"Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, not smart enough to debug it."

- Brian W. Kernighan

CSE341
Programming Languages

Lecture 4 – October 22, 2015

Data Types

Chapter 6 slides are adapted from R.W. Sebesta, C. Li & W. He and V. Shmatikov

Scope

- The range of statements where a variable is visible, i.e. can be accessed
- Local variables are visible in the program unit where they are declared
- Non-local variables are visible in a program unit but not declared there
- Scope rules determine how names are associated with variables

Static Scope

- Also called Lexical Scope
  - The scope of variable can be determined statically (prior to execution)
- Based on structure of program text
- To connect a name to a variable, one (you or the compiler) must find the declaration
- Search process:
  - Search declarations, first locally,
  - Then in increasingly larger outer enclosing scopes
  - Until declaration for the name is found
- Enclosing static scopes (to a specific scope) are called its static ancestors
  - The nearest static ancestor is called a static parent

Shadowed Variables

- Variables are shadowed (hidden) in part of the code where there is a more immediate ancestor (closer in scope) with the same name
- C++ and Ada allow access to hidden variables using longer names
  - In Ada: <unit> .<name>
  - In C++: <class_name> ::<name>
- Common Lisp
  - Packages variables accessible via longer name or package imported
- Java
  - this.<name>
  - <class_name>.this.<name>
  - super.<name> // shadowed field in superclass

Scope Blocks

- Static scopes can be created inside program units
- Started with ALGOL 60!

  C and C++:

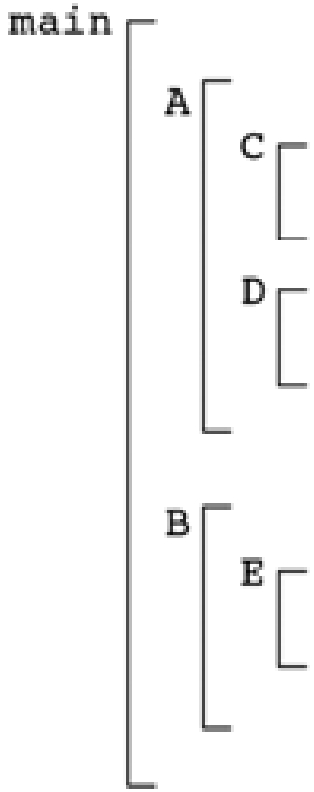
```
for (int index; …)  {
      int x;
       …
}
```

- Scope block
  - statements in between {…}, and
  - condition expression in preceding or following (…)

Declaration Order

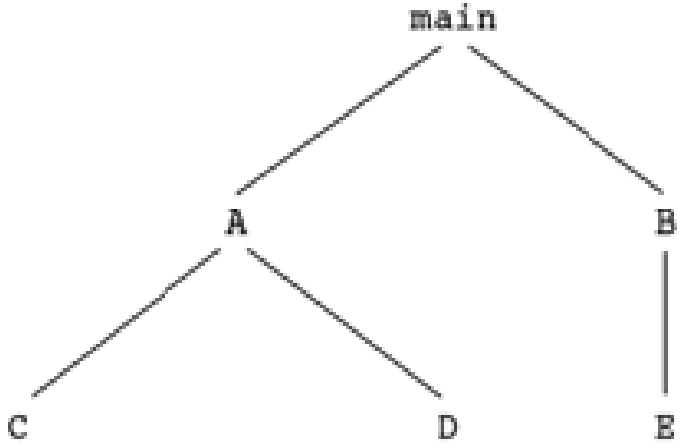
- Where should be variables declared
  - For some PLs, must appear at the beginning of functions
  - Some others, e.g., C++, Java, etc. can appear anywhere
- What scope
  - Only after declaration till the end of the block, e.g., in C++
  - Anywhere in the block, e.g., in C# and JavaScript
    - C# still requires declaration
    - JavaScript will result in “undefined”

Static Scoping Diagram



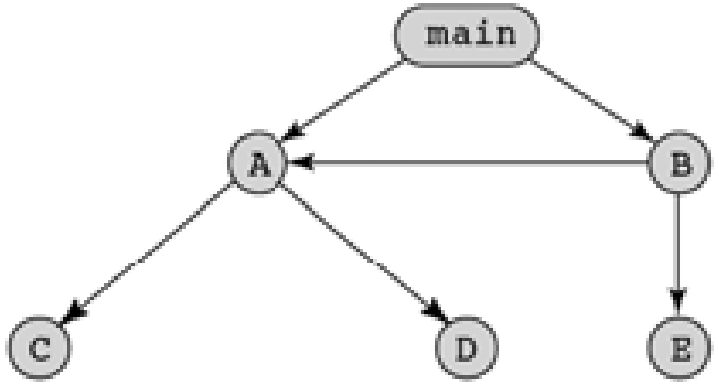
Example:

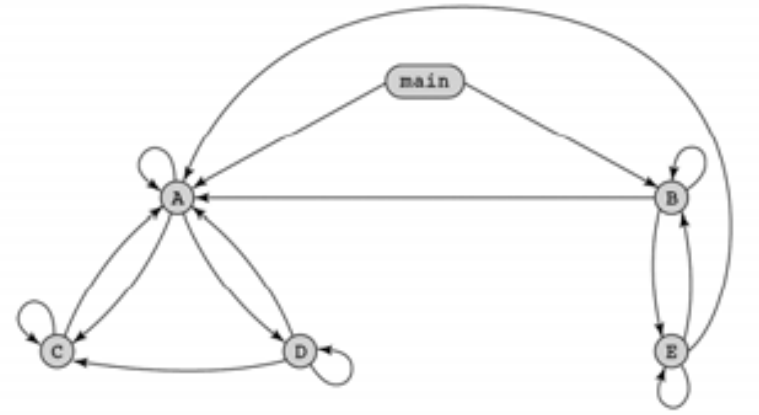
- MAIN calls A and B
- A calls C and D
- B calls A and E



Static Scope Problems

- Suppose the specs are changed so that D must access data in B
- Solutions:
  - Put D in B
    - but then C can 't call D and D can't access A's variables
  - Move the data from B that D needs to MAIN
    - but then all procedures can access them
- Same problem for procedure access
- Static scoping may encourage many global variables





Dynamic Scope

- Uses calling sequences of program units, not their textual layout
  - i.e. temporal versus spatial

- References are connected to declarations by searching back through the chain of subprogram calls in execution
  - i.e. search through the dynamic stack for the most recent variable with the name

Scope Example

```
MAIN
- declaration of x -

    SUB1
    - declaration of x -
    ...
    call SUB2
    ...

    SUB2
    ...
    - reference to x -
    ...

...
call SUB1
...
```

