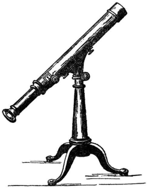
Names, Scope, and Types

Stephen A. Edwards

Columbia University

Spring 2016



Scope

Types

Types in C

Types of Type Systems

Overloading

Binding Time

Static Semantic Analysis

What's Wrong With This?

```
a + f(b, c)
```

What's Wrong With This?

```
a + f(b, c)
```

Is `a` defined?

Is `f` defined?

Are `b` and `c` defined?

Is `f` a function of two arguments?

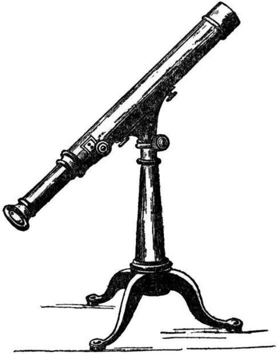
Can you add whatever `a` is to whatever `f` returns?

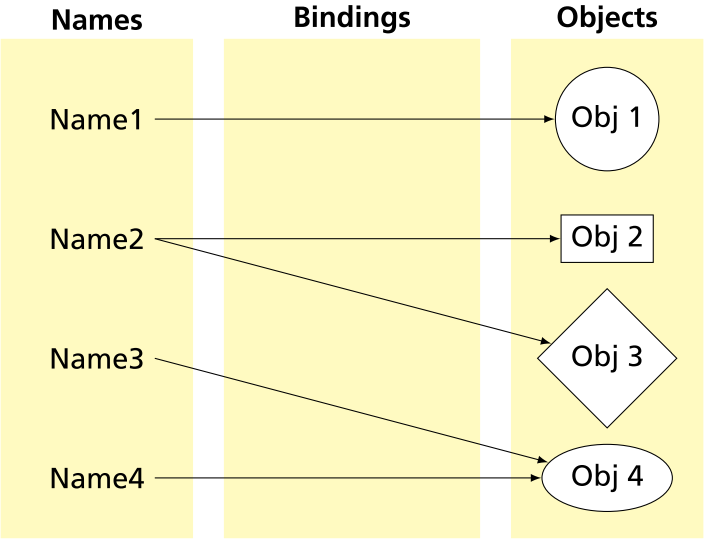
Does `f` accept whatever `b` and `c` are?

Scope questions Type questions

Scope

What names are visible?




Names
Bindings
Objects
Name1
Name2
Name3
Name4
Obj 1
Obj 2
Obj 3
Obj 4

Scope

Scope: where/when a name is bound to an object

Useful for modularity: want to keep most things hidden

Scoping Policy	Visible Names Depend On
Static	Textual structure of program
Dynamic	Run-time behavior of program

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 vs. Dynamic Scope

C

```c
int a = 0;

int foo() {
  return a + 1;
}

int bar() {
  int a = 10;

  return foo();
}
```

OCaml

```ocaml
let a = 0 in
let foo x = a + 1 in
let bar =
  let a = 10 in
  foo 0
```

Bash

```bash
a=0

foo ()
{
  a=`expr $a + 1`
}

bar ()
{
  local a=10
  foo
  echo $a
}

bar
```

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 x = 8
and y = 9 in
```

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

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

Forward Declarations

Languages such as C, C++, and Pascal require *forward declarations* for mutually-recursive references.

```
int foo(void);
int bar() { ... foo(); ... }
int foo() { ... bar(); ... }
```

Partial side-effect of compiler implementations. Allows single-pass compilation.

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"

Dynamic Definitions in TEX

```
% \x, \y undefined
{
  % \x, \y undefined
  \def \x 1
  % \x defined, \y undefined

  \ifnum \a < 5
    \def \y 2
  \fi

  % \x defined, \y may be undefined
}
% \x, \y undefined
```

Static vs. Dynamic Scope

Most modern languages use static scoping.

Easier to understand, harder to break programs.

Advantage of dynamic scoping: ability to change environment.

A way to surreptitiously pass additional parameters.

Application of Dynamic Scoping

```
program messages;
var message : string;

  procedure complain;
  begin
    writeln(message);
  end

  procedure problem1;
  var message : string;
  begin
    message := 'Out of memory';
    complain
  end

  procedure problem2;
  var message : string;
  begin
    message := 'Out of time';
    complain
  end
```

Open vs. Closed Scopes

An *open scope* begins life including the symbols in its outer scope.

Example: blocks in Java

```
{
  int x;
  for (;;) {
    /* x visible here */
  }
}
```

A *closed scope* begins life devoid of symbols.

Example: structures in C.

