
Tractable Learning for Complex Probability Queries

Jessa Bekker, Jesse Davis

KU Leuven, Belgium

{jessa.bekker, jesse.davis}@cs.kuleuven.be

Arthur Choi, Adnan Darwiche, Guy Van den Broeck

University of California, Los Angeles

{aychoi, darwiche, guyvdb}@cs.ucla.edu

Abstract

Tractable learning aims to learn probabilistic models where inference is guaranteed to be efficient. However, the particular class of queries that is tractable depends on the model and underlying representation. Usually this class is MPE or conditional probabilities $\Pr(\mathbf{x}|\mathbf{y})$ for joint assignments \mathbf{x}, \mathbf{y} . We propose a tractable learner that guarantees efficient inference for a broader class of queries. It simultaneously learns a Markov network and its tractable circuit representation, in order to guarantee and measure tractability. Our approach differs from earlier work by using Sentential Decision Diagrams (SDD) as the tractable language instead of Arithmetic Circuits (AC). SDDs have desirable properties, which more general representations such as ACs lack, that enable basic primitives for Boolean circuit compilation. This allows us to support a broader class of complex probability queries, including counting, threshold, and parity, in polytime.

1 Introduction

Tractable learning [1] is a promising new machine learning paradigm that focuses on learning probability distributions that support efficient querying. It is motivated by the observation that while classical algorithms for learning Bayesian and Markov networks excel at fitting data, they ignore the cost of reasoning with the learned model. However, many applications, such as health-monitoring systems, require efficient and (guaranteed) accurate reasoning capabilities. Hence, new learning techniques are needed to support applications with these requirements.

Initially, tractable learning focused on the first model class recognized to be tractable: low-treewidth graphical models [2–5]. Recent advances in probabilistic inference exploit other properties of a model, including local structure [6] and exchangeability [7], which even scale to models that have high treewidth. In particular, the discovery of local structure led to *arithmetic circuits* (ACs) [8], which are a much more powerful representation of tractable probability distributions. In turn, this led to new tractable learners that targeted ACs to guarantee efficient inference [9, 10]. In this context, ACs with latent variables are sometimes called sum-product networks (SPNs) [11, 12]. Other tractable learners target exchangeable models [13, 14] or determinantal point processes [15].

There is a trade-off in tractable learning that is poorly understood and often ignored: tractability is not absolute, and always relative to a *class of queries* that the user is interested in. Existing approaches define tractability as the ability to efficiently compute most-probable explanations (MPE) or conditional probabilities $\Pr(\mathbf{x}|\mathbf{y})$ where \mathbf{x}, \mathbf{y} are joint assignments to subsets of random variables. While these queries are indeed efficient on ACs, many other queries of interest are not. For example, computing partial MAP remains NP-hard on low-treewidth and AC models [16]. Similarly, various

decision [17, 18], monotonicity [19], and utility [20] queries remain (co-)NP-hard.¹ Perhaps the simplest query beyond the reach of tractable AC learners is for probabilities $\Pr(\phi|\psi)$, where ϕ, ψ are complex properties, such as counts, thresholds, comparison, and parity of sets of random variables. These properties naturally appear throughout the machine learning literature, for example, in neural nets [21], and in exchangeable [13] and statistical relational models [22]. We believe they have not been used to their full potential in the graphical models world due to their intractability. We call these types of queries *complex probability queries*.

This paper pushes the boundaries of tractable learning by supporting more queries efficiently. While we currently lack any representation tractable for partial MAP, we do have all the machinery available to learn tractable models for complex probability queries. Their tractability is enabled by the weighted model counting (WMC) [6] encoding of graphical models and recent advances in compilation of Boolean functions into Sentential Decision Diagrams (SDDs) [23]. SDDs can be seen as a syntactic subset of ACs with more desirable properties, including the ability to (1) incrementally compile a Markov network, via a conjoin operator, (2) dynamically minimize the size and complexity of the representation, and (3) efficiently perform complex probability queries.

Our first contribution is a tractable learning algorithm for Markov networks with compact SDDs, following the outer loop of the successful ACMN learner [9] for ACs, that uses SDD primitives to modify the circuit during the Markov network structure search. Support for the complex queries listed above also means that these properties can be employed as features in the learned network. Second, we prove that complex symmetric probability queries over n variables, as well as their extensions, run in time polynomial in n and linear in the size of the learned SDD. Tighter complexity bounds are obtained for specific classes of queries. Finally, we illustrate these tractability properties in an empirical evaluation on four real-world data sets and four types of complex queries.

2 Background

2.1 Markov Networks

A *Markov network* or *Markov random field* compactly represents the joint distribution over a set of variables $\mathbf{X} = (X_1, X_2, \dots, X_n)$ [24]. Markov networks are often represented as *log-linear models*, that is, an exponentiated weighted sum of features of the state \mathbf{x} of variables \mathbf{X} : $\Pr(\mathbf{X} = \mathbf{x}) = \frac{1}{Z} \exp \sum_j w_j f_j(\mathbf{x})$. The $f_j(\mathbf{X})$ are real-valued functions of the state, w_j is the weight associated with f_j , and Z is the partition function. For discrete models, features are often Boolean functions; typically a conjunction of tests of the form $(X_i = x_i) \wedge \dots \wedge (X_j = x_j)$. One is interested in performing certain inference tasks, such as computing the posterior marginals or most-likely state (MPE) given observations. In general, such tasks are intractable (#P- and NP-hard).

Learning Markov networks from data require estimating the weights of the features (parameter learning), and the features themselves (structure learning). We can learn the parameters by optimizing some convex objective function, which is typically the log-likelihood. Evaluation of this function and its gradient is in general intractable (#P-complete). Therefore, it is common to optimize an approximate objective, such as the pseudo-log-likelihood. The classical structure learning approach [24] is a greedy, top-down search. It starts with features over individual variables, and greedily searches for new features to add to the model from a set of candidate features, found by conjoining pairs of existing features. Other approaches convert local models into a global one [25]. To prevent overfitting, one puts a penalty on the complexity of the model (e.g., number of features).

2.2 Tractable Circuit Representations and Tractable Learning

Tractable circuit representations overcome the intractability of inference in Markov networks. Although we are not always guaranteed to find a compact tractable representation for every Markov network, in this paper we will guarantee their existence for the learned models.

