XML typing

MPRI 2.26.2: Web Data Management

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[a] Based on slides from the Webdam book by Serge Abiteboul, Ioana Manolescu, Philippe Rigaux, Marie-Christine Rousset, Pierre Senellart
`https://webdam.inria.fr/Jorge/files/TypingXML.ppt`

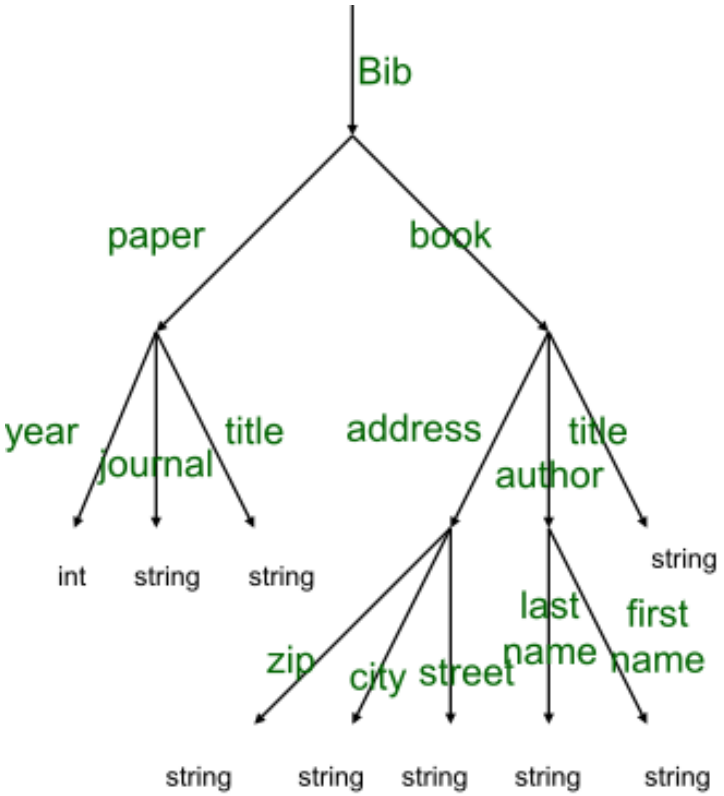
Introduction

XML typing

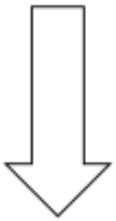
- XML documents must be well-formed
- However, typing is not required
- Why typing?
  - Formal specification of a format
  - Ensure interoperability between programs
  - Automatically detect bugs when generating
  - Make it easier to author a document
  - Make it easier to query it
  - Avoid introducing errors when updating
  - Make querying more efficient
- Many languages!

  `https://en.wikipedia.org/wiki/List_of_types_of_XML_schemas`

Improving storage




```
select X.title
from   Bib._ X
where X.*.zip = “12345”
```



```
select X.title
from   Bib.book X
where X.address.zip = “12345”
```

Verification

- Easy: when data is produced/received, check the schema at runtime
- Hard: verify statically that a program will always produce valid output
- Explored in the Cduce language `http://www.cduce.org/`
- Applicable to programs, to queries in XQuery, to XSLT, etc.

Verification example

```
for $p in doc("parts.xml")//part[color="red"]
return <part>
<name>{$p/name/text()}</name>
<desc>{$p/desc/node()}</desc>
</part>
```

- The type of the result will be:
  `(part (name (string) desc (any) )*`
- If the type of `parts.xml//part/desc` is `string`
  then the type will be:
  `(part (name (string) desc (string) )*`

Generating complicated types

```
for $x in $d/*, $y in $d/*
return <b/>
```

- When we run this on an input document of the form $(\texttt{<a/>})^n$ it will produce $(\texttt{<b/>})^{n^2}$
- No hope to describe this as a reasonable type

DTDs

Type declaration

- The simplest (and oldest) typing mechanism is based on *Document Type Definitions* (DTD).
- A DTD may be specified in the prologue with the keyword DOCTYPE using an ad hoc syntax.
- Note: the DTD is not itself an XML document

Example of an XML document with its DTD

```
<?xml version="1.0" standalone="yes" ?>
<!DOCTYPE email [
  <!ELEMENT email ( header, body )>
  <!ELEMENT header ( from, to, cc? )>
  <!ELEMENT to (#PCDATA)>
  <!ELEMENT from (#PCDATA)>
  <!ELEMENT cc (#PCDATA)>
  <!ELEMENT body (paragraph*) >
  <!ELEMENT paragraph (#PCDATA)> ]>
<email>
   <header>
     <from> af@abc.com </from>
     <to> zd@ugh.com </to>
   </header>
   <body></body>
</email>
```

Document Type Definition

A DTD may also be specified externally using an URI:

```
<!DOCTYPE docname SYSTEM "DTD-URI" [local-declarations]>
```

Some DTDs have established public identifiers:

```
<?xml version="1.0" encoding="utf-8"?>
<!DOCTYPE html PUBLIC
    "-//W3C//DTD XHTML 1.0 Transitional//EN"
    "http://www.w3.org/TR/xhtml1/DTD/xhtml1-transitional.dtd">
```

Simple declarations in a DTD

Declaring an empty element:

```
<!ELEMENT br EMPTY>
```

Declaring an element containing text:

```
<!ELEMENT from (#PCDATA)>
```

Declaring an element containing anything:

```
<!ELEMENT from ANY>
```

Declaring an element containing text or some elements among a list:

```
<!ELEMENT from (#PCDATA | a1 | a2 | a3)*>
```

Note: there can be only one declaration per element name!

More complex declarations in a DTD

Declaring an element with complex content:

```
<!ELEMENT complex (E)>
```

where *E* is a deterministic regular expression built with:

- `,`: concatenation
- `|`: or
- `?`: 0 or 1 occurrence
- `*`: arbitrary number of occurrences
- `+`: non-zero number of occurrences

Whitespace that shouldn't exist is ignored

Deterministic regexp

- To make validation easier, the regexp must be deterministic: while matching any word of element names, there must never be any choice in how to continue
- More formally: for any position in the regexp and element name, there must be at most one position where we can go
- Non-deterministic examples: `(e1 e2 | e1 e3)` or `e1? e1`

Deterministic regexp

- To make validation easier, the regexp must be deterministic: while matching any word of element names, there must never be any choice in how to continue
- More formally: for any position in the regexp and element name, there must be at most one position where we can go
- Non-deterministic examples: `(e1 e2 | e1 e3)` or `e1? e1`
- Some regular languages have no deterministic regular expressions, e.g., `(a|b)* a (a|b)`, see Bruggemann-Klein and Wood, *One-Unambiguous Regular Languages*, I&C 1998. `https://core.ac.uk/download/pdf/82738828.pdf`
- We can test in linear time if a regular expression is deterministic: see Groz, Maneth, and Staworko, *Deterministic Regular Expressions in Linear Time*, PODS 2012. `https://hal.inria.fr/inria-00618451/document`

Attributes

Declaring an attribute `att` on element `elt`:

```
<!ATTLIST element attribute type default>
```

The `type` can be one of the following (non-exhaustive):

- `CDATA`: anything
- `v1 | v2 | ... | vn`: one of these values (XML tokens)
- `ID`: a (unique) XML ID (at most one such attribute per element)
- `IDREF`: a reference to some ID value

The `default` can be:

- `"value"` Some default value (so the attribute is optional)
- `#IMPLIED` saying that the attribute is optional (no default)
- `#REQUIRED` saying that the attribute is required
- `#FIXED "value"`

Entities

DTDs allow us to define entities (like macros):

```
<!ENTITY author "John Doe">
```

and then to refer to them in the XML:

```
  &author;
```

There are also mechanisms for external entities.