```
struct foo {
  int x;
  float y;
}
```

Types

What operations are allowed?

Types

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

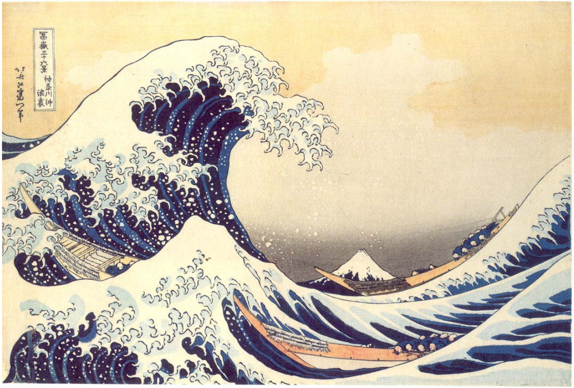
Two uses:

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

Optimization: eliminates certain runtime decisions

Types in C

What types are processors best at?



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 */
```

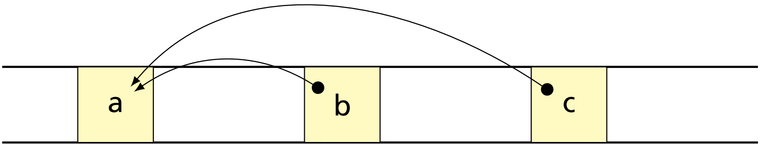
Pointers and Arrays

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?

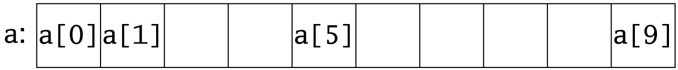
Pointers Enable Pass-by-Reference

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

Does this work?
Nope.

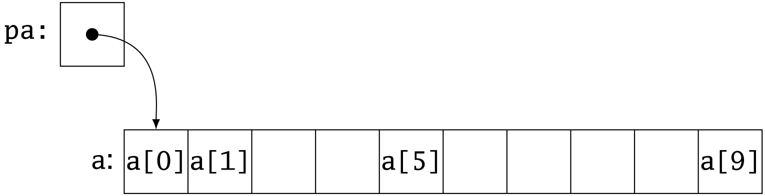
```
void swap(int *px, int *py)
{
  int temp;

  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



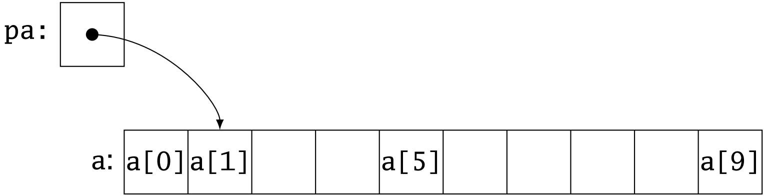

```
int a[10];
```

Arrays and Pointers



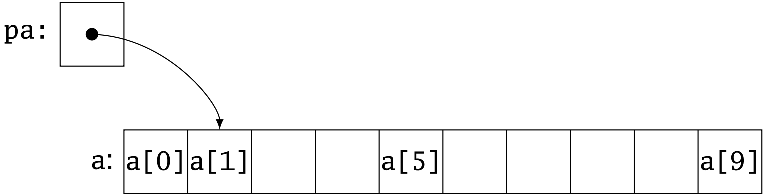

```
int a[10];
int *pa = &a[0];
```

Arrays and Pointers



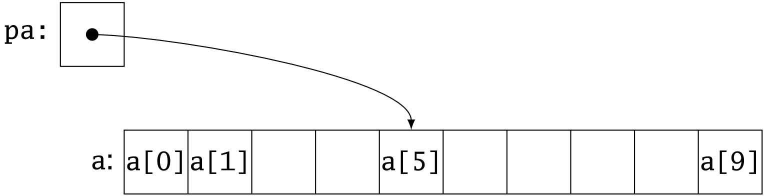

```
int a[10];
int *pa = &a[0];
pa = pa + 1;
```

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 */
```

Kind of like a bathroom on an airplane

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.

basic type

```
static unsigned int(*f[10])(int, char*);
```

specifiers — 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

What kinds of type systems do languages have?

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.

Parametric Polymorphism

In C++,

```
template <typename T>
T max(T x, T y)
{
  return x > y ? x : y;
}

struct foo {int a;} f1, f2, f3;

int main()
{
  int a = max<int>(3, 4); /* OK */
  f3 = max<struct foo>(f1, f2);  /* No match for operator> */
}
```

The `max` function only operates with types for which the > operator is defined.