AC Arithmetic Circuits (ACs) [8] are directed acyclic graphs whose leafs are inputs representing either indicator variables (to assign values to random variables), parameters (weights w_j) or constants. Figure 1c shows an example. ACs encode the partition function computation of a Markov network.

¹The literature typically shows hardness for polytrees. Results carry over because these have compact ACs.

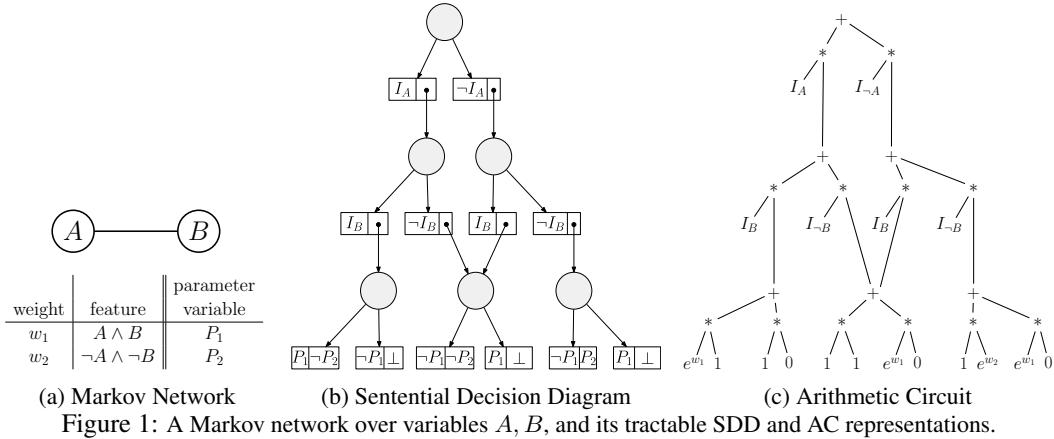


Figure 1: A Markov network over variables A, B , and its tractable SDD and AC representations.

By setting indicators to 1 and evaluating the AC bottom-up, the value of the partition function, Z , is obtained at the root. Other settings of the indicators encode arbitrary evidence. Moreover, a second, top-down pass yields all single-variable marginal probabilities; similar procedures exist for MPE. All these algorithms run in time linear in the size of the AC (number of edges). The *tractable learning* paradigm for Markov networks is best exemplified by ACMN [9], which concurrently learns a Markov network and its AC. It employs a complexity penalty based on the inference cost. Moreover, ACMN efficiently computes the exact log-likelihood (as opposed to pseudo-log-likelihood) and its gradient on the AC. ACMN uses the standard greedy top-down feature search outlined above.

SDD *Sentential Decision Diagrams* (SDDs) are a tractable representation of sentences in propositional logic [23]. The supplement² reviews SDDs in detail; a brief summary is next. SDDs are directed acyclic graphs, as depicted in Figure 1b. A circle node represents the disjunction of its children. A pair of boxes denotes the conjunction of the two boxes, and each box can be a (negated) Boolean variable or a reference to another SDD node. The detailed properties of SDDs yield two benefits. First, SDDs support an efficient conjoin operator that can incrementally construct new SDDs from smaller SDDs in linear time. Second, SDDs support dynamic minimization, which allows us to control the growth of an SDD during incremental construction.

There is a close connection between SDDs for logic and ACs for graphical models, through an intermediate *weighted model counting* formulation [6], which is reviewed in the supplement. Given a graphical model M , one can construct a logical sentence Δ whose satisfying assignments are in one-to-one correspondence with the possible worlds of M . Moreover, each satisfying assignment of Δ encodes the weights w_j that apply to its possible world in M . For each feature f_j of M , this Δ includes a constraint $f_j \Leftrightarrow P_j$, meaning that weight w_j applies when “parameter” variable P_j is true; see Figure 1a. A consequence of this correspondence is that, given an SDD for Δ , we can efficiently construct an AC for the original Markov network M ; see Figure 1. Hence, an SDD corresponding to M is a tractable representation of M . Different from ACs, SDDs have the following properties: support for efficient (linear) conjunction allows us to add new features f_j and incrementally learn a Markov network. Moreover, dynamic minimization lets us systematically search for more compact circuits for the same Markov network, mitigating the increasing complexity of inference as we learn more features. Such operations are not available for ACs in general.

3 Learning Algorithm

We propose LearnSDD, which employs a greedy, general-to-specific search that simultaneously learns a Markov network and its underlying SDD which is used for inference. The cost of inference in the learned model is dictated by the size of its SDD. Conceptually, our approach is similar to ACMN [9] with the key differences being our use of SDDs instead of ACs, which gives us more tractability and freedom in the types of features that are considered.

²<https://dtai.cs.kuleuven.be/software/learnsdd>

Algorithm 1 LearnSDD(T, e, α)

```
initialize model  $M$  with variables as features
 $M_{best} \leftarrow M$ 
while number of edges  $|SDD_M| < e$  and not timeout
    best_score =  $-\infty$ 
     $F \leftarrow \text{generateFeatures}(M, T)$ 
    for each feature  $f$  in  $F$  do
         $M' \leftarrow M.\text{add}(f)$ 
        if  $\text{score}(M', T, \alpha) > \text{best\_score}$ 
            best_score =  $\text{score}(M', T, \alpha)$ 
             $M_{best} \leftarrow M'$ 
     $M \leftarrow M_{best}$ 
```

LearnSDD, outlined in Algorithm 1, receives as input a training set T , a maximum number of edges e , and a parameter α to control the relative importance of fitting the data vs. the cost of inference. As is typical with top-down approaches to structure learning [24], the initial model has one feature $X_i = \text{true}$ for each variable, which corresponds to a fully-factorized Markov network. Next, LearnSDD iteratively constructs a set of candidate features, where each feature is a logical formula. It scores each feature by compiling it into an SDD, conjoining the feature to the current model temporarily, and then evaluating the score of the model that includes the feature. The supplement shows how a feature is added to an SDD. In each iteration, the highest scoring feature is selected and added to the model permanently. The process terminates when the maximum number of edges is reached or when it runs out of time. Inference time is dictated by the size of the learned SDD. To control this cost, we invoke dynamic SDD minimization each time a feature is evaluated, and when we permanently add a feature to the model.

