Types and Static Semantic Analysis

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Types in C

Types of Type Systems

Static Semantic Analysis

Scope

A Static Semantic Analyzer

Types

A restriction on the possible interpretations of a segment of memory or other program construct.

Two uses:

Safety: avoids data being treated as something it isn't

Optimization: eliminates certain runtime decisions

Types in C

Basic C Types

C was designed for efficiency: basic types are whatever is most efficient for the target processor.

On an (32-bit) ARM processor,

```
char c;             /* 8-bit binary */

short d;            /* 16-bit two's-complement binary */
unsigned short d;   /* 16-bit binary */

int a;              /* 32-bit two's-complement binary */
unsigned int b;     /* 32-bit binary */

float f;            /* 32-bit IEEE 754 floating-point */
double g;           /* 64-bit IEEE 754 floating-point */
```

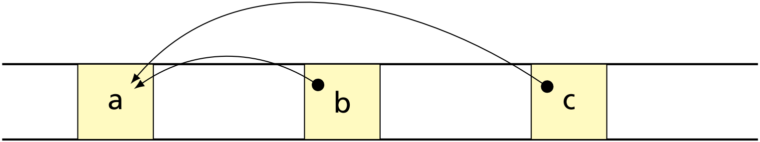
Pointers and Arrays

A pointer contains a memory address.

Arrays in C are implemented with arithmetic on pointers.

A pointer can create an *alias* to a variable:

```
int a;
int *b = &a;  /* "pointer to integer b is the address of a" */
int *c = &a;  /* c also points to a */

*b = 5;       /* sets a to 5 */
*c = 42;      /* sets a to 42 */

printf("%d %d %d\n", a, *b, *c); /* prints 42 42 42 */
```



Pointers Enable Pass-by-Reference

```
void swap(int x, int y)
{
  int temp;
  temp = x;
  x = y;
  y = temp;
}
```

Does this work?

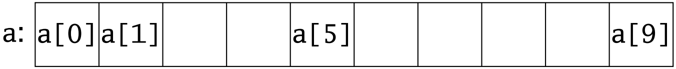
Pointers Enable Pass-by-Reference

```
void swap(int x, int y)
{
  int temp;
  temp = x;
  x = y;
  y = temp;
}
```

Does this work?
Nope.

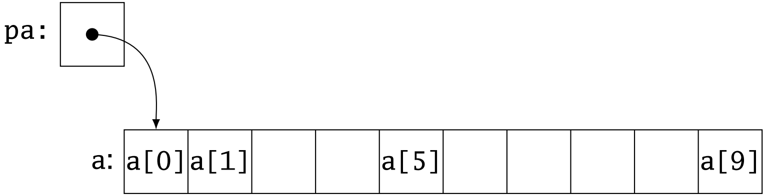
```
void swap(int *px, int *py)
{
  int temp;

  temp = *px; /* get data at px */
  *px = *py;  /* get data at py */
  *py = temp; /* write data at py */
}

void main()
{
  int a = 1, b = 2;

  /* Pass addresses of a and b */
  swap(&a, &b);

  /* a = 2 and b = 1 */
}
```

Arrays and Pointers



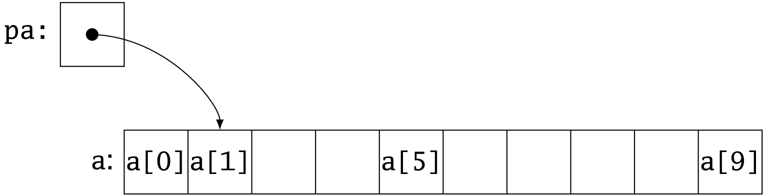

```
int a[10];
```

Arrays and Pointers



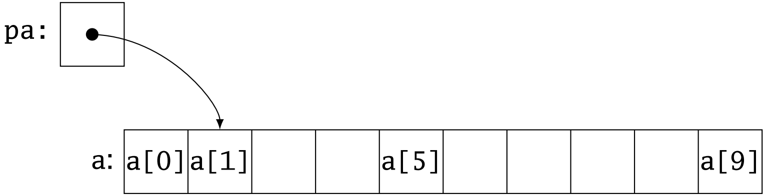

```
int a[10];
int *pa = &a[0];
```

Arrays and Pointers



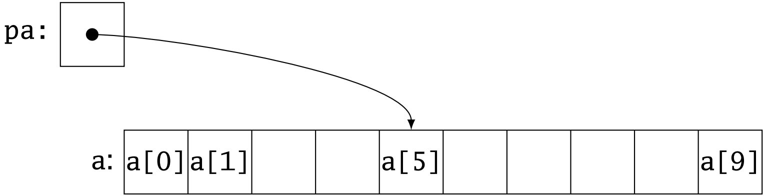

```
int a[10];
int *pa = &a[0];
pa = pa + 1;
```