External DTDs

The use of external DTDs poses some problems:

- We may be offline
- They may be down
- Fetching them causes loss of privacy

If we do not want to access the external DTD, we:

- Cannot validate the document (duh)
- Cannot replace entities defined in the DTD
- Cannot know about default attribute values

XML Schema

Key points of XML Schema (XSD for XML Schema Definition))

- More recent and more expressive than the DTD standard
- More complex
- Support for namespaces
- Constraints on data types, e.g., dates, numbers, etc. (19 primitive types)
- May have multiple definitions for the same element in different contexts
- More powerful uniqueness constraints (can be scoped to part of the document)
- An XML schema is an XML document so there is an XML Schema schema:
  `https://www.w3.org/2009/XMLSchema/XMLSchema.xsd`
- In XSD 1.1, assertions with XPath expressions

Example of XML Schema

```
<xsd:schema xmlns:xsd="http://www.w3.org/2001/XMLSchema">
<xsd:element name="book">
  <xsd:complexType>
    <xsd:sequence>
      <xsd:element name="title" type="xsd:string"/>
      <xsd:element name="author" type="xsd:string"/>
      <xsd:element name="character" minOccurs="0" maxOccurs="unbounded">
        <xsd:complexType>
          <xsd:sequence>
            <xsd:element name="name" type="xsd:string"/>
            <xsd:element name="friend-of" type="xsd:string"
                minOccurs="0" maxOccurs="unbounded"/>
            <xsd:element name="since" type="xsd:date"/>
            <xsd:element name="qualification" type="xsd:string"/>
          </xsd:sequence>
        </xsd:complexType>
      </xsd:element>
    </xsd:sequence>
    <xsd:attribute name="isbn" type="xsd:string"/>
  </xsd:complexType>
</xsd:element>
</xsd:schema>
```

XML Schema simple types

- Built-in types: `string`, `integer`, `date`, `time`, ...
- Modifying basic types, e.g.:

```
<element name="age">
  <simpleType>
    <restriction base="integer">
      <minInclusive value="0"/>
      <maxInclusive value="150"/>
    </restriction>
  </simpleType>
</element>
```

  Also: enumeration of values, patterns, length, etc.

→ These simple types are used for attributes and for elements that contain only text

More XML Schema features

- `all`: we must have all elements but in an arbitrary order

```
<element name="person">
  <complexType>
    <all>
      <element name="firstname" type="string"/>
      <element name="lastname" type="string"/>
    </all>
  </complexType>
</element>
```

- Giving names to types and reusing them afterwards:

```
<complexType name="mytype">
  ...
</complexType>
<element name="myelt" type="mytype" />
```

- Assertions using XPath

More XML Schema features (2)

- Groups of elements and attributes
- `any` and `anyAttribute` to allow anything
- Substitution groups to indicate that an element can be substituted for another
- Including an existing schema (possibly in a different namespace)

```
<include schemaLocation="http://..." />
<import namespace="http://..."
    schemaLocation="http://..." />
```

- Redefining an existing schema:

```
<redefine schemaLocation="http://...">
  ...
</redefine>
```

XML Schema vs DTD

```
<!ELEMENT note
    (to, from, heading, body)>
<!ELEMENT to (#PCDATA)>
<!ELEMENT from (#PCDATA)>
<!ELEMENT heading (#PCDATA)>
<!ELEMENT body (#PCDATA)>
```

```
<?xml version="1.0"?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:element name="note">
    <xs:complexType>
      <xs:sequence>
        <xs:element name="to" type="xs:string"/>
        <xs:element name="from" type="xs:string"/>
        <xs:element name="heading" type="xs:string"/>
        <xs:element name="body" type="xs:string"/>
      </xs:sequence>
    </xs:complexType>
  </xs:element>
</xs:schema>
```

Criticism of XML Schema

- Very complex: 461 pages
- Extremely verbose
- Some unexpected shortcomings: no simple way to say what the root element must be
- Not sufficiently expressive, in particular not self-describing
- Still requires deterministic regular expressions

Beyond XML Schema

- Relax NG:
  - Simpler than XML Schema
  - More minimalistic default types
  - No way to specify a document's schema within the document
  - No way to add default values
  - No determinism requirement
- Schematron:
  - Different approach: list of rules that the document must pass
  - Can be used in conjunction with DTD/XSD/RelaxNG
- Many possible choices!

  `https://en.wikipedia.org/wiki/XML_schema#Languages`

RELAX NG example

```
<grammar xmlns="http://relaxng.org/ns/structure/1.0">
   <start>
      <element name="book">
         <oneOrMore>
            <ref name="page"/>
         </oneOrMore>
      </element>
   </start>
   <define name="page">
      <element name="page">
         <text/>
      </element>
   </define>
</grammar>
```

Also a short syntax:

```
start = element book { page+ }
page = element page { text }
```

Schematron example

```
<?xml version="1.0" encoding="UTF-8"?>
<sch:schema xmlns:sch="http://www.ascc.net/xml/schematron">
<sch:pattern name="Check structure">
<sch:rule context="Person">
  <sch:assert test="@Title">Person must have Title attribute</sch:assert>
  <sch:assert test="count(*)=2 and count(Name)=1 and count(Gender)=1">
    The element Person should have the child elements Name and Gender.
  </sch:assert>
  <sch:assert test="*[1] = Name">Name must be first.</sch:assert>
</sch:rule>
</sch:pattern>
<sch:pattern name="Check co-occurrence constraints">
<sch:rule context="Person">
  <sch:assert test="(@Title='Mr' and Gender='Male') or @Title!='Mr'">
    If the Title is "Mr" then the gender of the person must be "Male".
  </sch:assert>
</sch:rule>
</sch:pattern>
</sch:schema>
```

Tree automata

General presentation

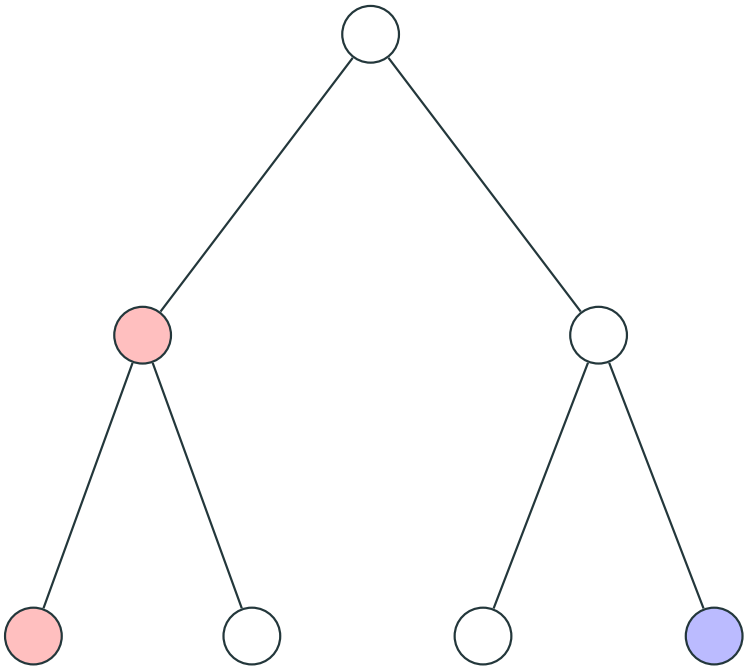
- Tree automata generalize word automata
- Remember that a deterministic word automaton A specifies:
  - An alphabet Σ of labels
  - A set Q of states
  - An initial state $q_0 \in Q$
  - A set $F \subseteq Q$ of final states
  - A transition function $\delta : Q \times \Sigma \to Q$

