Web Data Models

Typing: DTD, Schema

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XML Type Definition Language

- XML type definition language: a way to specify a certain subset of XML document — a type

  typing XML document : what for ? (next slide)

- specification should be simple: a validator should be built automatically and run efficiently

XML Typing : What for?

- a way to specify a certain subset of XML document
- writing programs, queries
- input program validity
- program correctness
- program (query) optimization
- storage optimization
- integration

DTD: Syntax

- <!**ELEMENT** elem_name elem_regexp> — an element named **elem_name** contains elements described by the regular expression **elem_regexp**

- <!**ATTLIST** elem_name att_name att_type att_values> — the element **elem_name** has an attribute named **att_name** of type **att_type** and having possible values described by **att_values**

DTD: Syntax

- regular expressions are formed of `*`,`+`,`?`, sequence `[,]`, `EMPTY`, `ANY`, `#PCDATA` (text)
- attribute types are `ID` (primary key), `IDREF` (foreign key), `CDATA` (text), `v1|v2|,…,vn` (fixed value list)
- attribute values are `v` (default value), `#REQUIRED` (mandatory attribute), `#IMPLIED` (optional attribute), `#FIXED v` (constant value `v`)

DTD

```
<!ELEMENT books (book*)>
<!ELEMENT book (publisher,edition, authors)>
<!ATTLIST book title CDATA #REQUIRED>
<!ELEMENT publisher #PCDATA>
<!ELEMENT edition #PCDATA>
<!ELEMENT authors (author+)>
<!ELEMENT author (first,last)>
<!ELEMENT first #PCDATA>
<!ELEMENT last #PCDATA>
```

Mixed Content

- Mixed content described by a repeatable OR group (between |):

```
(#PCDATA | element-name | … )
```

- `#PCDATA` must be first followed by 0 or more elements — can be repeated multiple times

DTD: Regular Expressions

- most interesting part of DTD — matching regular expressions on the contents

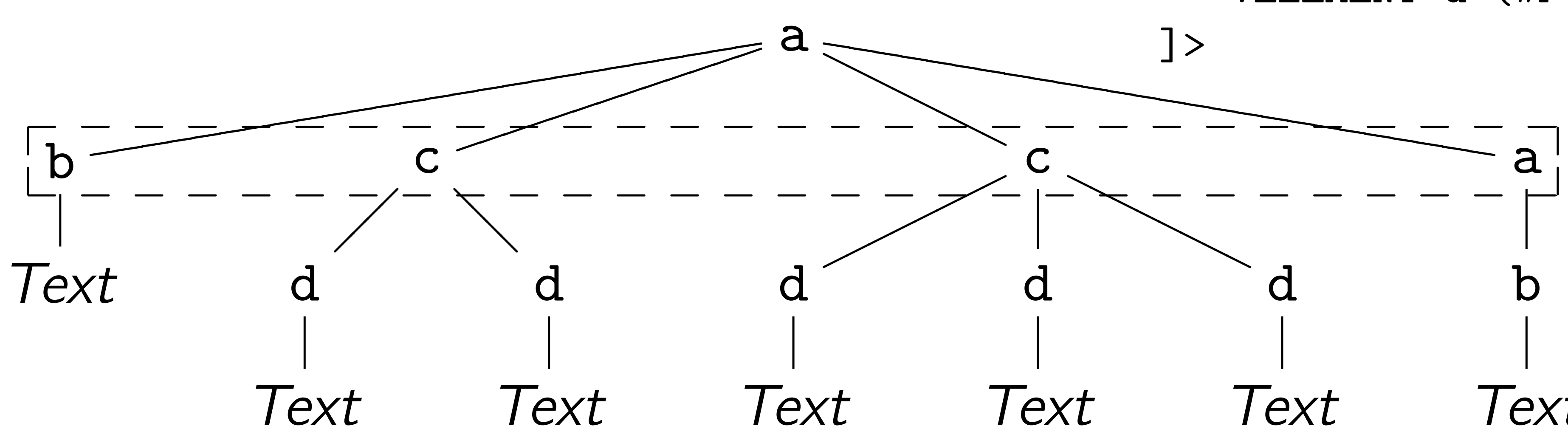
```
<!ELEMENT person

 (name, title?, address*, (fax|tel)*,
 email*) >
```

DTD: Regular Expressions

- The sequence of children labels has to match its regular expression content model:

```
<!DOCTYPE a [
  <!ELEMENT a (b, c*, a?)>
  <!ELEMENT b (#PCDATA)  >
  <!ELEMENT c (d, d+)    >
  <!ELEMENT d (#PCDATA)  >
]>
```



Questions to Answer

1. What is a regular expression? How can we match a string against it?

2. What is a finite-state automaton?

3. What is a deterministic regular expression?

4. What is an 1-unambiguous regular expression?

Regular Expressions

	meaning
a	tag/element *a* occurs
e1, e2	expression *e1* is followed by expression *e2*
e*	0 or more occurrences of *e*
e?	optional — 0 or 1 occurrences of *e*
e+	1 or more occurrences of *e*
e1 | e2	*e1* or *e2*
(e)	grouping

