http://cs.LTH.se/EDA040

Real-Time and Concurrent Programming

Lecture 1 (F1):

Embedded concurrent software

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Part I

Course Information

Outline

- Following information about the course, today's lecture will cover:

1. Concurrency
2. Minimalistic concurrent applications
3. Basic concepts
4. Semaphores
5. Threads

- Home-page of the course: `http://cs.lth.se/EDA040`
- All material/slides in English but remaining lectures in Swedish; Extra session for exchange students, when?
- On the course home-page, you find links to the enrolls for the labs (HT1) and later for the project (HT2 grouping).

Course material

The course program is available via the EDA040 home-page.
The combination of printed and electronic course material is under consideration. Also, we recently found some useful additional (electronically available) reading. Therefore, the printed booklet that earlier years was provided at first lecture (at a net/non-profit cost of 100SEK) will not be composed this year.

- What is the general interest in printed material? Learning outcome?
- Exercises and material for labs are available via the homepage. Bring (e.g., electronically) your course material to the exercise sessions!
- Some additional material for labs and for the project will be provided (at no or net cost) during the course.
- Practices, updates and reading instructions via web.

The printed booklet version from previous course instances works fine (for those retaking the course/exam).

Changes

Ongoing and planned improvements, as of last year:

- Booklet and articles updates.
- Mandatory review exercise after Lab2 forming a milestone.
- New hardware for Lab1.
- New camera hardware for the projects (Thanks to Axis!).
- Improved lab and project software, including Jaca2C translator.
- More course material available online.
- Labs are still done pairwise, but each individual should maintain/provide their solution.
- Addition of state-machines to course content (Lecture 7).
- More emphasis on deployment.

Major revision of written material ongoing...

Related courses

The following courses are technically related with this one, with small overlaps in initial content, but with quite different focus.

EDAN15; *Design of Embedded Systems*: Also embedded software with issues of parallelism and scheduling, but towards programmable hardware (VHDL) and System on Chip (SoC) `http://cs.lth.se/EDAN15` (See also EDA385)

FRTN01; *Real-Time Systems*: Introduces concurrent programming and covers real-time aspects for control purposes, but it is bigger course with the main parts about discrete-time feedback control `http://www.control.lth.se/user/FRTN01`

EDA050; *Operating Systems*: Concurrency and OS processes with resembling techniques, but not targeting embedded systems and the platform rather than application development is the focus. `http://cs.lth.se/EDA050`

EIEF01; *Applied Mechatronics*: Quite short introduction to concurrency and embedded software in line with lab 1, but emphasis is on the combination with electro-mechanical systems and engineering/project aspects. `http://iea.lth.se/tillmek`

There are extended/alternative lab assignments for students studying both this course and FRTN01 or EIEF01. The involved departments collaborate towards coherent software techniques and maximum learning outcome.

Threads are light-weigt and suitable for embedded systems; Processes have their own resources

Threads and processes

Threads in OS-process

- ◇ Semaphore object within program/JVM
- ◇ Monitor (mutex for shared data)
- ◇ Messages (data flow via event buffers)

- ○ sub-milliseconds

- Hosted in os-process
- Language support
- `class Thread`, `synchronized`

EDA040 practice

OS-process

- ◇ OS-Semaphore as a resource
- ◇ File content and file locking
- ◇ Pipe, stream and socket