MAIN calls Sub1
Sub1 calls Sub2
Sub2 uses x

Static scoping

Reference to x is to MAIN's x

Dynamic scoping

Reference to x is to SUB1's x

Static Scope Example

```
begin
   integer m, n;

   procedure hardy;
      begin
      print("in hardy -- n = ", n);
      end;

   procedure laurel(n: integer);
      begin
      print("in laurel -- m = ", m);
      print("in laurel -- n = ", n);
      hardy;
      end;

   m := 50;
   n := 100;
   print("in main program -- n = ", n);
   laurel(1);
   hardy;
   end;
```

```
in main program -- n = 100
in laurel -- m = 50
in laurel -- n = 1
in hardy -- n = 100
  /* note that here hardy is called from laurel */
in hardy -- n = 100
  /* here hardy is called from the main program */
```

Dynamic Scope Example

```
begin
   integer m, n;

   procedure hardy;
      begin
      print("in hardy -- n = ", n);
      end;

   procedure laurel(n: integer);
      begin
      print("in laurel -- m = ", m);
      print("in laurel -- n = ", n);
      hardy;
      end;

   m := 50;
   n := 100;
   print("in main program -- n = ", n);
   laurel(1);
   hardy;
   end;
```

```
in main program -- n = 100
in laurel -- m = 50
in laurel -- n = 1
in hardy -- n = 1
 ;; NOTE DIFFERENCE -- here hardy is called from laurel
in hardy -- n = 100
 ;; here hardy is called from the main program
```

Static Scope in Nested Loops

```
begin
   integer m, n;

   procedure laurel(n: integer);
      begin

      procedure hardy;
         begin
         print("in hardy -- n = ", n);
         end;

      print("in laurel -- m = ", m);
      print("in laurel -- n = ", n);
      hardy;
      end;

   m := 50;
   n := 100;
   print("in main program -- n = ", n);
   laurel(1);
   /* can't call hardy from the main program any more */
   end;
```

```
in main program -- n = 100
in laurel -- m = 50
in laurel -- n = 1
in hardy -- n = 1
```

Scope Evaluation

- Advantage of dynamic scoping
  - convenience (no need to pass vars)
  - flexibility

- Disadvantage
  - poor readability (same name different non-local vars)
  - reliability (accessibility from multiple subprograms)
  - longer access times for non-local variables

Scope and Lifetime

- Scope and lifetime are sometimes closely related, but are different concepts

- Consider a static variable in a C or C++ function
  - Scope is static and local to the function
  - Lifetime extends over the entire execution of the program

Referencing Environments

- Referencing environment (RE) of a statement
  - all names that are visible in the statement
- In statically-scoped language RE is
  - Local variables, and
  - All of the visible variables in all of the enclosing scopes
- In Dynamically-scoped languages RE is
  - Local variables, and
  - All visible variables in all active subprograms
  - Active
    - execution of the subprogram has begun and
    - is not yet terminated

Named Constants

- A variable that is bound to a value only once
- Improved readability
  - E.g., “pi” instead of “3.14….”
- Parameterize a program
  - E.g., parameterizing length of an array
- C++ allows dynamic binding of values to named constants
  - “const int result = results * width + 1;”
- C# allows static “const” as well as dynamic “readonly”

Initialization

- The binding of a variable to a value at the time it is bound to storage
- Static
  - Binding and initialization occur before run time
  - Initial value must be specified as a literal or an expression whose only non-literals are named constants
- Dynamic
  - Initialization is dynamic

Examples

- Consider the C preprocessor

```
#define ADD(x) x + a
```

Examples

- LISP calls dynamically scoped variables as special variables

```
> (defvar *special* 5)
*SPECIAL*
> (defun check-special () *special*)
CHECK-SPECIAL
> (check-special)
5
> (let ((*special* 6)) (check-special))
6
```

Examples

- Perl
- “my” for lexical scoping
  - A “my” variable has a block of code as its scope
  - A block is often declared with braces {}, but as far as Perl is concerned, a file is a block
  - A variable declared with “my” does not belong to any package, it 'belongs' only to its block
- “local” for dynamic scoping

Examples

```
first();
sub first {
  local $x = 1;
  my    $y = 1;
  second();
}
sub second {
  print "x=", $x, "\n";
  print "y=", $y, "\n";
}
```

Local creates a new `local' value for a global variable, which persists until the end of the enclosing block.

When control exits the block, the old value is restored.

But the variable, and its new `local' value, are still global, and hence accessible to other subroutines that are called before the old value is restored.

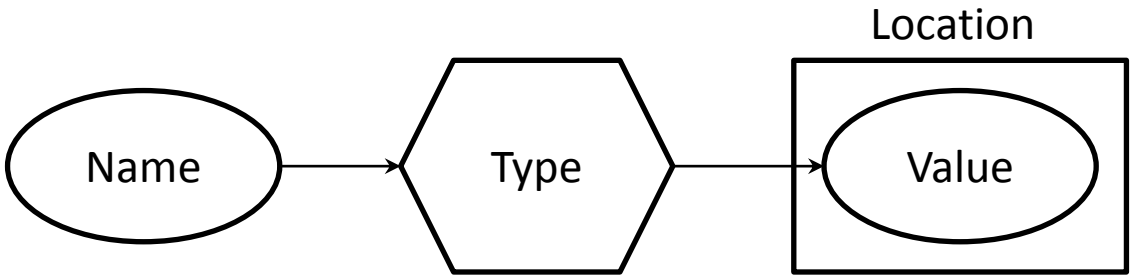
second() therefore prints "x=1", because $x is a global variable that temporarily happens to have the value 1.

Type

- A type is a collection of computable values that share some structural property
- A type is also a set of operations on the values
- Examples:
  - Integers, Strings, int → bool, (int → int) → bool, …
- Not type examples:
  - {3, true}, , Even integers
- Distinction between sets that are types and sets that are not types is language-dependent

Variables Revisited

- Recall that variables have six attributes
  - Name
  - Type
  - Location or reference (l-value)
  - Value (r-value)
  - Scope - where variable accessible and modifiable – static vs. dynamic
  - Lifetime - interval of time in which location bound to variable



- An identifier (or name) is used to identify the entities, e.g., variable names, function names, etc., in a programming language

Variables Revisited

- A **descriptor** is the collection of the attributes of a variable
  - Implementation: an area of the memory where attributes of a variable is stored
    - All static attributes: descriptors are required only at compile time. Built by compiler and stored usually in symbol table and used during compilation.
    - If dynamic: Part or all off the attributes need to be maintained during execution. The descriptor is used by the run-time system.
  - Used for type checking and building the code for allocation and deallocation