Automaton reminders

- The automaton can be:
  - deterministic: the transition function δ is a function
  - non-deterministic: δ is a relation $\subseteq Q \times \Sigma \times Q$;
    we may also have ϵ-transitions
- We can determinize automata but at the cost of an exponential blowup
- Some languages, e.g., $\{a^n b^n \mid n \in \mathbb{N}\}$, cannot be recognized by a finite word automaton

Bottom-up tree automata

Alphabet Σ: 



Bottom-up tree automata

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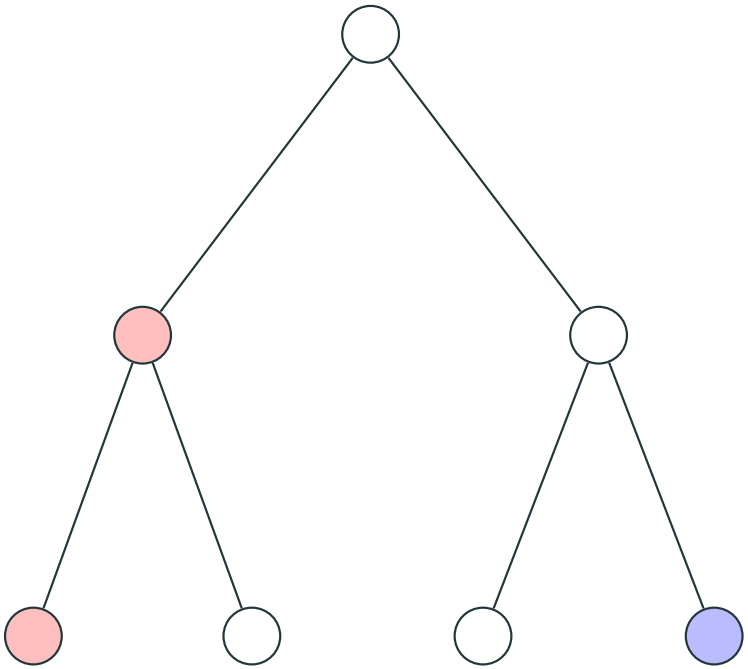

- Bottom-up deterministic tree automaton

Bottom-up tree automata

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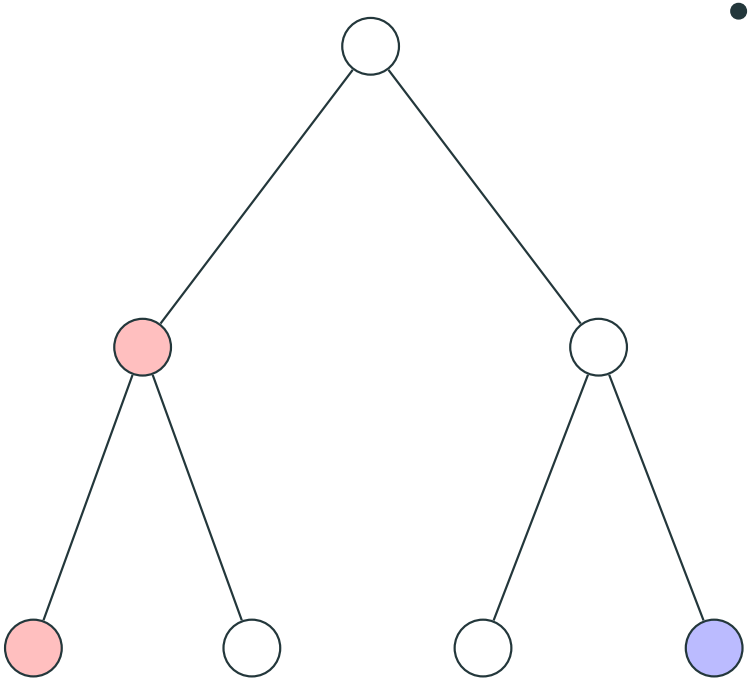

- Bottom-up deterministic tree automaton
- States Q: $\{\bot, B, P, \top\}$

Bottom-up tree automata

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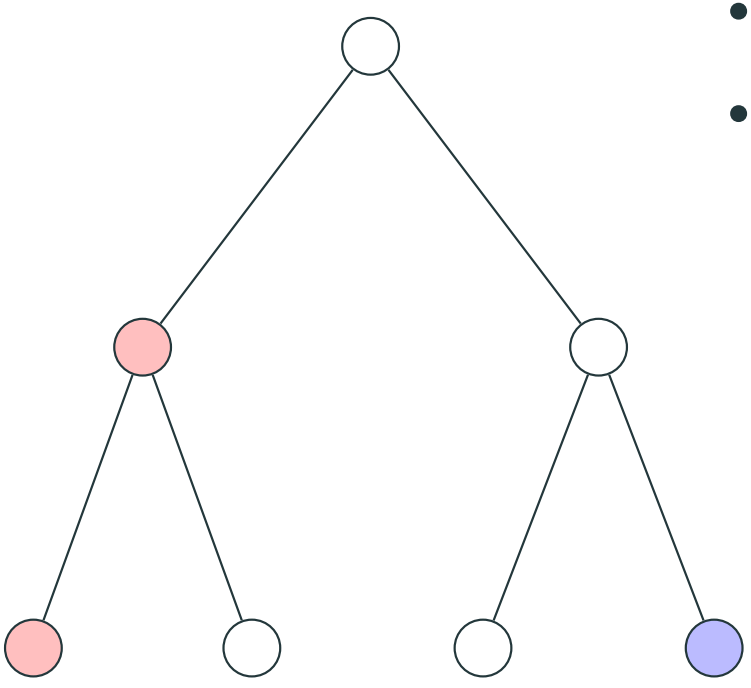

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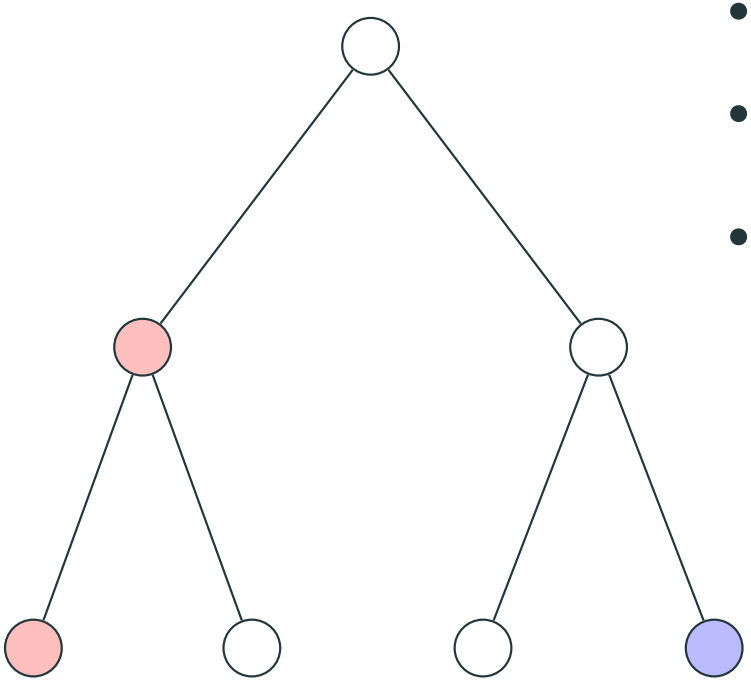
- Final states $F \subseteq Q$: $\{\top\}$

