Compilerconstructie

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`http://www.liacs.nl/home/rvvliet/coco/`

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Static Type Checking

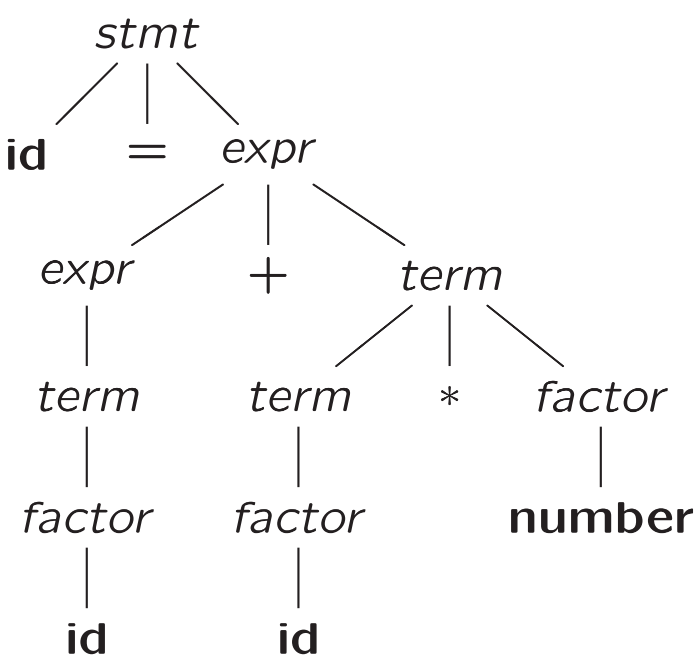
The Phases of a Compiler
(from college 1)

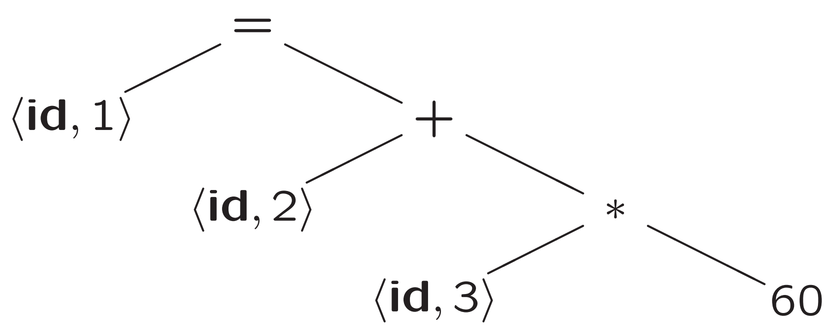
Token stream:

$$\langle \mathbf{id}, 1 \rangle \ \langle = \rangle \ \langle \mathbf{id}, 2 \rangle \ \langle + \rangle \ \langle \mathbf{id}, 3 \rangle \ \langle * \rangle \ \langle 60 \rangle$$

Syntax Analyser (parser)

Parse tree / syntax tree:





6.1 Variants of Syntax Trees

Directed Acyclic Graphs for Expressions

$a + a * (b - c) + (b - c) * d$

Syntax tree vs DAG. . .

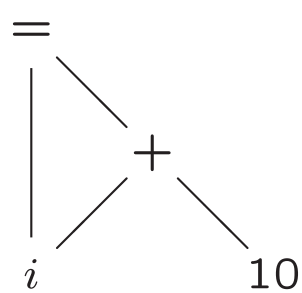
Producing Syntax Trees or DAG's

Production	Semantic Rules
1) $E \rightarrow E_1 + T$	$E.node = getNode('+', E_1.node, T.node)$
2) $E \rightarrow E_1 - T$	$E.node = getNode('-', E_1.node, T.node)$
3) $E \rightarrow T$	$E.node = T.node$
4) $T \rightarrow (\ E\ )$	$T.node = E.node$
5) $T \rightarrow$ **id**	$T.node = getLeaf(\textbf{id}, \textbf{id}.entry)$
6) $T \rightarrow$ **num**	$T.node = getLeaf(\textbf{num}, \textbf{num}.val)$