Performing structure learning with SDDs offers advantages over ACs. First, SDDs support a practical conjoin operation, which greatly simplifies the design of a top-down structure learning algorithm (ACMN instead relies on a complex special-purpose AC modification algorithm). Second, SDDs support dynamic minimization, allowing us to search for smaller SDDs, as needed. The following two sections discuss the score function and feature generation in greater detail.

3.1 Score Function and Weight Learning

Score functions capture a trade-off between fitting the training data and the preference for simpler models, captured by a regularization term. In tractable learning, the regularization term reflects the cost of inference in the model. Therefore, we use the following score function:

$$\text{score}(M', T) = [\log \Pr(T|M') - \log \Pr(T|M)] - \alpha [|SDD_{M'}| - |SDD_M|] / |SDD_M| \quad (1)$$

where T is the training data, M' is the model extended with feature f , M is the old model, $|SDD|$ returns the number of edges in the SDD representation, and α is a user-defined parameter. The first term is the improvement in the model's log-likelihood due to incorporating f . The second term measures the relative growth of the SDD representation after incorporating f . We use the relative growth because adding a feature to a larger model adds many more edges than adding a feature to a smaller model. Section 4 shows that any query's inference complexity depends on the SDD size. Finally, α lets us control the trade-off between fitting the data and the cost of inference.

Scoring a model requires learning the weights associated with each feature. Because we use SDDs, we can efficiently compute the exact log-likelihood and its gradient using only two passes over the SDD. Therefore, we learn maximum-likelihood estimates of the weights.

3.2 Generating Features

In each iteration, LearnSDD constructs a set of candidate features using two different feature generators: conjunctive and mutex. The **conjunctive generator** considers each pair of features f_1, f_2 in the model and proposes four new candidates per pair: $f_1 \wedge f_2, \neg f_1 \wedge f_2, f_1 \wedge \neg f_2$ and $\neg f_1 \wedge \neg f_2$.

The **mutex generator** automatically identifies mutually exclusive sets of variables in the data and proposes a feature to capture this relationship. Mutual exclusivity arises naturally in data. It occurs in tractable learning because existing approaches typically assume Boolean data. Hence,

any multi-valued attribute is converted into multiple binary variables. For all variable sets $\mathbf{X} = \{X_1, X_2, \dots, X_n\}$ that have exactly one “true” value in each training example, the *exactly one* feature $\bigvee_{i=1}^n (X_i \wedge \bigwedge_{j \neq i} \neg X_j)$ is added to the candidate set. When at most one variable is “true”, the *mutual exclusivity* feature $\bigvee_{i=1}^n (X_i \wedge \bigwedge_{j \neq i} \neg X_j) \vee \bigwedge_{j=1}^n \neg X_j$ is added to the candidate set.

4 Complex Queries

Tractable learning focuses on learning models that can efficiently compute the probability of a query given some evidence, where both the query and evidence are conjunctions of literals. However, many other important and interesting queries do not conform to this structure, including the following:

- Consider the task of predicting the probability that a legislative bill will pass given that some lawmakers have already announced how they will vote. Answering this query requires estimating the probability that a *count* exceeds a given threshold.
- Imagine only observing the first couple of sentences of a long review, and wanting to assess the probability that the entire document has more positive words than negative words in it, which could serve as proxy for how positive (negative) the review is. Answering this requires *comparing two groups*, in this case positive words and negative words.

Table 1 lists these and other examples of what we call complex queries, which are logical functions that cannot be written as a conjunction of literals. Unfortunately, tractable models based on ACs are, in general, unable to answer these types of queries efficiently. We show that using a model with an SDD as the target tractable representation can permit efficient exact inference for certain classes of complex queries: symmetric queries and their generalizations. No known algorithm exists for efficiently answering these types of queries in ACs. For other classes of complex queries, the complexity is never worse than for ACs, and in many cases SDDs will be more efficient. Note that SPNs have the same complexity for answering queries as ACs since they are interchangeable [12].

We first discuss how to answer complex queries using ACs and SDDs. We then discuss some classes of complex queries and when we can guarantee tractable inference in SDDs.

4.1 Answering Complex Queries

Currently, it is only known how to solve conjunctive queries in ACs. Therefore, we will answer complex queries by asking multiple conjunctive queries. We convert the query into DNF format $\bigvee \mathbf{C}$ consisting of n *mutually exclusive* clauses $\mathbf{C} = \{C_1, \dots, C_n\}$. Now, the probability of the query is the sum of the probabilities of the clauses: $\Pr(\bigvee \mathbf{C}) = \sum_{i=1}^n \Pr(C_i)$. In the worst case, this construction requires 2^m clauses for queries over m variables. The inference complexity for each clause on the AC is $O(|AC|)$. Hence, the total inference complexity is $O(2^m \cdot |AC|)$.

SDDs can answer complex queries without transforming them into mutually exclusive clauses. Instead, the query Q can directly be conjoined with the weighted model counting formulation Δ of the Markov network M . Given an SDD S_m for the Markov network and an SDD S_q for Q , we can efficiently compile an SDD S_a for $Q \wedge \Delta$. From S_a , we can compute the partition function of the Markov network after asserting Q , which gives us the probability of Q . This computation is performed efficiently on the AC that corresponds to S_a (cf. Section 2.2). The supplement explains the protocol for answering a query. The size of the SDD S_a is at most $|S_q| \cdot |S_m|$ [23], and inference is linear in the circuit size, therefore it is $O(|S_q| \cdot |S_m|)$. When converting an arbitrary query into SDD, the size may grow as large as 2^m , with m the number of variables in the query. But often it will be much smaller (see Section 4.2). Thus, the overall complexity is $O(2^m \cdot |S_m|)$, but often much better, depending on the query class.

4.2 Classes of Complex Queries

A first class of tractable queries are symmetric Boolean functions. These queries do not depend on the exact input values, but only on how many of them are true.

Definition 1. A Boolean function $f(X_1, \dots, X_n) : \{0, 1\}^n \rightarrow \{0, 1\}$ is a *symmetric query* precisely when $f(X_1, \dots, X_n) = f(X_{\pi(1)}, \dots, X_{\pi(n)})$ for every permutation π of the n indexes.