Arrays and Pointers




```
int a[10];
int *pa = &a[0];
pa = pa + 1;
pa = &a[1];
```

Arrays and Pointers




```
int a[10];
int *pa = &a[0];
pa = pa + 1;
pa = &a[1];
pa = a + 5;
```

`a[i]` is equivalent to `*(a + i)`

Multi-Dimensional Arrays

```
int monthdays[2][12] = {
  { 31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31 },
  { 31, 29, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31 } };
```

`monthdays[i][j]` is at address `monthdays + 12 * i + j`

Structures

Structures: each field has own storage

```
struct box {
  int x, y, h, w;
  char *name;
};
```

Unions: fields share same memory

```
union token {
  int i;
  double d;
  char *s;
};
```

Structs

Structs can be used like the objects of C++, Java, et al.

Group and restrict what can be stored in an object, but not what operations they permit.

```
struct poly { ... };

struct poly *poly_create();
void        poly_destroy(struct poly *p);
void        poly_draw(struct poly *p);
void        poly_move(struct poly *p, int x, int y);
int         poly_area(struct poly *p);
```

Unions: Variant Records

A `struct` holds all of its fields at once. A `union` holds only one of its fields at any time (the last written).

```
union token {
  int i;
  float f;
  char *string;
};

union token t;
t.i = 10;
t.f = 3.14159;        /* overwrite t.i */
char *s = t.string;  /* return gibberish */
```

Applications of Variant Records

A primitive form of polymorphism:

```
struct poly {
  int type;
  int x, y;
  union { int radius;
          int size;
          float angle; } d;
};

void draw(struct poly *shape)
{
  switch (shape->type) {
  case CIRCLE:  /* use shape->d.radius */

  case SQUARE:  /* use shape->d.size */

  case LINE:    /* use shape->d.angle */

  }

}
```

Name vs. Structural Equivalence

```
struct f {
  int x, y;
} foo = { 0, 1 };

struct b {
  int x, y;
} bar;

bar = foo;
```

Is this legal in C? Should it be?

C’s Declarations and Declarators

Declaration: list of specifiers followed by a comma-separated list of declarators.

$$\underbrace{\texttt{static unsigned }\overbrace{\texttt{int}}^{\text{basic type}}}_{\text{specifiers}}\underbrace{\texttt{(*f[10])(int, char*);}}_{\text{declarator}}$$

Declarator’s notation matches that of an expression: use it to return the basic type.

Largely regarded as the worst syntactic aspect of C: both pre- (pointers) and post-fix operators (arrays, functions).

Types of Type Systems

Strongly-typed Languages

Strongly-typed: no run-time type clashes (detected or not).

C is definitely not strongly-typed:

```
float g;

union { float f; int i } u;

u.i = 3;

g = u.f + 3.14159; /* u.f is meaningless */
```

Is Java strongly-typed?

Statically-Typed Languages

Statically-typed: compiler can determine types.

Dynamically-typed: types determined at run time.

Is Java statically-typed?

```
class Foo {
   public void x() { ... }
}

class Bar extends Foo {
   public void x() { ... }
}

void baz(Foo f) {
  f.x();
}
```

Polymorphism

Say you write a sort routine:

```
void sort(int a[], int n)
{
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if (a[j] < a[i]) {
        int tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
```

Polymorphism

To sort doubles, only need to change two types:

```
void sort(double a[], int n)
{
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if (a[j] < a[i]) {
        double tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
```

C++ Templates

```
template <class T> void sort(T a[], int n)
{
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if (a[j] < a[i]) {
        T tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}

int a[10];

sort<int>(a, 10);
```

C++ Templates

C++ templates are essentially language-aware macros. Each instance generates a different refinement of the same code.

```
sort<int>(a, 10);

sort<double>(b, 30);

sort<char *>(c, 20);
```

Fast code, but lots of it.

Faking Polymorphism with Objects

```
class Sortable {
  bool lessthan(Sortable s) = 0;
}

void sort(Sortable a[], int n) {
  int i, j;
  for ( i = 0 ; i < n-1 ; i++ )
    for ( j = i + 1 ; j < n ; j++ )
      if ( a[j].lessthan(a[i]) ) {
        Sortable tmp = a[i];
        a[i] = a[j];
        a[j] = tmp;
      }
}
```

Faking Polymorphism with Objects

This `sort` works with any array of objects derived from `Sortable`.

Same code is used for every type of object.

Types resolved at run-time (dynamic method dispatch).

Does not run as quickly as the C++ template version.