1) $p_1 = getLeaf(\textbf{id}, entry\text{-}a)$
2) $p_2 = getLeaf(\textbf{id}, entry\text{-}a) = p_1$
3) $p_3 = getLeaf(\textbf{id}, entry\text{-}b)$
4) $p_4 = getLeaf(\textbf{id}, entry\text{-}c)$
5) $p_5 = getNode('-', p_3, p_4)$

Implementation: Value-Number Method

DAG for $i = i + 10$



1	**id**	→ to entry for i	
2	**num**	10	
3	+	1	2
4	=	1	3
5	...		

- Search array for (existing) node
- Use hash table

Static Checking

- Type checks:
  Verify that type of a construct matches the expected one
- Flow-of-control checks:
  Example: break-statement must be enclosed in while-, for- or switch-statement
- ...

6.3 Types and Declarations

Types can be used for

- Type checking
- Translation
  Type information useful
  - to determine storage needed
  - to calculate address of array element
  - to insert explicit type conversions
  - to choose right version of operator
  - ...

6.3.1 Type Expressions

Types have structure

Example: array type `int[2][3]`

- Basic types: boolean, char, integer, float, void
- Type names: typedefs in C, class names in C++
- Type constructors:
  - array
  - record: data structure with named fields
  - $\rightarrow$ for function types: $s \rightarrow t$
  - Cartesian product $\times$: $s \times t$
  - ...

CFG for Function Declaration

$$
\begin{array}{rcl}
F & \rightarrow & B \ \textbf{id} \ (\mathit{OptL}) \\
B & \rightarrow & \textbf{int} \\
 & | & \textbf{float} \\
\mathit{OptL} & \rightarrow & \epsilon \\
 & | & \mathit{Ps} \\
\mathit{Ps} & \rightarrow & P \\
 & | & \mathit{Ps}, P \\
P & \rightarrow & T \ \textbf{id}
\end{array}
$$

CFG for Function Declaration

$$
\begin{array}{lcll}
F & \rightarrow & B\ \textbf{id}\ (\mathit{OptL}) & \{\ F.\mathit{type} = \rightarrow (\mathit{OptL}.\mathit{type}, B.\mathit{type});\} \\
B & \rightarrow & \textbf{int} & \{\ B.\mathit{type} = \mathit{integer};\} \\
 & | & \textbf{float} & \{\ B.\mathit{type} = \mathit{float};\} \\
\mathit{OptL} & \rightarrow & \epsilon & \{\ \mathit{OptL}.\mathit{type} = \mathit{void};\} \\
 & | & \mathit{Ps} & \{\ \mathit{OptL}.\mathit{type} = \mathit{Ps}.\mathit{type};\} \\
\mathit{Ps} & \rightarrow & P & \{\ \mathit{Ps}.\mathit{type} = P.\mathit{type};\} \\
 & | & \mathit{Ps}_1, P & \{\ \mathit{Ps}.\mathit{type} = \times(\mathit{Ps}_1.\mathit{type}, P.\mathit{type});\} \\
P & \rightarrow & T\ \textbf{id} & \{\ P.\mathit{type} = T.\mathit{type};\}
\end{array}
$$

6.3.2 Type Equivalence

$$S \rightarrow \textbf{id} = E \;\; \{\textbf{if } (id.\textit{type} == E.\textit{type}) \;\; \textbf{then } \ldots; \;\; \textbf{else } \ldots\}$$

When are type expressions equivalent?

- Structural equivalence
- Name equivalence
- Use graph representation of type expressions to check equivalence
  - Leaves for basic types and type names
  - Interior nodes for type constructors
  - Cycles in case of recursively defined types...

