Programming Paradigms

Unit 2 — Imperative and Object-oriented Paradigm

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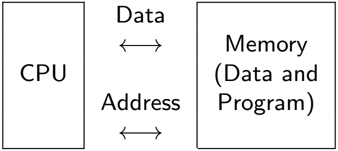
Outline

1. Imperative Programming Paradigm
2. Abstract Data Types
3. Object-oriented Approach

Outline

Imperative Paradigm/1

- The imperative paradigm is the oldest and most popular paradigm
- Based on the von Neumann architecture of computers
- Imperative programs define sequences of commands/statements for the computer that change a program state (i.e., set of variables)
  - Commands are stored in memory and executed in the order found
  - Commands retrieve data, perform a computation, and assign the result to a memory location



- The hardware implementation of almost all computers is imperative
  - Machine code, which is native to the computer, and written in the imperative style

Machine code

```
8B542408 83FA0077 06B80000
C9010000 008D0419 83FA0376
B84AEBF1 5BC3
```

Imperative Paradigm/2

- Central elements of imperative paradigm:
  - Assigment statement: assigns values to memory locations and changes the current state of a program
  - Variables refer to memory locations
  - Step-by-step execution of commands
  - Control-flow statements: Conditional and unconditional (GO TO) branches and loops to change the flow of a program
- Example of computing the factorial of a number:

```
unsigned int n = 5;
unsigned int result = 1;
while(n > 1) {
    result *= n;
    n--;
}
```

Procedural Programming

- Procedural programming is a refinement of the imperative paradigm adding subroutines (or procedures)
  - Procedures can be used the same way that built-in commands are used (allows re-usability)
  - Some state changes are localized in this way
- Creating a procedure from the previous example:

```
int factorial(unsigned int n) {
   unsigned int result = 1;
   while(n > 1) {
      result *= n;
      n--;
   }
   return result;
}
```

History of Imperative Paradigm/1

- Earliest imperative languages were the machine languages of the computers
  - Very simple instructions
  - Made hardware implementation easier, but difficult to create complex programs
- In 1954, FORTRAN was developed by John Backus at IBM
  - First major programming language
  - Removed problems of machine code for the creation of complex programs
  - Many features that are common in imperative languages, e.g., named variables, complex expressions, subprograms, etc.
  - FORTRAN was a compiled language
- The next two decades saw the development of a number of other major high-level imperative programming languages
  - In the late 1950s, ALGOL (short for ALGOrithmic Language) was developed in order to allow mathematical algorithms to be more easily expressed

History of Imperative Paradigm/2

- COBOL (1960) and BASIC (1964) were both attempts to make programming syntax look more like English
- In the 1970s, Niklaus Wirth at ETH Zurich developed Pascal as a small and efficient language intended to encourage good programming practices using structured programming and data structuring
- C was created by Dennis Ritchie at Bell Laboratories
  - Used to (re-)implement the Unix operating system
  - Has become one of the most widely used programming languages of all time

History of Imperative Paradigm/3

- In the 1980s, there is a rapid growth in interest in object-oriented programming
  - Imperative in style, but added features to support objects
- Simula was the first OO-language, and influenced other languages (1960s)
- Smalltalk-80 was released in 1980 by the Xerox Palo Alto Research Center
- Bjarne Stroustrup designed C++, an object-oriented language based on C
- OO languages in the late 1980s and 1990s:
  - Perl (Larry Wall in 1987)
  - Python (Guido van Rossum, 1990)
  - Visual Basic and Visual C++ (Microsoft, 1991 and 1993)
  - PHP (Rasmus Lerdorf, 1994)
  - Java (Sun Microsystems, 1994)
  - Ruby (Yukihiro Matsumoto, 1995)

Outline

Abstract Data Types

- The procedural approach in imperative programming was taken further by introducing abstract data types (ADT)
- In ADTs, everything related to a type is encapsulated in one bundle, most importantly
  - data itself and
  - operations on the data
- This hides the underlying representation and actual implementation (information hiding)

Information Hiding

- What are the advantages of information hiding?
  - Allows access to data only via a specified set of operations, thereby increasing type safety
  - An implementation of an ADT can be replaced by a different (more efficient) one without having to rewrite other parts of the code
  - Code becomes more portable and easier to reuse

