Compilers
Semantic Analysis

LEIC

FEUP-FCUP

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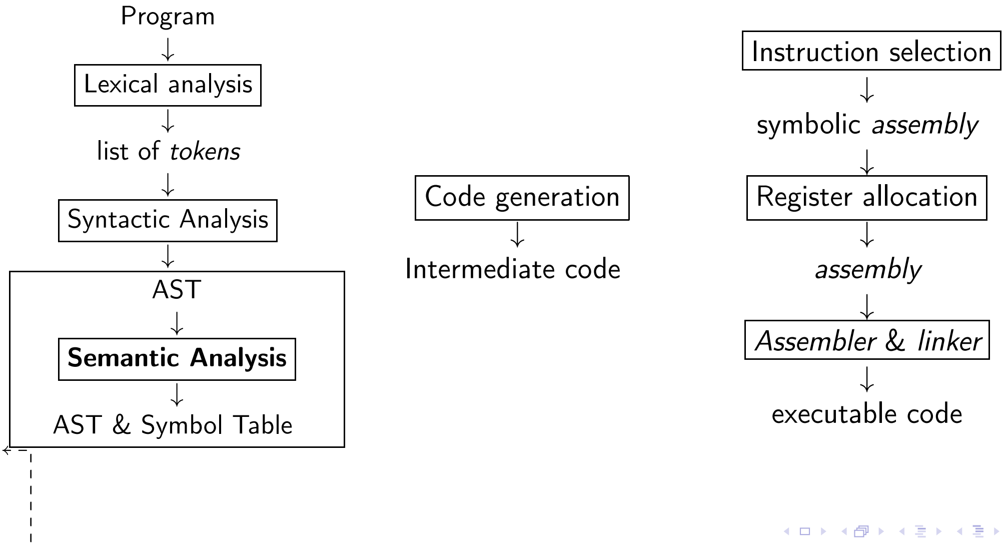
This lecture

Compiler


Program
Lexical analysis
list of *tokens*
Syntactic Analysis
AST
Semantic Analysis
AST & Symbol Table
Code generation
Intermediate code
Instruction selection
symbolic *assembly*
Register allocation
assembly
Assembler & linker
executable code

This lecture

Semantics analysis

Context dependent static verifications.

Examples:

- undeclared variables
- type checking
- type inference

Semantics analysis (cont.)

- This can be done while parsing takes place
- Usually it is done after parsing - AST is the input of semantic analysis
- Needs information about identifiers (variables, function names, etc.) stored in a symbol table
- The symbol table is also used later for code generation

This lecture

Scopes

- Variable declarations have a limited scope
  - e.g. we may declare a local variable with the same name as a global variable

Example

Scopes.

```
int i, j;
int f(int size)
{  char i, temp;
   ...
   { double j;
      ...
   }
   ...
   { char * j;
      ...
   }
}
```

Example

Scopes.

```
int i, j;            // global: i, j
int f(int size)      // global: f
{  char i, temp;
   ...
   { double j;
     ...
   }
   ...
   { char * j;
     ...
   }
}
```

Example

Scopes.

```
int i, j;             // global: i, j
int f(int size)       // global: f
{  char i, temp;      // function: size, i, temp
   ...                // new declaration for i
   { double j;
     ...
   }
   ...
   { char * j;
     ...
   }
}
```

Example

Scopes.

```
int i, j;             // global: i, j
int f(int size)       // global: f
{  char i, temp;      // function: size, i, temp
   ...                // new declaration for i
   { double j;        // block 1: j hides the global declaration
      ...
   }
   ...
   { char * j;
      ...
   }
}
```

Example

Scopes.

```
int i, j;              // global: i, j
int f(int size)        // global: f
{  char i, temp;       // function: size, i, temp
   ...                 // new declaration for i
   { double j;         // block 1: j hides the global declaration
     ...
   }
   ...
   { char * j;        // block 2: j hides the global declaration
     ...
   }
}
```

Lexical scope

Lexical scope (also known as *static scope*) each use of a variable corresponds to the closest declaration in the AST

