Automata on Finite Trees
Preliminaries
Trees

A tree over $\Sigma$ is a partial function $t : \mathbb{N}^* \to \Sigma$ such that $\text{dom}(t)$ is a prefix-closed set:

- for each $p \in \text{dom}(t)$ for all $q \leq p$ we have $q \in \text{dom}(t)$.

A word $p \in \text{dom}(t)$ is called a position.

If $p, q \in \text{dom}(t)$ such that $p \cdot n = q$ for some $n \in \mathbb{N}$:

- $p$ is the parent of $q$,
- $q$ is the $n$-th child of $p$. 
Trees

Given a finite tree $t \in T(\Sigma)$, the *frontier* of $t$ is the set

$$fr(t) = \{ p \in \text{dom}(t) \mid \text{for all } n \in \mathbb{N} \;pn \not\in \text{dom}(t) \}$$

A *path* in $t$ is a maximal subset $\pi$ of $\text{dom}(t)$ linearly ordered by $\leq$.

Given $p \in \text{dom}(t)$, the *subtree* $t_p$ is defined as

$$t_p : \{q \in \mathbb{N}^* \mid pq \in \text{dom}(t) \} \rightarrow \Sigma$$

such that $t_p(q) = t(pq)$, for all $q \in \text{dom}(t_p)$.

**Lemma 1 (König)** A finitely branching tree is infinite if and only if it has an infinite path.
**Coding ω-branching trees as binary trees**

Let $t : \mathbb{N}^* \rightarrow \Sigma$ be a tree of arbitrary (possibly infinite) branching.

Define $t' : \{0, 1\}^* \rightarrow \Sigma \cup \{\bullet\}$ as follows:

- $t'(\epsilon) = t(\epsilon)$
- for all $n_1 n_2 \ldots n_k \in dom(t)$, with $k > 0$, let
  $$t'(01^{n_1+1}01^{n_2+1} \ldots 01^{n_k+1}0) = t(n_1 n_2 \ldots n_k)$$
- for all other $p$ let $t'(p) = \bullet$
Tree Concatenation

Let $\sigma \in \Sigma$ and $T, T' \subseteq \mathcal{T}(\Sigma)$.

By $T \cdot_\sigma T'$ we denote the set of trees obtained from some $t \in T$ by replacing each occurrence of $\sigma$ on $fr(t)$ by a tree in $T'$.

If $\vec{\sigma} = \langle \sigma_1, \ldots, \sigma_n \rangle$, let $T \cdot_{\vec{\sigma}} \langle T_1, \ldots, T_m \rangle$ be the set of trees obtained from some $t \in T$ by replacing each occurrence of $\sigma_i$ on $fr(t)$ by a tree in $T_i$.

We denote by $T \cdot_{\vec{\sigma}} \langle T_1, \ldots, T_m \rangle^{\omega \vec{\sigma}}$ the set of infinite trees obtained by the infinite unfolding of the concatenation operation.
Terms

A *ranked alphabet* $\langle \Sigma, \# \rangle$ is a set of symbols together with a function $\# : \Sigma \to \mathbb{N}$. For $f \in \Sigma$, the value $\#(f)$ is said to be the *arity* of $f$.

Zero-arity symbols are called *constants*, and denoted by $a, b, c, \ldots$.

A *term* $t$ over $\Sigma$ is a partial function $t : \mathbb{N}^* \to \Sigma$:

- $\text{dom}(t)$ is a finite prefix-closed subset of $\mathbb{N}^*$, and
- for each $p \in \text{dom}(t)$, if $\#(t(p)) = n > 0$ then
  $\{i \mid pi \in \text{dom}(t)\} = \{0, \ldots, n - 1\}$.
**Contexts**

Let $X = \{x_1, \ldots, x_n\}$ be a finite set of variables, interpreted over terms.

A term $t \in \mathcal{T}(\Sigma \cup X)$ is said to be *linear* if each variable occurs in $t$ at most once.

