What is a Type?

- A set of values

What is a Type?

int

- A set of values
  - Together with a set of operations on these values that possess certain properties

Topics

- Data types in modern languages
  - simple and compound types
- Type declaration
- Type inference and type checking
- Type equivalence, compatibility, conversion and coercion
- Strongly/Weakly/Un-typed languages
- Static Vs Dynamic type checking

Simple Types

Built-in   User-defined

- Predefined
  - int, float, double, etc in C
- All other types are constructed, starting from predefined (aka primitive) types
  - Enumerated:
    - enum colors {red, green, blue} in C
    - type colors = Red|Green|Blue in OCAML

Algebraic data types

Detour: Evolution of Programming Languages

Imperative (Assignment-based)

FORTRAN (50's)

PL 1

ALGOL

PASCAL

C

OOL

SIMULA CSP

SmallTalk

LISP (50s)

Garbage collection

Scheme

Java

Python

C++

templates

lambda

Go

Rust

f(3)

Declarative

Functional

Standard ML

parametrized

first class datatypes

- type inference

"Pure Functional"

Haskell

Type classes

traits

Logic

Prolog

Automatic backtracking

$\exists x \; P(x)$

$x = \ldots$

Compound Types

- Types constructed from other types using type constructors
  - Cartesian product (*)
  - Function types (→)
  - Union types (∪)
  - Arrays
  - Pointers
  - Recursive types

predefined type constructors

user-defined

Cartesian Product

tuples

- Let I represent the integer type and R represent real type.
- The cross product $I \times R$ is defined in the usual manner of product of sets, i.e.,

$$I \times R = \{(i, r) | i \in I, r \in R\}$$

- Cartesian product operator is non-associative.

$A \times B \times C$

3-tuple

(a, b, c)

$(A \times B) \times C$

$((a, b), c)$

$A \times (B \times C)$

Labeled Product types

- In Cartesian products, components of tuples don't have names.
  - Instead, they are identified by numbers.
- In labeled products each component of a tuple is given a name.
- Labeled products are also called records (a language-neutral term)

Labeled Product types (Continued)

$I \times F \times ptr(c)$

$(3, 2.5, \ldots)[1]$

- `struct` is a term that is specific to C and C++

  `struct t {int a;float b;char *c;}; in C`

  int * float * ptr(char)

Function Types

- $T_1 \rightarrow T_2$ is a function type
  - Type of a function that takes one argument of type T_1 and returns type T_2

$int * float \rightarrow int$

- OCAML supports functions as first class values.
  - They can be created and manipulated by other functions.

int f(int a, float b)

$I \times F \rightarrow I$

- In imperative languages such as C, we can pass pointers to functions, but this does not offer the same level of flexibility.
  - E.g., no way for a C-function to dynamically create and return a pointer to a function;
  - rather, it can return a pointer to an EXISTING function
- Recent versions of C++ (as well Python, JavaScript and recent Java versions) support dynamically created functions (aka lambda abstractions)
  - See Functional Programming for Imperative Programmers for a discussion of functional programming features in C++.

Union types

- Union types correspond to set unions, just like product types corresponded to Cartesian products.
  - -> operator is right-associative, so we read the type as float -> (float -> float).
- Unions can be tagged or untagged. C/C++ support only untagged unions:

```
union v {
  int ival;
  float fval;
  char cval;
};
```

$I \cup F \cup C$

Stmt → Simple Stmt ;
| Compound Stmt
| error ;

Tagged Unions

- In untagged unions, there is no way to ensure that the component of the right type is always accessed.
  - E.g., an integer value may be stored in the above union, but due to a programming error, the fval field may be accessed at a later time.
  - fval doesn't contain a valid value now, so you get some garbage.
- With tagged unions, the compiler can perform checks at runtime to ensure that the right components are accessed.
- Tagged unions are NOT supported in C/C++.