Regular Expressions

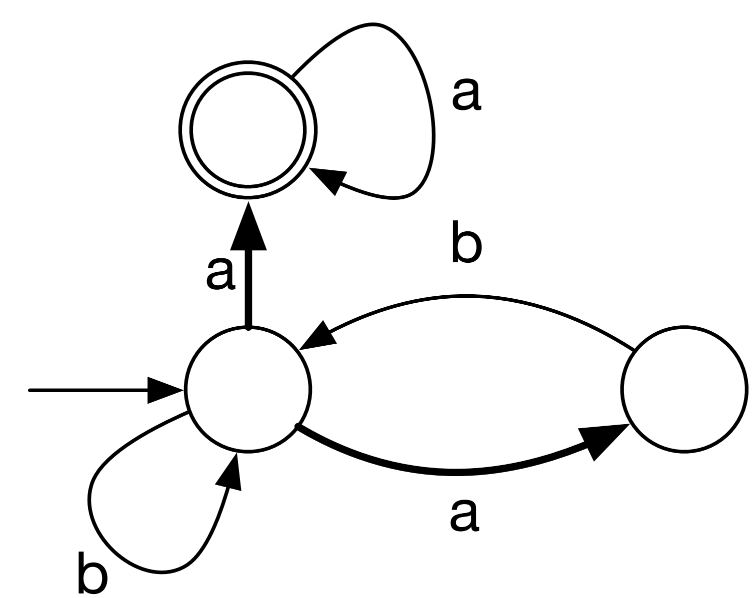
- very useful for defining programming language syntax
- in various Unix tools (`grep`), text editors (`vim`, `emacs`, …)
- classical concept in CS (starting from Kleene, 50s)

Implementing REs

- **input**: RE e, string s; **output**: does s match e?
- construct a **non-deterministic** or deterministic finite-state automaton (FA)

e = (ab|b)*a*a

s = abbaaba



Implementing REs

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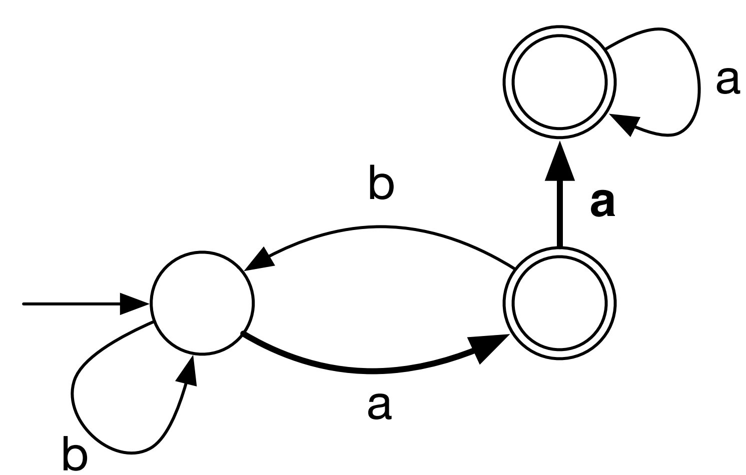


Implementing REs

- evaluation on a deterministic FA can be done in linear time (in the size of the string $|S|$) and in constant space (size of the FA = number of states) - **how?**

Implementing REs

- a non-deterministic FA can be transformed to a deterministic FA — but in exponential space; meaning that evaluation is not efficient
- for a deterministic FA one can build a minimal unique equivalent FA — equivalence between FAs is easy to check

DTDs and REs

W3C requires that the RE specified in DTD must be deterministic:

- evaluation is efficient if element-type definitions are deterministic

- resulting automaton = Glushkov automaton

  states = positions of symbols in the regular expression (semantic actions);

  transitions = based on the “follows set”

DTDs and REs

- **XML specification**: regular expressions are deterministic (1-unambiguous)
- unambiguous = *each word (string) is witnessed by at most one sequence of positions of symbols in the expression that matches the word* [**Brügemann-Klein, Wood 1998**]

  ambiguous: (a|b)*aa*

  equivalent unambiguous: (a|b)*a

DTDs and REs

- Is it enough for expressions to be only unambiguous?

- **No** = an expression can be unambiguous but the matching decision has to be done by looking at more states in advance

(a|b)*a

- without looking beyond the current symbol = 1-unambiguous

Glushkov Automaton

Can we recognize deterministic REs? [Brügemann-Klein, Wood 1998]

- a regular expression is deterministic iff its Glushkov automaton is deterministic

- the Glushkov automaton can be computed in time quadratic in the size of the regular expression

Glushkov Automaton

- character in RE = state in an automaton + one state of the beginning of the RE
- transitions show which characters can precede each other; incoming labels can only be the labels of the state
- construction is quadratic time $O(m^2)$

Glushkov Automaton

- What is the Glushkov automaton for:

a(b|c)(b|d)*

DTD: Validation Using FA

General algorithm for DTD (top-down):

1. for each `<!ELEMENT…` create its deterministic automaton A

2. for each element in document *D*, match the children using its corresponding automaton

