Streaming Tree Automata and XPath

Olivier Gauwin

Mostrare Project

Ph.D. Defense
September 28th, 2009

supervisors: Joachim Niehren and Sophie Tison

XML

A Format for Semi-Structured Data

XML Document

```
<bib>
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    <author> Hopcroft </author>
    <author> Ullman </author>
    <title> Introduction... </title>
  </book>
  <book>
    ⋮
  </book>
  <book>
    ⋮
  </book>
</bib>
```
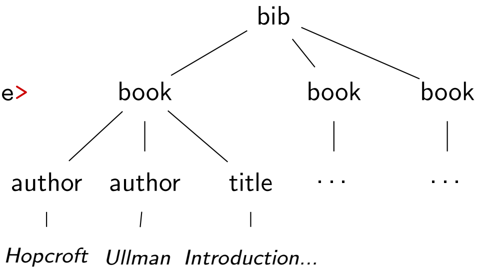

Corresponding Tree



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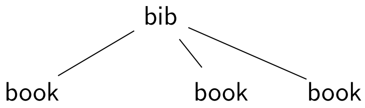

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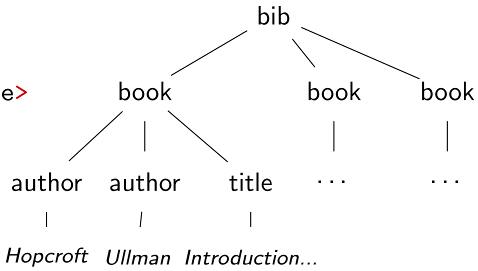

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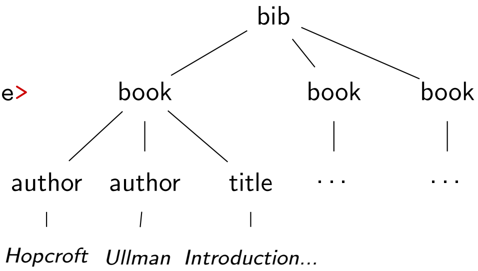

finite labeled ordered unranked trees

Streaming

- process data on-the-fly
- objective: low memory consumption (buffering)
- use cases:
  - huge data (larger than main memory)
  - natural stream sources:
    - network sockets
    - sensors
    - subscribed feeds
    - etc.

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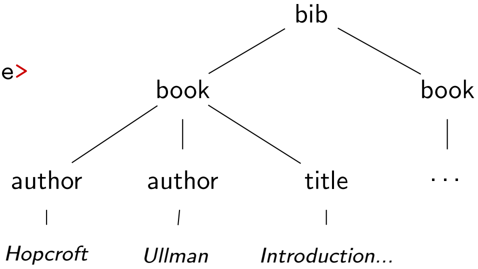

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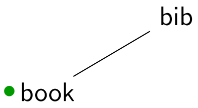

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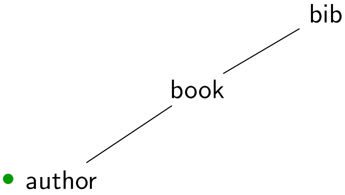

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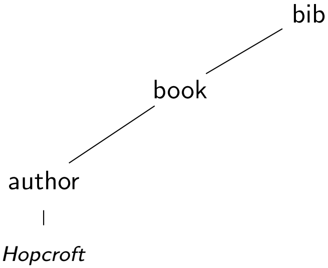

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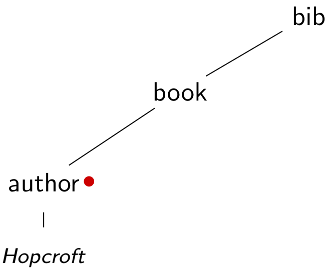

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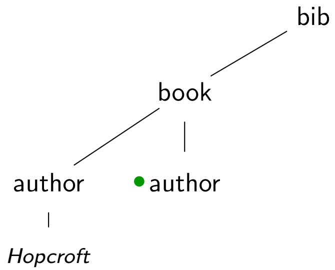

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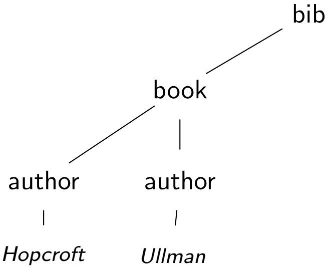

