Lecture 04

Object-Oriented Concurrent Programming

Shared objects

Object-Oriented Concurrent Programming, 2019-2020

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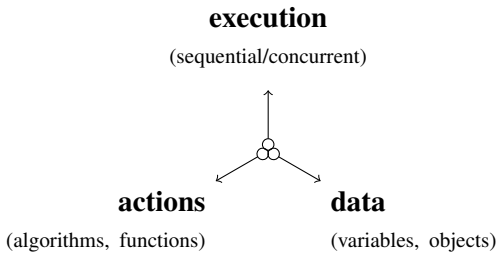
Object-Oriented Concurrent Programming

- A program contains mechanisms to allow the *execution* of some *actions* over some *data*. These are the *three forces* involved in computation.



- Procedural programming is structured around the algorithms, while object-oriented programming emphasizes data (though in an abstract way!);
- Concurrent programming aims to take advantage and give full expression to the third dimension: *execution*.

- The goal is to join both worlds – objects and concurrency – trying to get the best out of each one and, in the process, control their problems and limitations;
- Reuse the powerful OO techniques for program design and development;
- Maintain the simplicity and expressivity of objects in concurrent contexts;
- Tame the non-determinism inherent to concurrency by using appropriate object implementations that maintain its (explicit or implicit) contracts.

Challenge!: Practical approaches for concurrency that make it simple and safe!

2 Objects in a concurrent environment

- When concurrency applies to an object-oriented program, two problems arise:
  1. What active concurrent entities (e.g. threads) are allowed to execute within each object?
  2. How can active entities communicate using objects?
- In the first problem, a solution can be prescribed in which the same single active entity is allowed to execute each object.
  - In this case we are in the presence of an actor concurrency model (to be dealt later on the course).
- Another alternative is to allow objects to be shared between active entities (shared object model).

- The solution taken on this first problem leads to a default prescription to the second problem.
- If a single unique active entity is allowed to execute within each object of a program, then communication will naturally through (direct) messages.

- If, on the other hand, objects can be shared, then the indirect shared memory model is the natural solution.

3 Shared Objects

3.1 Correction

3.1.1 Object Concurrent Integrity

- The most important software quality factor to ensure in the introduction of concurrency in OOP is *correction*.
- In sequential languages the imposition that objects may only be externally used at *stable times* ensures the simplicity in the application of correction conditions to the object's ADT.
- However, a deregulated concurrent execution context may compromise this simplicity!

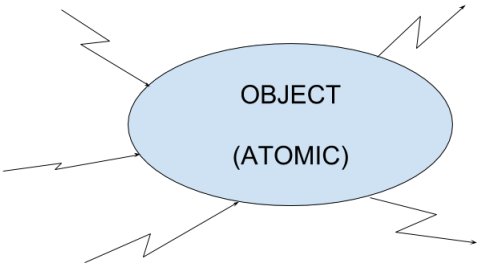
Object Concurrent Integrity: Concurrency cannot, in any case, compromise the implementation of the ADT of an object's class.

3.1.2 Sequential Consistency and Linearizability

Sequential Consistency: The result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.

Linearizability: An object is linearizable if each operation appears to take effect instantaneously at some point between the operation invocation and response.

- A *sufficient condition* to ensure the internal correctness of shared objects (i.e. to ensure its invariant) is the application of *mutual exclusion* in all of its public operations (monitor)!
- However, the linearizability criteria does not require mutual exclusion.
- In fact, an *atomic* behavior of shared objects is enough.



3.1.3 Total Object Covering

In this road towards object-oriented concurrent programming we will choose safe and simple programming design patterns against total flexibility.

A necessary condition to safely apply a synchronization scheme to objects, is that all of its public services are consistently synchronized. Note that the term "synchronization" is not the same thing as Java's `synchronized` language construct. A synchronized method has attached to itself (together with the remaining module's services) a synchronization scheme that ensures safety in concurrent uses.

Total Object Covering: A correctness condition for the synchronization of concurrent objects is the necessity that all of the object's exported services are protected with an appropriate synchronization mechanism.

(Note: A synchronization mechanism should not be confused with Java's synchronized language mechanism!

A mutual exclusion synchronization scheme is simply one possibility.)

3.2 Aspects of Synchronization

In object-oriented programming objects are considered autonomous entities whose meaning is defined by its Abstract Data Type (ADT). Using this modular perspective, two forms of interacting to objects can be defined:

- From *outside*; i.e., externally invoking one of its public services. In this case the object is only usable in its stable times (invariant verified). It is the client's responsibility to ensure the method's precondition.
- From the *inside*; i.e. invoking methods or updating fields of the object from inside an object's method. In this case, there is no assurance of the interaction to be done in stable times.