Structural Equivalence

- Same basic type:
  integer is equivalent to *integer*
- Formed by applying same constructor to structurally equivalent types
  pointer($integer$) is equivalent to *pointer*($integer$)
- One is type name of other

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

6.3.3 Declarations

- We need symbol tables to record global and local declarations in procedures, blocks, and structs to resolve names
- Symbol table contains type and relative adress of names

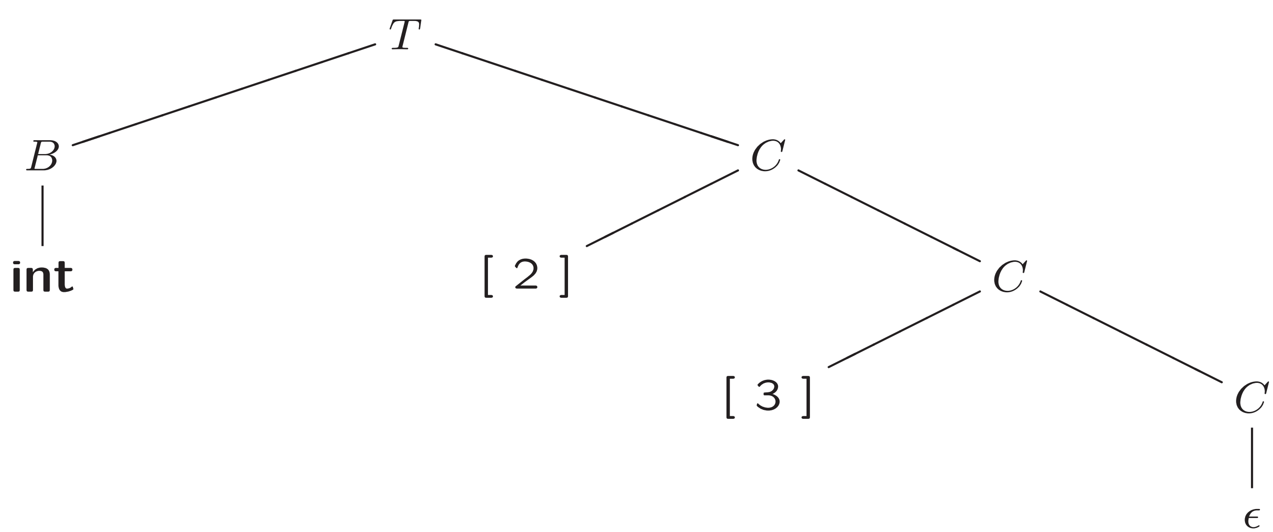
Example:

$$
\begin{array}{lcl}
D & \rightarrow & T\ \textbf{id}; D \ \mid\ \epsilon \\
T & \rightarrow & B\ C\ \mid\ \textbf{record}\ '\{'\ D\ '\}' \\
B & \rightarrow & \textbf{int}\ \mid\ \textbf{float} \\
C & \rightarrow & \epsilon\ \mid\ [\ \textbf{num}\ ]\ C
\end{array}
$$

Structure of Types (Example)

$$
\begin{array}{lcl}
T & \rightarrow & B\ C \ \mid\ \textbf{record}\ '\{'\ D\ '\}' \\
B & \rightarrow & \textbf{int} \ \mid\ \textbf{float} \\
C & \rightarrow & \epsilon \ \mid\ [\ \textbf{num}\ ]\ C
\end{array}
$$