- Used in Pascal, C, C++, Java, Haskell, SML, etc.
- Dynamic scope: first versions of LISP

Function scopes

- Functions may be used in any scope:
  - Pascal, Modula e Ada,...
  - Scheme, ML, Haskell,...
  - JavaScript, Ruby, Python,...
- C and Java limit the scope for functions to the global scope (C) or classes (C++/Java)

Function scopes (cont.)

```
// Pascal
function E(x: real): real;
    function F(y: real): real;
    begin
        F := x + y
    end;
begin
    E := F(3) + F(4)
end;
```

```
-- Haskell
e :: Float -> Float
e x = f 3 + f 4
   where f y = x + y
```

```
// GNU C (not standard C)
float e(float x) {
  float f(float y) {
     return x + y;
  }
  return f(3) + f(4);
}
```

Function scopes (cont.)

GCC (extention to the *standard*):

```
float E(float x)
{
    float F(float y)
    {
        return x + y;
    }
    return F(3) + F(4);
}
```

Function scopes (cont.)

Advantages of functions inside functions

- local auxiliary functions
- simplifies the control flow
- enable the use of local auxiliary functions instead of cycles

Function scopes (cont.)

Example: test primes (C vs. Haskell).

```c
int is_prime(int n) {
   int d = 2;
   if(n<=1)
       return FALSE;
   while(d*d <= n) {
     if (n%d == 0)
        return FALSE;
     d++;
   }
   return TRUE;
}
```

```haskell
isPrime :: Int -> Bool
isPrime n = n>1 && checkDivs 2
  where checkDivs d
          | n`mod`d==0 = False
          | d*d <= n   = checkDivs (d+1)
          | otherwise  = True
```

Function scopes (cont.)

Non-standard C extension:

```
int is_prime(int n) {
   int checkDivs() {
      int d = 2;
      while(d*d <= n) {
        if(n%d == 0)
          return FALSE;
      }
      return TRUE;
   }
   return n>1 && checkDivs();
}
```

This lecture

Symbol table

- Relates identifiers with semantic information informação; some examples:
  - *values* of variables (interpreters);
  - *types*;
  - *location* (registers or memory during code generation)

Name spaces

- Multiple name spaces
  - e.g. in Haskell we may have the same name for a *type* and a *constructor*

    ```
    data Expr = Int Int | Add Expr Expr
    ```

  - modules or *packages* usually have different name spaces
- We may use different symbol tables for different name spaces
- Or: use a global symbol table and prefixes

  ```
  Prelude.lookup
  Data.Map.lookup
  ```

Symbol table

Functions:

- **inicialize** an *empty table*;
- **insert** a pair *identifier* e *information*;
- **lookup** given an *identifier* returns the *information*

Use *tables* built-in in your programming language. Examples:

- `Map` in Java
- `Data.Map` in Haskell
- `dict` in Python
- `std::map` in C++

Symbol table (cont.)

New operations to deal with scopes:

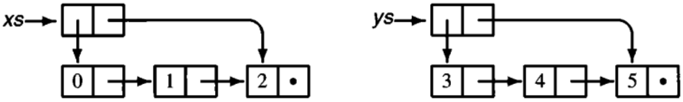
- **open** a new scope (i.e. in the beginning of a function/method)
- **close** finishes the actual scope

Note: it is not sufficient to delete information when closing the scope (we need to reconstruct the table as it was before).

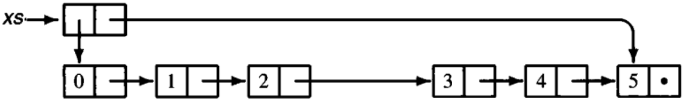
Implementation

C, Java, etc.

```
xs = new List(0,1,2);
ys = new List(3,4,5);
xs.append(ys);
```



(before)

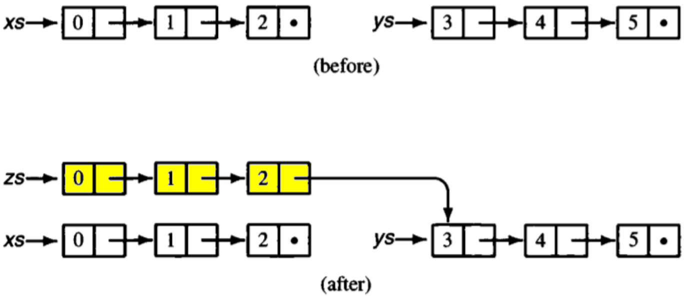


(after)

Implementation (cont.)

