

Learning and Evaluating Prerequisite Graphs from Student Performance Data

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ABSTRACT

Knowing the prerequisite structure of skills is crucial for designing curriculum, assessing mastery and for student modeling. These prerequisite structures are often hand-engineered by subject matter expert in a costly and time-consuming process. In this paper, we introduce Bayesian Network based Prerequisite Discovery (BNPD), a novel data-driven pipeline for inferring the prerequisite structure of skill from student performance on test items. By modeling the prerequisite relations as a Bayesian network, the pipeline estimates the causal structure and the probabilistic dependence among the skills via a two-stage learning process. In the first stage, the Structural Expectation Maximization (Structural EM) algorithm is used to select a class of Bayesian networks based on distribution fitting of student data; in the second stage, a single Bayesian network structure is determined by enforcing a constraint on the estimated conditional probability tables. We validate the proposed pipeline using simulations and by post-hoc analysis of student data. We show the discovered prerequisite structures can improve the student model in predicting student performance.

Keywords

ACM proceedings, L^AT_EX, text tagging

1. INTRODUCTION

Students learn much better when the skills are not randomly introduced but organized in a meaningful order which starts from relatively simple concepts and gradually introduces more complex ones. Further, among these skills, some are preliminary of others such that they must be mastered before the subsequent concepts can be learned. For instance, students have to know how to do addition before they learn to do multiplication. In this work, we use prerequisite structure to refer to the relationships among skills that place strict constraints on the order in which these skills can be acquired. Determining the prerequisite relations among skills is crucial for designing curriculum and for assessing mastery.

Most prerequisite structures of skills are hand-engineered by subject matter experts in a costly and time-consuming process. Further, the

prerequisite structures specified by the experts are seldom tested and might be unreliable in the sense that experts may hold “blind spots”. Nowadays, large volume of educational data has been cumulated through the online tutoring systems. Thus, learning prerequisite structures from educational data has drawn substantial interest from both education and data mining communities [6, 21, 2, 17, 4, 16]. However, inferring the prerequisite relationships between skills is still challenging since a student’s knowledge of a skill is a latent variable in the data. In this paper, we introduce BNPD, a novel pipeline for discovering prerequisite structure of skills from data. BNPD models the prerequisite structure of the skills with a statistical model called Bayesian network. It then learns the Bayesian network through a two-stage process.

2. PREVIOUS WORK

Many works have investigated the discovery of prerequisite structures within domain models from data. Some of these approaches discover the relationship of items without using latent variables. That is, the prerequisites do not use skill mappings, and only find dependencies between items [6, 21, 14, 16].

To learn the relationships among skills from data where a student’s knowledge of a skill is latent, Brunskill proposed a method of computing and comparing the log likelihoods between the prerequisite model and the flat model (skills are independent) on each skill pair to determine which model better fits the data [2]. Chen et al. [4] used DINA (Deterministic Input Noisy AND) model to infer the knowledge states of students from their response data on test items and then used probabilistic association rules mining to determine the prerequisite relationships between each pair of skills. Both methods focus on estimating the pairwise prerequisite relationships, instead of optimizing the full structure of the skills.

Bayesian network is a promising tool to model skill topologies as demonstrated in [11]. Bayesian network allows the modeling of full structure of skills and can encode conditional independence relationships between the skill. This enables more accurate modeling of the probabilistic dependence between skills. By modeling prerequisite relations as a Bayesian network, Scheines et al. converted the problem of prerequisite structure discovery to a Bayesian network structural learning problem, and proposed an algorithm to find the Bayesian network structures that fit the data [17]. However, the output from their algorithm is a class of Bayesian networks, which represent different prerequisite structures. They did not offer any solution to discriminate between these Bayesian networks.

In this paper, we propose a novel pipeline to infer the prerequisite



Figure 1: A hypothetical Bayesian network learned with Algorithm 1. Solid edges are given by the item to skill mapping, dashed edges between skill variables are to be discovered from data. The conditional probability tables are to be learned.

structures of skills from students’ response data on the test items. Our approach also uses Bayesian network to model the prerequisite relationships. The pipeline first use a popular Bayesian network structure learning algorithm, called Structural EM to select a class of Bayesian network models based on the distribution fitting of the data. It then uses constraint on the conditional probability tables to select one Bayesian network, which gives a unique prerequisite structure. We demonstrate the robustness of our proposed approach on noisy data that contains unaccounted hidden variables or missing values. Finally, we show the discovered prerequisite structures are useful for student modeling.

3. THE PREREQUISITE STRUCTURE DISCOVERY PIPELINE

BNPD learns the prerequisite structure of the skills using data with a statistical model called Bayesian network [15, 18]. Bayesian networks are also called probabilistic graphical models because they can be represented visually and algebraically as a collection of nodes and edges. A tutorial description of Bayesian networks in education can be found elsewhere [1], but for now we say that they are often described with two components: the nodes represent the random variables, which we describe using *conditional probability tables* (CPTs), and the set of edges that form a *directed acyclic graph* (DAG) represent the conditional dependencies between the variables. Bayesian networks are a flexible tool that can be used to model an entire curriculum.