Bottom-up tree automata

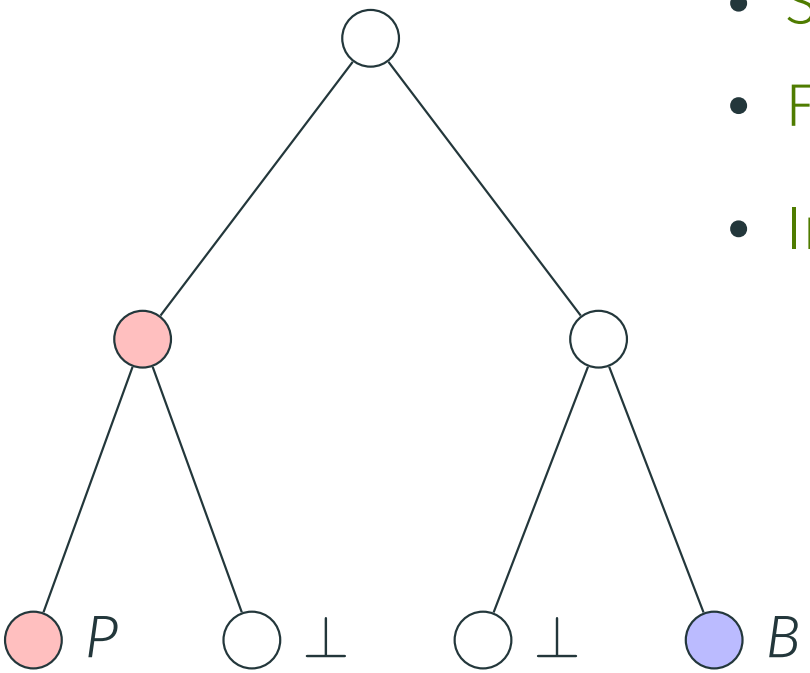
Alphabet Σ: ◯ ● ●



- Bottom-up deterministic tree automaton
- States Q: $\{\bot, B, P, \top\}$
- Final states $F \subseteq Q$: $\{\top\}$
- Initial function ι: ◯ $\bot$ ● P ● B

Bottom-up tree automata

Alphabet Σ: ○ ● ●



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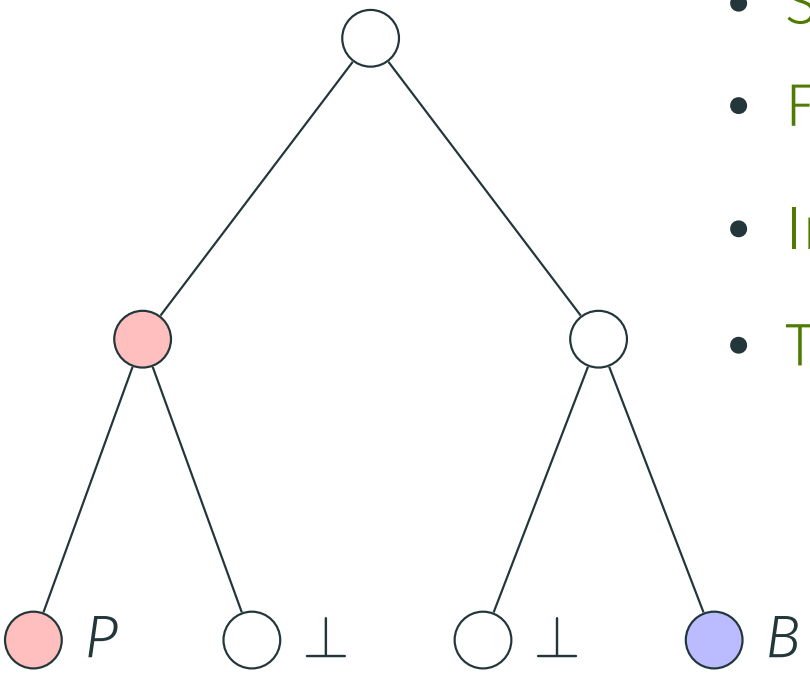

- Bottom-up deterministic tree automaton
- States Q: $\{\bot, B, P, \top\}$
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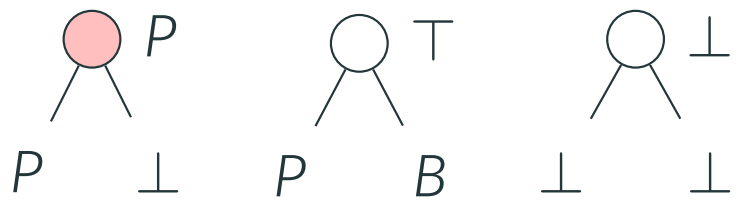
- Transitions δ (examples):



Bottom-up tree automata

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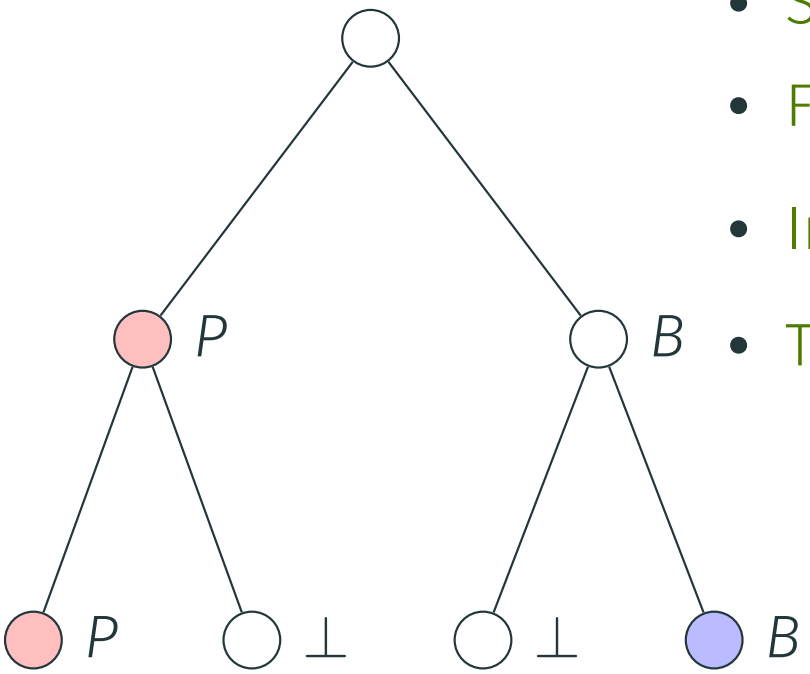

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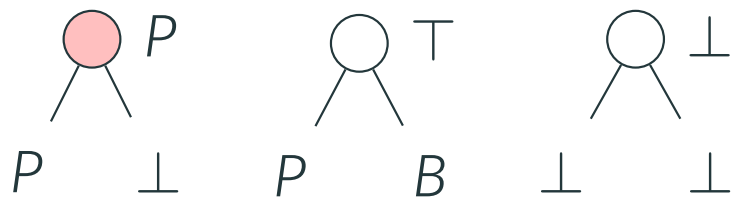

Bottom-up tree automata

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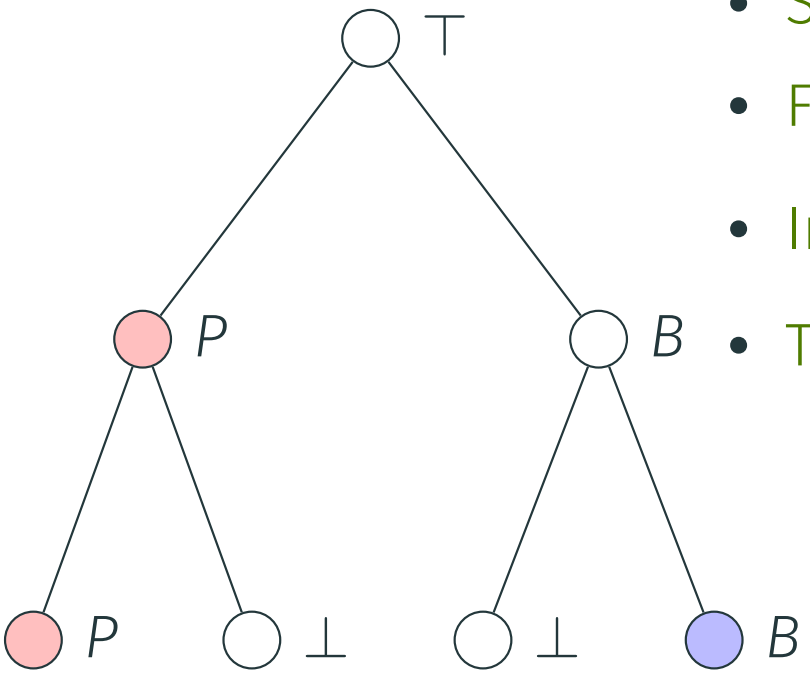

