COMP-520 – Review lecture

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Sable Lab
McGill University

Winter 2016

Plan

- We'll go over the different concepts we saw in class

Plan

- We'll go over the different concepts we saw in class
- **You** will have to provide the answers

Plan

- We'll go over the different concepts we saw in class
- **You** will have to provide the answers
- I know the names of many of you; if you don't want to be called out, volunteer an answer :)

Compiler overview

What is a compiler?

What is a compiler?

An *automated* program that *translates* programs written in a *source language* into *equivalent* programs in a *target language*.

Compiler vs interpreter?

Compiler vs interpreter?

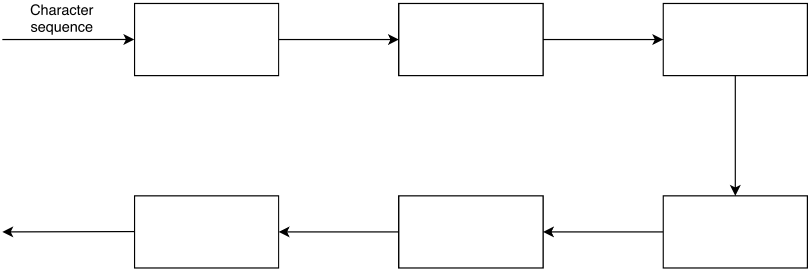
- Compiler: *translate* a program (execute the result later)
- Interpreter: *execute* a program immediately

AOT vs JIT?

AOT vs JIT?

- AOT: compile everything now, execute later
- JIT: execute now (interpreter), compile the hot parts during execution

Phases of the compilers



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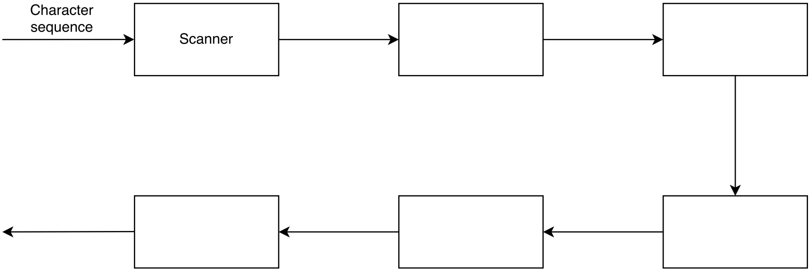

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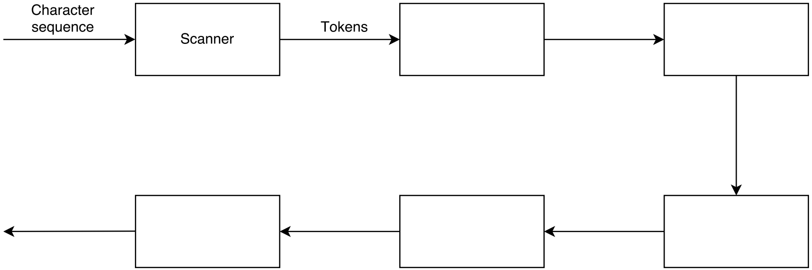

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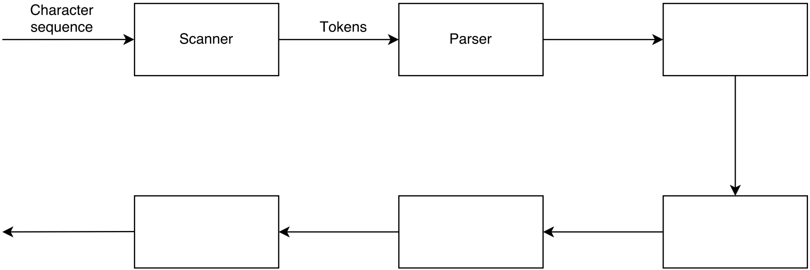

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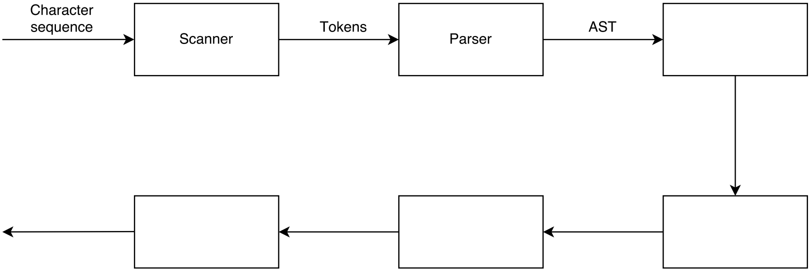