Uses for Types

- Program organization and documentation
  - Separate types for separate concepts
    - Represent concepts from problem domain
  - Indicate intended use of declared identifiers
    - Types can be checked, unlike program comments
- Identify and prevent errors
  - Compile-time or run-time checking can prevent meaningless computations such as 3 + true - “Bill”
- Support optimization
  - Example: short integers require fewer bits
  - Access record component by known offset

Uses for Types

- **Example: z = x / y; (Java)**
  - int x, y; x=5; y=2;
    - Integer division, x/y results in 2.
    - int z: z = 2;
    - double z: z=2.0;
  - double x, y; x=5; y=2;
    - floating-point division, x/y results in 2.5
    - int z: wrong!
    - double z: z=2.5;

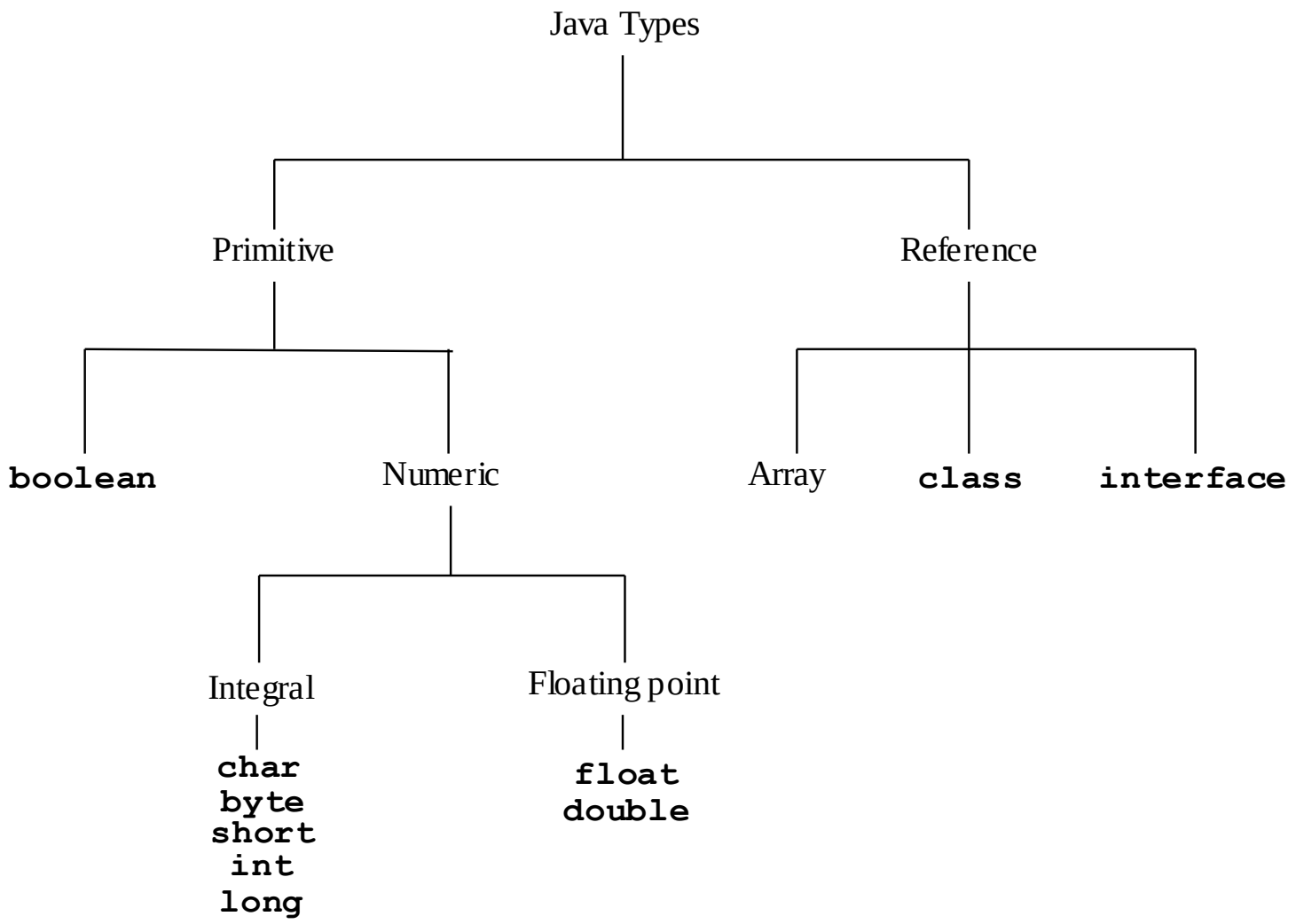
Operations on Typed Values

- Often a type has operations defined on values of this type
  - Integers: + - / * < > … Booleans: $\wedge$ $\vee$ $\neg$ …
- Set of values is usually finite due to internal binary representation inside computer
  - 32-bit integers in C: –2147483648 to 2147483647
  - Addition and subtraction may overflow the finite range, so sometimes a + (b + c) ≠ (a + b) + c
  - Exceptions: unbounded fractions in Smalltalk, unbounded Integer type in Haskell
  - Floating point problems

