and Medicine (1 participant); or other videos not listed
627 in our survey (5 participants). We also asked participants whether they had specifically seen the
628 videos used in our experiment. Of the 45 participants who reported having having taken at least
629 one Khan Academy course in the past, 44 participants reported that they had not watched the *Four*
630 *Fundamental Forces* video, and 1 participant reported that they were not sure whether they had
631 watched it. All participants reported that they had not watched the *Birth of Stars* video. When
632 we asked participants about non-Khan Academy online courses, they reported having watched
633 or taken courses on Mathematics (15 participants), Science and engineering (11 participants), Test
preparation (9 participants), Economics and finance (3 participants), Arts and humanities (2 partic-

635 ipants), Computing (2 participants), and other categories not listed in our survey (17 participants).
636 Finally, we asked participants about in-person courses they had taken in different subject areas.
637 They reported taking courses in Mathematics (38 participants), Science and engineering (37 par-
638 ticipants), Arts and humanities (34 participants), Test preparation (27 participants), Economics
639 and finance (26 participants), Computing (14 participants), College and careers (7 participants), or
640 other courses not listed in our survey (6 participants).

641 Experiment

642 We hand-selected two course videos from the Khan Academy platform: *Four Fundamental Forces*
643 (an introduction to gravity, electromagnetism, the weak nuclear force, and the strong nuclear force;
644 duration: 10 minutes and 29 seconds) and *Birth of Stars* (an introduction to how stars are formed;
645 duration: 7 minutes and 57 seconds). All participants viewed the videos in the same order (i.e., *Four*
646 *Fundamental Forces* followed by *Birth of Stars*). While we are not aware of any specific confounds
647 of viewing order, nor have we are we aware of how or why viewing order might influence our main
648 findings, we acknowledge that we did not control for potential order effects in our study.

649 We then hand-created 39 multiple-choice questions: 15 about the conceptual content of *Four*
650 *Fundamental Forces* (i.e., Lecture 1), 15 about the conceptual content of *Birth of Stars* (i.e., Lecture 2),
651 and 9 questions that tested for general conceptual knowledge about basic physics (covering material
652 that was not presented in either video). One of our group's undergraduate research assistants
653 worked alongside a rotating Masters student to develop this set of questions (these researchers
654 are acknowledged in our paper for their contribution, although they did not meet the criteria for
655 authorship discussed with all team members at the start of the project, as determined by J.R.M.) The
656 senior author (J.R.M.) tasked the pair of researchers with coming up with "15 conceptual questions
657 about each lecture, along with 9 additional questions about general physics knowledge." To
658 help broaden the set of lecture-specific questions, the researchers were further instructed to work
659 through each lecture in small segments, identify what each segment was "about" conceptually,
660 and then write a question about that concept. The general physics questions were drawn from the
661 researchers' coursework along with internet searches and brainstorming with the project team and

662 other members of J.R.M.’s lab. The final set of questions (and response options) was reviewed and
663 approved by J.R.M. before we collected or analyzed the text or experimental data.

664 We note that estimating the specific “amount” of conceptual understanding that each question
665 “requires” to answer is somewhat subjective, and might even come down to the “strategy” a given
666 participant uses to answer the question at that particular moment. The full set of questions and
667 answer choices may be found in Supplementary Table 1.

668 Over the course of the experiment, participants completed three 13-question multiple-choice
669 quizzes: the first before viewing Lecture 1, the second between Lectures 1 and 2, and the third
670 after viewing Lecture 2 (see Fig. 1). The questions appearing on each quiz, for each participant,
671 were randomly chosen from the full set of 39, with the constraints that (a) each quiz contained
672 exactly 5 questions about Lecture 1, 5 questions about Lecture 2, and 3 questions about general
673 physics knowledge, and (b) each question appear exactly once for each participant. The orders of
674 questions on each quiz, and the orders of answer options for each question, were also randomized.
675 We obtained informed consent from all participants, and our experimental protocol was approved
676 by the Committee for the Protection of Human Subjects at Dartmouth College. We used this
677 experiment to develop and test our computational framework for estimating knowledge and
678 learning.

679 **Analysis**

680 **Statistics**

681 All of the statistical tests performed in our study were two-sided. The 95% confidence intervals
682 we reported for each correlation were estimated by generating 10,000 bootstrap distributions of
683 correlation coefficients by sampling (with replacement) from the observed data.

