COMP3012/G53CMP: Lecture 5

Contextual Analysis: Scope I

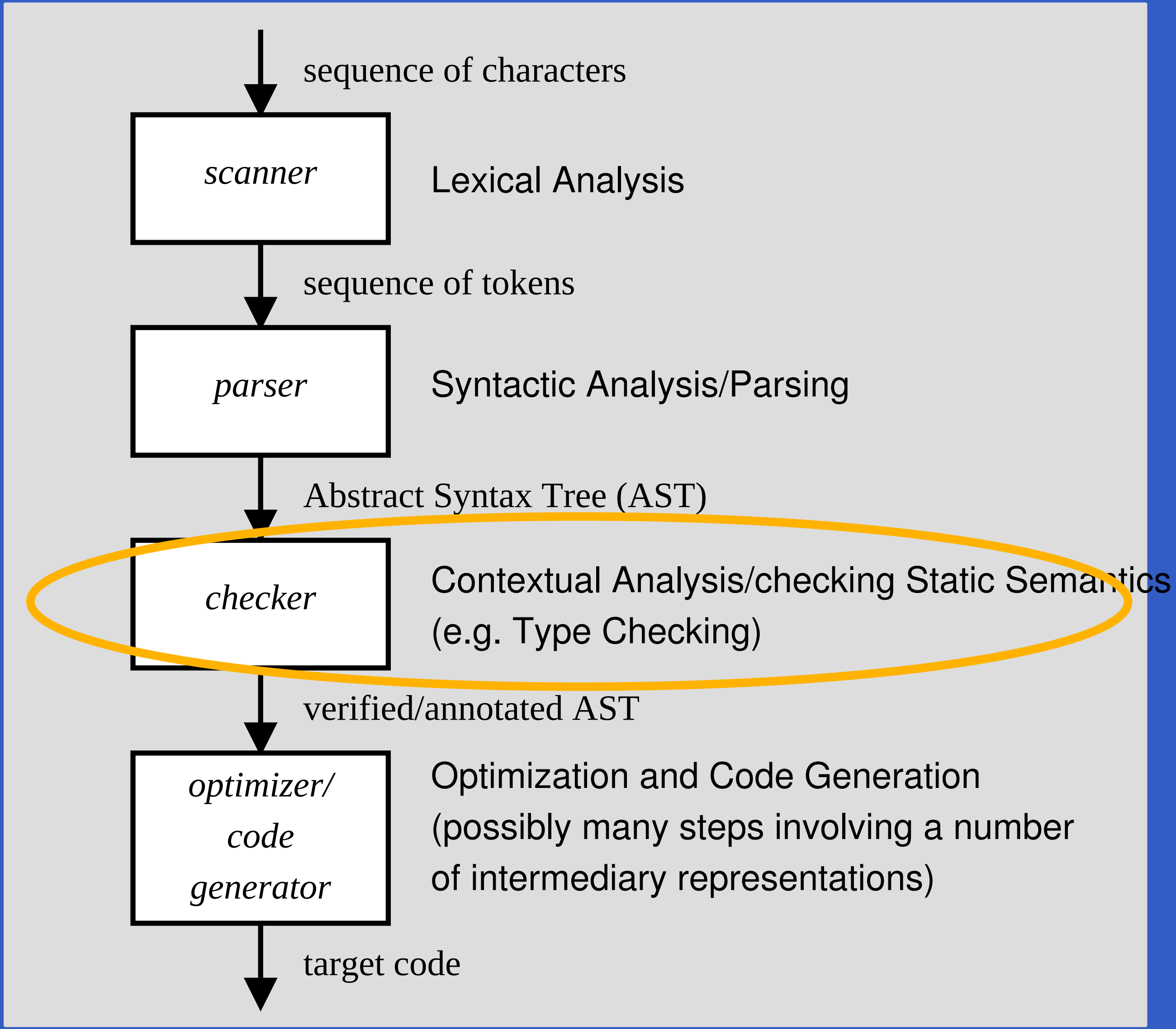
Henrik Nilsson

University of Nottingham, UK

This Lecture

- Limitations of context-free languages: Why checking contextual constraints is different from checking syntactical constraints.
- Identification (or Name Resolution)
- Block Structure
- Symbol table

Where Are We?



sequence of characters

scanner

Lexical Analysis

sequence of tokens

parser

Syntactic Analysis/Parsing

Abstract Syntax Tree (AST)

checker

Contextual Analysis/checking Static Semantics
(e.g. Type Checking)

verified/annotated AST

optimizer/
code
generator

Optimization and Code Generation
(possibly many steps involving a number
of intermediary representations)

target code

Contextual Analysis (1)

Our next major topic is ***contextual analysis*** or ***checking static semantics***.