A *context* is a linear term $C[x_1, \ldots, x_n]$, and $C[t_1, \ldots, t_n]$ denotes the result of replacing $x_i$ with the term $t_i$, for all $1 \leq i \leq n$.

A context is said to be *trivial* if it is reduced to a variable, and *non-trivial* otherwise.
Bottom Up Tree Automata
**Definition**

Let $\Sigma = \{f, g, h, \ldots\}$ be a finite *ranked alphabet*. A *bottom-up tree automaton* is a tuple $A = \langle S, T, F \rangle$ where:

- $S$ is a finite set of *states*,
- $T$ is a set of *transition rules* of the form:
  
  $$f(q_1, \ldots, q_n) \rightarrow q$$

  where $f \in \Sigma$, $\#(f) = n$, and $q_1, \ldots q_n, q \in S$.
- $F \subseteq S$ is a set of final states.

Notice that there are no initial states.

If $\#(f) = 0$ we have rules of the form $f \rightarrow q$. 
Runs

A run of $A$ over a tree $t : \mathbb{N}^* \rightarrow \Sigma$ is a mapping $\pi : \text{dom}(t) \rightarrow S$ such that, for each position $p \in \text{dom}(t)$, where $q = \pi(p)$:

- if $\#(t(p)) = n$ and $q_i = \pi(p_i)$, $1 \leq i \leq n$, then $T$ has a rule

$$t(p)(q_1, \ldots, q_n) \rightarrow q$$

A run $\pi$ is said to be accepting, if and only if $\pi(\epsilon) \in F$.

The language of $A$, denoted as $\mathcal{L}(A)$ is the set of all trees over which $A$ has an accepting run.

A set of trees $L \subseteq \mathcal{T}(\Sigma)$ is said to be recognizable iff there exists a bottom-up tree automaton $A$ such that $\mathcal{L}(A) = L$. 
Examples

1. Let $\Sigma = \{f, g, a\}$, where $\#(f) = 2$, $\#(g) = 1$ and $\#(a) = 0$.

Let $A = \langle S, T, F \rangle$, where:

- $S = \{q_f, q_g, q_a\}$,
- $F = \{q_f\}$,
- $T = \{a \rightarrow q_a, g(q_a) \rightarrow q_g, g(q_g) \rightarrow q_g, f(q_g, q_g) \rightarrow q_f\}$

2. Let $\Sigma = \{\text{red}, \text{black}, \text{nil}\}$ with $\#(\text{red}) = \#(\text{black}) = 2$ and $\#(\text{nil}) = 0$.

Let $A_{rb} = \langle \{q_b, q_r\}, T, \{q_b\} \rangle$ with

$$T = \{\text{nil} \rightarrow q_b, \text{black}(q_{b/r}, q_{b/r}) \rightarrow q_b, \text{red}(q_b, q_b) \rightarrow q_r\}$$
Determinism

A tree automaton is said to be *deterministic* iff there are no two transition rules with the same left-hand side.

**Proposition 1**  A *deterministic* tree automaton has at most one run for each input tree.

A tree automaton is said to be *complete* iff there exists at least one transition rule \( f(q_1, \ldots, q_n) \rightarrow q \), for each \( f \in \Sigma \), \( \#(f) = n \) and \( q_1, \ldots, q_n \in S \).

**Proposition 2**  A *complete* tree automaton has at least one run for each input tree.
**Determinism**

**Theorem 1** Let $L$ be a recognizable tree language. Then there exists a complete deterministic tree automaton $A$ such that $\mathcal{L}(A) = L$.

