Compiler Construction

Lecture 16: Semantic Analysis IV & Code Generation I

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Outline

Attribute Evaluation Methods

Given:
- (strongly) noncircular attribute grammar $\mathfrak{A} = \langle G, E, V \rangle \in AG$
- syntax tree t of G
- valuation $v : Syn_\Sigma \to V$ where $Syn_\Sigma := \{\alpha.k \mid k \text{ labelled by } a \in \Sigma, \alpha \in \text{syn}(a)\} \subseteq Var_t$

Goal: extend v to (partial) solution $v : Var_t \to V$

Methods:

1. Topological sorting of D_t:
   1. start with attribute variables which depend at most on synthesized attributes of terminals
   2. proceed by successive substitution
2. Recursive functions (for strongly noncircular AGs):
   1. for every $A \in N$ and $\alpha \in \text{syn}(A)$, define evaluation function $g_{A,\alpha}$ with the following parameters:
      - the node of t where α has to be evaluated and
      - all inherited attributes of A on which α (potentially) depends
   2. for every $\alpha \in \text{syn}(S)$, evaluate $g_{S,\alpha}(k_0)$ where k_0 denotes the root of t
3. Special cases: S-attributed grammars (`yacc`), L-attributed grammars

Outline

L-Attributed Grammars I

In an L-attributed grammar, attribute dependencies on the right-hand sides of productions are only allowed to run from left to right.

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Definition 16.1 (L-attributed grammar)

Let $\mathfrak{A} = \langle G, E, V \rangle \in AG$ such that, for every $\pi \in P$ and $\beta.i = f(\ldots, \alpha.j, \ldots) \in E_\pi$ with $\beta \in Inh$ and $\alpha \in Syn$, $j < i$. Then $\mathfrak{A}$ is called an L-attributed grammar (notation: $\mathfrak{A} \in LAG$).

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Corollary 16.2

Every $\mathfrak{A} \in LAG$ is noncircular.

L-Attributed Grammars II

Example 16.3

L-attributed grammar:

$$
\begin{array}{lll}
S \to AB & i.1 = 0 \\
 & i.2 = s.1 + 1 \\
 & s.0 = s.2 + 1 \\
A \to \mathtt{a}A & i.2 = i.0 + 1 \\
 & s.0 = s.2 + 1 \\
A \to \mathtt{c} & s.0 = i.0 + 1 \\
B \to \mathtt{b} & s.0 = i.0 + 1
\end{array}
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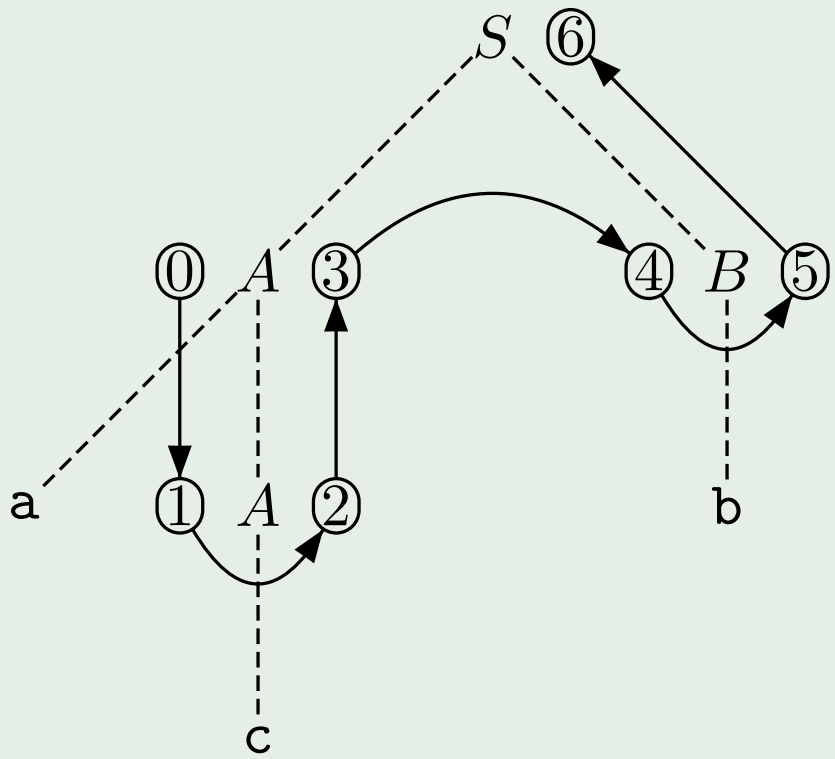
\end{array}
$$