Among other things, this involves:

Contextual Analysis (1)

Our next major topic is ***contextual analysis*** or ***checking static semantics***.

Among other things, this involves:

- Resolve the meaning of symbols.

Contextual Analysis (1)

Our next major topic is ***contextual analysis*** or ***checking static semantics***.

Among other things, this involves:

- Resolve the meaning of symbols.
- Report undefined symbols.

Contextual Analysis (1)

Our next major topic is ***contextual analysis*** or ***checking static semantics***.

Among other things, this involves:

- Resolve the meaning of symbols.
- Report undefined symbols.
- Type checking.

Contextual Analysis (2)

In short, contextual analysis is about ensuring that a program is ***statically well-formed***.

Contextual Analysis (2)

In short, contextual analysis is about ensuring that a program is ***statically well-formed***.

- But syntax has to do with “form” too.
  So what is new?

Contextual Analysis (2)

In short, contextual analysis is about ensuring that a program is ***statically well-formed***.

- But syntax has to do with “form” too.
  So what is new?
- Can’t we use context-free grammars (CFG) to express e.g. type constraints and thus make the parser do the checking for us?

Contextual Analysis (2)

In short, contextual analysis is about ensuring that a program is ***statically well-formed***.

- But syntax has to do with “form” too.
  So what is new?
- Can’t we use context-free grammars (CFG) to express e.g. type constraints and thus make the parser do the checking for us?

E.g., grammar productions like:

$$Cmd \quad \rightarrow \quad \texttt{\textbf{if}}\ BoolExpr\ \texttt{\textbf{then}}\ Cmd$$

Limitations of CFGs (1)

Attempt to express a "declare before use" requirement using a CFG.
Assumption: only a single variable `a`:

$$\begin{array}{lcl}
\mathit{Prog} & \rightarrow & \mathit{DeclA}\ \mathit{ProgA} \\
\mathit{ProgA} & \rightarrow & \mathit{StmtA}\ \mathit{ProgA} \quad | \quad \epsilon \\
\mathit{DeclA} & \rightarrow & \texttt{int a ;} \\
\mathit{StmtA} & \rightarrow & \texttt{a =}\ \mathit{ExprA}\ \texttt{;} \\
\mathit{ExprA} & \rightarrow & \texttt{a} \quad | \quad \mathit{ExprA}\ \texttt{+}\ \mathit{ExprA} \quad | \quad \mathit{Expr} \\
\mathit{Expr} & \rightarrow & \underline{\mathit{LitInt}} \quad | \quad \mathit{Expr}\ \texttt{+}\ \mathit{Expr}
\end{array}$$

Limitations of CFGs (2)

Generalization to two variables, `a` and `b`:

$$
\begin{array}{lcl}
\mathit{Prog} & \rightarrow & \mathit{DeclA}\ \mathit{ProgA} \mid \mathit{DeclB}\ \mathit{ProgB} \\
\mathit{ProgA} & \rightarrow & \mathit{StmtA}\ \mathit{ProgA} \mid \mathit{DeclB}\ \mathit{ProgAB} \mid \epsilon \\
\mathit{ProgB} & \rightarrow & \mathit{StmtB}\ \mathit{ProgB} \mid \mathit{DeclA}\ \mathit{ProgAB} \mid \epsilon \\
\mathit{ProgAB} & \rightarrow & \mathit{StmtAB}\ \mathit{ProgAB} \mid \epsilon \\
\mathit{DeclA} & \rightarrow & \mathbf{\texttt{int a ;}} \\
\mathit{DeclB} & \rightarrow & \mathbf{\texttt{int b ;}} \\
\mathit{StmtA} & \rightarrow & \mathbf{\texttt{a =}}\ \mathit{ExprA}\ \mathbf{\texttt{;}} \\
\mathit{StmtB} & \rightarrow & \mathbf{\texttt{b =}}\ \mathit{ExprB}\ \mathbf{\texttt{;}} \\
\mathit{StmtAB} & \rightarrow & (\mathbf{\texttt{a}} \mid \mathbf{\texttt{b}})\ \mathbf{\texttt{=}}\ \mathit{ExprAB}\ \mathbf{\texttt{;}} \\
\mathit{ExprA} & \rightarrow & \mathbf{\texttt{a}} \mid \mathit{ExprA}\ \mathbf{\texttt{+}}\ \mathit{ExprA} \mid \mathit{Expr} \\
\mathit{ExprB} & \rightarrow & \mathbf{\texttt{b}} \mid \mathit{ExprB}\ \mathbf{\texttt{+}}\ \mathit{ExprB} \mid \mathit{Expr} \\
\mathit{ExprAB} & \rightarrow & \mathbf{\texttt{a}} \mid \mathbf{\texttt{b}} \mid \mathit{ExprAB}\ \mathbf{\texttt{+}}\ \mathit{ExprAB} \mid \mathit{Expr} \\
\mathit{Expr} & \rightarrow & \underline{\mathit{LitInt}} \mid \mathit{Expr}\ \mathbf{\texttt{+}}\ \mathit{Expr}
\end{array}
$$