Table 1: Examples of complex queries, with m the SDD size and n the number of query variables.

Query class	Query Type	Inference Complexity	Example
Symmetric Query	Parity	$O(mn)$	$\#(A, B, C) \% 2 = 0$
	k -Threshold	$O(mnk^2)$	$\#(A, B, C) > 1$
	Exactly- k	$O(mnk^2)$	$\#(A, B, C) = 2$
	Modulo- k	$O(mnk)$	$\#(A, B, C) \% 3 = 0$
Asymmetric Tractable Query	Exactly- k	$O(mnk^2)$	$\#(A, B, \neg C) = 2$
	Hamming distance k	$O(mnk^2)$	$\#(A, B, \neg C) \leq 2$
	Group comparison	$O(mn^3)$	$\#(A, B, \neg C) > \#(D, \neg E)$

Table 1 lists examples of functions that can always be answered in polytime because they have a compact SDD. Note that the features generated by the mutex generator are types of exactly- k queries where $k = 1$, and therefore have a compact SDD. We have the following result.

Theorem 1. *Markov networks with compact SDDs support tractable querying of symmetric functions. More specifically, let M be a Markov network with an SDD of size m , and let Q be any symmetric function of n variables. Then, $\Pr_M(Q)$ can be computed in $O(mn^3)$ time. Moreover, when Q is a parity function, querying takes $O(mn)$ time, and when Q is a k -threshold or exactly- k function, querying takes $O(mnk^2)$ time.*

The proof shows that *any* SDD can be conjoined with these queries without increasing the SDD size by more than a factor polynomial in n . The proof of Theorem 1 is given in the supplement. This tractability result can be extended to certain non-symmetric functions. For example, negating the inputs to a symmetric functions still yields a tractable complex query. This allows queries for the probability that the state is within a given Hamming distance from a desired state. Moreover, Boolean combinations of a bounded number of tractable function also admit efficient querying. This allows queries that compare symmetric properties of different groups of variables.

We cannot guarantee tractability for other classes of complex queries, because some queries do not have a compact SDD representation. An example of such a query is the weighed k -threshold where each literal has a corresponding weight and the total weight of true literals must be bigger than some threshold. While the worst-case complexity of using SDDs and ACs to answer such queries is the same, we show in the supplement that SDDs can still be more efficient in practice.

5 Empirical Evaluation

The goal of this section is to evaluate the merits of using SDDs as a target representation in tractable learning for complex queries. Specifically, we want to address the following questions:

Q1 Does capturing mutual exclusivity allow LearnSDD to learn more accurate models than ACMN?

Q2 Do SDDs produced by LearnSDD answer complex queries faster than ACs learned by ACMN?

To resolve these questions, we run LearnSDD and ACMN on real-world data and compare their performance. Our LearnSDD implementation builds on the publicly available SDD package.³

5.1 Data

Table 2 describes the characteristics of each data set.

Table 2: Data Set Characteristics

Data Set	Train Set Size	Tune Set Size	Test Set Size	Num. Vars.
Traffic	3,311	441	662	128
Temperature	13,541	1,805	2,708	216
Voting	1,214	200	350	1,359
Movies	1,600	150	250	1000

³<http://reasoning.cs.ucla.edu/sdd/>

Mutex features We used the Traffic and Temperature data sets [5] to evaluate the benefit of detecting mutual exclusivity. In the initial version of these data sets, each variable had four values, which were binarized using a 1-of-n encoding.

Complex queries To evaluate complex queries, we used voting data from GovTrac.us and Pang and Lee’s Movie Review data set.⁴ The voting data contains all 1764 votes in the House of Representatives from the 110th Congress. Each bill is an example and the variables are the votes of the 453 congressmen, which can be yes, no, or present. The movie review data contains 1000 positive and 1000 negative movie reviews. We first applied the Porter stemmer and then used the Scikit Learn CountVectorizer,⁵ which counts all 1- and 2-grams, while omitting the standard Scikit Learn stop words. We selected the 1000 most frequent n-grams in the training data to serve as the features.

5.2 Methodology

For all data sets, we divided the data into a single train, tune, and test partition. All experiments were run on identically configured machines with 128GB RAM and twelve 2.4GHz cores.

Mutex features Using the training set, we learned models with both LearnSDD and ACMN. For LearnSDD, we tried setting α to 1.0, 0.1, 0.01 and 0.001. For ACMN, we did a grid search for the hyper-parameters (per-split penalty ps and the L1 and L2-norm weights $l1$ and $l2$) with $ps \in \{2, 5, 10\}$, $l1 \in \{0.1, 1, 5\}$ and $l2 \in \{0.1, 0.5, 1\}$. For both methods, we stopped learning if the circuit exceeded two million edges or the algorithm ran for 72 hours. For each approach, we picked the best learned model according to the tuning set log-likelihood. We evaluated the quality of the selected model using the log-likelihood on the test set.

Complex queries In this experiment, the goal is to compare the time needed to answer a query in models learned by LearnSDD and ACMN. In both SDDs and ACs, inference time depends linearly on the number of edges in the circuit. Therefore, to ensure a fair comparison, the learned models should have approximately the same number of edges. Hence, we first learned an SDD and then used the number of edges in the learned SDD to limit the size of the model learned by ACMN.

In the voting data set, we evaluated the threshold query: what is the probability that at least 50% of the congressmen vote “yes” on a bill, given as evidence that some lawmakers have already announced their vote? We vary the percentage of unknown votes from 1 to 100% in intervals of 1% point. We evaluated several queries on the movie data set. The first two queries mimic an active sensing setting to predict features of the review without reading it entirely. The evidence for each query are the features that appear in the first 750 characters of the stemmed review. On average, the stemmed reviews have approximately 3,600 characters. The first query is $\Pr(\#\text{(positive ngrams}) > 5)$ and second is $\Pr(\#\text{(positive ngrams}) > \#\text{(negative ngrams)})$, which correspond to a threshold query and a group comparison query, respectively. For both queries, we varied the size of the positive and negative ngram sets from 5 to 100 ngrams with an increment size of 1. We randomly selected which ngrams are positive and negative as we are only interested in a query’s evaluation time. The third query is the probability that a parity function over a set of features is even. We vary the number of variables considered by the parity function from 5 to 100. For each query, we report the average per example inference time for each learned model on the test set. We impose a 10 minute average time limit and 100 minutes individual time limit for each query. For completeness, the supplement reports run times for queries that are guaranteed to (not) be tractable for both ACs and SDDs as well as the conditional log-likelihoods of all queries.