Evaluation of L-Attributed Grammars

Observation 1: the syntax tree of an L-attributed grammar can be attributed by a depth-first, left-to-right tree traversal with two visits to each node

1. top-down: evaluation of inherited attributes
2. bottom-up: evaluation of synthesized attributes

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Observation 2: visit sequence fits nicely with parsing

1. top-down: expansion steps
2. bottom-up: reduction steps

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2. bottom-up: reduction steps

Idea: extend LL parsing to support reduction steps, and integrate attribute evaluation

$\Longrightarrow$ use $LR(0)$ items as stack alphabet
and store values of attribute variables in parsing stack

$LL(1)$ Parsing with Attribute Evaluation I

Definition 16.4 (Parsing automaton with attribute evaluation)

Let $\mathfrak{A} = \langle G, E, V \rangle \in LAG$ with $G = \langle N, \Sigma, P, S \rangle \in LL(1)$. The parsing automaton with attribute evaluation of $\mathfrak{A}$ is defined by the following components.

- Input alphabet Σ

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- Input alphabet Σ
- Pushdown alphabet $\Gamma := \bigcup_{\pi \in P \cup \{\rightarrow S\}} (LR(0)_\pi(G) \times Val_\pi)$ where
  - $LR(0)_\pi(G) := \{[A \rightarrow \delta_1 \cdot \delta_2] \mid \pi = A \rightarrow \delta_1 \delta_2\}$ and
  - $Val_\pi := \{v \mid v : Out_\pi \dashrightarrow V\}$

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  - $Val_\pi := \{v \mid v : Out_\pi \dashrightarrow V\}$
- Configurations $\Sigma^* \times \Gamma^*$
  - initial configuration: $(w, ([\rightarrow \cdot S], v_\emptyset))$
  - final configurations: $\{(\varepsilon, ([\rightarrow S \cdot], v)) \mid v \in Val_{\rightarrow S}\}$

Definition 16.4 (continued)

- Transitions:

  expand: (evaluate inherited attributes of expanded symbol)

  if $x \in \text{la}(B \to \delta')$, then

  $$(xw, ([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma)$$
  $$\vdash (xw, ([B \to \cdot\delta'], v')([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma)$$

  where $v' := [\beta.0 \mapsto f(v(\alpha_1.i_1), \dots, v(\alpha_n.i_n))]$ for $\beta \in \text{inh}(B)$ and $\beta.i = f(\alpha_1.i_1, \dots, \alpha_n.i_n) \in E_{A \to Y_1 \dots Y_{i-1} B\delta}$

$LL(1)$ Parsing with Attribute Evaluation II

Definition 16.4 (continued)

- Transitions:

  expand: (evaluate inherited attributes of expanded symbol)

  if $x \in \text{la}(B \to \delta')$, then

  $$(xw, ([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma)$$
  $$\vdash (xw, ([B \to \cdot\delta'], v')([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma)$$

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  match:
  $$(aw, ([A \to \delta_1 \cdot a\delta_2], v)\gamma)$$
  $$\vdash (w, ([A \to \delta_1 a \cdot \delta_2], v)\gamma)$$

$LL(1)$ Parsing with Attribute Evaluation II

Definition 16.4 (continued)

- Transitions:

expand: (evaluate inherited attributes of expanded symbol)

if $x \in \text{la}(B \to \delta')$, then

$$(xw, ([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma) \vdash (xw, ([B \to \cdot\delta'], v')([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma)$$

where $v' := [\beta.0 \mapsto f(v(\alpha_1.i_1), \dots, v(\alpha_n.i_n))]$ for $\beta \in \text{inh}(B)$ and $\beta.i = f(\alpha_1.i_1, \dots, \alpha_n.i_n) \in E_{A \to Y_1 \dots Y_{i-1} B\delta}$