Limitations of CFGs (3)

Some observations:

Limitations of CFGs (3)

Some observations:

- Already for two variables, things get quite complicated.

Limitations of CFGs (3)

Some observations:

- Already for two variables, things get quite complicated.
  Roughly, how many “$ExprXYZ$” rules for n variables?

Limitations of CFGs (3)

Some observations:

- Already for two variables, things get quite complicated.
- In fact, the number of nonterminals grow exponentially. E.g., for a set of n variables $V = \{\mathtt{a}_i \mid 1 \leq i \leq n\}$, we get 2^n nonterminals $Expr[W]$, one for each $W \subseteq V$.

Limitations of CFGs (3)

Some observations:

- Already for two variables, things get quite complicated.
- In fact, the number of nonterminals grow exponentially. E.g., for a set of n variables $V = \{\mathbf{a}_i \mid 1 \leq i \leq n\}$, we get 2^n nonterminals $Expr[W]$, one for each $W \subseteq V$.
- Normally, the number of variables is ***unlimited***. That would imply ***infinitely*** many productions. No longer a CFG!

Limitations of CFGs (4)

Attempt to describe simple type constraints using a CFG:

$$
\begin{array}{lcl}
\mathit{IntExpr} & \rightarrow & \underline{\mathit{LitInt}} \\
 & | & \underline{\mathit{IntVar}} \\
 & | & \mathit{IntExpr}\ \texttt{+}\ \mathit{IntExpr} \\
\mathit{BoolExpr} & \rightarrow & \texttt{false} \\
 & | & \texttt{true} \\
 & | & \underline{\mathit{BoolVar}} \\
 & | & \mathit{IntExpr}\ \texttt{<}\ \mathit{IntExpr} \\
 & | & \texttt{not}\ \mathit{BoolExpr} \\
 & | & \mathit{BoolExpr}\ \texttt{\&\&}\ \mathit{BoolExpr}
\end{array}
$$

Limitations of CFGs (5)

Might look reasonable at first sight.

Limitations of CFGs (5)

Might look reasonable at first sight.

Any problem? Unrealistic assumption?

Limitations of CFGs (5)

Might look reasonable at first sight. However:

- The scheme hinges on partitioning the variables ***by name*** into two groups: ***integer variables*** ($\underline{\mathit{IntVar}}$) and ***boolean variables*** ($\underline{\mathit{BoolVar}}$).

Limitations of CFGs (5)

Might look reasonable at first sight. However:

- The scheme hinges on partitioning the variables ***by name*** into two groups: ***integer variables*** ($\underline{IntVar}$) and ***boolean variables*** ($\underline{BoolVar}$).
- But in most languages the type of a variable is given by the ***context***, not its name.

Limitations of CFGs (5)

Might look reasonable at first sight. However:

- The scheme hinges on partitioning the variables ***by name*** into two groups: ***integer variables*** ($\underline{IntVar}$) and ***boolean variables*** ($\underline{BoolVar}$).
- But in most languages the type of a variable is given by the ***context***, not its name.
- And how could we in general infer argument types from the name of a procedure or function?

