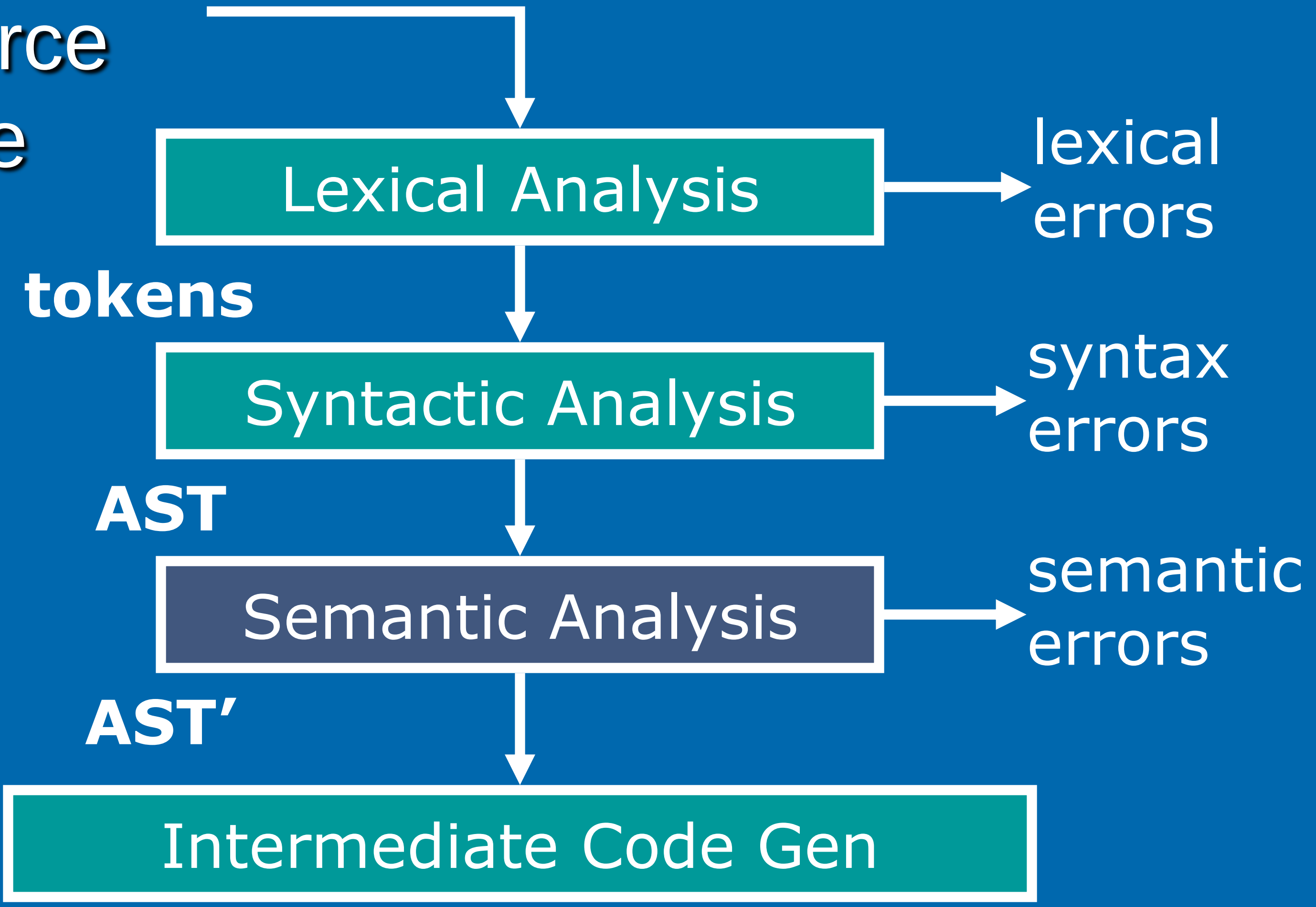
Semantic Analysis

Semantic Analysis

- Lexical analysis
  - Detects inputs with illegal tokens
    - e.g.: main$ ();
- Syntactic analysis
  - Detects inputs with ill-formed parse trees
    - e.g.: missing semicolons
- Semantic analysis
  - Last “front end” analysis phase
  - Catches all remaining errors

Semantic Analysis

- Source code



Beyond Syntax

What's wrong with this code?

(Note: it parses perfectly)

```
foo(int a, char * s){ … }

int bar() {
  int f[3];
  int i, j, k;
  char *p;
  float k;
  foo(f[6], 10, j);
  break;
  i->val = 5;
  j = i + k;
  printf("%s,%s.\n",p,q);
  goto label23;
}
```

Beyond Syntax

What's wrong with this code?

