Semantic Analysis and Intermediate Representation

Compilers course

Masters in Informatics and Computing Engineering (MIEIC), 3rd Year

U. PORTO

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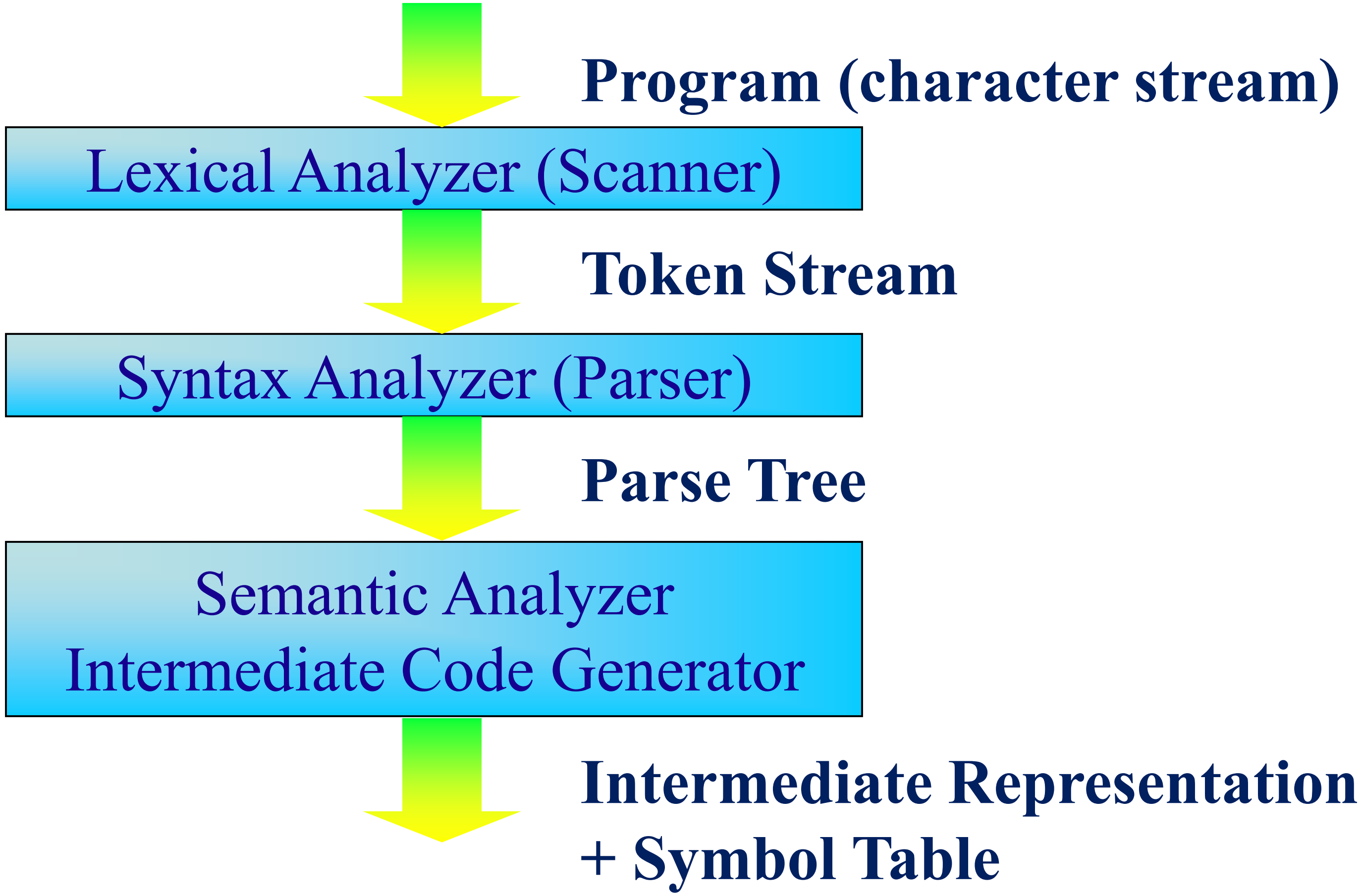
Compiler Stages



What is the Semantic of a Program?

- Syntax
  - How the program is structured
  - Textual representation or structure
- Semantic
  - What is the meaning of the program?

Goals of the Semantic Analysis

- Verify if the program is according to the definitions of the programming language
- Report, whenever there are semantic errors, useful messages to the user
- It is not needed too much additional work if the analysis is integrated in the generation of the intermediate representation

Errors Output by the Semantic Analysis

- Java (using the javac 1.7.0 compiler)

```
boolean sum(int A[], int N) {
   int i, sum;
   for(i=0; i<N; i++) {
      sum1 = sum + A[i];
   }
   return sum;
}
...
int s = sum(A);
```

```
6: error: cannot find symbol
      sum1 = sum + A[i];
      ^
  symbol:   variable sum1
  location: class semantic1
8: error: incompatible types
   return sum;
          ^
  required: boolean
  found:    int
```

```
12: error: method sum in class X cannot be applied to giv
en types;
        int s = sum(A);
                ^
  required: int[],int
  found: int[]
  reason: actual and formal argument lists differ in length
```

Errors Output by the Semantic Analysis

- Java (using the javac 1.7.0 compiler)

```
boolean sum(int A[], int N) {
    int i, sum;
    for(i=0; i<N; i++) {
        sum = sum + A[i];
    }
    return sum;
}
...
int s = sum(A, N);
```

```
8: error: incompatible types
  return sum;
         ^
 required: boolean
 found:    int
```

```
12: error: incompatible types
     int s = sum(A, 100);
                ^
 required: int
 found:    boolean
```

Errors Output by the Semantic Analysis

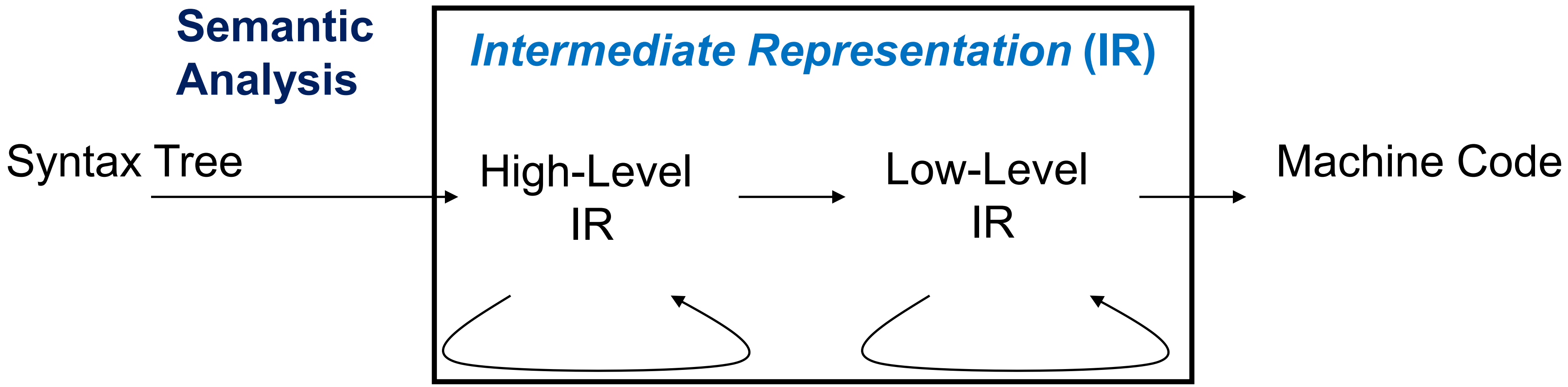
- Java (using the javac 1.7.0 compiler)

```
int sum(int A[], int N) {
   int i, sum;
   for(i=0; i<N; i++) {
      sum = sum + A[i];
   }
   return sum;
}
...
int s = sum(A, N);
```

```
6: error: variable sum might not have been initialized
      sum = sum + A[i];
            ^
8: error: variable sum might not have been initialized
   return sum;
          ^
```