Figure 1 illustrates an example of a prerequisite structure modeled with a Bayesian network. Here, we relate four test items with the skills of addition and multiplication. Addition is a prerequisite of multiplication thus there is an arrow from addition to multiplication. Modeling prerequisites as edges in a Bayesian network allows us to frame the discovery of the prerequisite relationships as the well-studied machine learning problem of learning a DAG (with the presence of latent variables).

Algorithm 1 describes the BNPD pipeline. Suppose we collect data from n students, answering p items. Then, the input of BNPD is a matrix \mathbf{D} with $n \times p$ dimensions, an item to skill mapping. Each entry in \mathbf{D} encodes the performance of a student (see Table 1 for an example).

Table 1: Example data matrix to use with BNPD. The performance of a student is encoded with 1 if the student answered correctly the item, and 0 otherwise.

User	Item 1	Item 2	Item 3	Item p
Alice	0	1		0
Bob	1	1	...	1
Carol	0	0		1
		...		

BNPD relies on a popular machine learning algorithm called Structural Expectation Maximization (EM), which has not been used in educational applications. A secondary contribution of our work is introducing Structural EM for learning Bayesian network structures from educational data. We now describe the steps of BNPD in detail.

Algorithm 1 The BNPD algorithm

Require: A matrix \mathbf{D} of student performance on a set of test items, skill-to-item mapping Q (containing a set of skills S).

```

1:  $G_0 \leftarrow \text{Initialize}(S, Q)$ 
2:  $i \leftarrow 0$ 
3: do
4:    $E$ -step:
5:      $\theta_i^* \leftarrow \text{ParametricEM}(G_i, \mathbf{D})$ 
6:      $\mathbf{D}_i^* \leftarrow \text{Inference}(G_i, \theta_i^*, \mathbf{D})$ 
7:    $M$ -step:
8:      $\langle G_{i+1}, \theta_{i+1} \rangle \leftarrow \text{BNLearning}(G_i, \mathbf{D}_i^*)$ 
9:      $i \leftarrow i + 1$ 
10: while Stop criteria is not met
11:  $RE \leftarrow \text{FindReversibleEdges}(G_i)$ 
12:  $EC \leftarrow \text{EnumEquivalent DAGs}(G_i)$ 
13:  $DE \leftarrow \{\}$ 
14: for every reversible edge  $S_i - S_j$  in  $RE$  do
15:    $ratio \leftarrow \frac{P(S_i=1|S_j=1) \cdot P(S_j=0|S_i=0)}{P(S_j=1|S_i=1) \cdot P(S_i=0|S_j=0)}$ 
16:   if  $ratio > 1$  then
17:      $ratio^* = ratio$ 
18:      $DE \leftarrow DE \cup S_i \rightarrow S_j$ 
19:   else
20:      $ratio^* = \frac{1}{ratio}$ 
21:      $DE \leftarrow DE \cup S_i \leftarrow S_j$ 
22:   end if
23: end for
24:  $sort(DE)$  by  $ratio^*$  in descending order
25: while  $DE$  is not empty do
26:    $e \leftarrow dequeue(DE)$ 
27:    $\forall G \in EC$ , remove  $G$  from  $EC$  if  $e \notin G$ 
28: end while
29: return  $EC$ 

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3.1 Initial Bayesian Network

BNPD represents the prerequisite structure using Bayesian networks that use latent variables to represent the student knowledge of a skill, and observed variables that represent the student performance answering items (e.g, correct or incorrect). We first create an initial Bayesian network that complies to the skill-to-item Q -matrix on the prerequisite structure. That is, we create an arc to each item from each of its required skills and leave all skill variables disconnected.

¹ $P(S_i = a | S_j = b)$ can be computed using any Bayesian network inference algorithm such as Junction tree algorithm[13]



Figure 2: An illustration of the Structure EM algorithm to discover the structure of the latent variables.

With the created Bayesian network as an initial network, we learn the arcs between the skill variables using Structural EM.

3.2 Structural EM

A common solution to learning a Bayesian network from data is the score-and-search approach [5, 10]. This approach uses a scoring function² to measure the fitness of a Bayesian network structure to the observed data, and manages to find the optimal model in the space of all possible Bayesian network structures. However, the conventional score-and-search approaches rely on efficient computation of the scoring function, which is only feasible for problems where data contains observations for all variables in the Bayesian network. Unfortunately, our domain has skill variables that are not directly observed. An intuitive work-around is to use the Expectation Maximization (EM) to estimate the scoring function. However, EM in this case takes a large number (hundreds) of iterations to converge and each iteration requires Bayesian network inference, which is computationally prohibitive. Further, we need run EM for each candidate structure. The number of possible Bayesian network structures is super-exponential with respect to the number of nodes. The Structural Expectation Maximization algorithm [7, 8] is an efficient alternative.

