Probabilistic XML: Survey and Challenges

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1 Motivation

2 Probabilistic XML Survey

3 Challenges
Uncertain data

Numerous sources of uncertain data:

- Measurement errors
- Data integration from contradicting sources
- Imprecise mappings between heterogeneous schemata
- Imprecise automatic process (information extraction, natural language processing, etc.)
- Imperfect human judgment
Managing this imprecision

Objective

Not to pretend this imprecision does not exist, and manage it as rigorously as possible throughout a long, automatic and human, potentially complex, process.

Especially:

- Use probabilities to represent the confidence in the data
- Query data and retrieve probabilistic results
- Allow adding, deleting, modifying data in a probabilistic way
- (If possible) Keep throughout the process lineage/provenance information, so as to ensure traceability
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Objective

Not to pretend this imprecision does not exist, and manage it as rigorously as possible throughout a long, automatic and human, potentially complex, process.

Especially:

- Use **probabilities** to represent the confidence in the data
- Query data and retrieve **probabilistic** results
- Allow adding, deleting, modifying data in a **probabilistic** way
- (If possible) Keep throughout the process **lineage/provenance** information, so as to ensure **traceability**
Extensive literature about probabilistic relational databases [DRS09, Wid05, Koc09]

Different typical querying languages: conjunctive queries vs tree-pattern queries (possibly with joins)

Cases where a tree-like model might be appropriate:
- No schema or few constraints on the schema
- Independent modules annotating freely a content warehouse
- Inherently tree-like data (e.g., mailing lists, parse trees) with naturally occurring queries involving the descendant axis

Remark
Some results can be transferred from one model to the other. In other cases, connection much trickier (see later)!
Outline

1 Motivation

2 Probabilistic XML Survey
   - Models
   - Querying
   - Other Problems of Interest

3 Challenges
1. Motivation

2. Probabilistic XML Survey
   - Models
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3. Challenges
Trees and possible worlds

Unordered data trees

Sample space: Set of all such data trees.

Probabilistic XML database: (Succinct) representation of a discrete probability distribution over this sample space (= a set of possible worlds).
Trees and possible worlds

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(multiset semantics)
Trees and possible worlds

Unordered data trees

Sample space: Set of all such data trees.

Probabilistic XML database: (Succinct) representation of a discrete probability distribution over this sample space (= a set of possible worlds).
Tree with ordinary (circles) and distributional (rectangles) nodes

Distributional nodes specify how their children can be randomly selected (here, independently or in a mutually exclusive way)

Possible-world semantics: every possible selection of children of distributional nodes, with associated probability

No long-distance probabilistic dependencies in the tree!
Types of distributional nodes [KKS08, AKSS09]

**det** all children of the node are **deterministically** selected

**ind** children of the node are chosen **independently** of one another, according to their probabilities

**mux** children of the node are chosen in a **mutually exclusive** way, depending of their probabilities, that must sum up to 1 or less

**exp** the distribution of all possible choices of children is **explicitly** given: each subset of the set of the children is associated with a probability, these probabilities summing up to 1

**Remark**

Clearly, **det** is a particular case of **ind**, and **det mux** are particular cases of **exp**. **ind** can be simulated with a hierarchy of **mux** and **exp**.
Arbitrary dependencies: event conjunctions [AS06]

Conjunctions of independent events on each node of the tree [IL84]

Expresses arbitrarily complex dependencies

Both \textit{ind} and \textit{mux} can be seen as particular cases (but not \textit{exp}!)

\begin{tabular}{ll}
\textbf{Event} & \textbf{Prob.} \\
\hline
\textit{w}_1 & 0.8 \\
\textit{w}_2 & 0.7 \\
\end{tabular}

\begin{align*}
\text{Probs:} & \quad \text{\textit{p}}_1 = 0.06 \\
& \quad \text{\textit{p}}_2 = 0.70 \\
& \quad \text{\textit{p}}_3 = 0.24
\end{align*}
Arbitrary dependencies: event conjunctions \cite{AS06}

\begin{itemize}
  \item Conjunctions of independent events on each node of the tree \cite{IL84}
  \item Expresses \textit{arbitrarily complex} dependencies
  \item Both \textit{ind} and \textit{mux} can be seen as particular cases (but not \textit{exp}!)
\end{itemize}
Events and lineage

- Event variables: can represent the **provenance** of data

- Typically:
  
  1. At each (probabilistic) update, a **new** event variable is introduced
  2. Query results are given with probabilities, but also with the **lineage** of the query [FGT08]

- Allow to keep **track**, with no additional cost, of the provenance of data!
Previously studied XML models

ProTDB [NJ02] $\text{ind} + \text{mux}$

Probabilistic XML [vKdKA05] $\text{mux} + \text{det}$, with alternation between the two kinds of nodes