Goals of the Intermediate Representations (IRs)

- To allow analysis and transformations
  - Optimizations
- To structure the translation to Machine Code
  - Sequence of steps



High-Level Intermediate Representation (HIR)

- It preserves the structured control flow
- Useful for optimizations at the loop level
  - Loop Unrolling, Loop Fusion, etc.
- It preserves the structure at class level
- Useful for optimizations for object-oriented languages

Low-Level Intermediate Representation (LIR)

- From an abstract data model to a flat region memory space
- Eliminates the structured control flow
- Useful for low-level compilation tasks
  - Register Allocation
  - Selection of Instructions
  - Scheduling

HIR Alternatives

- There are many possibilities
  - Tree of instructions and expressions (*we will look in more detail to this one!*)
  - Control-Flow-Graph + Acyclic Data Graphs(DAGs)
  - Three address code (e.g., C3E)
  - And others...
- Representation selected based on the language and target
- Next we will illustrate a possible tree of instructions and expressions

Compiler Tasks

- Determine format of the structures in the memory
  - Format of the arrays and objects in the memory
  - Format of the call stack in the memory
- Generate code
  - To read values (parameters, elements of the arrays, fields, etc.)
  - To evaluate expressions and compute new values
  - To write values
  - To implement control flow
- Enumerate functions and builds the symbol table
  - Invocation of a function accesses to the entry of the correspondent table of functions
- Generate code for the functions
  - Local variables and access to parameters
  - Invocations of functions

Symbol Tables (ST)

- Key concept in compilation
  - While processing type declarations, declarations of variables and functions we are going to assign meaning to those identifiers using symbol tables
- Compilers use symbol tables to produce:
  - Layout of the structures in the memory
  - Function tables
  - Code to access fields, local variables, parameters, etc.

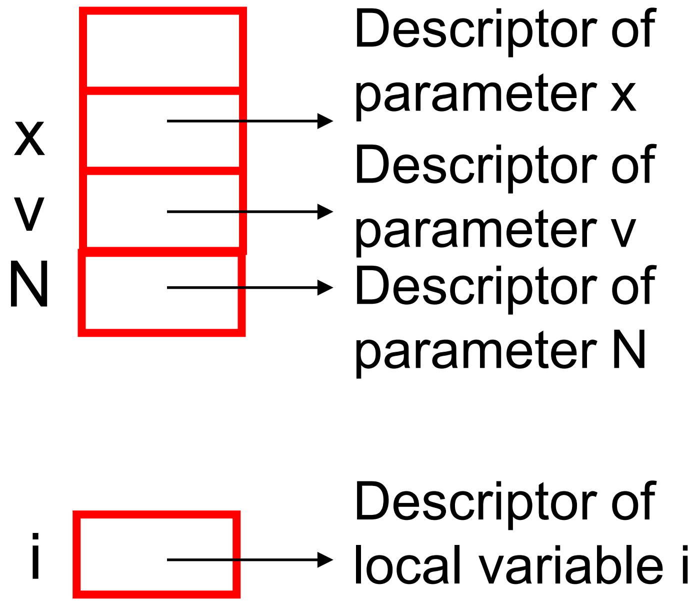
Symbol Tables

- During the creation/translation of syntax trees
- During the translation of syntax trees to intermediate representation
  - Symbol tables map identifiers (strings) to descriptors (information about the identifier)
  - Basic operation: Lookup
  - Given a string, find its descriptor
  - Typical implementation: hash table
- Example:
  - Given the name of a variable find its descriptor (local, parameter, global)

Symbol Table Example

```
void add(int x, int[] v, int N)
  {
  int i;
  i = 0;
  while (i < N) {
        v[i] = v[i]+x;
        i = i+1;
  }
}
```

Function add



Symbol Table Example

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   }
}
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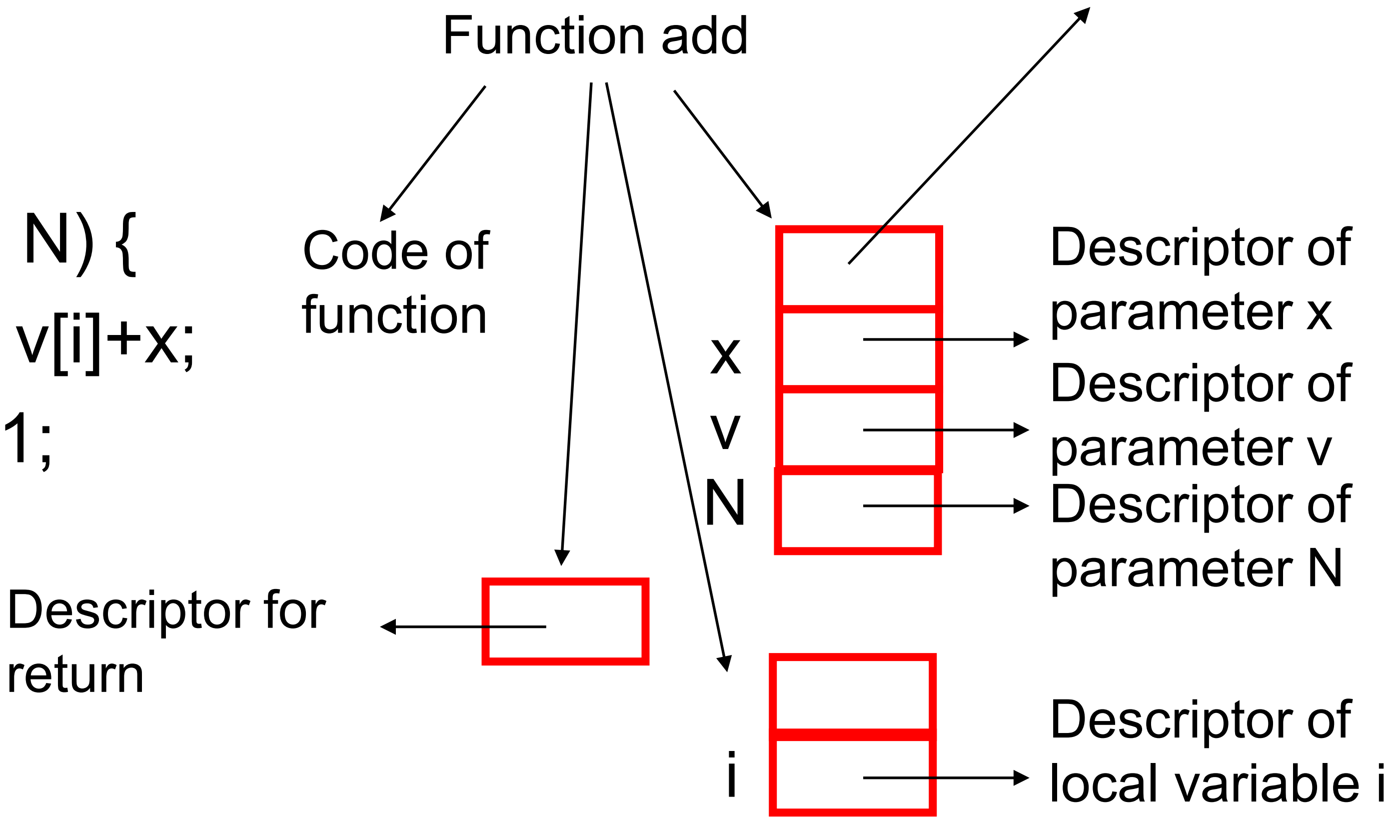

