2. Concurrency and Java

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Roadmap

> **Threads in Java**
  — Threads (vs. Processes)
  — Thread creation
  — Thread lifecycle

> **Synchronization in Java**
  — `wait()` and `notify()`

> **Modelling Concurrency**
  — Finite State Processes
  — Labelled Transition Systems
Threads (vs. Processes)

> Processes
  — have their own memory
  — communicate via IPC

> Threads (lightweight processes)
  — exist within a process
  — share memory and open files
Recall: processes are heavyweight and have their own memory; threads are lightweight and share the memory of the process they are contain in.

Within classical compiled languages (like C), threads are typically supported with the help of dedicated libraries. In languages that are compiled to bytecode (like Smalltalk or Java), threads are supported by the virtual machine.
Java’s concurrency model is based on monitors. An object optionally behaves like a monitor, if the `synchronized` keyword is used to synchronize its methods. Threads are created according to the fork and join model.
To define a thread extend Thread and override run()

```java
public class Competitor extends java.lang.Thread {

    public Competitor(String name) {
        super(name); // Call Thread constructor
    }

    @Override
    public void run() { // What the thread actually does
        for (int km = 0; km < 5; km++) {
            System.out.println(km + " " + getName());
            try {
                sleep(100);
            } catch (InterruptedException e) {
            }
        }
        System.out.println("DONE: " + getName());
    }
}
```
A thread is simply an object that has a `run` method. This method can be inherited from the `Thread` class and overridden, or (next slide) the object can simply implement the `Runnable` interface.

In this example `Competitor` extends `Thread` and overrides the `run` method to print a message every 100 milliseconds.

Source code of all Java examples are available from the git repo:

```bash
git clone git://scg.unibe.ch/lectures-cp-examples
```
... or implement Runnable

```java
public interface java.lang.Runnable {
    public abstract void run();
}
```

Since Java does not support multiple inheritance, it is impossible to inherit from both Thread and another class.

Instead, simply define:

```java
class MTUsefulStuff extends UsefulStuff implements Runnable ...
```

and instantiate:

```java
new Thread(new MTUsefulStuff())
```
Instantiating Threads

A Java thread can either *inherit* from java.lang.Thread, or *contain* a Runnable object:

```java
public class java.lang.Thread extends java.lang.Object implements java.lang.Runnable {

    public Thread();
    public Thread(String name);
    public Thread(Runnable target);
    public Thread(Runnable target, String name);
    ...
}
```
public class Clock extends Canvas implements Runnable {

    private Thread clockThread = null;

    public Clock() {
        super();
        if (clockThread == null) {
            clockThread = new Thread(this, "Clock");
            clockThread.start();
        }
    }

    public void paintComponent(Graphics g) {
        ...
        String time = dateFormat.format(new Date());
        g2d.drawString(...);
    }

}
In this example, Clock needs to extend Canvas, so it cannot also extend Thread. The solution is to implement the Runnable interface.

In order to create and start a new thread in Java, one must instantiate a Thread or a subclass of Thread and then invoke the start method.

The start method will execute the run method in a new thread. Note that directly invoking the run method will not start a new thread, but will just execute run synchronously within the current thread.

In order to execute a run method of an object that implements Runnable, one simply passes that object as a parameter to a newly instantiated Thread, as in this example. To start a clock thread, a new Thread is instantiated with this (the Runnable clock object) as a parameter. Then the start method is called as usual.
The `run()` repaints the canvas in a loop while the thread is not null

```java
... public void run() {
  // stops when clockThread is set to null
  while(Thread.currentThread() == clockThread) {
    repaint();
    try {clockThread.sleep(1000); }
    catch (InterruptedException e){ }
  }
}

public void stopThread() {
  clockThread = null;
}
```
NB: The `stopThread` method is invoked when the stop button is pressed.
After construction...

Thread

- start()
- yield()
- run() exits
- sleep()
- wait()
- i/o block
- time elapsed
- notify() / notifyAll()
- i/o completed

Runnable

Not Runnable
This UML statechart illustrates the lifecycle of a Java thread. Once a Thread instance has been created, nothing happens until the start method is called. At that point the thread becomes “Runnable”. This means that the thread scheduler may schedule it to run for a period of time. If the thread explicitly yields, then another thread may be scheduled, but the thread remains runnable.

If, on the other hand, the thread is forced to wait for something, i.e., a timer event (sleep), a monitor synchronization condition (wait), or an i/o event (reading or writing), then the thread becomes not runnable, until the awaited event occurs.

