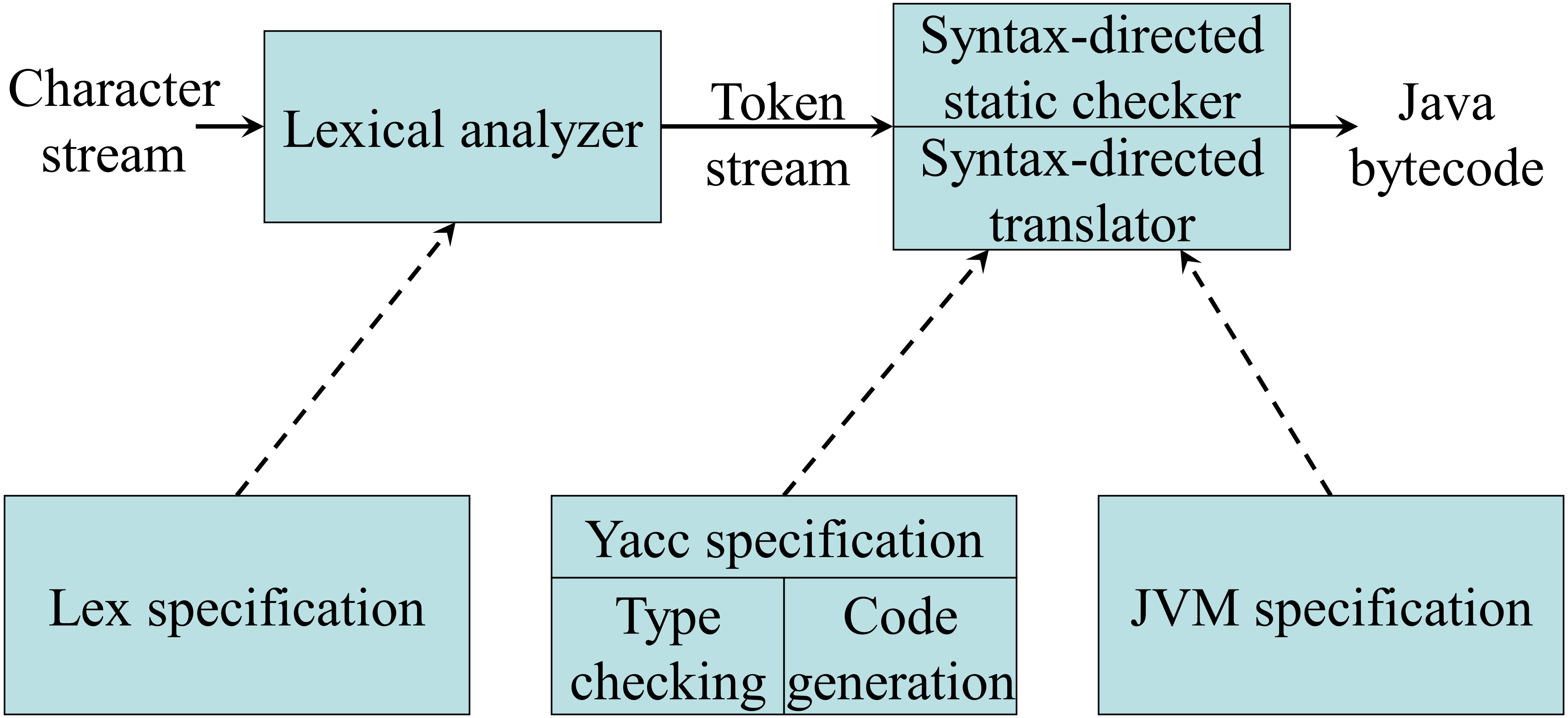
Static Checking and Type Systems

Chapter 6

The Structure of our Compiler Revisited



Character stream

Lexical analyzer

Token stream

Syntax-directed static checker

Syntax-directed translator

Java bytecode

Lex specification

Yacc specification

Type checking

Code generation

JVM specification

Static versus Dynamic Checking

- *Static checking*: the compiler enforces programming language's *static semantics*, which are checked at compile time
- *Runtime checking*: *dynamic semantics* are checked at run time by special code generated by the compiler