684 **Constructing text embeddings of multiple lectures and questions**

685 We adapted an approach we developed in prior work [24] to embed each moment of the two
686 lectures and each question in our pool in a common representational space. Briefly, our approach

687 uses a topic model [Latent Dirichlet Allocation; 6] trained on a set of documents, to discover a
688 set of (up to) k “topics” or “themes.” Formally, each topic is defined as a distribution of weights
689 over words in the model’s vocabulary (i.e., the union of all unique words, across all documents,
690 excluding “stop words.”). Conceptually, each topic is intended to give larger weights to words
691 that are semantically related (as inferred from their tendency to co-occur in the same document).
692 After fitting a topic model, each document in the training set, or any *new* document that contains at
693 least some of the words in the model’s vocabulary, may be represented as a k -dimensional vector
694 describing how much the document (most probably) reflects each topic. To select an appropriate
695 k for our model, as a starting point, we identified the minimum number of topics that yielded
696 at least one “unused” topic (i.e., in which all words in the vocabulary were assigned uniform
697 weights) after training. This indicated that the number of topics was sufficient to capture the set
698 of latent themes present in the two lectures (from which we constructed our document corpus, as
699 described below). We found this value to be $k = 15$ topics. We found that with a limited number
700 of additional adjustments following [7], such as removing corpus-specific stop-words, the model
701 yielded (subjectively) sensible and coherent topics. The distribution of weights over words in
702 the vocabulary for each discovered topic is shown in Supplementary Figure 1, and each topic’s
703 top-weighted words may be found in Supplementary Table 2.

704 As illustrated in Figure 2A, we start by building up a corpus of documents using overlapping
705 sliding windows that span each video’s transcript. Khan Academy provides professionally created,
706 manual transcriptions of all videos for closed captioning. However, such transcripts would not
707 be readily available in all contexts to which our framework could potentially be applied. Khan
708 Academy videos are hosted on the YouTube platform, which additionally provides automated
709 captions. We opted to use these automated transcripts [which, in prior work, we have found to be
710 of sufficiently near-human quality to yield reliable data in behavioral studies; 65] when developing
711 our framework in order to make it more directly extensible and adaptable by others in the future.

712 We fetched these automated transcripts using the `youtube-transcript-api` Python pack-
713 age [14]. The transcripts consisted of one timestamped line of text for every few seconds (mean:
714 2.34 s; standard deviation: 0.83 s) of spoken content in the video (i.e., corresponding to each indi-

715 individual caption that would appear on-screen if viewing the lecture via YouTube, and when those
716 lines would appear). We defined a sliding window length of (up to) $w = 30$ transcript lines, and
717 assigned each window a timestamp corresponding to the midpoint between the timestamps for its
718 first and last lines. This w parameter was chosen to match the same number of words per sliding
719 window (rounded to the nearest whole word, and before preprocessing) as the sliding windows
720 we defined in our prior work [24] (i.e., 185 words per sliding window).

721 These sliding windows ramped up and down in length at the beginning and end of each
722 transcript, respectively. In other words, each transcript's first sliding window covered only its first
723 line, the second sliding window covered the first two lines, and so on. This ensured that each line
724 from the transcripts appeared in the same number (w) of sliding windows. We next performed a
725 series of standard text preprocessing steps: normalizing case, lemmatizing, removing punctuation
726 and removing stop-words. We constructed our corpus of stop words by augmenting the Natural
727 Language Toolkit [NLTK; 3] English stop word list with the following additional words, selected
728 using the approach suggested by [7]: "actual," "actually," "also," "bit," "could," "e," "even,"
729 "first," "follow," "following," "four," "let," "like," "mc," "really," "saw," "see," "seen," "thing,"
730 and "two." This yielded sliding windows with an average of 73.8 remaining words, and lasting for
731 an average of 62.22 seconds. We treated the text from each sliding window as a single "document,"
732 and combined these documents across the two videos' windows to create a single training corpus
733 for the topic model.

734 After fitting a topic model to the two videos' transcripts, we could use the trained model to
735 transform arbitrary (potentially new) documents into k -dimensional topic vectors. A convenient
736 property of these topic vectors is that documents that reflect similar blends of topics (i.e., documents
737 that reflect similar themes, according to the model) will yield similar coordinates (in terms of
738 correlation, cosine similarity, Kullback-Leibler divergence, Euclidean distance, or other geometric
739 measures). In general, the similarity between different documents' topic vectors may be used to
740 characterize the similarity in conceptual content between the documents.