(Note: it parses perfectly)

```
foo(int a, char * s){ … }

int bar() {
  int f[3];
  int i, j, k;
  char *p;
  float k;
  foo(f[6], 10, j);
  break;
  i->val = 5;
  j = i + k;
  printf("%s,%s.\n",p,q);
  goto label23;
}
```

f[6] will cause a run-time failure

Goals of a Semantic Analyzer

- Compiler must do more than recognize whether a sentence belongs to the language…
- • Find remaining errors that would make program invalid
    - undefined variables, types
    - type errors that can be caught statically
- • Figure out useful information for later phases
    - types of all expressions
    - data layout
- <u>Terminology</u>
- Static checks – done by the compiler
- Dynamic checks – done at run time

Kinds of Checks

- Uniqueness checks
  - Certain names must be unique
  - Many languages require variable declarations

Flow-of-control checks

- Match control-flow operators with structures
- Example: break applies to innermost loop/switch

Type checks

- Check compatibility of operators and operands

Logical checks

- Program is syntactically and semantically correct, but does not do the “correct” thing

Examples of Reported Errors

- Undeclared identifier
- Multiply declared identifier
- Index out of bounds
- Wrong number or types of args to call
- Incompatible types for operation
- Break statement outside switch/loop
- Goto with no label

Program Checking

- *Why do we care?*
- Obvious:
  - Report mistakes to programmer
  - Avoid bugs: *f[6] will cause a run-time failure*
  - Help programmer verify intent
- How do these checks help compilers?
  - Allocate right amount of space for variables
  - Select right machine operations
  - Proper implementation of control structures

Can We Catch Everything?

- Try compiling this code:

```
void main()
{
    int i=21, j=42;
    printf("Hello World\n");
    printf("Hello World, N=%d\n");
    printf("Hello World\n", i, j);
    printf("Hello World, N=%d\n");
    printf("Hello World, N=%d\n");
}
```

Inlined TypeChecker and CodeGen

- You could type check and generate code as part of semantic actions:

```
expr : expr PLUS expr {
            if ($1.type == $3.type &&
              ($1.type == IntType ||
                $1.type == RealType)) $$.type = $1.type
            else error("+ applied on wrong type!");
            GenerateAdd($1, $3, $$);
          }
```

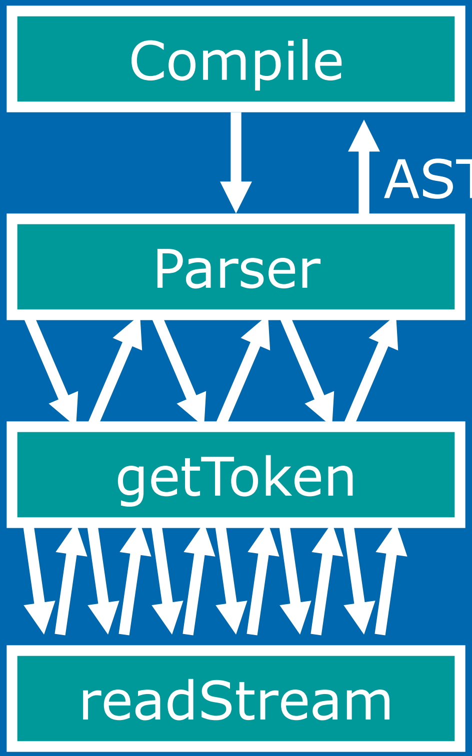
Problems

- Difficult to read
- Difficult to maintain
- Compiler must analyze program in order parsed

- Instead … we split up tasks

Compiler ‘main program’

```
void Compile() {
   AST tree = Parser(program);
   if (TypeCheck(tree))
      IR ir =
         GenIntermedCode(tree);
      EmitCode(ir);
   }
}
```



Typical Semantic Errors

- Multiple declarations: a variable should be declared (in the same scope) at most once
- Undeclared variable: a variable should not be used before being declared
- Type mismatch: type of the LHS of an assignment should match the type of the RHS
- Wrong arguments: methods should be called with the right number and types of arguments

A Sample Semantic Analyzer

- Works in two phases – traverses the AST created by the parser

1. For each scope in the program
   - **process the declarations**
     - add new entries to the symbol table and
     - report any variables that are multiply declared
   - **process the statements**
     - find uses of undeclared variables, and
     - update the "ID" nodes of the AST to point to the appropriate symbol-table entry.
2. Process all of the statements in the program again
   - use the symbol-table information to determine the type of each expression, and to find type errors.