Symbol Table Example

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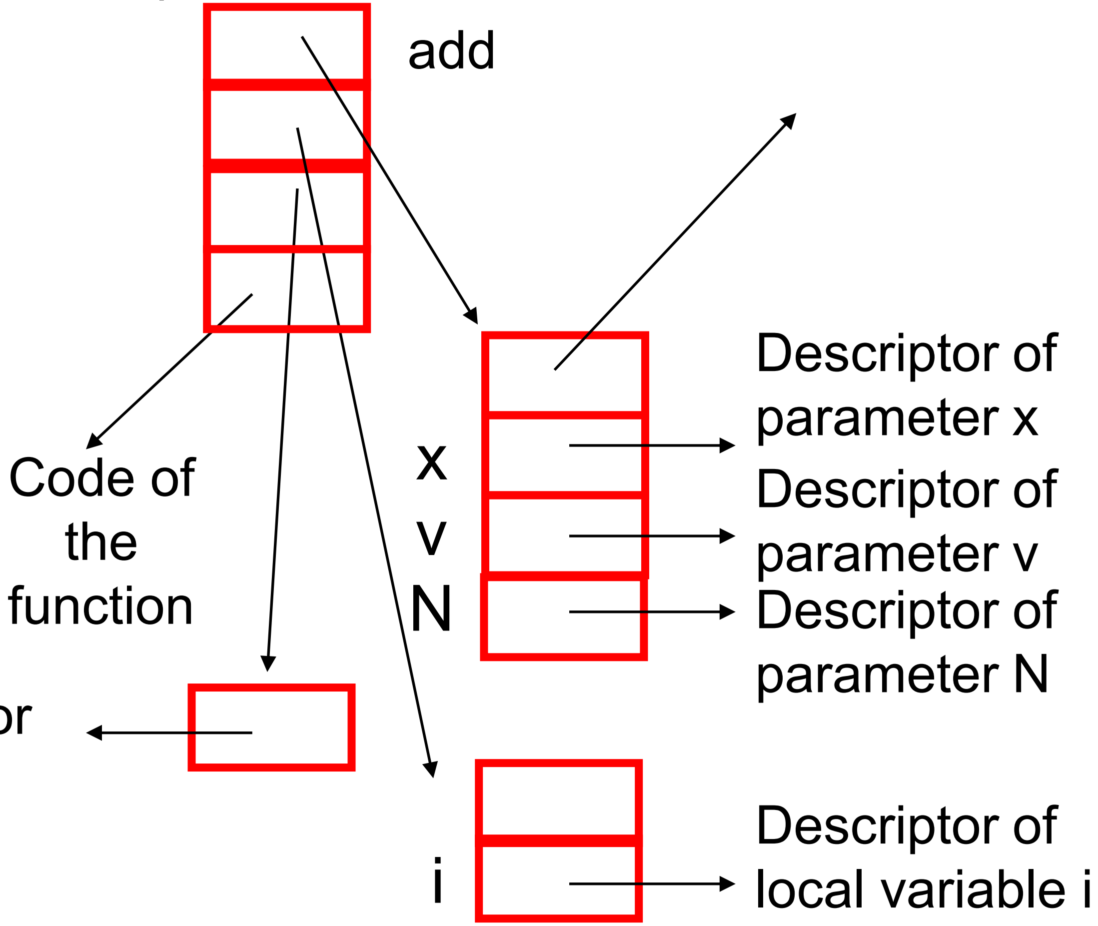
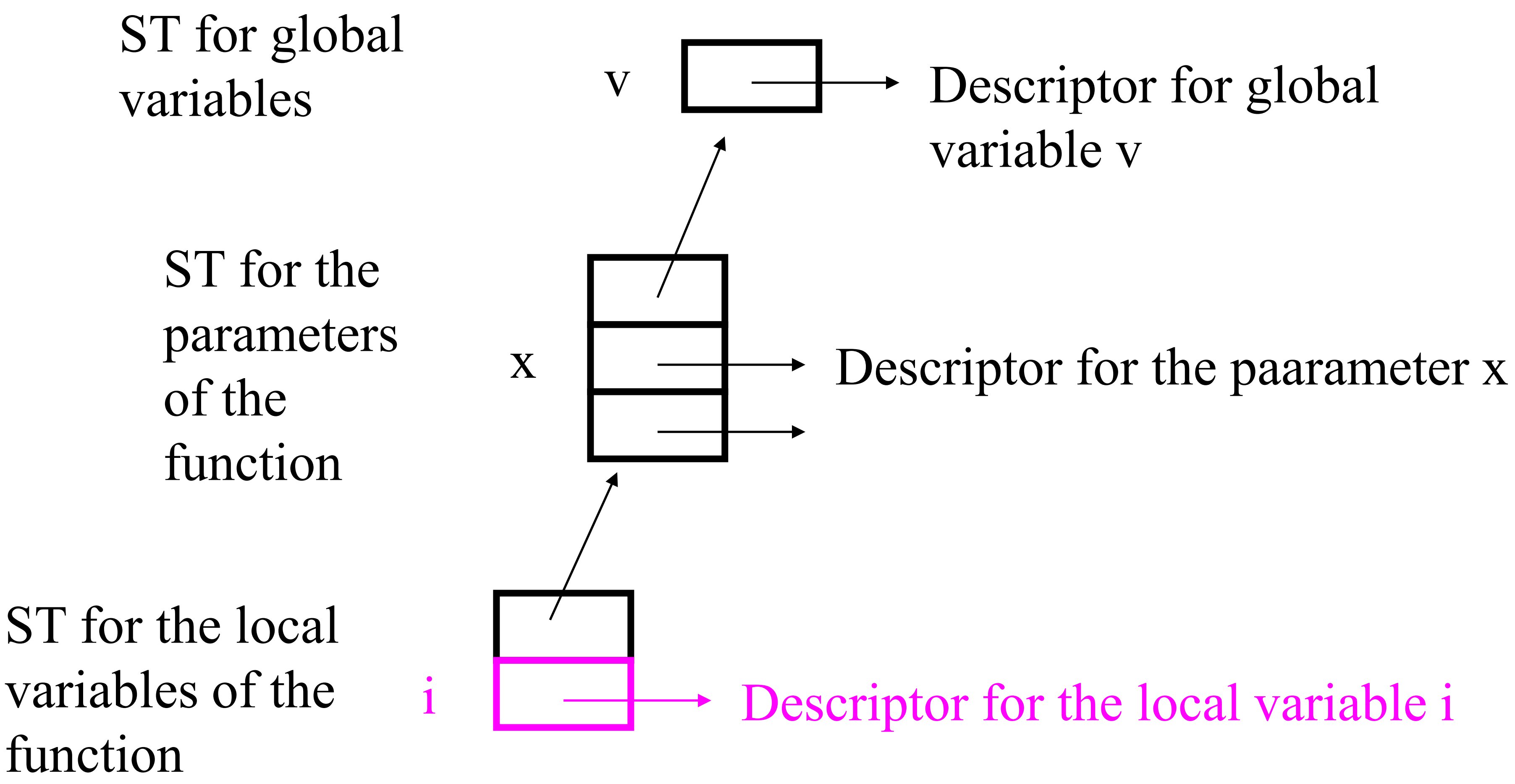
}
```



Hierarchy in Symbol Tables

- Sope
  - The same name for a variable can have different meanings in different code locations
  - It is necessary a symbol table for each scope
- The hierarchy derives from the nested scopes
- Hierarchy in the symbol tables reflects that hierarchy
- Lookup bottom-up traverses the hierarchy until it finds the descriptor

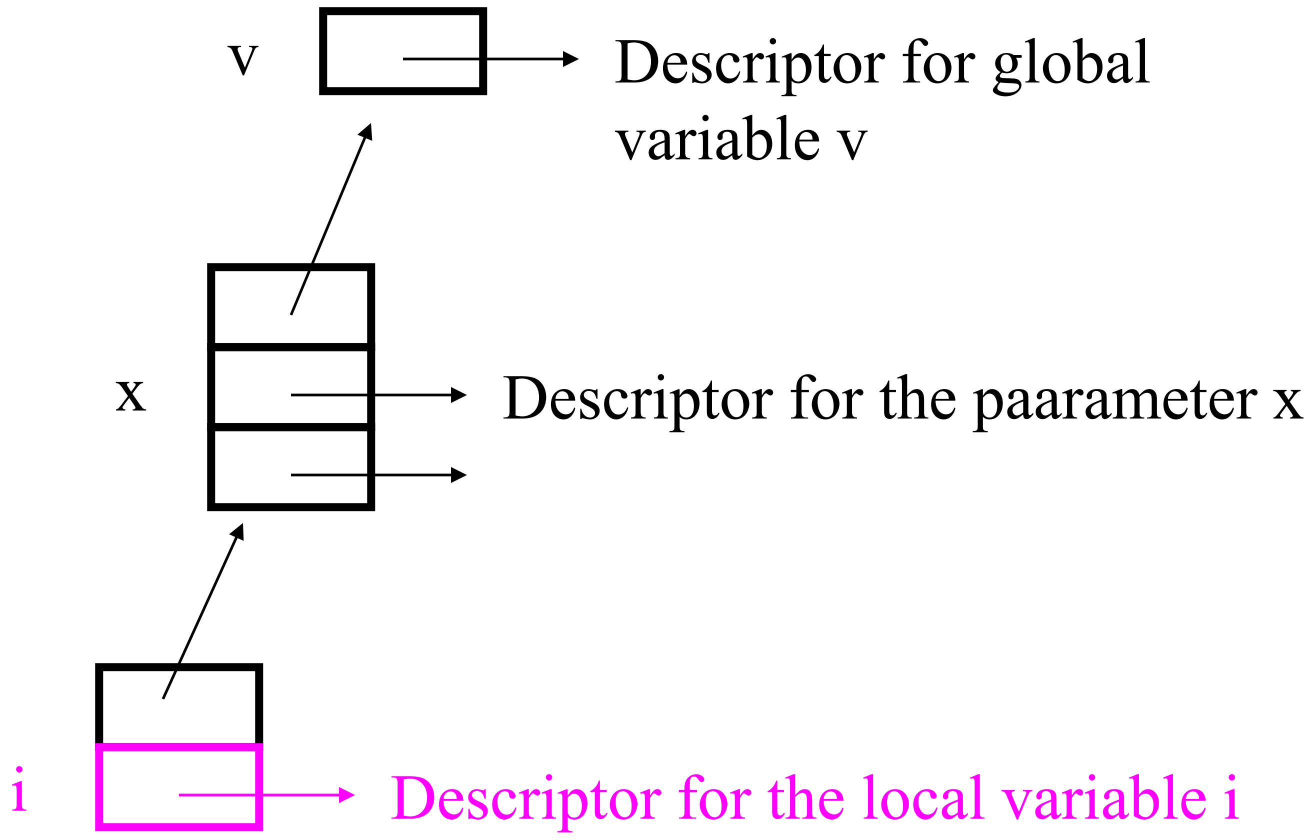
Lookup i in an Example



Lookup i in an Example

- v[i] = v[i]+x;

- First it searches in the ST of the local variables
- If don’t find it then goes up and searches in the next hierarchy level



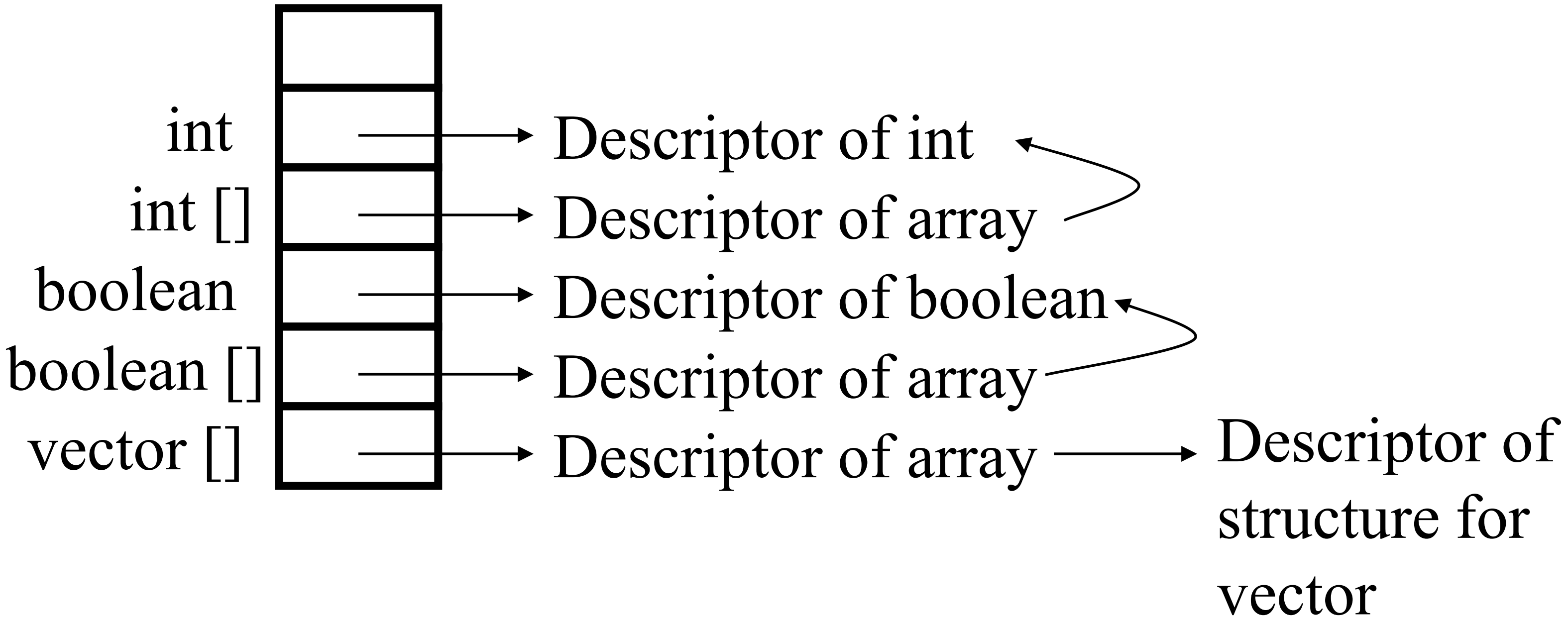
Descriptors

- What do they contain?
- Information used to perform semantic analysis and to generate code
  - Local descriptors: name, type, offset in the stack
  - Descriptors of functions
    - Signature (type of return, parameters)
    - Reference to the local symbol table
    - Reference to the code (IR) of the function

Parameters, Local, and Descriptors of Types