5.3 Results and Discussion

Mutex features Figure 2 shows the test set log-likelihoods as a function of the size of the learned model. In both data sets, LearnSDD produces smaller models that have the same accuracy as AC. This is because it can add mutex features without the need to add other features that are needed as building blocks but are redundant afterwards. These results allow us to affirmatively answer **(Q1)**.

Complex queries Figure 3 shows the inference times for complex queries that are extensions of symmetric queries. For all queries, we see that LearnSDD’s model results in significantly faster inference times than ACMN’s model. In fact, ACMN’s model exceeds the ten minute time limit on

⁴<http://www.cs.cornell.edu/people/pabo/movie-review-data/>

⁵<http://tartarus.org/martin/PorterStemmer/> and <http://scikit-learn.org/>

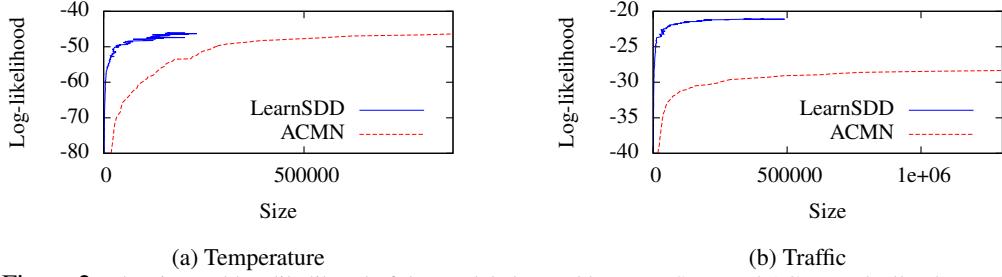


Figure 2: The size and log-likelihood of the models learned by LearnSDD and ACMN. Ideally, the model is small with high accuracy (upper left corner), which is best approached by the LearnSDD models.

334 out of 388 of the query settings whereas this only happens in 25 settings for LearnSDD. The SDD can answer all parity questions and positive word queries in less than three hundred milliseconds and the group comparison in less than three seconds. It can answer the voting query with up to 75% of the votes unknown in less than ten minutes. These results demonstrate LearnSDD's superior ability to answer complex queries compared to ACMN and allow us to positively answer **(Q2)**.

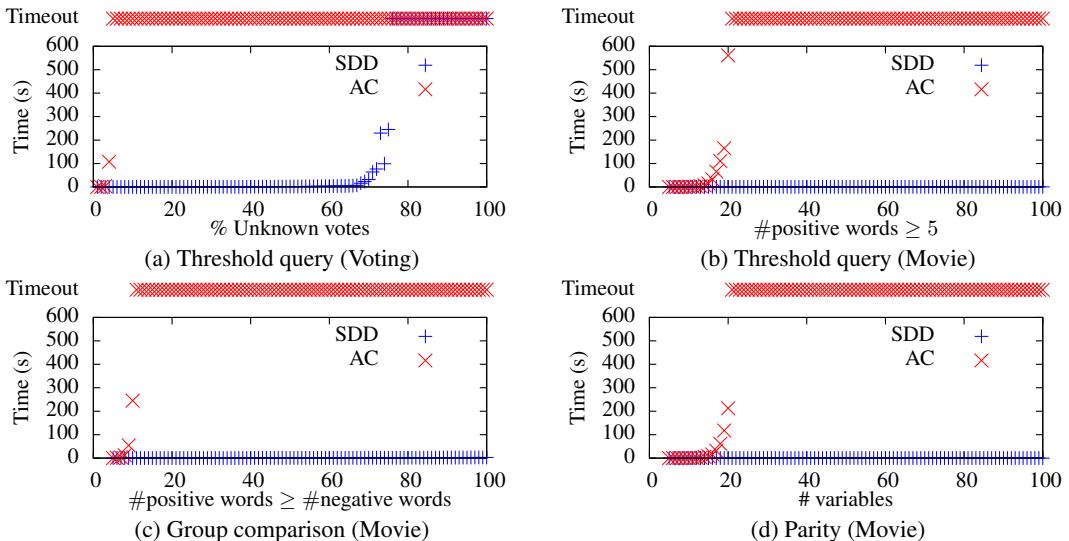


Figure 3: The time for SDDs vs. ACs to answer complex queries, varying the number of query variables. SDDs need less time in all settings, answering nearly all queries. ACs timeout in more than 85% of the cases.

6 Conclusions

This paper highlighted the fact that tractable learning approaches learn models for only a restricted classes of queries, primarily focusing on the efficient computation of conditional probabilities. We focused on enabling efficient inference for complex queries. To achieve this, we proposed using SDDs as the target representation for tractable learning. We provided an algorithm for simultaneously learning a Markov network and its SDD representation. We proved that SDDs support poly-time inference for complex symmetric probability queries. Empirically, SDDs enable significantly faster inference times than ACs for multiple complex queries. Probabilistic SDDs are a closely related representation: they also support complex queries (in structured probability spaces) [26, 27], but they lack general-purpose structure learning algorithms (a subject of future work).

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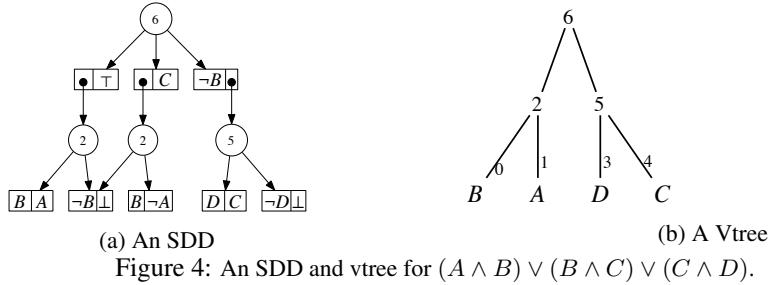


Figure 4: An SDD and vtree for $(A \wedge B) \vee (B \wedge C) \vee (C \wedge D)$.