`int[2][3]`



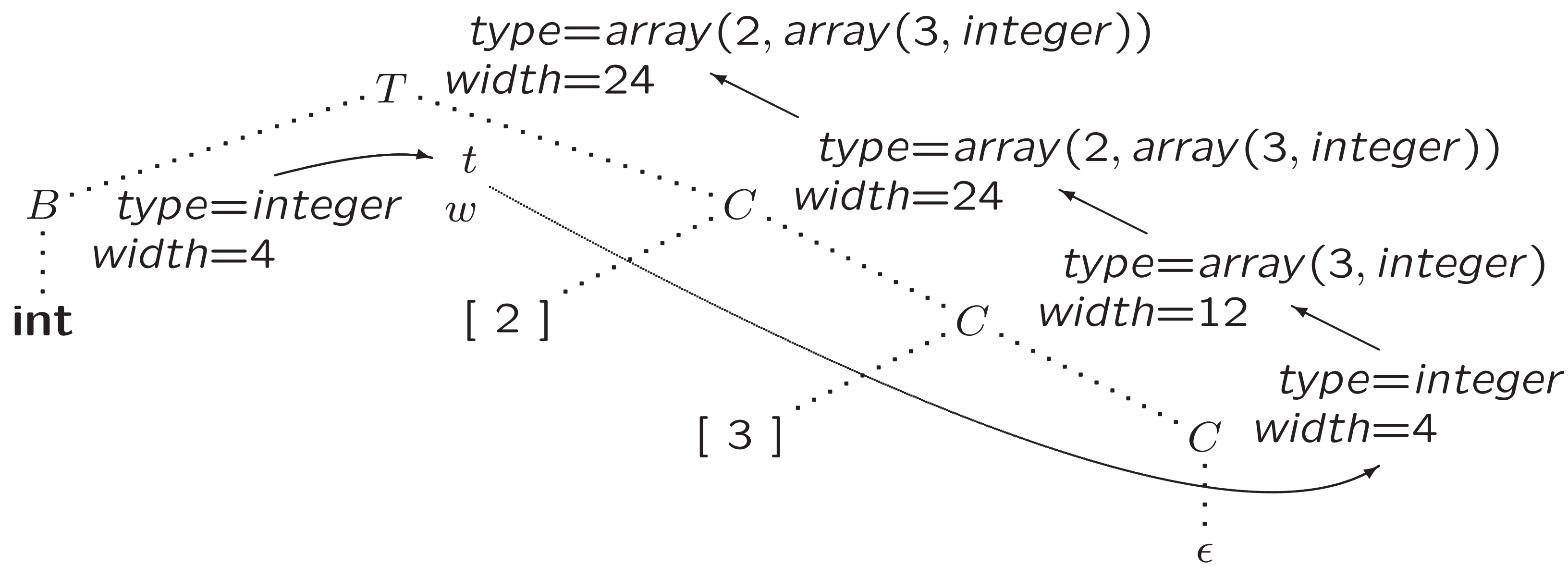
6.3.4 Storage Layout for Local Names

- Storage comes in blocks of contiguous bytes
- Width of type is number of bytes needed

$$
\begin{array}{lcll}
T & \rightarrow & B & \{\ t = B.\mathit{type};\ \ w = B.\mathit{width};\} \\
 & & C & \{\ T.\mathit{type} = C.\mathit{type};\ \ T.\mathit{width} = C.\mathit{width};\} \\
B & \rightarrow & \textbf{int} & \{\ B.\mathit{type} = \mathit{integer};\ \ B.\mathit{width} = 4;\} \\
B & \rightarrow & \textbf{float} & \{\ B.\mathit{type} = \mathit{float};\ \ B.\mathit{width} = 8;\} \\
C & \rightarrow & \epsilon & \{\ C.\mathit{type} = t;\ \ C.\mathit{width} = w;\} \\
C & \rightarrow & [\ \textbf{num}\ ]\ C_1 & \{\ C.\mathit{type} = \mathit{array}(\textbf{num}.\mathit{value},\ C_1.\mathit{type}); \\
 & & & \quad C.\mathit{width} = \textbf{num}.\mathit{value} \times C_1.\mathit{width};\}
\end{array}
$$

Types and Their Widths (Example)