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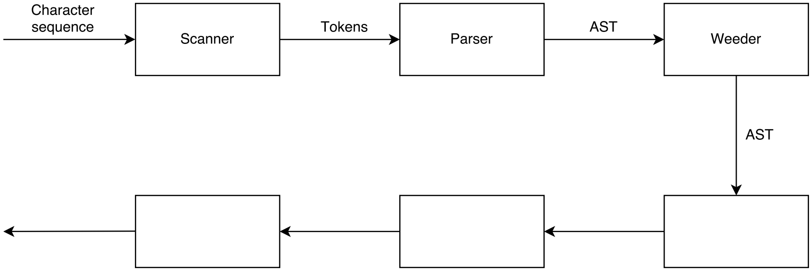

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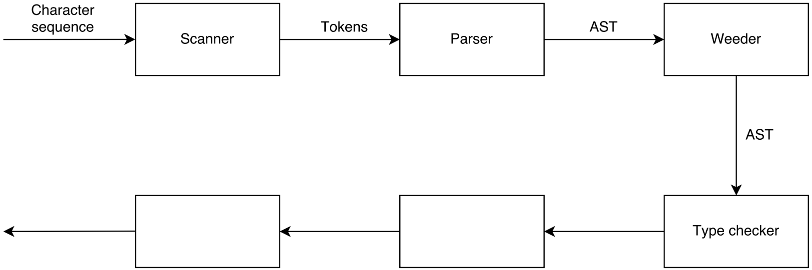

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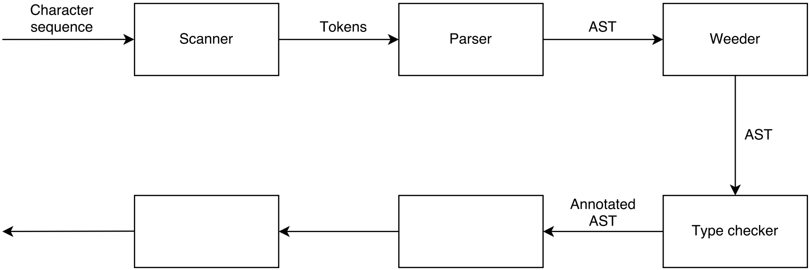

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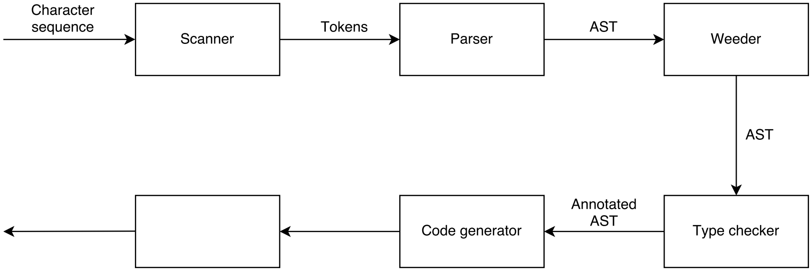

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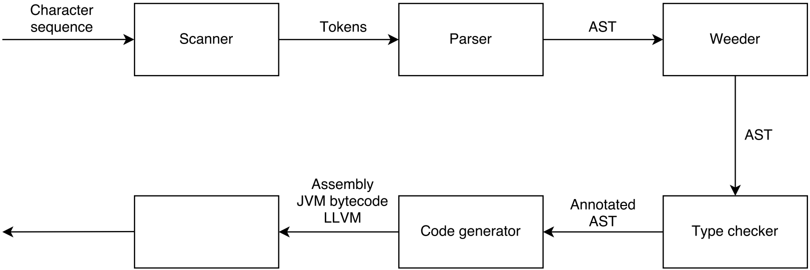

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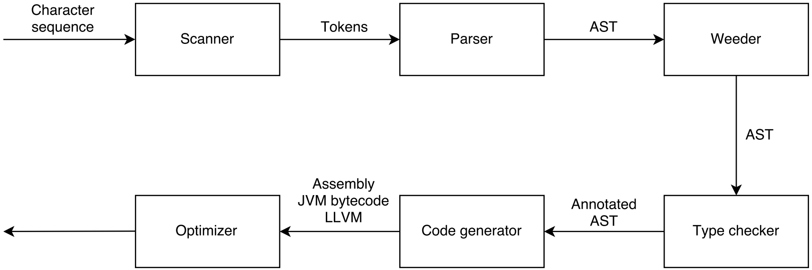