match:
$$(aw, ([A \to \delta_1 \cdot a\delta_2], v)\gamma) \vdash (w, ([A \to \delta_1 a \cdot \delta_2], v)\gamma)$$

reduce: (evaluate synthesized attributes of reduced symbol)

$$(w, ([B \to \delta' \cdot], v')([A \to Y_1 \dots Y_{i-1} \cdot B\delta], v)\gamma) \vdash (w, ([A \to Y_1 \dots Y_{i-1} B \cdot \delta], v'')\gamma)$$

where $v'' := v[\alpha.i \mapsto f(v'(\alpha_1.i_1), \dots, v'(\alpha_n.i_n))]$ for $\alpha \in \text{syn}(B)$ and $\alpha.0 = f(\alpha_1.i_1, \dots, \alpha_n.i_n) \in E_{B \to \delta'}$

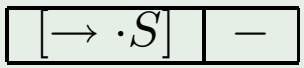
$LL(1)$ Parsing with Attribute Evaluation III

Example 16.5 (cf. Example 16.3)

$S \to AB$
$A \to \mathtt{a}A$
$A \to \mathtt{c}$
$B \to \mathtt{b}$

S

`acb`



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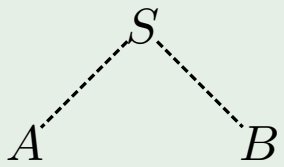

$\mathtt{acb}$
$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$

$LL(1)$ Parsing with Attribute Evaluation III

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$A \to \mathtt{a}A$
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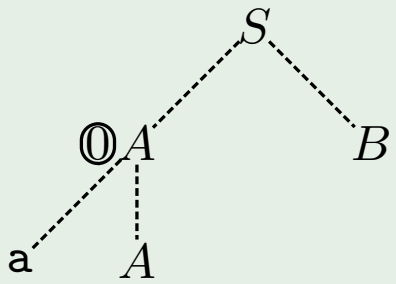

$\mathtt{acb}$

$[\to \cdot S]$	$-$

$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$

$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$LL(1)$ Parsing with Attribute Evaluation III

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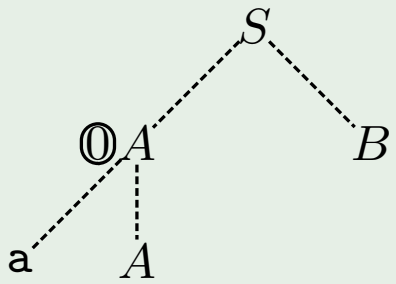
$A \to \mathtt{a}A$
$A \to \mathtt{c}$
$B \to \mathtt{b}$



$\mathtt{acb}$

$[\to \cdot S]$	$-$

$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$

$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash \mathtt{cb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$LL(1)$ Parsing with Attribute Evaluation III

Example 16.5 (cf. Example 16.3)

$S \to AB$
$A \to \mathtt{a}A$
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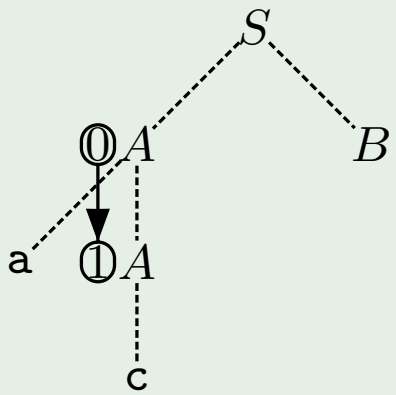
$B \to \mathtt{b}$



$\mathtt{acb}$

$[\to \cdot S]$	$-$

$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$

$\vdash \mathtt{acb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash \mathtt{cb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash \mathtt{cb}$

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$LL(1)$ Parsing with Attribute Evaluation III

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$S \to AB$
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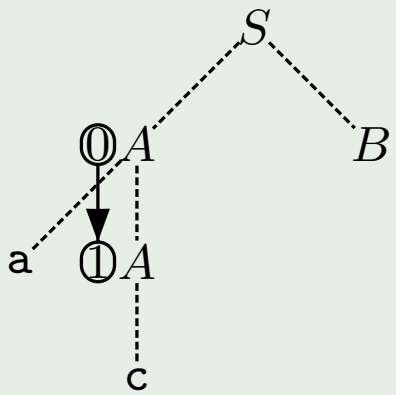
$A \to \mathtt{c}$
$B \to \mathtt{b}$