- ○ milliseconds

- Hosted in computer
- OS/API support
- classes System, Runtime, Process

See EDA050

Embedded threads

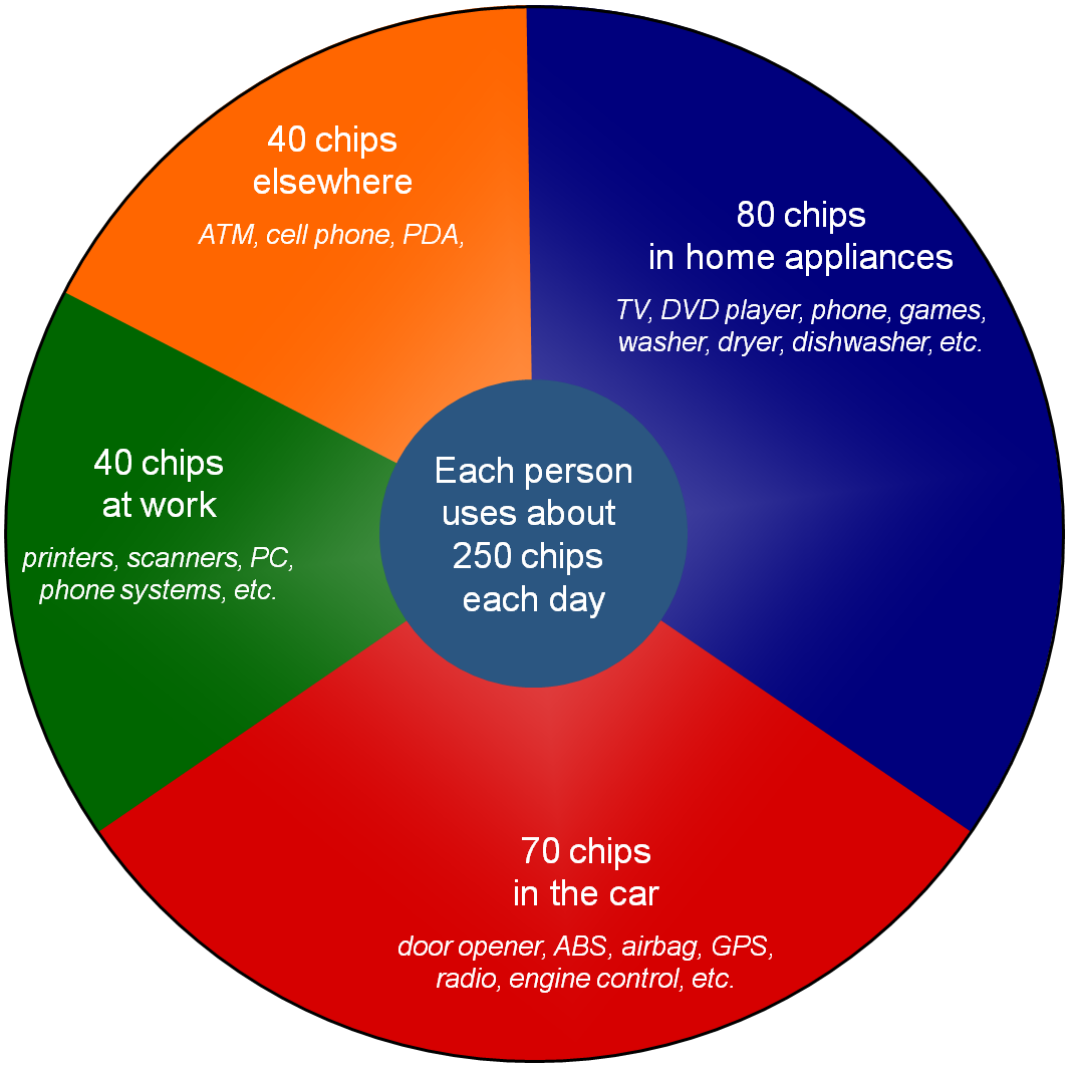
- ◇ Sem object and/or HW
- ◇ Monitor (on-board memory)
- ◇ Messages (network, fieldbus, event buff)

- ○ microseconds

- Hosted on board
- Language support
- `class Thread`, `synchronized`

EDA040 content

Embedded computing for you as a consumer



Software everywhere

- Most 'chips' programmed; you use a lot of software.
- Embedded microprocessors by far the most common type of computer.
- Scarce computing resources for market competitiveness.
- Should not behave (or crash) like desktop PCs.

Embedded computing for you as an engineer

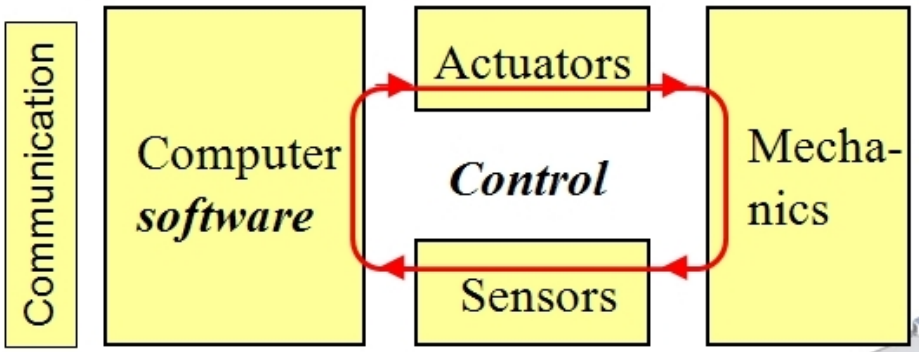
Likely roles for you in industry:

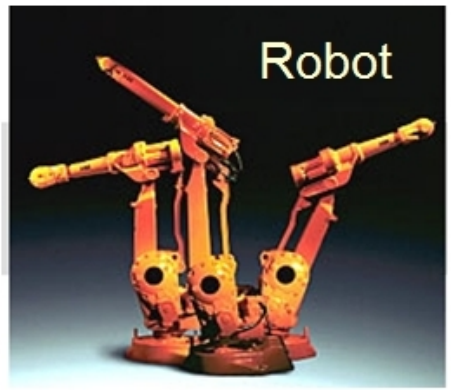
- Developer of core platforms
- Application engineering
- Technical support
- Sales or Purchasing (components, subsystems, outsourcing, ..)
- Management (of products, projects or departments)
- New company (systems and/or solutions)

The software technologies and the associated predictability/reliability issues we are covering in this course is highly relevant for all these professional roles.