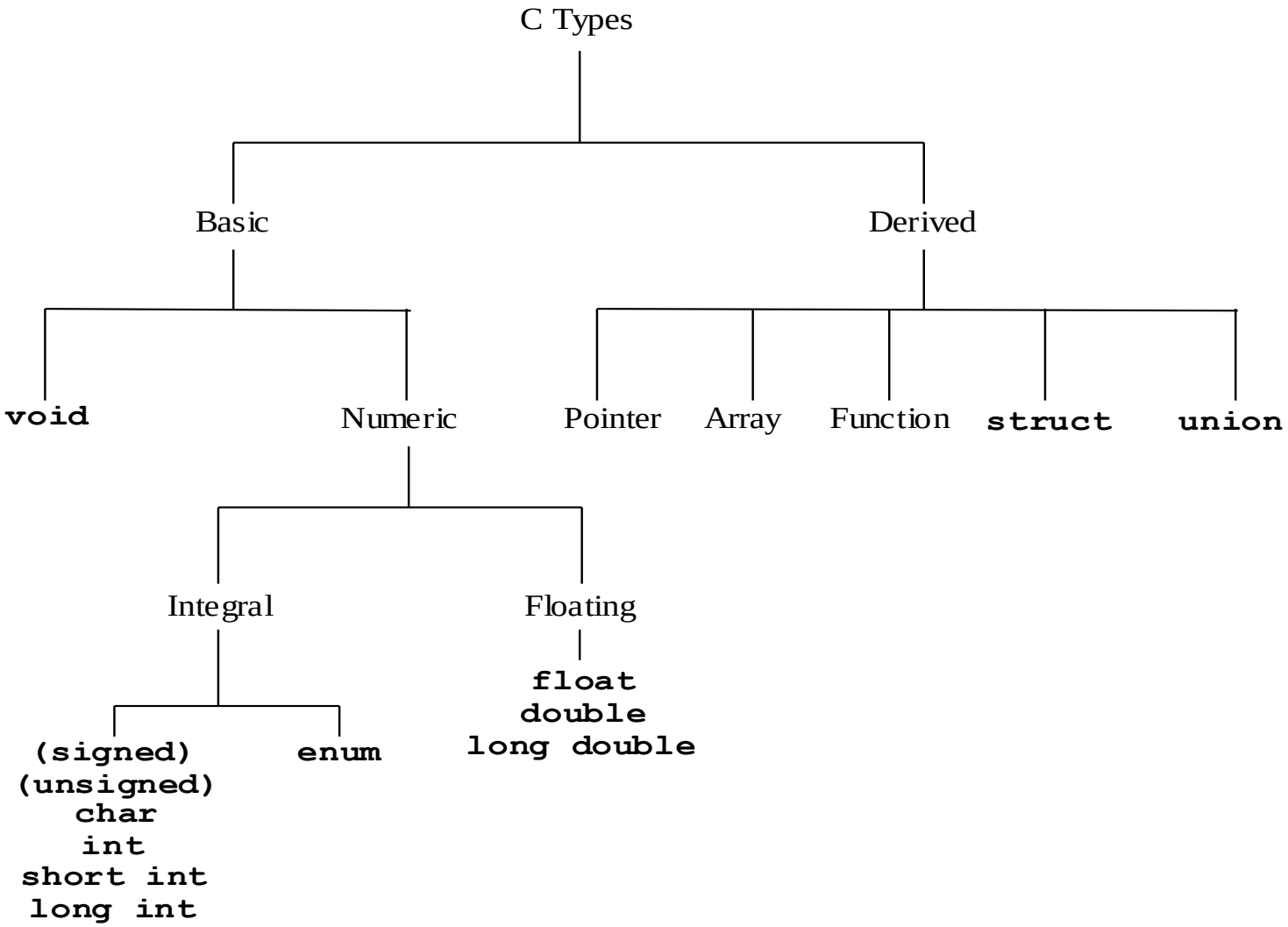
Type Errors

- Machine data carries no type information
  - 01000000010110000000000000000000 means…
    - Floating point value 3.375?
    - 32-bit integer 1,079,508,992?
    - Two 16-bit integers 16472 and 0?
    - Four ASCII characters @ X NUL NUL?
- A type error is any error that arises because an operation is attempted on a value of a data type for which this operation is undefined
  - Historical note: in Fortran and Algol, all of the types were built in. If needed a type "color," could use integers, but what does it mean to multiply two colors?

Java Types


Java Types
Primitive
Reference
boolean
Numeric
Array
class
interface
Integral
Floating point
char
byte
short
int
long
float
double

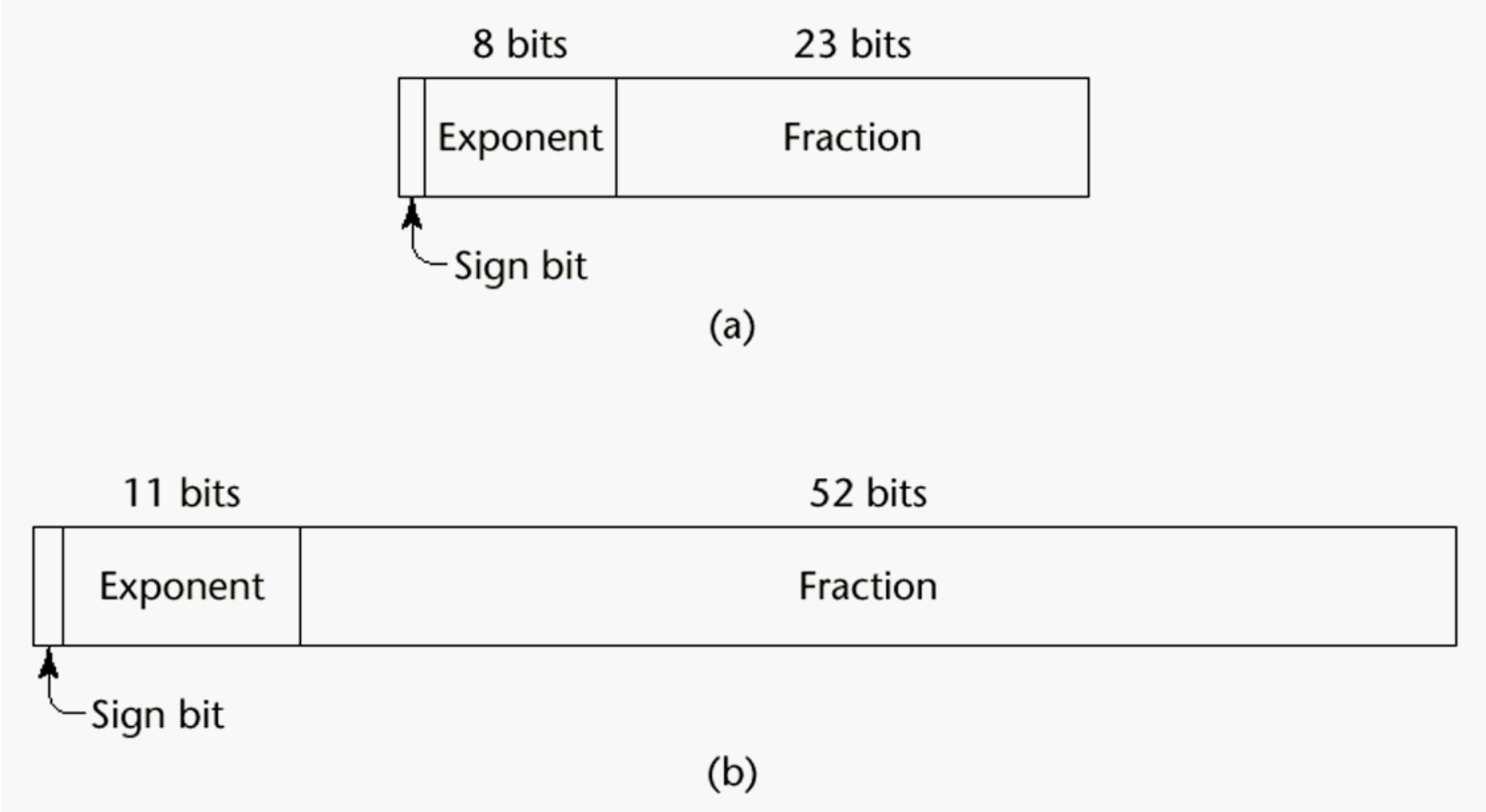
C Types


C Types
Basic
Derived
void
Numeric
Pointer
Array
Function
struct
union
Integral
Floating
(signed)
(unsigned)
char
int
short int
long int
enum
float
double
long double

Simple Data Types

- No internal structure:
  - e.g., integer, double, character, and boolean
- Often directly supported in hardware
  - machine dependency
- Most predefined types are simple types
  - Exceptions: String in Java.
- Some simple types are not predefined
  - Enumerated types
  - Subrange types

Floating Point



IEEE floating-point formats: (a) Single precision, (b) Double precision

Enumerated Types

Ordered set, whose elements are ***named*** and ***listed*** explicitly.