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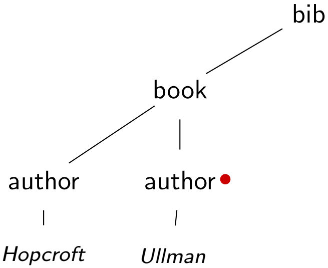

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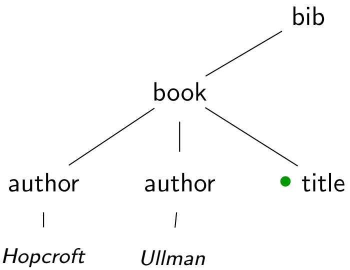

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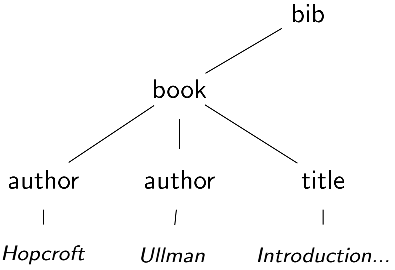

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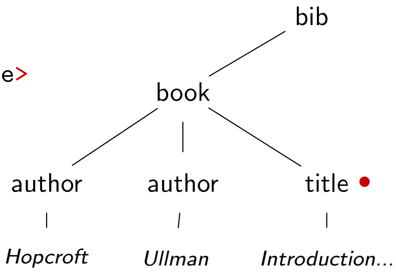

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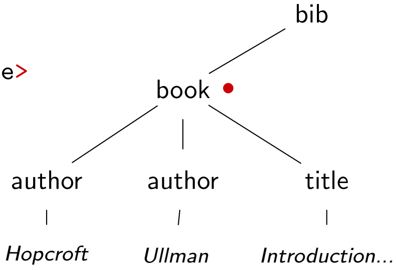

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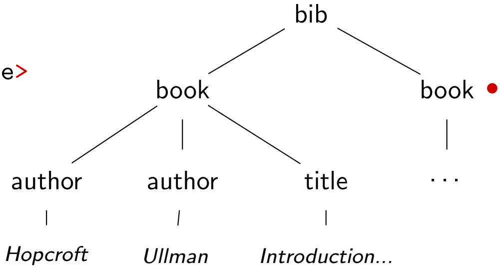

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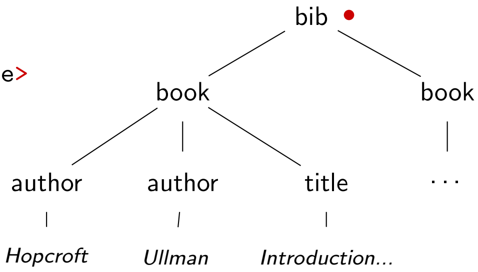
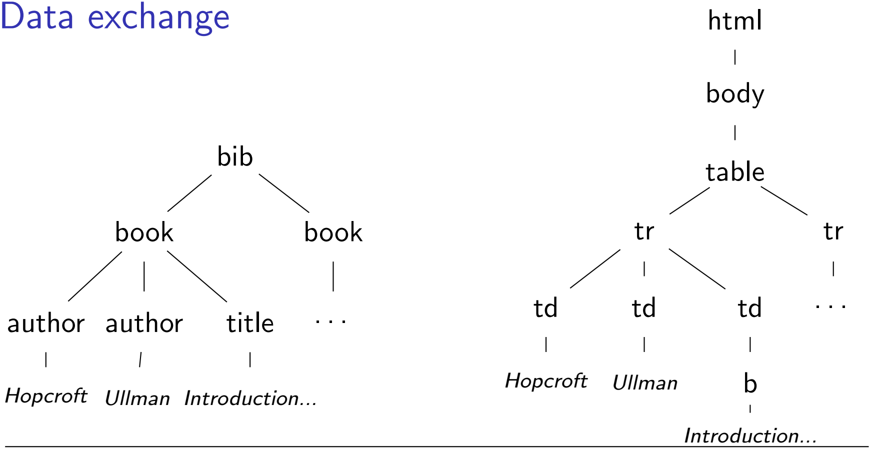


