CSE 504

Types in Programming Languages

What is a type?

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

Topics to be covered

- 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

- 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

Compound Types

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

Cartesian Product

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

$$I \text{ x } R = \{ (i, r) \mid i \text{ in } I,\ r \text{ in } R \}$$

- Note that cartesian product operator is neither commutative nor associative.

Product Types (Contd.)

- Products types correspond to "tuples" in SML.
- They are not supported in typical imperative languages, except with labels.
- Type on previous slide denoted `int*real` in SML.

```
- val v = (2,3.0);
val v = (2,3.0) : int * real
- type mytype = int * real;
type mytype = int * real
```


Labeled Product types

- In cartesian products, components of a tupes 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)
- `struct` is a term that is specific to C and C++

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

Function Types

- T1 → T2 is a function type
  - Type of a function that takes one argument of type T1 and returns type T2
- Standard ML supports functions as ***first class values***.
  - They can be created and manipulated by other functions.
- In imperative languages such as C/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

Union types

- Union types correspond to set unions, just like product types corresponded to cartesian products.
- Unions can be tagged (aka *discriminated)* or untagged *(undiscriminated).* C/C++ support only untagged unions:

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


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++.
- Pascal supports tagged unions using VARIANT RECORDs

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


Array types

- Array construction is denoted by
  - **array(<range>, <elememtType>).**
- 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, 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 → int)

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
- Example:
  - operator '+' is overloaded in most languages so that they can be used to add integers or reals.
  - 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
- Overloading:
  - due to differences in implementation of overloaded functions, there is no code reuse in their implementation
  - but client code is reused

Parametric polymorphism in C++

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

- 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".

Code reuse with Parametric Polymorphism

- With parametric ploymorphism, same function body reused with different datatypes.
- 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

```
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 C1 or C2 or ... or Cn,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.)

- 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/C++
  - Decl equiv used for structs, unions and classes
  - 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.

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 real variable is permitted, since integer is a subtype of real.
  - In OO-languages such as Java, an object of a derived type can be assigned to an object of the base type.

Type Compatibility (Contd.)

- 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

Examples of Static and Dynamic Type Checking

- C++ allows
  - casting of subclass to superclass (always type-safe)
  - superclass to subclass (not necessarily type-safe) – but no way to check since C++ is statically typed.
- Java uses combination of static and dynamic type-checking to catch unsafe casts (and array accesses) at runtime.

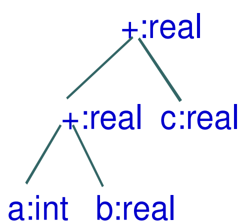
Strong Vs Weak Typing

- 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
- 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 Checking (Contd.)

- 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

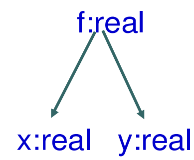


Type Checking (Contd.)

- In SML, type inference rules capture bottom-up as well as top-down flow of type info.

Example of Top-down:

fun f x y = (x+y): real



- Here types of x and y inferred from return type of f (real).

Note: Most of the time SML programs don't require type declaration.

Type Conversion

- **Explicit:** Functions are used to perform conversion.

  example: strtol, atoi, itoa in C; real and int etc.
- **Implicit** conversion (coercion)

  example:
  - If a is real and b is int then type of a+b is real
  - Before doing the addition, b must be converted to a real value. This conversion is done automatically.
- **Casting** (as in C)
- **Invisible "conversion:"** in untagged unions

Data Types Summary

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