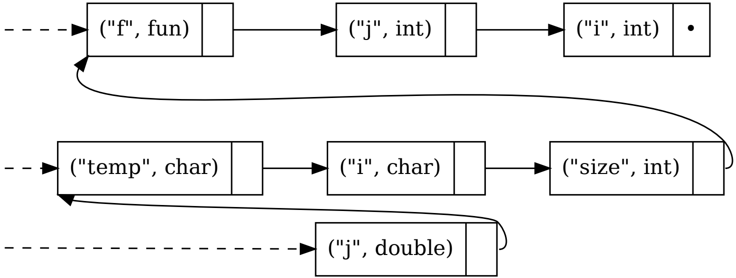
Haskell, SML, etc.

```
xs = [0,1,2]
ys = [3,4,5]
zs = xs ++ ys
```



Types (with lists)

```
int i, j;
int f(int size)
{  char i, temp;
   ...
   { double j;
     ...
```



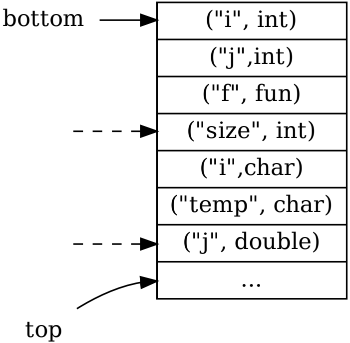
Types (with a stack)

Opera de forma similar às listas funcionais.

init	an empty stack;
insert	push *(name,info)*
lookup	pop;
open scope	store the top of the stack;
close scope	load the previous top of the stack.

Types (with a stack) (cont.)

```
int i, j;
int f(int size)
{  char i, temp;
   ...
   { double j;
     ...
```



Eficiency

- Lists and stacks use sequential search: $O(n)$ for a table with n elements
- Not efficient!
- Alternatives: search trees or hash tables

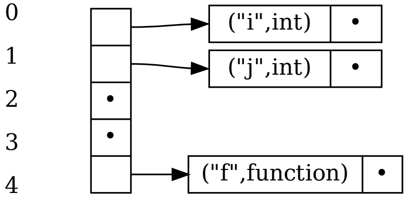
Search Trees

- Based on a total order on keys (>, <, ==)
- AVL or Red-Black trees are $O(\log n)$ in the worse case

Hash tables

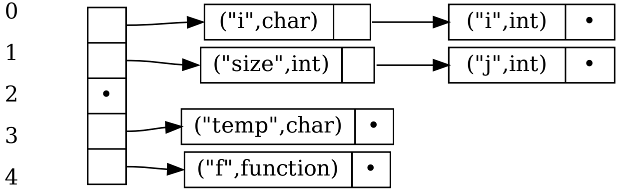
Examplo:

- Hash table with $N = 5$ *buckets* and 3 entries (`i`,`j`,`f`)
- Supose that $h(\texttt{i}) = 0$, $h(\texttt{j}) = 1$ e $h(\texttt{f}) = 4$
- No collisions: each *bucket* has one entry



Hash tables (cont.)

- Insert new entries for `i`, `size` and `temp`
- Collisions for (`i`) and suppose that: $h(\texttt{size}) = h(\texttt{j}) = 1$
- We solve collisions putting the new entries at the beginning:



- Search from the beginning of each list
- Closing the scope removes the entries

Hash tables

How to choose a good *hash function*?

$$x = x_0 x_1 \dots x_{k-1}$$

- There are lots of different heuristics depending on the *trade-offs* (speed / colisions)
- One simple solution: sum the character codes multiplied by powers of α

$$h(x) = (x_0 \alpha^{k-1} + x_1 \alpha^{k-2} + \cdots + x_{k-1} \alpha^0) \bmod N$$

Choose an α with a 2 exponent: multiplications may be implemented by *shifts*

Hash tables (cont.)