- Parameters and Locals refer to type descriptors
  - Descriptor of base type: int, boolean, etc.
  - Descriptor of the array type: contains reference to the descriptor of the type for the array elements
  - Descriptor of structure, etc.

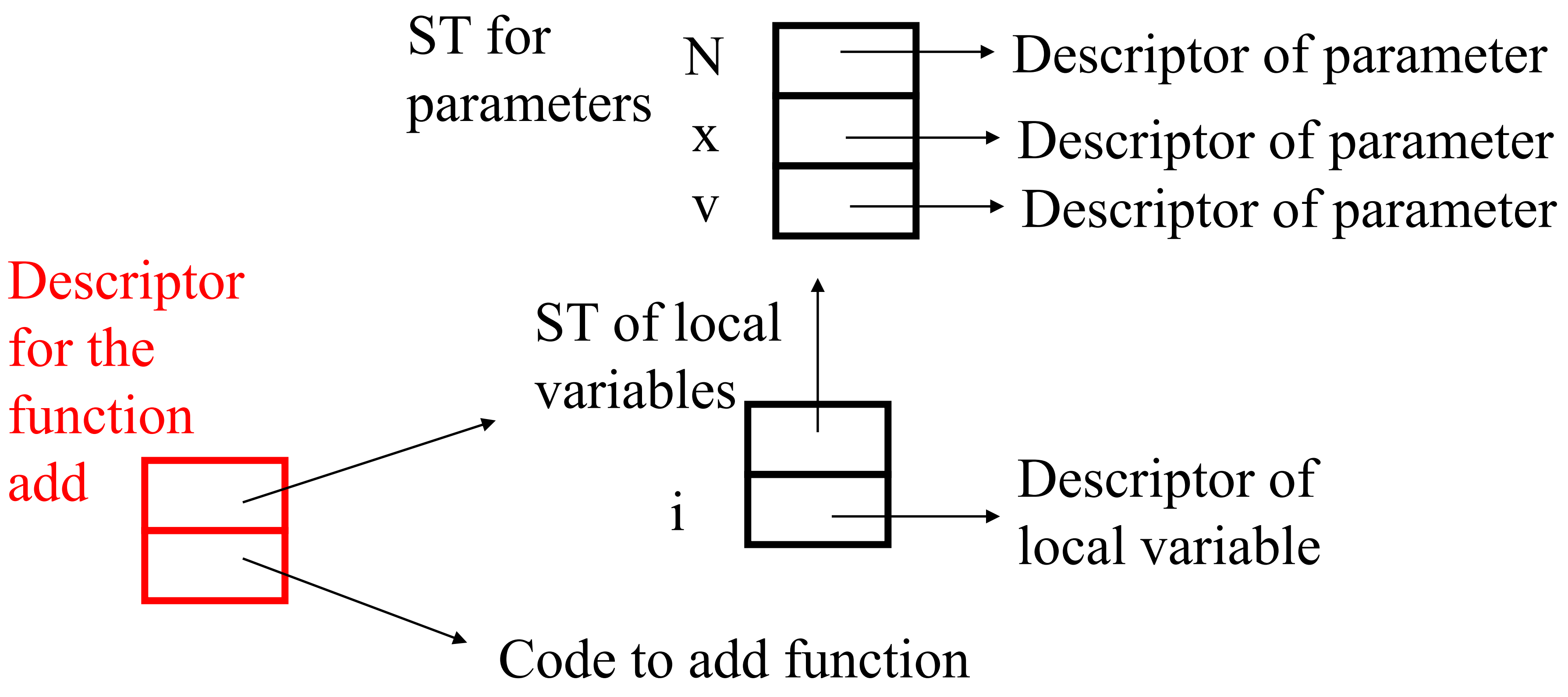
Example: Symbol Table for Types



Descriptor of Functions

- Contains reference to the code (IR) of the function
- Contains reference to the local symbol table (local variables of the function)
  - Note that the existence of more than one local scope implies the existence of a sub-hierarchy of local symbol tables
- In the hierarchy of the symbol tables the symbol table for the parameters is parent of the symbol table for the local variables

Descriptor of the Function add



What is a Syntax Tree?

- Tree that stores results of the syntactic analysis
- External nodes are terminals/tokens
- Internal nodes are non-terminals

Abstract Trees vs. Syntax Trees

- Remember modifications to grammars
  - Left factorization, elimination of ambiguity, precedence of operators…
- Modifications result in trees that do not reflect an interpretation of the program intuitive and clear
- It can be more convenient to work with ASTs (Abstract Syntax Trees)
  - ASTs can be seen as the syntax tree representing the grammar without the modifications

Alternative Constructions for Intermediate Representations

- Construct the concrete syntax tree, translate it to AST, then translate AST to another intermediate representation
- Construct AST, then translate AST to another intermediate representation
- Include the construction of the intermediate representation during the syntax analysis
  - Eliminated the construction of the syntax tree – improves compiler performance
  - Less code to write

Symbol Table

- Given a syntax tree (abstract or concrete)
  - Traverse recursively the tree
  - Construct the symbol table while traversing the tree

Nested Scopes

- Various forms of nesting
  - Symbol Table of the functions nested in the symbol table of the globals
  - Symbol Table of the locals nested in symbol table function
- Nesting solves ambiguity in possible conflicts
  - Same name used for a global and a local variable
  - Name refers a local variable in a function

Scopes in Nested Code

- Symbol tables can have arbitrary depth when considering nested code:

```
boolean x;
int foo(int x) {
        double x = 5.0;
        { float x = 10.0;
                { int x = 1; ... x ...}
          ... x ...
        }
        ... x ...
}
```

Note: Conflicts in names with nesting can be associated to program errors. Compilers usually report warning messages in the presence of this kind of conflicts.

High-Level Code Representation

- Basic idea
  - Moving towards the target language (e.g., assembly)
  - Preserve control structure
    - Format of objects
    - Structured control flow
    - Distinction between parameters, local variables, fields, etc.
  - High-level of abstraction of the assembly language
    - load and store nodes
    - Access to abstract local storage, parameters and fields, and not memory positions directly

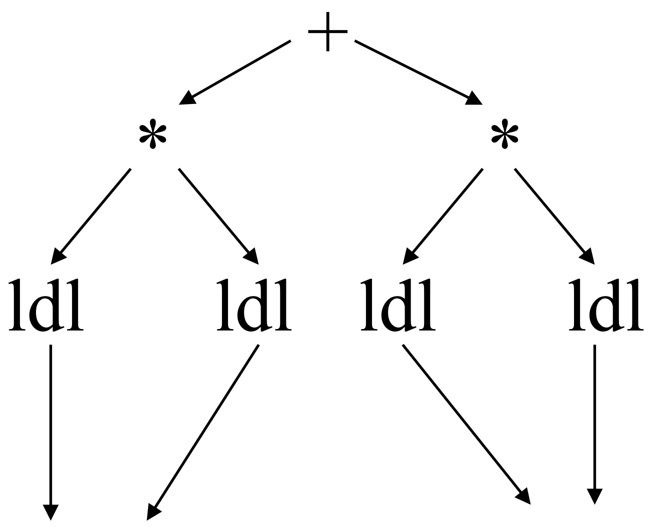
Representing Expressions

- Expression trees represent the expressions
  - Internal nodes – operations such as +, -
  - Leafs – Load nodes represent access to variables
- Load nodes
  - **ldl** to access local variables – local descriptors
  - **ldp** to access parameters – parameter descriptors
  - **lda** to access array elements
    - Expression tree for the value
    - Expression tree for the index
  - For loads of class attributes, of fields in structs…

Example of HIR

x and y are local variables

x*x + y*y



Local descriptor for **x**
In the local symbol table

Local descriptor for **y**
In the local symbol table

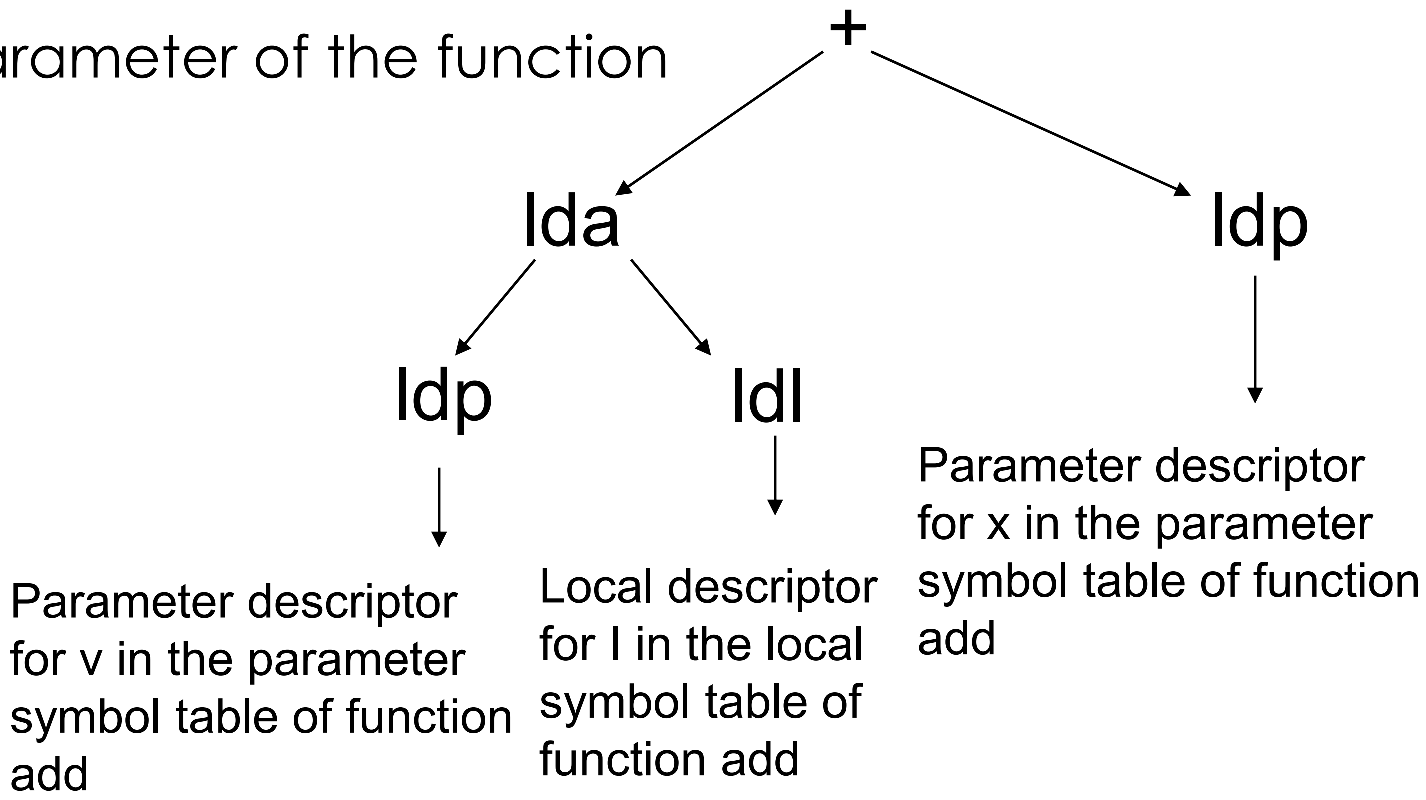
Example of HIR

