Introduction
Semantics and applications to verification

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Program of this first lecture

**Introduction to the course:**

1. a study of some **examples** of **software errors**
   - what are the causes? what kind of properties do we want to verify?

2. a panel of the main **verification methods**
   with a fundamental limitation: **indecidability**
   - many techniques allow to **compute semantic properties**
   - each comes with **advantages** and **drawbacks**

3. an introduction to the **theory of ordered sets**
   - **order relations** are pervasive in **semantics** and **verification**
   - **fixpoints** of operators are also very common
Ariane 5 – Flight 501

**Ariane 5:**
- a satellite launcher
- replacement of Ariane 4, a lot more powerful
- first flight, June, 4th, 1996: failure!

**Flight story:**
- nominal take-off, normal flight for 36 seconds
- $T + 36.7$ s: angle of attack change, trajectory lost
- $T + 39$ s: disintegration of the launcher

**Consequences:**
- loss of satellites: more than $370\,000\,000$
- launcher unusable for more than a year (delay!)
- impact on reputation (Ariane 4 was very reliable)

**Full report available online:**
http://esamultimedia.esa.int/docs/esa-x-1819eng.pdf
Jacques-Louis Lions, Gilles Kahn
Trajectory control system design overview

- **Sensors**: gyroscopes, inertial reference systems...

- **Calculators** (hardware + software):
  - “Inertial Reference System” (SRI):
    integrates data about the trajectory (read on sensors)
  - “On Board Computer” (OBC):
    computes the engine actuations that are required to follow the pre-determined theoretical trajectory

- **Actuators**: engines of the launcher follow orders from the OBC

- **Redundant systems** (failure tolerant system):
  - keep running even in the presence of one or several system failures
  - traditional solution in embedded systems: duplication of systems
    aircraft flight system: 2 or 3 hydraulic circuits
    launcher like Ariane 5: 2 SRI units (SRI 1 and SRI 2)
  - there is also a control monitor
The root cause: an unhandled arithmetic error

Processor registers

Each register has a size of 16, 32, 64 bits:

- **64-bits floating point**: values in range $[-3.6 \cdot 10^{308}, 3.6 \cdot 10^{308}]$
- **16-bits signed integers**: values in range $[-32768, 32767]$
- upon **copy of data**: conversions are performed such as rounding
- when the values are too large:
  - **interruption**: run error handling code if any, otherwise crash
  - or **unexpected behavior**: modulo arithmetic or other

Ariane 5:

- the SRI hardware runs in **interruption mode**
- it has **no error handling code** for arithmetic interruptions
- the **root cause is an unhandled arithmetic conversion overflow**
A not so trivial sequence of events:

1. a conversion from 64-bits float to 16-bits signed int overflows
2. an interruption is raised
3. due to the lack of error handling code, the SRI crashes
4. the crash causes an error return (negative integer value) value be sent to the OBC (On-Board Computer)
5. the OBC interprets this illegal value as flight data
6. this causes the computation of an absurd trajectory
7. hence the loss of control of the launcher
Addressing the software error

Several solutions would have prevented this misshapening:

1. Deactivate interruptions on overflows:
   - then, an overflow may happen, and cause wrong values be manipulated in the SRI
   - but, these wrong values will not cause the computation to stop! and most likely, the flight will not be impacted too much

2. Fix the SRI code, so that no overflow can happen:
   - all conversions must be guarded against overflows:
     ```
     double x = ...;
     short i = ...;
     if(−32768. \leq x \&\& x \leq 32767.)  i = (short)x;
     else  i = ...;
     ```
   - this may be costly (many tests), but redundant tests can be removed

3. Handle conversion errors (not trivial):
   - the handling code should identify the problem and fix it at run-time
   - the OBC should identify illegal input values
A crash due to a useless task

Piece of code that generated the error:
- part of a gyroscope re-calibration process
- very useful to quickly restart the launch process after a short delay
- can only be done before lift-off…
- … but not after!

Re-calibration task shut down:
- normally planned 50 seconds after lift-off…
- no chance of a need for such a re-calibration after $T_0 + 3$ seconds
- the crash occurred at 36 seconds
A crash due to legacy software

**Software history:**
- already used in Ariane 4 (previous launcher, before Ariane 5)
- the software was tested and ran in real conditions many times yet never failed...
- but Ariane 4 was a much less powerful launcher

**Software optimization:**
- many conversions were initially protected by a safety guard
- but these tests were considered expensive (a test and a branching take processor cycles, interact with the pipeline...)
- thus, conversions were ultimately removed for the sake of performance

Yet, Ariane 5 violates the assumptions that were valid with Ariane 4
- higher values of horizontal bias were generated
- those were never seen in Ariane 4, hence the failure
A crash not prevented by redundant systems

**Principle of redundant systems:** survive the failure of a component by the use of redundant systems

**System redundancy in Ariane 5:**
- one OBC unit
- two SRI units... yet running the same software

Obviously, physical redundancy does not address software issues

**System redundancy in Airbus FBW software:**
- two independent set of controls
- three computing units per set of controls
- each computing unit comprises two computers
  - distinct softwares
  - design and implementation is also performed in distinct teams
Ariane 501, a summary of the issues