We define $A_d = \langle S_d, T_d, F_d \rangle$ where $S_d = 2^S$, $F_d = \{s \subseteq S \mid s \cap F \neq \emptyset\}$ and:

- $f(s_1, \ldots, s_n) \rightarrow s \iff s = \{q \in S \mid \exists q_1 \in s_1, \ldots \exists q_n \in s_n . f(q_1, \ldots, q_n) \rightarrow q\}$
- $a \rightarrow s \iff s = \{q \in S \mid a \rightarrow q\}$

To prove $\mathcal{L}(A_d) = \mathcal{L}(A)$, we prove:

$$t \xrightarrow{A_d}^* s \iff s = \{q \in S \mid t \xrightarrow{A}^* q\}$$
Determinism

By induction on the structure of $t$.

If $t = a$, by definition we have $a ightarrow s$ $\iff$ $s = \{q \in S \mid a \rightarrow q\}$

If $t = f(t_1, \ldots, t_n)$, by ind. hyp. $t_i \xrightarrow{A_d} s_i \iff s_i = \{q \in S \mid t_i \xrightarrow{A} q\}$

"$\Rightarrow$" if $t \xrightarrow{A_d} f(s_1, \ldots, s_n) \xrightarrow{A_d} s$ we show:

$$\exists q_i \in s_i . f(q_1, \ldots, q_n) \xrightarrow{A} q \iff t \xrightarrow{A} q$$
Determinism

“⇐” Let \( s_i = \{ q \mid t_i \xrightarrow{A}^* q \} \), \( i = 1, \ldots, n \) and

\[
s' = \{ q \mid \exists q_i \in s_i \cdot f(q_1, \ldots, q_n) \xrightarrow{A} q \}\]

We conclude by showing \( s = s' \) \( \square \)
Closure Properties

**Theorem 2** The class of recognizable tree languages is closed under union, complementation and intersection.

**Union** Let $A_i = \langle S_i, T_i, F_i \rangle$ for $i = 1, 2$. Suppose that $S_1 \cap S_2 = \emptyset$. Let $A_\cup = \langle S_1 \cup S_2, T_1 \cup T_2, F_1 \cup F_2 \rangle$.

**Complementation** Let $A = \langle S, T, F \rangle$ be a complete deterministic tree automaton such that $\mathcal{L}(A) = L$. Define $\bar{A} = \langle S, T, S \setminus F \rangle$.

**Intersection** We use the fact that $L_1 \cap L_2 = \overline{L_1 \cup L_2}$. 
### Projection

Let $\Sigma = \Sigma_1 \times \Sigma_2 = \{(\sigma_1, \sigma_2) \mid \sigma_1 \in \Sigma_1, \sigma_2 \in \Sigma_2, \#(\sigma_1) = \#(\sigma_2)\}$

We define $pr_1(t) : \mathbb{N}^* \to \Sigma_1$, where $pr_1(t)(p) = \sigma_1$ iff there exist $\sigma_2 \in \Sigma_2$ such that $t(p) = \langle \sigma_1, \sigma_2 \rangle$.

$pr_2(t)$ is defined in a similar way.

**Theorem 3** If $L \subseteq \mathcal{T}(\Sigma_1 \times \Sigma_2)$ is a recognizable tree language, then so are the projections $pr_1(L)$ and $pr_2(L)$. 
Minimization

A relation $\equiv \subseteq \mathcal{T}(\Sigma) \times \mathcal{T}(\Sigma)$ is a congruence on $\mathcal{T}(\Sigma)$ iff for every context $C[x_1, \ldots x_n]$:

\[
\forall 1 \leq i \leq n . \ u_i \equiv v_i \Rightarrow C[u_1, \ldots , u_n] \equiv C[v_1, \ldots , v_n]
\]

For a given tree language $L$, we define $\equiv_L$:

\[
u \equiv_L v \text{ iff for all contexts } C[x] \text{ we have } C[u] \in L \iff C[v] \in L
\]

Exercise 1 Show that $\equiv_L$ is a congruence. □
A Myhill-Nerode Theorem for Tree Languages

Theorem 4 (Myhill-Nerode) A tree language is recognizable iff the congruence \( \equiv_L \) is of finite index.