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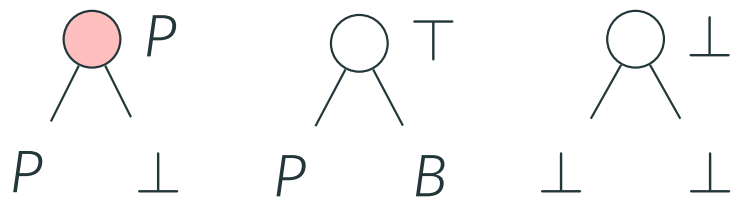

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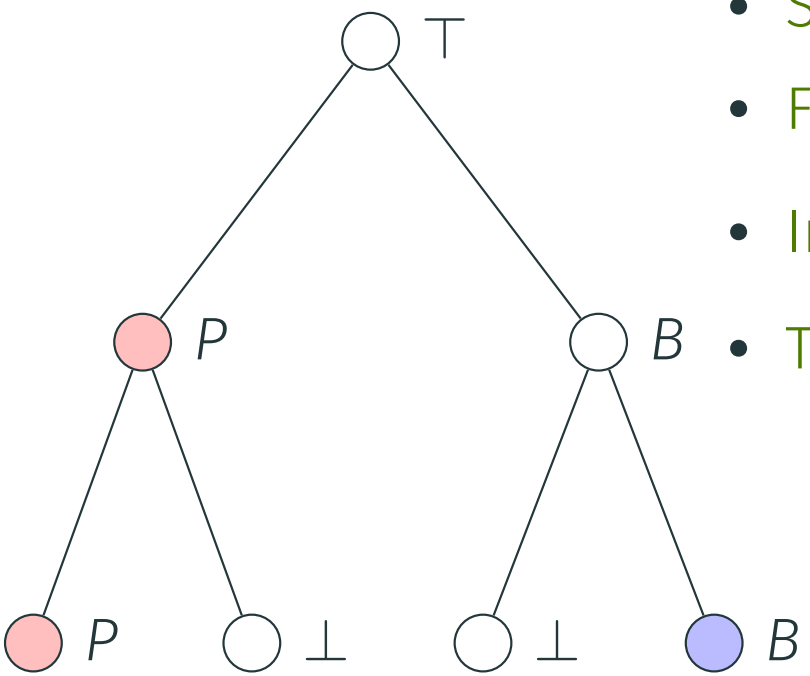

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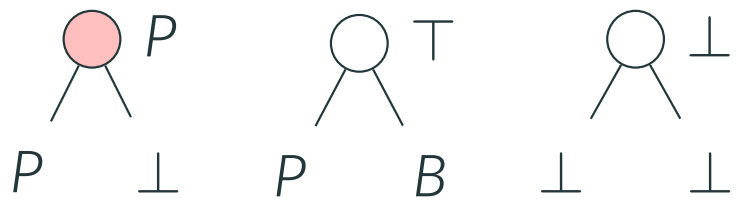


The automaton is...

- deterministic if δ is a function: $\delta : Q^2 \times \Sigma \to Q$
- non-deterministic if δ is a relation: $\delta \subseteq Q^2 \times \Sigma \times Q$

$\to$ Determinization for bottom-up tree automata (exp blowup).

Example: Boolean (tree) circuit evaluation

- Alphabet: $\Sigma = \{0, 1, \wedge, \vee\}$
- States: $Q = \{q_0, q_1\}$
- Final states: $F = \{q_1\}$
- Initial function:
  - $\iota(0) := q_0$
  - $\iota(1) := q_1$
- Transition function:
  - $\delta(q_i, q_j, \wedge) := q_{i \wedge j}$
  - $\delta(q_i, q_j, \vee) := q_{i \vee j}$

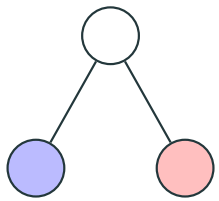
Top-down deterministic tree automata

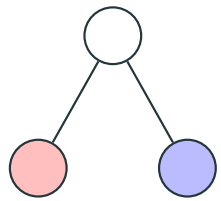
Like bottom-up deterministic automata but differences:

- We add two dummy leaves with some special label $\perp$ to all leaves
- The transition function is redefined:
  - Now $\delta : Q \times \Sigma \to Q \times Q$
  - Semantics: when we are at state q on a node with label a the state of the automaton on the left and right children is $\delta(q, a)$
- There is now an initial state q_0 for the root
- The semantics for final states is that all leaves should be in a final state

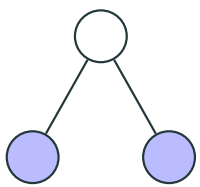
Top-down deterministic tree automata are weaker

- Consider the finite tree language containing the two trees:





- It can be accepted by a bottom-up tree automaton
- However, with a deterministic top-down tree automaton...
  - Let $(q, q') := \delta\left(q_0, \bigcirc\right)$
  - Let $(q_1, q_2) := \delta\left(q, \bullet\right)$ and $(q'_1, q'_2) := \delta\left(q', \bullet\right)$
  - The first tree is accepted so q_1, q_2 are final
  - The second tree is accepted so q'_1, q'_2 are final
  - Hence the automaton accepts:



Top-down nondeterministic tree automata

- We still add dummy leaves with label $\perp$
- Alphabet: Σ
- States: Q
- Multiple initial states $I \subseteq Q$
- Final states: $F \subseteq Q$
- Transition relation $\delta \subseteq Q \times \Sigma \times Q^2$

Can be rewritten to a bottom-up automaton A':

- I are the final states of A'
- F defines the initial states of A'
- Reversing δ gives the transition relation of A'

Connections and properties

- Regular tree language: accepted by a bottom-up tree automaton
- Equivalently: deterministic bottom-up tree automaton
- Regular tree languages are closed under union, intersection, complement
- Tree automata are equivalent to monadic second-order (MSO) logic:
  - First-order logic: variables, Boolean connectives $\wedge$, $\vee$, $\neg$, quantifiers $\forall$, $\exists$
  - Quantification over sets (unary predicates): $\forall S$, $\exists S$
  - Example: every a-node has a b-descendant:

$$\forall x \left(a(x) \to \forall X \big((X(x) \wedge \beta_E) \to (\exists y \, (X(y) \wedge b(y))) \big) \right)$$

where we have the following (E denotes the edge relation):

