Semantic Analysis and Intermediate Representation

Compilers course

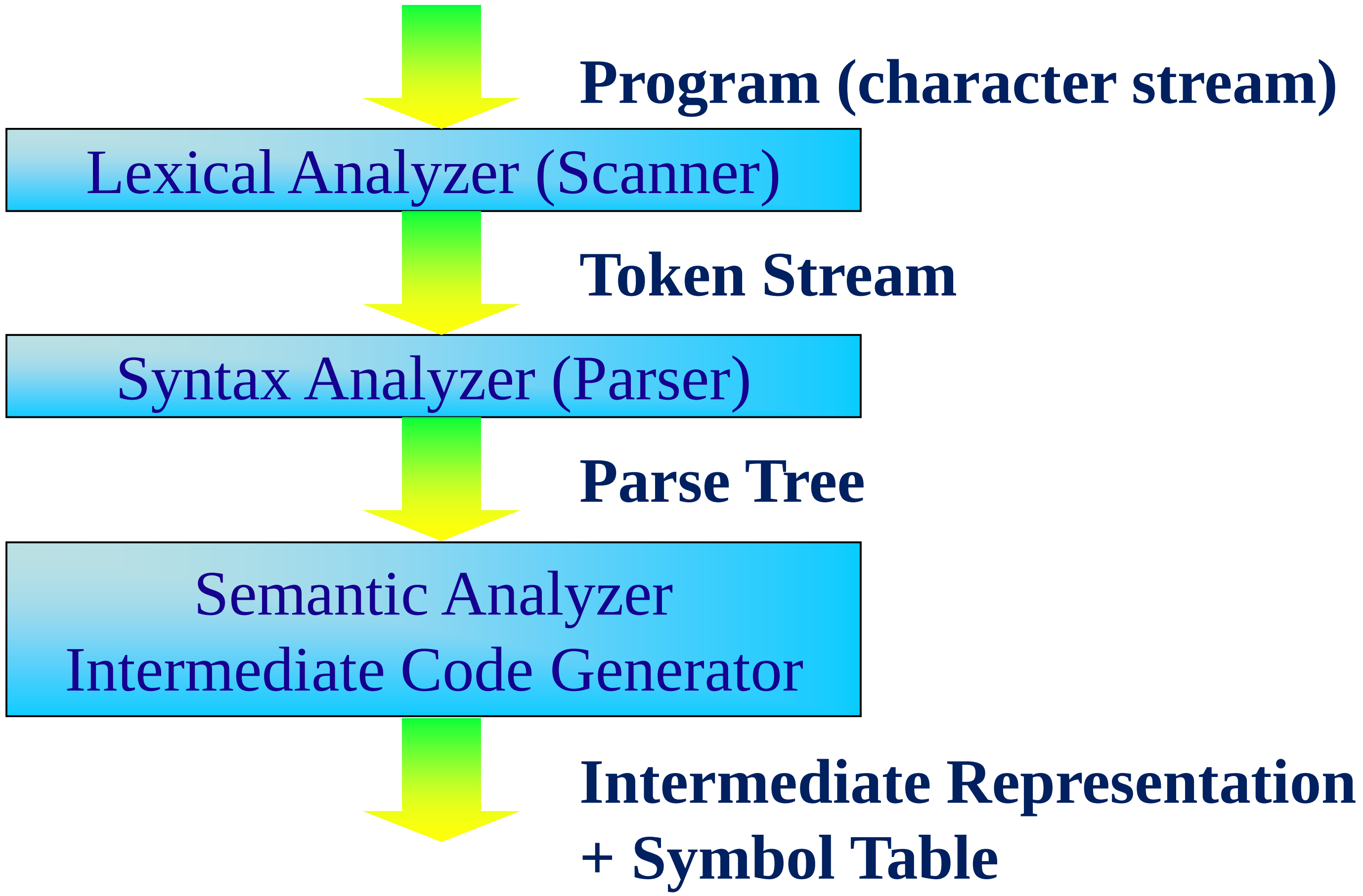
Masters in Informatics and Computing Engineering (MIEIC), 3rd Year

João M. P. Cardoso
Email: jmpc@fe.up.pt

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

DEI DEPARTAMENTO DE ENGENHARIA INFORMÁTICA

Compiler Stages


Program (character stream)
Lexical Analyzer (Scanner)
Token Stream
Syntax Analyzer (Parser)
Parse Tree
Semantic Analyzer
Intermediate Code Generator
Intermediate Representation
+ Symbol Table

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
- There 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