Static Semantic Analysis

Static Semantic Analysis

Lexical analysis: Make sure tokens are valid

```
if i 3 "This"                   /* valid Java tokens */
#a1123                          /* not a token */
```

Syntactic analysis: Makes sure tokens appear in correct order

```
for ( i = 1 ; i < 5 ; i++ ) 3 + "foo";  /* valid Java syntax */
for break                               /* invalid syntax */
```

Semantic analysis: Makes sure program is consistent

```
int v = 42 + 13;    /* valid in Java (if v is new) */
return f + f(3);    /* invalid */
```

What To Check

Examples from Java:

Verify names are defined and are of the right type.

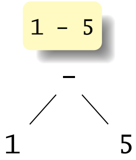
```
int i = 5;
int a = z;    /* Error: cannot find symbol */
int b = i[3]; /* Error: array required, but int found */
```

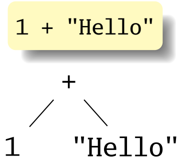
Verify the type of each expression is consistent.

```
int j = i + 53;
int k = 3 + "hello";   /* Error: incompatible types */
int l = k(42);         /* Error: k is not a method */
if ("Hello") return 5; /* Error: incompatible types */
String s = "Hello";
int m = s;             /* Error: incompatible types */
```

How To Check: Depth-first AST Walk

Checking function: environment → node → type





check(-)

- check(1) = int
- check(5) = int
- Success: int – int = int

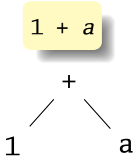
check(+)

- check(1) = int
- check("Hello") = string
- FAIL: Can't add int and string

Ask yourself: at each kind of node, what must be true about the nodes below it? What is the type of the node?

How To Check: Symbols

Checking function: environment → node → type



check(+)

check(1) = int

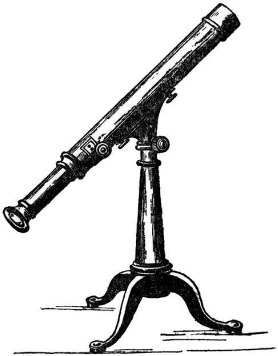
check(a) = int

Success: int + int = int

The key operation: determining the type of a symbol when it is encountered.

The environment provides a “symbol table” that holds information about each in-scope symbol.

Scope



Basic Static Scope in C, C++, Java, etc.

A name begins life where it is declared and ends at the end of its block.

From the CLRM, “The scope of an identifier declared at the head of a block begins at the end of its declarator, and persists to the end of the block.”

```
void foo()
{
   int x;



}
```

Hiding a Definition

Nested scopes can hide earlier definitions, giving a hole.

From the CLRM, “If an identifier is explicitly declared at the head of a block, including the block constituting a function, any declaration of the identifier outside the block is suspended until the end of the block.”

```
void foo()
{
  int x;

  while ( a < 10 ) {
    int x;

  }


}
```

Static Scoping in Java

```
public void example() {
  // x, y, z not visible

  int x;
  // x visible

  for ( int y = 1 ; y < 10 ; y++ ) {
    // x, y visible

    int z;
    // x, y, z visible
  }

  // x visible
}
```

Basic Static Scope in O'Caml

A name is bound after the "in" clause of a "let." If the name is re-bound, the binding takes effect *after* the "in."

```
let x = 8 in


let x = x + 1 in
```

Returns the pair (12, 8):

```
let x = 8 in
  (let x = x + 2 in
     x + 2),
x
```

Let Rec in O'Caml

The "rec" keyword makes a name visible to its definition. This only makes sense for functions.

```
let rec fib i =
  if i < 1 then 1 else
    fib (i-1) + fib (i-2)
in
  fib 5
```

```
(* Nonsensical *)
let rec x = x + 3 in
```

Let...and in O'Caml

Let...and lets you bind multiple names at once. Definitions are not mutually visible unless marked "rec."

```
let x = 8
and y = 9 in
```

```
let rec fac n =
      if n < 2 then
        1
      else
        n * fac1 n
and fac1 n = fac (n - 1)
in
fac 5
```

Nesting Function Definitions

```
let articles words =

  let report w =

    let count = List.length
      (List.filter ((=) w) words)
    in w ^ ": " ^
      string_of_int count

  in String.concat ", "
    (List.map report ["a"; "the"])

in articles
    ["the"; "plt"; "class"; "is";
     "a"; "pain"; "in";
     "the"; "butt"]
```

```
let count words w = List.length
  (List.filter ((=) w) words) in

let report words w = w ^ ": " ^
  string_of_int (count words w) in

let articles words =
  String.concat ", "
    (List.map (report words)
     ["a"; "the"]) in

articles
    ["the"; "plt"; "class"; "is";
     "a"; "pain"; "in";
     "the"; "butt"]
```

Produces “a: 1, the: 2”

A Static Semantic Analyzer

The Static Semantic Checking Function

A big function: “check: ast → sast”

Converts a raw AST to a “semantically checked AST”

Names and types resolved

AST:

```
type expression =
    IntConst of int
  | Id of string
  | Call of string * expression list
  | ...
```

⇓

SAST:

```
type expr_detail =
   IntConst of int
 | Id of variable_decl
 | Call of function_decl * expression list
 | ...

type expression = expr_detail * Type.t
```

The Type of Types

Need an OCaml type to represent the type of something in your language.