Parametric Polymorphism

In OCaml,

```
let max x y = if x - y > 0 then x else y

max : int -> int -> int
```

Only `int` arguments are allowed because in OCaml, – only operates on integers.

However,

```
let rec map f = function [] -> [] | x::xs -> f x :: map f xs

map : ('a -> 'b) -> 'a list -> 'b list
```

Here, `'a` and `'b` may each be *any type*.

OCaml uses parametric polymorphism: type variables may be of any type.

C++'s template-based polymorphism is ad hoc: there are implicit constraints on type parameters.

Overloading

What if there is more than one object for a name?

Overloading versus Aliases

Overloading: two objects, one name

Alias: one object, two names

In C++,

```
int foo(int x) { ... }
int foo(float x) { ... } // foo overloaded

void bar()
{
  int x, *y;
  y = &x;  // Two names for x: x and *y
}
```

Examples of Overloading

Most languages overload arithmetic operators:

```
1 + 2           // Integer operation
3.1415 + 3e-4   // Floating-point operation
```

Resolved by checking the *type* of the operands.

Context must provide enough hints to resolve the ambiguity.

Function Name Overloading

C++ and Java allow functions/methods to be overloaded.

```
int   foo();
int   foo(int a);   // OK: different # of args
float foo();        // Error: only return type
int   foo(float a); // OK: different arg types
```

Useful when doing the same thing many different ways:

```
int add(int a, int b);
float add(float a, float b);

void print(int a);
void print(float a);
void print(char *s);
```

Function Overloading in C++

Complex rules because of *promotions*:

```
int i;
long int l;
l + i
```

Integer promoted to long integer to do addition.

```
3.14159 + 2
```

Integer is promoted to double; addition is done as double.

Function Overloading in C++

1. Match trying trivial conversions
   `int a[]` to `int *a`, *T* to *const T*, etc.
2. Match trying promotions
   `bool` to `int`, `float` to `double`, etc.
3. Match using standard conversions
   `int` to `double`, `double` to `int`
4. Match using user-defined conversions
   `operator int() const { return v; }`
5. Match using the elipsis `...`

Two matches at the same (lowest) level is ambiguous.

Binding Time

When are bindings created and destroyed?

Binding Time

When a name is connected to an object.

Bound when	**Examples**
language designed	`if` `else`
language implemented	data widths
Program written	`foo` `bar`
compiled	static addresses, code
linked	relative addresses
loaded	shared objects
run	heap-allocated objects

Binding Time and Efficiency

Earlier binding time ⇒ more efficiency, less flexibility

Compiled code more efficient than interpreted because most decisions about what to execute made beforehand.

```
switch (statement) {

case add:
   r = a + b;
   break;

case sub:
   r = a - b;
   break;

   /* ... */
}
```

```
add %o1, %o2, %o3
```

Binding Time and Efficiency

Dynamic method dispatch in OO languages:

```
class Box : Shape {
  public void draw() { ... }
}

class Circle : Shape {
  public void draw() { ... }
}

Shape s;
s.draw();  /* Bound at run time */
```

Binding Time and Efficiency

Interpreters better if language has the ability to create new programs on-the-fly.

Example: Ousterhout's Tcl language.

Scripting language originally interpreted, later byte-compiled.

Everything's a string.

```
set a 1
set b 2
puts "$a + $b = [expr $a + $b]"
```

Binding Time and Efficiency

Tcl's `eval` runs its argument as a command.

Can be used to build new control structures.

```
proc ifforall {list pred ifstmt} {
  foreach i $list {
    if [expr $pred] { eval $ifstmt }
  }
}

ifforall {0 1 2} {$i % 2 == 0} {
  puts "$i even"
}

0 even
2 even
```

Static Semantic Analysis

How do we validate names, scope, and types?

Static Semantic Analysis

Lexical analysis: Each token is valid?

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

Syntactic analysis: Tokens appear in the correct order?

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

Semantic analysis: Names used correctly? Types 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.

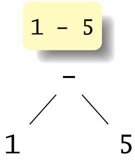
```
int i = 5;
int a = z;    /* Error: cannot find symbol */
int b = i[3]; /* Error: array required, but int found */
```

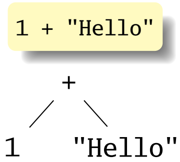
Verify the type of each expression is consistent.

```
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 Expressions: Depth-first AST Walk

Checking function: environment → node → type





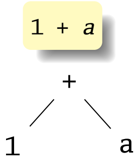
check(–)
- check(1) = int
- check(5) = int
- Success: int – int = int

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.

A 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 *)
```