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A Sentential Decision Diagrams

The Sentential Decision Diagram (SDD) is a newly introduced target representation for propositional knowledge bases [23, 28–31]. It is a strict subset of deterministic, decomposable negation normal form (d-DNNF), which has been used as a target representation for probabilistic graphical models, such as Markov networks and Bayesian networks [8, 6]. The ACE system is a state-of-the-art system for probabilistic inference, which is based on encoding a network as a propositional knowledge base (in CNF), which in turn is compiled into d-DNNF.⁶ SDDs and d-DNNFs impose two properties on propositional knowledge bases, decomposability and determinism, that enable the tractability of probabilistic (and logical) inference queries [32]. For example, decomposability asserts that the branches of a conjunction have sets of variables that are pairwise disjoint; this enables (pure) MAP queries in Markov networks (and satisfiability queries in propositional knowledge bases).

Figure 4a depicts an SDD: paired-boxes $[p|s]$ are called *elements* and represent conjunctions $(p \wedge s)$, where p is called a *prime* and s is called a *sub*. Circles are called *decision nodes* and represent disjunctions of the corresponding elements. SDDs satisfy stronger properties than d-DNNFs, allowing one, for example, to conjoin or disjoin two SDDs in polytime. In contrast, this is not possible in general with d-DNNFs (corresponding to ACs) [32], and other tractable representations for probabilistic graphical models. As we describe later, the ability to conjoin and disjoin SDDs efficiently is critical for the incremental learning of Markov networks.

An SDD is constructed for a given *vtree*, which is a full binary tree whose leaves are in one-to-one correspondence with the given variables; see Figure 4b. The SDD is canonical for a given vtree (under some conditions) and its size depends critically on the vtree used. Ordered Binary Decision Diagrams (OBDDs) [33] are a strict subset of SDDs: OBDDs correspond precisely to SDDs that are constructed using a special type of vtree, called a right-linear vtree [23]. Theoretically, SDDs come with size upper bounds (based on treewidth) [23] that are tighter than the size upper bounds that OBDDs come with (based on pathwidth) [34–36]. In practice, dynamic compilation algorithms can find SDDs that are orders-of-magnitude more succinct than those found using OBDDs. Such algorithms are enabled by the canonicity of SDDs, which allows one to search the space of vtrees

⁶ACE is available at <http://reasoning.cs.ucla.edu/ace/>, which uses C2D to compile CNFs to d-DNNFs, which is also available at <http://reasoning.cs.ucla.edu/c2d/>.

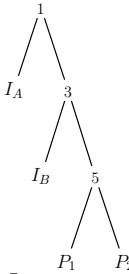


Figure 5: Vtree for Figure 1

to find succinct SDDs. As we shall describe later, the ability to dynamically minimize an SDD is critical for learning tractable representations of Markov networks.

Every decision node in an SDD is *normalized* for some vtree node. In Figure 4a, each decision node is labeled with the vtree node it is normalized for. Consider a decision node with elements $[p_1 | s_1], \dots, [p_n | s_n]$, and suppose that it is normalized for a vtree node v which has variables \mathbf{X} in its left subtree and variables \mathbf{Y} in its right subtree. We are then guaranteed that each prime p_i will only mention variables in \mathbf{X} and that each sub s_i will only mention variables in \mathbf{Y} (this ensures decomposability). Moreover, the primes are guaranteed to represent propositional sentences that are consistent, mutually exclusive, and exhaustive (this ensures determinism). For example, the top decision node in Figure 4a has elements that represent the following sentences:

$$\{(A \wedge B, \text{true}), (\neg A \wedge B, C), (\neg B, D \wedge C)\}$$

prime sub prime sub prime sub

One can verify that these primes and subs satisfy the properties above.

In our experiments, we use the SDD package provided by the Automated Reasoning Group at UCLA.⁷ This package allows one to efficiently conjoin, disjoin and negate SDDs, in addition to computing weighted model counts (i.e., the partition function of a Markov network and its derivatives) in linear time [8, 37]. Moreover, this package supports the dynamic minimization of SDDs, by searching the space of vtrees [29], which is critical for controlling the complexity of inference in an SDD representation of a Markov network.

B Weighted Model Counting

We review here how to reduce inference in Markov networks to weighted model counting [6]. Figure 1a in the main text highlights a simple Markov network over two binary variables A and B ; we note that the reduction to weighted model counting also generalizes to multi-valued variables in a straightforward way.

We can encode a Markov network as a propositional knowledge base Δ whose weighted model count will correspond to the partition function of the Markov network: $Z = \sum_x \exp\left(\sum_j w_j f_j(x)\right)$. We first define the propositional variables of the knowledge base Δ . First, for each Markov network variable X_i we define *indicator variables* I_{X_i} of Δ . Second, for each feature f_j with weight w_j , we define a *parameter variables* P_j . In Figure 1a, we have two binary features, with their corresponding parameter variables in the knowledge base Δ .

Our knowledge base Δ is composed of certain constraints, one for each feature f_j in the Markov network. Assuming each feature is a term (a conjunction of literals), then we denote α_j as the corresponding term over indicator variables I_{X_i} . Our knowledge base Δ is then composed of the constraints $\alpha_j \Leftrightarrow P_j$ for each feature f_j . In our example, we include four constraints in the knowledge base Δ , one for each feature. For the two binary features of Figure 1a, we introduce two constraints: for the term $A \wedge B$ we introduce the constraint $P_1 \Leftrightarrow (I_A \wedge I_B)$ and for the term $\neg A \wedge \neg B$ we introduce the constraint $P_2 \Leftrightarrow (\neg I_A \wedge \neg I_B)$. Figure 1b highlights an SDD representation of this example, and the corresponding vtree in Figure 5.

⁷The SDD package is available at <http://reasoning.cs.ucla.edu/sdd/>.