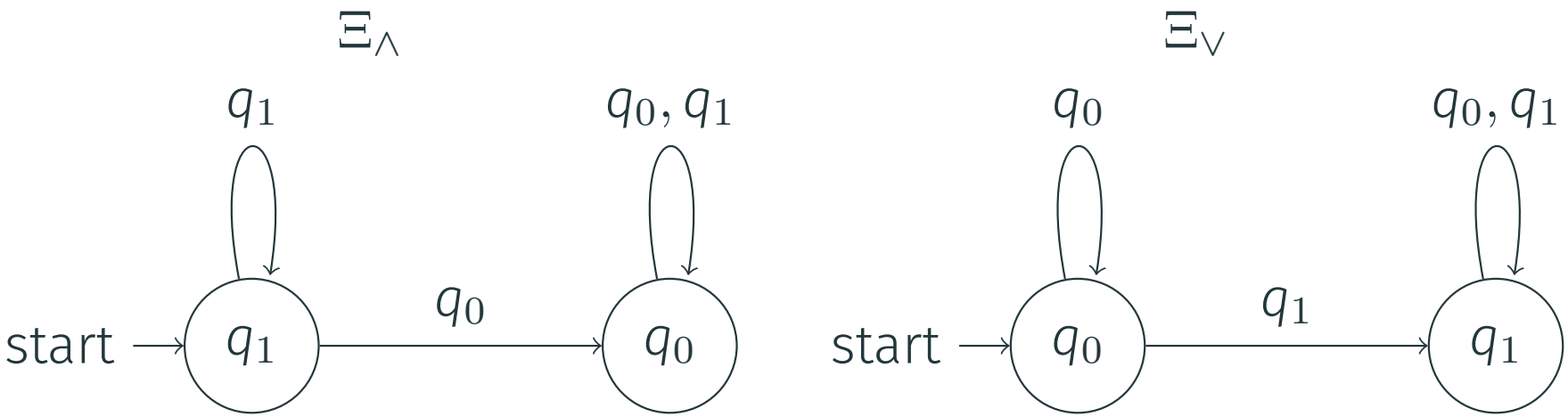
$$\beta_E := \forall yz \, (E(y,z) \wedge X(y) \to X(z))$$

Unranked tree automata

- XML documents are unranked: each node can have multiple children
- We need specific automata formalisms to work on unranked trees
- How can we specify infinitely many transition rules?
  - $\delta(q_0, \wedge) = q_0$
  - $\delta(q_0, q_0, \wedge) = q_0$
  - $\delta(q_0, q_0, q_0, \wedge) = q_0$
  - $\delta(q_0, q_0, q_0, q_0, \wedge) = q_0$
  - $\vdots$
- Intuition: define transitions like $\delta((q_0 + q_1)^* q_1 (q_0 + q_1)^*, \vee) = q_1$

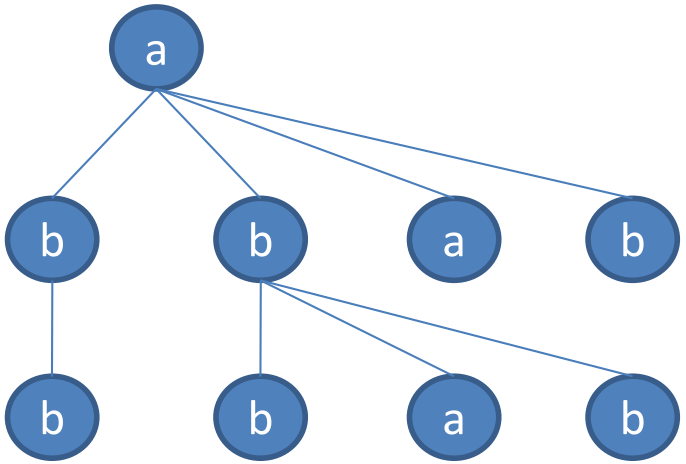
Defining transitions for unranked tree automata

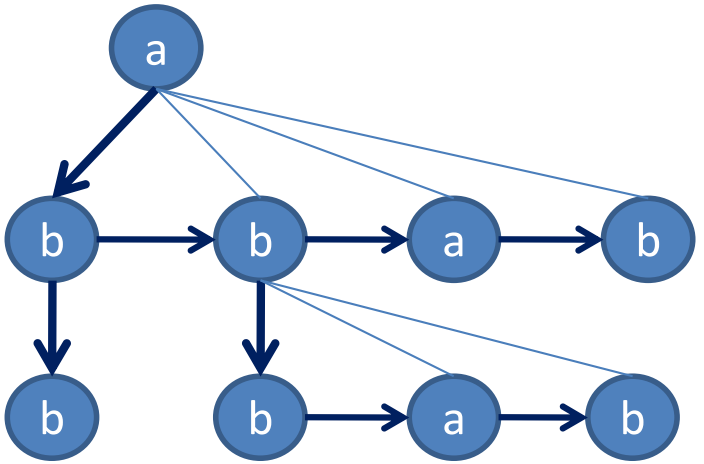
- Idea: use an automaton on words to define the new state
- We still have the alphabet Σ, the states Q, the final states $F \subseteq Q$, the initial function $\iota : \Sigma \to Q$
- For each $a \in \Sigma$ we have a word automaton Ξ_a on the alphabet Q, whose states are also identified with Q



- Deterministic: the word automata are deterministic

Building on ranked trees





Ranked tree: FirstChild-NextSibling

F: encoding into a ranked tree

- F is a bijection

F^{-1}: decoding

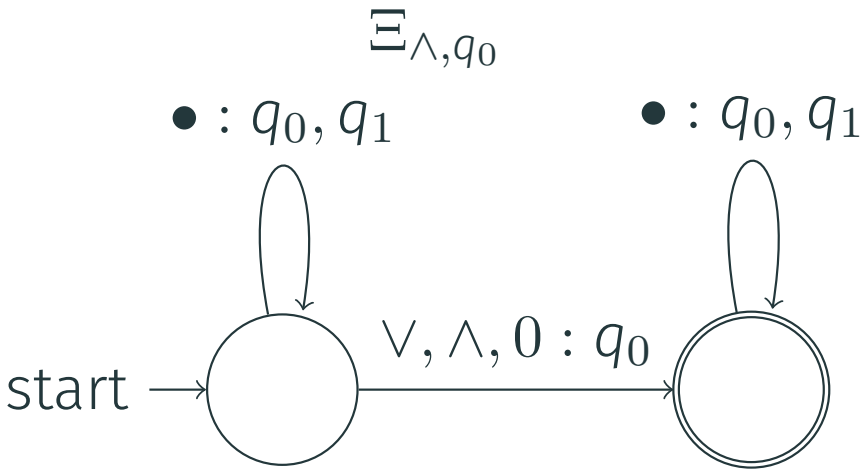
Building on bottom-up ranked trees (2)

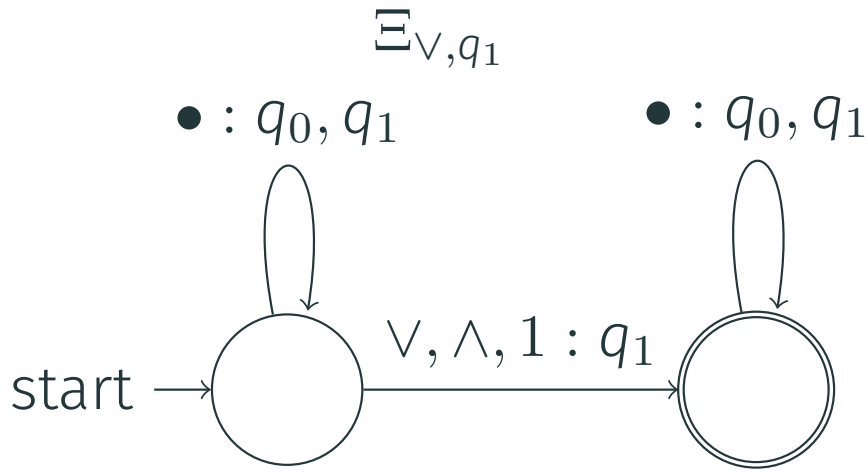
- For each Unranked TA A, there is a Ranked TA accepting F(L(A))
- For each Ranked TA A, there is an unranked TA accepting $F^{-1}(L(A))$
- Both are easy to construct