Limitations of CFGs (5)

Might look reasonable at first sight. However:

- The scheme hinges on partitioning the variables ***by name*** into two groups: ***integer variables*** ($\underline{IntVar}$) and ***boolean variables*** ($\underline{BoolVar}$).
- But in most languages the type of a variable is given by the ***context***, not its name.
- And how could we in general infer argument types from the name of a procedure or function?
- We should not expect to be able to capture ***context-sensitive*** information using a ***context-free*** grammar.

Unrestricted Grammars (1)

- These examples do not prove that it is impossible to achieve what we tried to achieve using CFGs.

Unrestricted Grammars (1)

- These examples do not prove that it is impossible to achieve what we tried to achieve using CFGs.
- However, it ***can*** be proved that this indeed is the case: contextual constraints result in ***context sensitive*** or even ***recursively enumerable*** languages; such languages ***cannot*** be described by CFGs.

Unrestricted Grammars (2)

- ***Unrestricted grammars*** with productions

  $$\alpha \to \beta$$

  where α and β both are ***arbitrary strings*** could be used to express arbitrary contextual constraints.

Unrestricted Grammars (2)

- ***Unrestricted grammars*** with productions

  $$\alpha \to \beta$$

  where α and β both are ***arbitrary strings*** could be used to express arbitrary contextual constraints.
- However, unrestricted grammars are in fact equivalent to Turing Machines!

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

- Specifying contextual constraints:

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

- Specifying contextual constraints:
  - Informally, using natural language.

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

- Specifying contextual constraints:
  - Informally, using natural language.
  - Formally, using a mathematical formalism like attribute grammars, logical inference rules.

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

- Specifying contextual constraints:
  - Informally, using natural language.
  - Formally, using a mathematical formalism like attribute grammars, logical inference rules.
- Implementing contextual checks:

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

- Specifying contextual constraints:
  - Informally, using natural language.
  - Formally, using a mathematical formalism like attribute grammars, logical inference rules.
- Implementing contextual checks:
  - General purpose programming language.

Expressing Contextual Constraints

Neither Turing Machines nor Unrestricted Grammars are very practical languages.

- Specifying contextual constraints:
  - Informally, using natural language.
  - Formally, using a mathematical formalism like attribute grammars, logical inference rules.
- Implementing contextual checks:
  - General purpose programming language.
  - Direct support of mathematical formalism, unifying specification and implementation.

Contextual Analysis (1)

Two important kinds of contextual constraints:

Contextual Analysis (1)

Two important kinds of contextual constraints:

- ***Scope rules***: visibility; which declarations take effect where.

Contextual Analysis (1)

Two important kinds of contextual constraints:

- ***Scope rules***: visibility; which declarations take effect where.
- ***Type rules***: internal consistency; ensuring that every expression computes a value of acceptable form, i.e., has a valid type.

Contextual Analysis (1)

Two important kinds of contextual constraints:

- ***Scope rules***: visibility; which declarations take effect where.
- ***Type rules***: internal consistency; ensuring that every expression computes a value of acceptable form, i.e., has a valid type.

These are the ones we mainly will be concerned with in this course.

Contextual Analysis (2)

Corresponding subphases of the contextual analysis:

Contextual Analysis (2)

Corresponding subphases of the contextual analysis:

- ***Identification*** or ***Name Resolution***: applying the scope rules in order to relate each applied identifier occurrence to its declaration.

Contextual Analysis (2)

Corresponding subphases of the contextual analysis:

- ***Identification*** or ***Name Resolution***: applying the scope rules in order to relate each applied identifier occurrence to its declaration.
- ***Type checking***: applying the type rules to infer the type of each expression, and compare it with the expected type.

Contextual Analysis (3)

Many other possible kinds of contextual constraints. E.g. Java has rules concerning:

Contextual Analysis (3)

Many other possible kinds of contextual constraints. E.g. Java has rules concerning:

- ***Abstract classes***; e.g.:
  - Only abstract classes can have abstr. methods

```
abstract class A {
    abstract void callme();
}
```

Contextual Analysis (3)

Many other possible kinds of contextual constraints. E.g. Java has rules concerning:

- ***Abstract classes***; e.g.:
  - Only abstract classes can have abstr. methods

    ```
    abstract class A {
        abstract void callme();
    }
    ```

  - Abstract classes may not be instantiated:

    Not allowed: `new A();`

Contextual Analysis (4)

- ***Final classes***; e.g.:
  - a final class cannot be extended
  - a class cannot be both final and abstract.