Finally, if the run method terminates, the thread will exit.
To start a thread... call `start()`

A Thread’s run method is never called directly but is executed when the Thread is `start()-ed`:

```java
class Race5K {
    public static void main (String[] args) {
        // Instantiate and start threads
        new Competitor("Tortoise").start();
        new Competitor("Hare").start();
    }
    ...
}
```
The Racing Day!

Different runs can have different results.

No given ordering of threads is guaranteed by the JVM.

Could the output be garbled? Why? Why not?

0 Hare 0 Tortoise
0 Hare
0 Tortoise
1 Hare
1 Tortoise
1 Hare
2 Tortoise
2 Hare
2 Tortoise
3 Hare
3 Tortoise
3 Hare
4 Tortoise
4 Tortoise
4 Hare
DONE: Tortoise
DONE: Hare
DONE: Hare
DONE: Hare
DONE: Tortoise
...
We see that the outputs of the two threads can be arbitrarily interleaved, but only on a line-by-line basis. Why don't we see individual characters interleaved?
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Without synchronization, an arbitrary number of threads may run at any time within the methods of an object.

—Class invariant may not hold when a method starts!
—So can’t guarantee any post-condition!

A solution: consider critical sections that lock access to the object while it is running.
In sequential software, the *class invariant*, which expresses the valid states of instances of the class, is assumed to hold when the object is first created, and before and after every public method. During a public method (or any internal private or protected method) the invariant may be temporarily invalid, while the object’s state is being updated. This poses a problem for concurrent programs. Without synchronization, a thread may enter a public method when another thread is active elsewhere, and the class invariant may not hold, i.e., the object may be in an inconsistent state. As a consequence, the second method is likely to produce incorrect results.

See also: [https://en.wikipedia.org/wiki/Class_invariant](https://en.wikipedia.org/wiki/Class_invariant)
Critical Section...

> ... a piece of code that accesses a shared resource (e.g. memory location) that must not be concurrently accessed by multiple threads.

> This works as long as methods cooperate in locking and unlocking access!

```c
/* This is the critical section object (statically allocated). */
static pthread_mutex_t cs_mutex = PTHREAD_MUTEX_INITIALIZER;

void f()
{
    /* Enter the critical section -- other threads are locked out */
    pthread_mutex_lock( &cs_mutex );

    /* Do some thread-safe processing! */

    /* Leave the critical section -- other threads can now
     * pthread_mutex_lock() */
    pthread_mutex_unlock( &cs_mutex );
}
```

Critical section in C/C++ on Unix/Linux
A critical section is a piece of code that accesses (reads or writes) shared resources. Inconsistencies may arise if two threads try to access the same resources during overlapping critical sections. A common solution is to guarantee mutual exclusion with the help of locks or semaphores. Of course all critical sections must be protected. If even a single critical section is not protected, two threads entering the same critical section can interfere.
Either: synchronize an individual block within a method with respect to a shared resource:

```java
public Object aMethod() {
    // unsynchronized code
    ...
    synchronized (resource) {
        // lock resource
        ...
    }
    // unlock resource
    ...
}
```
Critical sections can be protected in Java by declaring the relevant code as a **synchronized** block. Such a block takes as a parameter the object that is accessed as a shared resource. The resource is *locked* when the block is entered, and *unlocked* when the block ends.

Note that only a single resource can be passed as an argument to the synchronized block, even if multiple resources are accessed. If there are multiple critical sections, it is important that the same resource be locked to ensure consistency.

Aside: actually, an arbitrary object be used as the lock, not necessarily one of the resources accessed.
Synchronized methods

Or: declare an entire method to be synchronized with other synchronized methods of this object:

```java
public class PrintStream extends FilterOutputStream {
    ...
    public synchronized void println(String s);
    public synchronized void println(char c);
    ...
}
```

Note: synchronized methods are a particular case of synchronizing on this object.
It is also possible to declare an *entire method* as *synchronized*. This is just syntactic sugar for declaring the entire body of the method as a *synchronized* block, with *this* object as the shared resource to be locked.

Note that by declaring *all* public methods as being synchronized, you effectively turn the object into a *monitor*. 
wait() and notify()

Synchronization must sometimes be interrupted:

```java
public class Account {
    protected long assets = 0;
    public synchronized void withdraw(int amount) {
        while (amount > assets) {
            try {
                wait();
            } catch (InterruptedException e) {
            }
        }
        assets -= amount;
    }
    public synchronized void deposit(int amount) {
        assets += amount;
        notifyAll();
    }
}
```

NB: you must either catch or throw InterruptedException
This Account class is a monitor, with methods withdraw and deposit being critical sections accessing the assets variable as a shared resource.

