CSE3322, 2005: Programming Language Concepts & Issues II
Comp. Sci. and Software Eng.
Monash U., .au

This is the second of 5 lectures looking at programming language concepts. In the first lecture of CSE3322 we discussed the history of programming languages and the reasons for their development.

In this and the next few lectures we will examine the main underlying issues and concepts.

In the last lecture we will examine the main programming language paradigms.

In this lecture we will study

- variables

The material is largely based on Watt but also draws upon Mitchell and Pratt & Zelkowitz.

Variables

Variables are at the core of programming languages. They are usually understood in terms of storage.

- All data in a computer is stored as a sequence of bits grouped into bytes or words.
- A data object is a collection of bytes which represents one logical data value.
- A data object that is named or defined by the programmer is called a variable.
- A variable contains a data value which may be read and written.

The most familiar kind of variable is a program variable, e.g.,

```
x = y+1
```

Constants are also "variables" in this sense: they just cannot have their value changed.

And files and databases are also variables in this sense.

Updatable variables are at the core of state-based imperative and OO languages such as C or C++.

Logic and functional programming languages provide logical variables. These are not updatable, i.e their values may not be changed.

Overview

Understanding variables requires understanding:

- **lifetime**
- **binding mechanisms**
- **scope**

Lifetime

Every variable is created (allocated) at some point during program execution and may be deleted (de-allocated) at some later time when it is no longer needed.

The period between creation and deletion is called the variable's lifetime.

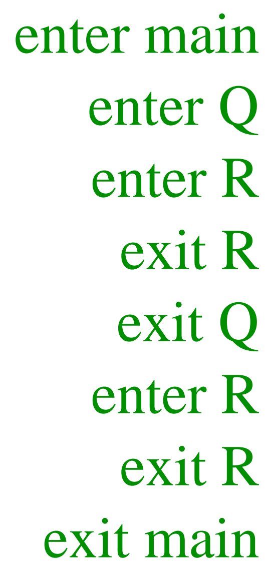
A local variable is defined within a program block and is only usable within that block. It is created on entry to the block and deleted on exit from the block. It does not retain its value, or even exist, between different activations of the block.

A global variable is a local variable defined in the outermost block of the program. Thus, it has the same lifetime as the program.

Local variables are usually implemented using a stack.

Lifetime (Cont.)

```
int x; /* global variable */

void R(void)
{ int z; /* local variable */
  ...
}

void Q(void)
{ int y; /* local variable */
  R();
}

main ()
{ Q();
  R();
}
```



Heap Variables

Heap variables can be created or deleted at any time and they continue to live when the block in which they are created has been exited.

The programmer (or the compiler) uses an explicit command to create them (eg `malloc` or `new`) and may need to explicitly delete them (eg `free`).

Usually, they are explicitly manipulated using pointers but may be implicitly manipulated using references.

Most imperative languages support recursive types, such as lists or trees, by pointers to heap variables.
– It is the programmer's job to do all of the work!

Question: **Does ML provide heap variables?**

Dangling References

In imperative languages pointers to heap variables are usually first class values, while pointers to local or global variables are often not.

In Pascal for instance, you cannot store a pointer to a local variable.

The reason is that after you exit a block, local variables in that block are deleted, thus a pointer to such a variable would be pointing at nothing. Such a pointer is said to be a 'dangling reference'.

Setting a pointer to refer to a heap variable cannot cause this type of error since, by definition, it is alive for as long as something points to it.

Unfortunately, explicit deallocation can allow the programmer to deallocate the object while it is still alive.

Dangling Reference Example

```
int *p(void)
{
  int i=1;
  return &i;        (* bad idea *)
}

main()
{
  int *q, *r;
  q = p();
  *q = 4;
  r = p();
  printf("%d", *q);
}
```

Garbage Collection

Because of the difficulty and error-proneness of explicitly managing allocation and deallocation of heap storage, starting with Lisp, many languages, such as Haskell, Java, and ML, provide automatic memory management in which the language automatically allocates and deallocates memory locations.

More specifically, at a given time in the execution of a program P, a memory location m is garbage if no further execution of P from this time can access location m.

Garbage collection is the process of finding memory locations that are garbage, and deallocating and reclaiming them.

Mark-Scan Garbage Collection

Many algorithms have been developed for garbage collection. A simple one is Mark-Scan.

It assumes that each data-object has a spare tag that can be set to 0 or 1. (This need not be in the object.)

It also assumes that we can tell which sequences of bits are pointers, e.g. from compile-time information.

Mark-Scan Garbage Collection

1. Set all tag bits to 0.
2. Start from every pointer location used in the program. Follow all links (pointers), changing the tag bit of each location visited to 1.
3. Return all memory locations with tag still equal to 0 to the free-list.

Note that g.c. takes time proportional to the size of allocated memory, here.

Advantages and Disadvantages

The main advantage of automatic garbage collection is that memory management errors never occur. It also simplifies code.

The main disadvantage is that it has some space and time overhead (Mitchell suggests 5%). Simple g.c. methods can make a program "pause" – not good in real-time applications.

And in general, garbage collection requires all pointers to be identifiable at run-time.

Question: **Why do you think C and C++ do not provide garbage collection while Java does?**

Persistent Variables

Files are composite variables (made up of subcomponents):
– a serial file is a sequence of components and
– a direct file is an array of components.

However, most programming languages treat files very differently to other data structures manipulated by the program.

Conceptually, the distinguishing feature of a file is that it is 'persistent', that is, their lifetime is longer than that of any particular program.

We note that persistent variables reside in a file store which has the same abstract properties as does the ordinary variable store.

In Pascal files may be passed as parameters to the main procedure program. In most languages persistent data types are completely disjoint from the usual transient data types.

Simplicity and orthogonality suggests that all of the types in the programming language should be allowed for both persistent and transient variables.

This would mean that the language would not need special commands for input/output and that format conversion when reading or writing from a file would not be needed.

Persistent Variables (Cont.)