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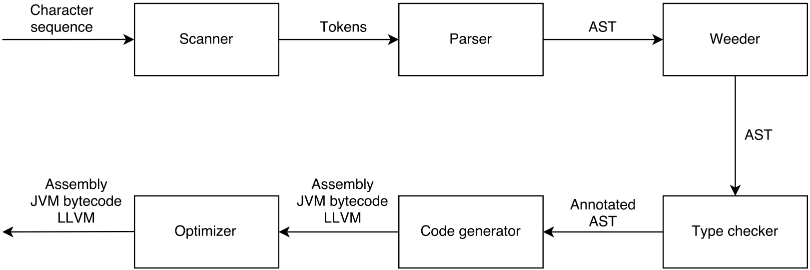


Scanner

Scanner generalities

- What is the input of a scanner?

Scanner generalities

- What is the input of a scanner? **Characters**

Scanner generalities

- What is the input of a scanner? **Characters**
- What is the output of a scanner?

Scanner generalities

- What is the input of a scanner? **Characters**
- What is the output of a scanner? **Tokens**

Scanner generalities

- What is the input of a scanner? **Characters**
- What is the output of a scanner? **Tokens**
- What formalism did we use to specify scanners?

Scanner generalities

- What is the input of a scanner? **Characters**
- What is the output of a scanner? **Tokens**
- What formalism did we use to specify scanners? **Regular expressions**

Regular expressions

What are the **5** building blocks of regular expressions?

- C
- E
- C
- A
- R

Regular expressions

What are the **5** building blocks of regular expressions?

- Character **'c'**
- E
- C
- A
- R

Regular expressions

What are the **5** building blocks of regular expressions?

- Character **'c'**
- Empty string ϵ
- C
- A
- R

Regular expressions

What are the **5** building blocks of regular expressions?

- Character **'c'**
- Empty string ϵ
- Concatenation **AB**
- A
- R

Regular expressions

What are the **5** building blocks of regular expressions?

- Character **'c'**
- Empty string ϵ
- Concatenation **AB**
- Alternation **A | B**
- R

Regular expressions

What are the **5** building blocks of regular expressions?

- Character **'c'**
- Empty string ϵ
- Concatenation **AB**
- Alternation **A | B**
- Repetition **A***

Regular expressions

More regular expressions

- Optional

Regular expressions

More regular expressions

- Optional **A? = A |** ϵ

Regular expressions

More regular expressions

- Optional **A? = A |** ϵ
- One-or-more

Regular expressions

More regular expressions

- Optional **A? = A |** ϵ
- One-or-more **A+ = A(A*)**

Regular expressions

More regular expressions

- Optional **A? = A |** ϵ
- One-or-more **A+ = A(A*)**
- Range of characters

Regular expressions

More regular expressions

- Optional **A? = A |** ϵ
- One-or-more **A+ = A(A*)**
- Range of characters **[a-c] = 'a' | 'b' | 'c'**

Scanner

How does flex match tokens?

Scanner

How does flex match tokens?

Scanner

How does flex handle multiple matches?

Scanner

How does flex handle multiple matches?

- Longest match rule (e.g. `var` vs `variance`)

Scanner

How does flex handle multiple matches?

- Longest match rule (e.g. `var` vs `variance`)
- First match rule (e.g. keywords vs identifiers)

Scanner

How does flex make regular expressions executable?

Scanner

How does flex make regular expressions executable?

Regular expression $\rightarrow$ NFA $\rightarrow$ DFA

Regular languages

Given a language, what is one sign that it is not a regular language?

Regular languages

Given a language, what is one sign that it is not a regular language?

Arbitrary nesting (e.g. parentheses, control structures)

Regular languages cannot be defined recusively.

Parser

Parser generalities

- What is the input of a parser?

Parser generalities

- What is the input of a parser? **Tokens**

Parser generalities

- What is the input of a parser? **Tokens**
- What is the output of a parser?