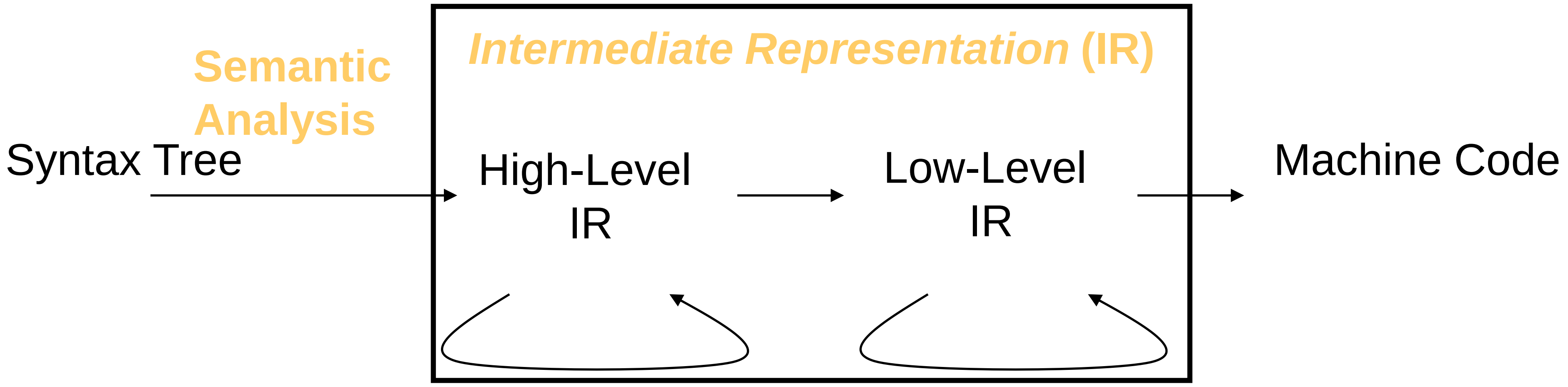
- Java (using the javac 1.7.0 compiler)

```
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 translation to *Machine Code*
  - Sequence of steps



High-Level Intermediate Representation

- Known as HLIR or 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

- Known as LLIR or LIR
- From an abstract data model to a flat region memory space
- Eliminates the structured control flow
  - Control flow is now represented as low-level instructions (e.g., using conditional branches and jumps)
- Useful for low-level compilation tasks
  - Register Allocation
  - Selection of Instructions
  - Scheduling

IR Alternatives

- There are many possibilities
  - Tree of instructions and expressions
  - Control-Flow + Acyclic Data Graphs(DAGs)
  - Three address code (C3E)
  - And others...
- Representation selected based on the language and target
- The following content illustrates 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 eva,uate expressions and compute new values
  - To write values
  - For control structures
- 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

Symbol Tables

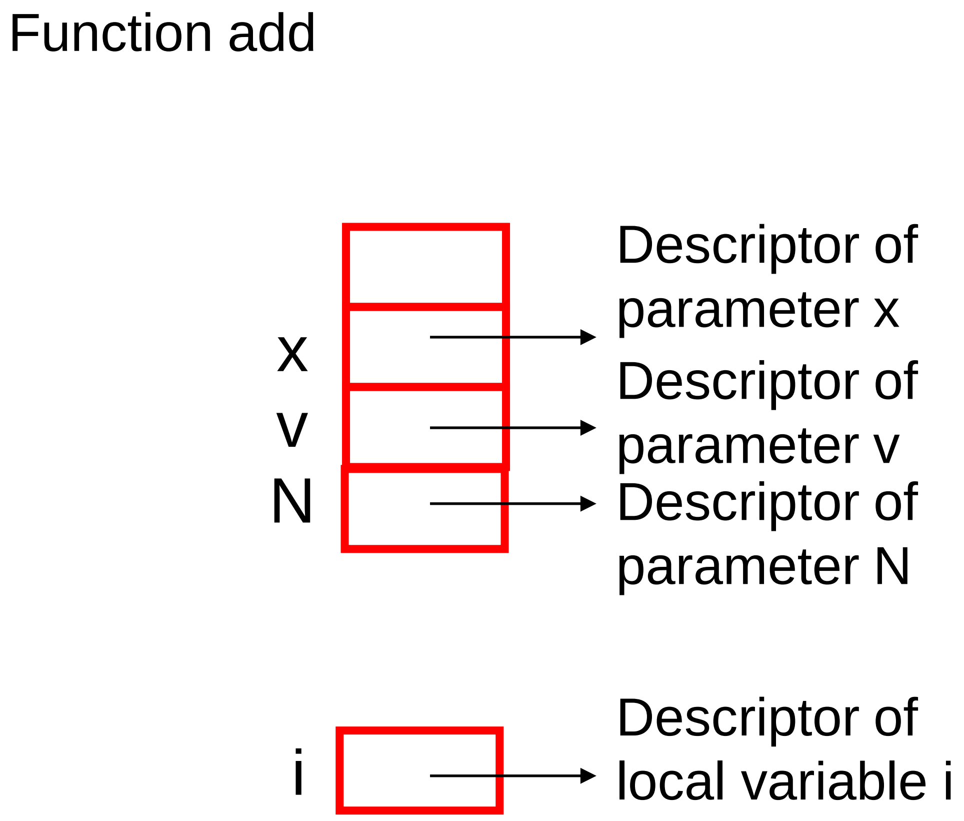
- Key concept in compilation
  - While processing type declarations, declarations of variables and functions we are going to assign meaning to those identifiers using symbol tables
- Compilers use symbol tables to produce:
  - Layout of the structures in the memory
  - Function tables
  - Code to access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

Symbol Tables

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

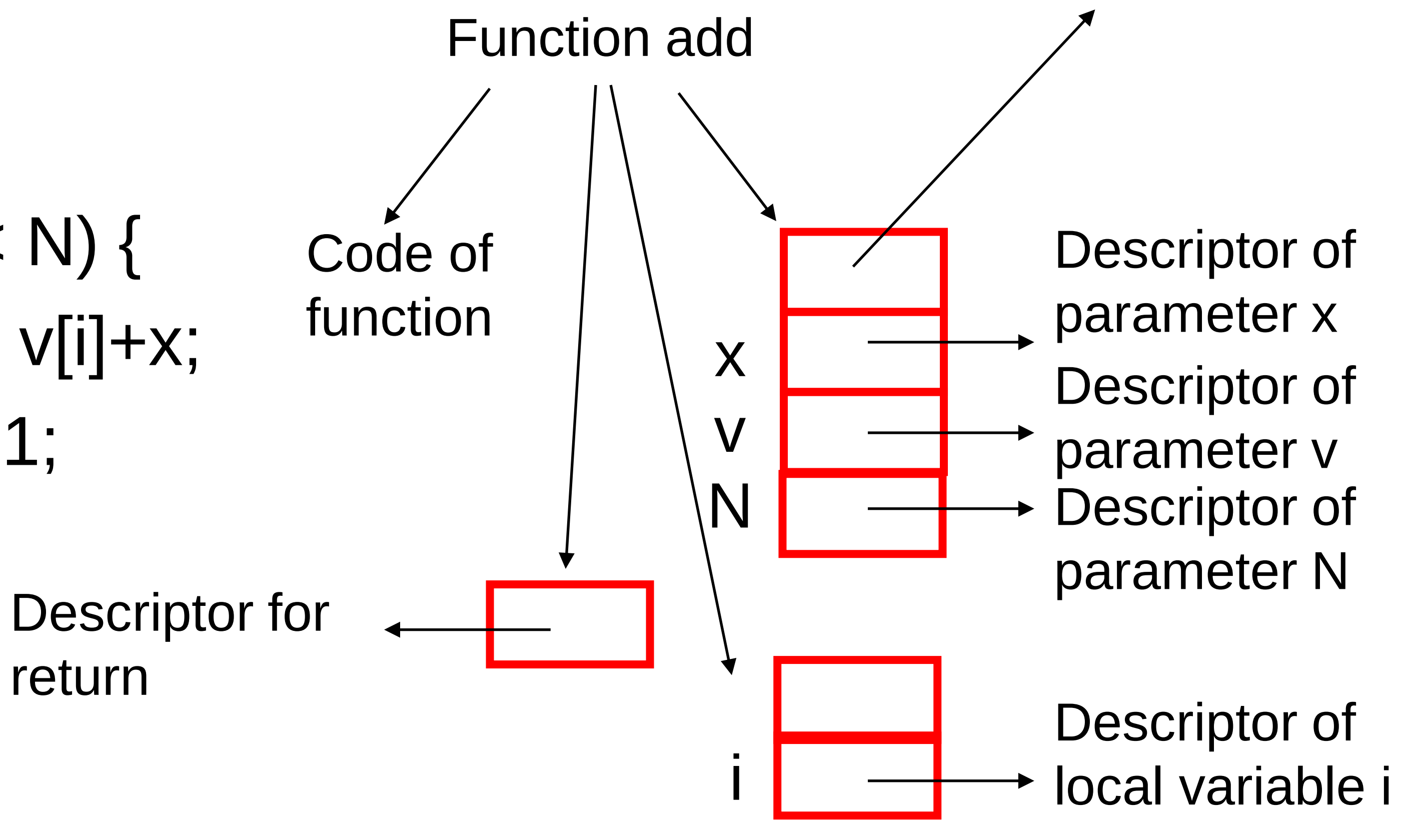
Example of Symbol Table