Structural EM is an iterative algorithm that inputs a matrix **D** of student performance (see example Table 1). Figure 2 illustrates one iteration of the Structural EM algorithm. The relevant steps are also sketched in Algorithm 1. Each iteration consists of an Expectation step (*E-step*) and a Maximization step (*M-step*). In *E-step*, we first find the maximum likelihood estimate θ^* of the parameters for the current structure G calculated from previous iteration using parametric EM.³ We then do Bayesian inference to compute the expected values for the hidden variables using the current model (G, θ^*) and use the values to complete the data. In the *M-step*, we use the conventional score-and-search approach to optimize the structure according to the completed data. Since the space of possible Bayesian network structures is super-exponential, exhaustive search is intractable and local search algorithms, such as greedy hill-climbing search, are often used. The *E-step* and *M-step* interleave and iterate until some stop criteria is met, e.g., the scoring function does not change significantly. Contrast to the conventional score-and-search algorithm, Structural EM runs EM only on one structure in each iteration, thus is computationally more efficient.

BNPD's initialization step fixes the arcs from skills to items accord-

²A commonly used scoring function is Bayesian information criterion (BIC), which is composed of a likelihood term and a term to penalize the model complexity

³In the first iteration, the current network is created from the initialization step.

ing to the Q -matrix. In the *M-step* of our Structural EM implementation we only consider the candidate structures that comply with the Q -matrix.

An advantage of using Structural EM to discover the prerequisite relationship of skills, is that it is easily extensible to incorporate domain knowledge. For example, we can place constraints on the output structure to force or to disallow a skill to be a prerequisite from another other skill. Consider, an intelligent tutor that teaches the content of a book. The book content structure provides a natural ordering of the chapters. We may use the book structure to engineer domain knowledge that an introductory chapter cannot be prerequisite of content that appears later in the book.

Another advantage of Structural EM is that it can be applied when there are missing data in the student performance matrix **D**. That is, some students do not answer all the items thus some responses are missing. This "missing values" problem is very common in real-world situations. Structural EM can be applied to this type of data since it was originally developed to solve the "missing values" problem [7]. The general idea is, in the *E-step*, the algorithm also computes the expected values for missing data points, in addition for hidden variables, .

3.3 Discriminate Between Equivalent BNs

3.3.1 Use Domain Knowledge

Structural EM selects Bayesian network model based on how well it explains the distribution of the data. Bayesian network theory states that some Bayesian networks are statistically equivalent in representing the data. Thus, the output from Structure EM is an equivalence class that may contain many Bayesian network structures. These equivalent Bayesian networks have the same skeleton and the same v -structures⁴. For instance, Figure 3 gives an example of two simple Bayesian networks that are not distinguishable by Structural EM algorithm. They share the skeleton but differ in the orientation of the edge. They apparently represent two different prerequisite structures. To determine which structure is the case, we shall determine the orientation of each reversible edge. For this purpose, we can use the following domain knowledge.

Knowledge 1. If S_1 is a prerequisite of S_2 , i.e., $S_1 \rightarrow S_2$, then $P(S_1 = 1 | S_2 = 1) = 1$ and $P(S_2 = 0 | S_1 = 0) = 1$.

Knowledge 1 says if a skill S_1 is the prerequisite of a skill S_2 , a student must master skill S_1 before he masters S_2 and it is impossible for him to master S_2 if he has not mastered S_1 . In other words, S_1 is not a prerequisite of S_2 if at least one of the conditions does not hold. This puts a constraint on the joint distribution encoded by the Bayesian network to be learned. We can check for each reversible edge $S_i - S_j$ in the Bayesian network, either $P(S_i = 1 | S_j = 1) = 1$ and $P(S_j = 0 | S_i = 0) = 1$, or $P(S_j = 1 | S_i = 1) = 1$ and $P(S_i = 0 | S_j = 0) = 1$. If the former holds, $S_i \rightarrow S_j$; otherwise, $S_j \leftarrow S_i$. However, in real situations, it is possible for a student to master the post-requisite even he does not know the prerequisite. Further, there is always noise in the data. Thus, the two conditional probabilities $P(S_1 = 1 | S_2 = 1)$ and $P(S_2 = 0 | S_1 = 0)$ are not exactly but close to 1. Thus, we use the following empirical rule: if $P(S_1 = 1 | S_2 = 1) \cdot P(S_2 = 0 | S_1 = 0) \geq P(S_2 = 1 | S_1 = 1) \cdot P(S_1 = 0 | S_2 = 0)$, we determine $S_1 \rightarrow S_2$; otherwise, we determine $S_1 \leftarrow S_2$. The

