Compilerconstructie

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http://www.liacs.leidenuniv.nl/~vlietrvan1/coco/

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Syntax DAG / Types

The Phases of a Compiler

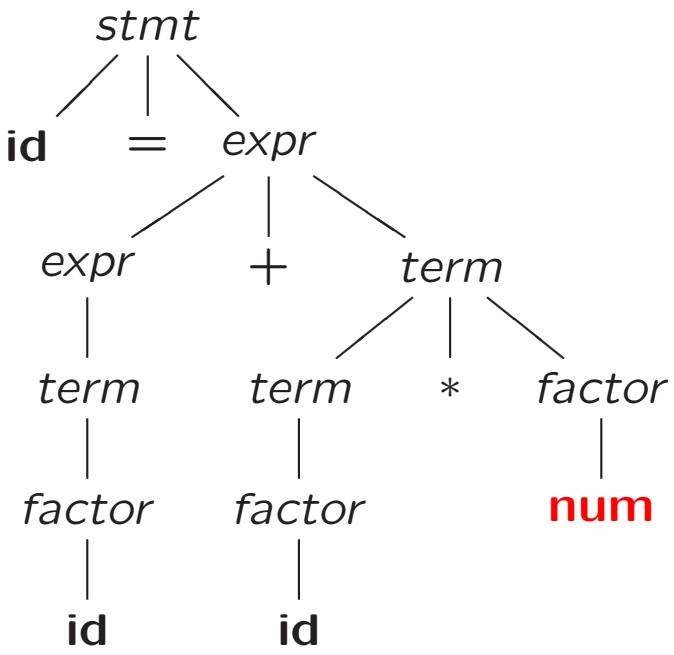
(from lecture 1)

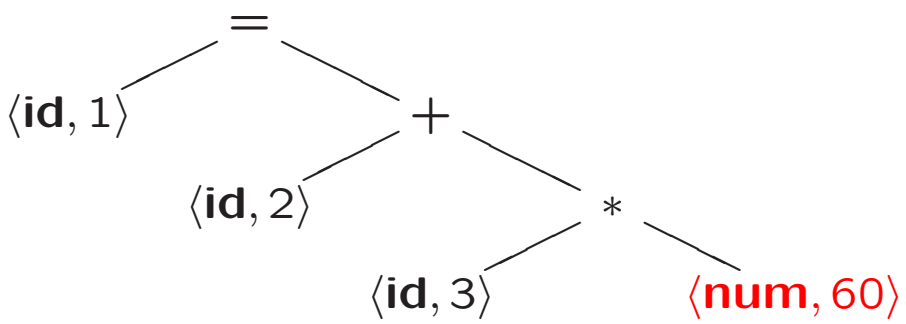
Token stream:

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

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. . .

Pros DAG. . .

Producing Syntax Trees or DAG's

Production	Semantic Rules
1) $E \to E_1 + T$	$E.node = getNode('+', E_1.node, T.node)$
2) $E \to E_1 - T$	$E.node = getNode('-', E_1.node, T.node)$
3) $E \to T$	$E.node = T.node$
4) $T \to T_1 * F$	$T.node = getNode('*', T_1.node, F.node)$
5) $T \to T_1/F$	$T.node = getNode('/', T_1.node, F.node)$
6) $T \to F$	$T.node = F.node$
7) $F \to (\ E\ )$	$F.node = E.node$
8) $F \to$ **id**	$F.node = getLeaf($**id**$,$ **id**$.entry)$
9) $F \to$ **num**	$F.node = getLeaf($**num**$,$ **num**$.val)$