- Examples:

```
enum Color_Type {Red, Green, Blue};          ( C )
type Color_Type is (Red, Green, Blue);     (Ada)
datatype Color_Type = Red | Green | Blue;  (ML)
```

- Operations:

  Successor and predecessor

Ada Example

```
type Color_Type is (Red, Green, Blue);

x : Color_Type := Green;
x : Color_Type'Succ(x);
x : Color_Type'Pred(x);
put(x);          -- prints Green
```

- No assumptions about the internal representation of values
- Print the value name itself

Pascal Example

```
type
     cardsuit = (club, diamond, heart, spade);
     card = record
               suit: cardsuit;
               value: 1 .. 13;
            end;
var
     hand: array [ 1 .. 13 ] of card;
```

- `Succ(diamond) = heart; Pred(spade) = heart;`
- `club < heart;` is true.
- `for acard := club to heart do`

C Example

```
#include <stdio.h>
enum Color {Red, Green, Blue};
enum Courses {CSE1111=1, CSE3302=3, CSE3310=3, CSE5555=4};
main() {
    enum Color x = Green;
    enum Courses c = CSE3302;
    x++;
    printf("%d\n“,x);
    printf("%d\n",Blue+1);
    printf("%d\n",c);
   return 0;
}
```

- `enum` in C is simply `int`
- Can customize the values

Java Example

```
public enum Planet { MERCURY (2.4397e6), EARTH (6.37814e6);
   private final double radius; // in meters
   Planet(double radius) {this.radius = radius; }
   private double radius() { return radius; }

   public static void main(String[] args) {
      for (Planet p : Planet.values())
         System.out.printf("The radius of  %s is %f\n", p, p.radius());
  }
}
```

`java.util.Enumeration has different meaning`

```
for (Enumeration e = v.elements(); e.hasMoreElements(); )
    System.out.println(e.nextElement());
```

Evaluation of Enumeration Types

- **Efficiency** – e.g., compiler can select and use a compact efficient representation (e.g., small integers)
- **Readability** -- e.g. no need to code a color as a number
- **Maintainability** – e.g., adding a new color doesn't require updating hard-coded constants.
- **Reliability** -- e.g. compiler can check operations and ranges of value.

C Example for Maintainability

```
enum Color {White, Green, Blue, Black};
enum Color {White, Yellow, Green, Blue, Black};
main(){
    enum Color x = Black;
    int i = x;
    while (i >= White){
        if (i < Green)
            printf("this is a light color!\n");
        i--;
    }
}
```

What if no enumeration?

```
if (i < 1) printf("this is a light color!\n");
```

Has to be changed to:

```
if (i < 2) printf("this is a light color!\n");
```

Ada Example for Reliability

```
type DAY is (MON, TUE, WED, THU, FRI, SAT, SUN);
type DIRECTION is (NORTH, EAST, SOUTH, WEST);

GOAL : DIRECTION;
TODAY : DAY;
START : DAY;

TODAY := MON;
GOAL := WEST;
START := TODAY;

TODAY := WEST; -- Illegal: WEST is not a DAY value
TODAY := 5; -- Illegal: 5 is not a DAY value
TODAY := TODAY + START; -- Illegal: "+" is not defined for DAYS
```

Subrange Types

Contiguous subsets of simple types, with a ***least*** and **greatest** element.

- Example:

```
type Digit_Type is range 0..9;          ( Ada)
```

- Not available in C, C++, Java. Need to use something like:

```
byte digit;    //-128..127
...
if (digit>9 || digit <0) throw new DigitException();
```

- Defined over **ordinal types:**
  - ordered, every value has a next/previous element
    - E.g., integer, enumerations, and subrange itself

Type constructors: Defining New Types

- **Type constructors as set operations:**
  - Cartesian product
  - Union
  - Subset
  - Functions (Arrays)
- **Some type constructors do not correspond to set operations** (e.g., pointers)
- **Some set operators do not have corresponding type constructors (e.g., intersection)**

Cartesian Product

- **Ordered pairs of elements from U and V**

  $U \times V = \{(u, v) \mid u \in U \text{ and } v \in V\}$

- **Operations:**
  - **projection**

  $p_1: U \times V \rightarrow U; \quad p_2 : U \times V \rightarrow V$

  $p_1((u,v))=u; \qquad p_2((u,v))=v$

Examples

`struct` in C

```
struct IntCharReal
{
    int i;
    char c;
    double r;
}
```

int × char × double

The same type?

```
struct IntCharReal
{     int i;
      char c;
      double r;
}

struct IntCharReal
{     char c;
      int i;
      double r;
}
```

The same type?

```
struct IntCharReal
{     int i;
      char c;
      double r;
}

struct IntCharReal
{     int j;
      char ch;
      double d;
}
```

Record/Structure not Exactly Cartesian Products

- Component selector: projection by component names

```
struct IntCharReal x;
x.i;
```

- Most languages consider component names to be part of the type
- Thus the previous two types can be considered different, even though they represent the same Cartesian product