v is an array passed as parameter in function add

i is a local variable

x is a parameter of the function

v[i]+x

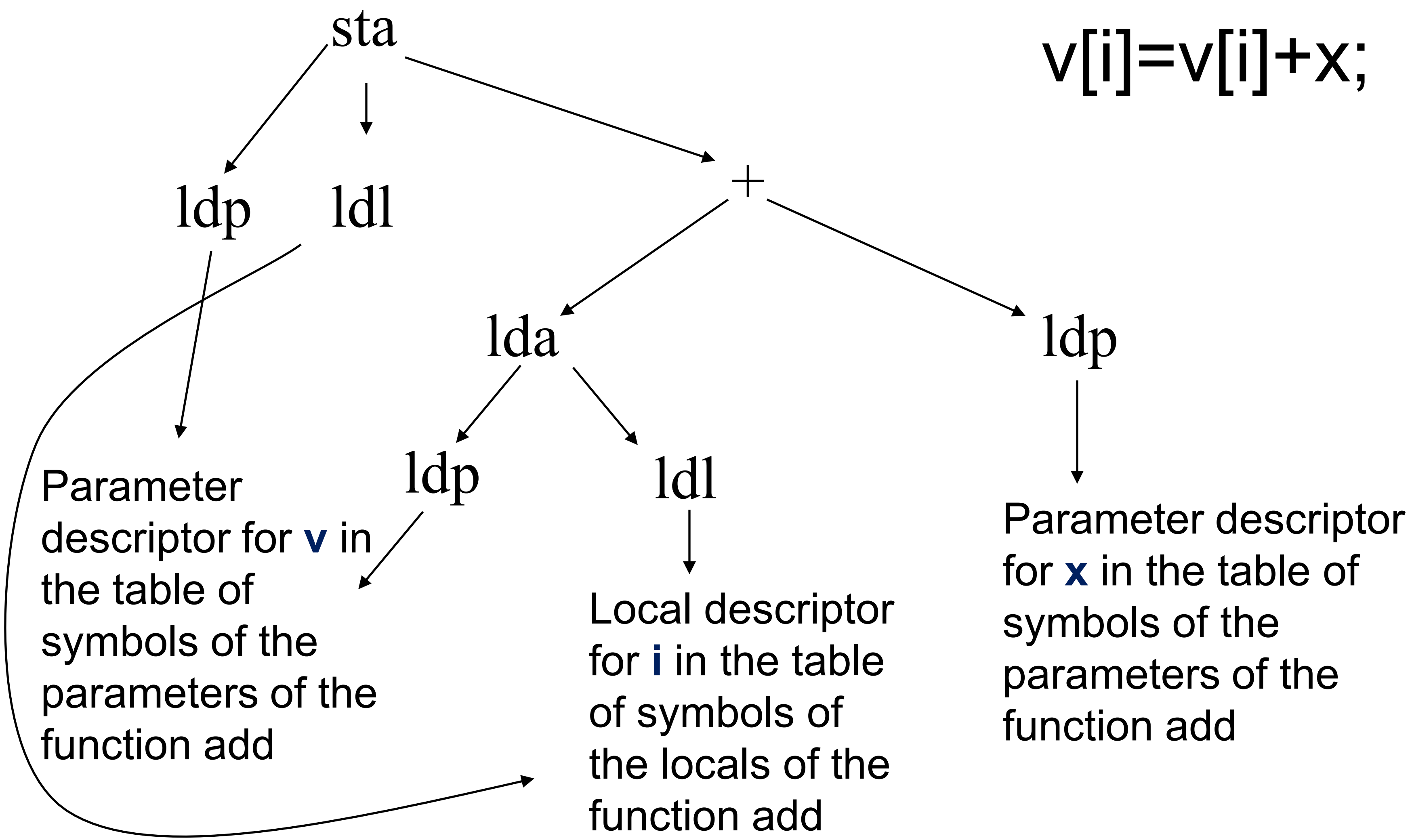


Representing Assignment Statements

- Store Nodes
  - **stl** for *stores* of local variables
    - Local descriptor
    - Expression tree for the value to store
  - **sta** for *stores* in array elements
    - Expression tree for the array
    - Expression tree for the index
    - Expression tree for the value to store
  - For stores in class attributes, in fields of structs…

Example of HIR

$v[i]=v[i]+x;$



Orientation

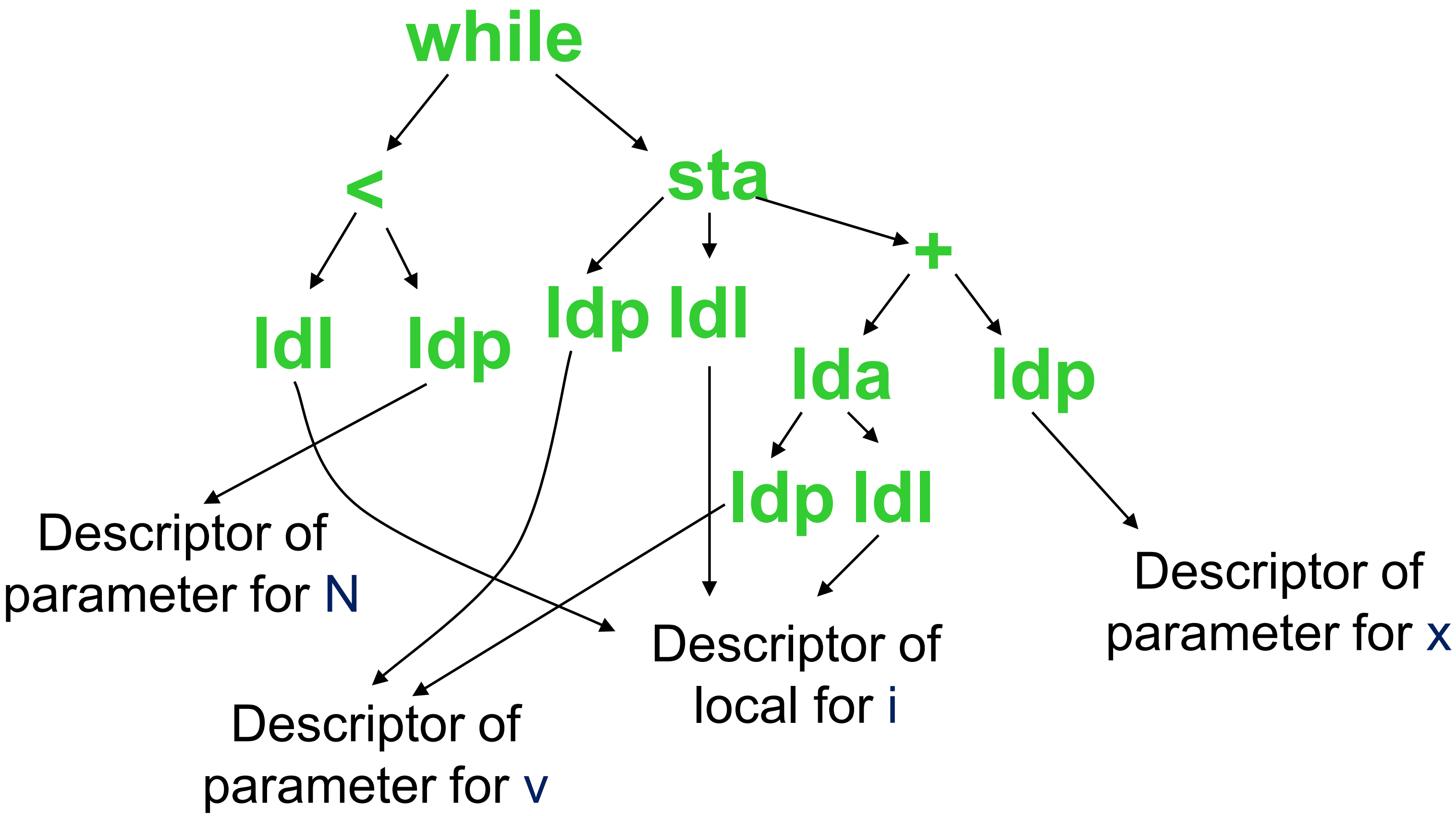
- Intermediate representations
  - Moving in the direction of the target language (e.g., machine language)
  - Support for compiler analysis and transformations
- High-Level IR (*HIR*)
  - Preserves the structure of objects, arrays, control flow,…
  - Symbol Tables
  - Descriptors

Representing Control Flow

- Nodes of statements
  - **if** node
    - Expression tree for condition
    - Node for the body of the then and node for the body of the else
  - **while** node
    - Expression tree for condition
    - Node for the body
  - **return** node
    - Expression tree for the return value/expression
  - **One can easily think about what is needed for:**
    - **For** node
    - **Do while** node
    - **Switch** node
    - Etc.

Example of HIR

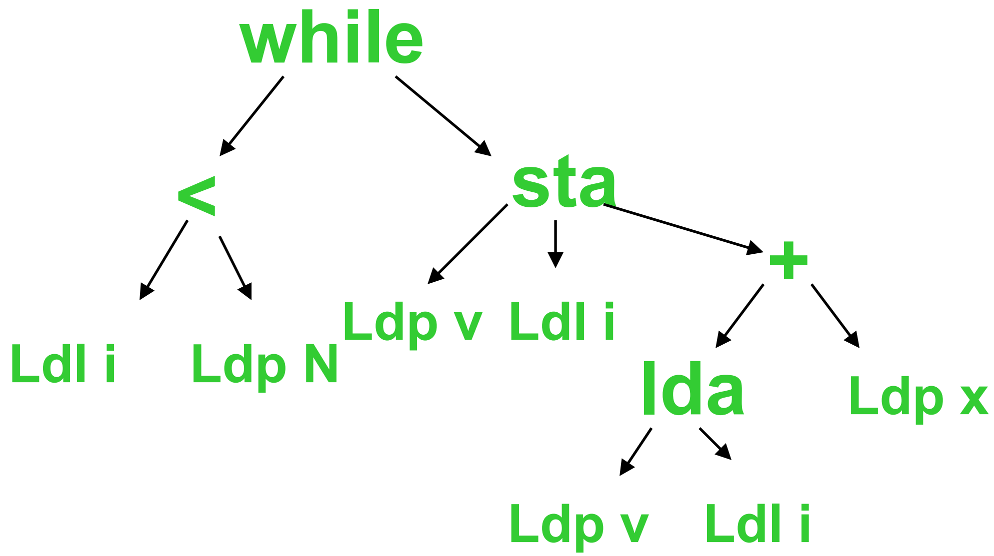
```
while (i < N)
  v[i] = v[i]+x;
```



Example of HIR

- Abbreviated notation