Parse tree $a + a * (b - c) + (b - c) * d \ldots$

1) $p_1 = getLeaf($**id**$, entry\text{-}a)$

$\ldots$

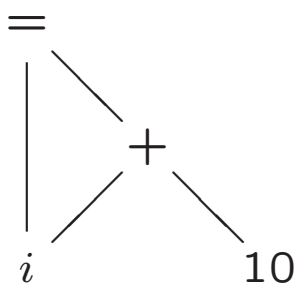
Producing Syntax Trees or DAG's

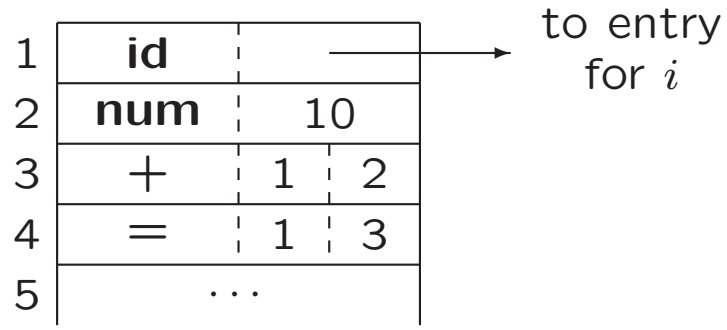
1) $p_1 = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}a)$
2) $p_2 = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}a) = p_1$
3) $p_3 = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}b)$
4) $p_4 = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}c)$
5) $p_5 = \mathit{getNode}('-', p_3, p_4)$
6) $p_6 = \mathit{getNode}('*', p_2, p_5) = \mathit{getNode}('*', p_1, p_5)$
7) $p_7 = \mathit{getNode}('+', p_1, p_6)$
8) $p_8 = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}b) = p_3$
9) $p_9 = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}c) = p_4$
10) $p_{10} = \mathit{getNode}('-', p_8, p_9) = \mathit{getNode}('-', p_3, p_4) = p_5$
11) $p_{11} = \mathit{getLeaf}(\mathbf{id}, \mathit{entry}\text{-}d)$
12) $p_{12} = \mathit{getNode}('*', p_{10}, p_{11}) = \mathit{getNode}('*', p_5, p_{11})$
13) $p_{13} = \mathit{getNode}('+', p_7, p_{12})$

6.1.2 The Value-Number Method

An implementation of DAG

DAG for $i = i + 10$





- 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 Types and Declarations

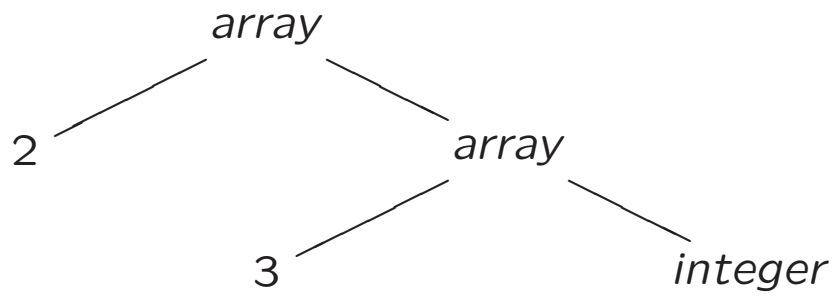
- Type expressions
- Function declaration
- Type equivalence
- Declarations of variables
- Storage layout
- Sequences of declarations
- Records and classes

6.3.1 Type Expressions

Types have structure

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

$array(2, array(3, integer))$



Type Expressions

- 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 $\times$: $s \times t$
  - ...

6.3 Types and Declarations

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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

$$
\begin{array}{rcll}
F & \rightarrow & B\ \textbf{id}\ (OptL) & \{\ F.type = \rightarrow (OptL.type, B.type);\ \} \\
B & \rightarrow & \textbf{int} & \{\ B.type = integer;\ \} \\
 & | & \textbf{float} & \{\ B.type = float;\ \} \\
OptL & \rightarrow & \epsilon & \{\ OptL.type = void;\ \} \\
 & | & Ps & \{\ OptL.type = Ps.type;\ \} \\
Ps & \rightarrow & P & \{\ Ps.type = P.type;\ \} \\
 & | & Ps_1, P & \{\ Ps.type = \times(Ps_1.type, P.type);\ \} \\
P & \rightarrow & T\ \textbf{id} & \{\ P.type = T.type;\ \}
\end{array}
$$