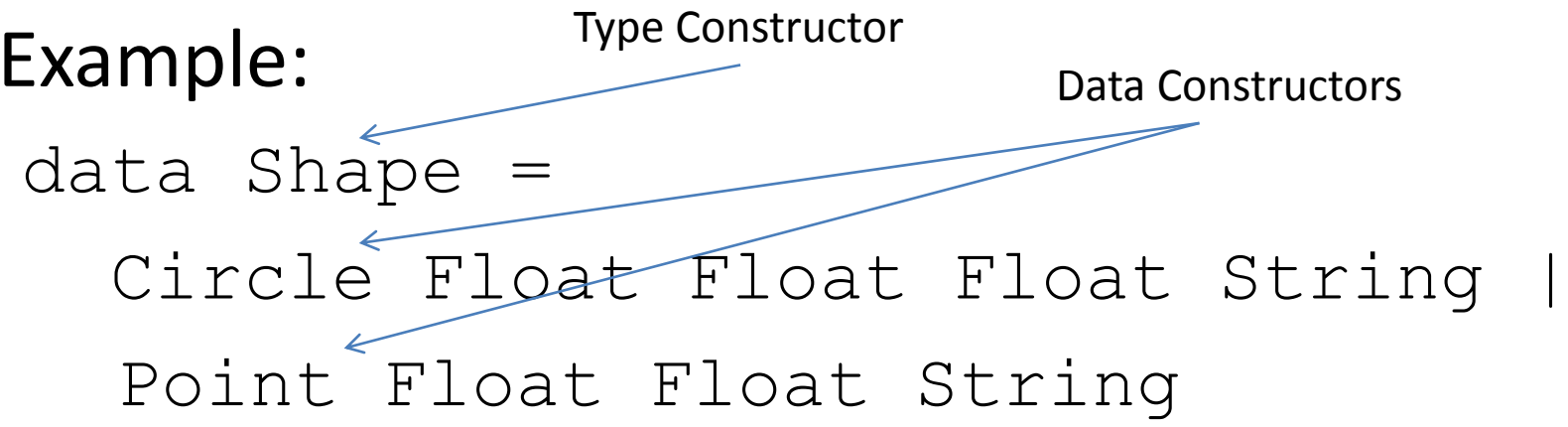
ML: Pure Cartesian Product

```
type IntCharReal = int * char * real;

(2, #"a", 3.14)
#3(2, #"a", 3.14) = 3.14
```

Haskell

- Example:



- Example uses…

```
let c = Circle 0 0 10 "c"
let p = Point 0 0 "p"
```

Haskell

- Example:

```
data Point a = Pt a a
```

- Notes:

  Single constructor → tuple type (a Cartesian product of other types)

- Above type is also polymorphic

```
Pt  2.0  3.0          :: Point Float
Pt  'a'  'b'          :: Point Char
Pt True False         :: Point Bool
Pt 1 'a'
```

Union

- $U \cup V = \{ x \mid x \in U \text{ or } x \in V \}$
  - data items with different types are stored in overlapping region, reduce memory allocation
  - Only one type of value is valid at one time
  - E.g.,

```
union IntOrReal {
      int i;
      double r;
}
```

- Different from records?

C Style Unions

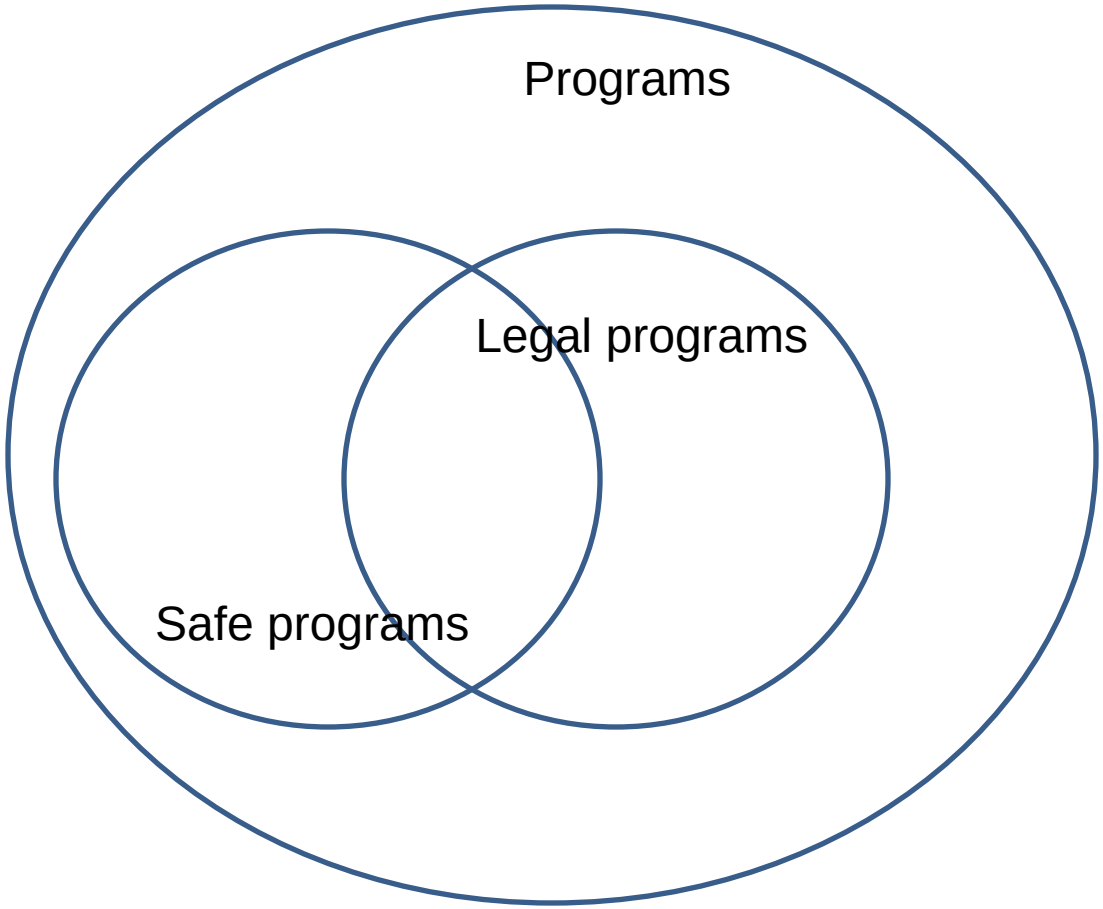
- C style unions allow the same bit pattern to be interpreted in multiple ways.
- E.g., it's common to use a union to pack/unpack a fixed length binary blob into its constituent fields.
- Useful in some systems programming contexts.
- But it's a very low level feature and was excluded in most languages

Undiscriminated Union in C

```
union IntOrReal {
        int i;
        double r;
}
union IntOrReal x;
x.i = 1;
printf("%f\n", x.r);
```

- Can be unsafe

Safe vs. Legal



Type Equivalence

- How to decide if two types are the same?
- Structural Equivalence
  - Types are sets of values
  - Two types are equivalent if they contain the same values
- Name Equivalence
  - Same type names