In the first form, we want the maximum safety and simplicity given by the object's Abstract Data Type. That is, to use objects as external clients, all we need to know is the object's ADT (no knowledge of how the object is implemented is required).

In the last form, we want maximum efficiency and access to the object's internal "machinery" in order to fulfill the goal (meaning) of the method (postcondition and invariant).

In the external utilization of objects we can also identify two typical patterns of use: One in which a single use of the object is enough for the goals of the client; And another in which more than one uses are required. For example, in an implementation of a simple calculator using a postfix notation (reverse polish notation[1]), the application of a binary operation (for instance, a multiplication) implies that two values must be removed from the real number stack, and then a new real number is added to the stack with the result of the operation. Thus, it is necessary to perform two `pop` and one `push` operations on the stack. Any interference in the middle of these operations (i.e. other uses of the stack), may seriously compromise the calculator correctness.

From these findings we come to the need to identify three synchronization aspects for shared objects:

- *internal* (intra-object);
  - Ensure the minimum protection of the object's internal state in the presence of a concurrent use
- *conditional*;
  - Required when the object access depends on a condition that might depend on the execution of other threads
- *external* (inter-object);
  - To enable the use of one or more shared objects for more than one operation (as if it was a single one)

3.3 Internal Synchronization

- Serves to guarantee the *basic object correction*.
- It should be the *responsibility of the object*.
- The object should ensure that its *invariant* is (also) not compromised by unsynchronized uses of its services.

[1] `https://en.wikipedia.org/wiki/Reverse_Polish_notation`

- In the same way, the object should ensure sanity in the execution of all its services.
- A possibility for synchronization that warrants all these conditions is simply impose mutual exclusion in the use of all its public services (we shall see that there are others).

3.4 Conditional Synchronization

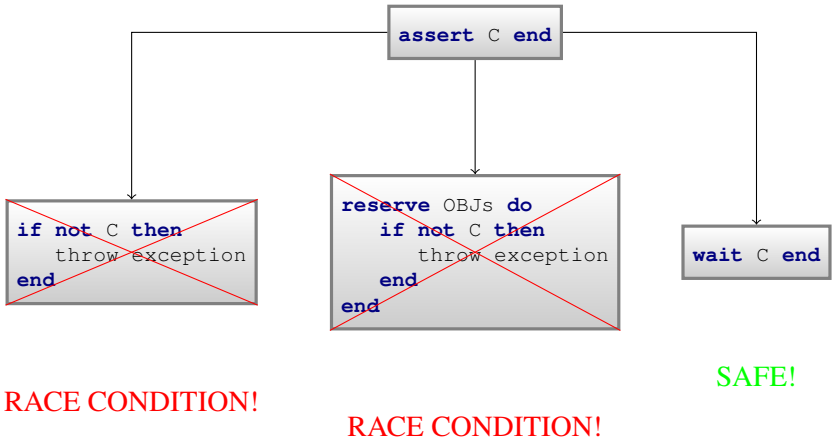
- Serves to ensure a specific *access condition to the object*.
- It can be *internal*, if the condition is directly related with the object internal state and contract;
- Or *external*, if other condition is externally imposed;
- Requires a process of *conditional waiting* or the possibility of *failure* in the access to the object (this failure can be part of try/error cycle until its verification).

3.5 External Synchronization

- Serves to ensure a *sequential (alike) access* to the object for the realization of a sequence of operations;
- The need for this synchronization aspect comes from outside client code, thus failures in this synchronization do not compromise the object's invariant.
- The simplest synchronization scheme for external synchronization is mutual exclusion.

4 Contracts and Concurrency

- The meaning of contracts in a sequential program is simple and clear: an assertion is a correctness condition that must be true in its application point (or else, we are in the presence of a program error.
- It is the type of the false assertion (invariant, precondition, postcondition, etc.) that determines the code responsible for the error.
- What about in a concurrent context?
- What is *meaning of a concurrent assertion?* (i.e. an assertion with a condition whose truthness may depend on the execution of another thread.)



- So we come to the following rule:

Concurrent Assertions: A concurrent assertion only makes sense if it is a waiting condition for the condition!

- As a corollary we have that condition synchronization (internal or external) is closely related with assertion semantics.