For instance, compare

```
main()
 { FILE *inp;
   int ch;
   inp = fopen("plasmodiumFalciparum", "r");
   while((ch = fgetc(inp)) != EOF)
    { ... }
   ...
 }
```

with the Persistent C program

```
persistent char * plasmodiumFalciparum;

main()
 { int ch;
   for(i=0; ... )
    { int ch = plasmodiumFalciparum[i]; ... }
   ...
 }
```

Persistence is a relatively recent idea in programming language design. E.g. Napier 88.

Bindings

A binding “assigns” an entity (i.e., a function, constant, variable, etc.) to an identifier.

A value which may be bound to an identifier is said to be bindable or denotable.
In ML virtually all values are bindable.

An environment is a set of bindings. Each expression and command is interpreted in the context of a particular environment.

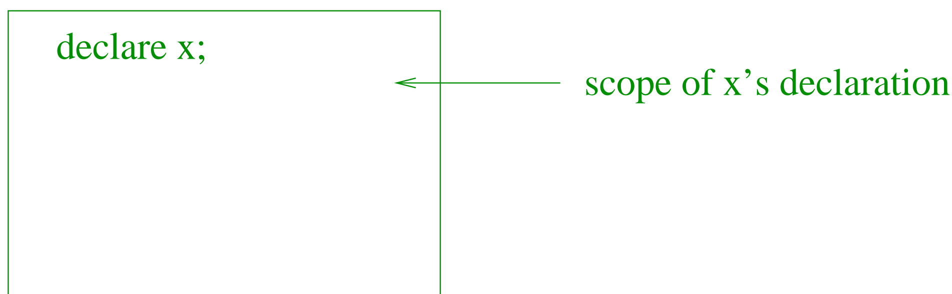
```
const double e = 2.7182;
const char msg[]= "Warning!";

main()
{
  int e = 1;      (* ! *)
  int n;
  char s[];

  n = e;
  s = msg;
}
```

Scope

The scope of an identifier is that part of the program text over which the declaration is effective. A block is any program phrase that delimits the scope of declared identifiers.

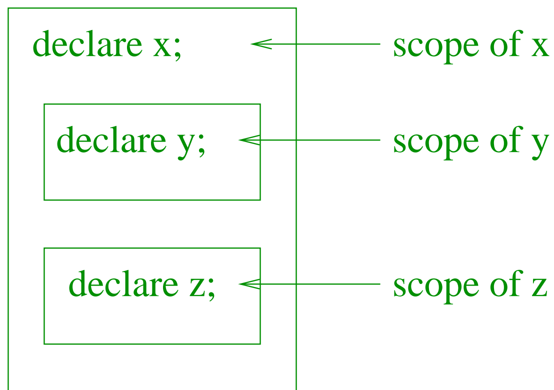
Languages may have a variety of block structures.

The simplest is a monolithic block structure in which the entire program is a single block.



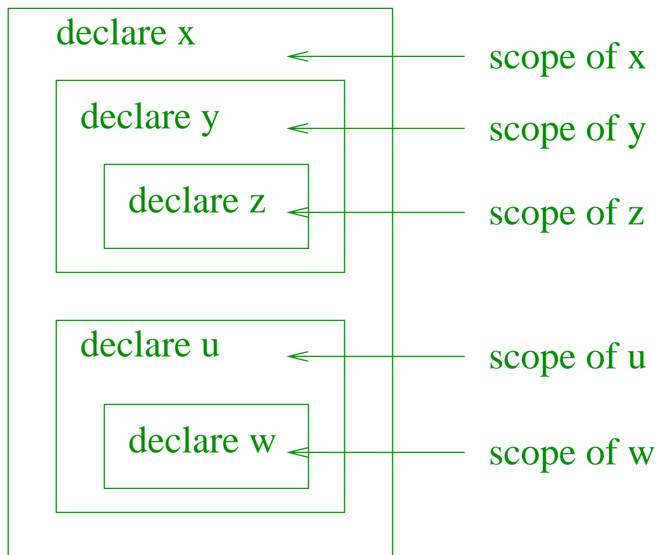
Earlier versions of COBOL were like this.

Some languages have a flat block structure in which each subroutine or function in the program forms a single block. Subroutine and function names are global. A variable can be declared within a subroutine in which case it is local to that subroutine or else it may be declared in the outermost block, in which case it is global and all subroutines may refer to it.



Early Fortran was like this.

Other languages have a nested block structure in which blocks may be arbitrarily nested inside each other. Algol, Haskell,



ML, Pascal are like this. In ML `local ... in ... end` is used to nest declarations and `let ... in ... end` is used to nest expressions.

C is a mixture of the flat and (part) nested block structures since you cannot nest subroutine definitions (which is important) but you can nest variable declarations:

```
p(int i) {
  while (i-- > 0) {
    real i=0.0;
  ...  }
}
```

Notice that where multiple bindings for the same identifier are within scope, the innermost binding is used. That is binding an identifier I within a block usually hides any outer block bindings to I.

Cascal

In this part of the unit we will make use of an imaginary language Cascal to illustrate different design choices.

As its name suggests Cascal syntax is a cross between C and Pascal.

We are free to decide on the semantics, i.e. what the language means.

Dynamic v. Static Binding

Consider the Cascal program: what does it write?

```
int s := 2;

int scaled(d:int)
 {
 return d*s;     (* which s? *)
 }

void A(void)
 {
 int s := 3;
 int h := 4;
 writeln( scaled(h));
 }

void B(void)
 {
 int h := 4;
 writeln( scaled(h));
 }

void main(void)
{
 A(); B();
}
```

Dynamic v. Static Binding (Cont.)

The result of calling function A depends on how we interpret the occurrence of `s` in the body of `scaled`.

The most common interpretation is called 'static binding'. In this case the function body is evaluated in the environment of the function definition.

The alternative interpretation is called 'dynamic binding'. In this case the function body is evaluated in the environment of the function call.

Dynamic binding does not mix-well with static type checking, since you cannot know the type of an identifier until runtime!