```
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
x
v
N
i
Descriptor of parameter x
Descriptor of parameter v
Descriptor of parameter N
Descriptor of local variable i

Example of Symbol Table

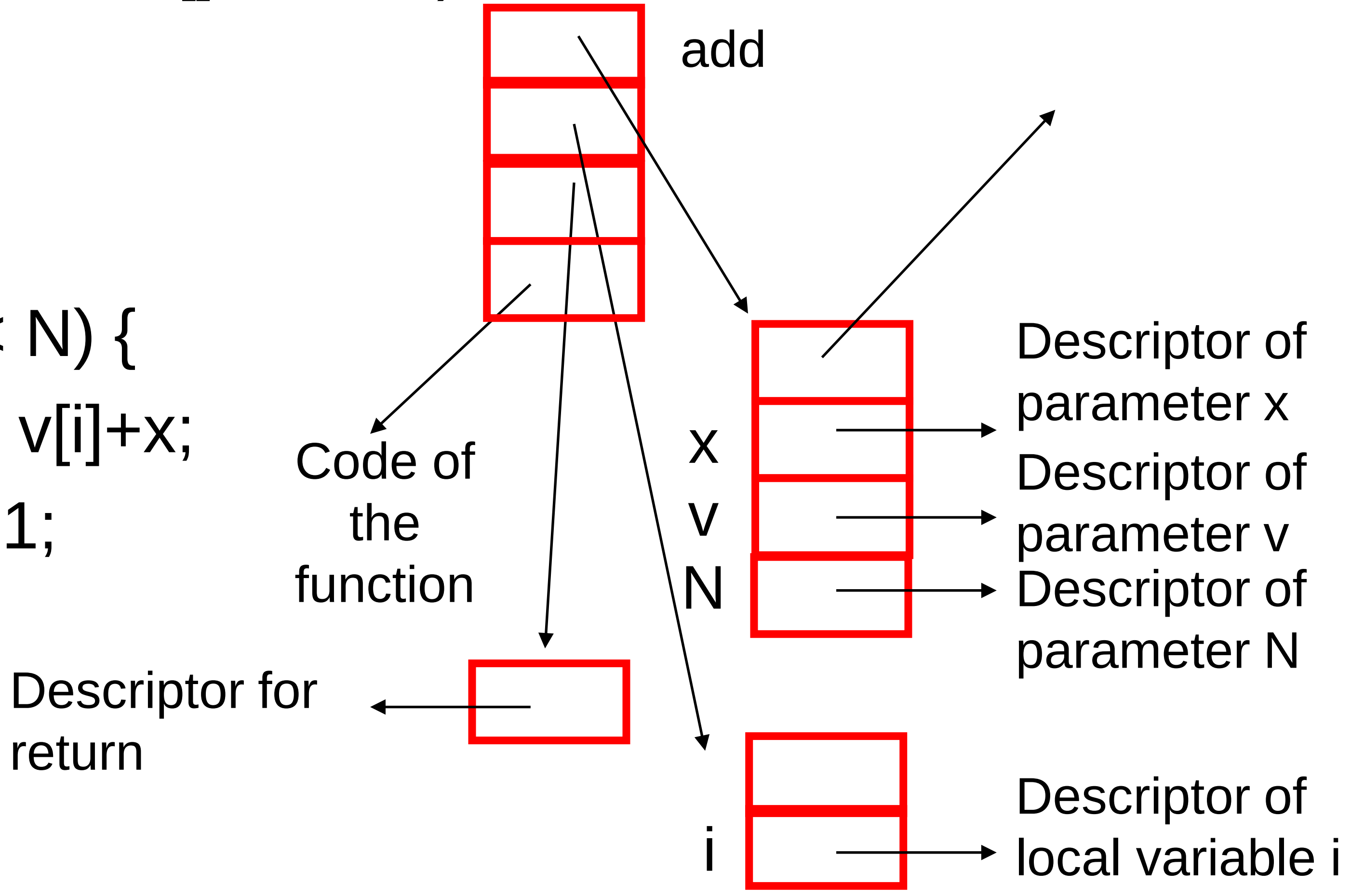
```
void add(int x, int[] v, int N)
    {
    int i;
    i = 0;
    while (i < N) {
            v[i] = v[i]+x;
            i = i+1;
    }
}
```