An example for a language with integer, structures, arrays, and exceptions:

```
type t = (* can't call it "type" since that's reserved *)
    Void
  | Int
  | Struct of string * ((string * t) array) (* name, fields *)
  | Array of t * int                       (* type, size *)
  | Exception of string
```

Translation Environments

Whether an expression/statement/function is correct depends on its context. Represent this as an object with named fields since you will invariably have to extend it.

An environment type for a C-like language:

```
type translation_environment = {
    scope : symbol_table;                    (* symbol table for vars *)

    return_type : Types.t;                  (* Function's return type *)
    in_switch : bool;                   (* if we are in a switch stmt *)
    case_labels : Big_int.big_int list ref; (* known case labels *)
    break_label : label option;             (* when break makes sense *)
    continue_label : label option;       (* when continue makes sense *)
    exception_scope : exception_scope;     (* sym tab for exceptions *)
    labels : label list ref;                   (* labels on statements *)
    forward_gotos : label list ref; (* forward goto destinations *)
  }
```

A Symbol Table

Basic operation is string → type. Map or hash could do this, but a list is fine.

```
type symbol_table = {
  parent : symbol_table option;
  variables : variable_decl list
}

let rec find_variable (scope : symbol_table) name =
  try
     List.find (fun (s, _, _, _) -> s = name) scope.variables
  with Not_found ->
    match scope.parent with
      Some(parent) -> find_variable parent name
    | _ -> raise Not_found
```

Checking Expressions: Literals and Identifiers

```
(* Information about where we are *)
type translation_environment = {
  scope : symbol_table;
}

let rec expr env = function

    (* An integer constant: convert and return Int type *)
    Ast.IntConst(v) -> Sast.IntConst(v), Types.Int

    (* An identifier: verify it is in scope and return its type *)
  | Ast.Id(vname) ->
     let vdecl = try
       find_variable env.scope vname (* locate a variable by name *)
     with Not_found ->
        raise (Error("undeclared identifier " ^ vname))
     in
     let (_, typ) = vdecl in (* get the variable's type *)
     Sast.Id(vdecl), typ

  | ...
```

Checking Expressions: Binary Operators

```
(* let rec expr env = function *)

| A.BinOp(e1, op, e2) ->
   let e1 = expr env e1    (* Check left and right children *)
   and e2 = expr env e2 in

   let _, t1 = e1           (* Get the type of each child *)
   and _, t2 = e2 in

   if op <> Ast.Equal && op <> Ast.NotEqual then
     (* Most operators require both left and right to be integer *)
     (require_integer e1 "Left operand must be integer";
      require_integer e2 "Right operand must be integer")
   else
     if not (weak_eq_type t1 t2) then
       (* Equality operators just require types to be "close" *)
       error ("Type mismatch in comparison: left is " ^
            Printer.string_of_sast_type t1 ^ "\" right is \"" ^
            Printer.string_of_sast_type t2 ^ "\""
           ) loc;

   Sast.BinOp(e1, op, e2), Types.Int  (* Success: result is int *)
```

Checking Statements: Expressions, If

```
let rec stmt env = function

    (* Expression statement: just check the expression *)
    Ast.Expression(e) -> Sast.Expression(expr env e)

    (* If statement: verify the predicate is integer *)
  | Ast.If(e, s1, s2) ->

      let e = check_expr env e in  (* Check the predicate *)
      require_integer e "Predicate of if must be integer";

      Sast.If(e, stmt env s1, stmt env s2) (* Check then, else *)
```

Checking Statements: Declarations

```
(* let rec stmt env = function *)

| A.Local(vdecl) ->
    let decl, (init, _) = check_local vdecl (* already declared? *)
    in

   (* side-effect: add variable to the environment *)
    env.scope.S.variables <- decl :: env.scope.S.variables;

    init (* initialization statements, if any *)
```

Checking Statements: Blocks

```
(* let rec stmt env = function *)

| A.Block(sl) ->

    (* New scopes: parent is the existing scope, start out empty *)

    let scope' = { S.parent = Some(env.scope); S.variables = [] }
    and exceptions' =
      { excep_parent = Some(env.exception_scope); exceptions = [] }
    in

    (* New environment: same, but with new symbol tables *)
    let env' = { env with scope = scope';
                 exception_scope = exceptions' } in

    (* Check all the statements in the block *)

    let sl = List.map (fun s -> stmt env' s) sl in
    scope'.S.variables <-
       List.rev scope'.S.variables; (* side-effect *)

    Sast.Block(scope', sl) (* Success: return block with symbols *)
```