G53CMP: Lecture 5

Contextual Analysis: Scope I

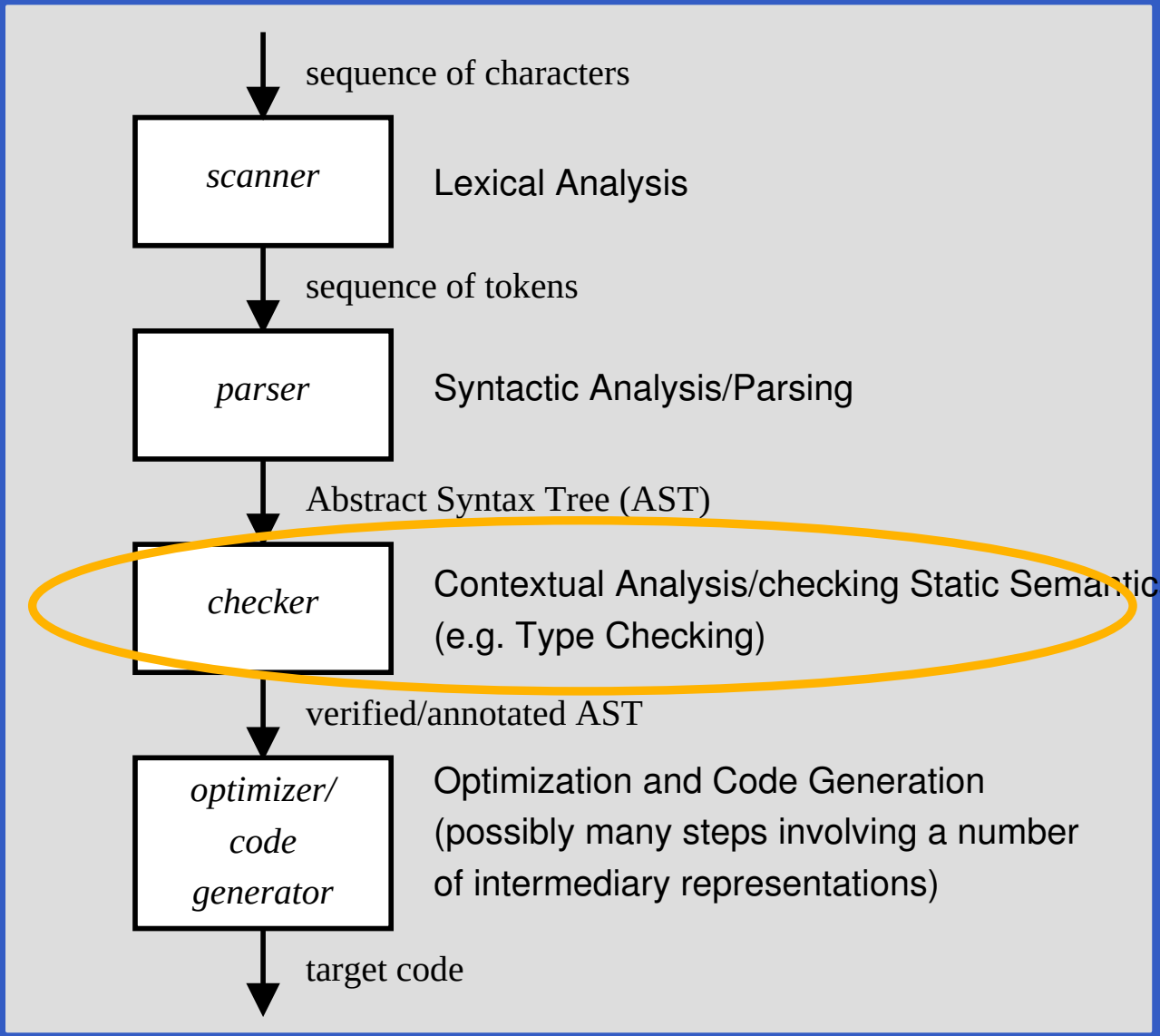
Henrik Nilsson

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)

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  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:

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

Limitations of CFGs (1)