Early versions of Lisp and SmallTalk have dynamic binding and have dynamic type checking. TeX also has dynamic binding.

Most other languages, e.g. C, Haskell and ML, as well as Scheme and some later versions of Lisp have static binding. We will usually assume static binding in our examples.

Even in languages with static binding, choosing which exception handler to use when an exception is thrown is usually dynamic (though exception types and declarations will be static). Why?

Dynamic v. Static Binding Exercise

Consider the Cascal program:

```
const int s = 2;
const int d = 3;

int inc(void) {
  return d+s;
  }

void main(void) {
  int s := 5;
  int d := 4;
  s := d;
  writeln( inc() );
}
```

What will be written by the above program if Cascal uses dynamic binding?
What if Cascal uses static binding?

Summary

We have looked at

- variables
- lifetime and garbage collection
- binding mechanisms
- scoping

Homework

- Read Chapter 3 and 4 of Watt.
- Design a persistent variable extension to C. Use this to rewrite your favorite C file manipulation program.
- Consider an extension to C which would allow nesting of functions. Do you see any problems?
- What sort of block structure does C++ have?
- Does C++ use dynamic or static binding?

Programming Language Concepts & Issues III

In the last lecture we examined

- variable storage and lifetime
- identifier bindings and their scope

In this lecture we will look at

- types
- ad hoc, subtype and parametric polymorphism
- coercion
- type checking and type inference

The material is loosely based on Watt and Mitchell.

Types

An expression is evaluated to produce a value. A value may be passed as an argument, stored etc..

Most programming languages group values into "types."

But what is a type?

A type is a set of values whose elements exhibit uniform behaviour with respect to the operators defined for that type.

For instance, integers exhibit (almost) uniform behavior for the arithmetic operations.

The set of even-length lists (potentially) forms a type with respect to list concatenation.

```
List     (@, length, null)
 |
EvenList (@, length, null,
          eSplit: 'a EvenList -> 'a List * 'a List)
```

Types (Cont.)

Types in modern programming languages can be divided into

Primitive types **These are types whose values are atomic in the language. The choice of these reflects the use of the language.**
Eg, ML has primitive types `real`, `int`, `char` `bool`, **etc..**

Composite types **These are types made by combining other types. Examples include tuples, records, disjoint union, and reference or pointer types.**
A little unusually, Pascal provides powersets of finite types:

```
type Colour = {red, green, blue};
     Hue = set of Colour
```

Recursive types

Mapping types

Mapping Types

A mapping $m : S \to T$ maps elements in type S to elements in type T.

Arrays are a type of mapping – they map the index set to the array's element set.

In Pascal and Ada the index set can be any discrete primitive type.

```
type Colour = {red, green, blue};
     Pixel = array [Colour] of 0..1
```

Functions implement a mapping by giving an algorithm which computes the result from the argument. In this case S need not be finite.

Since both arrays and functions can be thought of as mappings, the choice of which to use is sometimes an implementation decision.

Recursive Types

A list is an example of a recursive type.

```
datatype intlist = Null | Cons of int * intlist;
```

In general, a recursive type T is defined in terms of recursive type equations, e.g.

$$T = ...T...$$

To understand the meaning, we can think of the recursive type equations as a grammar. The type is the language generated by the grammar.

For instance,

```
<intlist> ::= Null | Cons( <int>, <intlist>)
<int> ::= 0 | 1 | -1 | ...
```

Exercise: **What is the meaning of**

```
datatype foo = Empty | Comp of foo * string * foo;
```

Subtypes

There are two sorts of subtypes in typing.

Domain subtypes. Type T_1 is a domain subtype of T_2 if the elements in T_1 are a subset of the elements in T_2.

Pascal allows the programmer to declare such subtypes.

```
type monthlength = 28..31;
```

Class subtypes. Type T_1 is a class subtype of T_2 if T_1 supports at least the same functions and operations as does T_2 (and possible some more). This is based on the class hierarchies in object oriented languages and type-classes in some functional- (e.g. Haskell) and logic-programming languages.

Class Subtype Example

The following C++ code states that `ColourPoint` is a class subtype of `Point`.

```
class Point {
public:
    int getX();
    int getY()
    void move(int,int);
protected: ...
private: ...
}

class ColourPoint: public Point {
public:
    int getX();
    int getY()
    void move(int,int);
    int getColour();
    void setColour(int);
protected: ...
private: ...
}
```

Type Systems

In C every value has a specific type. The corresponding type system is said to monomorphic.

C forces us to define the exact type of every formal parameter and function return type meaning that every programmer defined function is monomorphic.

However (like almost all other languages) C is not strictly monomorphic.

For example, many built-in operators such as ‘<’ and ‘–’ work for more than one type.

Such operations are said to be generic in the sense that the same operation makes sense on more than one type.

Generic Operations

Strachey (1967) distinguished between:

Parametric polymorphism (often just called polymorphism) in which the function behaves uniformly regardless of the type of the input.

For example, determining the length of the list does not depend on the type of the elements.

Ad hoc polmorphism (often called overloading) in which the function has different definitions depending on the type of the operands.

For instance, < does very different things in ML depending on if the elements being compared are integers, floats or strings.

Generally an overloaded function does not work for all types, just for more than one, while a parametric polymorphic function works for all instantiations of its type parameters.

Subtype polymorphism in which a function expecting an argument of type T_1 can take any type T_2 which is a class subtype of T_1.

Subtype polymorphism is a core part of object oriented languages. However it is also found (under the name type-classes) in recent functional and logic programming languages.

In some senses it is a natural generalisation of both parametric and ad hoc polymorphism.

Parametric Polymorphism

We have seen that ML supports parametric polymorphic functions. Eg.

```
fun len []       = 0
  | len (x::xs) = 1 + len xs;
```

has type `'a list → int`.

Note that a single piece of compiled code for `len` will work for all instantiations of `'a`.

Types, such as `'a list`, with variables are said to be polytypes. Those with no variables are said to be monotypes.

Exercise: How many functions have the type `'a→'a`?

Overloading

An operator is overloaded if it simultaneously denotes two or more functions.