Tagged Unions (Continued)

- Pascal supports tagged unions using VARIANT RECORDs

```
RECORD
  CASE b:  BOOLEAN OF
    TRUE: i:  INTEGER; |
    FALSE: r:  REAL END
  END
END
```

- Tagged union is also called a discriminated union

x.i = 10

= x.r

OCAML

→ Scala

type x =

INT of int |

FLOAT of float;

INT(10)

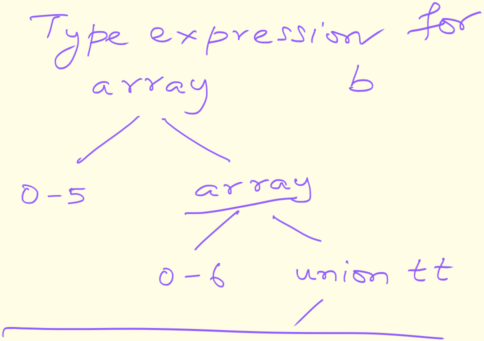
FLOAT(5.0)

algebraic

datatype

Array types

- Array construction is denoted by
  - array(<range>, <elementType>).
- C-declaration
  - `int a[5];`
  - defines a variable a of type array(0-4, int)
- A declaration
  - `union tt b[6][7];`
  - declares a variable b of type array(0-~~4~~ 5, array(0-6, union tt))
- We may not consider range as part of type



Pointer types

- A pointer type will be denoted using the syntax
  - ptr(<elementType>)
  - where <elementType> denote the types of the object pointed by a pointer type.
- The C-declaration
  - `char *s;`
  - defines a variable s of type ptr(char)
- A declaration
  - `int (*f)(int s, float v)`
  - defines a (function) pointer of type ptr(int*float $\rightarrow$ int)

int *f (int s)

f is a fn that takes int param & returns pointer to integer

(*f) is an integer

f is a ptr to a fn that returns int

Recursive types

- Recursive type: a type defined in terms of itself.
- Example in C:

```
struct IntList {
  int hd;
  intList tl;
};
```

- Does not work:
  - This definition corresponds to an infinite list.
  - There is no end, because there is no way to capture the case when the tail has the value "nil"

Recursive types (Continued)

- Need to express that tail can be nil or be a list.
- Try: variant records:

```
TYPE charlist = RECORD
   CASE IsEmpty:  BOOLEAN OF
     TRUE: /* empty list */ |
     FALSE:
       data:  CHAR;
       next:  charlist;
   END
END
```

- Still problematic: Cannot predict amount of storage needed.

Recursive types (Continued)

- Solution in typical imperative languages:
- Use pointer types to implement recursive type:

```
struct IntList {
  int hd;
  IntList *tl;
};
```

- Now, tl can be:
  - a NULL pointer (i.e., nil or empty list)
  - or point to a nonempty list value
- Now, IntList structure occupies only a fixed amount of storage

Recursive types In OCAML

- Direct definition of recursive types is supported in OCAML using type declarations.
- Use pointer types to implement recursive type:

```
# type intBtree =
    LEAF of int
  | NODE of int * intBtree * intBtree;;
type intBtree = LEAF of int | NODE of int * intBtree * intBtree
```

→ INTLEAF of int
→ FLOATLEAF of float
→ BINNODE of int * int BTree * int BTree
→ TERNODE of int * int * int BTree * int BTree * int BTree

- We are defining a binary tree type inductively:
  - Base case: a binary tree with one node, called a LEAF
  - Induction case: construct a binary tree by constructing a new node that sores an integer value, and has two other binary trees as children

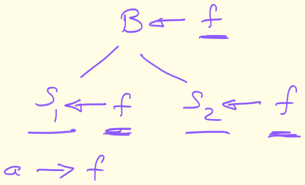
Polymorphism

- Ability of a function to take arguments of multiple types.
- The primary use of polymorphism is code reuse.
- Functions that call polymorphic functions can use the same piece of code to operate on different types of data.

Overloading (adhoc polymorphism)

- Same function NAME used to represent different functions   + *
  - implementations may be different
  - arguments may have different types   a.f()
- Example:
  - operator '+' is overloaded in most languages so that they can be used to add integers or floats.
  - But implementation of integer addition differs from float addition.
  - Arguments for integer addition or ints, for float addition, they are floats.
- Any function name can be overloaded in C++, but not in C.
- All virtual functions are in fact overloaded functions.

Polymorphism & Overloading



- Parametric polymorphism:
  - same function works for arguments of different types
  - same code is reused for arguments of different types.
  - allows reuse of "client" code (i.e., code that calls a polymorphic function) as well

implementation of polymorphic fn.