Function add
Code of function
x
v
N
Descriptor of parameter x
Descriptor of parameter v
Descriptor of parameter N
Descriptor for return
i
Descriptor of local variable i

Example of Symbol Table

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

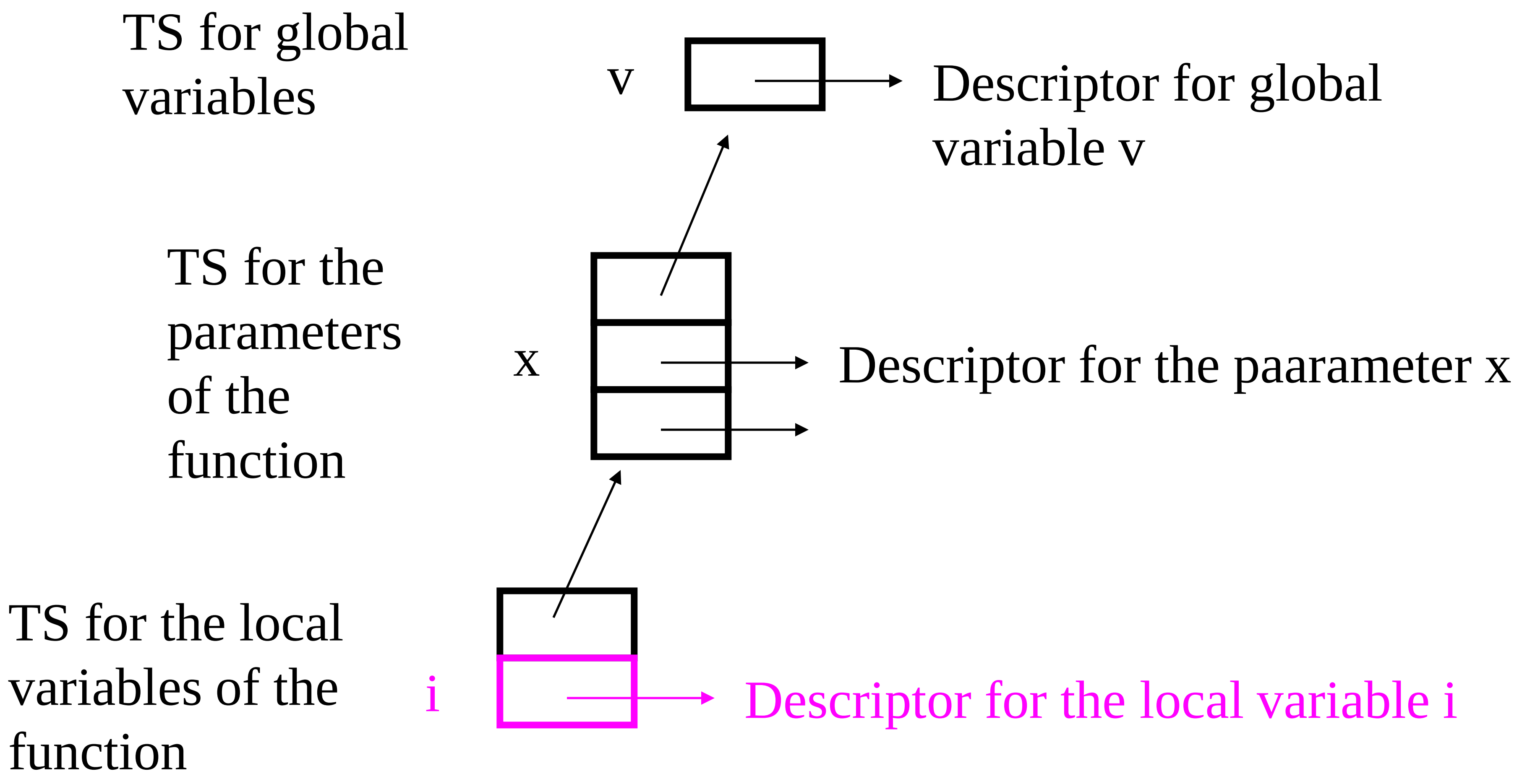


add
Code of the function
Descriptor for return
x
v
N
i
Descriptor of parameter x
Descriptor of parameter v
Descriptor of parameter N
Descriptor of local variable i