Scoping

- In most languages, the same name can be declared multiple times
  - if its declarations occur in different scopes, and/or
  - involve different kinds of names
- Java: can use the same name for
  - a class
  - field of the class
  - a method of the class
  - a local variable of the method

```
class Test {
      int Test;
      void Test( ) { double Test; }
}
```

Scoping: Overloading

- Java and C++ (but not in Pascal or C):
  - can use the same name for more than one method
  - as long as the number and/or types of parameters are unique

```
int add(int a, int b);
float add(float a, float b);
```

Scoping: General Rules

- The scope rules of a language:
  - Determine which declaration of a named object corresponds to each use of the object
  - Scoping rules map uses of objects to their declarations

- C++ and Java use *static scoping*:
  - Mapping from uses to declarations at compile time
  - C++ uses the "most closely nested" rule
    - a use of variable **x** matches the declaration in the most closely enclosing scope
    - such that the declaration precedes the use

Scope levels

- Each function has two or more scopes:
- One for the function body
  - Sometimes parameters are separate scope!
  - (Not true in C)

```
void f( int k ) { // k is a parameter
  int k = 0;      // also a local variable
  while (k) {
      int k = 1;  // another local var, in a loop
  }
}
```

- Additional scopes in the function
  - each **`for`** loop and
  - each nested block (delimited by curly braces)

Checkpoint #1

- **Match each use to its declaration, or say why it is a use of an undeclared variable.**

```
int k=10, x=20;
void foo(int k) {
    int a = x; int x = k; int b = x;
    while (...) {
        int x;
        if (x == k) {
            int k, y;
            k = y = x;
        }
        if (x == k) { int x = y; }
    }
}
```

Dynamic Scoping

- Not all languages use static scoping
- Lisp, APL, and Snobol use *dynamic* scoping

- Dynamic scoping:
  - A use of a variable that has no corresponding declaration in the same function corresponds to the declaration in the **most-recently-called still active** function

Example

- For example, consider the following code:

```
int i = 1;
void func() {
    cout << i << endl;
}
int main () {
    int i = 2;
    func();
    return 0;
}
```

If C++ used dynamic scoping, this would print out 2, not 1

Checkpoint #2

- Assuming that dynamic scoping is used, what is output by the following program?

```
void main() { int x = 0; f1(); g(); f2(); }
void f1() { int x = 10; g(); }
void f2() { int x = 20; f1(); g(); }
void g() { print(x); }
```

Keeping Track

- Need a way to keep track of all identifier types in scope

```
{
    int i, n = …;
    for (i=0; i < n;
        boolean b= …
}
```

i → int
n → int

i → int
n → int
b → boolean

?

Symbol Tables

- Purpose:
  - keep track of names declared in the program
- Symbol table entry:
  - associates a name with a set of **attributes**, e.g.:
    - **kind** of name (variable, class, field, method, …)
    - **type** (int, float, …)
    - **nesting** level
    - mem **location** (where will it be found at runtime)
- Functions:
- Type Lookup(String id)
- Void Add(String id, Type binding)
- Bindings: name type pairs {a $\rightarrow$ string, b $\rightarrow$ int}

Environments

- Represents a set of mappings in the symbol table

$\sigma 0$

- function f(a:int, b:int, c:int) =
- (print_int(a+c);
-     let var j := a+b
-         var a := "hello"
-       in print(a); print_int(j)
-     end;
-     print_int(b)
-)

Lookup in $\sigma 1$

$\sigma 1 = \sigma 0 + a \rightarrow \text{int}$

$\sigma 2 = \sigma 1 + j \rightarrow \text{int}$

$\sigma 1$

$\sigma 0$

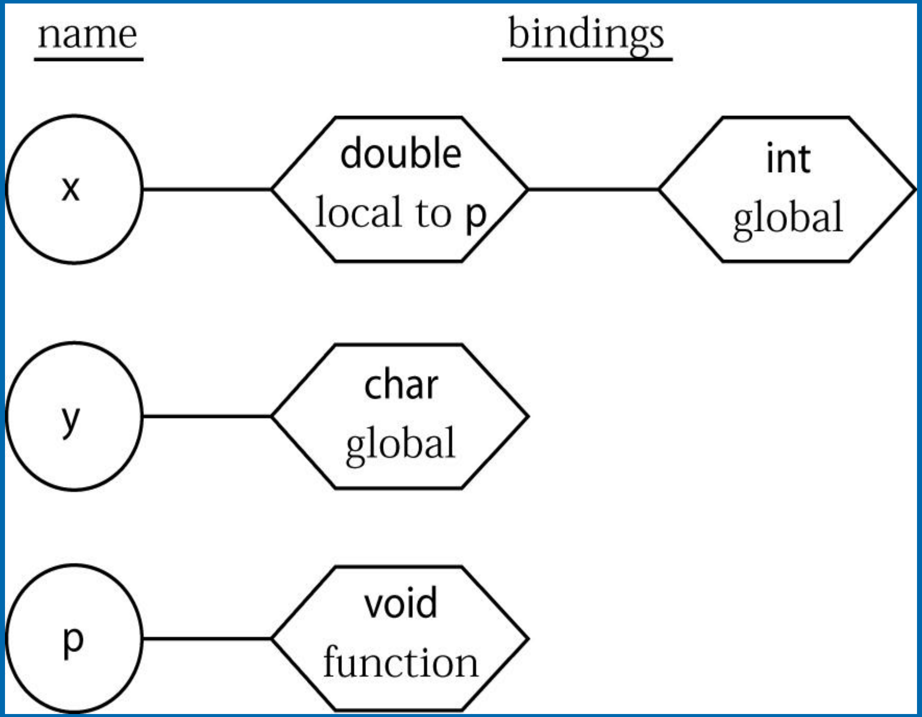
How Symbol Tables Work (1)

```
int x;
char y;

void p(void)
{ double x;
    …
  { int y[10];
    …
  }
    …
}

void q(void)
{ int y;
    …
}

main()
{ char x;
   …
}
```