Static Checking

- Typical examples of static checking are
  - Type checks
  - Flow-of-control checks
  - Uniqueness checks
  - Name-related checks

Type Checks, Overloading, Coercion, and Polymorphism

```
int op(int), op(float);
int f(float);
int a, c[10], d;

d = c+d;            // FAIL

*d = a;             // FAIL

a = op(d);          // OK: overloading (C++)

a = f(d);           // OK: coersion

vector<int> v;      // OK: template instantiation
```

Flow-of-Control Checks

```
myfunc()
{ …
  break; // ERROR
}
```

```
myfunc()
{ …
  while (n)
  { …
    if (i>10)
      break; // OK
  }
}
```

```
myfunc()
{ …
  switch (a)
  { case 0:
      …
      break; // OK
    case 1:
      …
  }
}
```

Uniqueness Checks

```
myfunc()
{ int i, j, i; // ERROR
  …
}
```

```
cnufym(int a, int a) // ERROR
{    …
}
```

```
struct myrec
{ int name;
};
struct myrec // ERROR
{ int id;
};
```

Name-Related Checks

```
LoopA: for (int I = 0; I < n; I++)
       { …
         if (a[I] == 0)
           break LoopB;
         …
       }
```

One-Pass versus Multi-Pass Static Checking

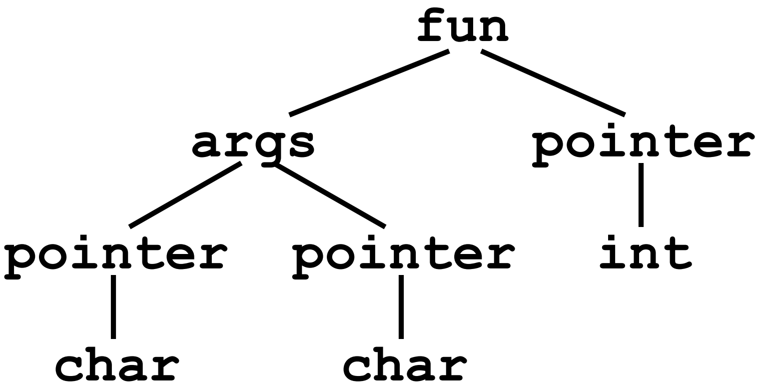
- *One-pass compiler*: static checking for C, Pascal, Fortran, and many other languages can be performed in one pass while at the same time intermediate code is generated
- *Multi-pass compiler*: static checking for Ada, Java, and C# is performed in a separate phase, sometimes requiring traversing the syntax tree multiple times

Type Expressions

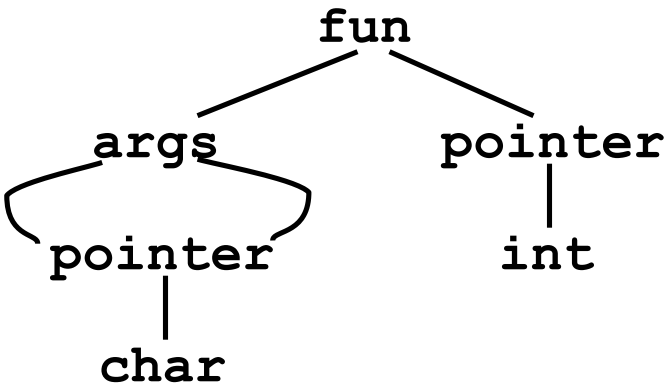
- *Type expressions* are used in declarations and type casts to define or refer to a type
  - *Primitive types*, such as **`int`** and **`bool`**
  - *Type constructors*, such as pointer-to, array-of, records and classes, templates, and functions
  - *Type names*, such as typedefs in C and named types in Pascal, refer to type expressions