Limits of Data Abstraction

- While ADTs exhibit important features such as encapsulation and information hiding, there are still shortfalls
- We will have a look at these with a concrete (though simplified) example
  - Assume we want to define an ADT implementing a counter

ADT Counter

- This ADT provides a counter of type integer, which can be read, incremented, and reset

```
abstracttype Counter {
   type
      Counter = int x;
   operations
      int get(Counter x) { return x; };
      void inc(Counter x) { x++; };
      void reset(Counter x) { x := 0; };
}
```

ADT NewCounter/1

- Assume we want to extend this type by adding an operation that tells us how many times we have reset the counter
- We could define a completely new ADT

```
abstracttype NewCounter {
   type
      NewCounter = struct {int c;
                           int noOfResets = 0;}
   operations
      int get(NewCounter x) { ...};
      void inc(NewCounter x) { ...};
      void reset(NewCounter x) { ...};
      int howManyResets(NewCounter x) { ...};
}
```

ADT NewCounter/2

- In terms of encapsulation and information hiding this is fine
- However, we have to redefine and re-implement all operations, even though most of them work exactly the same way as in `Counter`
- Gets worse if we want more extensions to the type `Counter` or `NewCounter`
- Adding more types leads to redundancy
  - This causes unnecessary work (and increases the size of the code)
  - More difficult to maintain, may result in inconsistencies

ADT NewCounter/3

- Another approach would be to re-use the ADT `Counter` when defining `NewCounter`

```
abstracttype NewCounter {
   type
      NewCounter = struct {Counter c; int noOfResets = 0;}
   operations
      int get(NewCounter x) { ...};
      void inc(NewCounter x) { ...};
      void reset(NewCounter x) { ...};
      int howManyResets(NewCounter x) { ...};
}
```

ADT NewCounter/4

- What would the implementation of the operators looks like in this case?
- Re-uses the implementation of Counter:

```
    int get(NewCounter x) {
        return get(x.c);
    }
    ...
    void reset(NewCounter x) {
        reset(x.c);
        x.noOfResets++;
    }
    ...
}
```

ADT NewCounter/5

- This solution still has drawbacks
  - We have to map new operators explicitly to old operators
  - If we extend `NewCounter` again, an operator is mapped to the `NewCounter` operator, which is mapped to the `Counter` operator ...
  - It would be great if the derived ADT could just inherit the operators from the original ADT ($\rightarrow$ OO languages)

ADT NewCounter/6

- Further problems with typing
- Assume we have a group of counters, some of type `Counter` and some of type `NewCounter`
  - If we want to store these in an array, what would the array look like?
  - `Counter Z[20]` cannot store `NewCounter`
  - `NewCounter Z[20]` cannot store `Counter`

Type Compatibility

- When we introduced type systems, we briefly mentioned compatibility rules, i.e., one type can be substituted for another
- Let us define type compatibility between type S and type T in more detail:
    - T is compatible with S when all operations over values of type S are also possible over values of T
    - So `NewCounter` is compatible with `Counter`
- Substitutability allows us to use `NewCounter` whenever a `Counter` is expected

ADT NewCounter/7

- Using substitutability we can define an array `Counter Z[20]` and put counters of type `NewCounter` into it
- However, what happens if we run the following code?

```
for(int i; i < 20; i++)
   reset(Z[i]);
```

ADT NewCounter/8

- During compilation a type checker will be satisfied, as `reset()` is a valid operation on `Counter`
- But which version of `reset()` will be executed?
- If this is determined statically (e.g. during compilation), then
  - this will be `reset()` of `Counter`, as `Z` is of type `Counter`
  - As a consequence, `noOfResets` of `NewCounter` will not be updated
- In order to make this work we need to check the "true" type of a counter stored in `Z` and select the correct operator dynamically

Outline

Object-oriented Approach

- In the object-oriented paradigm, all the previously mentioned issues are resolved
  - There is encapsulation and information hiding
  - Under certain conditions, inheritance of operator implementations is permitted
  - Types can be substituted for one another if they are compatible
  - Operators are selected dynamically depending on the actual type