$\vdash \mathtt{b}$

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

$\mathtt{acb}$

$[\to \cdot S]$	–

$\vdash \mathtt{acb}$

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–

$\vdash \mathtt{acb}$

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash \mathtt{cb}$

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash \mathtt{cb}$

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$LL(1)$ Parsing with Attribute Evaluation III

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$A \to \mathtt{c}$
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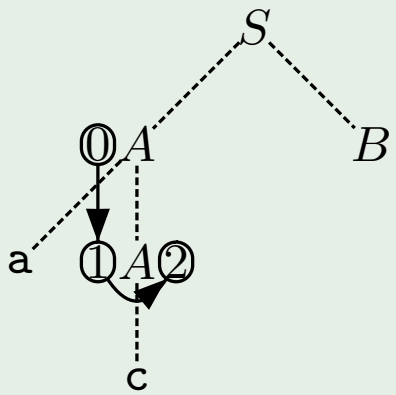


acb

$[\to \cdot S]$	$-$

$\vdash$ acb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$

$\vdash$ acb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

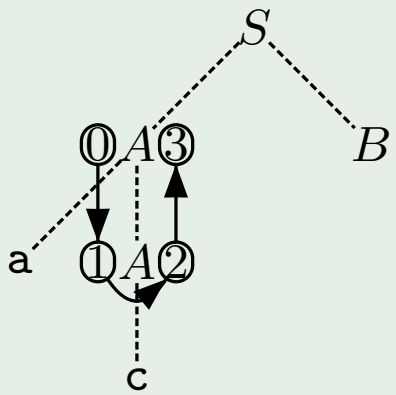
$\vdash$ b

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a}A\cdot]$	$i.0 = 0, s.2 = 2$

$LL(1)$ Parsing with Attribute Evaluation III

Example 16.5 (cf. Example 16.3)

$S \to AB$
$A \to \mathtt{a}A$
$A \to \mathtt{c}$
$B \to \mathtt{b}$



acb

$[\to \cdot S]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a}A\cdot]$	$i.0 = 0, s.2 = 2$

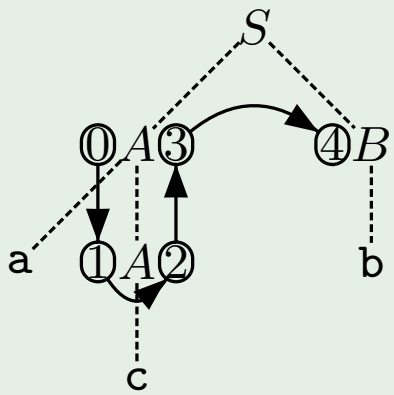
$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$

$LL(1)$ Parsing with Attribute Evaluation III

Example 16.5 (cf. Example 16.3)

$S \to AB$
$A \to \mathtt{a}A$
$A \to \mathtt{c}$
$B \to \mathtt{b}$



acb

$[\to \cdot S]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a}A\cdot]$	$i.0 = 0, s.2 = 2$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$

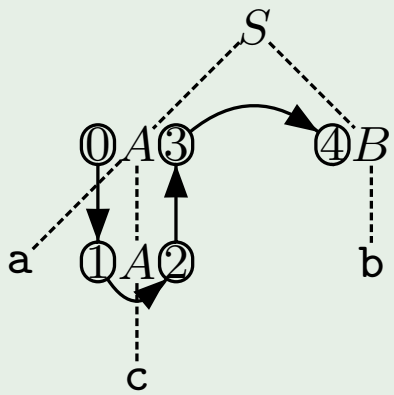
$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$
$[B \to \cdot \mathtt{b}]$	$i.0 = 4$

$LL(1)$ Parsing with Attribute Evaluation III

Example 16.5 (cf. Example 16.3)

$S \to AB$
$A \to \mathtt{a}A$
$A \to \mathtt{c}$
$B \to \mathtt{b}$



acb

$[\to \cdot S]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a}A\cdot]$	$i.0 = 0, s.2 = 2$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$
$[B \to \cdot \mathtt{b}]$	$i.0 = 4$