Parser generalities

- What is the input of a parser? **Tokens**
- What is the output of a parser? **Syntax tree (abstract or concrete)**

Parser generalities

- What is the input of a parser? **Tokens**
- What is the output of a parser? **Syntax tree (abstract or concrete)**
- What formalism did we use to specify parsers?

Parser generalities

- What is the input of a parser? **Tokens**
- What is the output of a parser? **Syntax tree (abstract or concrete)**
- What formalism did we use to specify parsers? **Context-free grammars**

Context-free grammars

What are the **4** components of context-free grammars?

- T
- N
- P
- S

Context-free grammars

What are the **4** building blocks of context-free grammars?

- Terminals (tokens)
- N
- P
- S

Context-free grammars

What are the **4** building blocks of context-free grammars?

- Terminals (tokens)
- Non-terminals (e.g. *stmt* or *expr*)
- P
- S

Context-free grammars

What are the **4** building blocks of context-free grammars?

- Terminals (tokens)
- Non-terminals (e.g. *stmt* or *expr*)
- Productions (e.g. $stmt \rightarrow PRINT\ '('\ expr\ ')'$)
- S

Context-free grammars

What are the **4** building blocks of context-free grammars?

- Terminals (tokens)
- Non-terminals (e.g. *stmt* or *expr*)
- Productions (e.g. $stmt \rightarrow PRINT\ '('\ expr\ ')'$)
- Start symbol

Context-free grammars

When is a grammar ambiguous?

Context-free grammars

When is a grammar ambiguous?

When *at least* **one sentence that has** *more than one* **derivation.**

Ambiguous grammar

Grammar: `E` $\rightarrow$ `id | E '+' E`

Program: `id + id + id`

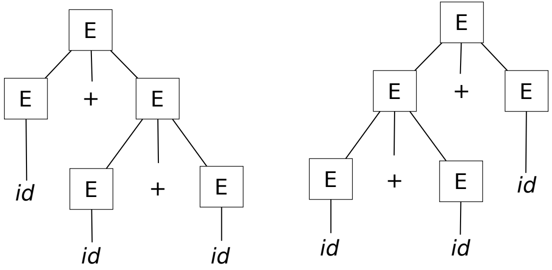
What are the two derivations for this sentence?

Ambiguous grammar

Grammar: `E` $\rightarrow$ `id | E '+' E`

Program: `id + id + id`

What are the two derivations for this sentence?



Ambiguous grammar

What are the two ways to fix this ambiguity?

Ambiguous grammar

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Factoring the grammar:

```
E = E '+' T | T;

T = id;
```

Ambiguous grammar

What are the two ways to fix this ambiguity?

Factoring the grammar:

```
E = E ‘+’ T | T;

T = id;
```

Precedence+associativity declarations:

```
%left ‘+’

E = id | E ‘+’ E;
```

Parsers

What do LL(1) and LR(1) mean?

Parsers

What do LL(1) and LR(1) mean?

- LL(1): left-to-right processing, **left-most derivation**, one token of lookahead
- LR(1): left-to-right processing, **right-most derivation**, one token of lookahead

Parsers

What is a left-most derivation? A right-most derivation?

Parsers

What is a left-most derivation? A right-most derivation?

```
stmt = IF expr THEN stmt ENDIF
     | PRINT expr
expr = ID
```

Parsers

What is a left-most derivation? A right-most derivation?

```
stmt = IF expr THEN stmt ENDIF
     | PRINT expr
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```
if x then print x endif
```

Parsers

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```
// left-most derivation
IF expr THEN stmt ENDIF ==>
```

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// left-most derivation
IF expr THEN stmt ENDIF ==>
    IF ID THEN stmt ENDIF
```

```
// right-most derivation
IF expr THEN stmt ENDIF ==>
```

Parsers

What is a left-most derivation? A right-most derivation?

```
stmt = IF expr THEN stmt ENDIF
     | PRINT expr
expr = ID
```

```
if x then print x endif
```

```
// left-most derivation
IF expr THEN stmt ENDIF ==>
    IF ID THEN stmt ENDIF
```

```
// right-most derivation
IF expr THEN stmt ENDIF ==>
    IF expr THEN PRINT expr ENDIF
```

Parsers

What are the two types of parser we saw in class?

- T
- B

Parsers

What are the two types of parser we saw in class?