Example ($\alpha = 2^4 = 16$).

```
#define N ...

unsigned hash(char *ptr) {
   unsigned h = 0;
   while(*ptr) {
       h = (h<<4) + (unsigned)(*ptr++);
  }
  return (h % N);
}
```

Symbol Table - Example

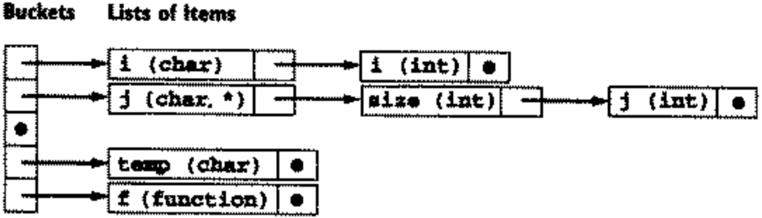
Consider the following C code fragment illustrating nested scopes:

```
int i,j;

inf f(int size)
 { char i, temp;
   ...
   { double j;
     ...
   }
   ...
   { char *j;
     ...
   }
 }
```

Symbol Table - Example

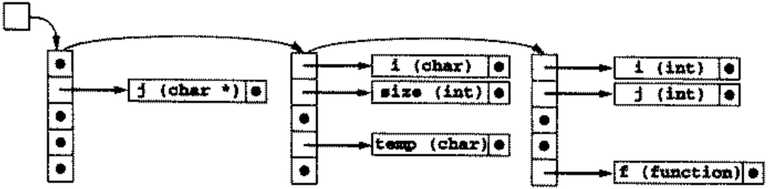
Symbol table contents:



After processing the declaration of the second nested compound statement within the body of f

Separate Symbol Tables

Symbol table structure:



Using separate tables for each scope - corresponding to the same example)

This lecture

Type Systems

Type System A set of logical rules which programs must respect.

Exemples:

- `+`, `-`, `*`, `/` are only applied to numbers
- the condition in an `if` command must be a *boolean*
- On an assignment `var = expr` the *variable var* must have the same type as the *expression expr*

Type Systems

Classification of type Systems:

Static	type checking is done at compile time
vs.	
Dinamic	type checking is done at run-time

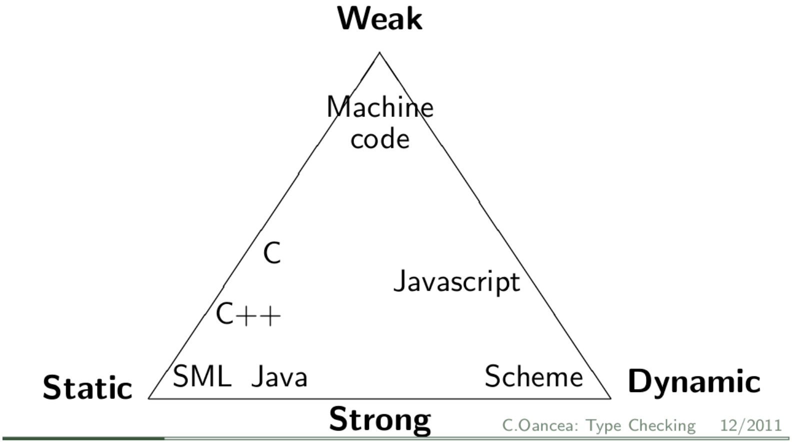
Strong	type errors are not allowed
vs.	
Weak	some type errors may be allowed

Type Systems (cont.)

Examples:

- Haskell, SML, Java: static and strong typing
- Python, Scheme: dynamic and strong typing
- C: static ans weak typing
- Note that these classifications are gradua and not mandatory
  e.g. o Java type system is stronger than for C and weaker than Haskell

Type Systems (cont.)



(Image: *Introduction to Compiler Design*, Torben Mogensen.)

Why do we need types?