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

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

Limitations of CFGs (2)

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

$$
\begin{array}{lcl}
Prog & \rightarrow & DeclA\ ProgA \mid DeclB\ ProgB \\
ProgA & \rightarrow & StmtA\ ProgA \mid DeclB\ ProgAB \mid \epsilon \\
ProgB & \rightarrow & StmtB\ ProgB \mid DeclA\ ProgAB \mid \epsilon \\
ProgAB & \rightarrow & StmtAB\ ProgAB \mid \epsilon \\
DeclA & \rightarrow & \texttt{int a ;} \\
DeclB & \rightarrow & \texttt{int b ;} \\
StmtA & \rightarrow & \texttt{a =}\ ExprA\ \texttt{;} \\
StmtB & \rightarrow & \texttt{b =}\ ExprB\ \texttt{;} \\
StmtAB & \rightarrow & (\texttt{a} \mid \texttt{b})\ \texttt{=}\ ExprAB\ \texttt{;} \\
ExprA & \rightarrow & \texttt{a} \mid ExprA\ \texttt{+}\ ExprA \mid Expr \\
ExprB & \rightarrow & \texttt{b} \mid ExprB\ \texttt{+}\ ExprB \mid Expr \\
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  Roughly, how many "$ExprXYZ$" rules for n variables?

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- 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 $W \subseteq V$.

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- 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:

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

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Any problem? Unrealistic assumption?

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

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- 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.

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$$\alpha \rightarrow \beta$$

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  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!

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  - 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.

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- ***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.

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- ***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.

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abstract class A {
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- ***Abstract classes***; e.g.:
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abstract class A {
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```

  - Abstract classes may not be instantiated:
    Not allowed: `new A();`

Contextual Analysis (4)

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  - 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***.

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An example of a Java "definite assignment" rule:

V is definitely assigned after

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

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

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Consider the MiniTriangle `let` block command:

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

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

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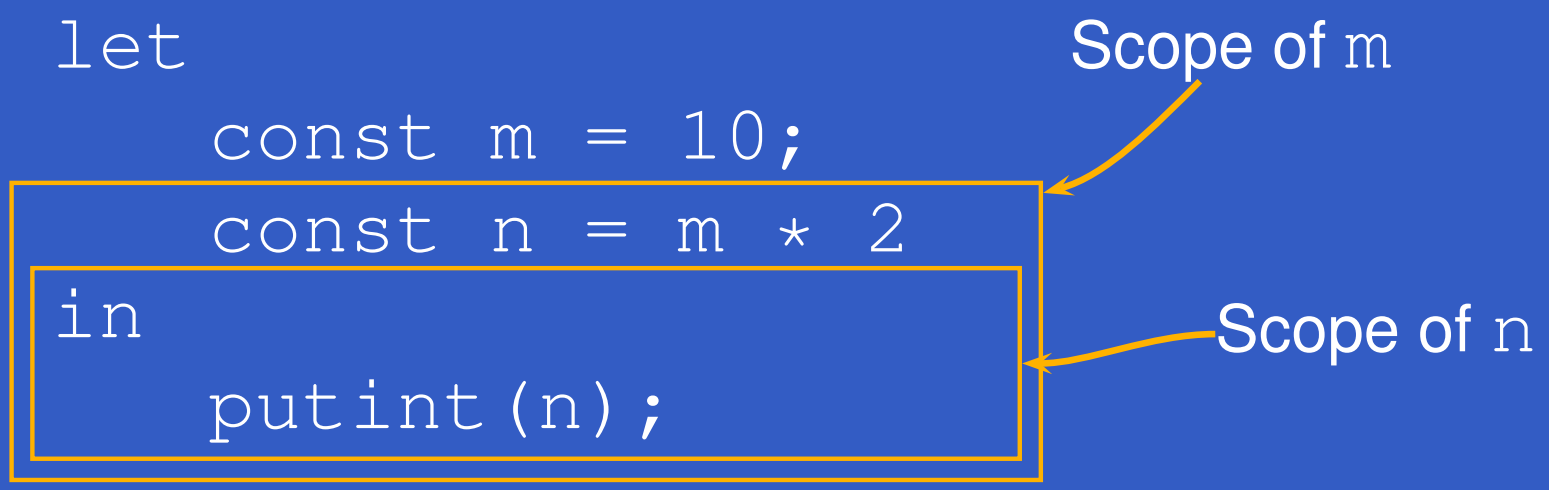