Contextual Analysis (4)

- ***Final classes***; e.g.:
  - a final class cannot be extended
  - a class cannot be both final and abstract.
- ***Exceptions***; e.g., the set of exceptions a method can raise must be declared (except for unchecked exceptions):

```
public void writeList()
    throws IOException { ...  }
```

Contextual Analysis (5)

- ***Definite assignment***; a local variable must not be read unless it has been “definitely assigned before”.
  For example, the code fragment

  ```
  int k, n = 5;
  if (n > 2) k = 3;
  System.out.println(k);
  ```

  is ***rejected***.

Contextual Analysis (6)

An example of a Java "definite assignment" rule:

V is definitely assigned after

`if (`e`)` S `else` T

iff V is definitely assigned after S and V is definitely assigned after T.

Contextual Analysis (6)

An example of a Java "definite assignment" rule:

> V is definitely assigned after
>
> `if (`e`)` S `else` T
>
> iff V is definitely assigned after S and V is definitely assigned after T.

Note: The rule does not take the ultimate ***run-time value*** of e into account. That is what makes the analysis decidable.

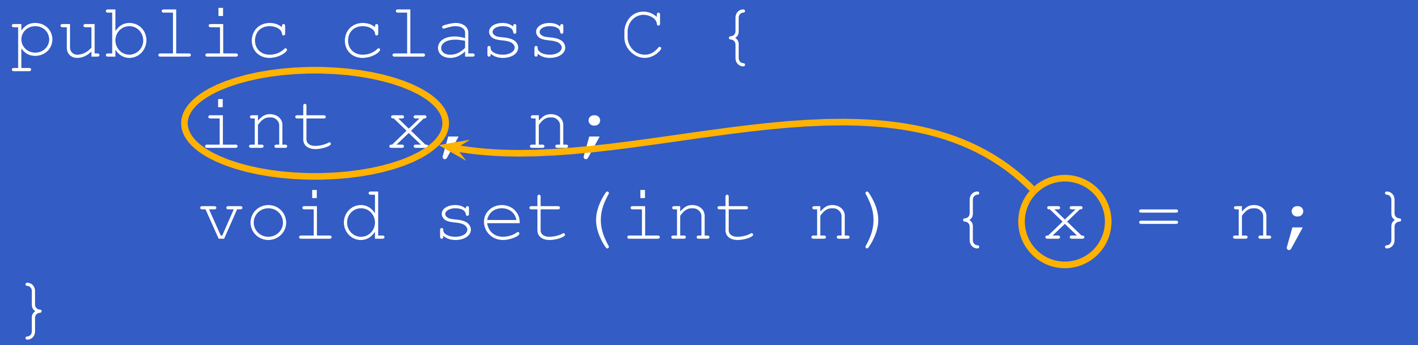
Identification

Identification (or ***Name Resolution***) is the task of relating each ***applied*** identifier occurrence to its ***declaration***.

```
public class C {
    int x, n;
    void set(int n) { x = n; }
}
```

Identification

Identification (or ***Name Resolution***) is the task of relating each ***applied*** identifier occurrence to its ***declaration***.



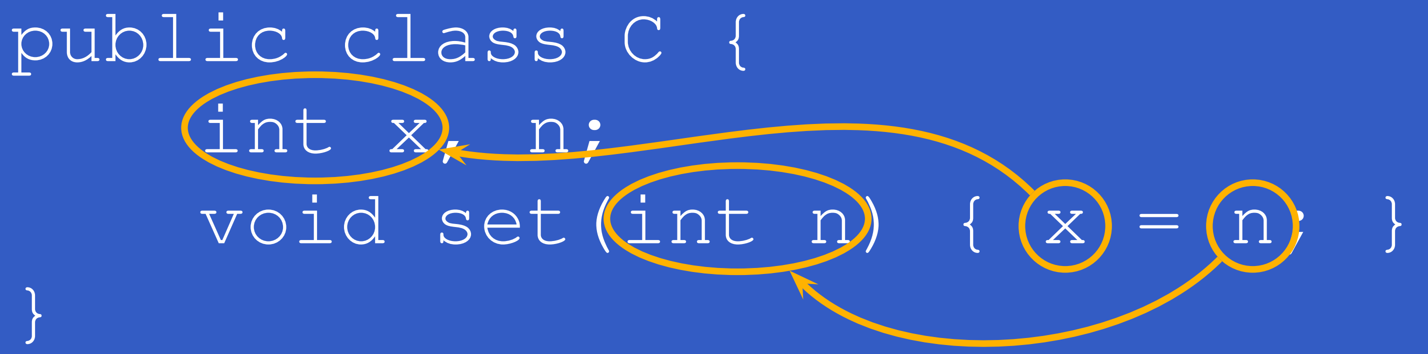
```
public class C {
    int x, n;
    void set(int n) { x = n; }
}
```