To perform weighted model counting, we need to specify weights on each literal of the knowledge base Δ . For each indicator variable X_i , we set both literal weights $W(I_{X_i})$ and $W(\neg I_{X_i})$ to one. For each parameter variable, we set the positive literal weight $W(P_j)$ to the weight of the corresponding feature, i.e., $W(P_j) = \exp(w_j)$. We further set the negative literal weight $W(\neg P_j)$ to one. The models w of the resulting knowledge base Δ are now in one-to-one correspondence with rows of the joint distribution table induced by our Markov network. In particular, consider the weight $W(w)$ of a model w , and the weighted model count $W(\Delta)$ of our knowledge base Δ :

$$W(w) = \prod_{w \models \ell} W(\ell) \quad W(\Delta) = \sum_{w \models \Delta} W(w)$$

Note that if model w is consistent with term α_j of feature f_j , then the corresponding parameter variable P_j is set to true in model w , and the model weight $W(w)$ includes the feature weight w_j . For example, we have the following model w and model weight $W(w)$:

$$\begin{aligned} w &= (I_A, I_B, P_1, \neg P_2) \\ W(w) &= W(P_1) \\ &= \exp(w_1) = \Pr(A, B) \cdot Z. \end{aligned}$$

Further, the weighted model count yields the partition function Z . We incorporate evidence by setting to zero the weights of any indicator variable I_{X_i} that is not compatible with the evidence. The weighted model count then corresponds to the probability of evidence (after normalization by the partition function).

C Protocols for SDD Manipulation

This section provides insight in how to manipulate SDDs for learning and answering queries. First we show how to add a feature to an existing model and then we show how to use an SDD to answer complex probability queries with evidence.

C.1 Adding Features

Given: Markov network M with a corresponding SDD S_M and a feature f_i with corresponding weight w_i . Feature f_i is a logical formula over variables or previously added features, e.g. $a \wedge f_j$, where a is a variable and f_i a previously added feature.

Construct: A new SDD $S_{M'}$ that corresponds to the model M' which is the combination of the original model M and the new feature f_i

Protocol:

1. Introduce a new parameter variable P_{f_i} .
2. Compile the formula $P_{f_i} \Leftrightarrow f_i$ (e.g. $P_{f_i} \Leftrightarrow a \wedge f_j$) to SDD S_{f_i} .
3. Add the feature to the model by conjoining the two SDDs: $S_{M'} = \text{conjoin}(S_M, S_{f_i})$
4. During weighted model counting, the new variable P_{f_i} will have w_i as a positive weight and 1 as a negative weight.

C.2 Answering Queries

Given: Markov network M with a corresponding SDD S_M and evidence e where e is a subset of the variables with their given values, e.g. $e = \{E = 1, F = 0\}$.

Answer: A query $\Pr(q|e, M)$, e.g. threshold query $\Pr(\#(A, B, C, D) > 1|e, M)$.

Protocol:

1. Compile q to SDD S_q .

As an example, consider the following formula for the query $\#(A, B, C, D) > 1$:

$$\alpha_{\#(A,B,C,D)>1} = (A \wedge \alpha_{\#(B,C,D)>0}) \vee (\neg A \wedge \alpha_{\#(B,C,D)>1})$$

which has the following sub-formula

$$\alpha_{\#(B,C,D)>1} = (B \wedge \alpha_{\#(C,D)>0}) \vee (\neg B \wedge \alpha_{\#(C,D)>1})$$

$$\alpha_{\#(C,D)>1} = (C \wedge \alpha_{\#(D)>0}) \vee (\neg C \wedge \alpha_{\#(D)>1})$$

$$\alpha_{\#(D)>1} = \perp$$

$$\alpha_{\#(B,C,D)>0} = (B \wedge \top) \vee (\neg B \wedge \alpha_{\#(C,D)>0})$$

$$\alpha_{\#(C,D)>0} = (C \wedge \top) \vee (\neg C \wedge \alpha_{\#(D)>0})$$

$$\alpha_{\#(D)>0} = D$$

The above formulas correspond to sub-SDDs (each corresponds to a decision node, except for $\alpha_{\#(D)>1}$ and $\alpha_{\#(D)>0}$ which correspond to terminal nodes). These formulas can be constructed recursively using the apply operation for SDDs, to conjoin SDD literals and SDD sub-formula. We also observe that the sub-formulas $\alpha_{\#(C,D)>0}$ and $\alpha_{\#(D)>0}$ appear multiple times, and can be re-used via caching.

2. Set the evidence e in SDD S_M by conditioning on the values, this results in a new SDD $S_{M,e}$. As a bonus, this step will reduce the size of the SDD and therefore speed up the next steps.
3. If the query also contains evidence variables, condition the S_q on the evidence values as well. This results in a new SDD $S_{q,e}$
4. Use SDD $S_{M,e}$ to calculate $WMC_{M,e}$
5. Conjoin the model and the query $S_{M \wedge q,e} = \text{conjoin}(S_{M,e}, S_{q,e})$
6. Use SDD $S_{M \wedge q,e}$ to calculate $WMC_{M \wedge q,e}$
7. The answer to the query is

$$\Pr(q|e, M) = \frac{WMC_{M \wedge q,e}}{WMC_{M,e}}$$

D Proof of Theorem 1

Proof. First, we have $\Pr_M(q) = \frac{WMC(q \wedge M)}{WMC(M)}$. We can compute the weighted model count of network M , $WMC(M)$, in time $O(m)$ given an SDD for network M of size m . Thus, it suffices to show that we can compute $WMC(q \wedge M)$ in time $O(mn^3)$. First, any symmetric function q has a structured d-DNNF of size $O(n^3)$, for any vtree [38]. Second, conjoining two structured d-DNNFs, with sizes m_1 and m_2 , takes time $O(m_1 m_2)$, when they share the same vtree [38]. Since any SDD is a structured d-DNNF, conjoining an SDD of size m with any symmetric function takes time $O(mn^3)$, and results in a structured d-DNNF of size $O(mn^3)$. Since we can also perform weighted model-counting on a structured d-DNNF in time linear in its size, we can compute $WMC(q \wedge M)$ in time $O(mn^3)$. Similarly, for the special cases of parity, k -threshold, and exactly- k functions, where the number of structured d-DNNF nodes respecting each vtree node can be bounded by a function of k [38]. \square

E Complex Query Experiments

E.1 Time Needed by Simpler and Harder Queries

To contrast the symmetric queries with simpler and harder cases, we also evaluated simple conjunctive queries and weighted k -threshold queries using the movie data set. We vary the number

of variables involved in the query from 5 to 100 variables. Each literal in the weighted k -threshold query has a corresponding weight and the total weight of true literals must be bigger than some threshold. For the experiment, all the variables were assigned random weights and the threshold was set to half of the maximum total weight.