- It is important to emphasize that an assertion can both be sequential or concurrent depending on its execution context (hence is it a dynamic property).
- That is, an assertion using one or more shared objects might be sequential or concurrent depending of an exclusive access to those objects.

```
assert (CONDITION);
```

```
assert (!lockIsMine() || CONDITION);
if (!lockIsMine()) {
   // waiting cycle for the condition...
}
```

- Another very important aspect in the behavior of concurrent assertions is related with the different *meaning for different types of assertions*.
- A *precondition* requires that a condition to be verified in the beginning of the execution of the method. Hence, besides the conditional waiting involved in a concurrent precondition, it is necessary to ensure also that the objects involved in that condition can only be modified by the method itself (i.e. an eventual external synchronization also applies).
- For *postconditions* the same situation does not apply because the code it asserts is terminating.
- In this subject, *invariants* behave like a precondition in the beginning of (public) methods, and like postcondition at the end.

5 Flux Control and Concurrency

- In imperative programming the *flux control* of programs is determined by the following instructions:
  - sequence;
  - conditional instruction;
  - iterative instruction;
  - functions.
- A sequential programs the meaning of each one of these mechanisms is very clear. Lets take as an example the *conditional instruction*:

```
if(CONDITION) {

   COMMANDS;
}
else {

   COMMANDS;
}
```

```
if(CONDITION) {
   assert CONDITION;
   COMMANDS;
}
else {
   assert !CONDITION;
   COMMANDS;
}
```

- Thus, it makes no sense to select code with a conditional (or iterative) instruction if the language does not ensure the contracts (meaning) attached to those instructions.
- The problem arises when we consider the possibility of the selecting condition to be a *concurrent boolean condition*.
- That is, a condition whose value might depend on a thread other than the one execution the instruction.
- The semantics attached to each one of these elementary instructions is only kept if it is ensured that the condition value remains the same in the selected code block.

- So we reach the following rule:

Code selection instructions: The instructions that conditionally select code through concurrent conditions only make sense if the reservation (or an atomic alternative) of the shared objects present in the condition is atomically attached to the condition test.

- As a corollary we have that external synchronization is closely associated with the semantics of instructions that conditionally select code.

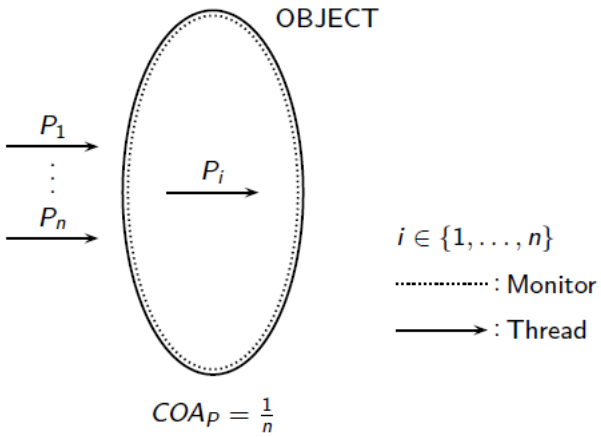
```
if (!stack.isEmpty()) {
   int elem = stack.top();
   stack.pop();
}
else
   System.out("Empty stack!!!");
```

```
synchronized(stack) {
   if (!stack.isEmpty())
   {
      int elem = stack.top();
      stack.pop();
   }
   else
      System.out("Empty stack!!!");
}
```

6 Internal synchronization schemes

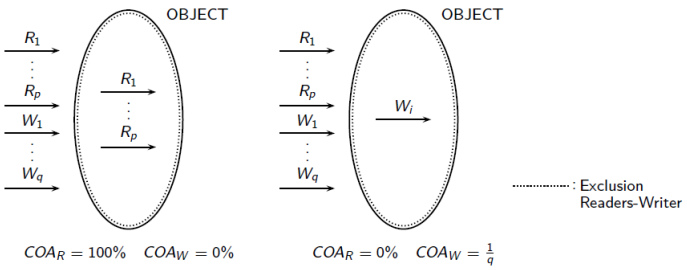
6.1 Monitor

- Force mutual exclusion in the use of all the object's public methods.



6.2 Readers-writer exclusion

- Take advantage on the command-query separation;
- Commands are *writers* and queries are *readers*.



7 Shared objects synchronization programming

7.1 Requirements

- Correctness criteria:
  - Concurrent integrity of objects;
  - Total object covering.
- Support for the three aspects of synchronization:
  - internal (intra-object);
    - Necessary to ensure the internal correctness of the object (object usable only in its stable times).
    - Two synchronization schemes were already presented: monitor and readers-writer exclusion.
  - conditional;
    - Assumes a safe waiting for the desired condition.
    - It can be applied with condition variables (over locking schemes, such as monitors, readers-writer exclusion, or others).
  - external (inter-object).
    - "Exclusive" access to more than one operation on a shared object.
    - Implemented with a mutual exclusion scheme eventually with a mixed exclusion scheme (discussed in next lecture).