⁴A v -structure in a Bayesian network G is an ordered triple of nodes (u, v, w) such that G contains the directed edges $u \rightarrow v$ and $w \rightarrow v$ and u and w are not adjacent in G . [20].

intuition behind this is that the two probabilities $P(S_1 = 1|S_2 = 1)$ and $P(S_2 = 0|S_1 = 0)$ are certificates of the prerequisite structure $S_1 \rightarrow S_2$. The larger of these two probabilities, the more likely the relationship $S_1 \rightarrow S_2$ holds. Since here we are concerned with which direction the edge goes, we simply compare the products of two probabilities and select the direction that is more probable.



Figure 3: Two equivalent Bayesian networks representing different prerequisite structures.

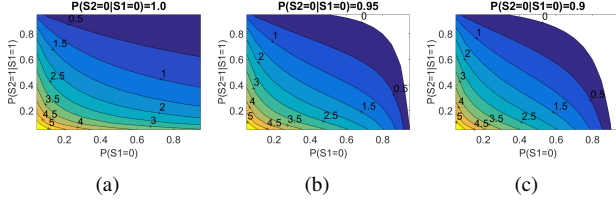


Figure 4: Contour plot of $\log(\text{ratio})$ for various values of $P(S_2 = 0|S_1 = 0)$.

3.3.2 Theoretical Justification

The empirical rule proposed in section 3.3.1 needs theoretical justification. We consider the simple Bayesian network in Figure 3a, which has only one reversible edge $S_1 - S_2$. This model has three free conditional probability parameters: $P(S_1 = 0) = p$, $P(S_2 = 0|S_1 = 0) = q$, $P(S_2 = 1|S_1 = 1) = r$. If we observe data generated from this model, can we determine the edge $S_1 \rightarrow S_2$? Equivalently, we use rule $\text{ratio} = \frac{P(S_i=1|S_j=1) \cdot P(S_j=0|S_i=0)}{P(S_j=1|S_i=1) \cdot P(S_i=0|S_j=0)} \geq 1$. Using Bayes rule and rules of probability, the rule becomes

$$\text{ratio} = \frac{(1-p)(qp + 1 - r - p + pr)}{p[r(1-p) + p(1-q)]} \geq 1, \quad (1)$$

which can be simplified to

$$\frac{(1-p)(1-r) - p(1-q)}{p[r(1-p) + p(1-q)]} \geq 0. \quad (2)$$

The rule holds only if $(1-p)(1-r) - p(1-q) \geq 0$. Thus, we can use the rule to orient edges if $(1-p)(1-r) - p(1-q) \geq 0$. Since ratio depends on p , q and r , we study how ratio changes with these parameters. Figure 4 shows the contour plots of $\log(\text{ratio})$ against $P(S_1 = 0)$ and $P(S_2 = 1|S_1 = 1)$ for three different values of $P(S_2 = 0|S_1 = 0)$. The white region in each contour plot is the region where the rule is not applicable. As it is showed, if $P(S_2 = 0|S_1 = 0) = q = 1$, the rule is always applicable no matter what values $P(S_1 = 0)$ and $P(S_2 = 1|S_1 = 1)$ are. With $P(S_2 = 0|S_1 = 0)$ decreasing, the white region becomes larger and the rule becomes more inapplicable. $P(S_2 = 0|S_1 = 0)$ can be interpreted as the strength of the prerequisite relationship. When the prerequisite relationship is weak, the rule is less applicable and it is harder to discover the prerequisite relationship.

3.3.3 Orient All Reversible Edges

Using the empirical rule, we can orient every reversible edge in the network structure. However, determining orientations of each reversible edge is not independent and may conflict each other.

Having oriented one edge would constrain the orientation of other reversible edges because we have to ensure the graph is a DAG and the equivalence is not violated. For example, in Figure 3a, if we have determined $S_1 \rightarrow S_2$, the edge $S_2 \rightarrow S_3$ is enforced. In this paper, we take an ad-hoc strategy to determine the orientation for all reversible edges. For each reversible edge $S_i - S_j$, we let $\text{ratio}^* = \text{ratio}$ if $\text{ratio} > 1$ and $\text{ratio}^* = \frac{1}{\text{ratio}}$ otherwise. The larger the ratio^* is, the more confidently when we decide the orientation. We sort the list of reversible edges by ratio^* in descending order. We then orient the edges in this order. When one edge is oriented, the constraint is propagated to other reversible edges. In practical implementation, we use a different strategy: we first enumerate all equivalent Bayesian networks and make them a list of candidates; when an edge is oriented to $S_i \rightarrow S_j$, we remove all contradicting Bayesian networks from the list. Eventually only one Bayesian network structure stands. This procedure is detailed in the *Orient edges* section of Algorithm 1. The *EnumEquivalentDAGs*(G_i) implements the algorithm of enumerating equivalent DAGs in [3].