A long series of design errors, all related to a lack of understanding of what the software does:

1. Non-guarded conversion raising an interruption due to overflow
2. Removal of pre-existing guards, too high confidence in the software
3. Non revised assumptions on the inputs when moving from Ariane 4 to Ariane 5
4. Redundant systems running the same software
5. Useless task not shutdown at the right time

Current status: such issues can be found by static analysis tools
High-speed runway overshoot at landing

**Landing** at Warsaw airport, Lufthansa A320:
- **bad weather conditions:** rain, high side wind
- **wet runway**
- landing (300 km/h) followed by **aqua-planing**, and **delayed braking**
- **runway overrun** at 132 km/h
- **impact** against a hillside at about 100 km/h

**Consequences:**
- **2 fatalities, 56 injured** (among 70 passengers + crew)
- **aircraft completely destroyed** (impact + fire)

**Full report available online:**
http://www.rvs.uni-bielefeld.de/publications/Incidents/DOCS/ComAndRep/Warsaw/warsaw-report.html
Causes of the accident

1 Root cause:
   - **bad weather conditions** not well assessed by the crew
   - side wind **exceeding** aircraft certification specification
   - **wrong action from the crew:**
     a “Go Around” (missed landing, acceleration + climb) should have been done

2 Contributing factor: **delayed action of the brake system**

<table>
<thead>
<tr>
<th>time (seconds)</th>
<th>distance (meters) from runway threshold</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>770 m</td>
<td>main landing gear landed</td>
</tr>
<tr>
<td>$T_0 + 3$ s</td>
<td>1030 m</td>
<td>nose landing gear landed <strong>brake command activated</strong></td>
</tr>
<tr>
<td>$T_0 + 12$ s</td>
<td>1680 m</td>
<td>spoilers activated</td>
</tr>
<tr>
<td>$T_0 + 14$ s</td>
<td>1800 m</td>
<td>thrust reversers activated</td>
</tr>
<tr>
<td>$T_0 + 31$ s</td>
<td>2700 m</td>
<td>end of runway</td>
</tr>
</tbody>
</table>
Protection of aircraft brake systems

- **Braking systems inhibition**: Prevent in-flight activation!
  - **spoilers**: increase in aerodynamic load (drag)
  - **thrust reversers**: could destroy the plane if activated in-flight!
    (ex: crash of a B 767-300 ER Lauda Air, 1991, 223 fatalities; thrust reversers in-flight activation, electronic circuit issue)

- **Braking software specification**:
  DO NOT activate spoilers and thrust reverse **unless the following condition is met**:
  - thrust lever should be set to **minimum** by the flight crew
  - **AND** either of the following conditions:
    - **weight** on the main gear should be at least 12 T
      i.e., 6 T for each side
    - **OR** wheels should be spinning, with a speed of at least 130 km/h
  
  
  \[\text{[Minimum Thrust]} \text{ AND } (\text{[Weight]} \text{ OR } \text{[Wheels spinning]})\]
Understanding the braking delay

- **Landing configuration:**

- **Braking systems:** inhibited
  - thrust command properly set to minimum
  - no weight on the left landing gear due to the wind
  - no speed on wheels due to aquaplaning

  \[\text{[Minimum Thrust]} \land (\text{[Weight]} \lor \text{[Wheels spinning]})\]
Flight 2904, a summary of the issues

Main factor is human (landing in weather conditions the airplane is not certified for), but the specification of the software is a contributing factor:

- **Old condition** that failed to be satisfied:

  \[(P_{\text{left}} > 6T) \text{ AND } (P_{\text{right}} > 6T)\]

- **Fixed condition** (used in the new version of the software):

  \[(P_{\text{left}} + P_{\text{right}}) > 12T\]

- The fix can be understood **only with knowledge of the environment**
  - conditions which the airplane will be used in
  - behavior of the sensors
The anti-missile “Patriot” system

- **Purpose**: destroy foe missiles before they reach their target
- **Use in wars**:
  - **first Gulf war** (1991)
    protection of towns and military facilities in Israël and Saudi Arabia (against “Scud” missiles launched by Irak)
  - **success rate**:
    ★ around 50 % of the “Scud” missiles are successfully destroyed
    ★ almost all launched Patriot missiles destroy their target
    ★ failures are due to *failure to launch a Patriot missile*

- **Constraints on the system**:
  - **hit very quickly moving targets**:
    “Scud” missiles fly at around 1700 m/s ; travel about 1000 km in 10 minutes
  - **not to destroy a friendly target** (it happened at least twice!)
  - **very high cost**: about $1 000 000 per launch
System components

Detection / trajectory identification:

- detection using radar systems
- trajectory confirmation (to make sure a foe missile is tracked):
  1. trajectory identification using a sequence of points at various instants
  2. trajectory confirmation
     computation of a predictive window (from position and speed vector)
     + confirmation of the predicted trajectory
  3. identification of the target (friend / foe)