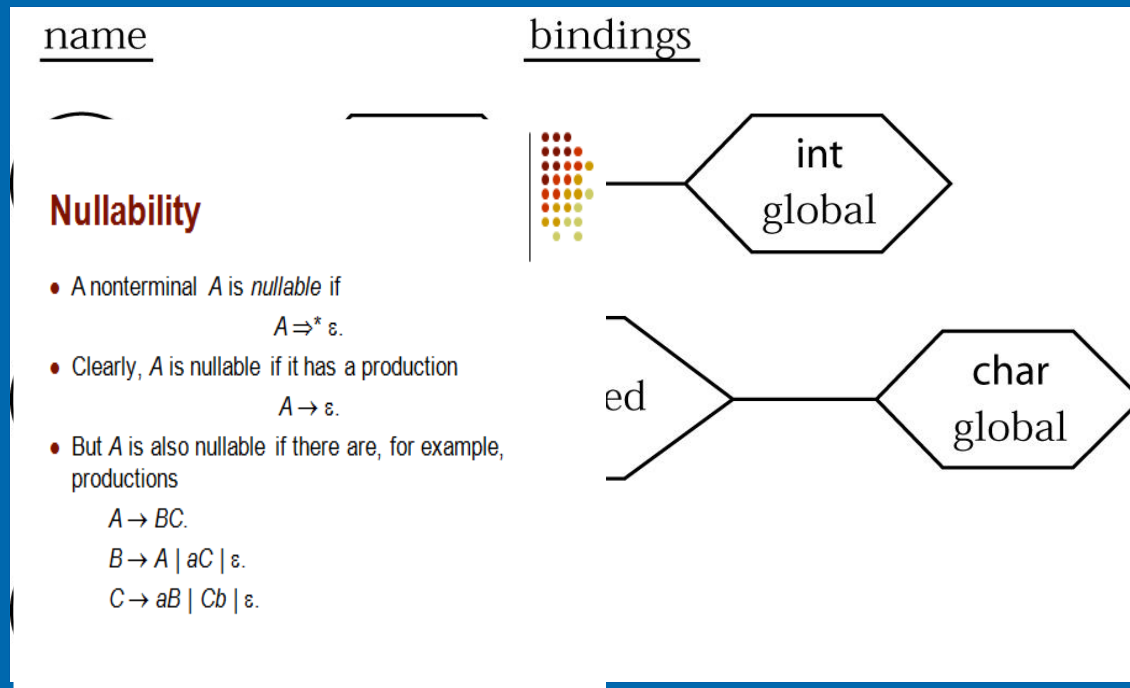
How Symbol Tables Work (2)

```
int x;
char y;

void p(void)
{ double x;
    …
  { int y[10];
    …
  }
   …
}

void q(void)
{ int y;
   …
}

main()
{ char x;
  …
}
```



Nullability

- A nonterminal A is *nullable* if

  $$A \Rightarrow^* \varepsilon.$$

- Clearly, A is nullable if it has a production

  $$A \to \varepsilon.$$

- But A is also nullable if there are, for example, productions

  $A \to BC.$

  $B \to A \mid aC \mid \varepsilon.$

  $C \to aB \mid Cb \mid \varepsilon.$

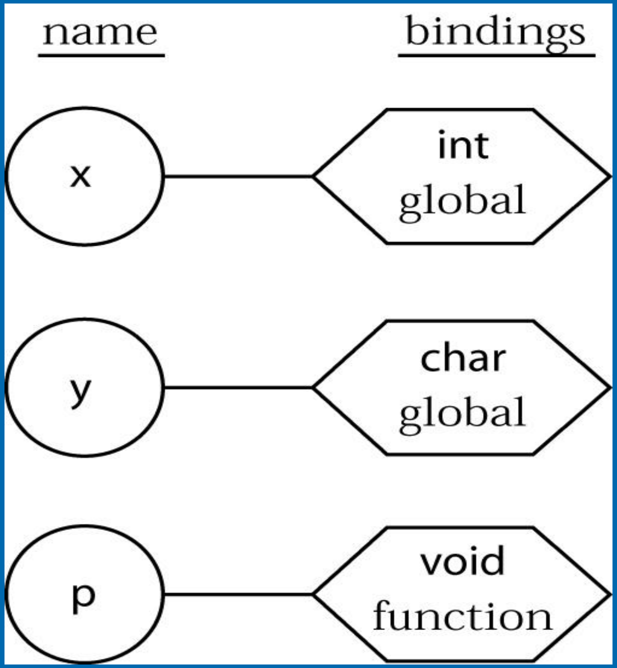
How Symbol Tables Work (3)

```
int x;
char y;

void p(void)
{ double x;
    …
  { int y[10];
    …
  }
    …
}

void q(void)
{ int y;
    …
}

main()
{ char x;
  …
}
```