In the body of `set`, the one applied occurrence of

- `x` refers to the ***instance variable*** `x`

Identification

Identification (or ***Name Resolution***) is the task of relating each ***applied*** identifier occurrence to its ***declaration***.



```
public class C {
    int x, n;
    void set(int n) { x = n; }
}
```

In the body of `set`, the one applied occurrence of

- `x` refers to the ***instance variable*** `x`
- `n` refers to the ***argument*** `n`.

Scope and Scope Rules (1)

The identification process is governed by the ***scope rules*** of the language.

Important terms:

Scope and Scope Rules (1)

The identification process is governed by the ***scope rules*** of the language.

Important terms:

- ***Scope:*** the portion of a program over which a declaration takes effect.

Scope and Scope Rules (1)

The identification process is governed by the ***scope rules*** of the language.

Important terms:

- ***Scope:*** the portion of a program over which a declaration takes effect.
- ***Block:*** a program phrase that delimits the scope of declarations within it.

Scope and Scope Rules (2)

Consider the MiniTriangle `let` block command:

`let` *decls* `in` *body*

The scope of each declaration is the rest of the block.

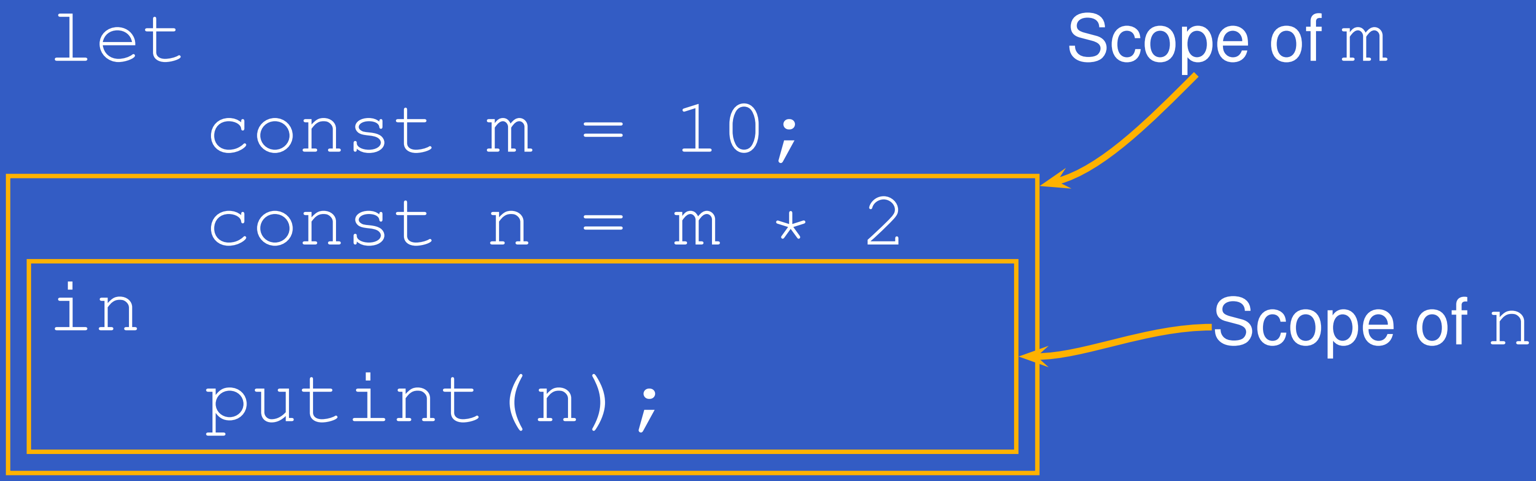
Scope and Scope Rules (2)

Consider the MiniTriangle `let` block command:

`let` *decls* `in` *body*

The scope of each declaration is the rest of the block.