$\vdash \varepsilon$

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$
$[B \to \mathtt{b}\cdot]$	$i.0 = 4$

$LL(1)$ Parsing with Attribute Evaluation III

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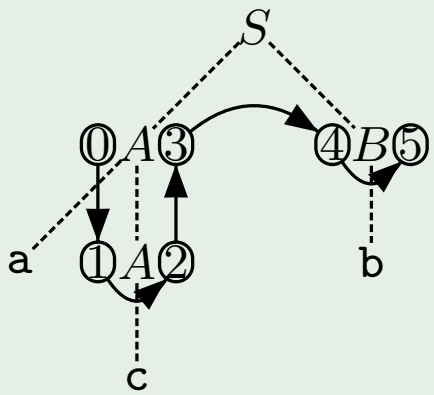


acb

$[\to \cdot S]$	$-$

$\vdash$ acb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$

$\vdash$ acb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \cdot \mathtt{c}]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	$-$
$[S \to \cdot AB]$	$-$
$[A \to \mathtt{a}A\cdot]$	$i.0 = 0, s.2 = 2$

$\vdash$ b

$[\to \cdot S]$	$-$
$[S \to A \cdot B]$	$s.1 = 3$

$\vdash$ b

$[\to \cdot S]$	$-$
$[S \to A \cdot B]$	$s.1 = 3$
$[B \to \cdot \mathtt{b}]$	$i.0 = 4$

$\vdash \varepsilon$

$[\to \cdot S]$	$-$
$[S \to A \cdot B]$	$s.1 = 3$
$[B \to \mathtt{b}\cdot]$	$i.0 = 4$

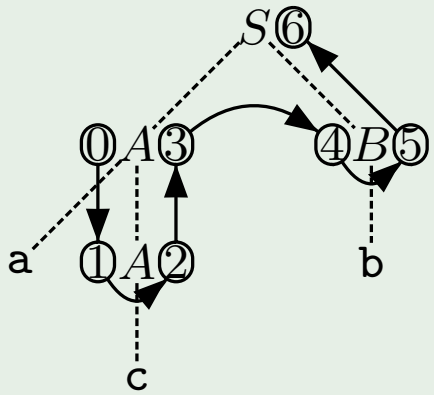
$\vdash \varepsilon$

$[\to \cdot S]$	$-$
$[S \to AB\cdot]$	$s.1 = 3, s.2 = 5$

$LL(1)$ Parsing with Attribute Evaluation III

Example 16.5 (cf. Example 16.3)

$S \to AB$
$A \to \mathtt{a}A$
$A \to \mathtt{c}$
$B \to \mathtt{b}$



acb

$[\to \cdot S]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–

$\vdash$ acb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \cdot \mathtt{a}A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$

$\vdash$ cb

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
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$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a} \cdot A]$	$i.0 = 0$
$[A \to \mathtt{c}\cdot]$	$i.0 = 1$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to \cdot AB]$	–
$[A \to \mathtt{a}A\cdot]$	$i.0 = 0, s.2 = 2$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$