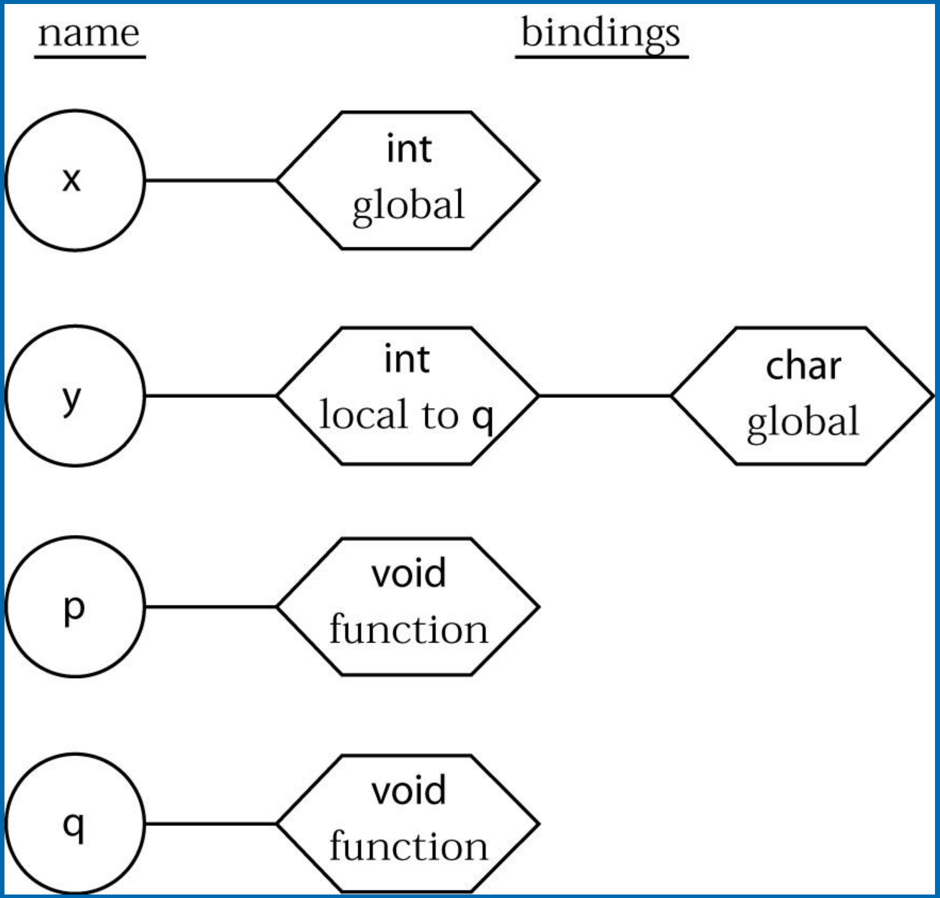
How Symbol Tables Work (4)

```
int x;
char y;

void p(void)
{ double x;
    …
  { int y[10];
   …
  }
   …
}

void q(void)
{ int y;
   …
}

main()
{ char x;
  …
}
```



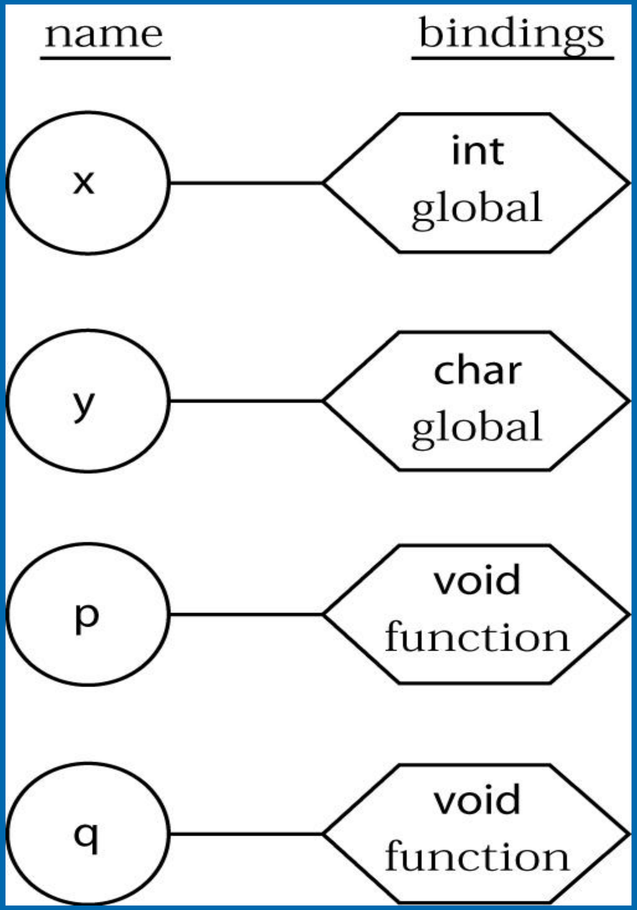
How Symbol Tables Work (5)

```
int x;
char y;

void p(void)
{ double x;
    …
  { int y[10];
    …
  }
    …
}

void q(void)
{ int y;
    …
}

main()
{ char x;
   …
}
```