T	$\rightarrow$	B	$\{\ t = B.\mathit{type};\ \ w = B.\mathit{width};\}$
		C	$\{\ T.\mathit{type} = C.\mathit{type};\ \ T.\mathit{width} = C.\mathit{width};\}$
B	$\rightarrow$	**int**	$\{\ B.\mathit{type} = \mathit{integer};\ \ B.\mathit{width} = 4;\}$
B	$\rightarrow$	**float**	$\{\ B.\mathit{type} = \mathit{float};\ \ B.\mathit{width} = 8;\}$
C	$\rightarrow$	ϵ	$\{\ C.\mathit{type} = t;\ \ C.\mathit{width} = w;\}$
C	$\rightarrow$	[**num**] C_1	$\{\ C.\mathit{type} = \mathit{array}(\mathbf{num}.\mathit{value},\ C_1.\mathit{type});$ $C.\mathit{width} = \mathbf{num}.\mathit{value} \times C_1.\mathit{width};\}$



6.3.5 Sequences of Declarations

$$D \rightarrow T\ \textbf{id}; D \ \mid\ \epsilon$$

Use *offset* as next available address

$$\begin{array}{lll} P & \rightarrow & \{\ \textit{offset} = 0; \} \\ & & D \\ D & \rightarrow & T\ \textbf{id};\ \{\ \textit{top.put}(\textbf{id}.\textit{lexeme},\ \mathsf{T}.\textit{type},\ \textit{offset}); \\ & & \qquad \textit{offset} = \textit{offset} + T.\textit{width}; \} \\ & & D_1 \\ D & \rightarrow & \epsilon \end{array}$$

6.3.6 Fields in Records and Classes

Example

```
float x;
record { float x; float y; } p;
record { int tag; float x; float y; } q;
x = p.x + q.x;
```

$$
\begin{array}{lcl}
D & \rightarrow & T\ \textbf{id} ; D \ \mid \ \epsilon \\
T & \rightarrow & \textbf{record}\ '\{'\ D\ '\}'
\end{array}
$$

- Fields are specified by sequence of declarations
  - Field names within record must be distinct
  - Relative address for field is relative to data area for that record

Fields in Records and Classes

Stored in separate symbol table t

Record type has form *record*(t)

$$
\begin{array}{lll}
T \rightarrow & \textbf{record}\ '\{' & \{\ \textit{Env.push(top)};\ \textit{top} = \textbf{new}\ \textit{Env}();\\
& & \quad \textit{Stack.push(offset)};\ \textit{offset} = 0;\}\\
& D\ '\}' & \{\ T.\textit{type} = \textit{record(top)};\ T.\textit{width} = \textit{offset};\\
& & \quad \textit{top} = \textit{Env.pop}();\ \textit{offset} = \textit{Stack.pop}();\}
\end{array}
$$

6.5 Type Checking

- Type system contains information about
  - Syntactic constructs of language
  - Notion of types
  - Logical rules to assign types to language constructs
    - if both operands of $+$ are integers, then result is integer
    - if f has type $s \rightarrow t$ and x has type s, then expression $f(x)$ has type t

- Sound type system

- Strongly typed implementation of language

A Simple Type Checker

A language example (Pascal-like)

- $P \rightarrow D; S$
- $D \rightarrow D; D \quad | \quad$ **id** $: T$
- $T \rightarrow$ **boolean** $\quad | \quad$ **char** $\quad | \quad$ **integer** $\quad | \quad$ **array [num] of** $T \quad | \quad \hat{}T$
- $S \rightarrow$ **id** $:= E \quad | \quad$ **if** E **then** $S \quad | \quad$ **while** E **do** $S \quad | \quad S; S$
- $E \rightarrow$ **true** $\quad | \quad$ **false** $\quad | \quad$ **literal** $\quad | \quad$ **num** $\quad | \quad$ **id** $\quad | \quad E$ **and** E
  $\quad | \quad E$ **mod** $E \quad | \quad E[E] \quad | \quad E\hat{}$