Data exchange



conform to schema 1 → conform to schema 2

- requires transformations
- usually based on selection of tuples of nodes
- via queries

Queries

Monadic Queries

we only deal with monadic queries ($n = 1$) in this talk, i.e.:

$$Q(t) \subseteq nod(t)$$

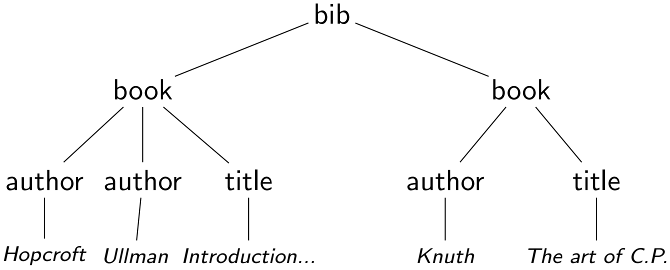
For clarity, we ignore schemas.

Studied Query Classes

- XPath
- Queries by Automata

XPath

- W3C query language for XML documents
- navigational language



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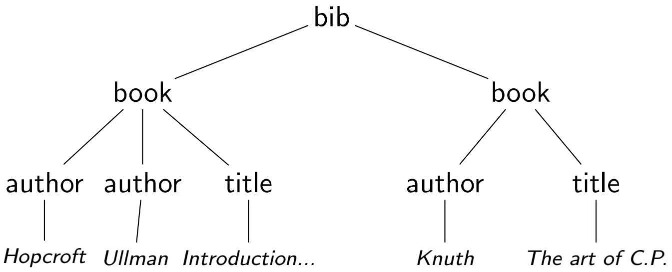

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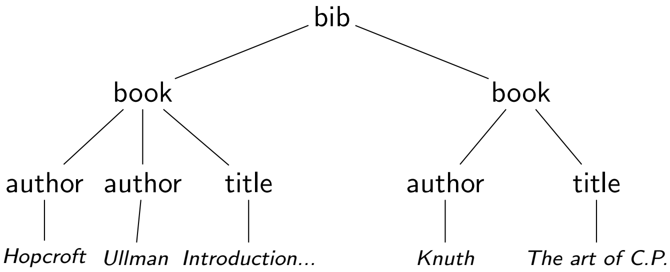

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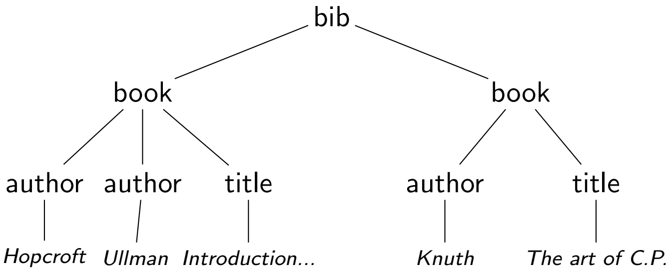

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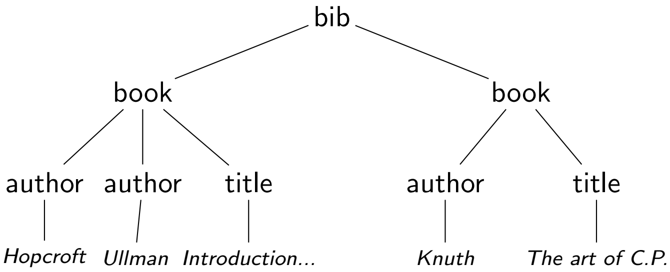

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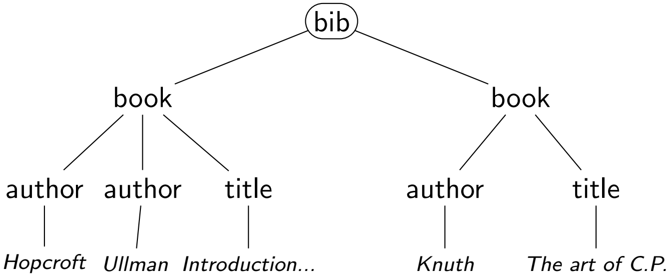