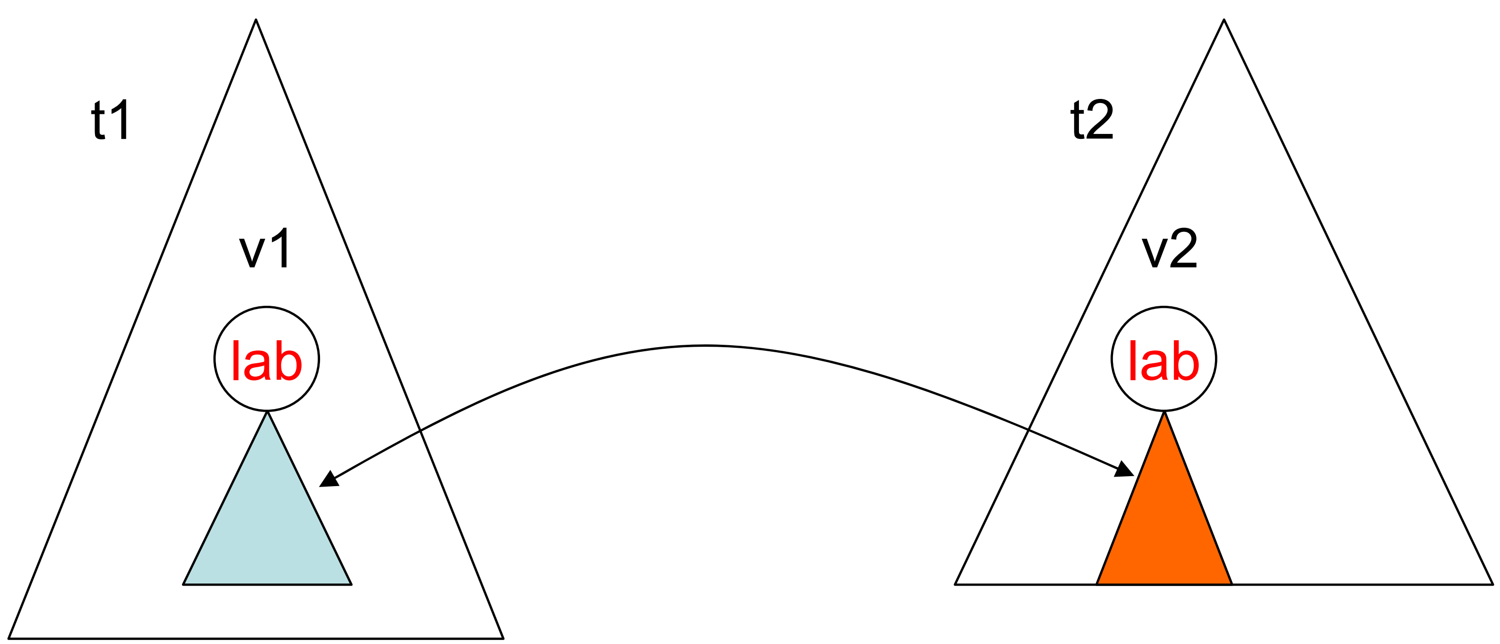
3. if one does not match = document invalid

4. if all match = document valid

DTD: Validation Using FA

Why does this work?

- label-guarded subtree exchange property = trees obtained by exchanging the subtrees rooted at v1 and v2 are in the same languages if v1 and v2 have the same label lab



DTD Validation: Example

```
<a>
  <a>
    <a />
  </a>
  <b>
    <e />
    <f />
    <g />
  </b>
  <c>
    <e />
    <e />
    <e />
    <d />
  </c>
  <b>
    <e />
    <g />
  </b>
  <b>
    <e />
    <f />
  </b>
</a>
```

```
<!ELEMENT a (a,(b|c)*)>
<!ELEMENT b (e, f?, g?)>
<!ELEMENT c (e+, d)>
<!ELEMENT d EMPTY>
<!ELEMENT e EMPTY>
<!ELEMENT f EMPTY>
<!ELEMENT g EMPTY>
```

DTD: Limits

- DTD is compact, easy to understand, easy to validate (with the W3C restrictions…)

- But:

1. it is not in XML (dealing with another language)
2. no distinguishable types (everything is characters)
3. no value constraints (cardinality of sequences)
4. no built-in scoping (elements only used in subtrees)

XML Schema

XML Schema

- **W3C Standard** — schema description language that goes beyond the capabilities of the DTD
- XML Schema specifications are XML documents themselves
- XML Schema has built-in data types (based on Java and SQL types)
- control over the values a data type can assume
- users can define their own data types

XML Schema Constructs

- declaring an element (by default, can only contain string values)

```
<xsd:element name="author" />
```

- bounded occurrences (absence of minOccurs / maxOccurs implies once)

```
<xsd:element name="address" minOccurs="1"
maxOccurs="unbounded" />
```

- types (considered atomic with respect to the schema)

```
<xsd:element name="year" type="xsd:date" />
```

other types: string, boolean, number, float, duration, time, base64binary, AnyURI, …

XML Schema Constructs

- non atomic complex types are built from simple types using type constructors

```
<xsd:complexType name="Persons">
 <xsd:sequence>
  <xsd:element name="person" minOccurs="0"
  maxOccurs="unbounded"/>
 </xsd:sequence>
</xsd:complexType>
<xsd:element name="persons" type="Persons" />
```

XML Schema Constructs

- new complex types can be derived from an existing type (see specification)
- attributes are declared within the element

```
<xsd:element name="book">
 <xsd:attribute name="title" />
 <xsd:attribute name="year" type="xsd:gYear"/
 >
</xsd:element>
```

XML Schema Example

- What is the schema of this XML?

```
<?xml version="1.0" encoding="UTF-8"?>
<books>
  <book id="1" title="Theory of Computation">
    <authors>
      <author>Michael Sipser</author>
    </author>
    <publisher>Cengage Learning</publisher>
    <year>2012</year>
    <edition>3</edition>
  </book>
  <book id="2" title="Artificial Intelligence">
    <authors>
      <author>Peter Norvig</author>
      <author>Stuart Russell</author>
    </authors>
    <publisher>Pearson</publisher>
    <year>2013</year>
    <edition>3</edition>
  </book>
</books>
```

Validating XML In General

- RE / FA on strings (words) are very good and very efficient for DTDs (and, as we will see, for XPath)
- What about XML schema? … how do XML schema compare to DTD? other schema languages?
- Is there a formalism like RE / FA that can express / implement XML typing in general?