Products with embedded software

Embedded control imposes real-time requirements

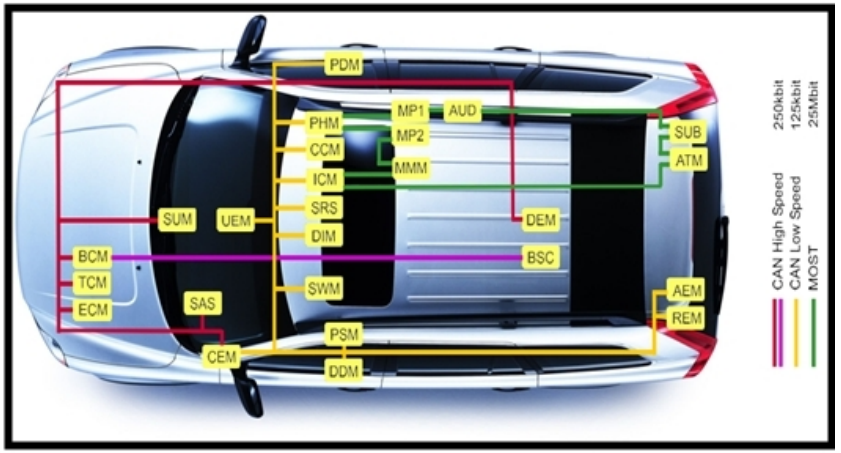




Distributed software and real-time networking

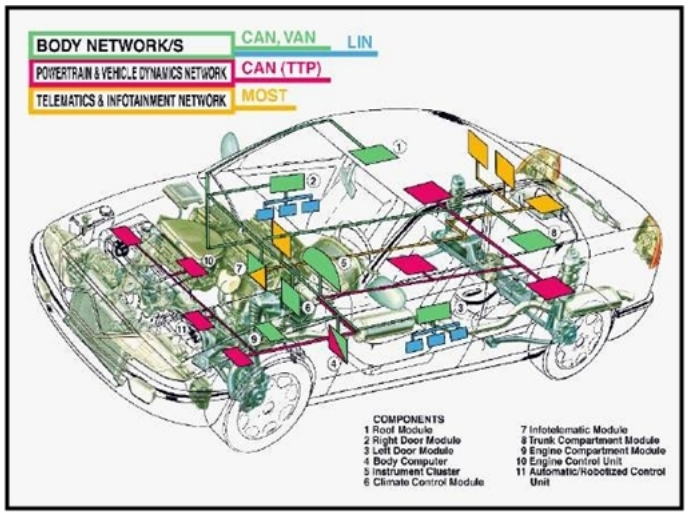
Volvo XC 90:

- **3 CAN-buses**
- **+ other buses**



40-100 ECUs in a new car

~ 2-5 miljon lines of code



Part II

Embedded concurrent real-time software

Concurrent computing and correctness

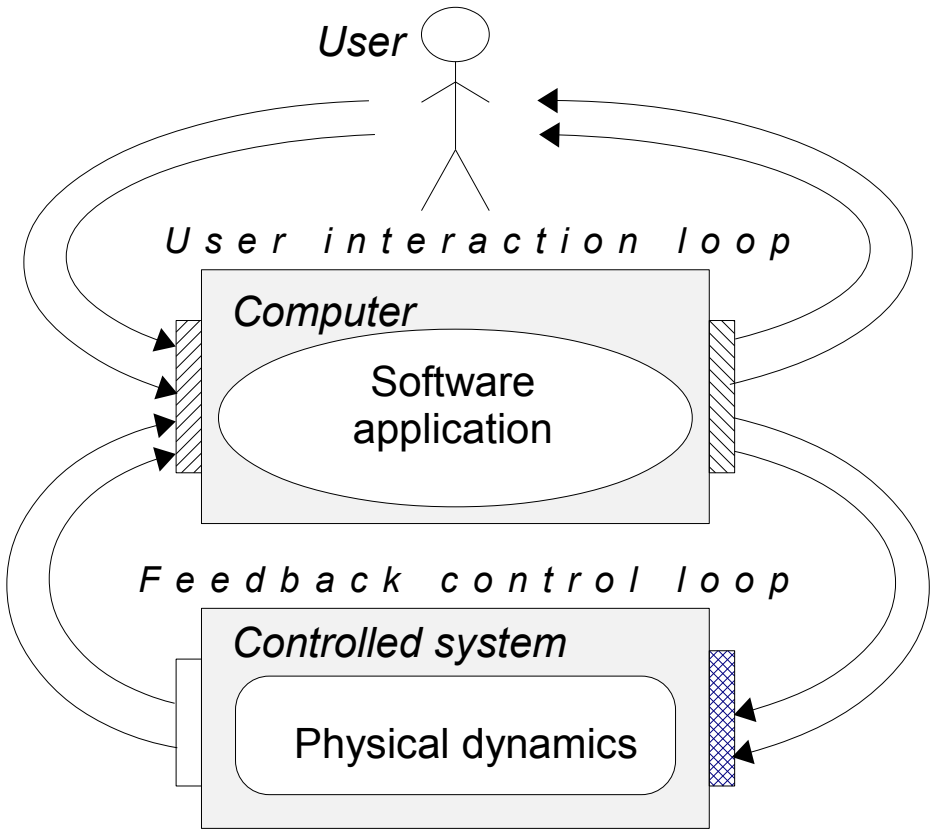
Correctness

The software must

- perform computations logically correct in each activity, and
- react on input events concurrently and give the correct output for any possible execution order,

otherwise the systems may fail (is not correct).