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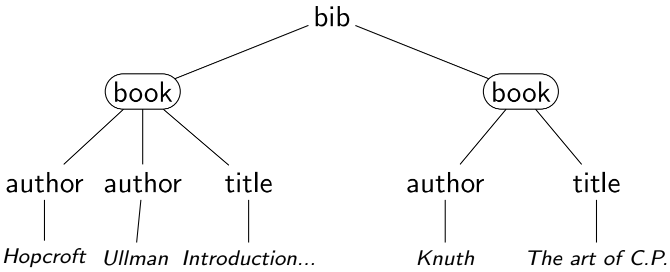

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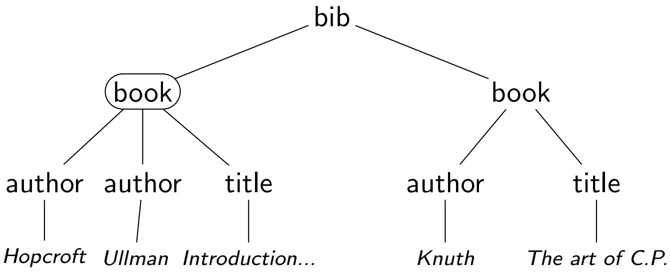

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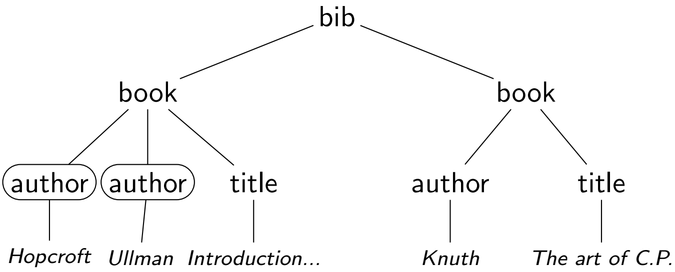

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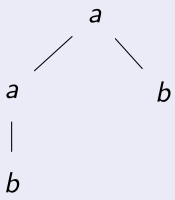
XPath fragments

- Core XPath : navigational core (no data values)
- Forward XPath : Core XPath restricted to forward axes
- Downward XPath : Core XPath restricted to axes *ch*, ch^*

Queries by Automata

Canonical trees

$t =$ 

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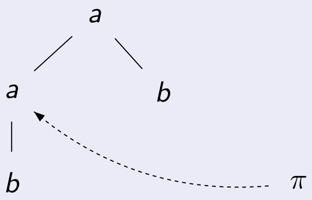

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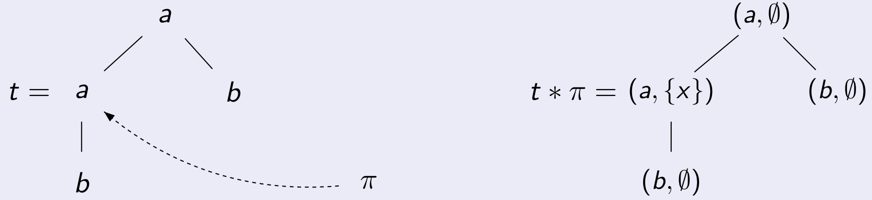

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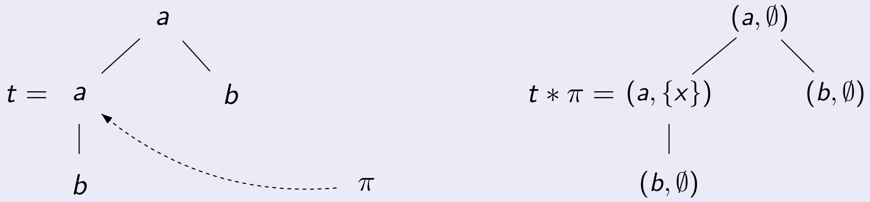

Canonical language

- A monadic query Q defines the tree language $L_Q = \{t * \pi \mid \pi \in Q(t)\}$
- A language L of canonical trees defines the query $Q(t)$ such that $\pi \in Q(t)$ iff $t * \pi \in L$

A tree automaton over $\Sigma \times 2^{\{x\}}$ recognizing canonical trees defines a query over Σ.