- Overloading:
  - due to differences in implementation of overloaded functions, there is no code reuse in their implementation
  - but client code is reused

↑ implementation is not shared

Parametric polymorphism in C++

Type Traits < >

- Example:

```
template <class C>
C min(const C* a, int size, C minval) {
  for (int i = 0; i < size; i++)
    if (a[i] < minval)
      minval = a[i];
  return minval;
}
```

implementation is reusable for all classes C (or types)

- Note: same code used for arrays of any type.
  - The only requirement is that the type support the "<" and "=" operations
- The above function is parameterized wrt class C
  - Hence the term "parametric polymorphism".
- Unlike C++, C does not support templates.

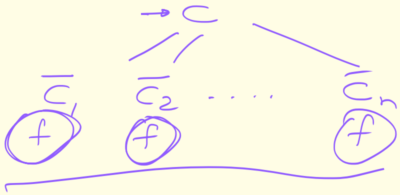
Code reuse with Parametric Polymorphism

- With parametric polymorphism, same function body reused with different types.
- Basic property:
  - does not need to "look below" a certain level
  - E.g., min function above did not need to look inside each array element.
  - Similarly, one can think of length and append functions that operate on linked lists of all types, without looking at element type.

Code reuse with overloading

- No reuse of the overloaded function
  - there is a different function body corresponding to each argument type.
- But client code that calls a overloaded function can be reused.
- Example
  - Let C be a class, with subclasses C1,...,Cn.
  - Let f be a virtual method of class C
  - We can now write client code that can apply the function f uniformly to elements of an array, each of which is a pointer to an object of type C1,...,Cn.

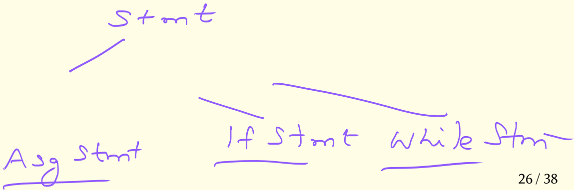
Example



- Example:

```
void g(int size, C *a[]) {
  for (int i = 0; i < size; i++)
    a[i]->f(...);
}
```

- Now, the body of function g (which is a client of the function f) can be reused for arrays that contain objects of type C_1 or C_2 or ... or C_n,or even a mixture of these types.



Type Equivalence

- Structural equivalence: two types are equivalent if they are defined by identical type expressions.
  - array ranges usually not considered as part of the type
  - record labels are considered part of the type.
- Name equivalence: two types are equal if they have the same name.
- Declaration equivalence: two types are equivalent if their declarations lead back to the same original type expression by a series of redeclarations.

Type Equivalence (contd.)

VAR v5 : t1

- Structural equivalence is the least restrictive
- Name equivalence is the most restrictive.
- Declaration equivalence is in between
- TYPE t1 = ARRAY [1..10] of INTEGER; VAR v1: ARRAY [1..10] OF INTEGER;
- TYPE t2 = t1; VAR v3,v4: t1; VAR v2: ARRAY [1..10] OF INTEGER;

	Structurally equivalent?	Declaration equivalent?	Name equivalent?
t1,t2	Yes	Yes	No
v1,v2	Yes	No	No
v3,v4	Yes	Yes	Yes

Declaration equivalence

- In Pascal, Modula use decl equivalence
- In C
  - Decl equiv used for structs and unions
  - Structual equivalence for other types.

```
struct { int a ; float b ;} x ;
struct { int a; float b; }y;
```

- x and y are structure equivalent but not declaration equivalent.

```
typedef int* intp ;
typedef int** intpp ;
intpp v1 ;
intp *v2 ;
```

- v1 and v2 are structure equivalent.

typedef struct {int a; float b;} S;

S x;

S y;

x = y

typedef S T;

struct S { int a; float b; };

struct S

S x;

T y;

x = y;

Type Compatibility

- Weaker notion than type equivalence
- Notion of compatibility differs across operators
- Example: assignment operator:
  - v = expr is OK if <expr> is type-compatible with v.
  - If the type of expr is a Subtype of the type of v, then there is compatibility.
- Other examples:
  - In most languages, assigning integer value to a float variable is permitted, since integer is a subtype of float.
  - In OO-languages such as Java, an object of a derived type can be assigned to an object of the base type.