Guidance system:

- interception trajectory computation
- launch of a Missile, and control until it hits its target
  high precision required (both missiles travel at more than 1500 m/s)

Very short process: about ten minutes
Dahran failure (1991)

1. **Launch of a “Scud” missile**

2. **Detection** by the radars of the Patriot system but failure to confirm the trajectory:
   - imprecision in the computation of the clock of the detection system
   - computation of a wrong confirmation window
   - the “Scud” cannot be found in the predicted window
   - failure to confirm the trajectory
   - the detection computer concludes it is a false alert

3. The “Scud” missile hits its target:
   - **28 fatalities** and around 100 people injured
Fixed precision arithmetic

- **Fixed precision numbers** are of the form $\epsilon N 2^{-p}$ where:
  - $p$ is fixed
  - $\epsilon \in \{-1, 1\}$ is the **sign**
  - $N \in [-2^n, 2^n - 1] \mathbb{Z}$ is an **integer** ($n > p$)

- **In 32 bits fixed precision**, with one sign bit, $n = 31$; thus we may let $p = 20$

- **A few examples:**

<table>
<thead>
<tr>
<th>decimal value</th>
<th>sign</th>
<th>truncated value</th>
<th>fractional portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>000000000010</td>
<td>00000000000000000000</td>
</tr>
<tr>
<td>-5</td>
<td>1</td>
<td>000000000101</td>
<td>00000000000000000000</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>000000000000</td>
<td>10000000000000000000</td>
</tr>
<tr>
<td>-9.125</td>
<td>1</td>
<td>000000001001</td>
<td>00100000000000000000</td>
</tr>
</tbody>
</table>

- **Range of values that can be represented:**

$$\pm 2^{12}(1 - 2^{-32})$$
Rounding errors in fixed precision computations

- Not all real numbers in the right range can be represented. Rounding is unavoidable.
  - may happen both for basic operations and for program constants...

- **Example:** fraction 1/10
  - 1/10 cannot be represented exactly in fixed precision arithmetic
  - let us decompose 1/10 as a sum of terms of the form \( \frac{1}{2^i} \):

\[
\frac{1}{10} = \frac{1}{2} \cdot \frac{1}{5} \\
\frac{1}{5} = \frac{1}{8} + \frac{1}{16} + \frac{1}{16} \cdot \frac{1}{5} = \frac{1}{8} + \frac{1}{16} + \frac{1}{16} \cdot (\frac{1}{8} + \frac{1}{16} + \frac{1}{16} \cdot \frac{1}{5}) = \ldots
\]

  - infinite binary representation: 0.00011001100110011001100...
  - if \( p = 24 \):
    - representation: “0.000110011001100110011001”
    - rounding error is \(9.5 \cdot 10^{-8}\)

- Floating precision numbers (more commonly used today) have the same limitation
Case studies
Patriot missile (anti-missile system), Dahran (1991)

The root cause: a clock drift

Trajectory confirmation algorithm (summary):

- **hardware clock** $T_d$ ticks every tenth of a second
- time $T_c$ is computed in seconds: $T_c = \frac{1}{10} \times T_d$
- in binary: $T_c = 0.000110011001100110011001_{b} \times b \times T_d$
- relative error is $10^{-6}$
- after the computer has been running for 100 h:
  - the absolute error is 0.34 s
  - as a “Scud” travels at 1700 m/s: the predicted window is about 580 m from where it should be
    - this explains the trajectory confirmation failure!

Remarks:

- the issue was discovered by israeli users, who noticed the clock drift
- their solution: frequently restart the control computer... (daily)
- this was not done in Dahran... the system had been running for 4 days
Patriot missile failure, a summary of the issues

**Precision issues** in the fixed precision arithmetic:

- A scalar **constant** used in the code was **invalid**
  i.e., bound to be rounded to an approximate value, incurring a significant approximation the designers were unaware of

- There was **no adequate study of the precision** achieved by the system, although precision is clearly critical here!

**Current status:** such issues can be found by static analysis tools
Outline
Common issues causing software problems

The examples given so far are not isolated cases
See for instance:

www.cs.tau.ac.il/~nachumd/horror.html

(not up-to-date)

Typical reasons:

- **Improper specification** or understanding of the environment, conditions of execution...
- **Incorrect implementation of a specification**
  e.g., the code should be free of runtime errors
  e.g., the software should produce a result that meets some property
- **Incorrect understanding of the execution model**
  e.g., generation of too imprecise results
New challenges to ensure embedded systems do not fail

**Complex software architecture:** e.g. parallel softwares

- single processor multi-threaded, distributed (several computers)
- more and more common: multi-core architectures
- very hard to reason about
  - other kinds of issues: dead-locks, races...
  - very complex execution model: interleavings, memory models

**Complex properties to ensure:** e.g., security

- the system should resist even in the presence of an attacker (agent with malicious intentions)
- attackers may try to access sensitive data, to corrupt critical data...
- security properties are often even hard to express
Techniques to ensure software safety

Software development techniques:
- **software engineering**, with a focus on specification, and software quality (may be more or less formal...)
- **programming rules** for specific areas (e.g., DO 178 c in avionics)
- usually do not guarantee any strong property, but make softwares “cleaner”

Formal methods:
- should have **sound mathematical foundations**
- should allow to **guarantee** softwares meet some complex properties
- should be **trustable** (is a paper proof ok ???)
- **increasingly used in real life applications**, but still a lot of open problems
What is to be verified?

