Efficient Query Evaluation on Temporally Correlated Probabilistic Streams

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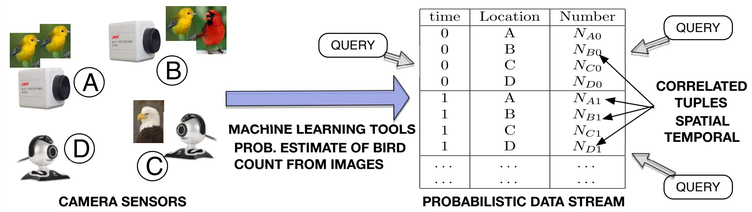
1. Motivation

Correlated probabilistic streams commonly occur in a large variety of applications.

A **Habitat Monitoring Application**



time	Location	Number
0	A	N_{A0}
0	B	N_{B0}
0	C	N_{C0}
0	D	N_{D0}
1	A	N_{A1}
1	B	N_{B1}
1	C	N_{C1}
1	D	N_{D1}
...	...	...

Problem: Execute *continuous* queries over *probabilistic streams*

Example queries:

- *What is the weekly average of the bird count at location A ?*
- *What is the likelihood that A has more birds than B for the past week ?*
- *List all days in which A has more than 100 birds*

Issues:

- Correlations significantly influence results of query evaluation
- SQL query semantics are ambiguous when results are probabilistic sequences

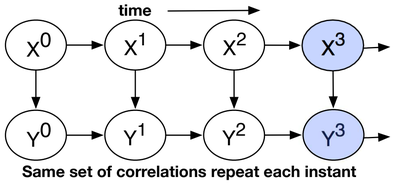
2. Previous work

- Probabilistic databases (*Mystiq, Trio, Orion, MayBMS*) focus on static data and not streams, also cannot handle these complex correlations
- *Lahar, Caldera* are applicable to probabilistic streams, but focus on pattern identification queries

3. Our Approach

Observation: Many naturally occuring probabilistic streams are both *structured* and *Markovian* in nature.

- **Structured**: Same set of correlations and independences repeat across time
- **Markovian**: The values of variables at time $t+1$ is independent of those at time $t-1$ given their values at time t



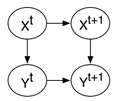
A Markov sequence as a PGM

We exploit this to:

- Design **compact, lightweight data structures** to represent and modify them
- Enable **incremental query processing** using the iterator framework

4. Markov sequence

- *Special case* of a probabilistic sequence. Completely determined by specifying successive joint distributions for all time instants $p(V_t, V_{t+1})$
- **Efficient Representation:** We represent Markov sequences using a combination of the schema graph and the actual data



t	$p(X^t)$	$p(X^{t+1}\|X^t)$	$p(Y^t\|X^t)$	$p(Y^{t+1}\|X^{t+1}, Y^t)$
1	[0.5,0.5]	[0.3,0.7,0.1,0.9]	[0.2, 0.8, 0.5, 0.5]	[0.7, 0.3, 0.6, 0.4 0.4, 0.6, 0.9, 0.1]

(a) Schema graph (b) Distributions representing the Markov sequence

- **Efficient Query Processing:** Only transmit these numbers between operators. Only operators with the knowledge of the schema can interpret these numbers.

5. Formal Semantics

Possible World Semantics (+ small modification for *sequences*)

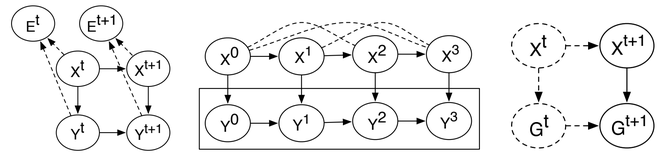
- Operators: *Select, Project, Joins, Aggregate, Windowing*
- *MAP, ML*: Convert a Markovian sequence into a deterministic sequence
- The set of Markov sequences is not closed under these operators, i.e., some operators return non-Markovian sequences (Projection, Windowing)
- *Op* is safe for input schema $I \Leftrightarrow Op(I)$ is a Markovian sequence

6. Operator Design

- **Schema routine:** Output schema is computed based on the input schema
- **get_next() routine:** Operates on each of the input data tuples to compute the output tuples.

Selection: Add new boolean random variable to each slice; Always safe

Projection: Eliminate all variables not of interest; Can be unsafe for some schemas



(a) selection (b) projection (c) aggregation

Join: Combine the schemas, concatenate the tuples; Always safe

Aggregation: Maintain the joint distribution of the aggregate variable along with the other variables in the time slice; Always safe

$$p(X^{t+1}, G^{t+1}) = \sum_{X^t, G^t} p(X^t, G^t) p(X^{t+1}|X^t) p(G^{t+1}|G^t, X^{t+1})$$

Operator Design (contd)

Windowing:

- Sliding window operator is always unsafe (We use approximations)
- For the special case when shift = window size, we can reduce the windowing operation to a projection

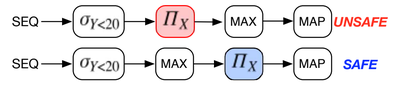
ML: Simply marginalize the joint distribution

MAP: Viterbi-style dynamic programming

7. Query Planning Algorithm

- Unsafe Operators: Projection, Window operator reduced to a projection
- Query Planning = Determining the *correct position for Projection*
- Strategy: Pull up Projection operator until it is safe. If no safe position for projection, check its parent: ML $\Rightarrow$ we can determine a safe plan, MAP $\Rightarrow$ we cannot determine a safe plan

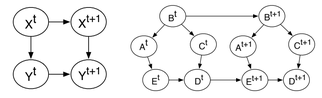
SELECT_MAP MAX(x) **FROM** S **WHERE** y < 20



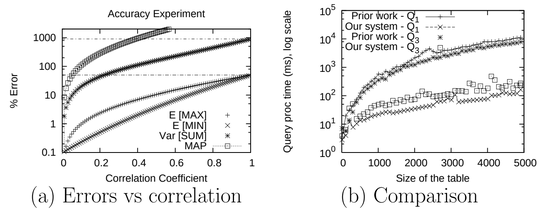
- The query planning algorithm is *sound* and *complete*

8. Results

Markov sequence generator: Generate Markov sequences for different schemas with correlations ranging from (indep., perfectly correlated)



- Capturing and reasoning about temporal correlations is critical for obtaining accurate query answers
- Our incremental operators can process up to 500 tuples per second, for domain sizes below 200
- Our get_next() query processing framework that exploits the structure in Markov sequences is much more efficient that previous generic approaches



(a) Errors vs correlation (b) Comparison

Q1: **SELECT_MAP Agg**(A) **FROM** S

Q3: **SELECT_MAP MAX**(A) **FROM** S[size,size]