Hierarchy in Symbol Tables

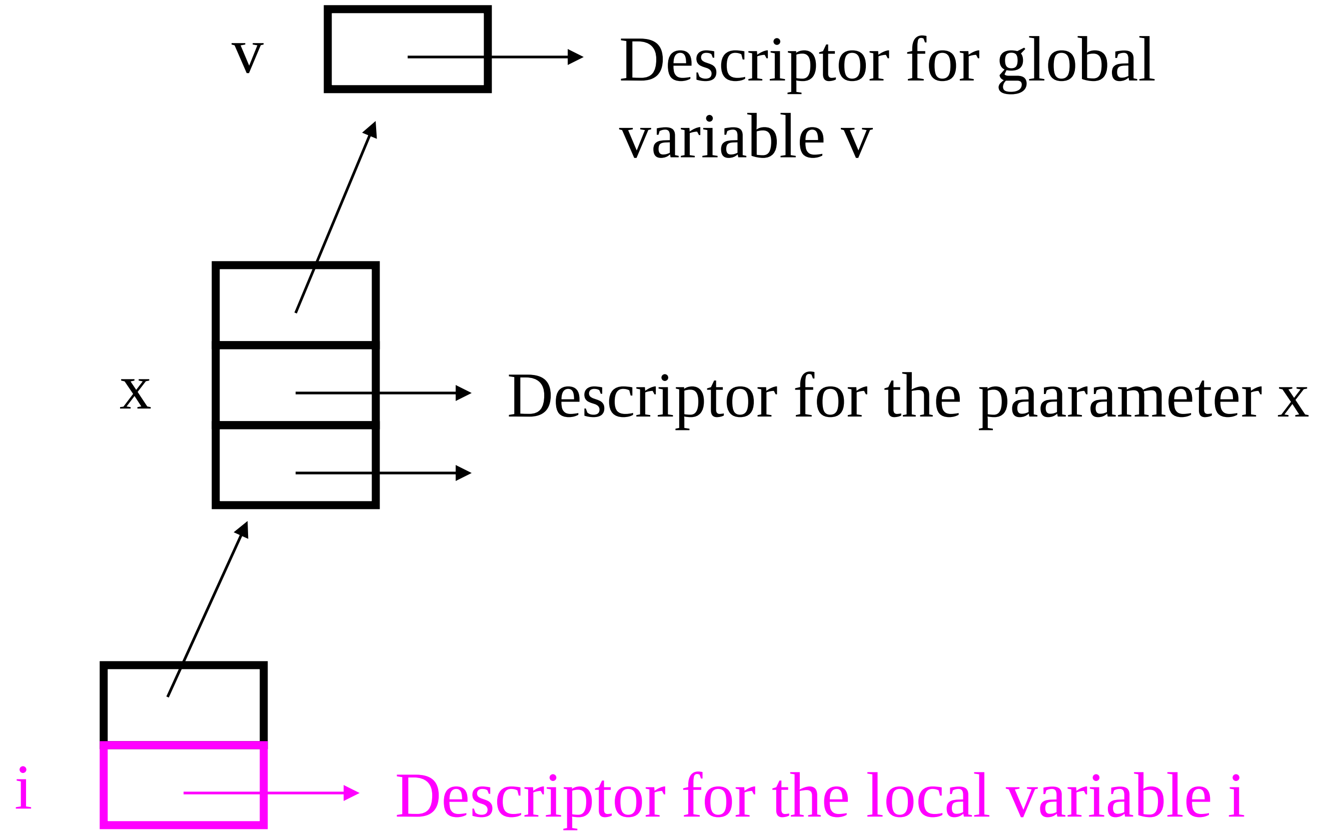
- Scope
  - The same name for a variable can have different meanings in different code locations
  - It is necessary a symbol tables for each scope
- The hierarchy derives from the nested scopes
- Hierarchy in the symbol tables reflects that hierarchy
- Lookup bottom-up traverses the hierarchy until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

Lookup i in an Example


TS for global variables
v
Descriptor for global variable v
TS for the parameters of the function
x
Descriptor for the paarameter x
TS for the local variables of the function
i
Descriptor for the local variable i

Lookup i in an Example

- v[i] = v[i]+x;
- First it searches in the TS of the local variables
- If don’t find it then goes up and searches in the next hierarchy level


v
Descriptor for global variable v
x
Descriptor for the paarameter x
i
Descriptor for the local variable i

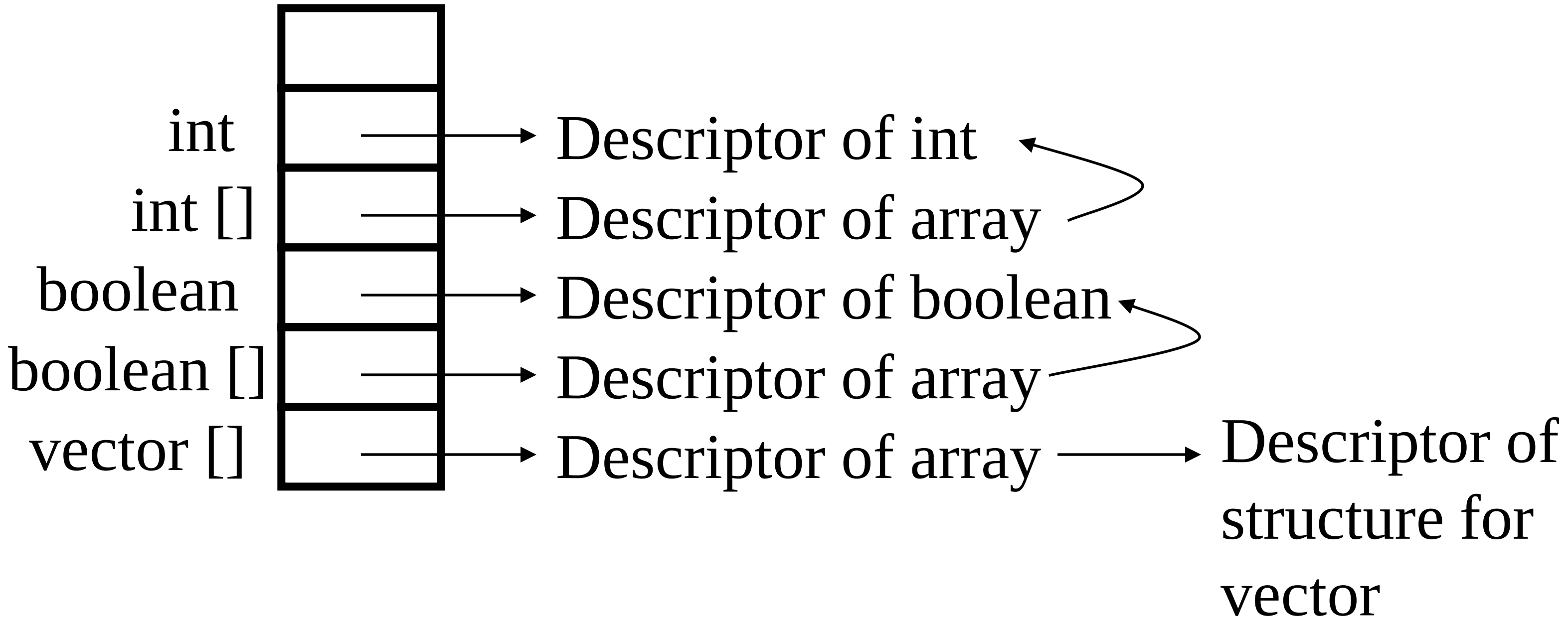
Descriptors

- What they contain?
- Information used to perform semantic analysis and to generate code
  - Local descirptors: 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.