Querying XML Streams

Example: co-authors of Hopcroft

XML stream	Buffers	Actions
<bib>$_1$		

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  - new measure: *m-Streamability*
  - hardness results for queries by automata and XPath
  - *Bounded Concurrency and Delay* (not presented here)

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  - *k-Downward XPath*: a streamable fragment of XPath

Buffering Requirements

of query answering algorithms over XML streams

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    - for Positive Core XPath, there is no streaming algorithm using bounded buffering, even on non-recursive documents (Benedikt, Jeffrey 07)
    - $O(1)$ is impossible for co-authors of Hopcroft

Concurrency

(Bar-Yossef, Fontoura, Josifovski 05)

Alive nodes

A node π of t is alive for Q at event η if:

- there is a continuation t' of t after η s.t. $\pi \in Q(t')$
- there is a continuation t'' of t after η s.t. $\pi \notin Q(t'')$

Concurrency

The concurrency of Q wrt t is the maximal number of simultaneous alive nodes.

Concurrency

Example

Query Q: co-authors of Hopcroft

	XML stream	Alive nodes
	<bib>$_1$	
	<book>$_2$	
	<author>$_3$	3
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The concurrency of Q wrt t is 2.

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Concurrency

A space lower bound?

The concurrency was known to be a lower bound on a very special case.

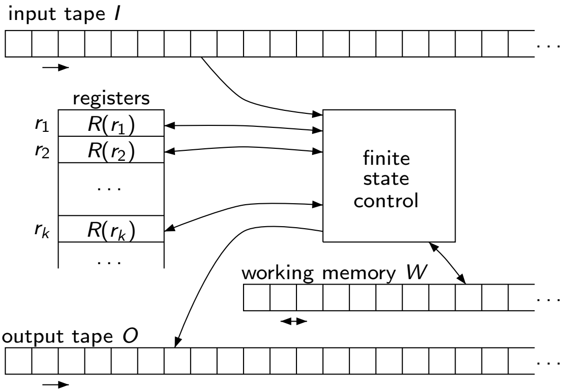
Theorem (Bar-Yossef, Fontoura, Josifovski 05)

Let t be a non-recursive tree, Q a query in Downward XPath without wildcard, and c the close-concurrency of Q wrt t. Then there is a tree t' similar to t for which evaluating Q requires space at least c.

Is concurrency a lower bound for all query answering algorithms on XML streams?

- in general no, due to possible compaction of buffered candidates
- in known algorithms yes

Streaming Random Access Machines (SRAMs)



- node identifiers are stored in registers, and unknown from controller
  - this avoids compaction tricks
- space used = number of registers + used working memory

Streaming Random Access Machines (SRAMs)

Theorem

Concurrency is a space lower bound for queries computed by SRAMs.

Deciding Bounded Concurrency

Hardness results

$$\underbrace{\exists k.\ \forall t.\ \text{concurrency of } Q \text{ on } t \leq k}_{\text{bounded concurrency}} \quad \Rightarrow \quad \text{bounded buffering is possible}$$

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Hard queries

$$all(Q) = /self::*[lastchild::*[Q]]/ch::*$$

Given a query class $\mathcal{Q}$ for which *all* and *not* can be defined in polynomial time, deciding whether a query has bounded concurrency is harder than universality of the corresponding Boolean query.

Consequences

- coNP-hard for Downward XPath
- EXPTIME-hard for queries by non-deterministic automata

Deciding Bounded Concurrency

Positive results

Theorem

For queries defined by deterministic Streaming Tree Automata:

- *deciding bounded concurrency is in* PTIME
- *deciding k-bounded concurrency is in* PTIME *when k is fixed*

Similar results for bounded delay.

This result is obtained through properties of recognizable relations over unranked trees, and a reduction to bounded valuedness of transducers (SEIDL 92).

Bounded vs Unbounded Concurrency

We also want to deal with queries with unbounded concurrency:

- on real documents, concurrency may be bounded, even though not specified in schemas (e.g. co-authors)
- concurrency may be large for some trees, and small for others

Towards a Measure of Streamability

- Space and time restrictions
  - time also has to be considered:
  - deciding aliveness of a node at a given event is often computationally hard
    - ⋆ coNP-hard for Downward XPath,
    - ⋆ EXPTIME-hard for queries by automata
- Streamability concerns query classes, not queries
  - a query class $\mathcal{Q}$ is a set of query definitions $e \in \mathcal{Q}$ with size $|e| \geq 1$ and defining queries Q_e
  - for instance: XPath expressions, automata, etc.