4. EVALUATION

In § 4.1, we evaluate BNPD with simulated data to assess the quality of the discovered prerequisite structures. Then, in § 4.2 we use data collected from real students. In all our experiment, we use the Bayesian information criterion (BIC) as the scoring function in Structural EM.

4.1 Simulated Data

Synthetic data allows us to study how BNPD compares to ground truth. For this, we engineered three prerequisite structures (DAGs), shown in Figure 5. Here, each figure represents different causal relations between the simulated latent skill variables.

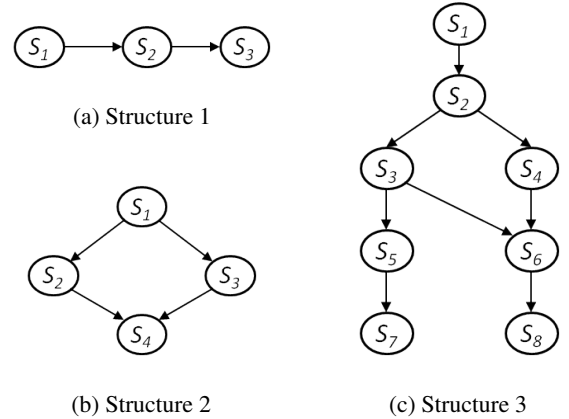


Figure 5: Three different DAGs between latent skill variables. Item nodes are omitted.

For clarity, Figure 5 omits the item nodes; but each skill node is parent of six item variables and each item variable has 1-3 skill nodes as parents. All of these nodes are modeled using binary random variables. More precisely, the latent nodes represent whether the student achieves mastery of the skill, and the observed nodes indicate if the student answers the item correctly. Notice that these Bayesian networks include the prerequisite structures as well as the skill-item mapping.

We consider simulated data with different number of observations ($n = 150, 500, 1000, 2000$). For each sample size and each DAG, we generate ten different sets of conditional probability tables randomly,

with two constraints. First, we enforce that achieving mastery of the prerequisites of a skill will increase the likelihood of mastering the skill. Second, mastery of a skill increases the probability of student correctly answering the test item. Thus, in total we generated 120 synthetic datasets (3 DAGs x 4 sample sizes x 10 CPTs), and report the average results.

We evaluate how BNPD can discover the true prerequisite structure using metrics designed to evaluate Bayesian networks structure discovery. In particular, we use the F_1 adjacency score and the F_1 orientation score. The adjacency score measure how well we can recover connections between nodes. It is a weighted average of the true positive adjacency rate and the true discovery adjacency rate. On the other hand, the orientation score measures how well we can recover the direction of the edges. It is calculated as a weighted average of the true positive orientation rate and true discovery orientation rate. In both cases, the F_1 score reaches its best value at 1 and worst at 0. Moreover, for comparison, we compute the F_1 adjacency score for Bayesian network structures whose skill nodes are fully connected with each other. These fully connected DAGs will serve as baselines for evaluating the adjacency discovery.⁵ For completeness, we list these formulas in tables 2 and 3, respectively.

Table 2: Formulas for measuring adjacency rate (AR)

Metric	Formula
True positive ($TPAR$)	$\frac{\# \text{ of correct adjacencies in learned model}}{\# \text{ of adjacencies in true model}}$
True discovery ($TDAR$)	$\frac{\# \text{ of correct adjacencies in learned model}}{\# \text{ of adjacencies in learned model}}$
$F_1\text{-}AR$	$\frac{2 \cdot TPAR \cdot TDAR}{TPAR + TDAR}$

Table 3: Formulas for measuring orientation rate (OR)

Metric	Formula
True positive ($TPOR$)	$\frac{\# \text{ of correctly directed edges in learned model}}{\# \text{ of directed edges in true model}}$
True discovery ($TDOR$)	$\frac{\# \text{ of correctly directed edges in learned model}}{\# \text{ of directed edges in learned model}}$
$F_1\text{-}OR$	$\frac{2 \cdot TPOR \cdot TDOR}{TPOR + TDOR}$

We use these metrics to evaluate the effect of varying the number of observations of the training set (sample size) on the quality of learning the prerequisite structure. We designed experiments to specifically answer the following four questions:

1. How does the type of items affect BNPD’s ability to recover the prerequisite structure? We consider the case where in the model each item requires only one skill and the case where item require multiple skills.
2. How well does BNPD perform when there is noise in the data? We focus on studying noise due to the presence of unaccounted hidden variables.
3. How well does BNPD perform when the student performance data has missing values?
4. How is BNPD compared with other prerequisite discovery methods? Here we compare BNPD to the Probabilistic Association Rules Mining (PARM) method [4].

We now investigate these questions.

⁵We do not compute F_1 orientation score for fully connected DAGs because all edges in a fully connected DAG are reversible.

4.1.1 Single-skill vs Multi-skill Items