A Simple Type Checker

Translation scheme for saving type of identifier

$$
\begin{array}{lcll}
P & \rightarrow & D; S & \\
D & \rightarrow & D; D & \\
D & \rightarrow & \textbf{id} : T & \{\mathit{addType}(\textbf{id}.\mathit{entry}, T.\mathit{type});\} \\
T & \rightarrow & \textbf{boolean} & \{T.\mathit{type} = \mathit{boolean};\} \\
T & \rightarrow & \textbf{char} & \{T.\mathit{type} = \mathit{char};\} \\
T & \rightarrow & \textbf{integer} & \{T.\mathit{type} = \mathit{integer};\} \\
T & \rightarrow & \hat{}\,T_1 & \{T.\mathit{type} = \mathit{pointer}(T_1.\mathit{type});\} \\
T & \rightarrow & \textbf{array}\ [\textbf{num}\ ]\ \textbf{of}\ T_1 & \{T.\mathit{type} = \mathit{array}(1 \ldots \textbf{num}.\mathit{val}, T_1.\mathit{type});\}
\end{array}
$$

A Simple Type Checker

Type Checking of Expressions

E	$\rightarrow$	**true**	$\{E.\mathit{type} = \mathit{boolean};\}$
E	$\rightarrow$	**false**	$\{E.\mathit{type} = \mathit{boolean};\}$
E	$\rightarrow$	**literal**	$\{E.\mathit{type} = \mathit{char};\}$
E	$\rightarrow$	**num**	$\{E.\mathit{type} = \mathit{integer};\}$
E	$\rightarrow$	**id**	$\{E.\mathit{type} = \mathit{lookup}(\mathbf{id}.\mathit{entry});\}$
E	$\rightarrow$	E_1 **and** E_2	$\{$**if** $(E_1.\mathit{type} == \mathit{boolean})$ **and** $(E_2.\mathit{type} == \mathit{boolean})$ **then** $E.\mathit{type} = \mathit{boolean};$ **else** $E.\mathit{type} = \mathit{type\_error};\}$
E	$\rightarrow$	E_1 **mod** E_2	$\{$**if** $(E_1.\mathit{type} == \mathit{integer})$ **and** $(E_2.\mathit{type} == \mathit{integer})$ **then** $E.\mathit{type} = \mathit{integer};$ **else** $E.\mathit{type} = \mathit{type\_error};\}$
E	$\rightarrow$	$E_1[E_2]$	$\{$**if** $(E_2.\mathit{type} == \mathit{integer})$ **and** $(E_1.\mathit{type} == \mathit{array}(s, t))$ **then** $E.\mathit{type} = t;$ **else** $E.\mathit{type} = \mathit{type\_error};\}$
E	$\rightarrow$	$E_1\hat{}$	$\{$**if** $(E_1.\mathit{type} == \mathit{pointer}(t))$ **then** $E.\mathit{type} = t;$ **else** $E.\mathit{type} = \mathit{type\_error};\}$