Consequence: Unranked TA are closed under union, intersection, complement

Top-down unranked tree automata

- We adapt the definition of top-down unranked tree automata
- We have one initial state at the root
- For each $a \in \Sigma$ and each $q \in Q$ we have a word transducer $\Xi_{a,q}$
- Semantics: knowing the label and state of the parent, we read the labels of the children and we give them a state
- To accept, the transducers runs must be accepting, and all leaves must be labeled with a final state





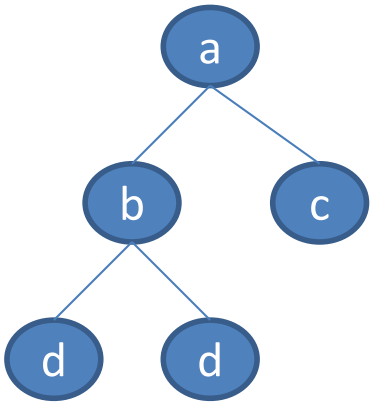
DTD validation

DTDs can be checked with a deterministic pushdown automaton:

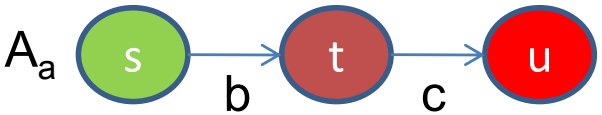
- The stack is used to remember the nesting of elements
- While inside an element we can check that the word of its children satisfies the deterministic regular expression used to define it
- Can be implemented with a SAX parser

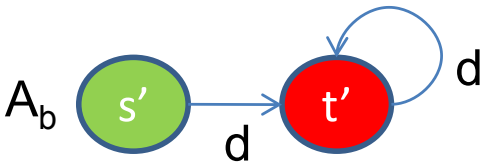
Very efficient validation (2)

```
<!ELEMENT a ( b c ) >
<!ELEMENT b ( d+ ) >
```



<a><d/><d/><c/>





Very efficient validation (2)

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<!ELEMENT a ( b c ) >
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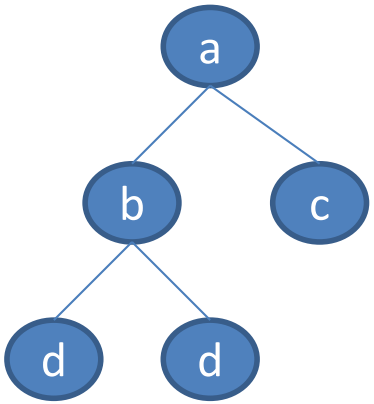
```



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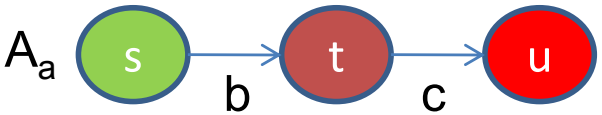

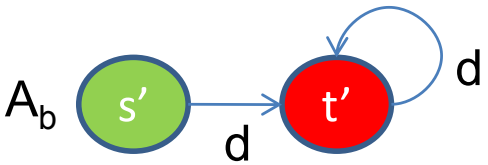

Very efficient validation (2)

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<!ELEMENT a ( b c ) >
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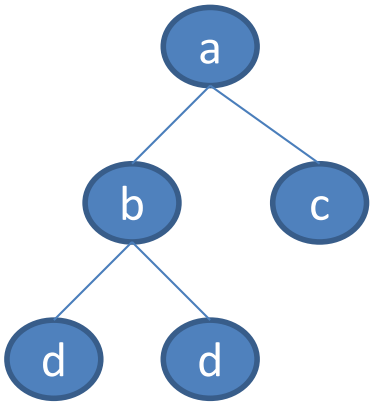
```



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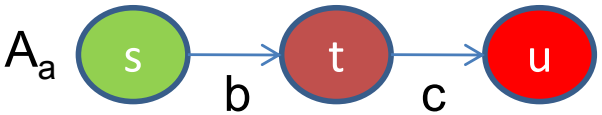