$\vdash$ b

$[\to \cdot S]$	–
$[S \to A \cdot B]$	$s.1 = 3$
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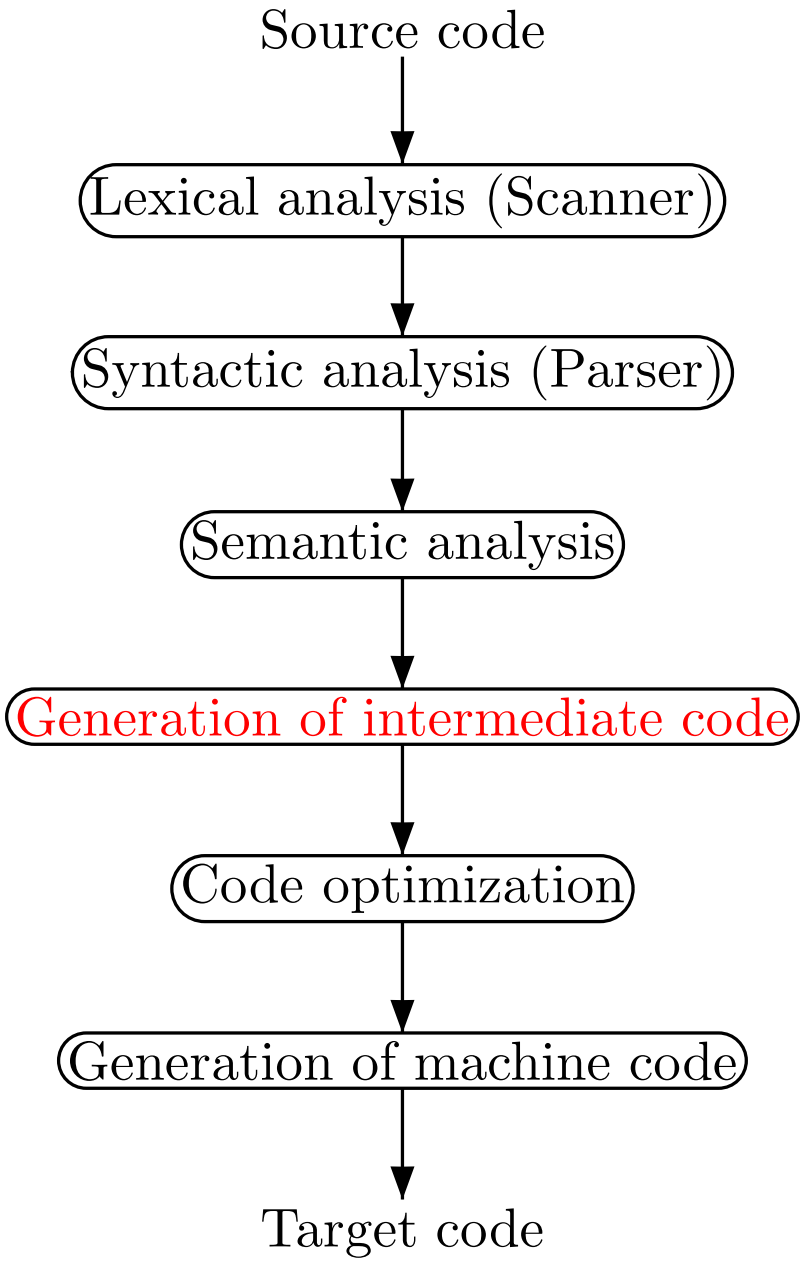
$\vdash \varepsilon$

$[\to \cdot S]$	–
$[S \to AB\cdot]$	$s.1 = 3, s.2 = 5$

$\vdash \varepsilon$

$[\to S\cdot]$	$s.1 = 6$

Conceptual Structure of a Compiler



Outline

Modularization of Code Generation I

Splitting of code generation for programming language PL:

$$\text{PL} \xrightarrow{\text{trans}} \text{IC} \xrightarrow{\text{code}} \text{MC}$$

Frontend: trans generates machine-independent intermediate code (IC) for abstract (stack) machine

Backend: code generates actual machine code (MC)

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Frontend: trans generates machine-independent intermediate code (IC) for abstract (stack) machine

Backend: code generates actual machine code (MC)

Advantages: IC machine independent $\Longrightarrow$

Portability: much easier to write IC compiler/interpreter for a new machine (as opposed to rewriting the whole compiler)

Fast compiler implementation: generating IC much easier than generating MC

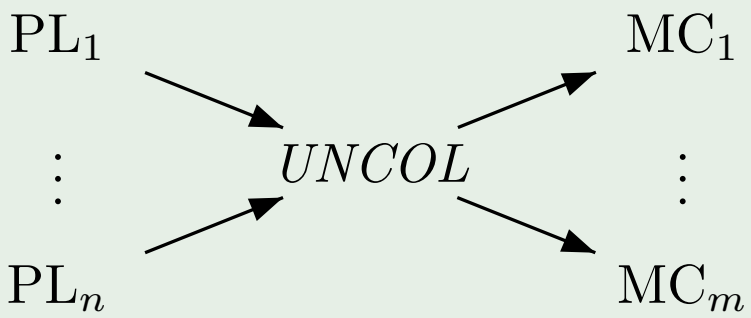
Code size: IC programs usually smaller than corresponding MC programs