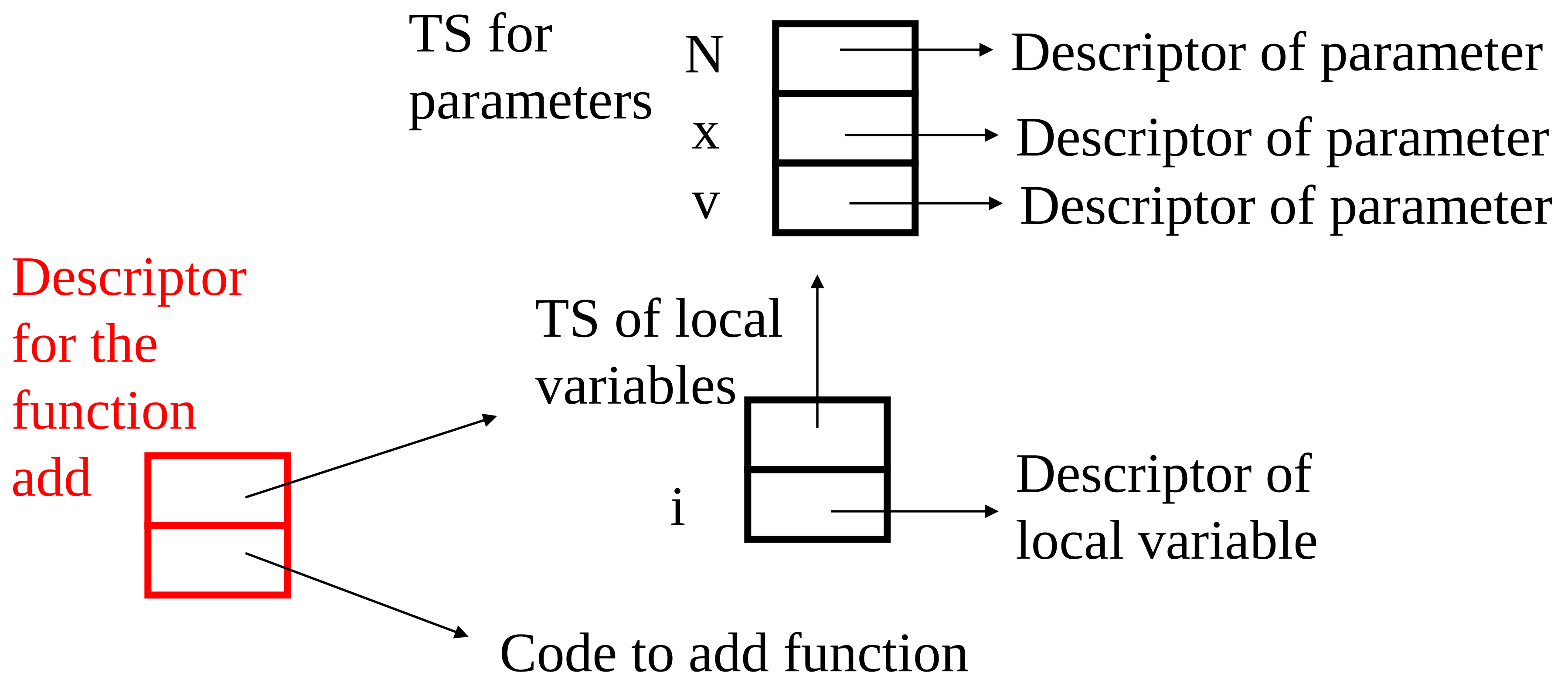
Example: Symbol Table for Types



Descriptor of Functions

- Contain reference for the code (IR) of the function
- Contain 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 subhierarchy 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
  - 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 refer program errors. Compilers usually report warning messages in the presence of this kind of conflicts.

HIGH-LEVEL INTERMEDIATE REPRESENTATION (HIR)

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, fileds, 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

Representation of 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 of structs…

Example

x and y are local variables

x*x + y*y

$$\begin{tikzcd}
 & & & + \arrow[dll] \arrow[drr] & & & \\
 & * \arrow[dl] \arrow[dr] & & & & * \arrow[dl] \arrow[dr] & \\
\text{ldl} \arrow[dr] & & \text{ldl} \arrow[dl] & & \text{ldl} \arrow[dr] & & \text{ldl} \arrow[dl] \\
 & \begin{array}{l}\text{Local descriptor for } x\\ \text{In the local symbol table}\end{array} & & & & \begin{array}{l}\text{Local descriptor for } y\\ \text{In the local symbol table}\end{array} &
\end{tikzcd}$$