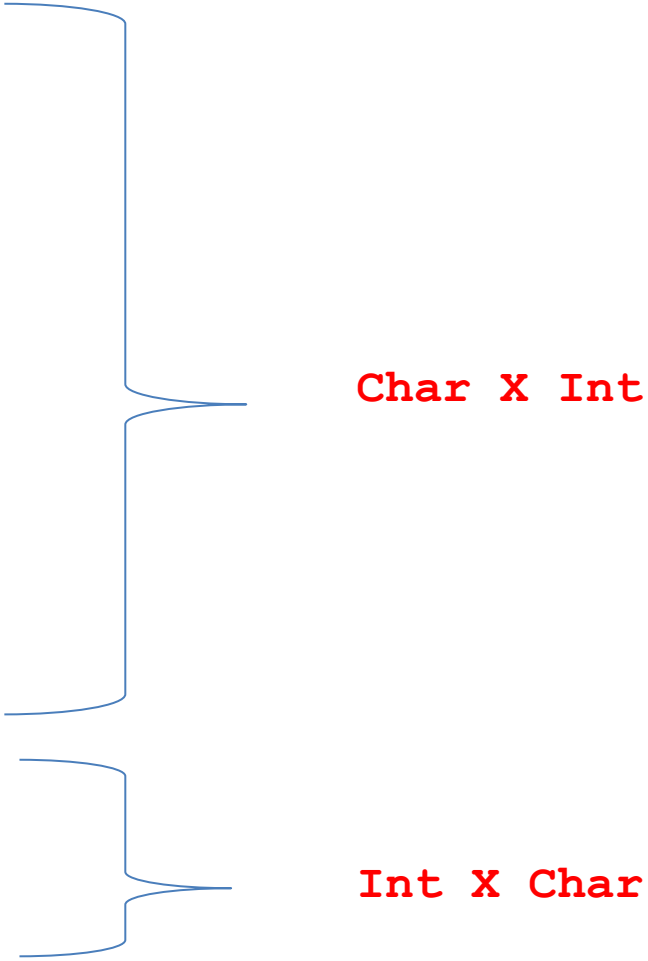
- Which one is more flexible?
  - Structural equivalence

Structural Equivalence of Type

- Two type expressions are structural equivalent if they are
  - same basic type, or
  - formed by applying the same constructor to two structurally equivalent types, or
  - after type declaration type n=T the type name n is structurally equivalent to T
- → two type expressions are structural equivalent if and only if they are identical
- Example:
  - *integer* is equivalent to *integer*
  - *pointer(char)* is equivalent to *pointer(char)*
- Modification is needed for structural equivalence: When array are passed as parameter, we may not wish to include the array bounds as part of the type

Structural Equivalence

```
struct RecA {
    char x;
    int  y;
}
struct RecB {
    char x;
    int  y;
}
struct RecC {
    char u;
    int  v;
}
struct RecD {
    int  y;
    char x;
}
```



But are they equivalent in these languages?

In C:

```
struct RecA {
    char x;   int  y;
};
struct RecB {
    char x;   int  y;
};
struct RecA a;
struct RecB b;

b = a;
```

(Error: incompatible types in assignment)

Use structural equivalence for everything except unions and structs, which use name equivalence

But are they equivalent in these languages?

In C:

```
struct RecA {
    char x;   int  y;
};
struct RecB {
    char x;   int  y;
};
struct RecA a;
struct RecB* b;

b = &a;
```

(Warning: incompatible types in assignment)

But are they equivalent in these languages?

In C:

```
struct RecA {
    char x;   int  y;
};
struct RecB {
    char x;   int  y;
};
struct RecA a;
struct RecB* b;

b=(struct RecB*)&a;
```

(OK, but does not mean they are equivalent)

But are they equivalent in these languages?

In Java:

```
class A {
    char x;   int  y;
};
class B {
    char x;   int  y;
};
```

```
A a = new B();
```

Java enforces "name equivelency" – two types T_1 and T_2 are equivalent if and only if they have identical names.

Structural Equivalence Alg.

```
boolean sequiv(s, t)
begin
        if s and t are the same basic type return true
        else if s = array (s1, s2)  and t = array(t1, t2) then
                return sequiv(s1, t1) and sequiv(s2, t2)
        else if s = s1× s2 and t = t1× t2 then
                return sequiv(s1, t1) and sequiv(s2, t2)
        else if s = pointer(s1) and t = pointer(t1) then
                return sequiv(s1, t1)
        else if s = s1 → s2 and t = t1 → t2 then
                return sequiv(s1, t1) and sequiv(s2, t2)
        else   return false
end
```

Equivalence Algorithm

If structural equivalence is applied:

```
struct RecA {
       char x;   int  y;
};
struct RecB {
       char u;   int  v;
};
struct RecA a;
struct RecB b;

b = a;
```

Replacing the names by declarations

```
typedef struct {
    char x;   int  y;
} RecB;
RecB b;

struct {
    char x;   int  y;
} c;
```

Replacing the names by declarations

```
typedef struct { char x; char y } SubRecA;
typedef struct { char x; char y } SubRecB;

struct RecA {
    int ID;  SubRecA content;
};

struct RecB {
    int ID;  SubRecB content;
};
```

Replacing the names by declarations?

```
typedef struct CharListNode* CharList;
typedef struct CharListNode2* CharList2;

struct CharListNode {
    char data;   CharList  next;
};

struct CharListNode2 {
    char data;   CharList2  next;
};
```

Cannot do that for recursive types

```
typedef struct CharListNode* CharList;
typedef struct CharListNode2* CharList2;

struct CharListNode {
    char data;  struct CharListNode*  next;
};

struct CharListNode2 {
    char data;  struct CharListNode2*  next;
};
```

There are techniques for dealing with this

Structural Equivalence

- Can be complicated when there are names, anonymous types, and recursive types

- Simpler, and more strict rules: name equivalence

Name Equivalence

```
struct RecA  { char x;   int  y;   };
typedef struct RecA RecB;
struct RecA *a;
RecB *b;
struct RecA c;
struct {  char x;   int  y;   } d;
struct  {  char x;   int  y;   } e,f;
a=&c;          ( ok )
a=&d;          (Warning: incompatible pointer type)
b=&d;          (Warning: incompatible pointer type)
a=b;           ( ok. Typedef creates alias for existing name )
e=d;           ( error: incompatible types in assignment )
```

Type Equivalence in C

- Name Equivalence: `struct, union`
- Structural Equivalence: everything else
  - `typedef` doesn't create a new type

Example

```
struct A { char x; int y; };
struct B { char x; int y; };
struct { char x; int y;};
typedef struct A C;
typedef C* P;
typedef struct A * R;
typedef int S[10];
typedef int T[5];
typedef int Age;
typedef int (*F)(int);
typedef Age (*G)(Age);
```

struct A and C
struct A and B; B and C
struct A and struct { char x; int y;};
P and R
S and T
int and Age
F and G

Type Equivalence in Java

- No `typedef`: so less complicated
- `class/interface`: new type (name equivalence, class/interface names)
- arrays: structural equivalence

Example

```
long y;
float x;
double c;
x = y/2+c;
```

- `y` long, `2` is int, so promoted to long, `y/2` long.
- `c` is dobule, `y/2` is long, so promoted to double, `y/2+c` is double.
- `x` Is float, `y/2+c` is double, what happens?
  - C?
  - Java?