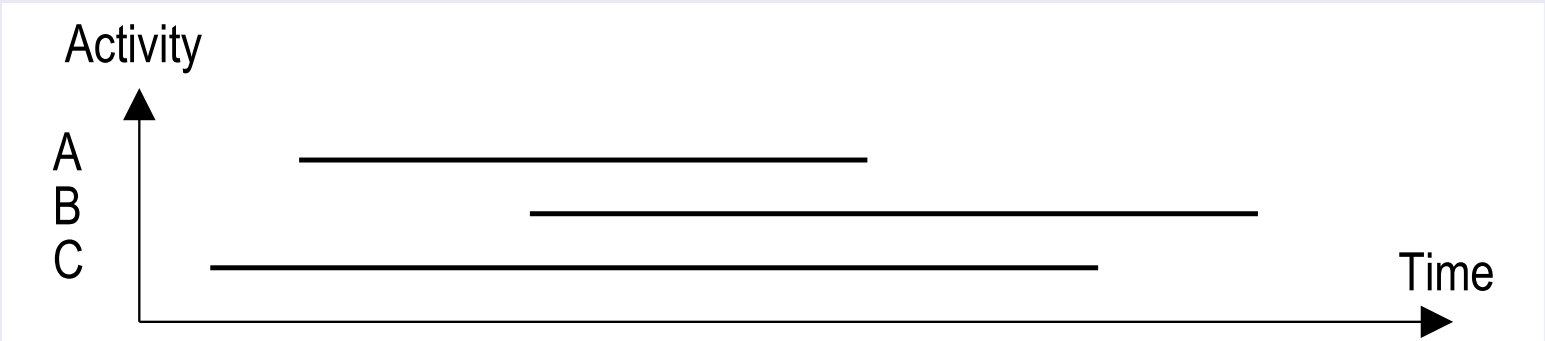
Generic system



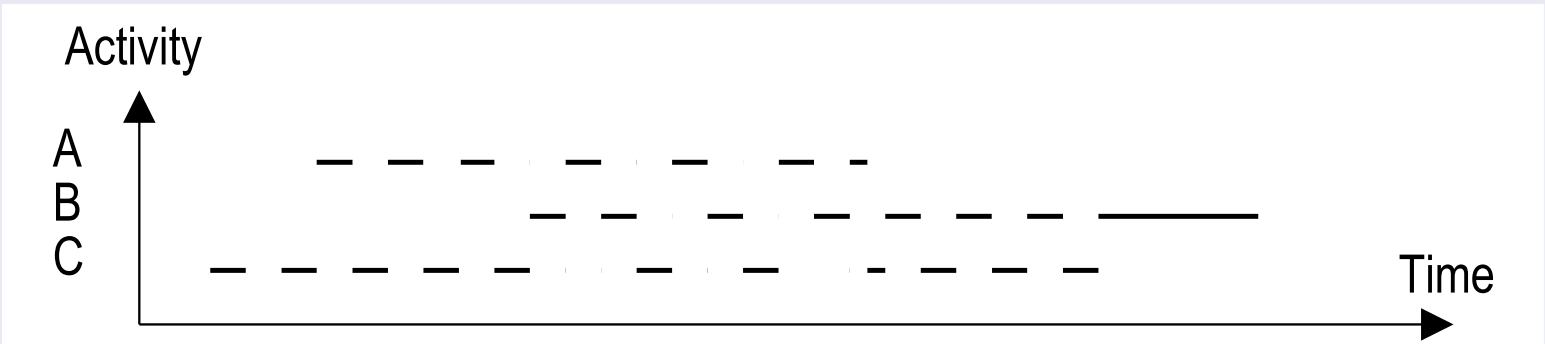
Each activity should be a *reactive*; responding to time increments and external events, but not executing when nothing happens.

Concurrency on a single-core CPU

Logical concurrency



Time-sharing concurrency

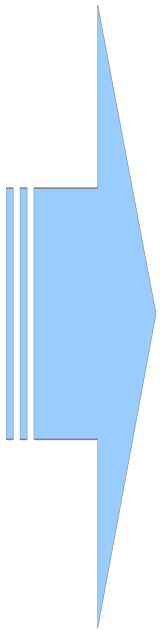


- Each concurrent activity needs to be a logically correct sequential program.
- All concurrent activities together must be concurrently correct.