What do the C programs below do?

\[ P_0 \]

```c
int x = 0;

int f_0(int y){
    return y * x;
}

int f_1(int y){
    x = y;
    return 0;
}

void main(){
    z = f_0(10) + f_1(100);
}
```

\[ P_1 \]

```c
void main(){
    int i;
    int t[100] = {0, 1, 2, \ldots, 99};
    while(i < 100){
        t[i] ++;
        i ++;
    }
}
```

\[ P_2 \]

```c
void main(){
    float f = 0.;
    for(int i = 0; i < 1000000; i ++){
        f = f + 0.1;
    }
}
```
Semantic subtleties...

\[ P_0 \]

```c
int x = 0;

int f_0(int y) {
    return y * x;
}

int f_1(int y) {
    x = y;
    return 0;
}

void main() {
    z = f_0(10) + f_1(100);
}
```

**Execution order:**

- not specified in C
- specified in Java
  - if left to right, \( z = 0 \)
  - if right to left, \( z = 1000 \)
Semantic subtleties...

Initialization:
- runtime error in Java
- read of a random value in C (the value that was stored before)

Floating point semantics:
- 0.1 is not representable exactly
- what is it rounded to by the compiler?
- rounding errors
  what is the rounding mode at runtime?
The two main parts of this course

1. **Semantics**
   - allow to **describe precisely the behavior of programs** should account for execution order, initialization, scope...
   - allow to **express the properties to verify** several important families of properties: safety, liveness, security...
   - also important to **transform** and **compile** programs

2. **Verification**
   - aim at **proving** semantic properties of programs
   - a very strong limitation: **indecidability**
   - **several approaches**, that make various compromises around indeducibility
Outline
The termination problem

Termination

Program $P$ terminates on input $X$ if and only if any execution of $P$, with input $X$ eventually reaches a final state.

- **Final state:** final point in the program (i.e., not error)
- **We may want to ensure termination:**
  - processing of a task, such as, e.g., printing a document
  - computation of a mathematical function
- **We may want to ensure non-termination:**
  - operating system
  - device drivers

The termination problem

Can we find a program $P_t$ that takes as argument a program $P$ and data $X$ and that returns “TRUE” if $P$ terminates on $X$ and “FALSE” otherwise?
The termination problem is not computable

- **Proof by reductio ad absurdum**, using a *diagonal argument*
  
  We assume there exists a program $P_a$ such that:
  
  - $P_a$ always terminates
  - $P_a(P, X) = 1$ if $P$ terminates on input $X$
  - $P_a(P, X) = 0$ if $P$ does not terminate on input $X$

- We consider the following program:

```c
void P0(P){
    if(Pa(P, P) == 1){
        while(TRUE){}  //loop forever
    }else{
        return;  //do nothing...
    }
}
```

- **What is the return value of** $P_a(P_0, P_0)$ ?
  
i.e., $P_0$ does it terminate on input $P_0$ ?
The termination problem is not computable

- **What is the return value of** $P_a(P_0, P_0)$ **?**
  
  We know $P_a$ always terminates and returns either 0 or 1 (assumption). Therefore, we need to consider only two cases:
  
  - if $P_a(P_0, P_0)$ returns 1, then $P_0(P_0)$ loops forever, thus $P_a(P_0, P_0)$ should return 0, so we have reached a contradiction
  
  - if $P_a(P_0, P_0)$ returns 0, then $P_0(P_0)$ terminates, thus $P_a(P_0, P_0)$ should 1, so we have reached a contradiction

- In both cases, we reach a contradiction

- Therefore we conclude no such a $P_a$ exists

The termination problem is not decidable

There exists no program $P_t$ that always terminates and always recognizes whether a program $P$ terminates on input $X$
Absence of runtime errors

- Can we find a program $P_c$ that takes a program $P$ and input $X$ as arguments, always terminates and returns
  - 1 if and only if $P$ runs safely on input $X$, i.e., without a runtime error
  - 0 if $P$ crashes on input $X$
- Answer: **No**, the same diagonal argument applies if $P_c(P, X)$ decides whether $P$ will run safely on $X$, consider

```c
void P_1(P){
    if($P_c(P, P)$){
        crash();  // fail (unsafe)
    }else{
        return;  // do nothing (safe)...
    }
}
```

Non-computability result

The absence of runtime errors is not computable
Rice theorem

- **Semantic specification**: set of *correct* program executions
- “Trivial” semantic specifications:
  - empty set
  - set of all possible executions

⇒ intuitively, the non interesting verification problems...