Graph Representations for Type Expressions

```
int *f(char*,char*)
```



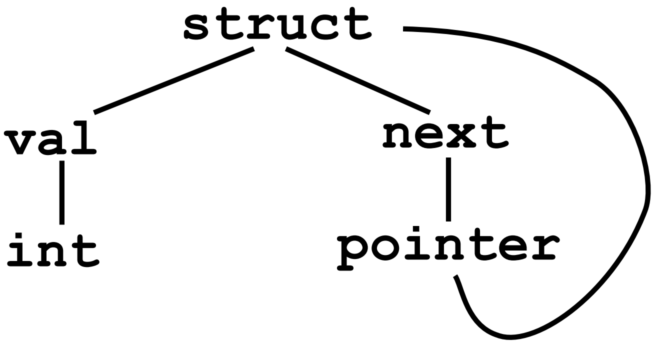
Tree forms



DAGs

Cyclic Graph Representations

```
struct Node
{ int val;
  struct Node *next;
};
```



Cyclic graph

Name Equivalence

- Each type name is a distinct type, even when the type expressions the names refer to are the same
- Types are identical only if names match
- Used by Pascal (inconsistently)

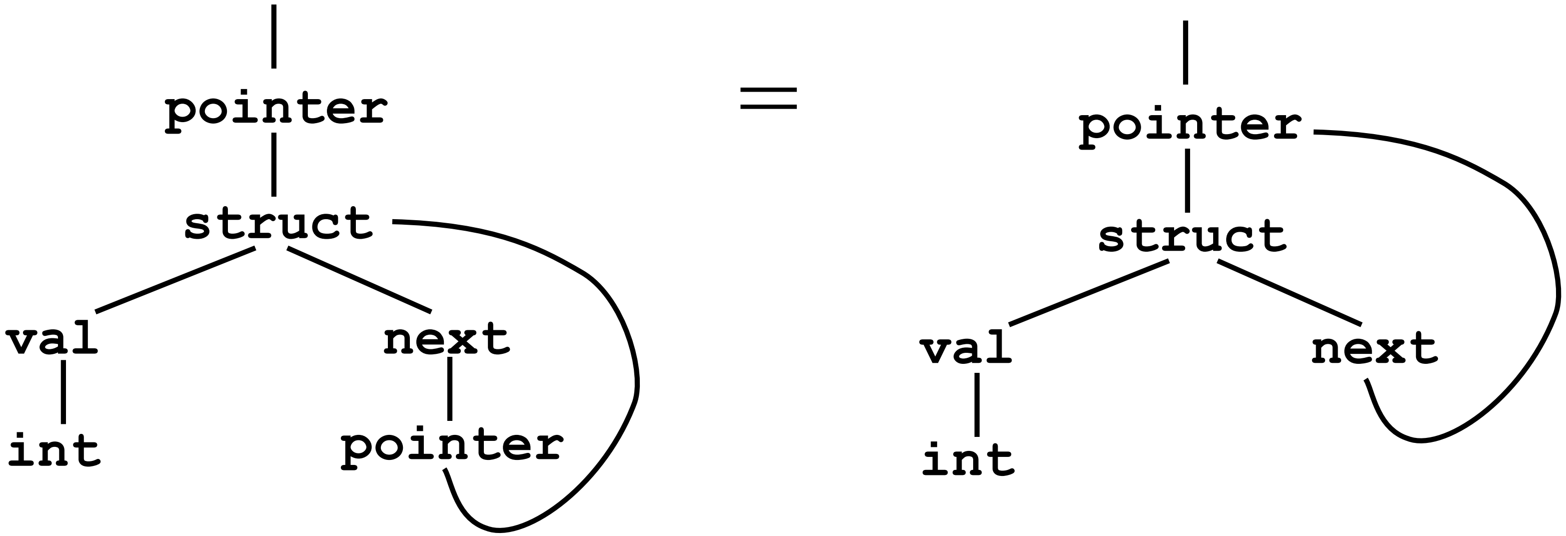
```
type link = ^node;
var next : link;
    last : link;
       p : ^node;
    q, r : ^node;
```

With name equivalence in Pascal:

`p` ≠ `next`
`p` ≠ `last`
`p` = `q` = `r`
`next` = `last`

Structural Equivalence of Type Expressions

- Two types are the same if they are structurally identical
- Used in C, Java, C#