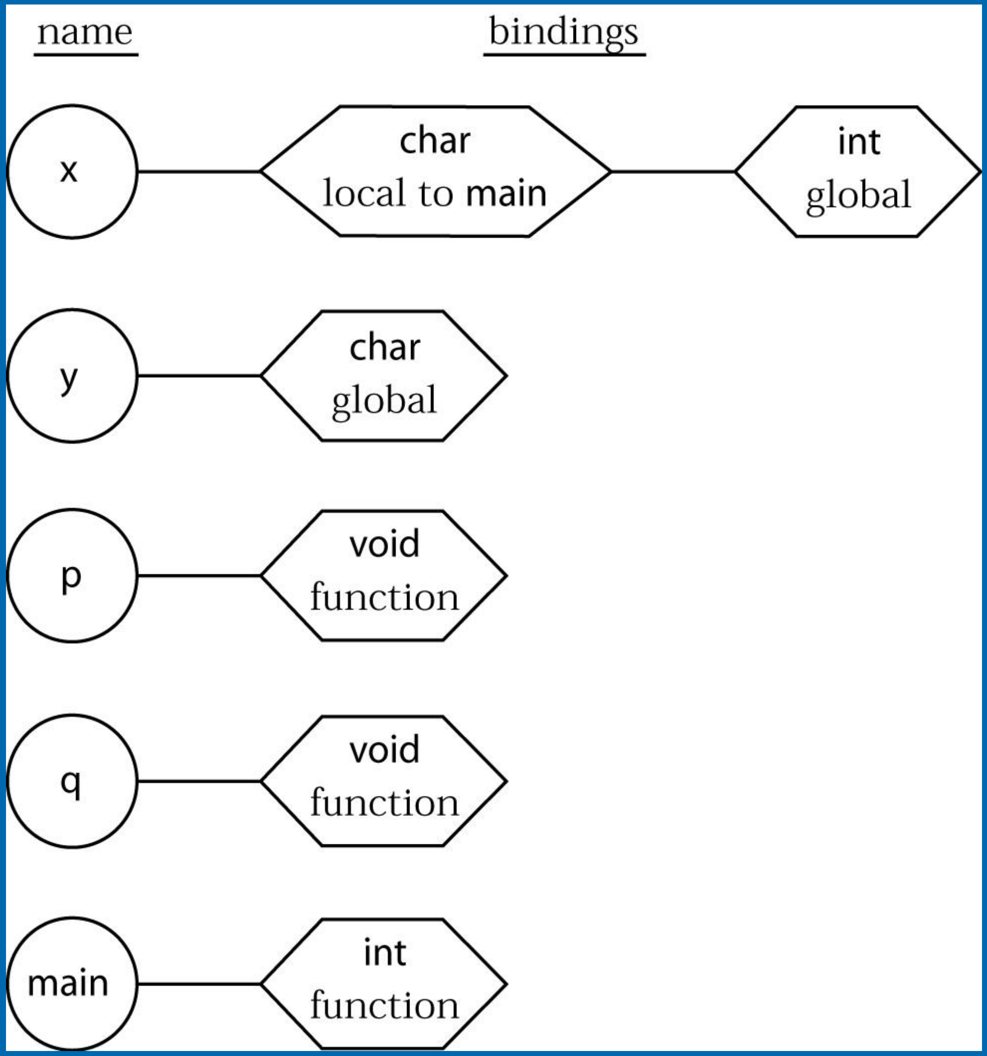
How Symbol Tables Work (6)

```
int x;
char y;

void p(void)
{ double x;
    …
  { int y[10];
   …
  }
   …
}

void q(void)
{ int y;
   …
}

main()
{ char x;
  …
}
```