Rice theorem (1953)

Considering a Turing complete language, any non trivial semantic specification is not computable

- **Intuition**: there is no algorithm to decide non trivial specifications, starting with only the program code
- Therefore **all interesting properties are not computable**:
  - termination,
  - absence of runtime errors,
  - absence of arithmetic errors, etc...
Towards partial solutions

- The initial verification problem is **not computable**

- **Solution:** solve a weaker problem

- **Several compromises can be made:**
  - **Simulation / testing:** observe only **finitely many finite executions** infinite system, but only finite exploration (no proof beyond that)
  - **Assisted theorem proving:** we **give up on automation** (no proof inference algorithm in general)
  - **Model checking:** we consider only **finite systems** (with finitely many states)
  - **Bug-finding:** search for “patterns” indicating “likely errors” (may miss real program errors, and report non existing issues)
  - **Static analysis with abstraction:** attempt at automatic correctness proofs (yet, may fail to verify some correct programs)
Safety verification method characteristics

Safety verification problem
- **Semantics** $[P]$ of program $P$: set of behaviors of $P$ (e.g., states)
- **Property to verify** $S$: set of admissible behaviors (e.g., safe states)

- **Automation**: existence of an algorithm
- **Scalability**: should allow to handle large softwares
- **Soundness**: identify any wrong program
- **Completeness**: accept all correct programs
- **Apply to program source code**, i.e., not require a **modelling phase**
## 1. Testing by simulation

### Principle

Run the program on **finitely many finite inputs**

- maximize **coverage**
- **inspect erroneous traces** to fix bugs

- **Very widely used:**
  - **unit testing**: each function is tested separately
  - **integration testing**: with all surrounding systems, hardware
    - e.g., **iron bird** in avionics

- **Automated**

- **Complete**: will never raise a false alarm

- **Unsound** unless exhaustive: **may miss program defects**

- **Costly**: needs to be re-done when software gets updated
2. Machine assisted proof

**Principle**

Have a *machine checked* proof, that is partly *human written*

- *tactics / solvers* may help in the inference
- the *hardest invariants* have to be user-supplied

**Applications**

- software industry (rare): Line 14 in Paris Subway
- hardware: ACL 2
- academia: CompCert compiler, SEL4 verified micro-kernel

*Not fully automated*

often turns out *costly* as complex proof arguments have to be found

*Sound* and *complete*
3. Model-Checking

**Principle**

Consider *finite systems* only, using algorithms for
- exhaustive exploration,
- symmetry reduction...

- **Applications:**
  - *hardware* verification
  - *driver protocols* verification (Microsoft)

- Applies on a *model*: a model extraction phase is needed
  - for infinite systems, this is *necessarily approximate*
  - not always automated

- **Automated, sound, complete with respect to the model**
4. "Bug finding"

**Principle**

Identify "likely" issues, i.e., patterns known to often indicate an error

- use bounded symbolic execution, model exploration...
- rank "defect" reports using heuristics

**Example**: Coverity

**Automated**

- **Not complete**: may report false alarms
- **Not sound**: may accept false programs thus **inadequate** for safety-critical systems
5. Static analysis with abstraction (1/4)

**Principle**

*Use some approximation*, but **always in a conservative manner**

- **Under-approximation** of the property to verify: $S_{\text{under}} \subseteq S$
- **Over-approximation** of the semantics: $\llbracket P \rrbracket \subseteq \llbracket P \rrbracket_{\text{upper}}$

We let an automatic static analyzer attempt to prove that:

$\llbracket P \rrbracket_{\text{upper}} \subseteq S_{\text{under}}$

If it succeeds, $\llbracket P \rrbracket \subseteq S$

- In practice, the static analyzer **computes** $\llbracket P \rrbracket_{\text{upper}}, S_{\text{under}}$
5. Static analysis with abstraction (2/4)

Soundness

The abstraction will catch any incorrect program

- If $[P] \not\subseteq S$, then $[P]_{\text{upper}} \not\subseteq S_{\text{under}}$

since

$$S_{\text{under}} \subseteq S \quad \subseteq \quad [P] \subseteq [P]_{\text{upper}}$$

error found
5. Static analysis with abstraction (3/4)

**Incompleteness**

The abstraction may fail to certify **some correct programs**

Dangerous states not ruled out by the abstract semantics

**Case of a false alarm:**

- program $P$ is **correct**
- but the static analysis **fails**
5. Static analysis with abstraction (4/4)

**Incompleteness**

The abstraction may fail to certify *some correct programs*.

- In the following case, the analysis cannot conclude anything.

- One goal of the static analyzer designer is to avoid such cases.