Code optimization: division into machine-independent and machine-dependent parts

Modularization of Code Generation II

Example 16.6

1. UNiversal Computer-Oriented Language (UNCOL; $\approx$ 1960; `http://en.wikipedia.org/wiki/UNCOL`):
   universal intermediate language for compilers (never fully specified or implemented; too ambitious)



only $n + m$ translations
(in place of $n \cdot m$)

Modularization of Code Generation II

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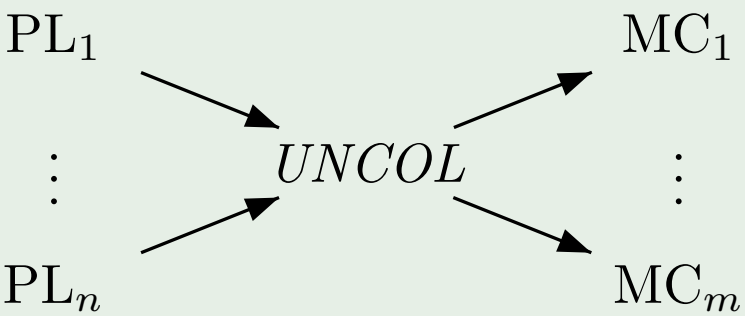

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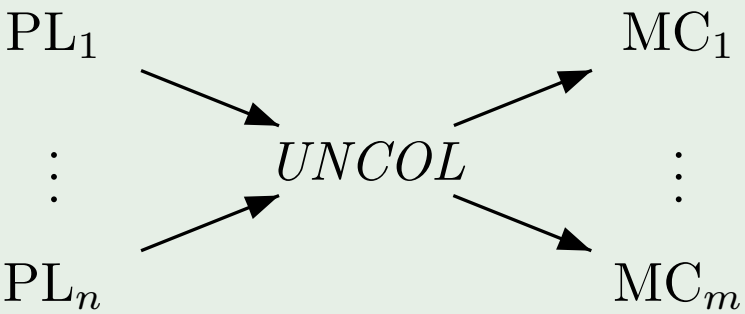

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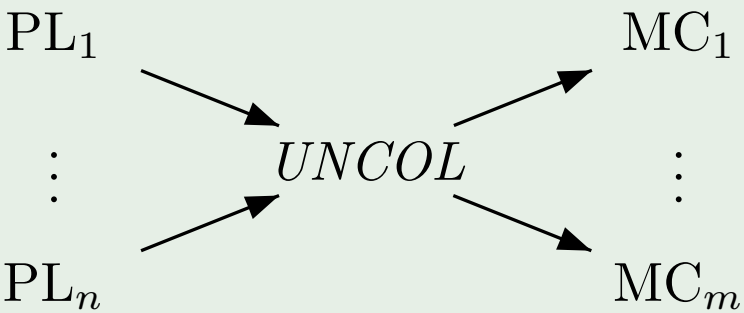

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Modularization of Code Generation II

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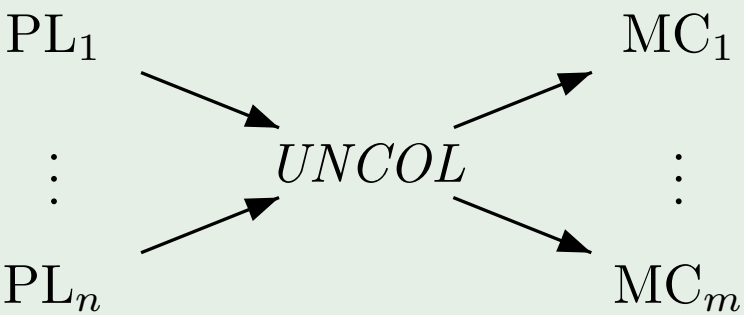

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5. Common Intermediate Language (CIL; Microsoft; `http://en.wikipedia.org/wiki/Common_Intermediate_Language`)

Language Structures I

Structures in imperative programming languages:
(object-oriented, declarative [functional/logic]: see special courses)

- Basic data types and basic operations
- Static and dynamic data structures
- Expressions and assignments
- Control structures (sequences, branching statements, loops, ...)
- Procedures and functions
- Modularity: blocks, modules, and classes

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- Control structures (sequences, branching statements, loops, ...)
- Procedures and functions
- Modularity: blocks, modules, and classes

Use of procedures and blocks:

- FORTRAN: non-recursive and non-nested procedures
  $\Longrightarrow$ static memory management (memory requirement determined at compile time)
- C: recursive and non-nested procedures
  $\Longrightarrow$ dynamic memory management using runtime stack (memory requirement only known at runtime), no static links
- Algol-like languages (Pascal, Modula): recursive and nested procedures
  $\Longrightarrow$ dynamic memory management using runtime stack with static links

Language Structures II

Structures in machine code: (von Neumann/SISD)

Memory hierarchy: accumulators, registers, cache, main memory, background storage

Instruction types: arithmetic/Boolean/... operation, test/jump instruction, transfer instruction, I/O instruction, ...