A Simple Type Checker

Type Checking of Statements

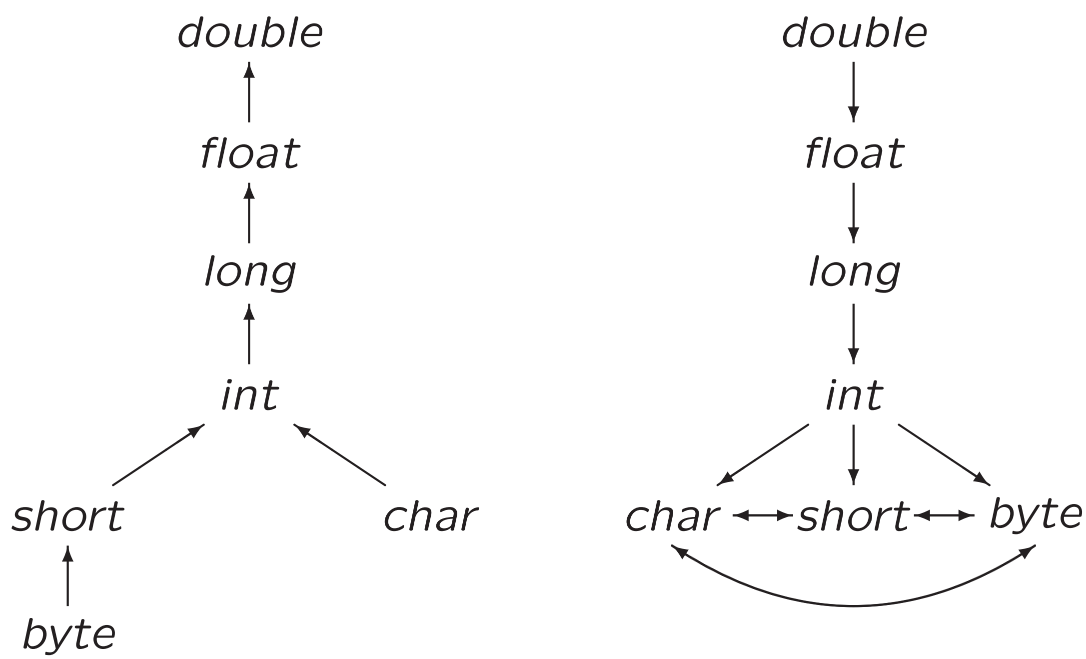
$$
\begin{array}{lcll}
S & \rightarrow & \textbf{id} := E & \{\textbf{if}\ (id.\mathit{type} == E.\mathit{type}) \\
 & & & \ \textbf{then}\ S.\mathit{type} = \mathit{void};\ \textbf{else}\ S.\mathit{type} = \mathit{type\_error};\} \\
S & \rightarrow & \textbf{if}\ E\ \textbf{then}\ S_1 & \{\textbf{if}\ (E.\mathit{type} == \mathit{boolean}) \\
 & & & \ \textbf{then}\ S.\mathit{type} = S_1.\mathit{type};\ \textbf{else}\ S.\mathit{type} = \mathit{type\_error};\} \\
S & \rightarrow & \textbf{while}\ E\ \textbf{do}\ S_1 & \{\textbf{if}\ (E.\mathit{type} == \mathit{boolean}) \\
 & & & \ \textbf{then}\ S.\mathit{type} = S_1.\mathit{type};\ \textbf{else}\ S.\mathit{type} = \mathit{type\_error};\} \\
S & \rightarrow & S_1; S_2 & \{\textbf{if}\ (S_1.\mathit{type} == \mathit{void})\ \textbf{and}\ (S_2.\mathit{type} == \mathit{void}) \\
 & & & \ \textbf{then}\ S.\mathit{type} = \mathit{void};\ \textbf{else}\ S.\mathit{type} = \mathit{type\_error};\}
\end{array}
$$

Type Conversions

$y = x + i$ with x float and i integer

- widening conversion
- narrowing conversion
- explicit conversion (= cast)
- implicit conversion (= coercion), automatically by compiler

Conversions in Java



Widening conversions   Narrowing conversions

Coercion (Example)

Semantic action for $E \rightarrow E_1 + E_2$ uses two functions:

- *max*(t_1, t_2)
- *widen*(a, t, w)

```
Addr widen(Addr a, Type t, Type w)
{       if (t==w) return a;
        else if (t == integer and w == float)
              { temp = new Temp();
                gen(temp '=' '(float)' a);
                return temp;
              }
              else error;
}
```

Coercion (Example)

$$
\begin{array}{lll}
E \rightarrow E_1 + E_2 & \{ & E.type = max(E_1.type, E_2.type); \\
 & & a_1 = widen(E_1.addr, E_1.type, E.type); \\
 & & a_2 = widen(E_2.addr, E_2.type, E.type); \\
 & & E.addr \ = \textbf{new} \ Temp(); \\
 & & gen(E.addr\ '=' \ a_1 \ '+' \ a_2); \\
 & \} &
\end{array}
$$