Example: C

```
struct RecA {int i; double r;};
int p( struct {int i;double r;} x)
{ ... }
int q( struct RecA x)
{ ... }

struct RecA a;
int b;

b = p(a);
b = q(a);
```

Type Conversion

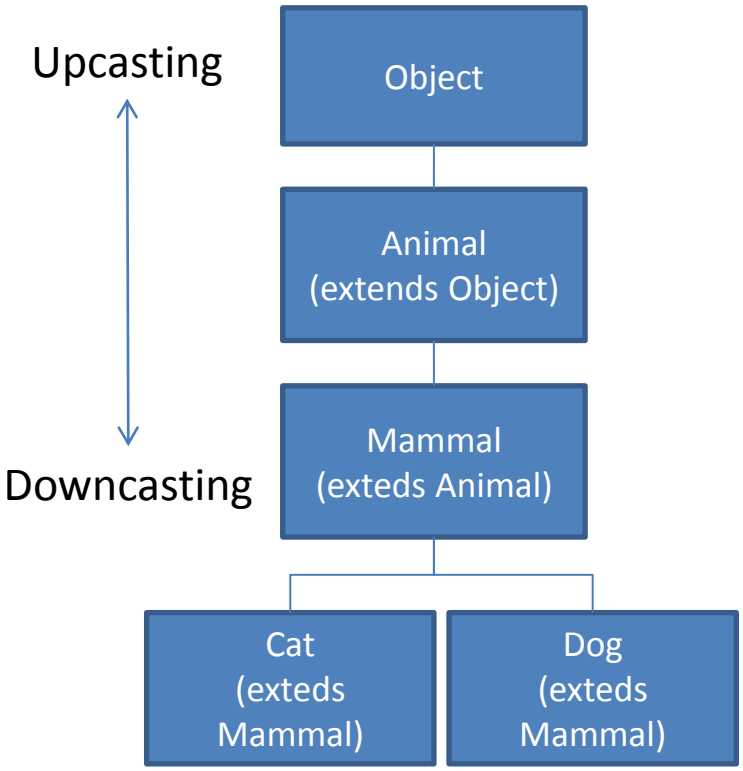
- Use code to designate conversion?
  - No: automatic/implicit conversion
  - Yes: manual/explicit conversion
- Data representation changed?
  - No, just the type
  - Yes

Example: Java

- Implicit conversion:
  - Representation change (type promotion, e.g., `int` to `double`)
  - No representation change (`upcasting`)
- Explicit conversion:
  - Representation change (`double x = 1.5; int y = (int)x`)
  - No representation change (`downcasting`)

Upcasting and Downcasting

- Upcasting and downcasting allow building of complicated programs using simple syntax, and gives great advantages, like Polymorphism or grouping different objects.
- upcasting: allowing an object of a subclass type to be treated as an object of any superclass type.
  - Upcasting is done automatically, while downcasting must be manually done by the programmer



Casting in Java

```
class A {public int x;}
class SubA extends A { public int y;}
A a1 = new A( );
A a2 = new A( );
SubA suba = new SubA( );
```

a1 = suba;	OK (upcasting)
suba = (SubA) a1;	OK (downcasting)
suba = a2;	compilation error
suba = (SubA) a2;	compiles OK, runtime error
a1.y;	compilation error
if (a1 instanceof SubA) { ((SubA) a1).y; }	OK

Type System

- ***Type Constructors***:
  - Build new data types upon simple data types

- ***Type Checking***: The translator checks if data types are used correctly.
  - ***Type Inference***: Infer the type of an expression, whose data type is not given explicitly.

    e.g., x/y
  - ***Type Equivalence***: Compare two types, decide if they are the same.

    e.g., x/y and z
  - ***Type Compatibility:*** Can we use a value of type A in a place that expects type B?

  Nontrivial with user-defined types and anonymous types

Type Checking vs. Type Inference

- Standard type checking

```
int f(int x) { return x+1; };
int g(int y) { return f(y+1)*2; };
```

  - Look at the body of each function and use declared types of identifiers to check agreement

- Type inference

```
int f(int x) { return x+1; };
int g(int y) { return f(y+1)*2; };
```

  - Look at the code without type information and figure out what types could have been declared

ML is designed to make type inference tractable

Motivation

- Types and type checking
  - Type systems have improved steadily since Algol 60
  - Important for modularity, compilation, reliability
- Type inference
  - Widely regarded as important language innovation
  - ML type inference is an illustrative example of a flow-insensitive static analysis algorithm

Type Inference Summary

- Type of expression computed, not declared
  - Does not require type declarations for variables
  - Find most general type by solving constraints
  - Leads to polymorphism
- Static type checking without type specifications
  - Idea can be applied to other program properties
- Sometimes provides better error detection than type checking
  - Type may indicate a programming error even if there is no type error

Costs of Type Inference

- More difficult to identify program line that causes error
- ML requires different syntax for values of different types
  - integer: 3, real: 3.0
- Complications with assignment took years to work out

Param. Polymorphism: ML vs. C++

- ML polymorphic function
  - Declaration has no type information
  - Type inference: type expression with variables, then substitute for variables as needed
- C++ function template
  - Declaration gives type of function argument, result
  - Place inside template to define type variables
  - Function application: type checker does instantiation

ML also has module system with explicit type parameters

Example: Swap Two Values

- ML

```
fun swap(x,y) =
        let val z = !x in x := !y; y := z end;
val swap = fn : 'a ref * 'a ref -> unit
```

- C++

```
template <typename T>
void swap(T& x, T& y){
    T tmp = x;  x=y;  y=tmp;
}
```

Declarations look similar, but compiled very differently

Implementation

- ML
  - Swap is compiled into one function
  - Typechecker determines how function can be used
- C++
  - Swap is compiled into linkable format
  - Linker duplicates code for each type of use
- Why the difference?
  - ML reference cell is passed by pointer, local x is a pointer to value on heap
  - C++ arguments passed by reference (pointer), but local x is on stack, size depends on type

Another Example

- C++ polymorphic sort function

```
template <typename T>
void sort( int count, T * A[count] ) {
    for (int i=0; i<count-1; i++)
        for (int j=i+1; j<count-1; j++)
            if (A[j] < A[i]) swap(A[i],A[j]);
}
```

- What parts of implementation depend on type?

  Indexing into array

  Meaning and implementation of <

Summary

- Types are important in modern languages
  - Organize and document the program, prevent errors, provide important information to compiler
- Type inference
  - Determine best type for an expression, based on known information about symbols in the expression
- Polymorphism
  - Single algorithm (function) can have many types
- Overloading
  - Symbol with multiple meanings, resolved when program is compiled