“\( \Rightarrow \)” Let \( A = \langle S, T, F \rangle \) be a \textit{complete} TA such that \( L = \mathcal{L}(A) \).

Let \( u \equiv_A v \) iff \( u \xrightarrow{*} q \iff v \xrightarrow{*} q \), for all \( q \in S \). We have \( u \equiv_A v \Rightarrow u \equiv_L v \).

“\( \Leftarrow \)” Define \( A_{\text{min}} = \langle S_{\text{min}}, T_{\text{min}}, F_{\text{min}} \rangle \), where:

- \( S_{\text{min}} = \{ [u]_L \mid u \in \mathcal{T}(\Sigma) \} \)
- \( T_{\text{min}} = \{ f([u_1]_L, \ldots, [u_n]_L) = [f(u_1, \ldots, u_n)]_L \mid u_1, \ldots, u_n, u \in \mathcal{T}(\Sigma) \} \)
- \( F_{\text{min}} = \{ [u]_L \mid u \in L \} \)
Pumping Lemma for Recognizable Tree Languages

Lemma 2 (Pumping) Let $L$ be a recognizable tree language. Then there exists a constant $N > 0$ such that, for every $t \in L$ with $\text{height}(t) > N$, there exists a context $C$, a non-trivial context $D$ and a tree $u$ such that $C[D[u]] \in L$, and, for all $n \geq 0$ we have $C[D^n[u]] \in L$.

Corollary 1 Let $A = \langle S, T, F \rangle$ be a tree automaton.

1. $\mathcal{L}(A) \neq \emptyset$ iff there exists $t \in \mathcal{L}(A)$ with $\text{height}(t) < \|S\|$, 
2. $\|\mathcal{L}(A)\| = \omega$ iff there exists $t \in \mathcal{L}(A)$ with $\|S\| < \text{height}(t) < 2\|S\|$.
Pumping Lemma for Recognizable Tree Languages

Exercise 2 Show that \( \{ f(g^n(a), g^n(a)) \mid n \geq 0 \} \) is not recognizable. □

Exercise 3 (Homework) Let \( L \) be a recognizable tree language over the alphabet \( \Sigma = \{ f, a, b \} \), where \( \#(f) = 2 \) and \( \#(a) = \#(b) = 0 \). Let \( L^{ac} \supseteq L \) be the smallest tree language which is closed by the application of the two rules below:

- **commutativity**: for all context \( C \) and subtrees \( t_1, t_2 \):
  \[
  C[f(t_1, t_2)] \in L^{ac} \iff C[f(t_2, t_1)] \in L^{ac}
  \]

- **associativity**: for all context \( C \) and subtrees \( t_1, t_2, t_3 \):
  \[
  C[f(f(t_1, t_2), t_3)] \in L^{ac} \iff C[f(t_1, f(t_2, t_3))] \in L^{ac}
  \]

Show that there exists a recognizable tree language \( L \) for which \( L^{ac} \) is not recognizable. □
Decidability

- Emptiness $\mathcal{L}(A) = \emptyset$ ?
- Equality $\mathcal{L}(A) = \mathcal{L}(B)$ ?
- Infinity $\|\mathcal{L}(A)\| < \infty$ ?
- Universality $\mathcal{L}(A) = \mathcal{T}(\Sigma)$ ?

Theorem 5 The emptiness, equality, infinity and universality problems on tree automata are decidable. In particular, emptiness is decidable in time polynomial in the size (number of states) of automata.
Top Down Tree Automata
**Definition**

A top-down tree automaton is a tuple $A = \langle S, I, T \rangle$ where:

- $S$ is a set of *states*,
- $I \subseteq S$ is a set of *initial states*,
- $T$ is a set of *transition rules* of the form
  
  \[ q(f) \rightarrow \langle q_1, \ldots, q_n \rangle \]

  where $\#(f) = n > 0$.