In C++ we might define

```
int max(int i, int j)
  { return (i>j) ? i : j;}
float max(float i, float j)
  { return (i>j) ? i : j;}
char *max(char *s, char *t)
  { return strcmp(s,t) > 0 ? s : t;}
```

More generally consider the overloaded identifier F which denotes both of the functions:
- $F_1 : S_1 \to T_1$ **and**
- $F_2 : S_2 \to T_2$.

(Note that S_1 and S_2 may be tuples.)

There are two kinds of overloading:

- **Context-independent overloading requires that S_1 and S_2 are distinct. This is provided in C++.**
- **Context-dependent overloading requires that either S_1 and S_2 are distinct or that T_1 and T_2 are distinct. This is provided in Ada.**

Overloading (Cont.)

Context-independent overloading allows the function to be called to be uniquely identified by the types of the actual parameters.

Context-dependent overloading sometimes leads to compile-time ambiguity.

For instance in Ada "/" is overloaded to denote integer division

$$Integer \times Integer \to Integer$$

and real division

$$Float \times Float \to Float.$$

We can overload it further

```
function "/" (m,n : Integer) return Float is
begin
  return Float(m) / Float(n)
end
```

Exercise: **Now give an expression which is ambiguous.**

Subtype Polymorphism

All object oriented languages provide subtype polymorphism.

For instance the function `translatePoint` in the C++ code will also work with `ColourPoint`s.

```
class Point {
public:
    int getX();
    int getY()
    void move(int,int);
protected: ...
private: ...
}

class ColourPoint: public Point {
public:
    int getX();
    int getY()
    void move(int,int);
    int getColour();
    void setColour(int);
protected: ...
private: ...
}

/* function to move point p by (x,y) */
void translatePoint(Point *p, int x, int y) {
  p->move(p->getX() + x, p->getY() + y);
}
```

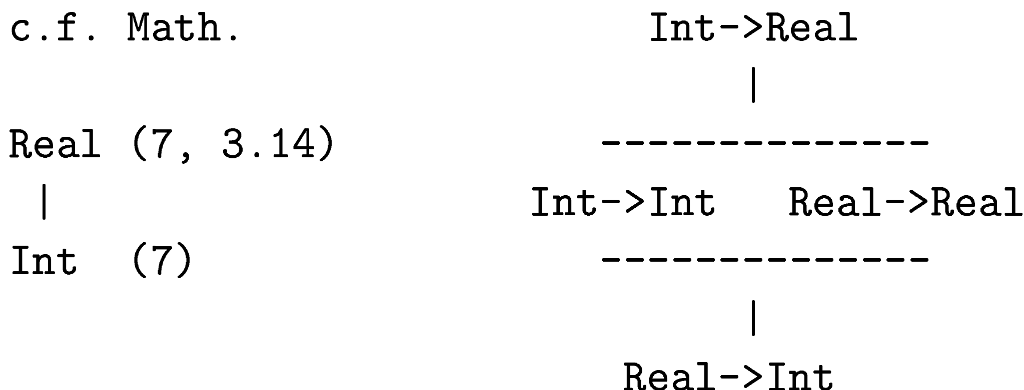
Subtype Polymorphism

One subtlety of subtype polymorphism is precisely defining what being a class subtype means.

Recall that type T_1 is a class subtype of T_2 if T_1 supports at least the same functions and operations as does T_2. This means that T_1 can be safely substituted for T_2.

So if T_2 has a function $f_2 : A_2 \to B_2$ and T_1 has a function $f_1 : A_1 \to B_1$ what should be the relationship between A_2 and A_1 and between B_2 and B_1?

This has led to a lot of debate. However we require that f_1 can be safely substituted for f_2. This means that we require that A_1 should be a class subtype of A_2 and that B_2 should be a class subtype of B_1.
NB. $\to$ is anti-monotonic on its left-hand parameter.



Type Classes

Recall the home work in which you were asked to write a polymorphic ML function to find the largest item in a list. This was impossible.

```
fun max [x] = x
  | max (x::xs) =
     let val xsmax = max xs in
       if x > xsmax then x else xsmax
     end;
```

val max = fn : int list -> int

However, the most general type should be any type supporting a comparison operation >.

Type classes allow this generic form of subclass polymorphism. They were introduced into the functional programming language Haskell by Phil Wadler and were inspired by the equality-type mechanism in SML and by classes in object-oriented languages. Now used in some logic programming languages.

Type Classes (Cont.)

Unfortunately ML was designed before type-classes existed. But if ML had type-classes we would be able to write

```
class Orderable 'a where
 op > : ('a * 'a) -> bool;
 op < : ('a * 'a) -> bool;
end;

instance Orderable int where
 op > = op > : (int * int) -> bool;
 op < = op < : (int * int) -> bool;
end;

instance Orderable string where
 op > = op > : (string * string) -> bool;
 op < = op > : (string * string) -> bool;
end;
```

Type Classes (Cont.)

Type inference would now deduce that:

```
fun max [x] = x
  | max (x::xs) =
     let val xsmax = max xs in
       if x > xsmax then x else xsmax
     end;
```

has type

val max = fn : Orderable 'a => 'a list -> 'a

which is what happens in Haskell.

Type Classes Ordering

Like classes in object oriented languages, the programmer can organise type-classes into a hierarchy.

```
class Orderable 'a where
     op > : ('a * 'a) -> bool;
     op < : ('a * 'a) -> bool;
    end;
class Equality 'a where
    op = : ('a * 'a) -> bool;
    op <> : ('a * 'a) -> bool;
end

class Orderable 'a, Equality 'a => Comparable 'a where
   op >= : ('a * 'a) -> 'a;
   op <= : ('a * 'a) -> 'a;
end;
```

Indicates that `Comparable` **is a subclass of both** `Orderable` **and** `Equality`**. An instance of** `Comparable` **must provide the 6 functions** `>`, `<`, `=`, `<>`, `>=`, `<=`**.**

Another Type Class Example

As another example consider

```
fun square x = x*x;
```

ML will give `x` either the type `integer` (or `real`) but not both.