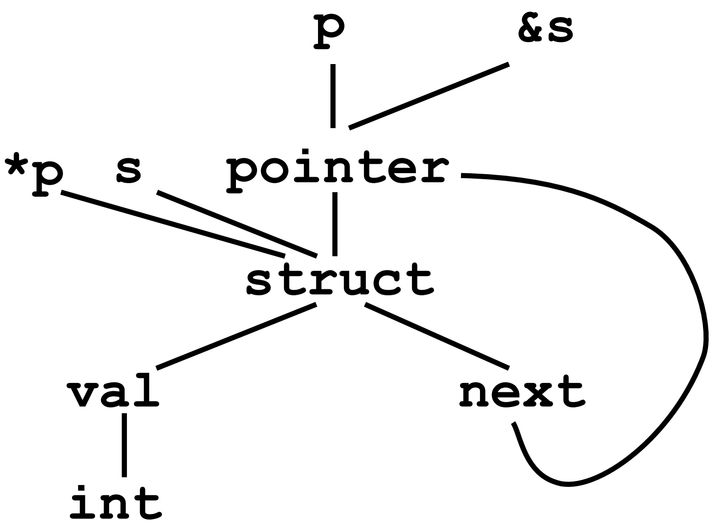


Structural Equivalence of Type Expressions (cont'd)

- Two structurally equivalent type expressions have the same pointer address when constructing graphs by sharing nodes

```
struct Node
{ int val;
  struct Node *next;
};
struct Node s, *p;

… p = &s; // OK
… *p = s; // OK
```



Constructing Type Graphs in Yacc

`Type *mkint()`	construct int node if not already constructed
`Type *mkarr(Type*,int)`	construct array-of-type node if not already constructed
`Type *mkptr(Type*)`	construct pointer-of-type node if not already constructed

Syntax-Directed Definitions for Constructing Type Graphs in Yacc

```
%union
{ Symbol *sym;
  int num;
  Type *typ;
}
%token INT
%token <sym> ID
%token <int> NUM
%type <typ> type
%%
decl : type ID                 { addtype($2, $1); }
     | type ID `[’ NUM `]’ { addtype($2, mkarr($1, $4)); }
     ;
type : INT                     { $$ = mkint(); }
     | type `*’                { $$ = mkptr($1); }
     | /* empty */             { $$ = mkint(); }
     ;
```

Type Systems

- A *type system* defines a set of types and rules to assign types to programming language constructs
- Informal type system rules, for example "*if both operands of addition are of type integer, then the result is of type integer*"
- Formal type system rules: Post system

Type Rules in Post System Notation

$$\frac{E(v) = T}{E \vdash v : T}$$

$$\frac{E(v) = T \quad E \vdash e : T}{E \vdash v := e}$$

$$\frac{E \vdash e_1 : \text{integer} \qquad E \vdash e_2 : \text{integer}}{E \vdash e_1 + e_2 : \text{integer}}$$

Environment E maps variables v to types T: $E(v) = T$

A Simple Language Example

P → *D* **;** *S*
D → *D* **;** *D*
| **id :** *T*
T → **boolean**
| **char**
| **integer**
| **array [num] of** *T*
| **^** *T*
S → **id :=** *E*
| **if** *E* **then** *S*
| **while** *E* **do** *S*
| *S* **;** *S*

E → **true**
| **false**
| **literal**
| **num**
| **id**
| *E* **and** *E*
| *E* **mod** *E*
| *E* **[** *E* **]**
| *E* **^**

Simple Language Example: Declarations

$D \rightarrow$ **id :** T	{ *addtype*(**id**.entry, T.type) }
$T \rightarrow$ **boolean**	{ T.type := *boolean* }
$T \rightarrow$ **char**	{ T.type := *char* }
$T \rightarrow$ **integer**	{ T.type := *integer* }
$T \rightarrow$ **array [num] of** T_1	{ T.type := *array*(1..**num**.val, T_1.type) }
$T \rightarrow$ **^** T_1	{ T.type := *pointer*(T_1)