SP trees [AS06], PEPX [LSC06] $\text{ind}$ without hierarchies of distributional nodes

PXML [HGS03] $\text{exp}$ without hierarchies, extended to graphs

Probabilistic interval XML [HGS07] $\text{exp}$ without hierarchies, when intervals are collapsed into points

Prob-trees [AS06, SA07] Event conjunctions
Expressiveness

Theorem ([AS06, KKS08, AKSS09])

1. ind alone, or mux alone, are not a complete representation system.
2. det $+$ mux is enough to have full expressive power. Consequently, ind $+$ mux, exp alone, or event conjunctions, have full expressive power.
3. Hierarchies (allowing a distributional node below another distributional node) are important.
Tractable reductions between models \cite{KKS08, AKSS09}

$$\text{exp} + \text{Event conjunctions}$$

$$\text{det} + \text{mux} = \text{ind} + \text{mux}$$
Tractable reductions between models \[\text{[KKS08, AKSS09]}\]

\[
\begin{align*}
\exp + \text{Event conjunctions} & \quad \longrightarrow \quad \text{Event conjunctions} \\
\exp & \quad \longrightarrow \quad \text{det + mux = ind + mux} \\
\end{align*}
\]
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Semantics of a (Boolean) query = probability:

1. Generate all possible worlds of a given probabilistic document

2. In each world, evaluate the query

3. Add up the probabilities of the worlds that make the query true

EXPTIME algorithm! Can we do better, i.e., can we apply directly the algorithm on the probabilistic document?

We shall talk about data complexity of query answering.
Semantics of a (Boolean) query = probability:

1. Generate all possible worlds of a given probabilistic document (possibly exponentially many)
2. In each world, evaluate the query
3. Add up the probabilities of the worlds that make the query true

**EXPTIME** algorithm! Can we do better, i.e., can we apply directly the algorithm on the probabilistic document?

We shall talk about data complexity of query answering.
Boolean query languages on trees

Single-path queries (SP) \(/A//B/C\) (no branching)

Tree-pattern queries (TP) \(/A[C/D]/B\)

Tree-pattern queries with joins (TPJ) for $x$ in $\text{doc}/A/C/D$

return $\text{doc}/A//B[.=x]$

Monadic second-order queries (MSO) generalization of TP, do not cover TPJ
The $\#P$ and $\text{FP}^{\#P}$ complexity classes

- A (counting) problem is in $\#P$ if there is a non-deterministic Turing machine whose number of accepting paths, given as input the input of the problem, is the output of the problem.

- A problem is $\#P$-hard if any $\#P$ problem can be $\text{PTIME}$-reduced to it (via a Karp reduction). $\#2\text{DNF}$, the problem of counting the number of assignments satisfying a formula in 2-DNF, is $\#P$-complete.

- A (computation) problem is in $\text{FP}^{\#P}$ if it is computable by a Turing machine with access to a $\#P$ oracle.

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### Complexity of query evaluation

<table>
<thead>
<tr>
<th>Local dependencies</th>
<th>Arbitrary dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>PTIME</td>
</tr>
<tr>
<td>TP</td>
<td>PTIME [KS07, KKS08, KKS09]</td>
</tr>
<tr>
<td>TPJ</td>
<td>FP(^P)-complete</td>
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<tr>
<td>MSO</td>
<td>PTIME [CKS09]</td>
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**Remark**

Project-free queries are tractable with arbitrary dependencies. [SA07]
Complexity of query evaluation

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| **TPJ** | }

Remark: Project-free queries are tractable with arbitrary dependencies. [SA07]
Bottom-up dynamic programming algorithm.
Query: /A//B

mux \ convex sum
ind \ inclusion-exclusion

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<tr>
<th></th>
<th>$A_1$</th>
<th>$\text{ind}_2$</th>
<th>$\text{mux}_3$</th>
<th>$B_4$</th>
<th>$C_5$</th>
<th>$B_6$</th>
</tr>
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<tbody>
<tr>
<td>/B</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>//B</td>
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Bottom-up dynamic programming algorithm.

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mux  convex sum
ind  inclusion-exclusion
TP PTIME for local dependencies [KS07]

Bottom-up dynamic programming algorithm.
Query: /A//B

Pr(ind$_2$ $|$ /B) = 1 − (1 − 0.8 × Pr(mux$_3$ $|$ /B)) × (1 − 0.6 × Pr(B$_6$ $|$ /B))
= 1 − (1 − 0.8 × 0.3) × (1 − 0.6) = 0.696
Bottom-up dynamic programming algorithm.