Constructing Type Graphs in Yacc

```
enum Types {Tint, Tfloat, Tpointer, Tarray, ...};
typedef struct Type
{ Types type;
  struct Type *child
} Type;
```

- Type *mkint() construct int node if not already constructed
- Type *mkfloat() construct float node if not already constructed
- Type *mkarray(Type*, int) construct array-of-type node if not already constructed
- Type *mkptr(Type*)construct pointer-of-type node if not already constructed

Yacc Specification (Example)

from college 4

```
expr   : expr '+' term    { $$ = $1 + $3; }
       | term
       ;
term   : term '+' factor  { $$ = $1 * $3; }
       | factor
       ;
factor : '(' expr ')'     { $$ = $2; }
       | DIGIT
       ;

%%
/* auxiliary functions section */
yylex()
{   int c;
    c = getchar();
    if (isdigit(c))
    {   yylval = c-'0';
        return DIGIT;
    }
    return c;
}
```

Constructing Type Graphs in Yacc

Syntax-directed definitions

```
%union
{ Symbol *sym;
int num;
Type *typ;
}
%token INT
%token <sym> ID
%token <num> NUM
%type  <typ> typevar

%%
decl : typevar ID                 { addType($2, $1); }
     | typevar ID '[' NUM ']'     { addType($2, mkarr($1,$4)); }
     ;
typevar : INT                     { $$ = mkint(); }
        | typevar '^'             { $$ = mkptr($1); }
        | /* empty */             { $$ = mkint(); }
        ;
```

Type Checking in Yacc

Syntax-directed definitions

```
%{
enum Types {Tint, Tfloat, Tpointer, Tarray, ...};
typedef struct Type
{ 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 +");
                       else
                       { $$ = mkint();
                         gen(int-add instruction for $1 and $3);
                       }
                     }
```

Type Coercion in Yacc

Syntax-directed definitions

```
%{ ... %}
%%
expr : expr '+' expr
       { if ($1->type == Tint && $3->type == Tint)
         { $$ = mkint(); gen(int-add instruction for $1 and $3);
         }
         else if ($1->type == Tfloat && $3->type == Tfloat)
         { $$ = mkfloat(); gen(float-add instruction for $1 and $3);
         }
         else if ($1->type == Tfloat && $3->type == Tint)
         { $$ = mkfloat(); gen(int2float instruction for $3);
           gen(float-add instruction for $1 and $3);
         }
         else if ($1->type == Tint && $3->type == Tfloat)
         { $$ = mkfloat(); gen(int2float instruction for $1);
           gen(float-add instruction for $1 and $3);
         }
         else
         { semerror ("type error in +");
           $$ = mkint();
         }
       }
```

L-Values and R-Values

- $E_1 = E_2$;

- What can E_1 and E_2 be?
  $i = i + 1$;
  $i = 5$;

- L-value: left side of assignment, location
  Example: identifier i, array acces $a[2]$

- R-value: right side of assignment, value
  Example: identifier i, array acces $a[2]$, constant 5, addition $i + 1$

L-Values and R-Values in Yacc

Syntax-directed definitions (C)

```
%{
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;
           gen(...);
       }
     | expr '=' expr
       { if ( !$1->islval || $1->typ != $3->typ )
             semerror ("invalid assignment");
           $$->typ = $1->typ;
           $$->islval = FALSE;
           gen(...);
       }
     | ID
       { $$->typ = lookup($1);
         $$->islval = TRUE;
         gen(...);
       }
```

Volgende week

- Practicum over opdracht 2
- Direct naar 302/304
- Staat al online
- Inleveren 28 oktober

Over twee weken

- ’s Ochtends hoorcollege
- ’s Middags werkcollege

Compiler constructie

college 5
Static Type Checking

Chapters for reading: 6.1, 6.3, 6.5.1, 6.5.2