- Top-down
- B

Parsers

What are the two types of parser we saw in class?

- Top-down
- Bottom-up

Parsers

What is the difference between top-down and bottom-up?

Parsers

What is the difference between top-down and bottom-up?

- Top-down: start symbol $\downarrow$ leaves
- Bottom-up: leaves $\uparrow$ start symbol

Recursive descent parser

```
// Grammar
stmt = ID '=' expr ';'
     | PRINT expr ';'
     | ...
```

Recursive descent parser

```
// Grammar
stmt = ID '=' expr ';'
     | PRINT expr ';'
     | ...
```

```
// Python code
def stmt():
    next_tok = peek()
    if next_tok == TOK_ID:
        id = consume(TOK_ID)
        consume(TOK_EQ)
        e = expr()
        consume(TOK_SEMI)
        return astnode(AST_ASSIGN, lhs=id, rhs=e)
    elif next_tok == TOK_PRINT:
        consume(TOK_PRINT)
        e = expr()
        consume(TOK_SEMI)
        return astnode(AST_PRINT, expr=e)
    elif ...
```

Bottom-up parsers

What are the three actions of a bottom-up parser?

- S
- R
- A

Bottom-up parsers

What are the three actions of a bottom-up parser?

- Shift (move a token from input to stack)
- R
- A

Bottom-up parsers

What are the three actions of a bottom-up parser?

- Shift (move a token from input to stack)
- Reduce (replace the rhs of a production that's on top of the stack with its lhs)
- A

Bottom-up parsers

What are the three actions of a bottom-up parser?

- Shift (move a token from input to stack)
- Reduce (replace the rhs of a production that's on top of the stack with its lhs)
- Accept

Bottom-up parsers

What type of conflict is exhibited in this grammar?

```
%{
%}

%token ID
%start start

%%
start: rule1 | rule2
rule1: ID
rule2: ID
%%
```

Bottom-up parsers

What type of conflict is exhibited in this grammar?

```
%{
%}

%token ID
%start start

%%
start: rule1 | rule2
rule1: ID
rule2: ID
%%
```

Reduce/reduce

Bottom-up parsers

What type of conflict is exhibited in this grammar?

```
%{
%}

%token ID
%start start

%%
start: ID ID | rule1 ID
rule1: ID
%%
```

Bottom-up parsers

What type of conflict is exhibited in this grammar?

```
%{
%}

%token ID
%start start

%%
start: ID ID | rule1 ID
rule1: ID
%%
```

Shift/reduce

AST

Concrete syntax tree

- What is a CST?

Concrete syntax tree

- What is a CST? **The tree that traces a parser derivation**

Concrete syntax tree

- What is a CST? **The tree that traces a parser derivation**
- What are the inner nodes of a CST?

Concrete syntax tree

- What is a CST? **The tree that traces a parser derivation**
- What are the inner nodes of a CST? **The non-terminals**

Concrete syntax tree

- What is a CST? **The tree that traces a parser derivation**
- What are the inner nodes of a CST? **The non-terminals**
- What are the leaves of a CST?

Concrete syntax tree

- What is a CST? **The tree that traces a parser derivation**
- What are the inner nodes of a CST? **The non-terminals**
- What are the leaves of a CST? **The terminals**

Abstract syntax tree

- What is a AST?

Abstract syntax tree

- What is a AST? **A tree representation of the program without the extraneous stuff (e.g. punctuation, extra non-terminals)**

Abstract syntax tree

- What is a AST? **A tree representation of the program without the extraneous stuff (e.g. punctuation, extra non-terminals)**
- What are the inner nodes of an AST?

Abstract syntax tree

- What is a AST? **A tree representation of the program without the extraneous stuff (e.g. punctuation, extra non-terminals)**
- What are the inner nodes of an AST? **Statements and expressions**

Abstract syntax tree

- What is a AST? **A tree representation of the program without the extraneous stuff (e.g. punctuation, extra non-terminals)**
- What are the inner nodes of an AST? **Statements and expressions**
- What are the leaves of an AST?

Abstract syntax tree

- What is a AST? **A tree representation of the program without the extraneous stuff (e.g. punctuation, extra non-terminals)**
- What are the inner nodes of an AST? **Statements and expressions**
- What are the leaves of an AST? **Literals and identifiers**

AST vs CST

- Can you use a CST for type checking?