Concurrency and software constructs

Application concurrency

- Sequential computing within activity



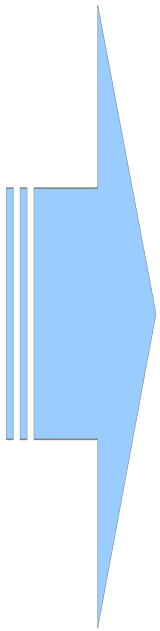
Programming means

- Normal Java (or C/C#/..) code/execution

Concurrency and software constructs

Application concurrency

- Sequential computing within activity
- Parallel/physical environment



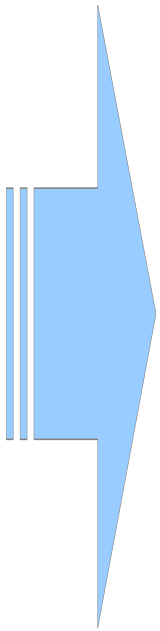
Programming means

- Normal Java (or C/C#/..) code/execution
- Concurrent threads (or processes or tasks)

Concurrency and software constructs

Application concurrency

- Sequential computing within activity
- Parallel/physical environment
- Data and operations



Programming means

- Normal Java (or C/C#/..) code/execution
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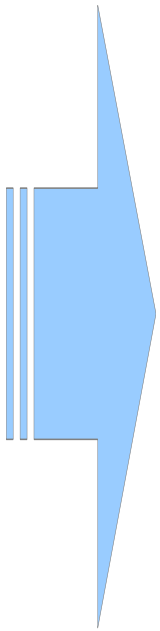
- Object-Oriented Progr.

Concurrency and software constructs

Application concurrency

- Sequential computing within activity
- Parallel/physical environment
- Data and operations
- Mutual exclusion; critical sections



Programming means

- Normal Java (or C/C#/..) code/execution
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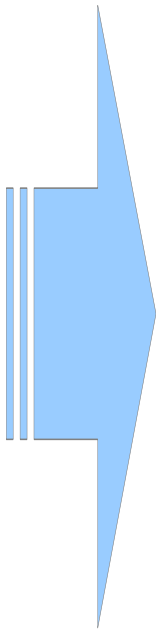
- Mutex-semaphore or `synchronized`

Concurrency and software constructs

Application concurrency

- Sequential computing within activity
- Parallel/physical environment
- Data and operations
- Mutual exclusion; critical sections
- Signaling between activities



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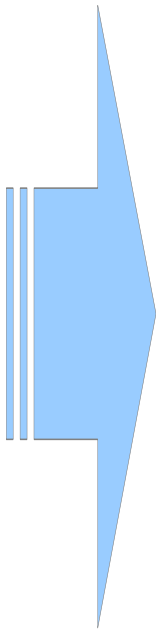
- Mutex-semaphore or `synchronized`
- Counting-semaphore or `wait/notify`

Concurrency and software constructs

Application concurrency

- Sequential computing within activity
- Parallel/physical environment
- Data and operations
- Mutual exclusion; critical sections
- Signaling between activities
- Response time requirements



Programming means

- Normal Java (or C/C#/..) code/execution
- Concurrent threads (or processes or tasks)
- Object-Oriented Progr.
- Mutex-semaphore or `synchronized`
- Counting-semaphore or `wait/notify`
- Real-time scheduling, scheduling analysis

Our focus now: The upcoming first lab

- The first halv of the lectures the focus is on introducing the labs.
- The first five exercises also do that, either as direct preparation or by introducing the concepts.

Exercise 1:

1. Semaphores
2. Signaling and mutex
3. Place operations inside methods and objects.

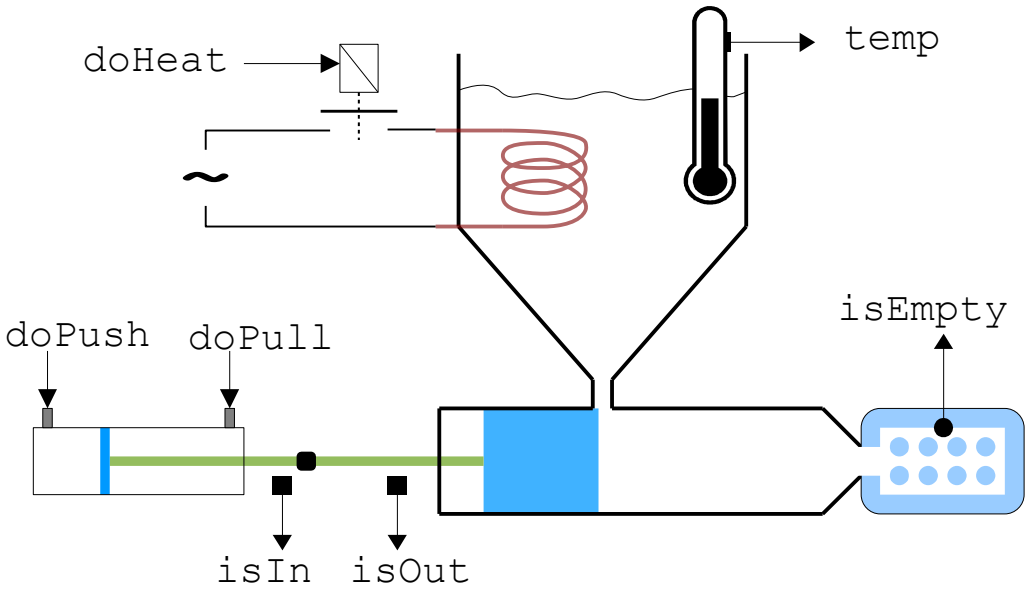
Basics for Lab 1.