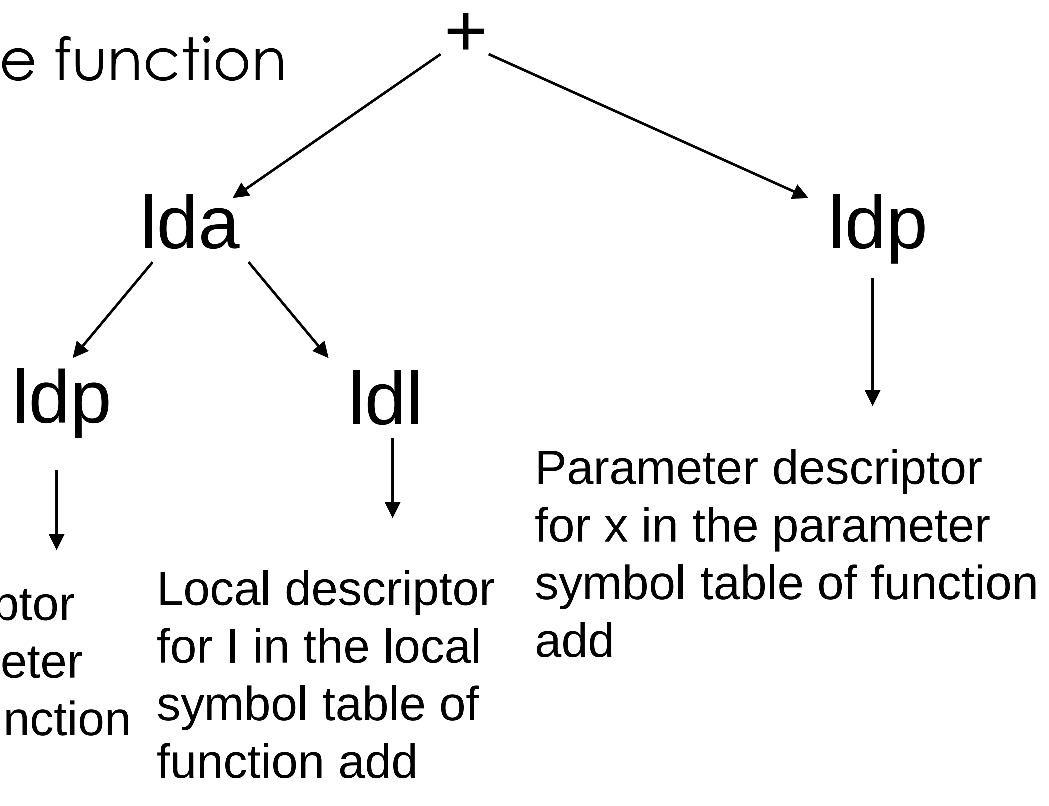
Example

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

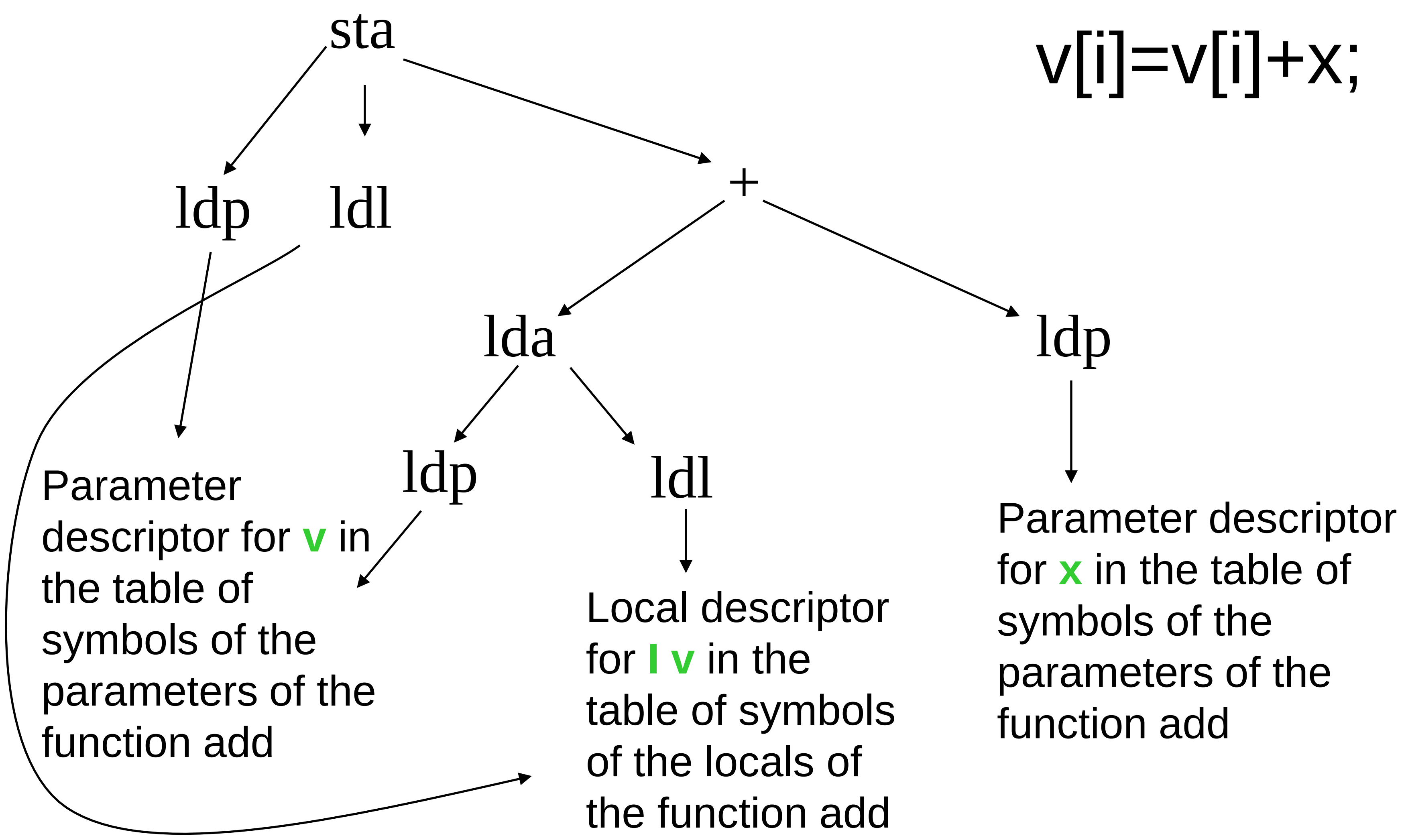

+
lda
ldp
ldp
ldl
Parameter descriptor for v in the parameter symbol table of function add
Local descriptor for I in the local symbol table of function add
Parameter descriptor for x in the parameter symbol table of function add

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

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



Parameter descriptor for **v** in the table of symbols of the parameters of the function add

Local descriptor for **l v** in the table of symbols of the locals of the function add

Parameter descriptor for **x** in the table of symbols of the parameters of the function add