However the most general type would be any type supporting the usual arithmetic operations including `*`.

If ML had type-classes we would be able to write

```
class Num 'a where
 op + : ('a * 'a) -> 'a;
 op - : ('a * 'a) -> 'a;
 op * : ('a * 'a) -> 'a;
 op / : ('a * 'a) -> 'a;
 op ~ : 'a -> 'a;
end;
```

Another Type Class Example (Cont.)

Type inference will now deduce that:

```
- fun square x = x*x;
 val square = fn : Num 'a => 'a -> 'a
```

and similarly

```
- fun square2 (x,y) = (square x, square y);
 val square2 = fn : Num 'a, Num 'b =>
                  ('a * 'b) -> 'a * 'b
```

(Haskell has a rich collection of numeric and comparison type-classes.)

Coercion

Many programming languages have operators that explicitly coerce (convert) a value from one type to another type.
For example, type casts in C.

Also many languages have implicit coercion. In C, for example, an integer may be automatically coerced to a float and a float to a double.

In ML no implicit coercion takes place. This is because coercion does not work well with type inference.

In C++ you may define your own coercion rules. This is quite complex and may lead to subtle errors or ambiguities.

Type Safety

A programming language is type safe if no program is allowed to violate its type distinctions.

Haskell, Java, Lisp, ML and Smalltalk are all type safe. C and C++ are not. Why?

In statically typed languages each variable has a well-defined type either provided by the programmer or inferred at compile-time. E.g. ML.

This catches more programmer errors and allows more efficient implementation but sometimes, since the type checking must be conservative, the type system is restrictive.

In dynamically typed languages arguments are tested for type correctness at run-time. E.g. Smalltalk.

This is more flexible but cannot be used to guarantee that a program is free from type errors, It also introduces some runtime overhead.

Sometimes a mixture of static and dynamic typing is used in which case as much type checking as possible is done at compile time while some type checking is done at run-time. E.g. Java.

An active area of research is to develop more flexible type systems which can still be checked at compile-time.

Type Checking and Inference

For statically typed languages we distinguish between:

- Type checking where all function and variable type declarations are provided by the programmer, e.g. C and C++.
- Type inference where some type declarations are inferred, e.g. Haskell, ML.

Generally speaking, type inference is harder to implement than type checking (but nicer to use).

Summary

In this lecture we have looked at

- types
- ad hoc, subclass and parametric polymorphism
- coercion
- type checking and type inference

Homework

- Read relevant chapters of Watt (2 and 7).
- C++ provides context-independent overloading. In the lecture we stated that context-independent overloading allows the function to be called to be uniquely identified by the types of the actual parameters. Then why does C++ sometimes complain of ambiguity when you use overloaded operators?
- How would you implement type-classes? One way would be to have different version of the function for each possible class. Thus `square` would give rise to

```
fun square_int x = x*x : int;
fun square_real x = x*x : real;
```

And the compiler would call the appropriate version. This is how templates work in C++.

Another way would be to associate an appropriate 'dictionary' of operations with each variable and pass this along with the variable. This is similar to how most object oriented languages support objects.

```
fun square NumDict x = NumDict.* (x,x);
```

Consider the implementation of `square2`**, and a similar** `square3`**, etc.. Which method do you prefer and why?**

Programming Language Concepts & Issues IV

In the last two lectures we examined

- **variables**
- **types**

In this lecture we examine abstraction mechanisms.

The material is loosely based on Watt but also draws upon Mitchell and Pratt & Zelkowitz.

Abstraction

Abstraction is a mode of thought in which we concentrate on general ideas rather than specific instances.

In programming languages abstraction mechanisms allow us to hide implementation details of a program component from the client using the program component. How the client can use the component is specified by an interface.

We will look at 4 types of abstraction mechanisms:

- **Procedural abstraction including parameter passing mechanisms**
- **Abstract data types**
- **Modules**
- **Objects**

Procedural Abstraction

In computer programming we define an procedural abstraction to be an entity that embodies a computation, i.e. abstracts a sequence of program commands.

A procedural abstraction has a well-defined interface made explicit in the code. This gives the name of the function and the input parameters. It may provide type information. Usually the implementation may use local variables to hide information.

Only the programmer who implements the procedural abstraction is concerned with details of how it is done. Other programmers who use it are only interested in what it does.

Procedural Abstraction (Cont.)

An expression is a program command that is evaluated to give a value, e.g. (`x+y`, `3.0`).

A command is a program command which when executed updates the values of variables. (Sometimes they are called statements). E.g. `a[i] = j`

A selector provides variable access. E.g. In C, `V[E]` **for arrays and** `V.I` **for records.**

Based on this Watt distinguishes between:

- **Function abstractions These abstract an expression to be evaluated. They return a single value and should have no side effects.**
- **Procedure abstractions These abstract a command that updates variable values.**
- **Selector abstractions These embody a command to access a variable and return a reference to the variable.**

In C and ML there is no real syntactic distinction between function and procedure abstractions — they are both regarded as "functions."

Pascal (sort of) distinguishes between the two using `function` **for the first and** `procedure` **for the second.**

Few languages provide selector abstractions, although C++ does.

Parameters

An identifier used within an abstraction to denote an argument is called a formal parameter.

An expression that yields an argument to an application of an abstration is called an actual parameter.

```
val pi = 3.14;
fun circum (r) = 2.0 * pi * r;

- circum(4.0+pi);
```

There have been many mechanisms suggested for "passing" parameters. In essence we assign the value of the actual parameter to the formal parameter. Thus these mechanisms are often related to variable assignment.

Variable Assignment

Variable assignment is usually implemented in one of two ways:
– copying the RHS to the LHS
– assigning a reference from the LHS to the RHS.

Copying is expensive for larger data structures, but assigning a reference is error-prone, since changes within the structure change all references to it.

Furthermore it is hard for the programmer to know when all references to an object have died. This is the problem of tracking aliasing, i.e. knowing when two variables refer to the same object.