- avoids type errors at run-time
- helps the compiler to generate more efficient code
- helps the programmer to detect bugs (a first program verification technique)

This lecture

Attribute Grammars

- Type checking may be made by traversing the AST (one or more times) and may make several passes over this
- Each pass is a recursive walk over the AST gathering information or using information gathered in previous passes: such information is called *attributes* of the AST
- The compiler builds node attributes; examples:
  - Types;
  - Symbol Table (context);
  - Values of expressions;
  - Target code
- Synthesized attributes: bottom-up from the leaves up to the root
- Inherited attributes: top-down, passed downwards the AST
- Atributes maybe synthesized and inherited
  (e.g. the symbol table is synthesized on the variable declarations and inherited on expressions)

Expressions

- A language with *variables*, *arithmetic expressions* and *boolean expressions*
- Types: int (integer numbers) e bool (boolean values)

Examples:

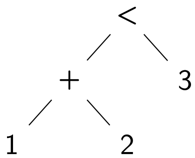
`1+2*3`
`(1+2)<3`
`1+x*3` *(valid if x has type int)*
`(1+x)<y` *(valid if x and y have type int*

A type error:

`1+(2<3)`

Inherited and Synthesized Attributes

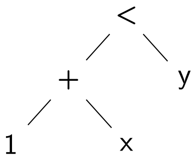
We calculate the type of an expression from the type of its sub-expressions (synthesized attribute).



bool

synthesized attribute

We use a symbol table with the types of variables (inherited attribute).



inherited attribute

$\{x \mapsto \mathit{int},\ y \mapsto \mathit{int}\}$

Type Checking

Grammar Rule	Semantic Rules
decl → *type var-list*	
type → **int**	*dtype* = *integer*
type → **float**	*dtype* = *real*
$var\text{-}list_1$ → **id** , $var\text{-}list_2$	*insert*(**id** .*name*, *dtype*)
var-list → **id**	*insert*(**id** .*name*, *dtype*)

(Attribute Grammar for Type Declarations)

Type Checking

Grammar Rule	Semantic Rules
var-decl → **id** : *type-exp*	*insert*(**id**.*name*, *type-exp.type*)
type-exp → **int**	*type-exp.type* := *integer*
type-exp → **bool**	*type-exp.type* := *boolean*
$type\text{-}exp_1$ → **array** [**num**] **of** $type\text{-}exp_2$	$type\text{-}exp_1$.*type* := *makeTypeNode*(*array*, **num**.*size*, $type\text{-}exp_2$.*type*)
stmt → **if** *exp* **then** *stmt*	**if not** *typeEqual*(*exp.type*, *boolean*) **then** *type-error*(*stmt*)
stmt → **id** := *exp*	**if not** *typeEqual*(*lookup*(**id**.*name*), *exp.type*) **then** *type-error*(*stmt*)
exp_1 → exp_2 + exp_3	**if not** (*typeEqual*(exp_2.*type*, *integer*) **and** *typeEqual*(exp_3.*type*, *integer*)) **then** *type-error*(exp_1) ; exp_1.*type* := *integer*

(Attribute Grammar for Types)

Type Checking

$exp_1 \rightarrow exp_2$ **or** exp_3	**if not** (*typeEqual*(exp_2.*type*, *boolean*) **and** *typeEqual*(exp_3.*type*, *boolean*)) **then** *type-error*(exp_1) ; exp_1.*type* := *boolean*
$exp_1 \rightarrow exp_2$ **[** exp_3 **]**	**if** *isArrayType*(exp_2.*type*) **and** *typeEqual*(exp_3.*type*, *integer*) **then** exp_1.*type* := exp_2.*type.child1* **else** *type-error*(exp_1)
$exp \rightarrow$ **num**	*exp.type* := *integer*
$exp \rightarrow$ **true**	*exp.type* := *boolean*
$exp \rightarrow$ **false**	*exp.type* := *boolean*
$exp \rightarrow$ **id**	*exp.type* := *lookup*(**id** .*name*)

(Attribute Grammar for Types)

Implementation (two phases)

1. Fill the symbol table with type declarations (visitor which builds the symbol table)
    1.1 variables bound with their types
    1.2 method names bound to their parameters, result type and local variables
    1.3 class names bound to their variable and method declarations
2. Type check expressions and statements (visitor which type checks)