For example:



```
let
    const m = 10;
    const n = m * 2
in
    putint(n);
```

Scope of `m`

Scope of `n`

Scope and Scope Rules (3)

Haskell's `let`-expressions:

$$\texttt{let}\ \ id\ =\ expr\ \ \texttt{in}\ \ body$$

The scope of id includes both $expr$ and $body$!

Scope and Scope Rules (3)

Haskell’s `let`-expressions:

`let` $id = expr$ `in` $body$

The scope of id includes both $expr$ and $body$!

For example:

```
let xs = 1:xs in take 7 xs
```

Scope of `xs`

Scope and Scope Rules (4)

Part II of the coursework uses a version of Mini-Triangle extended with procedures and functions:

```
let
    const n : Integer = 2;
    proc p(x : Integer) begin
                 ... p(x * m) ...
         end;
    const m : Integer = n * n
in
    ...
```

Scope and Scope Rules (5)

In the extended version:

Scope and Scope Rules (5)

In the extended version:

- The scope of a declared entity is extended to include the bodies of ***all*** procedures and functions declared in the same `let`-block.

Scope and Scope Rules (5)

In the extended version:

- The scope of a declared entity is extended to include the bodies of ***all*** procedures and functions declared in the same `let`-block.
- This allows procedures and functions to be (mutually) recursive.

Scope and Scope Rules (5)

In the extended version:

- The scope of a declared entity is extended to include the bodies of ***all*** procedures and functions declared in the same `let`-block.
- This allows procedures and functions to be (mutually) recursive.
- However, definition/initialization expressions for constants/variables must not use functions defined in the same `let`-block.

Scope and Scope Rules (5)

In the extended version:

- The scope of a declared entity is extended to include the bodies of ***all*** procedures and functions declared in the same `let`-block.
- This allows procedures and functions to be (mutually) recursive.
- However, definition/initialization expressions for constants/variables must not use functions defined in the same `let`-block.
- This avoids calling functions that may refer to as-yet uninitialized variables.

Scope and Scope Rules (6)

In addition to deciding the range of declarations, the scope rules also also deal with issues like

Scope and Scope Rules (6)

In addition to deciding the range of declarations, the scope rules also also deal with issues like

- whether explicit declarations are required

Scope and Scope Rules (6)

In addition to deciding the range of declarations, the scope rules also also deal with issues like

- whether explicit declarations are required
- whether multiple declarations at the same level are allowed

Scope and Scope Rules (6)

In addition to deciding the range of declarations, the scope rules also also deal with issues like

- whether explicit declarations are required
- whether multiple declarations at the same level are allowed
- whether shadowing/hiding is allowed.

Some Java Scope Rules (1)

From the Java Language Specification ver. 1.0:

Some Java Scope Rules (1)

From the Java Language Specification ver. 1.0:

- The scope of a member declared in or inherited by a class type or interface type is the entire declaration of the class or interface type. The declaration of a member needs to appear before it is used only when the use is in a field initialization expression.

Some Java Scope Rules (1)

From the Java Language Specification ver. 1.0:

- The scope of a member declared in or inherited by a class type or interface type is the entire declaration of the class or interface type. The declaration of a member needs to appear before it is used only when the use is in a field initialization expression.
- The scope of a parameter of a method is the entire body of the method.

Some Java Scope Rules (2)

- Hiding the name of a local variable is not permitted. For example, the following code fragment is rejected:

```
static int x = 10;
public void foo(int x) {
    if (x < 0) {
        int x = 10;
        ...
    }
    ...
}
```

OK, hides class variable x

Not OK, hides parameter x

Symbol Table

A ***symbol table***, also called ***identification table*** or ***environment***, is used during identification to keep track of ***symbols*** and their ***attributes***, such as:

- kind of symbol (class name, local variable, etc.)
- scope level
- type
- source code position

Block Structure (1)

The organisation of the symbol table depends on the source language's ***block structure***. Three main possibilities:

Block Structure (1)

The organisation of the symbol table depends on the source language's ***block structure***. Three main possibilities:

- ***Monolithic block structure***: one common, global scope.
  (Old Basic dialects, Cobol, Assembly lang., . . .)