Streamability

Definition

Let $m \in \mathbb{N} \cup \{\infty\}$. A query class $\mathcal{Q}$ is m-streamable iff

there exists a polynomial p such that for all $e \in \mathcal{Q}$:

- an SRAM $\mathcal{M}_e$ computing Q_e can be built in time $p(|e|)$
- for all trees t with $concur_{Q_e}(t) \leq m$:

  $\mathcal{M}_e$ uses per event space and time in $p(|e|)$

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0-streamable $\supseteq$ 1-streamable $\supseteq$ 2-streamable $\supseteq \ldots \supseteq$ ∞-streamable

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∞-streamability vs finite streamability

$\mathcal{Q}$ is ∞-streamable iff:

- $\mathcal{Q}$ is m-streamable for all $m \in \mathbb{N}$ (with the same polynomial p) and
- $\mathcal{Q}$ has polynomially bounded concurrency, i.e., there is a polynomial p' s.t. $\forall e \in \mathcal{Q}$, $\forall t$, $concur_{Q_e}(t) \leq p'(|e|)$

Hardness of Streamability

Theorem

If $\mathcal{Q}$ is a query class such that:

1. *queries $all(Q_e)$ can be defined in* $\text{P}\small{\text{TIME}}$ *in* $|e|$
2. *membership $a \in L_{[Q_e]}$ can be tested in* $\text{P}\small{\text{TIME}}$ *in* $|e|$
3. *$\mathcal{Q}$ is 0-streamable*

then universality of Boolean queries $\{[Q_e] \mid e \in \mathcal{Q}$ descending$\}$ can be solved in $\text{P}\small{\text{TIME}}$.

$all(Q) = /self::*[lastchild::*[Q]]/ch::*$

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Consequences

- Forward XPath is not 0-streamable except if P=NP.
- queries by automata are not 0-streamable.

Positive results?

Question

Are there streamable and expressive fragments of XPath and automata?

Streamability of Queries by Automata

- non-deterministic automata are not 0-streamable

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- automata will be evaluated according to pre-order traversal of trees
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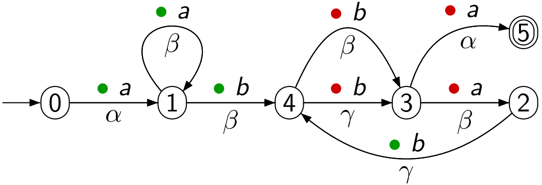
Streamability of Queries by Automata

- non-deterministic automata are not 0-streamable
- automata will be evaluated according to pre-order traversal of trees
  - we use the corresponding notion of determinism
  - we define Streaming Tree Automata, a variant of:
    - Pushdown Forest Automata (Neumann, Seidl 98)
    - Visibly Pushdown Automata (Alur, Madhusudan 04)
    - Nested Word Automata (Alur 07)
    - etc.

Streaming Tree Automata (STAs)



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and $stat_e = \{0, 1, 2, 3, 4, 5\}$
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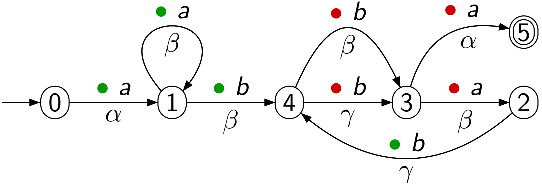

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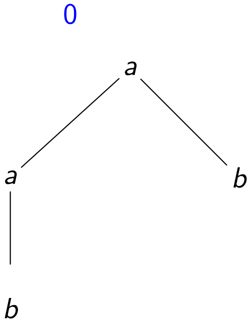

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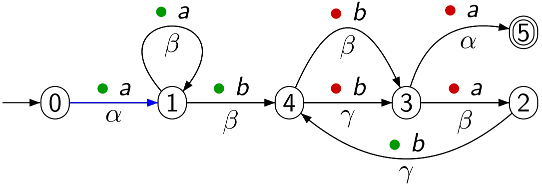

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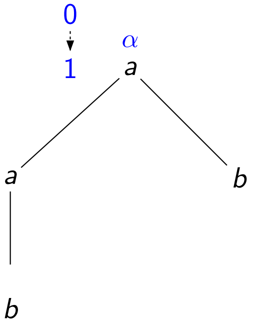