741 We transformed each sliding window's text into a topic vector, and then used linear interpo-
742 lation (independently for each topic dimension) to resample the resulting timeseries to one vector

743 per second. We also used the fitted model to obtain topic vectors for each question in our pool (see
 744 Supp. Tab. 1). Taken together, we obtained a *trajectory* for each video, describing its path through
 745 topic space, and a single coordinate for each question (Fig. 2C). Embedding both videos and all of
 746 the questions using a common model enables us to compare the content from different moments
 747 of videos, compare the content across videos, and estimate potential associations between specific
 748 questions and specific moments of video.

749 **Estimating dynamic knowledge traces**

750 We used the following equation to estimate each participant’s knowledge about timepoint t of a
 751 given lecture, $\hat{k}(t)$:

$$\hat{k}(f(t, L)) = \frac{\sum_{i \in \text{correct}} \text{ncorr}(f(t, L), f(i, Q))}{\sum_{j=1}^N \text{ncorr}(f(t, L), f(j, Q))}, \quad (1)$$

752 where

$$\text{ncorr}(x, y) = \frac{\text{corr}(x, y) - \text{mincorr}}{\text{maxcorr} - \text{mincorr}}, \quad (2)$$

753 and where mincorr and maxcorr are the minimum and maximum correlations between any lecture
 754 timepoint and question, taken over all timepoints in the given lecture, and all five questions *about*
 755 that lecture appearing on the given quiz. We also define $f(s, \Omega)$ as the s^{th} topic vector from the set
 756 of topic vectors Ω . Here t indexes the set of lecture topic vectors, L , and i and j index the topic
 757 vectors of questions used to estimate the knowledge trace, Q . Note that “correct” denotes the set
 758 of indices of the questions the participant answered correctly on the given quiz.

759 Intuitively, $\text{ncorr}(x, y)$ is the correlation between two topic vectors (e.g., the topic vector from one
 760 timepoint in a lecture, x , and the topic vector for one question, y), normalized by the minimum and
 761 maximum correlations (across all timepoints t and questions Q) to range between 0 and 1, inclusive.
 762 Equation 1 then computes the weighted average proportion of correctly answered questions about
 763 the content presented at timepoint t , where the weights are given by the normalized correlations
 764 between timepoint t ’s topic vector and the topic vectors for each question. The normalization step
 765 (i.e., using ncorr instead of the raw correlations) ensures that every question contributes some

766 non-negative amount to the knowledge estimate.

767 **Estimating the “smoothness” of knowledge**

768 In the analysis reported in Figure 7A, we show how participants’ quiz performance changes as
769 a function of distance to a given correctly or incorrectly answered reference question. We used
770 a bootstrap-based approach to estimate the maximum distances over which these proportions of
771 correctly answered questions could be reliably distinguished from participants’ overall average
772 proportion of correctly answered questions.

773 In our bootstrap procedure, we ran 10,000 iterations to estimate the relationship between partic-
774 ipants’ performance and the distance to a given reference question. For each of these iterations, for
775 every individual quiz (q), we first determined the across-participants average “simple” proportion
776 correct and its 95% confidence interval. This interval was established by repeatedly (1,000 times)
777 subsampling participants with replacement, computing the mean “simple” proportion correct for
778 each subsample, and then deriving the 2.5th and 97.5th percentiles from the distribution of these
779 subsample means. We used this interval as our benchmark for determining whether the propor-
780 tion of correctly answered questions for a given subset of questions was reliably different (at the
781 $p < 0.05$ significance level) from the average proportion correct across all questions.

782 Next, for each participant, we examined all 15 questions they answered on quiz q . We treated
783 each question as the “reference question” in turn. Around this reference, we constructed a series of
784 15-dimensional spheres (starting with a radius of 0), where each successive sphere had a radius of
785 0.01 (correlation distance) greater than its predecessor. Within each of these spheres, we calculated
786 the proportion of questions answered correctly by the participant. This yielded two distinct sets
787 of proportion-correct values for each binned distance (radius) for a specific participant and quiz:
788 one set of values where the reference questions had been answered correctly, and another set
789 where the reference questions had been answered incorrectly. From these, we established the
790 average proportion correct within each radius for both categories of reference questions. Finally,
791 we identified the minimum binned distance from the correctly answered reference questions for
792 which the average proportion correct intersected the 95% confidence interval of the simple average

793 proportion correct computed earlier. We display the resulting distance estimates, for each quiz
794 and reference question status, in Figure 7B.