Example: Variable Assignment in Java

In Java what happens depends on the type of the variable: primitive types such as `char` are copied while objects are assigned a reference.

Compare execution of the Java code

```
char c='c';
char d='d';

c = d;
d = 'e';
System.out.print(""+c+d);
```

with that of

```
public class MyChar {
 private char c;
 public MyChar(char c) {this.c = c;}
 public char get() {return c;}
 public void set(char c) {this.c = c;}
}

MyChar c=new MyChar('c');
MyChar d=new MyChar('d');

c = d;
d.set('e');
System.out.print(""+c.get()+d.get());
```

Variable Assignment

In C++ primitive types are copied while the programmer is free to define what assignment means for other types.

In functional programming and logic programming complex objects are always manipulated by reference since because variables cannot have their value changed, this is equivalent to copying. Thus you get efficiency + safeness!

Copy Mechanisms

Just like variable assignment the two most common approaches to parameter passing are copying and reference assignment.

A copy mechanism allows for values to be copied in or out of an procedural abstraction. The formal parameter X is a local variable in the abstraction. The actual parameter's value is copied into X on entry and/or copied out of X (to a nonlocal variable) on exit.

So called pass-by-value parameter (passing) is used in C. In this mechanism the actual parameter is copied to the local variable X when calling the procedure. Since X is a local variable any updating of X has no effect on any non-local variables.

The mirror-image to this is the (pass-by-) result parameter. In this case the argument is a (reference) to a variable. Again the local variable is created but it is uninitialized. On exit from the abstraction, the final value of X is assigned to the argument variable. Used in Ada.

We can combine these to give a (pass-by-) value-result parameter. In this case the argument is a reference to a variable and the formal argument is copied to X on call and on exit the final value of X is copied to the argument variable. Used in Algol W and Ada

Exercise **Consider the Cascal program. Write down the result when each of the above parameter passing mechanisms is used**

```
void dummy(int x)
{
  x := x+1;
  print(x);
}

main()
{
  int y;
  y := 1;
  dummy(y);
  print(y);
}
```

Pass-by-reference

pass-by-reference is the other main approach to parameter passing. In this the formal parameter X becomes bound directly to the actual argument, i.e. it is just another name for the argument.

In the case of a variable parameter the argument is a reference to a variable. Thus the procedure can also update the argument variable.

In the case of procedural or functional parameters the argument is a procedure or function abstraction.

Notice that these are not really distinct, all bind the formal parameter to the actual parameter. Thus Watt calls this the definitional mechanism.

FORTRAN and ML use only pass-by-reference.

What happens in:

```
void dummy(ref int x) {
  x := x+1;
  print(x);
}

main() {
  int y;
  y := 1;
  dummy(y);
  print(y);
}
```

Aliasing

The advantage of pass-by-reference is efficiency for larger data structures. The disadvantage is that aliasing between the parameters may make the program hard to understand.

```
void dummy(ref int x, ref int y)
{
  x := 1;
  x := x + y;
}

main()
{
  int i;
  i := 4;
  dummy(i,i);
  print(i);
}
```

Here aliasing is easy to detect but in general it is impossible to determine!

Parameter Passing in Ada

Aliasing between the arguments in pass-by-reference causes problems only if we modify the value of one of these arguments inside the procedure.

For this reason Ada requires the programmer to indicate whether a parameter is:
– in: an input parameter whose value is passed into the procedure and can only be read inside the procedure
– out: an output parameter whose value is only passed out of the procedure but which can be read and written inside the procedure but must be written first
– in out: the value is passed in and out of the procedure and can be read and written inside the procedure.

```
  type DirNode is record
    entryname: Name;
    entrynumber: Number;
  end record;

  type Directory is record
    dict: array(0...100) of DirNode;
    num: 0..101;
  end record;

procedure init(dir: out Directory);
procedure insert(dir: in out Directory;
                 newname: in Name;
                 newnumber: in Number);
```

Parameter Passing in Ada (Cont.)

In Ada 83 the compiler was free to choose to use pass-by-reference or pass-by-value for input parameters, pass-by-reference or pass-by-result for output parameters and for in-out parameters pass-by-reference for compound types and pass-by-value/result for primitive types.

This was not a good idea: Why?

Now Ada is uses pass-by reference for all compound types, and for primitive types pass-by-value, pass-by-result and pass-by-value/result respectively for in, out and in out parameters.

Call-by-Name

Call-by-name parameter passing is as though a formal parameter is textually replaced by the actual parameter in the abstraction body (but any name-clash with a local variable is removed). A by-name parameter can be implemented by an implicit procedure called a 'thunk'.

Call-by-name was the default parameter passing mechanism used in Algol 60. It is also how macros work in C.

Despite its intuitive simplicity, call-by-name was largely given up after Algol 60 because the presence of side effects made it too difficult to understand some programs.

```
void swap(name int x, y)
{
  int t;
  t := x; x := y; y := t;
}
```

Exercise: **What does** `swap(n,A[n])` **do?**

Evaluation Order

An important issue in parameter passing is when is the actual parameter evaluated?

There are three main methods:

- Eager evaluation – i.e. at the time of procedure call. Also called applicative-order evaluation.
- Call-by-name parameter passing ("normal order" evaluation).
- Lazy evaluation – i.e. when needed. Evaluation is only performed once when (if) first needed and the result is "memoed" for subsequent re-use (the 'by-need' optimization).

For pure functional languages we have that if they terminate, all three methods give the same result. And if eager terminates then lazy and name terminate but not necessarily v.v.. This is called the Church-Rosser property.

However for languages with side-effects (i.e. updatable variables) it is not necessarily true.

Data Abstraction

A procedural abstraction allows the programmer to abstract program commands. However commands are only part of programming: there is also data.

Since the 1970s a focus of programming language design has been supporting programming in the large. In particular, it has focused on providing support for data abstraction, i.e. ways to hide the representation of data from the rest of the program.