Lab 1 (& exercise 2):

- Use semaphores to implement software for an alarm clock.
- Event-driven and time-driven threads sharing time data.

Essence of threads and semaphores.

Implementation without concurrent programming support

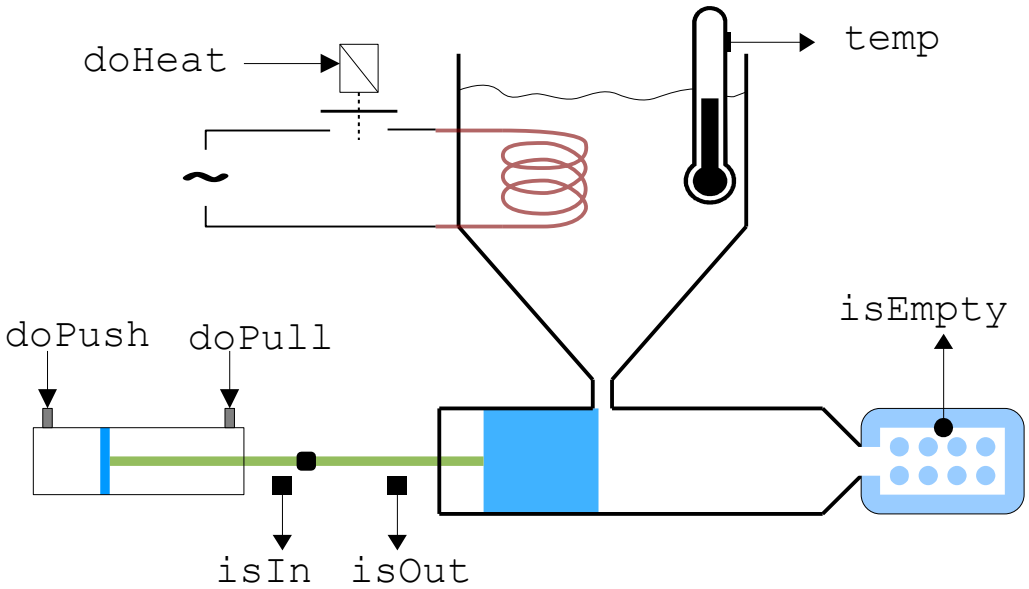


Using single activity of the `main` program

- Control temperature (periodically) and the piston (event driven).
- As one program/activity (note the code duplication):

```
while (true) {
  while (! isEmpty) {
    tempControl();
    sleep(dT);
  }
  On(doPush);
  while (!isOut) {
    tempControl();
    sleep(dT);
  }
  off(doPush); on(doPull);
  while (! isIn) {
    tempControl();
    sleep(dT);
  }
  off(doPull);
}
```

Improved structure by concurrent programming



Application concurrency reflected in code

Software more natural and easy to change/maintain if expressed as two concurrently running activities (assuming such run-time support):

```
// Activity 1: Temperature
while (true) {
  if (temp > max)
    off(doHeat);
  else if (temp < min)
    on(doHeat);
  sleep(dT);
}
// Activity 2: Piston
while (true){
  await(isEmpty);
  on(doPush);
  await(isOut);
  off(doPush);
  on(doPull);
  await(isIn);
  off(doPull);
}
```

Correct concurrency

Consider bank account transactions by you (A) and your employer (B)

Case 1: Withdraw first

```
A: Read 5000
A: amount = 5000 - 1000
A: Write 4000
   B: Read 4000
   B: amount = 4000 + 10000
   B: Write 14000
```

Case 2: Salary first

```
   B: Read 5000
   B: amount = 5000 + 10000
   B: Write 15000
A: Read 15000
A: amount = 15000 - 1000
A: Write 14000
```

Two activities (threads or processes) independently make their transactions, but not at the same time. Correct result in both cases.