Block Structure (1)

The organisation of the symbol table depends on the source language's ***block structure***. Three main possibilities:

- ***Monolithic block structure***: one common, global scope.
  (Old Basic dialects, Cobol, Assembly lang., . . .)
- ***Flat block structure***: blocks with local scope enclosed in a global scope. (Fortran)

Block Structure (1)

The organisation of the symbol table depends on the source language's ***block structure***. Three main possibilities:

- ***Monolithic block structure***: one common, global scope.
  (Old Basic dialects, Cobol, Assembly lang., . . .)
- ***Flat block structure***: blocks with local scope enclosed in a global scope. (Fortran)
- ***Nested block structure***: blocks can be nested to arbitrary depth.
  (Ada, C, C++, Java, C#, Haskell, ML, . . .)

Block Structure (2)

We will focus on nested block structure in the following because:

- monolithic and flat block structure can be considered special cases of nested block structure
- variations on nested block structure is by far the most common in modern high-level languages.

Using the Symbol Table (1)

For a simple language with a declare-before-use rule, redeclarations not allowed, the symbol table would be used as follows during identification:

Using the Symbol Table (1)

For a simple language with a declare-before-use rule, redeclarations not allowed, the symbol table would be used as follows during identification:

- Initialise the table; e.g., enter the standard environment.

Using the Symbol Table (1)

For a simple language with a declare-before-use rule, redeclarations not allowed, the symbol table would be used as follows during identification:

- Initialise the table; e.g., enter the standard environment.
- When a declaration is encountered:

Using the Symbol Table (1)

For a simple language with a declare-before-use rule, redeclarations not allowed, the symbol table would be used as follows during identification:

- Initialise the table; e.g., enter the standard environment.
- When a declaration is encountered:
  - check if declared identifier clashes with existing symbol

Using the Symbol Table (1)

For a simple language with a declare-before-use rule, redeclarations not allowed, the symbol table would be used as follows during identification:

- Initialise the table; e.g., enter the standard environment.
- When a declaration is encountered:
  - check if declared identifier clashes with existing symbol
  - report error if it does

Using the Symbol Table (1)

For a simple language with a declare-before-use rule, redeclarations not allowed, the symbol table would be used as follows during identification:

- Initialise the table; e.g., enter the standard environment.
- When a declaration is encountered:
  - check if declared identifier clashes with existing symbol
  - report error if it does
  - if not, enter declared identifier into table along with its attributes.

Using the Symbol Table (2)

- When an applied identifier occurrence is encountered:

Using the Symbol Table (2)

- When an applied identifier occurrence is encountered:
  - look up identifier in table, taking scope rules into account

Using the Symbol Table (2)

- When an applied identifier occurrence is encountered:
  - look up identifier in table, taking scope rules into account
  - report error if not found

Using the Symbol Table (2)

- When an applied identifier occurrence is encountered:
  - look up identifier in table, taking scope rules into account
  - report error if not found
  - if found, annotate applied occurrence with symbol attributes from table.

Using the Symbol Table (3)

Before identification:

```
let int x = 1
in
  let int y = x * 3
  in
    x + y
```

Using the Symbol Table (4)

After identification:

```
let int x = 1
in
  let int y =
        x [level 0, type int, line 1]
        * 3
  in
    x [level 0, type int, line 1]
    + y [level 1, type int, line 3]
```

(Textual representation of annotated AST.)

Using the Symbol Table (5)

Suppose variables have to be declared, and that redeclarations are not allowed.

```
let int x = 1; int x = x * 3
in
  x + y
```

During symbol table insert and lookup it would be discovered that:

- `x` is declared twice at the same scope level,
- `y` is not declared at all.

Using the Symbol Table (6)

- When entering a new block, arrange so that subsequently entered symbols become associated with the scope corresponding to the block (“open scope”).

Using the Symbol Table (6)

- When entering a new block, arrange so that subsequently entered symbols become associated with the scope corresponding to the block (“open scope”).
- When leaving a block, remove/make inaccessible symbols declared in that block (“close scope”).

Using the Symbol Table (7)

```
let int x = 1
in
   (let y = x * 3 in x) + y
```

- A new scope is opened for the inner `let`-block when it is analysed.
- When the inner `let`-block has been analysed, its scope is closed.
- It is then discovered that `y` is no longer in scope. (However, `x` is still in scope.)

Summary

- Contextual analysis includes checking scope rules and types.
- Contextual constraints lead to ***context-sensitive*** languages and thus cannot be captured by a context-free grammar.
- ***Identification*** is the task of relating each ***applied*** identifier occurrence to its declaration. A key step for any contextual analysis.
- The ***Symbol Table*** or ***Environment*** records information about declared entities and is the central data structure during contextual analysis.