We consider two situations where different types of Q -matrix are used. In the first situation, each item node maps to only one skill node. In the second one, each item loads 1-3 skills. Figure 6 compares the F_1 of adjacency discovery and edge orientation result under two types of Q -matrix. We observe that the accuracy for both the adjacency and the edge orientation improves with the amount of data. With just 2000 observations, the algorithm can recover the true structures almost perfectly. Additionally, when the model contains multiple-skill items, the accuracy is slightly lower than that where all items in the model are single-skilled items, probably because there are more parameters to be estimated in the case of multi-skill items.

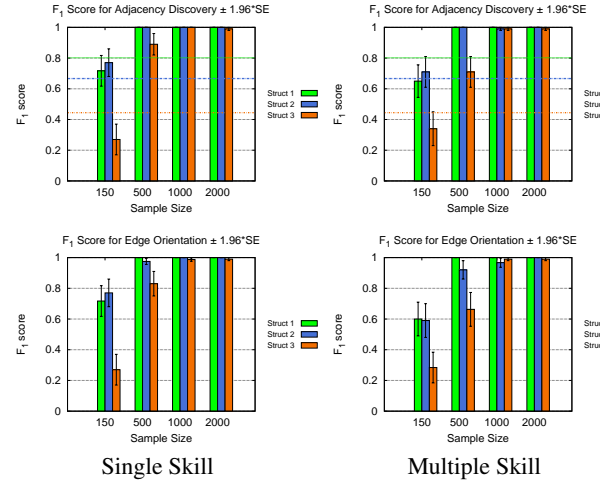


Figure 6: Comparison of F_1 scores for adjacency discovery (top row) and for edge orientation (bottom row). Horizontal lines are baseline F_1 scores computed for fully connected (complete) Bayesian networks.

4.1.2 Sensitivity to Noise

Real-world data sets often contain various types of noise. For example, noise may occur due to hidden variables that are not explicitly modeled. To evaluate the sensitivity of BNPD to noise, we synthesize Bayesian networks including a *StudentAbility* node that takes three possible states (low/med/high). In these Bayesian networks, students’ performance depends not only on whether they have mastered the skill, but also on their individual ability. For simplicity, all items in the setting are single-skilled items. We first simulated data from Bayesian networks that have a *StudentAbility* variable to generate “noisy” data samples, and then use this data to recover the prerequisite structure. Figure 7 illustrates the procedure of this sensitivity analysis experiment.

Figure 8 compare the results where noise was introduced or not. Interestingly, the noise does not harm the learning accuracy at all, and actually improves the accuracy. We hypothesize that the existence of additional hidden variable increases the variance of the data which can help the structure learning.

4.1.3 In Presence of Missing Values

To evaluate how BNPD performs on data with missing values, we generated data sets of size 1000 with varying fraction of missing values (10%, 20%, 30%, 40%, 50%) and ran BNPD to recover the

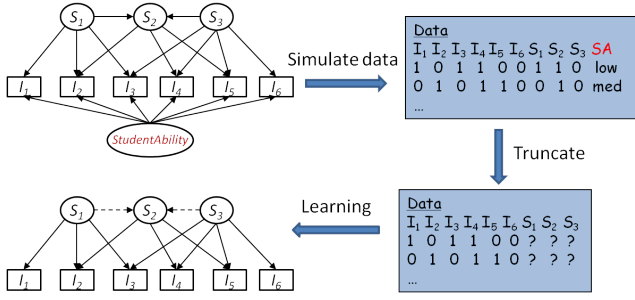


Figure 7: Evaluation of BNPD with noisy data

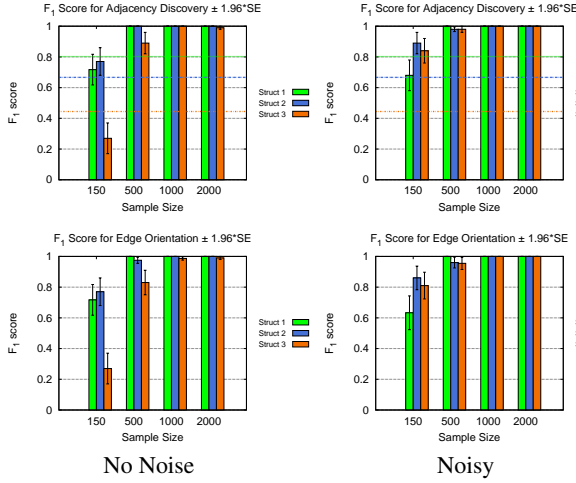


Figure 8: Results of adding systematic noise. Top: Comparison of F_1 scores for adjacency discovery. Horizontal lines are baseline F_1 scores computed for fully connected Bayesian networks. Bottom: Comparison of F_1 scores for edge orientation.

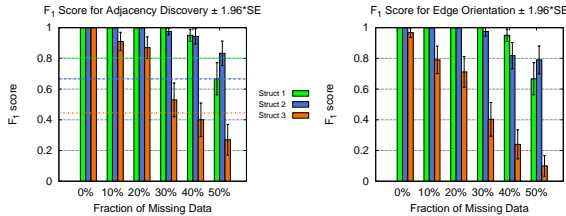


Figure 9: Results of learning with missing data. Left: Comparison of F_1 scores for adjacency discovery. Horizontal lines are baseline F_1 scores computed for fully connected Bayesian networks. Right: Comparison of F_1 scores for edge orientation.

structures from these data sets. Again, the models only contains single-skilled items. The results are presented in Figure 9. It is clearly seen that the accuracy decreases when the fraction of missing values increases. The algorithm is still able to recover the true structures of Structure 1 and 2 even the data contains up to 30% missing values.

4.1.4 Comparison With PARM

Chen and his colleagues proposed to use Probabilistic Association Rules Mining (PARM) for discovering the prerequisite relationships between skills [4]. Since PARM discovers pair-wise prerequisite relationship, instead of constructing the full structure, we only compare BNPD with PARM for discovering the pair-wise relationships from the Bayesian network structure and see how the two approaches discover these relationships. Here we simulated data from Structure 3 (Figure 5(c)) (with single-skilled items), which has 21 pair-wise prerequisite relationships. When experimenting with PARM, the following cutoff values were used: $minsup = 0.125$, $minconf = 0.76$, $minprob = 0.9$. These values have been used in the simulation experiments in [4]. The evaluation metric used is $F_1 = \frac{2 \cdot TPR \cdot TDR}{TPR + TDR}$, where $TPR = \frac{\text{\# of correct relationships learned}}{\text{\# of relationships in true model}}$ and $TDR = \frac{\text{\# of correct relationships learned}}{\text{\# of relationships in learned model}}$. The result is presented in Figure 10. It shows that BNPD significantly outperforms PARM for sample size $n \geq 500$. The low F_1 score by PARM is caused by low TPR , i.e., PARM failed to discover many prerequisite relationships (data not shown).

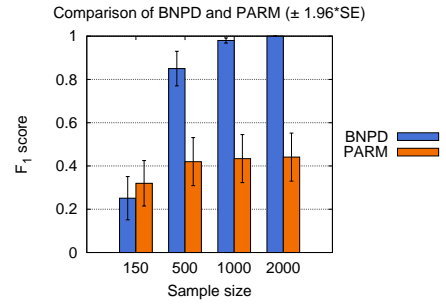