Orientation

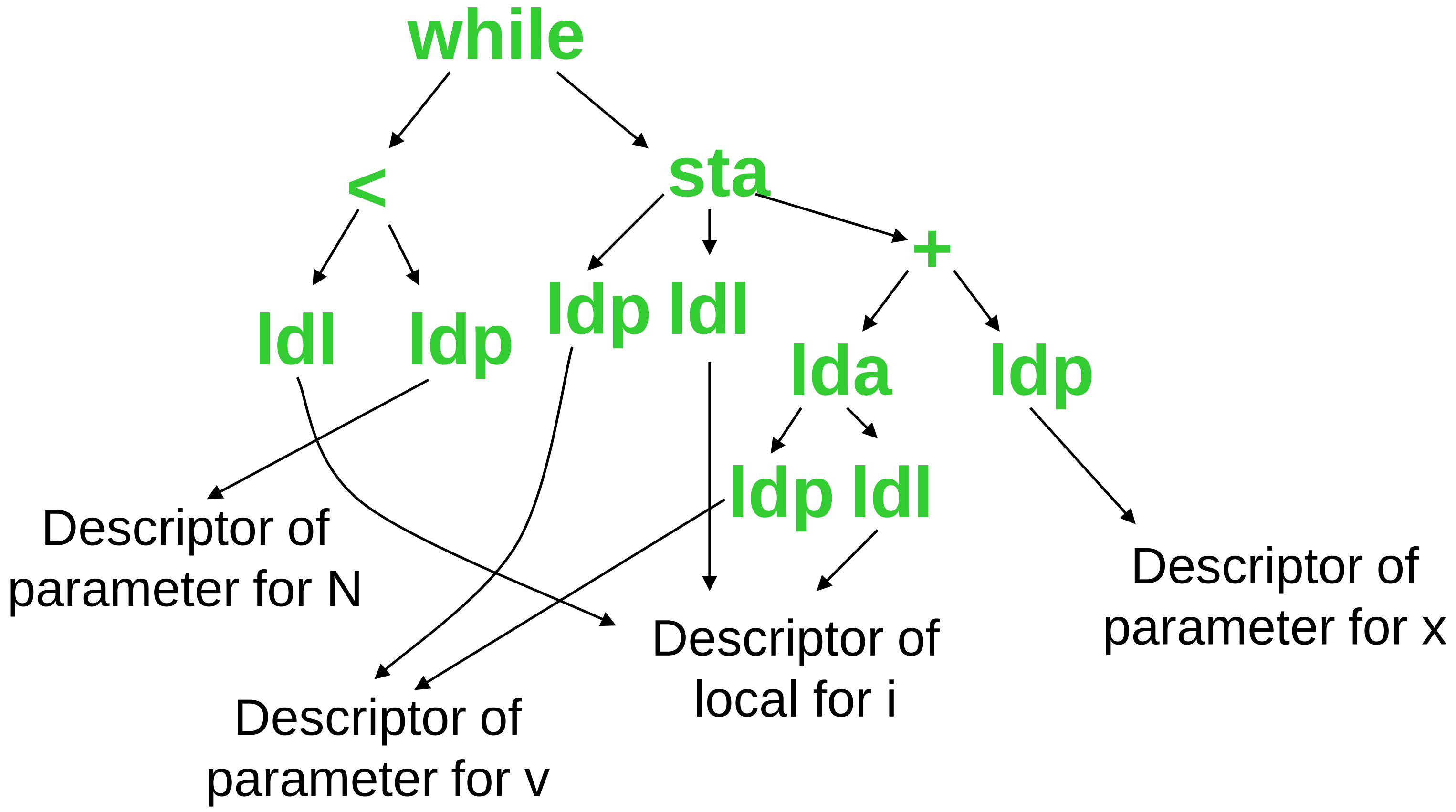
- Intermediate representations
  - Moving in the direction of the target language (e.g., machine language)
  - Support for compiler analysis and transformations
- High-Level IR (*intermediate representation*)
  - Preserves the structure of objects, arrays, control flow,…
  - Symbol Tables
  - Descriptors

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

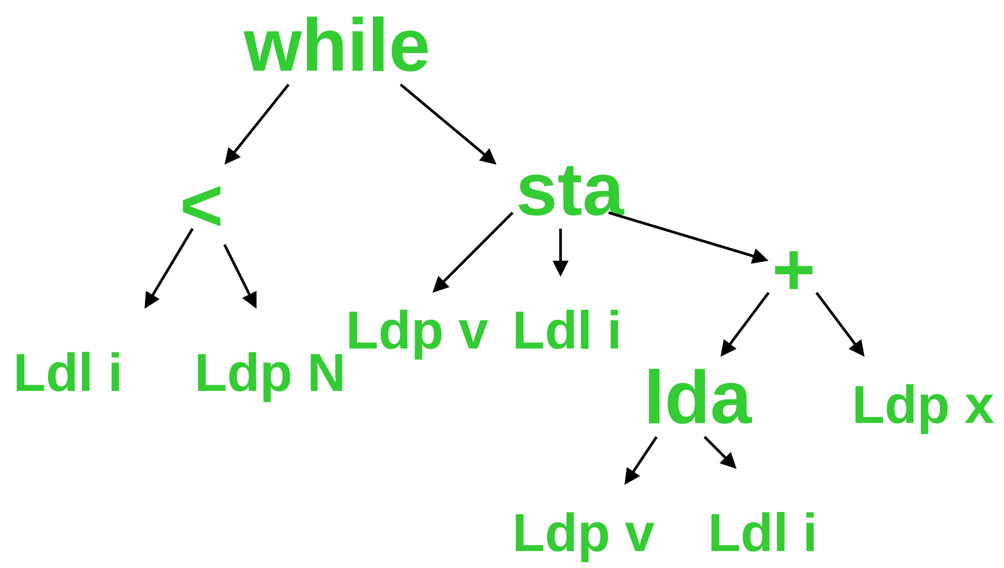
```
while (i < N)
    v[i] = v[i]+x;
```


while
<
sta
+
ldl
ldp
ldp
ldl
lda
ldp
ldp
ldl
Descriptor of parameter for N
Descriptor of local for i
Descriptor of parameter for x
Descriptor of parameter for v

Example

- 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

- Goal: to represent the program in an intuitive mode 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

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 (AST) level
  - In order errors be informative/clear, it is necessary that the tree nodes are annotated with locations 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
- We shall verify what?
  - 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 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 aray
- 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 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

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

Store Instruction

- What does have the compiler?
  - 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 have the compiler?
  - 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 have the compiler?
  - Name of the function, arguments
- Verifications:
  - Name of the function is identified in the table of the functions of the program
  - Type of arguments match with the type of parameters in the declaration of the function

SUMMARY

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
  - Preserves the structured control flow
  - Representation efficient for high level analysis and high-level optimizations (e.g., target-independent transformations)