Simple Language Example: Statements

$S \rightarrow$ **id :=** E	{ S.type := **if id**.type = E.type **then** *void* **else** *type_error* }
$S \rightarrow$ **if** E **then** S_1	{ S.type := **if** E.type = *boolean* **then** S_1.type **else** *type_error* }
$S \rightarrow$ **while** E **do** S_1	{ S.type := **if** E.type = *boolean* **then** S_1.type **else** *type_error* }
$S \rightarrow S_1$ **;** S_2	{ S.type := **if** S_1.type = *void* **and** S_2.type = *void* **then** *void* **else** *type_error* }

Simple Language Example: Expressions

$E \to$ **true**	{ E.type = *boolean* }
$E \to$ **false**	{ E.type = *boolean* }
$E \to$ **literal**	{ E.type = *char* }
$E \to$ **num**	{ E.type = *integer* }
$E \to$ **id**	{ E.type = *lookup*(**id**.entry) }

…

Simple Language Example: Expressions (cont’d)

$E \rightarrow E_1$ **and** E_2	{ E.type := **if** E_1.type = *boolean* **and** E_2.type = *boolean* **then** *boolean* **else** *type_error* }
$E \rightarrow E_1$ **mod** E_2	{ E.type := **if** E_1.type = *integer* **and** E_2.type = *integer* **then** *integer* **else** *type_error* }
$E \rightarrow E_1$ **[** E_2 **]**	{ E.type := **if** E_1.type = *array*(s, t) **and** E_2.type = *integer* **then** t **else** *type_error* }
$E \rightarrow E_1$ **^**	{ E.type := **if** E_1.type = *pointer*(t) **then** t **else** *type_error* }

Simple Language Example: Adding Functions

$T \rightarrow T_1$ **->** T_2 { T.type := *function*(T_1.type, T_2.type) }

$E \rightarrow E_1$ **(** E_2 **)** { E.type := **if** E_1.type = *function*(s, t) **and**
E_2.type = s
then t **else** *type_error* }

Example:

v : integer;
odd : integer -> boolean;
if odd(3) then
v := 1;

Syntax-Directed Definitions for Type Checking in Yacc

```
%{
enum Types {Tint, Tfloat, Tpointer, Tarray, … };
typedef struct Type
{ enum Types type;
  struct Type *child;
} Type;
%}
%union
{ Type *typ;
}
%type <typ> expr
%%
expr : expr ‘+’ expr { if ($1.type != Tint
                         || $3.type != Tint)
                          semerror(“non-int operands in +”);
                       $$ = mkint();
                       emit(iadd);
                     }
```

Type Conversion and Coercion

- *Type conversion* is explicit, for example using type casts
- *Type coercion* is implicitly performed by the compiler
- Both require a type system to check and infer types for (sub)expressions

Syntax-Directed Definitions for Type Coercion in Yacc

```
%{ … %}
%%
expr : expr ‘+’ expr
     { if ($1.type == Tint && $3.type == Tint)
         { $$ = mkint(); emit(iadd);
         }
         else if ($1.type == Tfloat && $3.type == Tfloat)
         { $$ = mkfloat(); emit(fadd);
         }
         else if ($1.type == Tfloat && $3.type == Tint)
         { $$ = mkfloat(); emit(i2f); emit(fadd);
         }
         else if ($1.type == Tint && $3.type == Tfloat)
         { $$ = mkfloat(); emit(swap); emit(i2f); emit(fadd);
         }
         else semerror(“type error in +”);
           $$ = mkint();
     }
```

Syntax-Directed Definitions for L-Values and R-Values in Yacc

```
%{
typedef struct Node
{ Type *typ;
  int islval;
} Node;
%}
%union
{ Node *rec;
}
%type <rec> expr
%%
```

```
expr : expr ‘+’ expr
     { if ($1.typ->type != Tint
         || $3.typ->type != Tint)
          semerror(“non-int operands in +”);
       $$.typ = mkint();
       $$.islval = FALSE;
       emit(…);
     }
     | expr ‘=’ expr
     { if (!$1.islval || $1.typ != $3.typ)
          semerror(“invalid assignment”);
       $$.typ = $1.typ; $$.islval = FALSE;
       emit(…);
     }
     | ID
     { $$.typ = lookup($1);
       $$.islval = TRUE;
       emit(…);
     }
```