int b;
float a;
a = b;

Base c;
Test d;
c = d;

Type Compatibility (Continued)

- Procedure parameter passing uses the same notion of compatibility as assignment
  - Note: procedure call is a 2-step process
    - assignment of actual parameter expressions to the formal parameters of the procedure
    - execution of the procedure body
- Formal parameters are the parameter names that appear in the function declaration.
- Actual parameters are the expressions that appear at the point of function call.

Type Checking

- Static (compile time)
  - Benefits
    - no run-time overhead
    - programs safer/more robust
- Dynamic (run-time)
  - Disadvantages
    - runtime overhead for maintaining type info at runtime
    - performing type checks at runtime
  - Benefits
    - more flexible/more expressive

eval

Typescript

Hack

Examples of Static and Dynamic Type Checking

RTTI

- C++ allows

  Upcasts: casting of subclass to superclass (always type-safe)

  Downcasts: superclass to subclass (not necessarily type-safe) – but no way to check since C++ is statically typed.

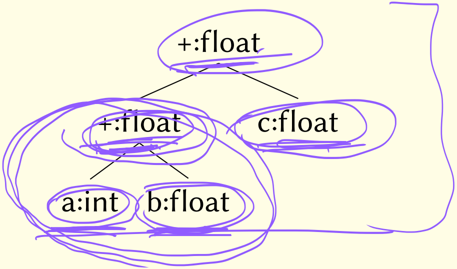
  - Actually, runtime checking of downcasts is supported in C++ but is typically not used due to runtime overhead

- Java uses combination of static and dynamic type-checking to catch unsafe casts (and array accesses) at runtime.

Object

Type Checking (Continued)

- Type checking relies on type compatibility and type inference rules.
- Type inference rules are used to infer types of expressions. e.g., type of (a+b)+c is inferred from type of a, b and c and the inference rule for operator '+'.
- Type inference rules typically operate on a bottom-up fashion.
- Example: (a+b)+c



Type Checking (Continued)

- In OCAML, type inference rules capture bottom-up *and* top-down flow of type info.
- Example of Top-down: let f x y:float*int = $\boxed{\text{(x, y)}}$

float * int

auto x = expr

$$
\begin{tikzcd}
 & \text{f:float*int} \arrow[dl] \arrow[dr] & \\
\text{x:float} & & \text{y:int}
\end{tikzcd}
$$

float * int

let f x y z =
x+y+z

- Here types of x and y inferred from return type of f.
- Note: Most of the time OCAML programs don't require type declaration.
  - But it really helps to include them: programs are more readable, and most important, you get far fewer hard-to-interpret type error messages.

Strong Vs Weak Typing

- Strongly typed language: such languages will execute without producing uncaught type errors at runtime.
  - no invalid memory access
    - no seg fault
    - array index out of range
    - access of null pointer
  - No invalid type casts

f = i

i = f;

memcpy

union {
char ...;
int i;
float f;
} x;

x.f = 1.0 .... y = x.i

- Weakly typed: uncaught type errors can lead to undefined behavior at runtime
- In practice, these terms used in a relative sense
- Strong typing does not imply static typing

Type Conversion

- Explicit: Functions are used to perform conversion.
  - example: strtol, atoi, itoa in C; float and int etc.
- Implicit conversion (coercion)
  - example:
    - If a is float and b is int then type of a+b is float
    - Before doing the addition, b must be converted to a float value. This conversion is done automatically.
- Casting (as in C)
- Invisible "conversion:" in untagged unions

i = (int) f;

f = i;

char * c;

int * x;

c = (char *) x;

c = x;

Data Types Summary

- Simple/built-in types
- Compound types (and their type expressions)
  - Product, union, recursive, array, pointer
- Parametric Vs subtype polymorphism, Code reuse
- Polymorphism in OCAML, C++,
- Type equivalence
  - Name, structure and declaration equivalence
- Type compatibility
- Type inference, type-checking, type-coercion
- Strong Vs Weak, Static Vs Dynamic typing