**Static analysis using abstraction**

- **Automatic**: $[P]_{\text{upper}}, S_{\text{under}}$ computed automatically.
- **Sound**: reports any incorrect program.
- **Incomplete**: may reject correct programs.
### A summary of common verification techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Automatic</th>
<th>Sound</th>
<th>Complete</th>
<th>Source level</th>
<th>Scalable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>Yes</td>
<td>No ¹</td>
<td>Yes</td>
<td>Yes</td>
<td>sometimes ²</td>
</tr>
<tr>
<td>Assisted proving</td>
<td>No</td>
<td>Yes</td>
<td>Almost</td>
<td>Partially ³</td>
<td>sometimes ⁴</td>
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<tr>
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</tr>
<tr>
<td>Static analysis</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>sometimes</td>
</tr>
</tbody>
</table>

- Obviously, no approach checks all characteristics
- Scalability is a challenge for all

¹ unless full testing is doable  
² full testing usually not possible except for small programs with finite state space  
³ only with respect to the finite models... but not with respect to infinite semantics  
⁴ quickly requires huge manpower
Outline
Order relations

Very useful in semantics and verification:

- **logical ordering**, expresses **implication** of logical facts
- **computational ordering**, useful to establish well-foundedness of fixpoint definitions, and for termination

**Definition: partially ordered set (poset)**

Let a set $S$ and a binary relation $\sqsubseteq \subseteq S \times S$ over $S$. Then, $\sqsubseteq$ is an **order relation** (and $(S, \sqsubseteq)$ is called a **poset**) if and only if it is

- **reflexive**: $\forall x \in S$, $x \sqsubseteq x$
- **transitive**: $\forall x, y, z \in S$, $x \sqsubseteq y \land y \sqsubseteq z \implies x \sqsubseteq z$
- **antisymmetric**: $\forall x, y \in S$, $x \sqsubseteq y \land y \sqsubseteq x \implies x = y$

- **notation**: $x \sqrel y ::= (x \sqsubseteq y \land x \neq y)$
Graphical representation

We often use **Hasse diagrams** to represent posets:

**Extensive definition:**
- \( S = \{x_0, x_1, x_2, x_3, x_4\} \)
- \( \sqsubseteq \) defined by:
  
  \[
  \begin{align*}
  x_0 & \sqsubseteq x_1 \\
  x_1 & \sqsubseteq x_2 \\
  x_1 & \sqsubseteq x_3 \\
  x_2 & \sqsubseteq x_4 \\
  x_3 & \sqsubseteq x_4 
  \end{align*}
  \]
We consider the classical notion of **finite automata** and let

- $L$ be a finite set of **letters**
- $Q$ be a finite set of **states**
- $q_i, q_f \in Q$ denote the **initial** state and **final** state
- $\rightarrow \subseteq Q \times L \times Q$ be a **transition relation**

Then, the set of words recognized by $A = (Q, q_i, q_f, \rightarrow)$ is defined by:

$$\mathcal{L}[A] = \{a_0a_1 \ldots a_n \mid \exists q_0 \ldots q_{n-1} \in Q, q_i \xrightarrow{a_0} q_0 \xrightarrow{a_1} q_1 \ldots q_{n-1} \xrightarrow{a_n} q_f\}$$
Example: automata and semantic properties

A simple automaton:

\[ L = \{a, b\} \quad Q = \{q_0, q_1, q_2\} \]
\[ q_i = q_0 \quad q_f = q_2 \]
\[ q_0 \xrightarrow{a} q_1 \quad q_1 \xrightarrow{b} q_2 \quad q_2 \xrightarrow{a} q_1 \]

A few semantic properties:

- \( P_0 \): no recognized word contains two consecutive \( b \)
  \[ L[A] \cap L^*bbL^* = \emptyset \]

- \( P_1 \): all recognized words contain at least one occurrence of \( a \)
  \[ L[A] \subseteq L^*aL^* \]
Total ordering

**Definition: total order relation**

Order relation $\sqsubseteq$ over $S$ is a **total** order if and only if

$$\forall x, y \in S, \; x \sqsubseteq y \vee y \sqsubseteq x$$

**Examples:**

- $(\mathbb{R}, \leq)$ is a total ordering
- If set $S$ has at least two distinct elements $x, y$ then its powerset $(\mathcal{P}(S), \subseteq)$ is **not** a total order
  - indeed $\{x\}, \{y\}$ cannot be compared
- Most of the order relations we will use are **not** be total
Minimum and maximum elements

Definition: extremal elements

Let \((S, \sqsubseteq)\) be a poset and \(S' \subseteq S\). Then \(x\) is

- **minimum element** of \(S'\) if and only if \(x \in S' \land \forall y \in S', \ x \sqsubseteq y\)
- **maximum element** of \(S'\) if and only if \(x \in S' \land \forall y \in S', \ y \sqsubseteq x\)

- maximum and minimum elements **may not exist**
  - example: \(\{\{x\}, \{y\}\}\) in the powerset, where \(x \neq y\)
- **infimum** \(\bot\) (**"bottom"**) : minimum element of \(S\)
- **supremum** \(\top\) (**"top"**) : maximum element of \(S\)
Upper bounds and least upper bound

**Definition: bounds**

Given poset \((S, \sqsubseteq)\) and \(S' \subseteq S\), then \(x \in S\) is

- an **upper bound** of \(S'\) if
  \[
  \forall y \in S', \ y \sqsubseteq x
  \]