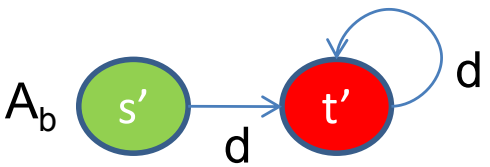

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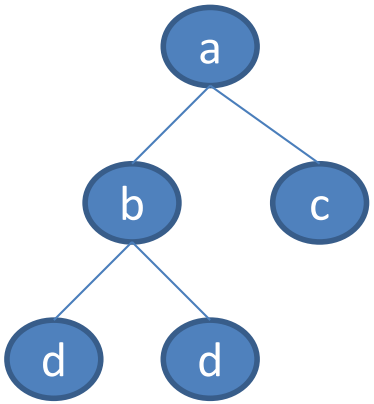
```



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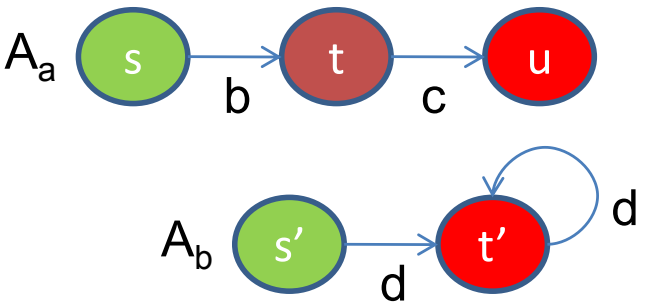

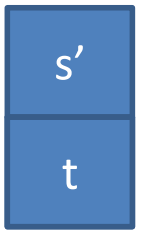

Very efficient validation (2)

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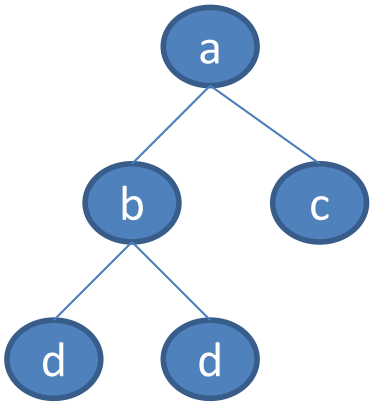
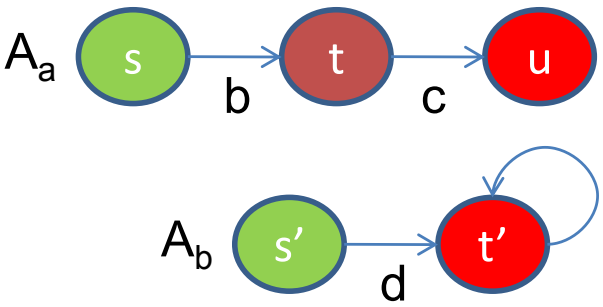
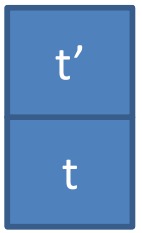


<a><d/><d/><c/>





Very efficient validation (2)

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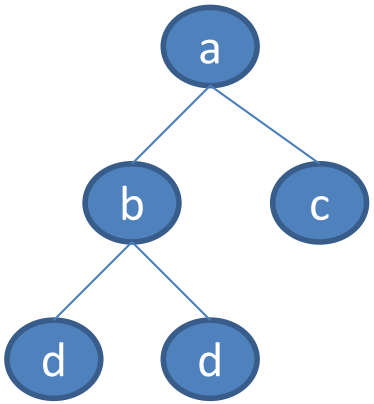

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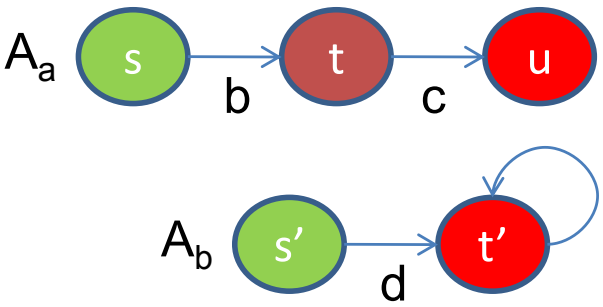

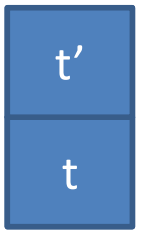

Very efficient validation (2)

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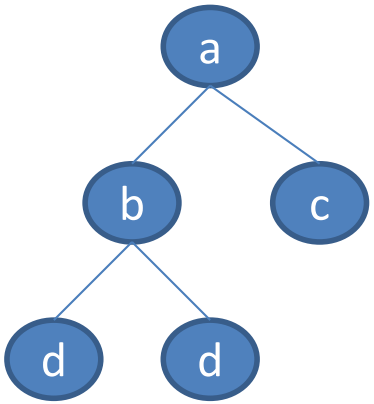
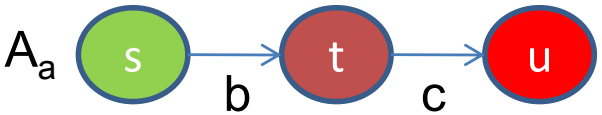
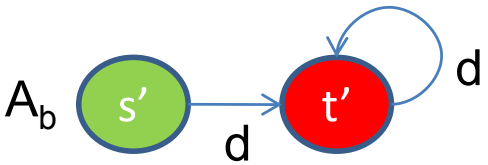


<a><d/><d/><c/>





Very efficient validation (2)

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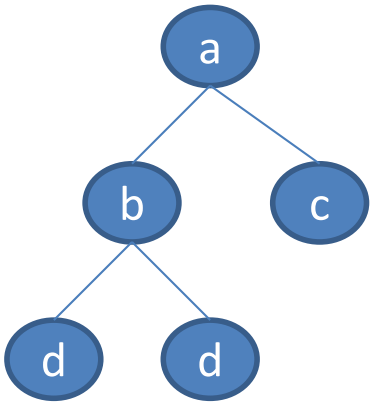
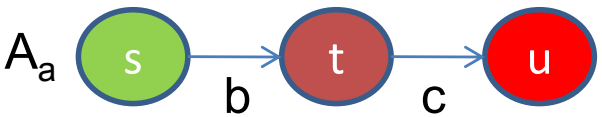
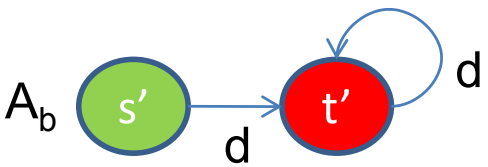


<a><d/><d/><c/>





Very efficient validation (2)

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<!ELEMENT a ( b c ) >
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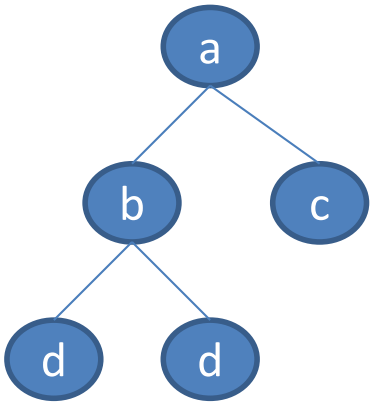

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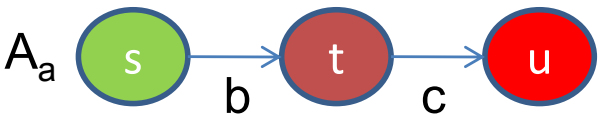
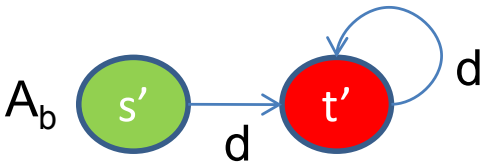




Accept

Warning

- The previous example can be checked with a simple automata on words
- But not the following one

  <!ELEMENT part (part*) >

- The stack is needed for accepting

  <a>…<a>…

Some bad news for DTD

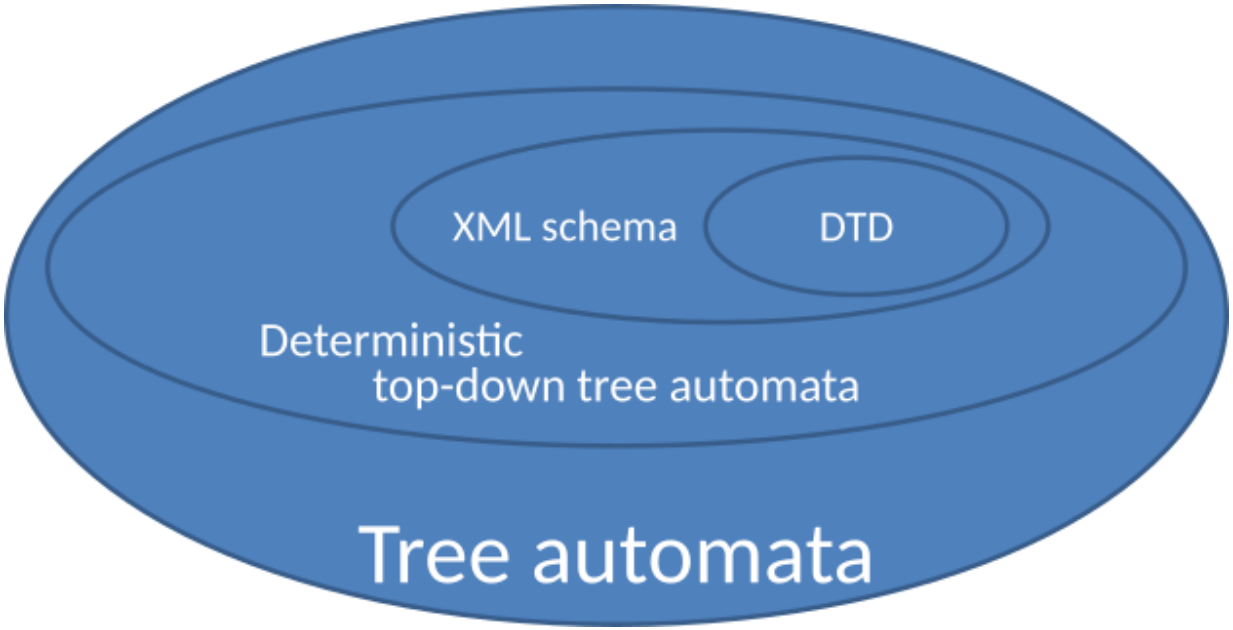
- Not closed under union

```
DTD1        …
    <!ELEMENT used( ad*) >
    <!ELEMENT ad ( year, brand )>
DTD2        …
    <!ELEMENT new( ad*) >
    <!ELEMENT ad ( brand )>
```

- L(DTD1) ∪ L(DTD2) cannot be described by a DTD but can be described easily by a tree automata
  - Problem with the type of **ad** that depends of its parent
- Also not closed under complement
- Limited expressive power

XML Schema validation for version 1.0

- The strange requirements of XSD version 1.0 make it a subset of the languages that can be checked with deterministic top-down tree automata



- With version 1.1, the use of assertions means that the tree language is no longer regular:

```
count(//a) = count(//b) and count(//b) = count(//c)
```

Sources

- Slide 11–14: https://www.irif.fr/~carton/Enseignement/XML/Cours/DTD/
- Slide 17: http://xmlfr.org/documentations/tutoriels/001218-0001
- Slide 24: https://en.wikipedia.org/wiki/RELAX_NG
- Slide 25: https://www.xml.com/pub/a/2003/11/12/schematron.html