Since both methods are synchronized, it is guaranteed that, no matter how many threads are attempting to execute either method, at most one thread will be running within the monitor at any point in time.

This example follows a classical structure. The withdraw method may not proceed if the requested amount is greater than the available assets. The method therefore tests this guard condition in a while loop. As long as the guard fails, the thread will wait, releasing the monitor lock, and making the thread not runnable.

Eventually (we hope) some thread will deposit some cash. At this point notifyAll is called (Java’s equivalent to signal), which will cause all threads waiting on this object to be made runnable. Awakened threads will again check the guard condition, and possibly proceed or wait again.

What could go wrong if withdraw were to use an if statement instead of a while loop?
A waiting thread may receive an `InterruptedException`, so it is advisable to always wrap calls to wait within a try-catch block. It is not a good idea to leave the body of the catch clause empty (you should decide what is the appropriate action), but for the example programs we will generally ignore this issue.
final Account myAccount = new Account();

new Thread() { // Withdrawing
    public void run() {
        int amount = 100;
        System.out.println("Waiting to withdraw"+amount+ "units...");
        myAccount.withdraw(amount);
        System.out.println("I withdrew " + amount + " units!");
    }
}.start();

Thread.sleep(1000); ... 

new Thread() { // Depositing
    public void run() {
        int amount = 200;
        System.out.println("Depositing " + amount + " units ...");
        myAccount.deposit(amount);
        System.out.println("I deposited " + amount + " units!");
    }
}.start();
java.lang.Object

NB: wait() and notify() are methods rather than keywords:

```java
public class java.lang.Object {
    ...
    public final void wait() throws InterruptedException;
    public final void notify();
    public final void notifyAll();
    ...
}
```
While `synchronized` is a keyword, `wait` and `notify` are methods defined in the class `Object`, i.e., the root of the Java class hierarchy, and are thus inherited by all classes.

The difference between `notify` and `notifyAll` is that the latter will wake up all waiting threads, while the former will only wake up one. As we shall see in a later lecture, it is generally a bad idea to use `notify` instead of `notifyAll`. (You risk waking up the wrong thread.)

NB: `wait` and `notify` may *only* be called within a `synchronized` block. Attempting to do otherwise will raise an `IllegalMonitorException`. (This is a common beginner’s mistake.)
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Non-determinism

- Multiple threads are rotated by the processor(s)
- A thread might be interrupted at any time
- No two runs are guaranteed to be the same
Modelling Concurrency

Because concurrent systems are non-deterministic, it can be difficult to build them and reason about their properties.

A model is an *abstraction of the real world* that makes it easier to focus on the points of interest.

**Approach:**

Model concurrent systems as *sets of sequential finite state processes*
**Finite State Processes**

**FSP** is a *textual notation* for specifying a finite state process:

\[ \text{SWITCH} = (\text{on} \rightarrow \text{off} \rightarrow \text{SWITCH}) \].

**LTS** (labeled transition system) is a *graphical notation* for interpreting a processes as a labelled transition system:

The *meaning* of a process is a set of possible *traces*:

\[ \text{on} \rightarrow \text{off} \rightarrow \text{on} \rightarrow \text{off} \rightarrow \text{on} \rightarrow \text{off} \rightarrow \text{on} \rightarrow \ldots \]
FSP and LTS are two complementary notations for representing finite state processes.

FSP is textual language for specifying processes as sequences of actions with choices, while LTS is a graphical notation that resembles finite state automata. In both cases, the semantics of the notations is a set of possible traces, i.e., sequences of actions.

**SWITCH** is a process that can participate in the action `on`, then in `off`, and then returns to its initial state. Note how process names start with an upper case letter and actions are in lower case. The examples can all be run with the LTSA tool. A snapshot of the tool and all examples from this course can be found in the examples repo:

```
git clone git://scg.unibe.ch/lectures,cp-examples
```

For the latest version of the tool, visit the LTSA web site:

[https://www.doc.ic.ac.uk/ltsa/](https://www.doc.ic.ac.uk/ltsa/)
| **Action prefix**       | (x→P)                     | **Parallel composition** | (P | | Q)                     |
|------------------------|---------------------------|--------------------------|---------------------------|
| **Choice**             | (x→P|y→Q)                  | **Replicator**           | forall [I:1..N] P(I)      |
| **Guarded Action**     | (when B x→P|y→Q)          | **Process labelling**    | a:P                       |
| **Alphabet extension** | P + S                     | **Process sharing**      | {a₁,...,aₙ}::P            |
| **Conditional**        | x→ If B then P else Q     | **Priority High**        | ||C=(P| Q)<<{a₁,...,aₙ}    |
| **Relabelling**        | /{new₁/old₁,...}          | **Priority Low**         | ||C=(P| Q)>{a₁,...,aₙ}     |
| **Hiding**             | \{a₁,...,aₙ}              | **Safety property**      | property P                |
| **Interface**          | @{a₁,...,aₙ}              | **Progress property**    | progress P = {a₁,...,aₙ}  |

*We will encounter and use these features in the lectures to come...*
This slide is provided both as a quick reference and as an overview to give a flavour of what the FSP language looks like. Each of these operators can be used to compose processes or modify processes, yielding a new process each time. We will encounter many of these operators in later lectures, and explain them in detail when necessary.

For a brief explanation, see the on-line appendix:

If $x$ is an action and $P$ a process then $(x \rightarrow P)$ is a process that initially engages in the action $x$ and then behaves like $P$.

**ONESHOT** = (once $\rightarrow$ STOP).

**Convention:**
Processes start with **UPPERCASE**, actions start with **lowercase**.
The most basic operator in FSP is *action prefix*. Here the process ONESHOT may participate in the action *once*, turning into the process STOP.

STOP is a predefined process that does nothing.

Note that a process expression in FSP also represents the *state* of a process. In the LTS graph of the process ONESHOT, state (0) is the same as ONESHOT while state (1) is the same as STOP.

The *meaning* of the process ONESHOT is the trivial set of traces: \{ *once* \}. 

Repetitive behaviour uses recursion:

\[
\text{SWITCH} = \text{OFF}, \\
\text{OFF} = (\text{on} \rightarrow \text{ON}), \\
\text{ON} = (\text{off} \rightarrow \text{OFF}).
\]
A recursively-defined process is one that, following a particular sequence of actions, may return to its initial state.

The process SWITCH starts in the state (process) OFF, then transitions to ON, and back again. In the LTS diagram, OFF is the same as state (0) and ON is state (1).

Note the syntax: SWITCH is defined as a comma-separated sequence of process definitions, terminated with a period. The meaning of SWITCH is the singleton set of traces

\{ on off on off ... \}
If $x$ and $y$ are actions then $(x \rightarrow P \mid y \rightarrow Q)$ is a process which initially engages in *either* of the actions $x$ or $y$.

If $x$ occurs, the process then behaves like $P$; otherwise, if $y$ occurs, it behaves like $Q$.

$$\text{DRINKS} = (\text{red} \rightarrow \text{coffee} \rightarrow \text{DRINKS} \mid \text{blue} \rightarrow \text{tea} \rightarrow \text{DRINKS})$$

**What are the possible traces of DRINKS?**
A process that can only follow a fixed sequence of actions is not very interesting. The *choice operator* allows a process to follow two possible different paths.

Note that the actions that DRINKS may participate in are *mutually exclusive*. If the red button is pushed (action “red”), then the drinks machine deterministically produces a cup of coffee.

Note how the notion of an “action” in FSP (“transition” in LTS) can be used to model different kinds of events (pushing a button, producing a cup of coffee or tea). Within FSP/LTS, there is no notion of a direction of an interaction between processes, but there may be in the world that is being modeled.

What are the possible traces of the DRINKS machine?
FSP — Non-determinism

\[(\text{x} \rightarrow P \mid \text{x} \rightarrow Q)\] performs \(\text{x}\) and then behaves as either \(P\) or \(Q\).

\[
\text{COIN} = \\
(\text{toss} \rightarrow \text{heads} \rightarrow \text{COIN} \\
\mid \text{toss} \rightarrow \text{tails} \rightarrow \text{COIN})
\]
This example is very similar to the DRINKS machine, except that the choices here are *not* mutually exclusive. A COIN can be tossed, at which point it non-deterministically moves either to the state `heads->COIN` or `tails->COIN`. 
FSP — Guarded actions

(when \( B \ x\rightarrow P \mid y\rightarrow Q \)) means that \emph{when the guard} \( B \) \emph{is true} then \emph{either} \( x \) or \( y \) may be chosen; otherwise if \( B \) is false then only \( y \) may be chosen. (default case is optional)

\[
\text{COUNT} (N=3) = \text{COUNT}[0],
\text{COUNT}[i:0..N] = \\
(\text{when}(i<N) \text{inc}\rightarrow \text{COUNT}[i+1] \\
| \text{when}(i>0) \text{dec}\rightarrow \text{COUNT}[i-1])
\]
Guards can be used as a high-level way to define more complex processes. It is important to realize that these guards are actually static, not dynamic. This means that the “variables” and guards can be macro-expanded.