7.2 Abstract synchronization

Shared objects synchronization programming

- In an object-oriented perspective, the implementation of shared objects only imposes the observation of the presented correctness criteria;
- As long as the criteria are met, any synchronization scheme can be used (from the simplest monitor alike scheme, until, eventually, lock-free schemes);
- Semantically all shared objects with a proper synchronization scheme are identical!
- Thus, it is easy to conclude that we have all the interest to separate, as clearly as possible, between the code that defines the logical sequential behavior of objects, from the synchronization code.
- The more common option is to put synchronization code together with logical business code inside the class (hard-coded).
- However, this option, has several problems:
  - It does not allow the reutilization of the class for purely sequential objects;
  - Mixes the synchronization logic with the business logic of the object.
  - Makes it very difficult to change the synchronization scheme.
- Thus, often it justifies to separate these two problems into different classes (programming of the object and synchronization programming);
- Synchronization programming can be done using the *inheritance* mechanism, redefining sequential methods and adding synchronization code;
- Alternatively, a *client* relation can be used to implement synchronization.
- These two alternatives are not equivalent from the point of view of OOP:
  - The first alternative although it directly uses fields and methods of the sequential parent class, makes it harder to provide a synchronization implementation for all objects that implement a given ADT (i.e. that are descendants of the sequential class);
  - The second, although it requires the declaration of a field that contains the reference to the sequential object, makes it possible to provide a synchronization implementation for a whole hierarchy of classes (that implement a given ADT). Hence, this is the preferred choice.

Shared objects synchronization: as a heir

```
public class Stack<T> {
  public void push(T e) {
    Node<T> n =
      new Node<T>();
    n.e = e;
    n.next = top;
    top = n;
    size++;
  }

  public void pop() {
    assert !isEmpty();

    top = top.next;
    size--;
  }

  ...

  protected Node<T> top = null;
  protected int size = 0;

  protected class Node<T> {
    Node<T> next = null;
    T e;
  }
}
```

```
public class SharedStack<T>
  extends Stack<T> {

  public synchronized void push(T e) {
    super.push(e);
    notifyAll();
  }

  public void pop() {
    assert !Thread.holdsLock(this) ||
           !isEmpty();
    synchronized(this) {
      try {
        while (isEmpty())
          wait();
        super.pop();
      }
      catch (InterruptedException e) {
        throw
  new UncheckedInterruptedException(e);
      }
    }
  }

  ...
}
```

Shared objects synchronization: as a client

```
public abstract class Stack<T> {

  public abstract void push(T e);

  //@ requires !isEmpty();
  public abstract void pop();

  //@ requires !isEmpty();
  public abstract T top();

  public boolean isEmpty() {
    return size() == 0;
  }

  public abstract int size();
}
```

```
public class SharedStack<T> {

  //@ requires stack != null;
  public SharedStack(Stack stack) {
    this.stack = stack;
  }

  public synchronized void push(T e) {
    stack.push(e);
    notifyAll();
  }

  public void pop() {
    assert !Thread.holdsLock(this) ||
           !stack.isEmpty();
    synchronized(this) {
      try {
        while (stack.isEmpty())
          wait();
        stack.pop();
      }
      catch (InterruptedException e) {
        throw
  new UncheckedInterruptedException(e);
      }
    }
  }
  ...
  protected final Stack<T> stack;
}
```

Abstract Synchronization

Subtype polymorphism inherent to OOP can also be applied to the programming of synchronization of shared classes:

```
public abstract class SharedStack<T>
{

  //@ requires stack != null;
  public SharedStack(Stack stack) {
    this.stack = stack;
  }

  public abstract void push(T e);

  //@ requires !isEmpty();
  public abstract void pop();

  //@ requires !isEmpty();
  public abstract T top();

  public boolean isEmpty() {
    return size() == 0;
  }

  public abstract int size();

  protected final Stack<T> stack;
}
```

```
public class MonitorStack<T>
  extends SharedStack<T> {

  public synchronized void push(T e) {
    stack.push(e);
    notifyAll();
  }

  public void pop() {
    assert !Thread.holdsLock(this) ||
            !stack.isEmpty();
    synchronized(this) {
      try {
        while (stack.isEmpty())
          wait();
        stack.pop();
      }
      catch (InterruptedException e) {
        throw
  new UncheckedInterruptedException(e);
      }
    }
  }

  ...
}
```