Validating XML In General

- Is there a formalism like RE / structure like FA that can express / validate XML typing in general?
  - Tree grammars
  - Tree automata

Next

Schemas and Tree Grammars : an example

- Schemas for XML documents can be formally expressed by Regular Tree Grammars (RTG)

  Book Example revisited:

  NTBooks —> Books [NTBook*]
  NTBook —> Book [NTPub, NTEd, NTAuths]
  NTPub —> Publisher [PCData]
  NTEd —> Editor [PCData]
  NTAuths —> Authors [NTAuth +]
  NTAuth —> Author [NTFirst , NTLast]
  NTFirst —> First [PCData]
  NTLast —> Last [PCData]

  NTxxx : non terminal symbols of the grammar
  [regular expression] : content model written based on non terminal

Schemas and Tree Grammars

- Schemas for XML documents can be formally expressed by Regular Tree Grammars (RTG)

Regular Tree Grammar (RTG)

A *regular tree grammar* (RTG) is a 4-tuple $G = (N, T, S, P)$, where :

- N is a finite set of *non-terminal symbols* ;
- T is a finite set of *terminal symbols* ;
- S is a set of *start symbols*, where $S \subseteq N$ and
- P is a finite set of *production rules* of the form $X \to a\,[R]$, where $X \in N$, $a \in T$, and R is a regular expression over N.

(We say that, for a production rule, X is the left-hand side, $a\,R$ is the right-hand side, and R is the content model.)

Tree Grammar : an other example

P_1
$Dir \rightarrow directory[Person^*]$
$Person \rightarrow student[DirA \mid DirB])$
$Person \rightarrow professor[DirB]$
$DirA \rightarrow direction[Name.Number?.Add?]$
$DirB \rightarrow direction[Name.Add?.Phone^*]$

- Provide one or two XML documents conforming to the grammar, and

- Let’s try to write it as a DTD ! …

Validity wrt Tree Grammar

- Given a RTG *G* what are the valid documents ?

Informal idea for **d** |= *G*:

1. Take the tree representation of **d**
2. Try to assigned a non terminal symbol *NTX* to each node *n* "following" the rules of the grammar *G (this assignment is an interpretation)*

success —> **d** is valid wrt *G*

Schemas and Tree Grammars

- Schemas for XML documents can be formally expressed by RTG …
- Expressivity ?

  1. RTG versus DTD … local tree grammars
  2. RTG versus XML schemas single-type tree grammars
  3. comparing DTD, XML schemas and others

- Easy validation ?

Competing Non-Terminals

Two different non-terminals A and B of the RTG G are said to be competing with each other if:

- a production rule has A in the left-hand side,
- another production rule has B in the left-hand side, and
- these two production rules share the same terminal symbol in the right-hand side.

Grammar Example

P_1	Δ_1
$Dir \rightarrow directory[Person^*]$	$directory[q^*_{person}] \rightarrow q_{dir}$
$Person \rightarrow student[DirA \mid DirB])$	$student[q_{dirA} \mid q_{dirB}] \rightarrow q_{person}$
$Person \rightarrow professor[DirB]$	$professor[q_{dirB}] \rightarrow q_{person}$
$DirA \rightarrow direction[Name.Number?.Add?]$	$direction[q_{name}.q_{number}?.q_{add}?] \rightarrow q_{dirA}$
$DirB \rightarrow direction[Name.Add?.Phone^*]$	$direction[q_{name}.q_{add}?.q^*_{phone}] \rightarrow q_{dirB}$

Local Tree Grammar

- A local tree grammar (LTG) is a regular tree grammar that does not have competing non-terminals

i.e. one and only one rule for each non terminal symbol

i.e. the relationship between non terminal symbols and terminal symbols is one-one.

- Local tree grammars match DTDs … more or less …
  + check that the REs of content models are 1-unambigous

Grammar Example

P_3	Δ_3
$Dir \rightarrow directory[Student^*.Professor^*]$	$directory[q^*_{stud}.q^*_{prof}] \rightarrow q_{dir}$
$Student \rightarrow student[Name.Number?.Add?]$	$student[q_{name}.q_{number}?.q_{add}?] \rightarrow q_{stud}$
$Professor \rightarrow professor[Name.Add?.Phone^*]$	$professor[q_{name}.q_{add}?.q^*_{phone}] \rightarrow q_{prof}$

Single-Type Tree Grammar

A single type tree grammar (STTG) is a regular tree grammar, where:

- for each production rule, non terminals in the RE (content model) do not compete with each other, and
- start symbols do not compete with each other.
- competing symbols allowed but in a way that makes it easy to distinguish from the context (parent node)

A single-type tree language (STTL) is a language that can be generated by at least one STTG.