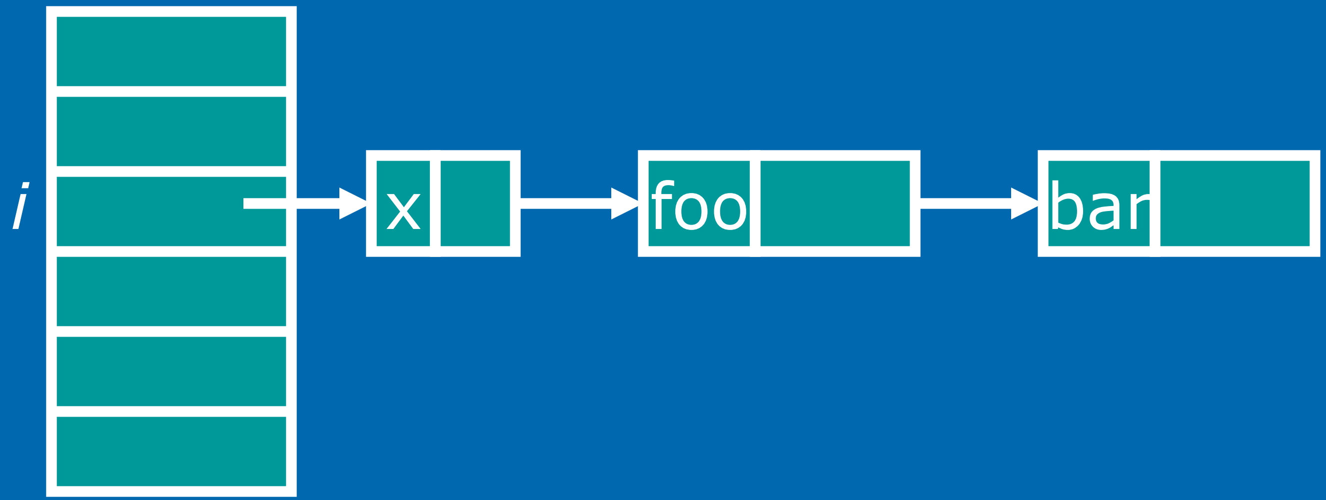


A Symbol Table Implementation

- Two structures: Hash table, Scope Stack

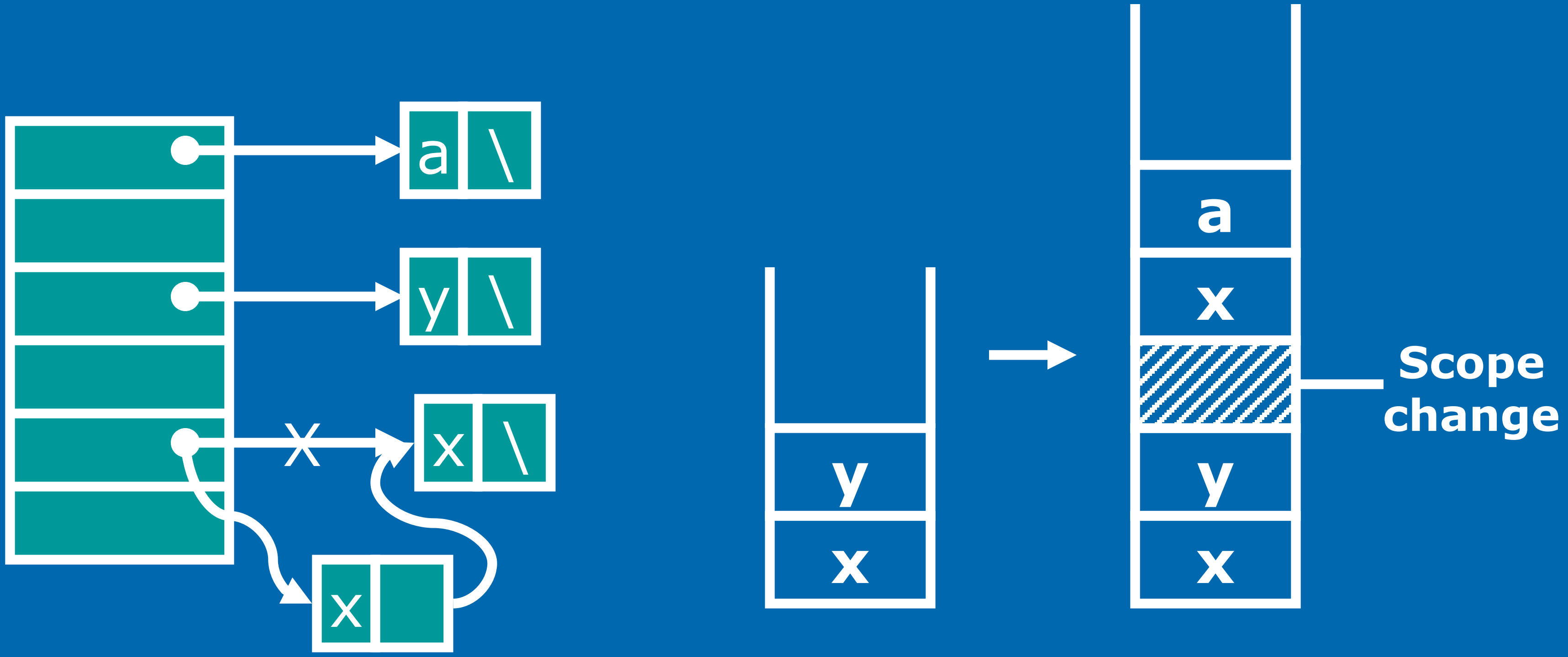
- Symbol = foo
- Hash(foo) = i

Symbol table



Enter/Exit Scope

- We also need a stack to keep track of the "nesting level" as we traverse the tree…