AST vs CST

- Can you use a CST for type checking? **Yes**

AST vs CST

- Can you use a CST for type checking? **Yes**
- Can you use a CST for code gen?

AST vs CST

- Can you use a CST for type checking? **Yes**
- Can you use a CST for code gen? **Yes**

AST vs CST

- Can you use a CST for type checking? **Yes**
- Can you use a CST for code gen? **Yes**
- Then why do we prefer ASTs?

AST vs CST

- Can you use a CST for type checking? **Yes**
- Can you use a CST for code gen? **Yes**
- Then why do we prefer ASTs? **Simpler and shorter**

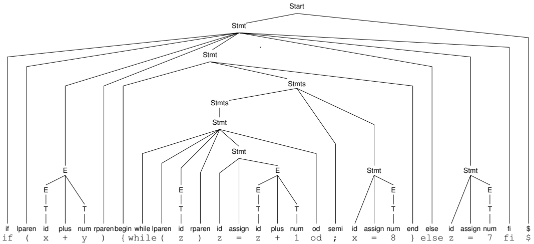

Figure 7.18: Concrete syntax tree.

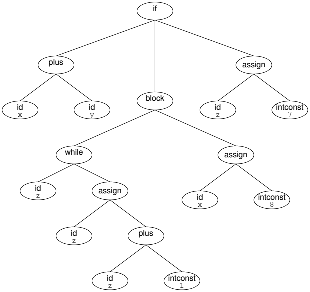

Figure 7.19: AST for the parse tree in Figure 7.18.

Weeder

Weeder

What is the role of the weeder?

Weeder

What is the role of the weeder?

Reject invalid programs that the parser cannot.

Weeder

What are some examples that a parser cannot reject and must be done in a weeder?

Weeder

What are some examples that a parser cannot reject and must be done in a weeder?

- Reject `break` and `continue` outside of loops
- Reject switch statements with multiple `default` branches
- Reject non-void functions without `return` statements

Weeder

Can we write a parser to reject `break` outside loops?

Weeder

Can we write a parser to reject `break` outside loops?

Probably, but the parser would be larger, more complicated and uglier.

Weeder

If a check can be done in the parser and in the weeder, where should we do it?

Weeder

If a check can be done in the parser and in the weeder, where should we do it?

- Where it makes our job easier
- Where it gives the better error message

Symbol tables

Symbol tables

What is stored in a symbol table?

Symbol tables

What is stored in a symbol table?

Identifiers and their related information.

Symbol tables

What information can be associated with a symbol?

Symbol tables

What information can be associated with a symbol?

- Type
- Offset in stack frame
- Resources for methods (e.g. number of locals, stack limit)
- Original name
- Etc.

Symbol tables

What data structure is typically used for symbol tables?

Symbol tables

What data structure is typically used for symbol tables?

Hash tables

Symbol tables

How do we handle multiple scopes where variables can be redeclared?

Symbol tables

How do we handle multiple scopes where variables can be redeclared?

Stack of hash tables

Symbol tables

How do we lookup a symbol?

Symbol tables

How do we lookup a symbol?

Search hash tables in the stack from top to bottom

Type checking

Type checking

What is the role of type checking?

Type checking

What is the role of type checking?

Reject programs that are *syntactically correct*, but *semantically wrong*.

Type checking

- What is the input of the type checker?

Type checking

- What is the input of the type checker? **AST**

Type checking

- What is the input of the type checker? **AST**
- What is the output of the type checker?

Type checking

- What is the input of the type checker? **AST**
- What is the output of the type checker? **Annotated AST**

Type checking

- Do declarations have a type?

Type checking

- Do declarations have a type? **No**

Type checking

- Do declarations have a type? **No**
- Do statements have a type?

Type checking

- Do declarations have a type? **No**
- Do statements have a type? **No**

Type checking

- Do declarations have a type? **No**
- Do statements have a type? **No**
- Do expressions have a type?

Type checking

- Do declarations have a type? **No**
- Do statements have a type? **No**
- Do expressions have a type? **Yes**

Type checking

Where do we store the type of expressions?

Type checking

Where do we store the type of expressions?