Grammar Example

P_2	Δ_2
$Dir \rightarrow directory[Person^*]$	$directory[q^*_{person}] \rightarrow q_{dir}$
$Person \rightarrow student[DirA])$	$student[q_{dirA}] \rightarrow q_{person}$
$Person \rightarrow professor[DirB]$	$professor[q_{dirB}] \rightarrow q_{person}$
$DirA \rightarrow direction[Name.Number?.Add?]$	$direction[q_{name}.q_{number}?.q_{add}?] \rightarrow q_{dirA}$
$DirB \rightarrow direction[Name.Add?.Phone^*]$	$direction[q_{name}.q_{add}?.q^*_{phone}] \rightarrow q_{dirB}$

XML Schema Languages

Grammar	Schema Language
LTG	DTD
STTG	XML Schema
RTG	RelaxNG

Classes of Regular Languages

$$\text{LTL} \subset \text{STTL} \subset \text{RTL}$$

local single regular

Some good news

- LTL (local) and STTL (single type) are closed under intersection but not union;
- RTL closed under union, intersection and difference

Tree Automata for XML Validation

Validating XML In General

- FA on strings (words) are very good and very efficient for DTDs (and, as we will see, for XPath)
- But what about XML schema? … how do XML schema compare to DTD? other schema language?
- Is there a formalism like (RE) / structure (automaton) that can express / validate XML in general?

Tree Automata

Two types:

1. on ranked trees: each node has a bounded number of children; each XML can be transformed by using the first child - next sibling encoding (more later)

2. on unranked trees: no bound on the number of children; better suited (directly) to XML,

Binary Tree Automata

Bottom-up non-deterministic tree automata

A non-deterministic bottom-up tree automata is a 4-tuple $\mathcal{A} = (\Sigma, Q, F, \Delta)$ where

- Σ is an alphabet. We usually distinguish between two disjoint alphabets : a leaf alphabet (Σ_{leaf}) and an internal one ($\Sigma_{internal}$).
- Q is a set of states.
- F is a set of accepting states $F \subseteq Q$.
- Δ is a set of transition rules having one of the forms :

$$l \rightarrow q \text{ when } l \in \Sigma_{leaf}$$
$$a(q_1, q_2) \rightarrow q \text{ when } a \in \Sigma_{internal}$$

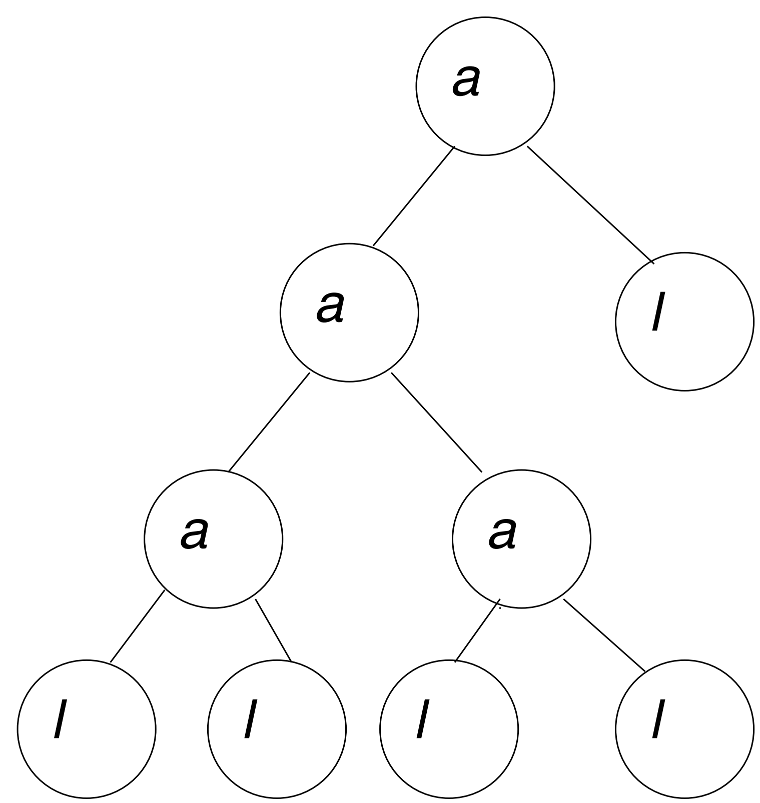
Binary Tree Automata: Semantics

- the semantics of automata A are described in terms of a **run**
- a run = a mapping from the domain of Q (states) such that for each p we have r(p) in Q
- a run is accepting if the state of the root is one of the final states

Automata Example

Let $\mathcal{A} = (\{a, l\}, \{q_0, q_1\}, \{q_0\}, \Delta)$ where

$$\Delta = \begin{cases} a(q_1, q_1) & \to q_0 \\ a(q_0, q_0) & \to q_1 \\ l & \to q_1 \end{cases}$$



Tree Languages

- The language $\mathbf{L(A)}$ is the set of trees accepted by $\mathbf{A}$
- A language accepted by a bottom-up tree automaton is called a regular tree language

Top-Down Tree Automata

Binary top-down tree automata

A non-deterministic top-down tree automata is a 5-tuple $\mathcal{A} = (\Sigma, Q, I, F, \Delta)$ where

- Σ is an alphabet.
- Q is a set of states.
- $I \subseteq Q$ is a set of initial states.
- F is a set of accepting states $F \subseteq Q$.
- Δ is a set of transition rules having the form :

$$q \to a(q_1, q_2).$$

  where $a \in \Sigma$ and $q, q_1, q_2 \in Q$

Top-Down Tree Automata: Semantics

Run

- A run of top-down automaton $\mathcal{A} = (\Sigma, Q, I, F, \Delta)$ on a binary tree t is a mapping $r : dom(t) \to Q$ such that
  - $r(\epsilon) \in I$;
  - for each node p with label a, rule $r(p) \to a(r(p.0), r(p.1))$ is in Δ.
- A run is accepting if for all leaves p we have $r(p) \in F$.