Figure 10: Comparison of BNPD and PARM for discovering prerequisite relationships in Structure 3. The cutoff values used for PARM experiments are: $minsup = 0.125$, $minconf = 0.76$, $minprob = 0.9$.

4.2 Real Student Performance Data

We now evaluate BNPD using two real-world student data sets.

4.2.1 ECPE Data Set

The ECPE (Examination for the Certification of Proficiency in English) data set was collected from a test by the English language Institute of the University of Michigan to examine individual cognitive skills required for understanding English language grammar [19]. It contains a sample of 2922 examinees who is tested by 28 items on 3 skills, i.e., *morphosyntactic rules* (S_1), *cohesive rules* (S_2) and *lexical rules* (S_3). Each item requires either one or two of the three skills. The prerequisite structure output from BNPD are depicted in Figure 11. The estimated conditional probability tables (CPT) are showed correspondingly. The discovered structure says *lexical rules* is a prerequisite of *cohesive rules* and *morphosyntactic rules*, and *cohesive rules* is a prerequisite of *morphosyntactic rules*. This totally agrees with the findings in [19] and by the PARM method in [4]. Further, BNPD also outputs the conditional probabilities associated with each skill and its direct prerequisite. And we clearly see that the probability of student mastering a skill increases when the student has acquired more prerequisites of the skill.

4.2.2 HED Data Set

We now evaluate BNPD using data collected from a commercial non-adaptive tutoring system. The data set, named as HED, is from

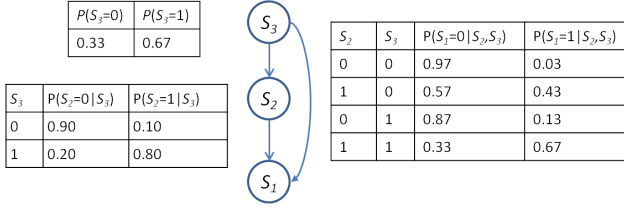


Figure 11: Result on ECPE data set. S_1 : Morphosyntactic rules; S_2 : Cohesive rules; S_3 : Lexical rules. The estimated conditional probability tables (CPTs) are shown correspondingly.

anonymized students interacting with an implementation of a seventh grade math curriculum. The textbook items are classified in chapters, sections, and objectives; but for this paper, we only use the data from Chapter 2 and Chapter 3 of the book. We use performance data while students solve test items.

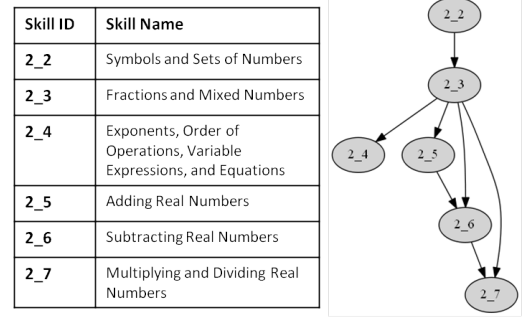
Q-matrix and preprocessing. We use an item-to-skill mapping (*Q*-matrix) that assigns each exercise to a skill solely as the book section in which the item appears. For each chapter, We process the data set to find a subset of items and students that does not have missing data. This is, the dataset we use in BNPD has students responding to *all* of the items.

After filtering, we obtained two data sets, HED-chap2 and HED-chap3 for Chapter 2 and 3 respectively. In HED-chap2, six skills (book sections) are included and each skill has three to eight items, for a total of 30 items. In HED-chap3, seven skills are included and each skill has three to seven items, for a total of 33 items. HED-chap2 includes student test results for 1720 students; while the HED-chap3 has the test results for 1245 students.

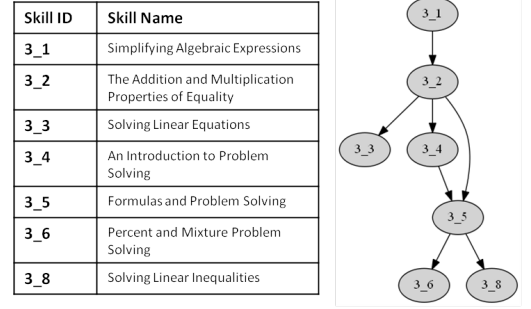
For simplicity we use binary variables to encode performance data (i.e., correct or incorrect) and skill variables (i.e., mastery or not mastery). This simplification is not necessary, as BNPD is able to use discrete variables with arbitrary number of states.

Prerequisite Structure Discovery. The Bayesian networks generated with the BNPD algorithm are illustrated in Figure 12. Our observation is that the topological order of the sections in both structures are fully consistent with the book ordering heuristic. This shows an agreement between our fully data-driven method and human experts. We also ran PARM approach to learn pair-wise prerequisite relationships from these data sets. As a result, $2_5 \rightarrow 2_6$ and $2_5 \rightarrow 2_7$ are discovered for HED-chap2, $3_1 \rightarrow 3_3$ and $3_2 \rightarrow 3_3$ are discovered for HED-chap3.

Predictive Performance of Prerequisite Models. BNPD not only discovers the topological relationships among skills, but also outputs a statistical model in the form of Bayesian network. This statistical model can be used for inference and predictive modeling. We now evaluate how well the generated Bayesian networks can predict student performance on a test item given performance on other items. In particular, we compute the posterior probability of a student's response to an item I_i given his performance on all



(a) Prerequisite structure learned for HED-chap2.



(b) Prerequisite structure learned for HED-chap3.

Figure 12: Prerequisite structures constructed by BNPD for HED data sets.

other items $\mathbf{I}_{-i} = \mathbf{I} \setminus \{I_i\}$, by marginalizing:

$$P(I_i = 1 | \mathbf{I}_{-i} = \mathbf{i}_{-i}) = \sum_{\mathbf{S}} P(I_i, \mathbf{S} | \mathbf{I}_{-i} = \mathbf{i}_{-i}), \quad (3)$$

This can be computed efficiently using the Junction tree algorithm [13]. We then do binary classification based on the posterior probability.

We compare the Bayesian network models generated from BNPD with four baseline predictors:

- A *majority* classifier which always classifies an instance to the majority class. For example, if majority of the students get an item wrong, other students would likely get it wrong.
- A Bayesian network model in which the skill variables are *disconnected*. This corresponds to using the *Q*-matrix Bayesian network of Figure ???. This model assumes that the skill variables are marginally independent of each other.
- A Bayesian network model in which the skill variables are connected in a *chain* structure, i.e., $2_2 \rightarrow 2_3 \rightarrow 2_4 \rightarrow \dots$. This assumes that a section (skill) only depends on the previous section. In other words, a first-order Markov chain dependency structure.
- A *fully connected* Bayesian network where skill variables are fully connected with each other. This model assumes no conditional independence between skill variables and can encode any joint distribution over the skill variables. However, it has exponential number of free parameters and thus can easily overfit the data.

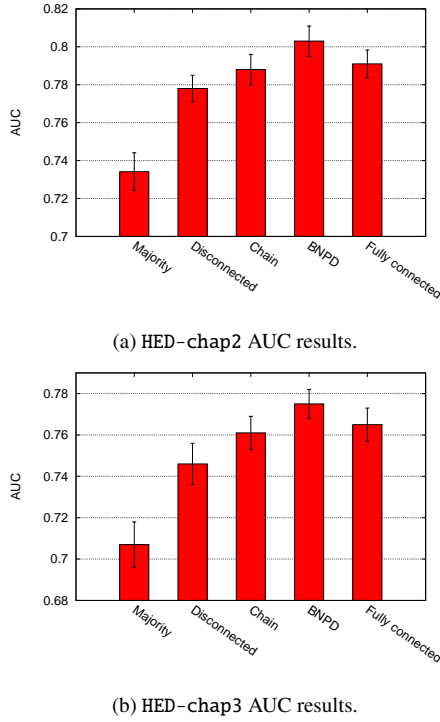


Figure 13: Comparison of AUC of five models to predict student performance on test items. The results are from 10 fold cross-validation.

The parameters of these baseline Bayesian network predictors are estimated from the data. We did 10-fold cross-validation to evaluate the classifiers. The model predictions were evaluated using the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve metric. Results are presented in Figure 13. The error bars show the 95% confidence intervals calculated from the cross-validation. On both HED-chap2 and HED-chap3 data sets, the BNPD models outperform the other four models. The *fully connected* models are the second best performing models. On HED-chap2, BNPD model has an AUC of 0.803 ± 0.008 and the *fully-connected* model has an AUC of 0.791 ± 0.007 (Figure 13a). A paired *t*-test reveals that the AUCs of two models are statistically different with a *p*-value of 0.0022. On HED-chap3, BNPD model has an AUC of 0.775 ± 0.007 and the *fully-connected* model has an AUC of 0.765 ± 0.008 (Figure 13b). The AUCs of two models are also statistically different with a *p*-value of 0.01. The *fully connected* models was outperformed by the simpler prerequisite models, suggesting overfitting.

5. CONCLUSION AND DISCUSSION

Discovering prerequisite structure of skills from data is challenging since skills are latent variables in the data. In this paper, we proposed BNPD, a novel pipeline for learning the prerequisite dependencies of hidden skill variables from students' response data on test items. We demonstrated our approach using both synthetic and real-world data under different conditions such as data contains missing values and noises. We show the discovered prerequisite models are useful for predicting student performance.

A contribution of our work is introducing the Structural EM algorithm to the educational community. This approach has many

advantages over prior work in that it does not require tuning of many parameters. For example, prior work [2] assumes domain parameters called *guess probability* and *slip probability* are provided for each pair of item and skill. Similarly, more recent approaches [4] require manually specified thresholds to determine the existence of a prerequisite relationship. The determination of these thresholds requires experts' intervention. By contrast, the only required input of our algorithm is the observed student performance.

Studying prerequisite structure discovery in the context of Bayesian network structure learning is not new [17]. However, existing approach does not discriminate between equivalent Bayesian network structures which represent different prerequisite structures. In our approach, we address this problem by using an ad-hoc strategy to refine the prerequisite model with a constraint on conditional distributions tables. This strategy is quite empirical. In future work, it may be wise to do Structural EM learning with edge orientation in one pass. For example, in Structural EM search, we can use a scoring function which combines the BIC score and a term that penalizes the structures that violate the CPT constraint. In such way, the prerequisite structure learning may be more accurate.

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