There are two common mechanisms for data abstraction:

- Abstract data types
- Modules

An abstract data type consists of a type together with a specified set of operations on the type. Access to the data type is limited to using these operations, so the representation can be hidden from the rest of the program.

ML provides the abstype for this purpose. According to Mitchell, CLU (Liskov et al c1979) was the first language to provide abstract data types.

Modules

Modules generalise abstract data types. They allow the programmer to group a collection of related functions, procedures and type declarations together.

Modules also allow the programmer to specify the module interface: i.e., which components are exported by the module and which components are hidden in the module.

In some languages modules can be hierarchical.

Watt calls modules packages.

The language Modula (Wirth c1977) provided the basis for modern module systems such as those provided in ML and Ada.

In ML packages are provided by structures and hiding is provided by declaring the structure's signature or by using local declarations.

C provides only a very primitive module system. A module is identified with a file and the programmer labels functions to indicate if they are exported or not.

Ada Modules

In Ada you use a package declaration to define a module. It has two parts: the interface or package specification and the implementation or package body.

As an example here is an Ada package defining an abstract type `Directory`**. The interface is defined by**

```
package directory_type is
  type Directory is limited private;
  procedure init(dir: out Directory);
  procedure insert(dir: in out Directory;
                   newname: in Name;
                   newnumber: in Number);
  procedure lookup(dir: in Directory;
                   name: in Name;
                   number: out Number;
                   found: out Boolean);
  private
      type DirNode is record
        entryname: Name;
        entrynumber: Number;
      end record;
      type Directory is record
        dict: array(0...100) of DirNode;
        num: 0..101;
      end record;
end directory_type
```

(c.f. ‘lookup tables’ in cse2304.)

Ada Modules (Cont.)

The actual implementation is defined in the "body"

```
package body directory_type is
 procedure init(dir: out Directory) is
  dir.num = 0;
 procedure insert(dir: in out Directory; newname: in Name;
                  newnumber: in Number) is
  ... put element in dictionary ...;
 procedure lookup(dir: in Directory; name: in Name;
                 number: out Number; found: out Boolean) is
  ... iterate through elements in array...;
end directory_type;
```

Values of type `Directory` **can only be accessed and displayed using the functions declared in the package interface.**

```
use directory_type;
homedir: Directory;
workdir: Directory;
init(homedir);
init(workdir);
insert(homedir, kim, 96088913);
insert(workdir, kim, 55525);
lookup(workdir, kim, kimNo, ok);
```

Abstract types and modules look similar to objects in C++. What is the essential difference?

Object-Based Programming

According to Watt an object is a hidden variable in a package or module recording its current state.

The following Ada package defines a dictionary "object":

```
package directory_object is
  procedure insert( newname: in Name;
                    newnumber: in Number)
  procedure lookup( name: in Name;
                    number: out Number;
                    found: out Boolean)
end directory_object
```

Object-Based Programming (Cont.)

The package definition is

```
package body directory_object is
  type DirNode is record
      entryname : Name;
      entrynumber: Number;
  end record
 num: 0..101;
 dict: array(0..100) of DirNode;

 procedure insert( newname: in Name;
                   newnumber: in Number) is
 ... put element in dictionary ...;
 procedure lookup( name: in Name;
            number: out Number; found: out Boolean) is
 ... iterate through elements in array...;
begin
  num = 0;
end directory_object;
```

Elaboration of this package creates a single object

```
directory_object.insert(kim, 55525);
directory_object.insert(bernd, 52240);
directory_object.lookup(kim, kimNo, ok);
```

Object-Based Programming (Cont.)

A generic package declaration does not create an object but rather defines a whole class of objects. To create an object we create a new instance of this class and its hidden variable.

```
generic package directory_class is
  procedure insert( newname: in Name;
                    newnumber: in Number)
  procedure lookup( name: in Name;
                    number: out Number;
                    found: out Boolean)
end directory_class
```

The definition is as before.

We can now creates multiple dictionary objects

```
package homedir is new directory_class;
package workdir is new directory_class;
homedir.insert(kim, 96088913);
workdir.insert(kim, 55525);
workdir.lookup(kim, kimNo, ok);
```

Programming languages which allow objects in the preceding sense are said to be object-based.

Summary

We have looked at

- Procedural abstractions
- Parameter passing
- Abstract data types
- Modules
- Object-based programming

Homework

- Read Chapters 5 and 6 of Watt.
- Give an example of a procedure which behaves differently if pass-by-reference and pass-by-value-result are used.
- Do you think verbatim replacement of the formal parameter by the actual parameter is the way to formalize call-by-name parameter passing? Consider what happens if a local variable has the same name as a variable in the actual parameter.
- What are the key differences between object classes and abstract types?

Programming Language Concepts & Issues V

This is the last of 5 lectures looking at programming language history, issues and concepts.

In previous lectures we have looked at unifying concepts for all programming languages

- **variables**
- **types and type checking**
- **abstraction mechanisms**

In this lecture we examine

- **main programming language paradigms**
- **possible new programming paradigms**
- **DNA computing**

This lecture is based on Watt but also draws upon Mitchell.

Programming Language Paradigms

Recall that programming languages provide

- An underlying computation model
- Data types and operations,
- Abstraction facilities
- Checking and enforcement

Different computation models lead to different programming language paradigms.

The traditional four main paradigms are

- Imperative (or procedural): based on the von Neumann architecture with updatable memory locations.
- Object-oriented: based on "objects" which encapsulate state and which communicate by method invocation.
- Functional: based on mathematical functions (more precisely the lambda calculus).
- Logic: based on mathematical relations (more precisely predicate calculus).

Imperative Programming Paradigm

Imperative programming is so called because it is based on commands that update variables held in storage. (imperare is Latin for to command)

The first high-level programming languages (FORTRAN, COBOL were imperative because of the close match with the underlying computer architecture with updatable memory locations meant that
– they were easily compiled
– could be implemented efficiently.

What are some more examples of imperative programming languages? What are they good for?

The imperative programming paradigm used to be the dominant programming paradigm, is this still true?