6.3 Types and Declarations

- Type expressions
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6.3.2 Type Equivalence

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

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;
```

Name equivalence ...

6.3 Types and Declarations

- Type expressions
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- Storage layout
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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

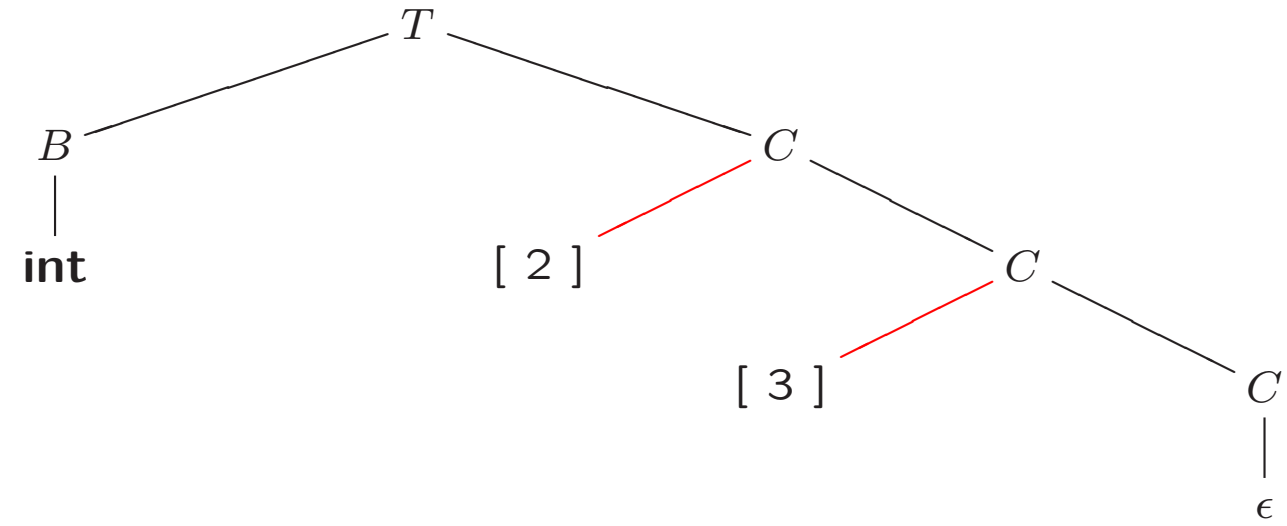
Example:

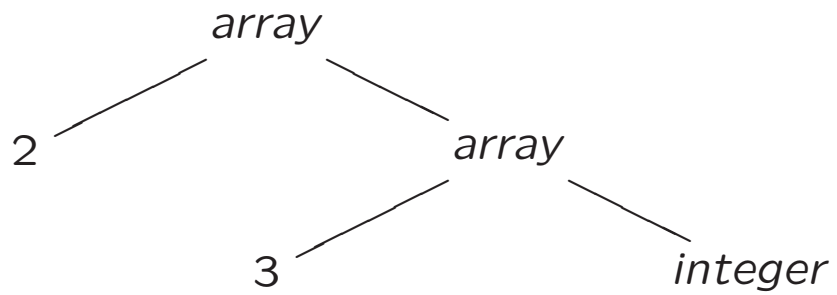
$$
\begin{aligned}
D &\rightarrow T\ \textbf{id}; D \mid \epsilon \\
T &\rightarrow B\ C \mid \textbf{record}\ '\{'\ D\ '\}' \\
B &\rightarrow \textbf{int} \mid \textbf{float} \\
C &\rightarrow \epsilon \mid [\ \textbf{num}\ ]\ C
\end{aligned}
$$

Structure of Types (Example)

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

`int[2][3]`





Interpretation C...

6.3 Types and Declarations

- Type expressions