Faulty concurrency

With run-time support for concurrent activities, we might get

Timing 1:

```
A: Read 5000
   B: Read 5000
A: amount = 5000 - 1000
   B: amount = 5000 + 10000
A: Write 4000
   B: Write 15000
```

Timing 2:

```
A: Read 5000
   B: Read 5000
   B: amount = 5000 + 10000
   B: Write 15000
A: amount = 5000 - 1000
A: Write 4000
```

- Concurrency fault: Wrong result for some interleavings.
- Needed: Mutual exclusion (critical sections, atomic actions)

Observations and reflections

The Lego-brick machine

- For the temperature control the loop is timed (timing?).
- The piston control is a sequencing control.
- Concurrency control is about ensuring machine performance.

The bank account

- Sequencing is due to computer/machine operations as such.
- Concurrency control is about maintaining system consistency.

The concurrent activities for the ..

- .. Lego-brick machine are only connected physically.
- .. Bank account are only connected via shared data.

[Sequential] Software execution

You know that the computer works sequentially, but:

- Consider the following code snippet:

```
int x = 2;
while (x>1) {
    if (x==10) x = 0;
    x++;
};
```

[Sequential] Software execution

You know that the computer works sequentially, but:

- Consider the following code snippet:

```
int x = 2;
while (x>1) {
    if (x==10) x = 0;
    x++;
};
```

- Easy: What value will x get?

[Sequential] Software execution

You know that the computer works sequentially, but:

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```
int x = 2;
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```

- Easy: What value will x get?
- Tricky: Why do many beginners give the answer 0?

[Sequential] Software execution

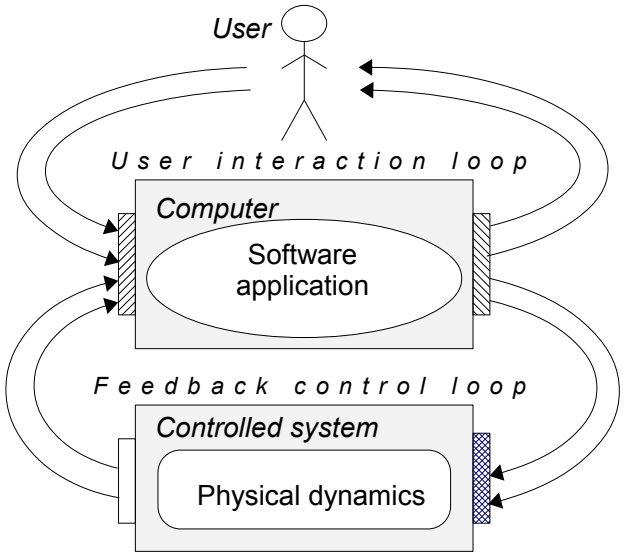
You know that the computer works sequentially, but:

- Consider the following code snippet:

```
int x = 2;
while (x>1) {
    if (x==10) x = 0;
    x++;
};
```

- Easy: What value will x get?
- Tricky: Why do many beginners give the answer 0?
- Answer: They do not think sequentially yet.

Sequential and parallel behaviors/objects



Sequential activities:

- Single actor/user actions.
- Software execution.

Inherently parallel:

- Physical dynamics.
- Electronic hardware.

but sequenced by IO system.

Concurrent programming: Use multiple sequences/activities to manage multiple actors and IO from/to a parallel environment

Embedded computers; control software: Sequential programs behaving concurrently and in real time to control a parallel environment. Control actions impose real-time requirements.

$\Rightarrow$ *We must think both sequentially and concurrently...*

Activity – Process – Thread

Definitions concerning concurrently running (swe: jämlöpande) software:

Activity An entity[0] performing[1] actions[2].

Process An entity, holding its own resources, performing[1] instructions[3], typically in a competing manner.

Job Sequential instructions to reach a well-defined state, such as the initial state, to be performed by an activity, within a given time with given resources and without interference of other activities.

Task A set of jobs being sequentially performed by some process.

Thread A sequential activity that performs instructions.

---

[0] That which is perceived or known or inferred to have its own distinct existence

[1] Actively doing, in a sequential fashion, possibly concurrently.

[2] Something being done/made/performed.

[3] A description of how to perform a set of actions.

Critical sections

- Parts of a program that access a shared resource/object
- May not be interrupted by each other, or by another invocation of itself, *for that shared data/object*.
- Accomplished by Semaphores, Monitors, or Mailboxes.
- In low-level/native code, such as device drivers, hardware interrupts can be disabled.

Well known concern in software, see for instance
`http://en.wikipedia.org/wiki/Critical_section`

In general terms, a resource need to be *locked* for exclusive access.

Locking the bank account for mutual exclusion

Temporarily locking the account (but not the bank) over *critical section*.

Case 1: Withdraw first

```
A: Lock account // First; no blocking
A: Read 5000
     B: Lock account  // Blocking
A: amount = 5000 - 1000
A: Write 4000
A: Unlock        //  Will unblock B
     B: Complete locking
     B: Read 4000
     B: amount = 4000 + 10000
     B: Write 14000
     B: Unlock
```

Case 2: Salary first

```
     B: Lock account // First; no block
     B: Read 5000
A: Lock account       // Blocking
     B: amount = 5000 + 10000
     B: Write 15000
     B: Unlock
A: Complete locking  // End blocking
A: Read 15000
A: amount = 15000 - 1000
A: Write 14000
A: Unlock
```

- Except the four lines with italic font, threads A&B are ready or running, managed by OS scheduler.
- The "Complete locking" requires that thread to be scheduled; with strict priorities a thread C could pass and lock.