Object-Oriented Programming Paradigm

According to Watt an object requires a hidden variable in a package recording its current state.
Since the programmer can change internal state of the object, object-oriented programming is really an extension of the imperative programming paradigm.

In object-oriented programming languages

- objects and classes (generic packages) are fundamental concepts
- objects are first-class values
- objects are characterised by the methods or actions which can be applied to it
- classes are organised into a hierarchy and a sub-class can be passed anywhere that a super-class is expected, i.e. subtype polymorphism is supported
- Typically sub-classes can inherit method definitions from their super-classes

Object-oriented languages originated with Simula, but with C++, Java and C# are rapidly becoming the dominant programming paradigm.

Arguably this is because they accord with the inbuilt human cognitive model for understanding the world in terms of entities, state and actions.

What are some more examples of OO programming languages? What are they good for?

Functional Programming Paradigm

Functional languages have the following characteristics:

- **Everything is a function or a value.**
- **First-class higher-order functions.**
- **The underlying conceptual model is the lambda calculus.**

They are high-level languages with implicit memory management and often provide lazy evaluation, type inference and type-classes.

What are some more examples of functional programming languages? What are they good for?

The Logic Programming Paradigm: History

- early 1970s Kowalski: computational interpretation of logic.

  The logic statement:

  A if B_1 and B_2 and $\cdots$ and B_n

  equivalently

  B_1 and B_2 and $\cdots$ and $B_n \Rightarrow A$

  is read computationally as:

  to solve (execute) A,
  solve (execute) B_1 and B_2 and,..., B_n

- early 1970s Colmerauer: develops a specialized theorem prover (written in Fortran) embedding Kowalski's procedural interpretation: Prolog (stands for Programmation et Logique).

- 1981 Japanese Fifth Generation Project: logic programming becomes the hot new programming paradigm.

- late 1980s Constraint Logic Programming (initially developed at Melbourne, Monash, Marseille, etc.) and Deductive Databases developed.

- Now typed logic and constraint logic programming languages (Mercury and HAL) are under development at Melbourne and Monash (amalgamate logic and functional programming).

Simple Prolog Example

Consider the Prolog program `solar.pl`

```
orbits(mercury, sun).
orbits(venus, sun).
orbits(earth, sun).
orbits(mars, sun).
orbits(moon, earth).
orbits(phobos, mars).
orbits(deimos, mars).
```

Using SICStus Prolog we can read in this Prolog program and interactively ask questions about the facts in it:

```
% sicstus
booting, please wait...
SICStus 3  #6: Mon Nov 3 19:53:41 MET 1997
| ?- consult('solar.pl').
yes
| ?- orbits(Planet,sun).

Planet = mercury ? ;
Planet = venus ? ;
Planet = earth ? ;
Planet = mars ?
yes
```

Simple Prolog Example (Cont.)

```
| ?- orbits(earth, X).

X = sun ? ;
no

| ?- orbits(Satelite, Planet), orbits(Planet,sun).

Planet = earth,
Satelite = moon ? ;
Planet = mars,
Satelite = phobos ? ;
Planet = mars,
Satelite = deimos ?

yes
```

Simple Prolog Example (Cont.)

The Prolog facts define a relational database which the programmer can query.

A query can have zero or more answers.

A query can be a conjunction.

Variables start with an uppercase letter, constants with a lower case letter.

Rules

Not all information is expressed as facts, we also have rules to deduce information:

> **A planet is a body that circles the sun.**

The Prolog rule is:

```
planet(B) :- orbits(B, sun).
```

The symbol *:-* **is read as "if."**

Another example of a rule is:

> **A satellite is a body that circles a planet:**

The corresponding Prolog rule is:

```
satellite(B) :- orbits(B, P), planet(P).
```

We can add these rules to our Prolog program and then read it in and query our solar system database

```
| ?- satellite(B).
B = moon ? ;
B = phobos ? ;
B = deimos ? ;
no
```

Execution Mechanism

Prolog executes a query by repeatedly

- **Selecting the leftmost atom and replacing it by its definition**
- **Trying the definitions in turn and backtracking when these lead to failure.**

Example of Execution

```
orbits(mercury, sun).
orbits(venus, sun).
orbits(earth, sun).
orbits(mars, sun).
orbits(moon, earth).
orbits(phobos, mars).
orbits(deimos, mars).

planet(B) :- orbits(B, sun).
satellite(B) :- orbits(B, P), planet(P).
```

How does Prolog execute the query `satellite(B)`**?**

(See http://www. ... /~lloyd/tildeLogic/Prolog.toy/Examples/solar/)

Data Structures

Prolog provides numbers (either floats or integers) and terms.

Terms are just like ML's data constructors.

Also like ML, pattern matching is used.

However, you do not have to define or declare the types since Prolog is typeless.

Logic Programming Paradigm

Logic programming languages are based on relations. They can be formalised in terms of predicate calculus.

PROLOG is the best known example.

Traditional application areas:

- natural language understanding (DCGs)
- expert systems
- other AI applications
- databases
- rapid prototyping

Constraint Logic Programming (CLP) application areas:

- engineering analysis and design
- financial modelling
- combinatorial optimization

New Paradigms

But these may not be the only programming language paradigms. As technology advances computer's underlying architecture may change enormously and we will need programming language that reflect this change.

Some promising new technologies include

- internet computing
- quantum computing
- DNA computing
- cellular computing

DNA computing, e.g.

D.Gifford. *On the path to computation with DNA.* Science, 266, pp.993-994, Nov., 1994.

J. Hartmanis *On the weight of computations.* Bull. of the European Assoc. for Theoretical Comp. Sci., 55, Feb., 1995.

(Lookup DNAcomputation in http://www. ... /~lloyd/tildeBIB/)

Summary

We have

- **reviewed the 4 main programming paradigms**
  – imperative, object-oriented, functional and logic.
- **used Prolog to introduce the logic programming paradigm**

Homework

- **Read Chapters 10, 12, 13 and 14 of Watt.**
- **Write a Prolog query to find out which objects orbit `mars`.**