- In the AST
- In an auxiliary table (SableCC)

Type checking

Exercise

```
var x int = expr
```

Type checking

Exercise

```
var x int = expr
```

- Type check *expr*

Type checking

Exercise

```
var x int = expr
```

- Type check *expr*
- Make sure `int = typeof(expr)`

Type checking

Exercise

`var x int = expr`

- Type check *expr*
- Make sure `int = typeof(expr)`
- Report an error if the types don't match

Type checking

Exercise

```
var x int = expr
```

- Type check *expr*
- Make sure `int = typeof(expr)`
- Report an error if the types don't match
- Try to add `x -> int` to the symbol table

Type checking

Exercise

`var x int = expr`

- Type check *expr*
- Make sure `int = typeof(expr)`
- Report an error if the types don't match
- Try to add `x -> int` to the symbol table
- Report an error if `x` is already defined in the current scope

Type checking

Exercise

```
if expr {
  then_stmts
} else {
  else_stmts
}
```

Type checking

Exercise

```
if expr {
  then_stmts
} else {
  else_stmts
}
```

- Type check *expr*, *then_stmts*, and *else_stmts*

Type checking

Exercise

```
if expr {
  then_stmts
} else {
  else_stmts
}
```

- Type check *expr*, *then_stmts*, and *else_stmts*
- Make sure `typeof(expr) = bool`

Type checking

Exercise

```
if expr {
  then_stmts
} else {
  else_stmts
}
```

- Type check *expr*, *then_stmts*, and *else_stmts*
- Make sure `typeof(expr) = bool`
- Report an error if the types don't match

Type checking

Exercise

```
// x is declared as an int
max(2+3, x)
```

Type checking

Exercise

```
// x is declared as an int
max(2+3, x)
```

- Type check `2+3`
- Type check `x`
- Type check `max`
- Make sure `max` accepts two parameters and that `2+3` has the type of the first formal parameter and `x` has the type of the second formal parameter
- The whole expression has the return type declared for `max`

Inference rules

What does this mean in English?

$$\frac{P}{C}$$

Inference rules

What does this mean in English?

$$\frac{P}{C}$$

"If P then C"

Inference rules

What about this?

$$\frac{P_1 \quad P_2}{C}$$

Inference rules

What about this?

$$\frac{P_1 \quad P_2}{C}$$

"If P_1 and P_2 then C"

Inference rules

What about this?

$$\frac{P_1 \quad P_2}{C}$$

"If P_1 and P_2 then C"

Short version for:

$$\frac{P_1 \wedge P_2}{C}$$

Inference rules

What does this mean in English?

$$\Gamma \vdash e : T$$

Inference rules

What does this mean in English?

$$\Gamma \vdash e : T$$

"Under the set of assumptions Γ, *it is provable* ($\vdash$) that e has type (:) T"

(Assumptions = symbol table)

Inference rules

$$\frac{\Gamma \vdash e_1 : int \quad \Gamma \vdash e_2 : int}{\Gamma \vdash e_1 + e_2 : int}$$

Inference rules

$$\frac{\Gamma \vdash e_1 : int \quad \Gamma \vdash e_2 : int}{\Gamma \vdash e_1 + e_2 : int}$$

"If under the set of assumptions Γ it is provable that e_1 has type *int* and under the set of assumptions Γ it is provable that e_2 has type *int*, then under the set of assumptions Γ it is provable that $e_1 + e_2$ has type *int*."

Inference rules

$$\frac{\Gamma \vdash e : \mathit{bool} \quad \Gamma \vdash s_1 \quad \Gamma \vdash s_2}{\Gamma \vdash \mathit{if}\ e\ \{s_1\}\ \mathit{else}\ \{s_2\}}$$

Inference rules

$$\frac{\Gamma \vdash e : bool \quad \Gamma \vdash s_1 \quad \Gamma \vdash s_2}{\Gamma \vdash if\ e\ \{s_1\}\ else\ \{s_2\}}$$

"If under the set of assumptions Γ it is provable that e has type *bool* and under the set of assumptions Γ it is provable that s_1 typechecks, and under the set of assumptions Γ it is provable that s_2 typechecks, then under the set of assumptions Γ it is provable that $if\ e\ \{s_1\}\ else\ \{s_2\}$ typechecks."