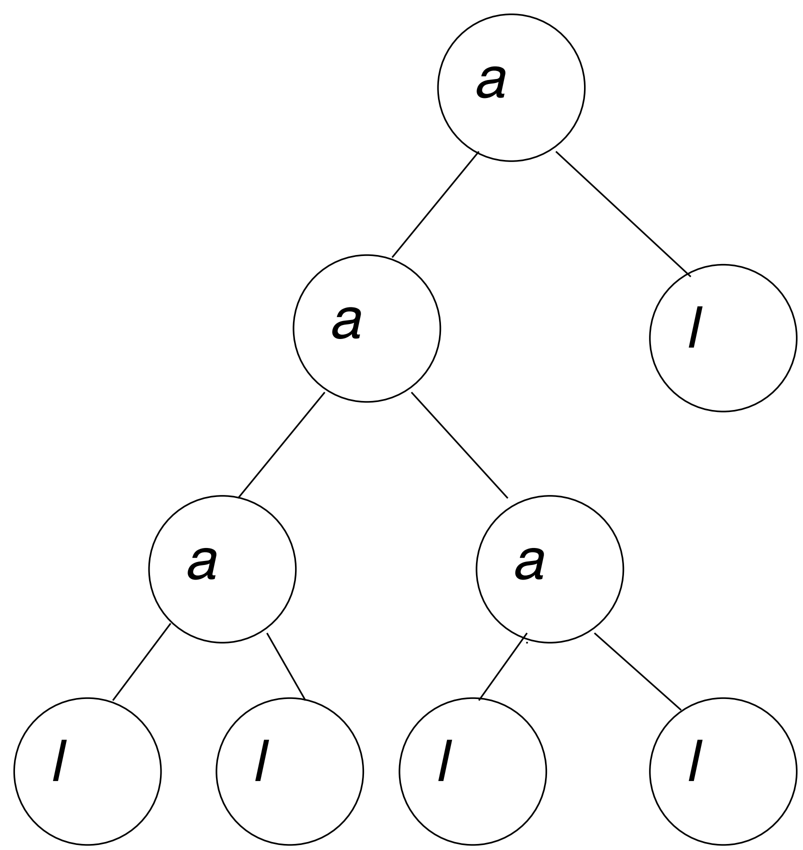
Deterministic binary top-down automata

We say that a binary tree automaton is (top-down) deterministic **if I is a singleton and for each $a \in \Sigma$ and $q \in Q$ there is *at most* one transition rule of the form** $q \to a(q_1, q_2)$.

Automata Example

Let $\mathcal{A} = (\{a, l\}, \{q_0, q_1\}, \{q_0\}, \{q_1\}, \Delta)$ where

$$\Delta = \begin{cases} q_0 & \rightarrow a(q_1, q_1) \\ q_1 & \rightarrow a(q_0, q_0) \end{cases}$$



Regular Tree Languages

The following statements are equivalent:

- L is a regular tree language
- L is accepted by a non-deterministic bottom-up tree automaton
- L is accepted by a deterministic bottom-up automaton
- L is accepted by a non-deterministic top-down automaton

Regular Tree Languages

Generally, the same results as for regular word/string languages (FA):