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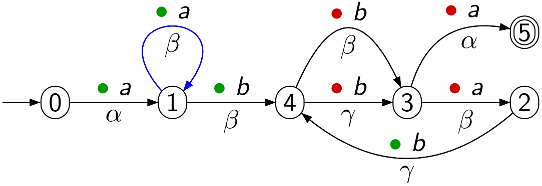

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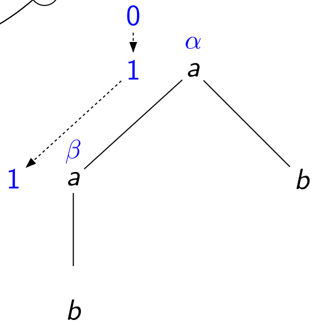

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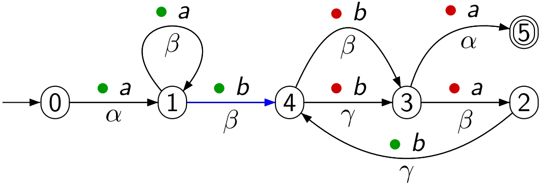

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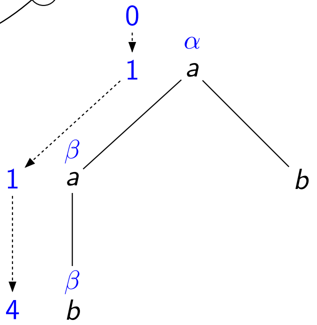

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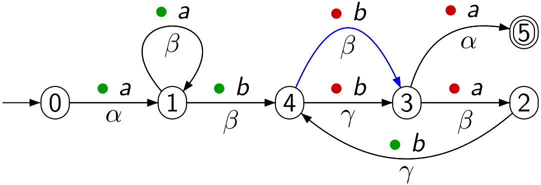

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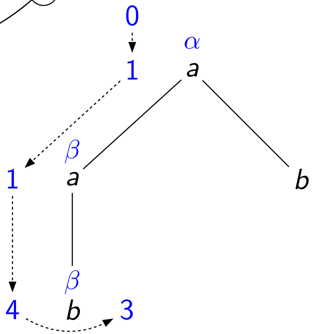

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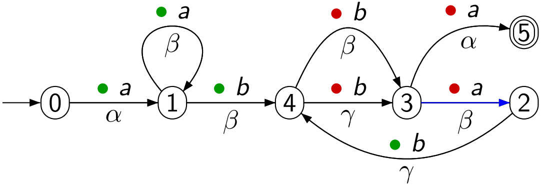

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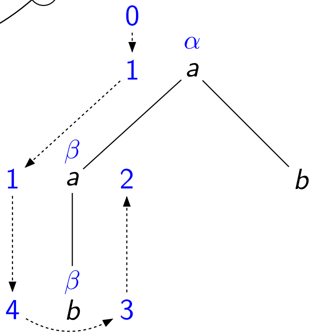

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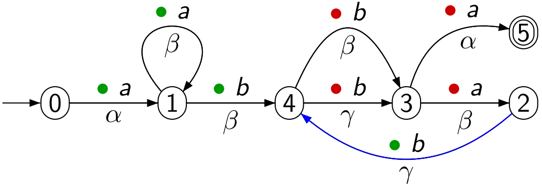

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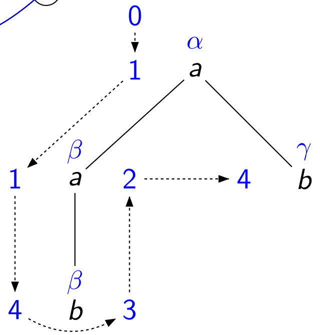

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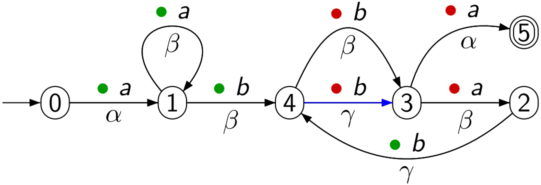