- Function declaration
- Type equivalence
- Declarations of variables
- Storage layout
- Sequences of declarations
- Records and classes

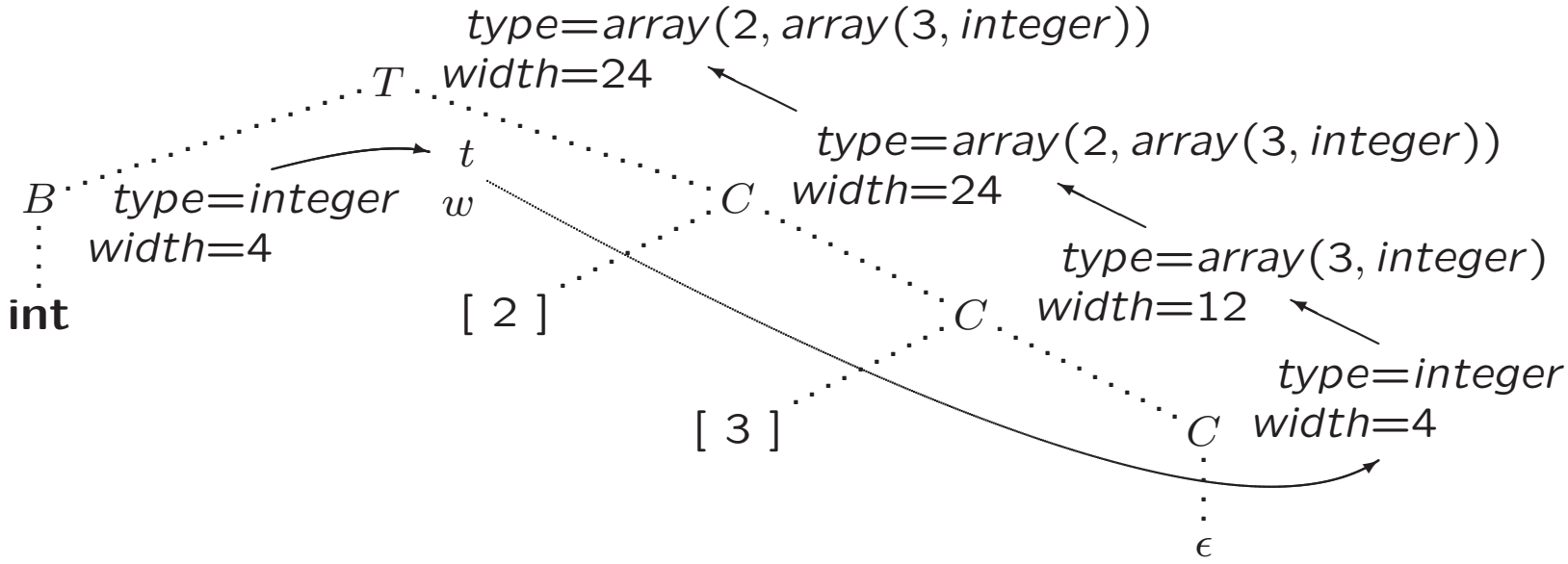
6.3.4 Storage Layout for Local Names

- 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)

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



6.3 Types and Declarations

- Type expressions
- Function declaration
- Type equivalence
- Declarations of variables
- Storage layout
- Sequences of declarations
- Records and classes

6.3.5 Sequences of Declarations

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

Use *offset* as next available (relative) address

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

Example: **int** x; **float** y;

6.3 Types and Declarations

- Type expressions
- Function declaration
- Type equivalence
- Declarations of variables
- Storage layout
- Sequences of declarations
- Records and classes

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;
```