Notice that, for $\#(f) = 0$, the rules are of the form $q(f) \rightarrow \langle \rangle$. 
## Runs

A **run** of $A$ over a tree $t : \mathbb{N}^* \rightarrow \Sigma$ is a mapping $\pi : \text{dom}(t) \rightarrow S$ such that, for each position $p \in \text{dom}(t)$, where $q = \pi(p)$, we have:

- if $p = \epsilon$ then $q \in I$, and
- if $\#(t(p)) = n$ and $q_i = \pi(p_i)$, $1 \leq i \leq n$, then $T$ has a rule
  \[ q(t(p)) \rightarrow \langle q_1, \ldots, q_n \rangle \]

A run $\pi$ is said to be **accepting**, if and only if the tree is completely labeled by the automaton.

In particular, there must exist a rule $t(p)(\pi(p)) \rightarrow \langle \rangle \in T$, for all $p \in fr(t)$. 
Top Down vs. Bottom Up

Theorem 6  Bottom up and top down tree automata recognize the same languages.

A top down tree automaton is said to be deterministic if it has one initial state and no two rules with the same left-hand side.

Proposition 3  A deterministic top down tree automaton has at most one run for each input tree.

Proposition 4  There exists a recognizable tree language that is not accepted by any top down deterministic tree automaton.

Proof: \( L = \{ f(g(a), h(a)), f(h(a), g(a)) \} \)
Tree Automata and WSkS
MSOL on Trees: (W)SωS

Let $\Sigma = \{a, b, \ldots\}$ be a tree alphabet. The alphabet of (W)SωS is:

- the function symbols $\{s_i \mid i \in \mathbb{N}\}$; $s_i(x)$ denotes the $i$-th successor of $x$
- the set constants $\{p_a \mid a \in \Sigma\}$; $p_a$ denotes the set of positions of $a$
- the first and second order variables and connectives.
Examples

Let us consider binary trees, i.e. the alphabet of WS2S.

- The formula

  \[ closed(X) : \forall x . X(x) \rightarrow X(s_0(x)) \land X(s_1(x)) \]

  denotes the fact that \( X \) is a downward-closed set.

- The prefix ordering on tree positions is defined by

  \[ x \leq y : \forall X . closed(X) \land X(x) \rightarrow X(y) \]
Examples

- The formula $\text{path}(X)$ denotes the fact that $X$ is a path in the tree:

  $$\text{linear}(X) : \forall x, y . X(x) \land X(y) \rightarrow x \leq y \lor y \leq x$$

  $$\text{path}(X) : \text{linear}(X) \land \forall Y . \text{linear}(Y) \land X \subseteq Y \rightarrow X = Y$$

- A leaf is defined by the formula:

  $$\text{leaf}(x) : \exists X . \text{path}(X) \land X(x) \land \forall y . X(y) \rightarrow y \leq x$$

- A tree is finite iff:

  $$\forall X . \text{path}(X) \rightarrow \exists x . X(x) \land \forall y . X(y) \rightarrow y \leq x$$
From Automata to Formulae

Let $X_1, \ldots, X_k, x_{k+1}, \ldots, x_m$, and $\Sigma = \{0, 1\}^m$.

Let $A = \langle S, I, T \rangle$ be a non-deterministic top-down tree automaton, where $S = \{s_1, \ldots, s_p\}$. 
Coding of $\Sigma$

Let $\sigma \in \{0, 1\}^m$ and $\vec{X} = \langle X_1, \ldots, X_m \rangle$.

We define the formula $\Phi_\sigma(x, \vec{X})$ as the conjunction of:

- $X_i(x)$, $1 \leq i \leq m$, if $\sigma_i = 1$,
- $\neg X_i(x)$, $1 \leq i \leq m$, if $\sigma_i = 0$.

It follows, that for any $t \in \mathcal{T}(\Sigma)$, we have $t \models \forall x . \bigvee_{\sigma \in \Sigma} \Phi_\sigma(x, \vec{X})$. 
Coding of $S$

Let $\vec{Y} = \{Y_1, \ldots, Y_p\}$ be set variables.