Implementation (example)

```
// PlusExp e1,e2;

public Type visit(Plus n) {
  if (! (n.e1.accept(this) instanceof IntegerType) )
     error.complain("Left side of Plus must be of type integer");
  if (! (n.e2.accept(this) instanceof IntegerType) )
     error.complain("Right side of Plus must be of type integer");
  return new IntegerType();
}
```

Type Declarations

- Type declarations add new information to the symbol table: (Identifier i, Type t)

```
public void visit(VarDecl n) {
  Type t = n.t.accept(this);
  String id = n.i.toString();

  if (currMethod == null) {
      if (!currClass.addVar(id,t))
         error.complain(id + "is already defined in " + currClass.getId());
       } else if (!currMethod.addVar(id,t))
              error.complain(id + "is already defined in "
                   + currClass.getId() + "." + currMethod.getId());
}
```

Type Declarations (cont.)

```
class ErrorMsg {
  boolean anyErrors;
  void complain(String msg) {
     anyErrors = true;
     System.out.println(msg);
  }
}
```

Type Checking for Commands

Assignment (*var := expr*) is well-typed if the type declaration for *var* is the type of *expr*

Conditional (*if cond then e1 else e2*) is well-typed if:

1. *cond* must have typebool
2. $e1$ and $e2$ must have the same type

Conditional (*if cond then expr*) is well-typed if:

1. *cond* must have type bool
2. *expr* must be well-typed

While (*while cond expr*) is well-typed if::

1. *cond* must have type bool
2. *expr* must be well-typed

Sequence (*e1; e2*) is well-typed if e_1 and e_2 are well-typed

Type Checking for Functions

- Let us extend the language with function definitions and function calls
- Functional types:

$$(t_1, t_2, \ldots, t_n) \rightarrow r$$

  (they can be trivially reconstructed by the type declarations for arguments and return values)

- $t_1, t_2, \ldots, t_n$ are the types of function arguments
- r is the type of the result value

Function calls

To type check a function call $f(e_1, \ldots, e_n)$

1. lookup for f in the symbol table and get a functional type $(t_1, \ldots, t_n) \rightarrow r$
2. type check $e_1, \ldots, e_n$
3. if the types are equal to types $t_1, \ldots, t_n$ return type (r); otherwise return a type error

Function Definition

To type check $f(x_1 : t_1, \ldots, x_n : t_n) : r = e$

1. Add the new binding $\{x_1 \mapsto t_1, \ldots, x_n \mapsto t_n\}$ to the symbol table
2. Using this new symbol table type check e
3. If the type of e is equal to r return a new symbol table with

$$\{f \mapsto (t_1, \ldots, t_n) \to r\}$$

   Otherwise return a type error.

(Note: the symbol table in this case is am *inherited* and *synthesized* attribute)

Recursive Functions

- This type checking algorithm does not work with *recursive calls*
- The solution to this problem is simple: add an entry for f to the symbol table used to type check the body of the function.

This lecture

Overloading and coercion

Overloading Use the *same operator* applied to different types (e.g. + for integers and reals)

```
1 + 2        -- int
1.0 + 2.5    -- float
```

Coercion Type conversion

```
int x = ...;
(float)x + 2.5   -- explicit coercion
x + 2.5          -- implicit coercion
```

Overloading and coercion (cont.)

- Type checking is trivial for built-in operators (e.g. C, Pascal)
- More (much more!) complex if the programmer may define operators for new types (e.g. C++, Haskell,. . .)

Polymorfism

polymorphic: something which has several forms.

In programming languages: the possibility of writing programs which work for different types

Parametric Polymorphism SML/Haskell or "generics" in Java/C#

```
reverse :: [t] -> [t]                 -- em Haskell
void reverse(List<T> list);            // em Java
```

Ad-hoc Polymorphism *overloading*, interfaces, inheritance in OO languages...

Type Inference

- For some type systems it is possible to automatically infer the types instead of just doing type checking
- Strongly typed functional languages (Haskell, ML) have type inference (*Damas-Milner* type inference algorithm)