795 **Creating knowledge and learning map visualizations**

796 An important feature of our approach is that, given a trained text embedding model and partic-
797 ipants’ quiz performance on each question, we can estimate their knowledge about *any* content
798 expressible by the embedding model—not solely the content explicitly probed by the quiz ques-
799 tions, or even appearing in the lectures. To visualize these estimates (Fig. 8, Supp. Figs. 7, 8, 9, 10,
800 and 11), we used Uniform Manifold Approximation and Projection [UMAP; 40, 41] to construct a
801 2D projection of the text embedding space. Sampling the original 100-dimensional space at high
802 resolution to obtain an adequate set of topic vectors spanning the embedding space would be
803 computationally intractable. However, sampling a 2D grid is trivial.

804 At a high level, the UMAP algorithm obtains low-dimensional embeddings by minimizing
805 the cross-entropy between the pairwise (clustered) distances between the observations in their
806 original (e.g., 100-dimensional) space and the pairwise (clustered) distances in the low-dimensional
807 embedding space (in our approach, the embedding space is 2D). In our implementation, pairwise
808 distances in the original high-dimensional space were defined as 1 minus the correlation between
809 each pair of coordinates, and pairwise distances in the low-dimensional embedding space were
810 defined as the Euclidean distance between each pair of coordinates.

811 In our application, all of the coordinates we embedded were topic vectors, whose elements
812 are always non-negative and sum to one. Although UMAP is an invertible transformation at
813 the embedding locations of the original data, other locations in the embedding space will not
814 necessarily follow the same implicit “rules” as the original high-dimensional data. For example,
815 inverting an arbitrary coordinate in the embedding space might result in negative-valued vectors,
816 which are incompatible with the topic modeling framework. To protect against this issue, we
817 log-transformed the topic vectors prior to embedding them in the 2D space. When we inverted
818 the embedded vectors (e.g., to estimate topic vectors or word clouds, as in Fig. 8C), we passed
819 the inverted (log-transformed) values through the exponential function to obtain a vector of non-

820 negative values, and normalized them to sum to one.

821 After embedding both lectures' topic trajectories and the topic vectors of every question, we
822 defined a rectangle enclosing the 2D projections of the lectures' and quizzes' embeddings. We then
823 sampled points from a regular 100×100 grid of coordinates that evenly tiled this enclosing rectangle.
824 We sought to estimate participants' knowledge (and learning, i.e., changes in knowledge) at each
825 of the resulting 10,000 coordinates.

826 To generate our estimates, we placed a set of 39 radial basis functions (RBFs) throughout the
827 embedding space, centered on the 2D projections for each question (i.e., we included one RBF for
828 each question). At coordinate x , the value of an RBF centered on a question's coordinate μ , is given
829 by:

$$\text{RBF}(x, \mu, \lambda) = \exp \left\{ -\frac{\|x - \mu\|^2}{\lambda} \right\}. \quad (3)$$

830 The λ term in the RBF equation controls the "smoothness" of the function, where larger values
831 of λ result in smoother maps. In our implementation we used $\lambda = 50$. Next, we estimated the
832 "knowledge" at each coordinate, x , using:

$$\hat{k}(x) = \frac{\sum_{i \in \text{correct}} \text{RBF}(x, q_i, \lambda)}{\sum_{j=1}^N \text{RBF}(x, q_j, \lambda)}. \quad (4)$$

833 Intuitively, Equation 4 computes the weighted proportion of correctly answered questions, where
834 the weights are given by how nearby (in the 2D space) each question is to the x . We also defined
835 *learning maps* as the coordinate-by-coordinate differences between any pair of knowledge maps.
836 Intuitively, learning maps reflect the *change* in knowledge across two maps.

837 Author contributions

838 Conceptualization: PCF, ACH, and JRM. Methodology: PCF, ACH, and JRM. Software: PCF.
839 Validation: PCF. Formal analysis: PCF. Resources: PCF, ACH, and JRM. Data curation: PCF.
840 Writing (original draft): JRM. Writing (review and editing): PCF, ACH, and JRM. Visualization:
841 PCF and JRM. Supervision: JRM. Project administration: PCF. Funding acquisition: JRM.

842 **Data availability**

843 All of the data analyzed in this manuscript may be found at <https://github.com/ContextLab/efficient-learning-khan>.
844

845 **Code availability**

846 All of the code for running our experiment and carrying out the analyses may be found at
847 <https://github.com/ContextLab/efficient-learning-khan>.

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