Intuitively, the set variable $Y_i$, $1 \leq i \leq p$ contains all tree positions labeled by $A$ with state $s_i$ during the run on some tree.

$$\Phi_S(\vec{Y}) : \forall z . \bigvee_{1 \leq i \leq p} Y_i(z) \land \bigwedge_{1 \leq i < j \leq p} \neg \exists z . Y_i(z) \land Y_j(z)$$
Coding of $I$ and $T$

Every run starts from an initial state:

$$\Phi_I(\vec{Y}) : \exists x \forall y . x \leq y \land \bigvee_{s_i \in I} Y_i(x)$$

If $A$ is at position $x$ and $t(x) \in \{0, 1\}^m$, $A$ moves on $\langle s_0(x), s_1(x) \rangle$:

$$\Phi_T(\vec{X}, \vec{Y}) : \bigwedge_{i=1}^{p} \forall x . Y_i(x) \land \bigvee_{\sigma \in \Sigma} \Phi_{\sigma}(x, \vec{X}) \rightarrow \bigvee_{s_i(\sigma) \rightarrow \langle s_j, s_k \rangle} Y_j(s_0(x)) \land Y_k(s_1(x))$$

If $A$ is at a frontier position it must be in a state with no successors:

$$\Phi_F(\vec{X}, \vec{Y}) : \forall x . \text{leaf}(x) \land \bigvee_{\sigma \in \Sigma} \Phi_{\sigma}(x, \vec{X}) \rightarrow \bigvee_{s_i(\sigma) \rightarrow \langle \rangle} Y_i(x)$$
From Formulae to Automata

Let $\varphi : x_2 \in X_1$.

We define $A_\varphi = \langle \{s_0, s_1\}, s_0, T\rangle$, where:

$\langle 0, 0\rangle(s_0) \rightarrow \{\langle s_0, s_1\rangle, \langle s_1, s_0\rangle\}$

$\langle 1, 0\rangle(s_0) \rightarrow \{\langle s_0, s_1\rangle, \langle s_1, s_0\rangle\}$

$\langle 1, 1\rangle(s_0) \rightarrow \langle s_1, s_1\rangle$

$\langle 0, 0\rangle(s_1) \rightarrow \langle s_1, s_1\rangle$

$\langle 1, 0\rangle(s_1) \rightarrow \langle s_1, s_1\rangle$

$\langle 0, 0\rangle(s_1) \rightarrow \langle \rangle$

$\langle 1, 0\rangle(s_1) \rightarrow \langle \rangle$
From Formulae to Automata

Let \( \varphi : s_0(x_1) = x_2 \).

We define \( A_\varphi = \langle \{s_0, s_1, s_2\}, T, \{s_0\} \rangle \), where:

\[
\begin{align*}
\langle 0, 0 \rangle & \rightarrow s_2 \\
\langle 0, 1 \rangle & \rightarrow s_1 \\
\langle 0, 0 \rangle(s_2, s_2) & \rightarrow s_2 \\
\langle 0, 1 \rangle(s_2, s_2) & \rightarrow s_1 \\
\langle 1, 0 \rangle(s_1, s_2) & \rightarrow s_0 \\
\langle 0, 0 \rangle(s_0, s_2) & \rightarrow s_0 \\
\langle 0, 0 \rangle(s_2, s_0) & \rightarrow s_0
\end{align*}
\]
From Formulae to Automata

As in the case of automata on words, $A_\Phi$ can be effectively constructed, for any formula $\Phi$ of $WSkS$.

**Theorem 7** Given a ranked alphabet $\Sigma$, a tree language $L \subseteq T(\Sigma)$ is definable in $WSkS$ iff it is recognizable.

**Corollary 2** The SAT problem for $WSkS$ is decidable.