- the **least upper bound** (lub) of \(S'\) (noted \(\sqcup S'\)) if
  \[
  \forall y \in S', \ y \sqsubseteq x \land \forall z \in S, (\forall y \in S', \ y \sqsubseteq z) \implies x \sqsubseteq z
  \]

- if it exists, the least upper bound is **unique**:
  if \(x, y\) are least upper bounds of \(S\), then \(x \sqsubseteq y\) and \(y \sqsubseteq x\), thus \(x = y\) by antisymmetry

- notation: \(x \sqcup y ::= \sqcup\{x, y\}\)

- upper bounds and least upper bounds **may not exist**

- **dual notions**: lower bound, greatest lower bound (glb, noted \(\sqcap S'\))
Duality principle

So far all definitions admit a symmetric counterpart

- given an order relation $\sqsubseteq$, $\mathcal{R}$ defined by $x \mathcal{R} y \iff y \sqsubseteq x$ is also an order relation
- thus all properties that can be proved about $\sqsubseteq$ also have a symmetric property that also holds

This is the **duality principle**:

- minimum element
- infimum
- lower bound
- greatest lower bound
- maximum element
- supremum
- upper bound
- least upper bound

... more to follow
Complete lattice

Definition: complete lattice

A **complete lattice** is a tuple \((S, \sqsubseteq, \bot, \top, \sqcup, \sqcap)\) where:

- \((S, \sqsubseteq)\) is a poset
- \(\bot\) is the infimum of \(S\)
- \(\top\) is the supremum of \(S\)
- any subset \(S'\) of \(S\) has a lub \(\sqcup S'\) and a glb \(\sqcap S'\)

Properties:

- \(\bot = \sqcup \emptyset = \sqcap S\)
- \(\top = \sqcap \emptyset = \sqcup S\)

Example: the powerset \((\mathcal{P}(S), \subseteq, \emptyset, S, \cup, \cap)\) of set \(S\) is a complete lattice
Lattice

The existence of lubs and glbs for all subsets is often a very strong property, that may not be met:

**Definition: lattice**

A **lattice** is a tuple \((S, \sqsubseteq, \bot, \top, \sqcup, \sqcap)\) where:

- \((S, \sqsubseteq)\) is a poset
- \(\bot\) is the infimum of \(S\)
- \(\top\) is the supremum of \(S\)
- any pair \(\{x, y\}\) of \(S\) has a lub \(x \sqcup y\) and a glb \(x \sqcap y\)

- let \(Q = \{q \in \mathbb{Q} \mid 0 \leq q \leq 1\}\); then \((Q, \leq)\) is a lattice but not a complete lattice
  - indeed, \(\{q \in Q \mid q \leq \frac{\sqrt{2}}{2}\}\) has no lub in \(Q\)
- property: a **finite** lattice is also a complete lattice
**Chains**

**Definition: increasing chain**

Let \((S, \sqsubseteq)\) be a poset and \(C \subseteq S\).

It is an **increasing chain** if and only if
- it has an infimum
- poset \((C, \sqsubseteq)\) is total (i.e., any two elements can be compared)

**Example**, in the powerset \((\mathcal{P}(\mathbb{N}), \subseteq)\):

\[
C = \{c_i \mid i \in \mathbb{N}\} \text{ where } c_i = \{2^0, 2^2, \ldots, 2^i\}
\]

**Definition: increasing chain condition**

Poset \((S, \sqsubseteq)\) **satisfies the increasing chain condition** if and only if any increasing chain \(C \subseteq S\) is finite.
Complete partial orders

Definition: complete partial order
A **complete partial order** (cpo) is a poset \((S, \sqsubseteq)\) such that any increasing chain \(C\) of \(S\) has a least upper bound. A **pointed cpo** is a cpo with an infimum \(\bot\).

- clearly, any complete lattice is a cpo
- the opposite is not true:
Outline
Towards a constructive definition of the automata semantics

We now look for a constructive version of the automaton semantics as hinted by the following observations

Observation 1: \( \mathcal{L}[A] = \llbracket A \rrbracket(q_f) \) where

\[
\llbracket A \rrbracket : \quad Q \longrightarrow \mathcal{P}(L^*)
\]

\[
q \quad \longmapsto \quad \{ w \in L^* \mid \exists n, w = a_0a_1 \ldots a_n \\
\quad \quad \quad \quad \quad \quad \quad \exists q_0 \ldots q_n-1 \in Q, q_i \overset{a_0}{\longrightarrow} q_0 \overset{a_1}{\longrightarrow} \ldots q_{n-1} \overset{a_n}{\longrightarrow} q \}
\]

Observation 2: \( \llbracket A \rrbracket = \bigcup \llbracket A \rrbracket_n \) where

\[
\llbracket A \rrbracket_n : \quad Q \longrightarrow \mathcal{P}(L^*)
\]

\[
q \quad \longmapsto \quad \{ a_0a_1 \ldots a_n \mid \exists q_0 \ldots q_n-1 \in Q, q_i \overset{a_0}{\longrightarrow} q_0 \overset{a_1}{\longrightarrow} \ldots q_{n-1} \overset{a_n}{\longrightarrow} q \}
\]