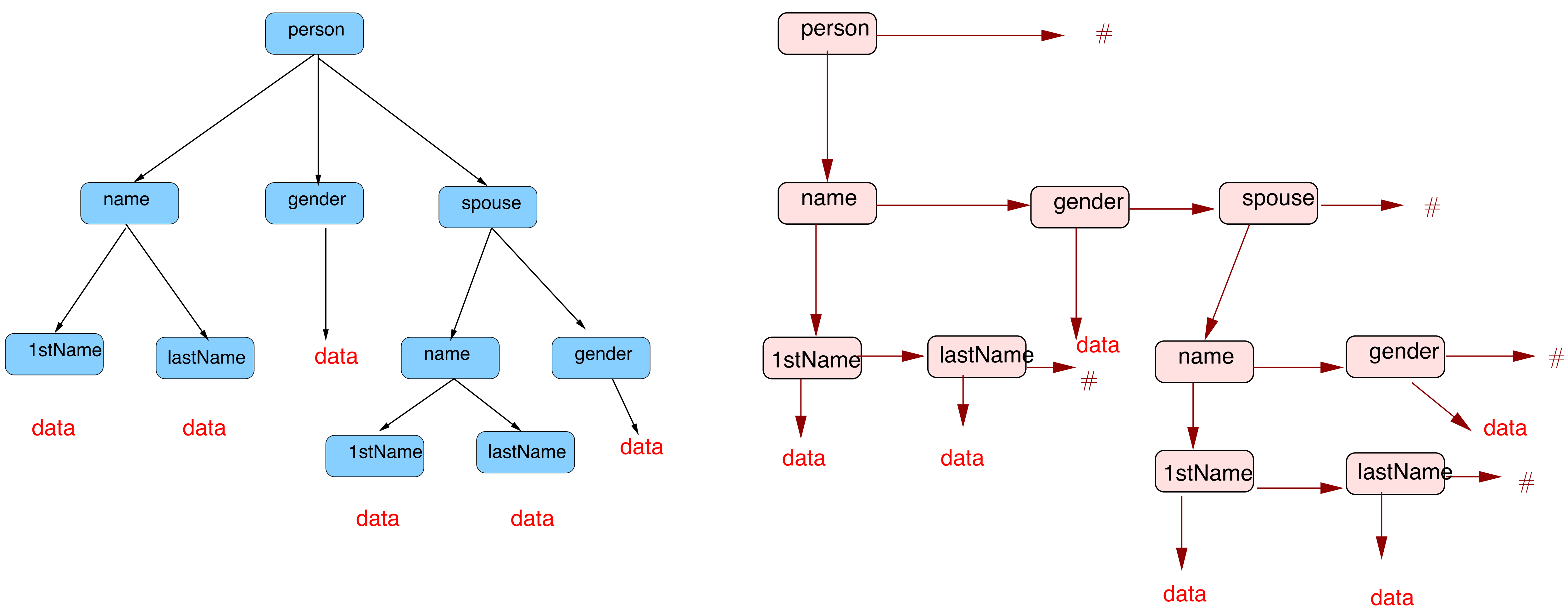
- given a tree automaton, one can find an equivalent bottom-up automaton that is deterministic (with exponential blowup)
- regular tree languages are closed under complement, intersection and union

Ranked Tree Automata

- We can represent any unranked tree (XML) by a binary tree where the left child is the first child and the right child is the next sibling

  called first-child next-sibling encoding (not the only one)

XML — Ranked Tree



Relation Between Ranked and Unranked Tree Automata

- For each unranked tree automaton, there exists a ranked tree automaton accepting the encoding of the XML in first child — next sibling
- For each ranked tree automaton, there exists an unranked tree automaton accepting the unranked tree seconded from first child — next sibling encoding

Unranked Bottom-Up Tree Automata

Non-deterministic bottom-up tree automata

A non-deterministic bottom-up tree automaton is a 4-tuple $\mathcal{A} = (\Sigma, Q, F, \Delta)$ where Σ is an alphabet, Q is a set of states, $F \subseteq Q$ is a set of final states an Δ is a set of transition rules of the form

$$a[E] \rightarrow q$$

where $a \in \Sigma$, E is a regular expression over Q and $q \in Q$

Unranked Bottom-Up Tree Automata: Semantics

Let $\mathcal{A} = (\Sigma, Q, F, \Delta)$ be an unranked tree automata.

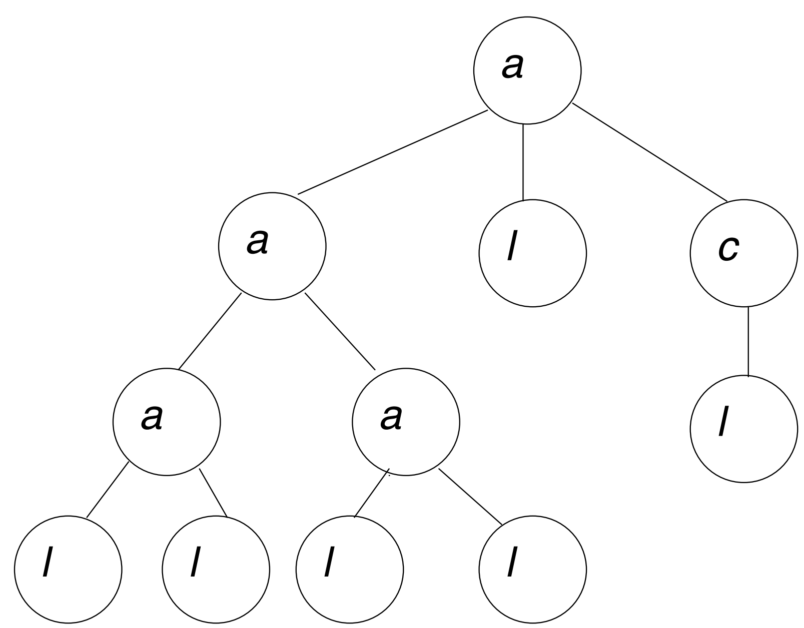
- The semantics of $\mathcal{A}$ is described in terms of runs
- Given an **unranked tree** *t*, a *run* of $\mathcal{A}$ on *t* is a mapping from *dom*(*t*) to *Q* where, for each position *p* whose children are at positions $p0, \ldots, p(n-1)$ (with $n \geq 0$), we have $r(p) = q$ if all the following conditions hold :
  - $t(p) = a \in \Sigma$,
  - the mapping *r* is already defined for the children of *p*, *i.e.*, $r(p.0) = q_0, \ldots, r(p.(n-1)) = q_{n-1}$ and
  - the word $q_0.q_1 \ldots q_{n-1}$ is in $L(E)$.
- A run *r* is *successful* if $r(\epsilon)$ is a final state.