This example is equivalent to:

\[
\begin{align*}
\text{COUNT} & = \text{COUNT0}, \\
\text{COUNT0} & = (\text{inc} \rightarrow \text{COUNT1}), \\
\text{COUNT1} & = (\text{inc} \rightarrow \text{COUNT2} \mid \text{dec} \rightarrow \text{COUNT0}), \\
\text{COUNT2} & = (\text{inc} \rightarrow \text{COUNT3} \mid \text{dec} \rightarrow \text{COUNT1}), \\
\text{COUNT3} & = (\text{dec} \rightarrow \text{COUNT2}).
\end{align*}
\]

Clearly the version with macro variables and guards is easier to read and write.
Competitor can be modelled as a single, sequential, finite state process:

\[
\text{Competitor } = ([1] \rightarrow [2] \rightarrow [3] \rightarrow [4] \rightarrow \text{ done} \rightarrow \text{ STOP}).
\]

Or, more generically:

\[
\begin{align*}
\text{const } N & = 4 \\
\text{COMPETITOR} & = \text{KM}[0], \\
\text{KM}[n:0..N] & = ( \text{when } (n<N) [n+1] \rightarrow \text{KM}[n+1] \\
& \quad \text{when } (n==N) \text{ done} \rightarrow \text{ STOP}).
\end{align*}
\]
Here we model the Competitor Java class we saw earlier in the lecture. From the process modeling perspective, the only interesting point is that every kilometer, the Competitor announces its progress.
We can relabel the transitions of Simple and concurrently compose two copies of it:

\[ ||\text{Race5K} = (\text{tortoise:Competitor} \mid \mid \text{hare:Competitor}). \]
There are two things going on in this example. First we *prefix* two instances of *Competitor*, one with “tortoise” and the other with “hare”. This has the effect of *relabeling all the actions* of each process, so \([1]\) becomes *tortoise*[1], and so on. These relabeled events are *independent* of each other, as their names are different.

Second, we *concurrently compose* these two processes with the `\|\|` operator. (Note that this is different from the choice operator `\|` we saw earlier.)

These two processes may now proceed independently, *arbitrarily interleaving* their actions. (In a later lecture we will see how two processes may synchronize with each other if they share common actions.)
If we restrict ourselves to two steps, the composition will have nine states:
Try this example with LTSA. Change the number of iterations from 5 to 2 to get this result.

How does LTSA decide which are the shared states of the composed processes?
The state space of two composed processes is (at most) the Cartesian product of the individual state spaces.
If two independent processes are composed, the resulting state space is potentially the Cartesian product of the two state spaces. Since the tortoise and the hare do not interact, we obtain 9 states. (Later we will see that if composed processes need to synchronize, the resulting state space may be drastically reduced.) Compare this diagram with the one in the previous slide produced by the LTSA tool.
Transitions between Thread States

Thread

Runnable

- start()
- run()
- yield()
- time elapsed
- notify() / notifyAll()
- i/o completed

Not Runnable

- sleep()
- wait()
- i/o block
- run() exits

i/o block
Recall the UML statechart describing the possible state transitions of a Java thread. We can easily model this with FSP.
LTS for Thread States

Thread = ( start -> Runnable ),
Runnable =
    ( yield -> Runnable
    | {sleep, wait, blockio} -> NotRunnable
    | stop -> STOP ),
NotRunnable =
    ( {awake, notify, unblockio} -> Runnable ).
The only new feature of FSP here is the ability to specify a set of actions in a transition to a new process state.
What you should know!

- What are finite state processes?
- How are they used to model concurrency?
- What are traces, and what do they model?
- How can the same FSP have multiple traces?
- How do you create a new thread in Java?
- What states can a Java thread be in?
- How can it change state?
- What is the Runnable interface good for?
- What is a critical section?
- When should you declare a method to be synchronized?
Can you answer these questions?

> How do you specify an FSP that repeatedly performs `hello`, but may stop at any time?
> How many states and how many possible traces does the full Race5K FSP have?
> When should your class inherit from `Thread`?
> How can concurrency invalidate a class invariant?
> What happens if you call `wait` or `notify` outside a synchronized method or block?
> When is it better to use synchronized blocks rather than methods?
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