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

- 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)

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

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 $s \to t$ and x has type s,
      then expression $f(x)$ has type t

- Sound type system

A Simple Type Checker

A language example (Pascal-like)

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

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

A Simple Type Checker

Type Checking of Statements

$S \rightarrow$ **id** $:= E$ {**if** $(id.type == E.type)$ **then** $S.type = void$; **else** $S.type = type\_error$;}

$S \rightarrow$ **if** E **then** S_1 {**if** $(E.type == boolean)$ **then** $S.type = S_1.type$; **else** $S.type = type\_error$;}

$S \rightarrow$ **while** E **do** S_1 {**if** $(E.type == boolean)$ **then** $S.type = S_1.type$; **else** $S.type = type\_error$;}

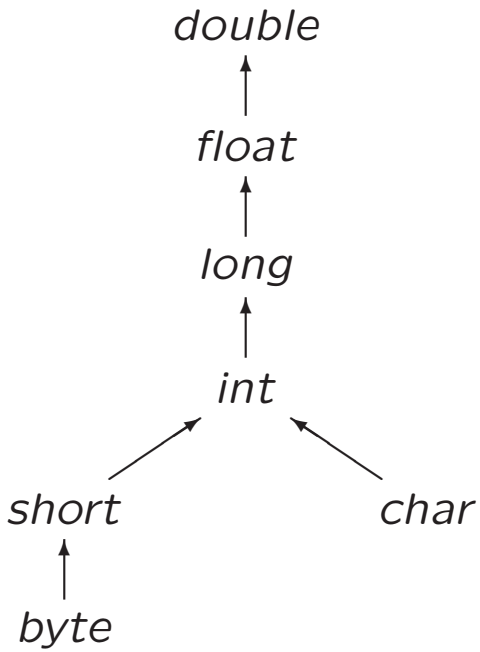
$S \rightarrow S_1; S_2$ {**if** $(S_1.type == void)$ **and** $(S_2.type == void)$ **then** $S.type = void$; **else** $S.type = type\_error$;}

6.5.2 Type Conversions

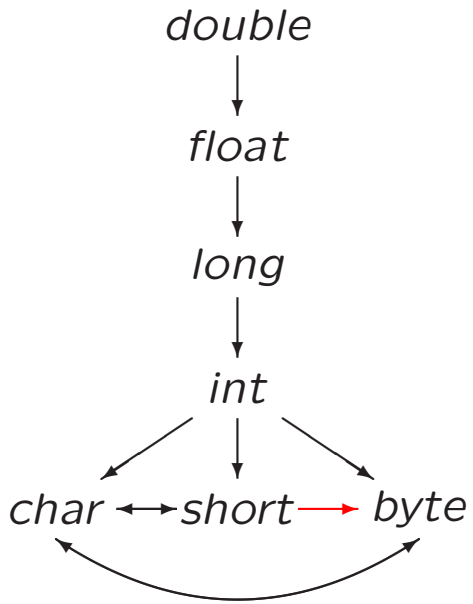
$y = x + i$ with x float and i integer

- 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:

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

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

Example: $x + i$ . . .

In book with three-address code

Coercion (Example)

```
Node widen(Node a, Type t, Type w)
{       if (t==w) return a;
        else if (t == integer and w == float)
                { temp = new Node(inttofloat, a);
                  return temp;
                }
                else error;
}
```

In book with three-address code

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 lecture 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

```
%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

```
%{
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

```
%{ ... %}
%%
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

```
%{
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(...);
       }
```

L-Values and R-Values in Yacc

Alternative

```
%{
typedef struct Node
{ Type *typ;
  int islval;
} Node;
%}
%union
{ Node *rec;
}

%%
```

```
expr : expr '+' expr
       { if ($<rec>1->typ->type != Tint ||
             $<rec>3->typ->type != Tint )
           semerror ("non-int operands in +");
         $<rec>$->typ = mkint();
         $<rec>$->islval = FALSE;
         gen(...);
       }
     | expr '=' expr
       ...
```

Vanmiddag, 14.15

- Introductie opdracht 2, 403
- Practicum opdracht 2, 302-304
- Inleveren 31 oktober

Volgende week

- 11.15, hoorcollege, B02
- 14.15, Practicum over opdracht 2, 302-304

Compilerconstructie

college 5

Static Type Checking

Chapters for reading: 6.1, 6.3, 6.5.1, 6.5.2