Address modes: direct/indirect, absolute/relative, ...

Architectures: RISC (few [fast but simple] instructions, many registers), CISC (many [complex but slow] instructions, few registers)

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Address modes: direct/indirect, absolute/relative, ...

Architectures: RISC (few [fast but simple] instructions, many registers), CISC (many [complex but slow] instructions, few registers)

Structures in intermediate code:

- Data types and operations like PL
- Data stack with basic operations
- Jumping instructions for control structures
- Runtime stack for blocks, procedures, and static data structures
- Heap for dynamic data structures

Outline

The Example Programming Language EPL

Structures of EPL:

- Only integer and Boolean values
- Arithmetic and Boolean expressions with strict and non-strict semantics
- Control structures: sequence, branching, iteration
- Nested blocks and recursive procedures with local and global variables
  ($\Longrightarrow$ dynamic memory management using runtime stack with static links)
- Procedure parameters and data structures later

Syntax of EPL

Definition 16.7 (Syntax of EPL)

The syntax of EPL is defined as follows:

$$
\begin{array}{lll}
\mathbb{Z}: & z & (*\ z \text{ is an integer } *) \\
Ide: & I & (*\ I \text{ is an identifier } *) \\
AExp: & A ::= z \mid I \mid A_1 \texttt{ + } A_2 \mid \ldots & \\
BExp: & B ::= A_1 \texttt{ < } A_2 \mid \texttt{not } B \mid B_1 \texttt{ and } B_2 \mid B_1 \texttt{ or } B_2 & \\
Cmd: & C ::= I \texttt{ := } A \mid C_1 \texttt{;} C_2 \mid \texttt{if } B \texttt{ then } C_1 \texttt{ else } C_2 \mid & \\
 & \quad \texttt{while } B \texttt{ do } C \mid I\texttt{()} & \\
Dcl: & D ::= D_C\ D_V\ D_P & \\
 & D_C ::= \varepsilon \mid \texttt{const } I_1 \texttt{ := } z_1 \texttt{,} \ldots \texttt{,} I_n \texttt{ := } z_n \texttt{;} & \\
 & D_V ::= \varepsilon \mid \texttt{var } I_1 \texttt{,} \ldots \texttt{,} I_n \texttt{;} & \\
 & D_P ::= \varepsilon \mid \texttt{proc } I_1 \texttt{;} K_1 \texttt{;} \ldots \texttt{;} I_n \texttt{;} K_n \texttt{;} & \\
Block: & K ::= D\ C & \\
Pgm: & P ::= \texttt{in/out } I_1 \texttt{,} \ldots \texttt{,} I_n \texttt{;} K \texttt{.} &
\end{array}
$$

Static Semantics of EPL I

- All identifiers in a declaration D have to be different.

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- Every identifier occurring in the command C of a block $D\ C$ must be declared
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  - in D or
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- Multiple declarations of an identifier in different blocks are possible. Each usage in a command C refers to the "innermost" declaration.
- Static scoping: the usage of an identifier in the body of a called procedure refers to its declaration environment (and not to its calling environment).

Static Semantics of EPL II

Example 16.8

```
in/out x;
  const c = 10;
  var y;
  proc P;
    var y, z;
    proc Q;
      var x, z;
      [... z := 1; P() ...]
    [... P() ... R() ...]
  proc R;
    [... P() ...]
  [... x := 0; P() ...] .
```

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- "Innermost" principle

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- "Innermost" principle
- Static scoping: body of `P` can refer to `x, y, z`
- Later declaration: call of `R` in `P` followed by declaration (in Pascal: `forward` declarations for one-pass compilation)