Automata Example

Let $\mathcal{A} = (\{a, l\}, \{q_a, q_c, q_l\}, \{q_a\}, \Delta)$ where

$$\Delta = \begin{cases} a\ [q_a^*.q_l^*.(q_c \mid \epsilon)] & \rightarrow q_a \\ c\ [q_l] & \rightarrow q_c \\ l\ [\epsilon] & \rightarrow q_l \end{cases}$$

Special rule for leaves



General Validation Algorithm

A run associates to each position **p** in the XML document a set of states in **Q** such that:

1. there exists a transition rule to a state in **Q** from a label **a**

2. the label at **p** is **a**

3. the string of the children labels matches the RE in the transition rule

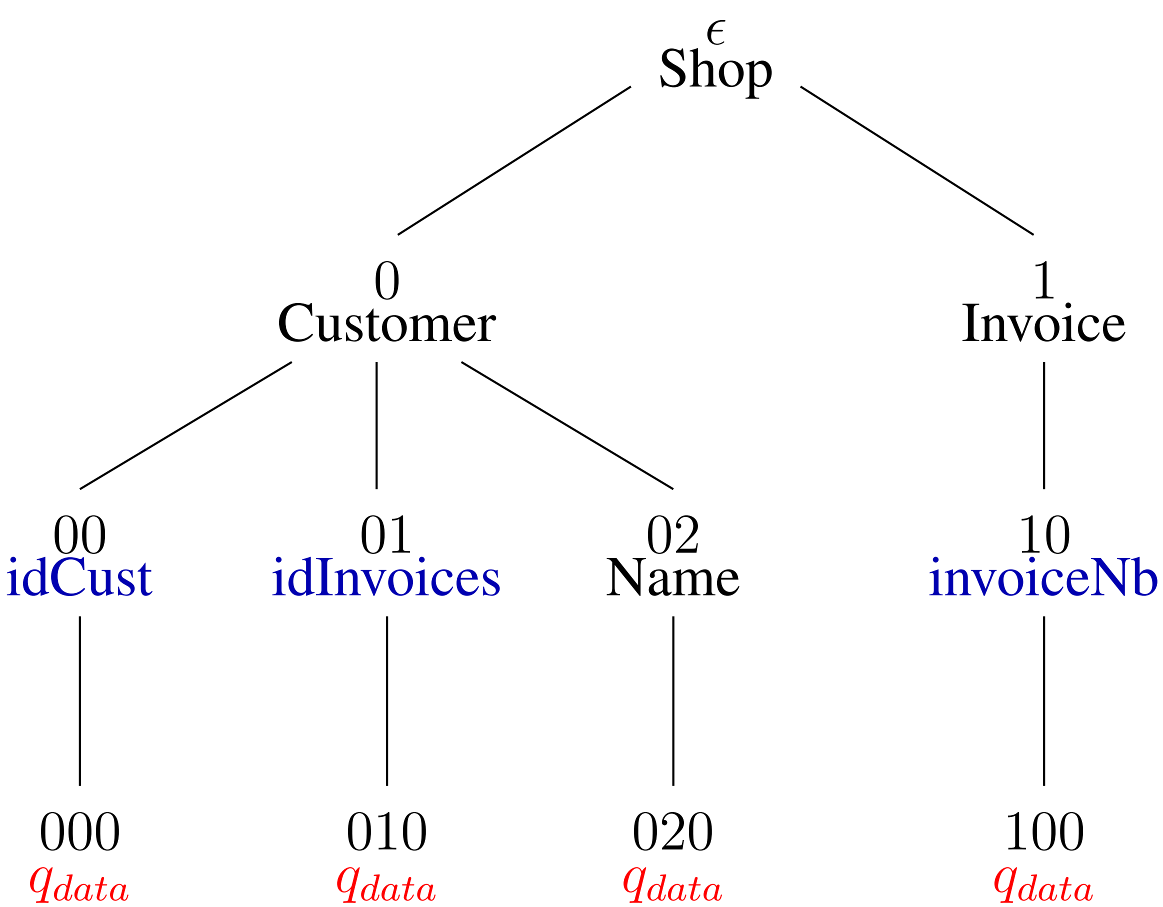
A run is successful if it contains at least one final state.

Simplified Versions for LTG and STTG

- LTG: the sets of states are always singletons, only one rule for each label

- STTG: the results of a run can consider just a single type for each node of the tree

Validation Example



$$Shop, (\emptyset, \emptyset), q^*_{Customer} q^*_{Invoice} \rightarrow q_{Shop}$$

$$Customer, (\{q_{idCust}\}, \{q_{idInvoices}\}), q_{Name} \rightarrow q_{Customer}$$

$$Invoice, (\{q_{invoiceNb}\}, \emptyset), \emptyset \rightarrow q_{Invoice}$$

$$idCust, (\emptyset, \emptyset), q_{data} \rightarrow q_{idCust}$$

$$idInvoices, (\emptyset, \emptyset), q_{data} \rightarrow q_{idInvoices}$$

$$Name, (\emptyset, \emptyset), q_{data} \rightarrow q_{Name}$$

$$invoiceNb, (\emptyset, \emptyset), q_{data} \rightarrow q_{invoiceNb}$$

Slide Credits

- Validation Using Trees: structure & examples from Mirian Hayfield Ferrari
- Figures & examples in slides 8, 12, 13, 24 (oups numbers have changed !!!) from C. Maneth's course