Semaphore – A minimal mechanism for synchronization

- Positive integer variable with two operations, `take` and `give`:

```
class SemaphorePrinciple {
  int count;
  public void take() {
    while (count < 1) "suspend execution of caller";
    --count; // Got the semaphore, continuing ....
  }
  public void give() {
    if ("anyone suspended") "resume the first in queue";
    count++;
  }
}
```

NOTE: `take` and `give` are 'atomic' (odelbara) operations which require system support to implement, e.g. by disabling hardware interrupts or using a Test-and-Set instruction.

NOTE: In `take`, as long as `count==0` the caller is blocked, i.e. the execution is stopped, which differs from methods that can be implemented by ordinary Java code.

Java — Mutex Semaphore

- Declaration

```
import se.lth.cs.realtime.semaphore.*;
Semaphore mutex1;           // Not that good/clear.
MutexSem mutex2;            // Better, more expressive.
```

- Create, initialize.

```
/* Possible but not recommended: */
mutex1 = new CountingSem();   // Assigns the value zero.
mutex1 = new CountingSem(1);  // Assigns the value 1.
/* Preferred: */
mutex2 = new MutexSem();      // Assigns 1 to internal state.
```

- Use

```
mutex2.take();
amount += change; // Bank account transaction in critical section
mutex2.give();
```

- Apart form clarity, using a `MutexSem` for mutual exclusion permits better efficiency and error detection.

Semaphore – usage

Mutual exclusion

```
// Thread A
mutex.take();
***
mutex.give();
●
```

```
        // Thread B
        ●
        mutex.take();
        ***
        mutex.give()
        ●
```

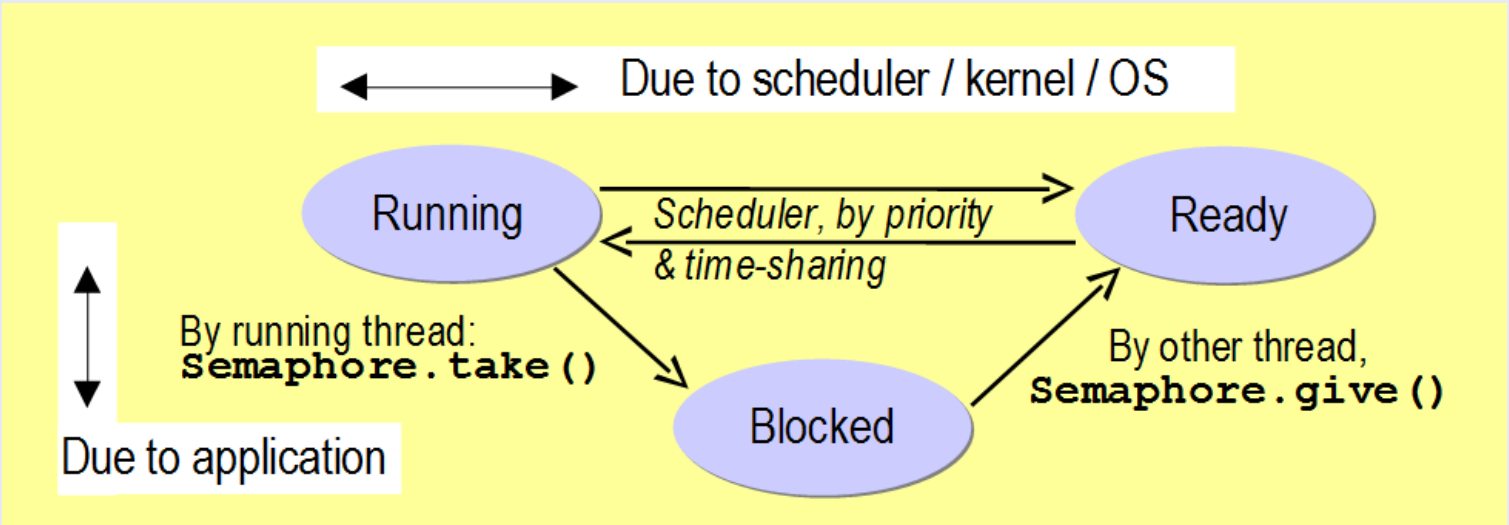
Signaling

```
// Thread A:
●
elements.give();
●
```

```
// Thread B:
●
elements.take();
●
```

Execution states and semaphores

A Thread is concurrently executing within a program, bore on that next lecture



Scheduling states

- Running
- Ready
- Blocked

Required for first lab:

- You have to use Semaphores appropriately in your code such that is gets concurrently correct!
- Proper blocking (only Ready/Running when needed).