Figure 6 shows the time needed to answer the conjunctive and weighted k -threshold query. As expected, both the AC and SDD can answer the conjunctive queries efficiently: they always need under 0.1 seconds. They both have difficulties with the weighted k -threshold query, but the SDD does outperform the AC. SDDs are not guaranteed to efficiently answer weighted k -threshold queries, but in practice they often do. Even when Figure 6b shows a timeout, the SDD was able to answer the query efficiently for most test examples, but at least one example exceeded the time limit. Thus even though we cannot guarantee efficient inference in all cases, it will still often be beneficial to use SDDs as the underlying tractable representation.

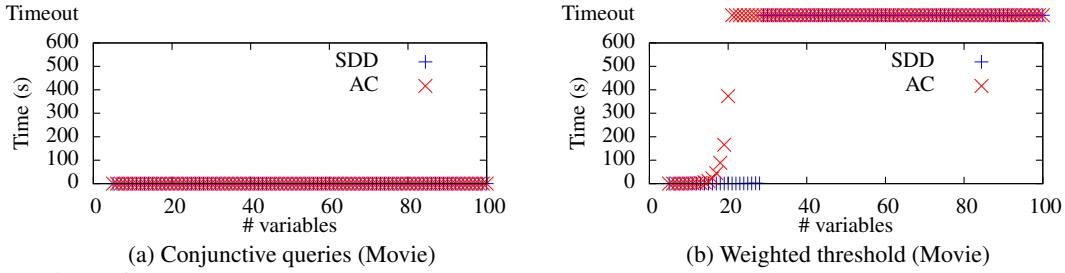


Figure 6: The time needed by an SDD vs. an AC to answer a conjunctive and a weighted k -threshold query, for various number of variables in the query. The SDD and AC perform similarly for the conjunctive query and the SDD outperform the AC for the weighted k -threshold query.

E.2 Conditional Log-Likelihoods

Using the training set, we learned models with both LearnSDD and ACMN. For LearnSDD, we tried setting α to 1.0, 0.1, 0.01 and 0.001. For ACMN, we tried setting the per-split penalty ps to 2, 5 and 10. Because the primary goal of experiment was to evaluate the inference time, the learned AC and SDD for each data set needed to be of similar size. To ensure this, we first picked the SDD with the best log-likelihood on the validation data. Subsequently, we selected the AC with the best validation set log-likelihood that was smaller than the chosen SDD. We picked an SDD first because the largest SDD for each setting was smaller than the largest AC for each setting.

Figure 7 shows the per example average conditional log-likelihood for the complex queries. The conditional log-likelihood expresses how close a query’s predicted answer is to its actual answer according to the data. The higher the log-likelihood of the model, the better it is at answering the query.

The SDD gives better results for the group query in Figure 7c, in all the other settings, the results are comparable.

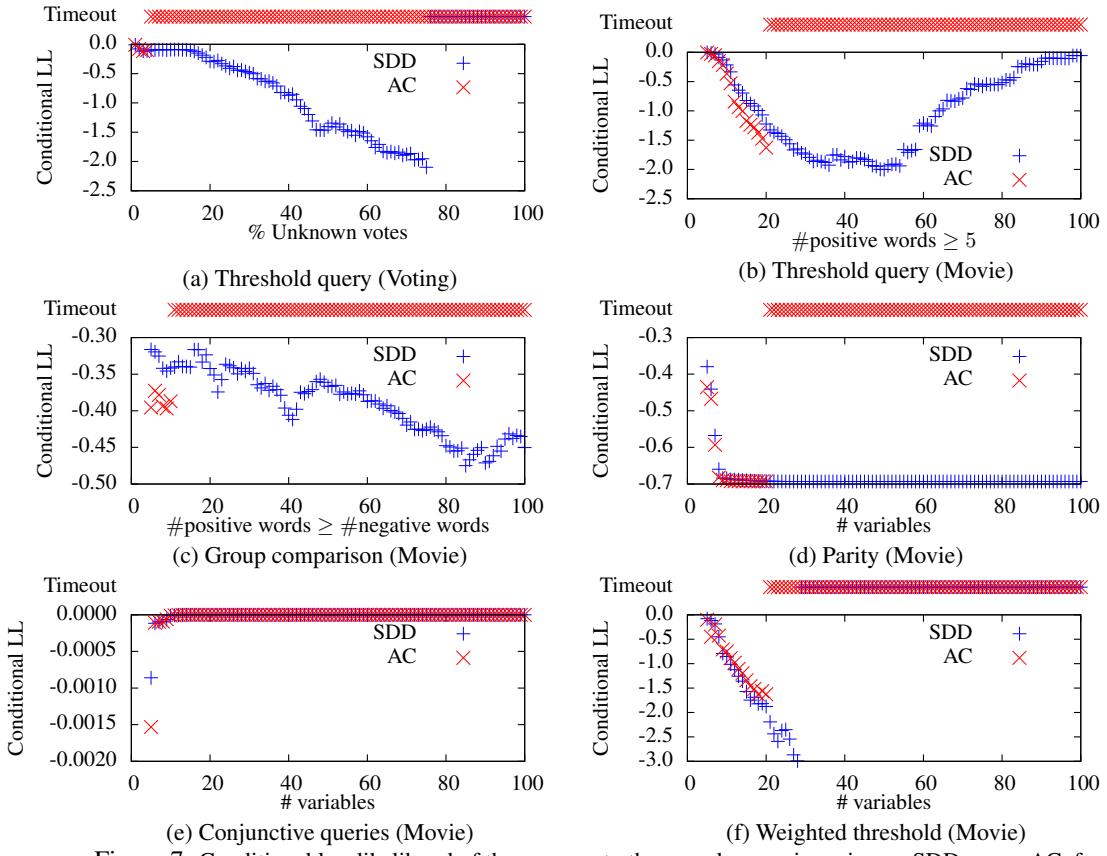


Figure 7: Conditional log-likelihood of the answers to the complex queries using an SDD vs. an AC, for various number of variables in the query. The SDD and AC result in most cases in similar conditional log-likelihoods.