Inference rules

This is not going to be on the exam (probably)

$$\frac{\begin{array}{l} L, C, M, V \vdash E_i : \sigma_i \\ \exists\, \vec{\tau}\colon\ \mathit{constructor}(L, \mathtt{C}, \vec{\tau}) \wedge \\ \qquad \vec{\tau} := \vec{\sigma} \wedge \\ \qquad (\forall \vec{\gamma}\colon\ \ \mathit{constructor}(L, \mathtt{C}, \vec{\gamma}) \wedge \vec{\gamma} := \vec{\sigma} \\ \qquad\qquad\quad \Downarrow \\ \qquad\qquad\quad \vec{\gamma} := \vec{\tau} \\ \qquad) \end{array}}{L, C, M, V \vdash \mathtt{new\ C(}E_1, \ldots, E_n\mathtt{)} : \mathtt{C}}$$

Type derivation
Grammar

```
expr = Id(x)
     | Int(n)

stmt = 'var' Id type '=' expr ';' stmt
     | 'print' expr ';' stmt
     | ϵ
```

Type derivation
Type rules

$$\frac{\Gamma(x) = T}{\Gamma \vdash x : T}\ Id(x) \qquad \frac{}{\Gamma \vdash n : int}\ Int(n)$$

$$\frac{\Gamma \vdash e : T \quad (\Gamma, x : T) \vdash s}{\Gamma \vdash var\ x\ T = e; s}\ var \qquad \frac{\Gamma \vdash e : T \quad \Gamma \vdash s}{\Gamma \vdash print\ e; s}\ print \qquad \frac{}{\Gamma \vdash \epsilon}\ empty$$

Type derivation

`var z int = 4; print z;` ϵ

$$\dfrac{\dfrac{}{\{\} \vdash 4 : int}\ Int \qquad \dfrac{\dfrac{\{z : int\}(z) = int}{\{z : int\} \vdash z : int}\ Id \qquad \dfrac{}{\{z : int\} \vdash \epsilon}\ empty}{\{z : int\} \vdash print\ z; \epsilon}\ print}{\{\} \vdash var\ z\ int = 4; print\ z; \epsilon}\ var$$

Code generation

Code generation

Code generation has many sub-phases:

- Computing resources
- Generating an IR of the code
- Optimizing the code
- Emitting the code

Computing resources

In JOOS, what resources did we need to compute?

- L
- S
- L
- O

Computing resources

In JOOS, what resources did we need to compute?

- Locals (how many?)
- S
- L
- O

Computing resources

In JOOS, what resources did we need to compute?

- Locals (how many?)
- Stack height (maximum)
- L
- O

Computing resources

In JOOS, what resources did we need to compute?

- Locals (how many?)
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- Labels (for control structures and some operators)
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Computing resources

In JOOS, what resources did we need to compute?

- Locals (how many?)
- Stack height (maximum)
- Labels (for control structures and some operators)
- Offsets (locals and formals)

IR

Which IRs did we see in class?

IR

Which IRs did we see in class?

JVM Bytecodes and VirtualRISC

JVM bytecodes

What does the body of this method look like in Jasmin?

```
public static void f(int x) {
    x = x + 3;
}
```

JVM bytecodes

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    x = x + 3;
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```

```
                            // [ TOP , BOT ]
                            // [     ,     ]
iload_0                     // [ x   ,     ]
ldc_int 3                   // [ 3   , x   ]
iadd                        // [ x+3 ,     ]
istore_0                    // [     ,     ]
```

JVM bytecodes

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- How many locals?

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```

- How many locals? **1**

JVM bytecodes

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- How many locals? **1**
- Stack height?

JVM bytecodes

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iadd                      // [ x+3 ,     ]
istore_0                  // [     ,     ]
```

- How many locals? **1**
- Stack height? **2**

JVM bytecodes

How would we generate code for the following pattern?

```
if (E) S1 else S2
```

JVM bytecodes

How would we generate code for the following pattern?

```
if (E) S1 else S2
```

```
<code for E>
ifeq else_branch
<code for S1>
goto end_if
else_branch:
<code for S2>
end_if:
```

JVM bytecodes

What invariant must be respected by *statement* code templates?

JVM bytecodes

What invariant must be respected by *statement* code templates?

Stack height is unchanged

JVM bytecodes

What invariant must be respected by *statement* code templates?

Stack height is unchanged

What invariant must be respected by *expression* code templates?

JVM bytecodes

What invariant must be respected by *statement* code templates?

Stack height is unchanged

What invariant must be respected by *expression* code templates?

Stack height increased by one