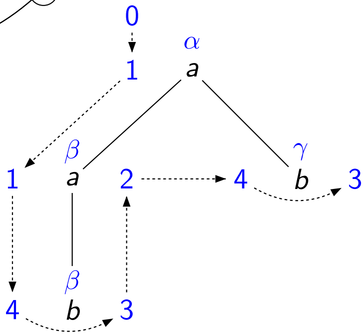

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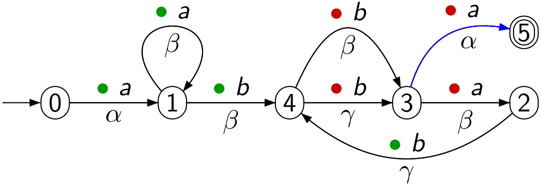

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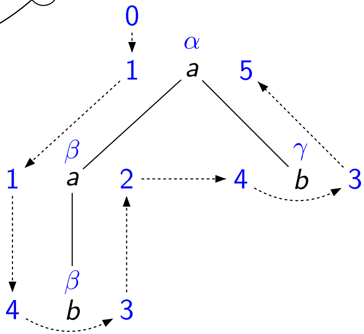

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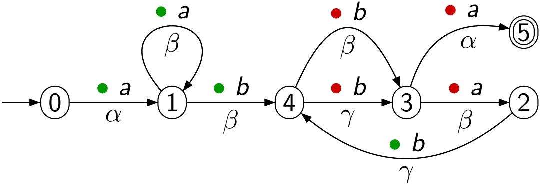

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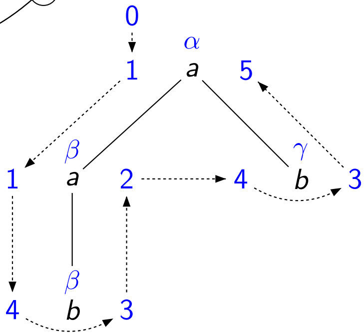

Deterministic STAs (dSTAs) respect the streaming order.

Streamability of Queries by dSTAs

Theorem

The class $\mathcal{Q}^{\delta}_{\text{dSTAs}}$ of queries defined by dSTAs on trees of depth at most δ is m-streamable for all $m \geq 0$.

- proved using an Earliest Query Answering algorithm
- $\mathcal{Q}^{\delta}_{\text{dSTAs}}$ is not ∞-streamable

Earliest Query Answering (EQA)

EQA algorithms:

- output selected nodes as soon as possible
- reject nodes that are not selected as soon as possible

In other words: only keep alive nodes in memory.

E_A: an STA for detecting sufficiency

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- ...but not for STAs: it depends on the context (i.e. the stack)
- dynamic computation of safe states for selection and rejection

EQA for Queries by dSTAs

Problem: E_A has size exponential in $|A|$

- and we want a $\textsc{Ptime}$ algorithm

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- safe states are updated at every event in $\textsc{Ptime}$
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Complexity

- PTIME precomputation
- PTIME per event and per alive node
- space = concurrency (alive nodes) + depth (stack)

$\rightarrow \mathcal{Q}^{\delta}_{\text{dSTAs}}$ is m-streamable for all $m \geq 0$.

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- the usual XPath $\rightarrow$ deterministic automata translation is doubly exponential (VARDI, WOLPER 94), (LIBKIN, SIRANGELO 08)

k-Downward XPath

=Downward XPath with the additional restrictions:

1. the total number of filters $[\ldots]$ is bounded by $k \geq 0$
2. all steps with ch^* have a label test (i.e. no $ch^*::*$)
3. if $ch^*::a$ appears, then no a-descendant of an a-node
4. bound on the depth of valid trees

PTIME Translation of k-Downward XPath to dSTAs

by induction on the structure of k-Downward XPath expressions

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Thanks to the restrictions, all steps preserve determinism, and the construction is in PTIME.

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k-Downward XPath (G., Niehren 09)	✓	✓	×	✓
Strict Backward XUntil (Benedikt, Jeffrey 07)	✓	✓	✓	×

etc.

Conclusion

Main contributions

Streamability

- SRAMs model for query answering algorithms on streams
- Streamability measure
  - Hardness results
- Testing bounded concurrency
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Streamable fragments

- Queries by deterministic STAs (IPL'08)
  - Earliest Query Answering algorithm (FCT'09)
- *k*-Downward XPath

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Thank you