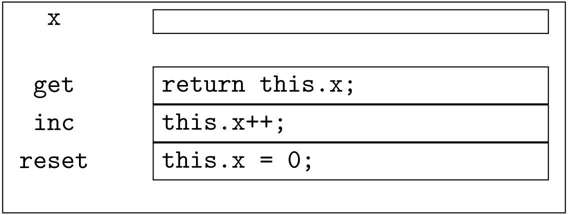
Objects/1

- Objects encapsulate both the data and the operations on the data (well, at least conceptually)
- Operations are usually called methods and are sent as a message to an object
  - This means, that the object receiving the message is an implicit parameter
  - So for our example, the operations on `Counter` would not need any additional parameters
    - Assuming we have an object `o` implementing a counter, then we would increase it by calling

      ```
      o.inc();
      ```

Objects/2

- So a Counter object would look like this:



- However, when implementing object-oriented languages, the code for operations is not stored explicitly with every object

Classes/1

- A class acts as a blueprint for objects and basically defines a type

```
class Counter {
   private:
      int x;
   public:
      int get();
      void inc();
      void reset();
}
```

- Parts declared private are not accessible from the outside
- Parts declared public are visible to all

Classes/2

- So classes accomplish encapsulation and information hiding
- In addition to this, Counter can be extended in a more elegant way

```
class NewCounter extending Counter {
   private:
      int noOfResets = 0;
   public:
      void reset() {
         x := 0;
         noOfResets++;
      };
      int howManyResets() {
         return noOfResets;
      };
}
```

Substitutability

- We also have substitutability
  - Every message understood by `Counter` objects is also understood by `NewCounter` objects
- `NewCounter` re-uses the methods `get()` and `inc()`
- it redefines the method `reset()`
  - This is also called overriding
- It also defines a new method `howManyResets()`
  - Clearly, additional methods do not pose a problem for substitutability

Inheritance

- We also say that all the methods that are not redefined inherit their implementation from the superclass
- Some languages (such as C++) allow multiple inheritance
  - That means a class can have more than one superclass
  - Can be problematic due to name clashes

Substitutability and Inheritance

- Although some languages implement substitutability and inheritance using the same constructs, these are different concepts
  - Substitutability allows the use of an object in another context
    - Object does not have to be of a subclass to understand same methods
  - Inheritance allows the re-use of code (for methods)
    - Private inheritance in C++ re-uses code, but does not allow substitutability

Dynamic Method Lookup/1

- A method defined for one object can be redefined in objects belonging to other classes
- That means there can be many versions of a method
- In order to figure out which one to use, we have to look at the actual type of the object the message is sent to
- This is also called dynamic dispatch

Dynamic Method Lookup/2

- Looking at our Counter example in an object-oriented setting

```
for(int i; i < 20; i++)
   reset(Z[i]);
```

  gives us the correct results using dynamic dispatch
- Not to be confused with operator overloading, in which multiple versions of a method with different parameters can exist, e.g.,

```
void reset();
void reset(int a);
int reset();
```

- Correct method would be selected by matching its signature

Polymorphism

- Nevertheless, dynamic method lookup and operator overloading are different facets of polymorphism
- Polymorphism means that an object or method can have more than one form
- Yet another kind of polymorphism is parametric polymorphism or generics
  - Also called templates in C++

Generics

- Generics consist of program fragments, where some types are indicated by parameters
- These parameters can then be instantiated by "concrete" types
- Depending on the generics, the type used for instantiation has to implement certain methods

Generics Example

- Implement a stack without having to re-implement it for every possible data type of its content

```
class Elem <A> {
   A content;
   Elem <A> next;
}
class Stack <A> {
   private:
      Elem <A> top = null;
   public:
      boolean isEmpty();
      void push(A object);
      A pop();
}
```

Summary

- Imperative paradigm is the oldest programming paradigm, based on von Neumann architecture
  - Program consists of sequence of statements that change the program state
- Procedural programming is a refinement that makes it easier to write complex programs
- Machine languages were the earliest imperative languages, followed by FORTRAN and ALGOL
- Abstract Data Types is a further extension of imperative programming
  - Data and operations are encapsulated into a bundle (information hiding)
  - This hides the underlying represenation and implementation
- Object-oriented paradigm extends ADTs
  - Classes are blueprints for objects that encapsulae both data and operations
  - Objects exchange messages
  - Provides encapsulation, information hiding, inheritance, and dynamic dispatching