```
while (i < N)
    v[i] = v[i]+x;
```



From Syntax Trees to IR

- Traverse recursively the syntax tree
- Build representation *Bottom-Up*
  - Check identifier of the variable in the symbol tables
  - Construct load nodes to access the variables
  - Construct expressions from the load nodes and the operation nodes
  - Construct store nodes for the assignments
  - Include while, if, return for the control constructs

Summary

High-Level Intermediate Representation (HIR)

- Goal: to represent the program in an intuitive mode in order to support further compilation stages
- Representation of the data in the program
  - Symbol tables
  - Hierarchic organization
- Representation of the computations
  - Expression trees
  - Various types of load and store nodes
  - Structured control flow

Semantic Analysis: Errors

- We assume the inexistence of problems during the construction of the IR
- However, it is necessary to do many verifications while constructing the IR
- Named by **Semantic Analysis**
- Semantic Analysis is usually done at the abstract syntax tree level
  - In order errors be informative/clear it is necessary that the tree nodes are annotated with positions in the program

Objective of the Semantic Analysis

- To ensure that the program obeys to a set of sanity checks, such as:
  - All the variables used have been declared
  - Types are used in a correct way
  - Calls to functions have the correct number of arguments, the correct types of the arguments, and the correct type for the return
- Verification while building the IR

Descriptors for Identifiers

- When the descriptor of a local variable, a parameter, etc. is built we have:
  - Name of the type
  - Name of the variable
- What is verified?
  - Verify if the name of the type identifies a valid type
    - *lookup* name in the symbol table for the types
      - If it was not found then semantic error

Local Table of Symbols

- When we build a local symbol table we have a list of local descriptors
- What shall we verify?
  - Duplicated names of variables
- When to do the verification?
  - When the descriptor is inserted in the local symbol table
- Similar to table of symbols of parameters, globals, etc.

Verification for loads, stores, etc.

- What does the compiler have?
  - Name of variable
- What does it do?
  - *Lookup* name of variable:
    - Verifies if it is in the symbol table of locals, reference to a local descriptor
    - Verifies if it is in the symbol table of parameters, reference to a parameter descriptor
    - Verifies if it is in the symbol table of globals, reference to a global descriptor
    - If a descriptor was not found then report a semantic error (the variable was not declared)

Verification for Load Instructions for Arrays

- What does the compiler have?
  - Name of the variable
  - Expression of indexing the array
- What does it do?
  - *Lookup* name of the variable
    - If it is not found then semantic error
  - Verifies type of expression
    - If it is not an integer then semantic error

Addition Operation

- What does the compiler have?
  - 2 expressions
- What can be wrong?
  - Expressions have the wrong type
  - E.g., they must be both integers
- It is why the compiler verifies the type of the expressions
  - Load instructions store the type of the variable accessed
  - Operations store the type of the produced expression
  - So, it is only necessary verify the types
    - If it fails then semantic error

Inference of types for addition operations

- Some languages let add floats, ints, doubles
- What are the problems?
  - Type of the result of the operation
  - Conversion of the operands of the operation
- Standard rules are usually applied:
  - If addition of an **int** with a **float**
    - Convert the **int** to **float**, add the two **floats**, and the result is a **float**
  - If addition of a **float** with a **double**
    - convert **float** to **double**, add the two **doubles**, result is a **double**

Rules for Addition

- Basic principle:
  - hierarchy of types for numbers (int, then float, then double)
- All the “forced” conversions are done in bottom-up mode in the hierarchy
  - E.g., int to float; float to double;
- Result has the type of the operand with type in the highest level of the hierarchy:
  - int + float → float,
  - int + double → double,
  - float + double → double

Note that rules depend on the programming language

Type Inference

- Addition is a restrict case of type inference
- Inference of types without explicit declaration of types
  - very important topic in the context of some programming languages (e.g., dynamic languages such as JavaScript, MATLAB)

Store Instruction

- What does the compiler have?
  - Name of the variable
  - expressions
- What does it do?
  - *Lookup* of the name of the variable
    - if it is not found: semantic error
  - Verifies if the type of the variable is compatible with the type of the expression
    - If not: semantic error

Store Instruction for Arrays

- What does the compiler have?
  - name of the variable, expression for indexing
  - expression
- What does it do?
  - *Lookup* with name of variable
    - if it is not found: semantic error
  - Verifies if the type of the indexing expression is integer
    - If not: semantic error
  - Verifies if the type of the elements of the array is compatible with the type of the expression
    - If not: semantic error

Function Calls

- What does the compiler have?
  - Name of the function, arguments
- Verifications:
  - Name of the function is identified in the table of the functions of the program
    - if it is not found: semantic error
  - Type of arguments match with the type of parameters in the declaration of the function
    - if it is not found: semantic error

Note that rules depend on the programming language

Summary of Semantic Verifications

- Do the semantic verifications during the construction of the Intermediate Representation (IR)
- Many verifications are to certify that we build a correct IR (i.e., an IR that represents the same functionality of the input program)
- Other verifications are simple sanity checks
- Each programming language has a list of verifications
- Semantic analysis can report many potential errors

Summary

- Translation of syntax trees to high-level IR (HIR)
  - Preserves the structured control flow
  - Representation efficient for high level analysis and high-level optimizations (e.g., target-independent transformations)