Variables vs. Types

- Often, compilers maintain separate symbol tables for Types vs. Variables/Functions
- Lecture Checkpoint:
- ✓ Scopes
- → Types

Types

- What is a type?
  - The notion varies from language to language
- Consensus
  - A set of values
  - A set of operations allowed on those values
- Certain operations are legal for each type
  - It doesn't make sense to add a function pointer and an integer in C
  - It does make sense to add two integers
  - But both have the same assembly language implementation!

Type Systems

- A language's type system specifies which operations are valid for which types

- The goal of type checking is to ensure that operations are used with the correct types
  - Enforces intended interpretation of values

- Type systems provide a concise formalization of the semantic checking rules

Why Do We Need Type Systems?

- Consider the assembly language fragment
- addi $r1, $r2, $r3
- What are the types of $r1, $r2, $r3?

Type Checking Overview

- Four kinds of languages:
  - **Statically typed**: All or almost all checking of types is done as part of compilation
  - **Dynamically typed**: Almost all checking of types is done as part of program execution (no compiler) as in Perl, Ruby
  - **Mixed Model** : Java
  - **Untyped**: No type checking (machine code)

Type Checking and Type Inference

- Type Checking is the process of verifying fully typed programs
  - Given an operation and an operand of some type, determine whether the operation is allowed
- Type Inference is the process of filling in missing type information
  - Given the type of operands, determine
    - the meaning of the operation
    - the type of the operation
  - OR, without variable declarations, infer type from the way the variable is used
- The two are different, but are often used interchangeably

Issues in Typing

- Does the language have a type system?
  - Untyped languages (e.g. assembly) have no type system at all
- When is typing performed?
  - Static typing: At compile time
  - Dynamic typing: At runtime
- How strictly are the rules enforced?
  - Strongly typed: No exceptions
  - Weakly typed: With well-defined exceptions
- Type equivalence & subtyping
  - When are two types equivalent?
    - What does "equivalent" mean anyway?
  - When can one type replace another?

Components of a Type System

- Built-in types
- Rules for constructing new types
  - Where do we store type information?
- Rules for determining if two types are equivalent
- Rules for inferring the types of expressions

Component: Built-in Types

- Integer
  - usual operations: standard arithmetic
- Floating point
  - usual operations: standard arithmetic
- Character
  - character set generally ordered lexicographically
  - usual operations: (lexicographic) comparisons
- Boolean
  - usual operations: not, and, or, xor

Component: Type Constructors

- Arrays
  - array(I,T) denotes the type of an array with elements of type T, and index set I
  - multidimensional arrays are just arrays where T is also an array
  - operations: element access, array assignment, products
- Strings
  - bitstrings, character strings
  - operations: concatenation, lexicographic comparison
- Records (structs)
  - Groups of multiple objects of different types where the elements are given specific names.

Component: Type Constructors

- Pointers
  - addresses
  - operations: arithmetic, dereferencing, referencing
  - issue: equivalency
- Function types
  - A function such as "int add(real, int)" has type $real \times int \rightarrow int$

Component: Type Equivalence

- Name equivalence
  - Types are equiv only when they have the same name
- Structural equivalence
  - Types are equiv when they have the same structure
- Example
  - C uses structural equivalence for structs and name equivalence for arrays/pointers

Component: Type Equivalence

- Type Coercion
  - If x is float, is x=3 acceptable?
    - Disallow
    - Allow and implicitly convert 3 to float
    - "Allow" but require programmer to explicitly convert 3 to float
  - What should be allowed?
    - float to int ?
    - int to float ?
    - What if multiple coercions are possible?
      - Consider 3 + "4" …

Formalizing Types: Rules of Inference

- We have seen two examples of formal notation specifying parts of a compiler
  - Regular expressions (for the lexer)
  - Context-free grammars (for the parser)

- The appropriate formalism for type checking is logical rules of inference

$$\frac{\vdash e_1 : \mathbf{int} \qquad \vdash e_2 : \mathbf{int}}{\vdash e_1 < e_2 : \mathbf{boolean}}$$

Semantic Analysis Summary

- Compiler must do more than recognize whether a sentence belongs to the language
- • Checks of all kinds
  - undefined variables, types
  - type errors that can be caught statically
- • Store useful information for later phases
  - types of all expressions

Thank you