Scope and Scope Rules (3)

Haskell's `let`-expressions:

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

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

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`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 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
    ...
```

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- 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.

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

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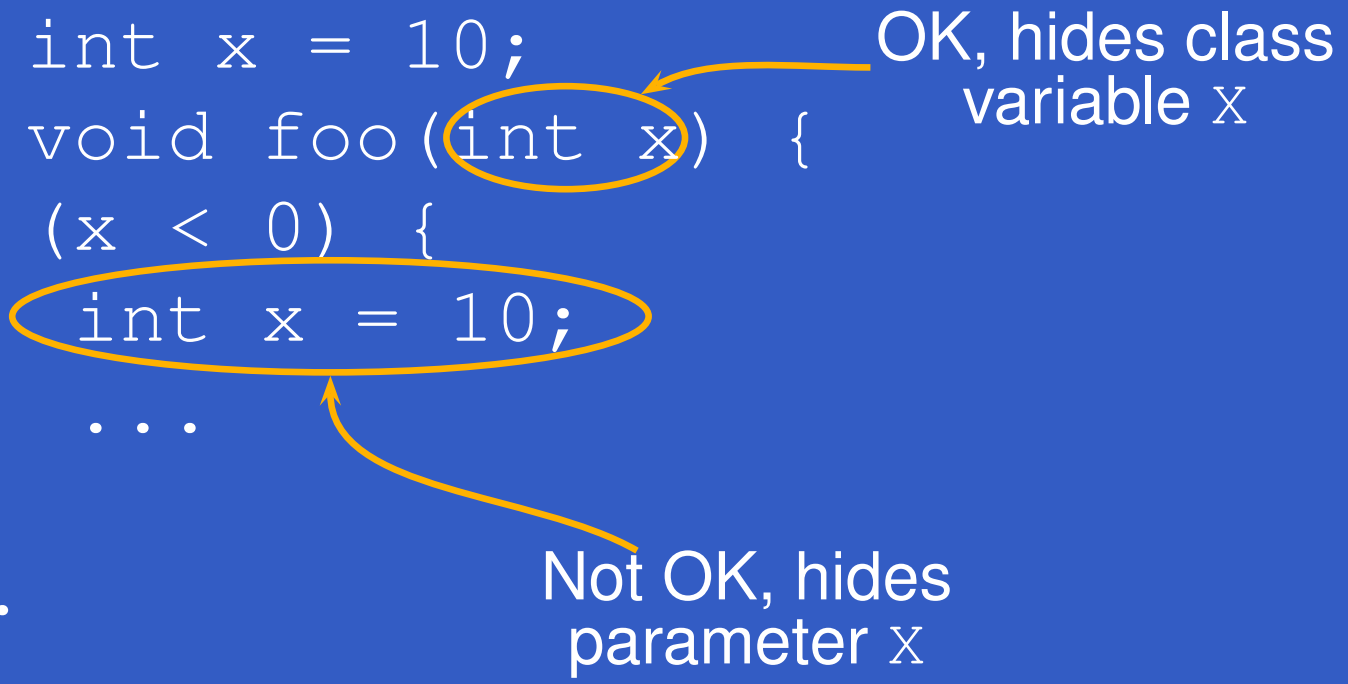
- The scope of a parameter of a method is the entire body of the method.

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;
        ...
    }
    ...
}
```



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

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  (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)

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- 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.

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  - report error if not found
  - if found, annotate applied occurrence with symbol attributes from table.

Using the Symbol Table (3)

Before identification:

```
1    let int x = 1
2    in
3       let int y = x * 3
4       in
5          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.

```
1    let int x = 1; int x = x * 3
2    in
3       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.

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- 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)

```
1    let int x = 1
2    in
3       (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.