Query: /A//B

\[
\begin{array}{c|cccccc}
 & A_1 & \text{ind}_2 & \text{mux}_3 & B_4 & C_5 & B_6 \\
\hline
/B & 0 & 0.696 & 0.3 & 1 & 0 & 1 \\
//B & 0.696 & 0.696 & 0.3 & 1 & 0 & 1 \\
/A//B & 0.696 & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]

\text{mux} \quad \text{convex sum}

\text{ind} \quad \text{inclusion-exclusion}
Complications \([\text{KS07, KKS08, KKS09}]\)

General case:

- Branching patterns: need to consider all \textit{conjunctions of subbranches} of a pattern (exponentially many!)
- Works also with \textit{exp}, but more complicated inclusion-exclusion
- Number of optimizations possible
- \textbf{Bottomline:} it works because bottom-up evaluation is possible
- \textbf{Generalization} \([\text{CKS09}]\): MSO queries can be converted (non efficiently) into bottom-up tree automata, therefore MSO is also tractable
Reduction from \#2DNF. Example: $\varphi = xy \lor x\neg z \lor yz$. 

\[
\begin{array}{c}
\text{mux} \\
\text{det} \\
0 \\
1 \\
\text{mux} \\
\text{det} \\
0 \\
2 \\
\text{mux} \\
1 \\
2 \\
\end{array}
\]
Aggregate Queries: sum, count, avg, countd, min, max, etc.
Distributions? Possible values? Expected value?

Summary of results

- Computing expected values of sum and count tractable with arbitrary dependencies. Everything else intractable.
- Computing expected values of every of these aggregate functions is tractable with local dependencies.
- Computing distributions and possible values is tractable for count, min, max, intractable for the others.

Always possible to approximate query answers with Monte Carlo sampling.
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Determining the probability that a probabilistic document with local dependencies matches a schema is **tractable** (uses the transformation of schemas into bottom-up automaton).

Determining the probability that a probabilistic document with arbitrary dependencies matches a schema is **intractable**.
Updates defined by a query (cf. XUpdate, XQuery Update). Semantics: for all matches of a query, insert or delete a node in the tree at a place located by the query.

Results

- Updates are intractable with local dependencies: the result of an update can require an exponentially larger representation size.
- Insertions are tractable with arbitrary dependencies; deletions are intractable.
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Missing complexity results

- Tractable reduction from exp to arbitrary dependencies?
- Tractable reduction from exp to mux + ind?
- More systematic study of updates (different semantics: insert once if there is at least one match).
- Combined complexity results.

Work in progress with U. Oxford and U. Bozen-Bolzano
Relational case
(Block-independent disjoint model, [DS07])

- Some conjunctive queries are PTIME
- Others are \#P-hard
- Complex conditions to separate the two

XML case (Local dependencies)

- Tree pattern queries are PTIME
- Tree pattern queries with (non-trivial) joins are \#P-hard

Why does the XML case seem simpler?

Is there some insight to be gained from one case to the other?

Translating XML data and queries to the relational case yields queries with self-joins, a less well-understood setting.
Relational case (Block-independent disjoint model, [DS07])

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- Is there some insight to be gained from one case to the other?
- Translating XML data and queries to the relational case yields queries with self-joins, a less well-understood setting
Continuous probability distributions

- Most probabilistic database models assume discrete probabilistic distributions
- Sensor networks, unknown values: need for continuous distributions! (uniform, Gaussian, Poisson, etc.)
- Some existing works on query answering over continuous distributions [CKP03, DGM+04] but no clear semantics
- **Claim:** this is not more difficult than the discrete case, as long as integration/differentiation are easy (symbolically or numerically) for the considered distributions
- Discrete distributions can be modeled as Diracs

Work in progress with U. Bozen-Bolzano
Tractable extensions of the local dependency model

- Arbitrary dependencies: not tractable
- Local dependencies: not practical
- Somewhere in between?
  - What makes the arbitrary dependency model hard?
  - How can the local dependency model be generalized, while remaining tractable?
- And can we go further? cf. XML schemas
  - Trees of unbounded depth
  - Trees of unbounded width
  - Infinite trees?

Work in progress with U. Oxford
But where do probabilities come from?!

- Do the numbers assigned as probabilities in PDBMS really make sense?
- In some cases, sources of “good” probabilities:
  - Statistics
  - Conditional Random Fields
- What about the rest? Does it really make sense to model uncertainty with probabilities?
A system that just works

- Nothing else than toy systems exist for probabilistic XML
- What should it be based upon:
  - a probabilistic relational DBMS?
  - a native XML DBMS?
- Systems issue: distribution, indexing, etc.
- And need for a killer application!
  - Probabilistic content warehouse?
  - Parse trees of natural language sentences?
  - Concise representation of a large corpus of XML documents?

PhD started on this topic in October 2009
Merci.

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