Observation 3: \( \llbracket A \rrbracket_{n+1} \) can be computed directly from \( \llbracket A \rrbracket_n \)

\[
\llbracket A \rrbracket_{n+1}(q) = \bigcup_{q' \in Q} \{ wa \mid w \in \llbracket A \rrbracket_n(q') \land q' \overset{a}{\longrightarrow} q \}
\]
Towards a constructive definition of the automata semantics

Alternate approach:

1. Let $[\mathcal{A}]_n$ denote:

   $$[\mathcal{A}](q) = \{ w \in [\mathcal{A}](q) \mid \text{length}(w) \leq n \}$$

2. Compute $[\mathcal{A}]_{n+1}$ from $[\mathcal{A}]_n$

3. Define the semantics of automaton as the union of the iterates of this sequence:

   $$[\mathcal{A}] = \bigcup [\mathcal{A}]_n$$
Operators over a poset

**Definition: operators and orderings**

Let \((S, \sqsubseteq)\) be a poset and \(\phi : S \rightarrow S\) be an operator over \(S\). Then, \(\phi\) is:

- **monotone** if and only if \(\forall x, y \in S, \ x \sqsubseteq y \implies \phi(x) \sqsubseteq \phi(y)\)
- **continuous** if and only if, for any chain \(S' \subseteq S\) then:
  \[
  \begin{cases}
    \text{if } \bigsqcup S' \text{ exists, so does } \biguplus \{\phi(x) \mid x \in S'\} \\
    \text{and } \phi(\bigsqcup S') = \biguplus \{\phi(x) \mid x \in S'\}
  \end{cases}
  \]
- **\(\sqcup\)-preserving** if and only if:
  \[
  \forall S' \subseteq S, \ \begin{cases}
    \text{if } \bigsqcup S' \text{ exists, then } \biguplus \{\phi(x) \mid x \in S'\} \text{ exists} \\
    \text{and } \phi(\bigsqcup S') = \biguplus \{\phi(x) \mid x \in S'\}
  \end{cases}
  \]

**Notes:**

- “monotone” in English means “croissante” in French; “décroissante” translates into “anti-monotone” and “monotone” into “isotone”
- the dual of “monotone” is “monotone”
Operators over a poset

A few interesting properties:

- **continuous ⇒ monotone:**
  if \( \phi \) is monotone, and \( x, y \in S \) are such that \( x \sqsubseteq y \), then \( \{x, y\} \) is a chain with lub \( y \), thus \( \phi(x) \sqcup \phi(y) \) exists and is equal to \( \phi(\sqcup\{x, y\}) = \phi(y) \); therefore \( \phi(x) \sqsubseteq \phi(y) \).

- **⊔-preserving ⇒ monotone:**
  same argument.
Fixpoints

Definition: fixpoints

Let \((S, \sqsubseteq)\) be a poset and \(f : S \to S\) be an operator over \(S\).

- A fixpoint of \(\phi\) is an element \(x\) such that \(\phi(x) = x\)
- A pre-fixpoint of \(\phi\) is an element \(x\) such that \(x \sqsubseteq \phi(x)\)
- A post-fixpoint of \(\phi\) is an element \(x\) such that \(\phi(x) \sqsubseteq x\)
- The least fixpoint \(\text{Lfp}\phi\) of \(\phi\) (if it exists, it is unique) is the smallest fixpoint of \(\phi\)
- The greatest fixpoint \(\text{Gfp}\phi\) of \(\phi\) (if it exists, it is unique) is the greatest fixpoint of \(\phi\)

Note: the existence of a least fixpoint, a greatest fixpoint or even a fixpoint is \textit{not guaranteed}; we will see several theorems that establish their existence under specific assumptions...
Tarski’s Theorem

Theorem

Let \((S, \sqsubseteq, \bot, \top, \sqcup, \sqcap)\) be a complete lattice and \(\phi : S \to S\) be a monotone operator over \(S\). Then:

1. \(\phi\) has a least fixpoint \(\text{lfp} \phi\) and \(\text{lfp} \phi = \sqcap\{x \in S \mid \phi(x) \sqsubseteq x\}\).
2. \(\phi\) has a greatest fixpoint \(\text{gfp} \phi\) and \(\text{gfp} \phi = \sqcup\{x \in S \mid x \sqsubseteq \phi(x)\}\).
3. the set of fixpoints of \(\phi\) is a complete lattice.

Proof of point 1:

We let \(X = \{x \in S \mid \phi(x) \sqsubseteq x\}\) and \(x_0 = \sqcap X\).

Let \(y \in X\):
- \(x_0 \sqsubseteq y\) by definition of the glb;
- thus, since \(\phi\) is monotone, \(\phi(x_0) \sqsubseteq \phi(y)\);
- thus, \(\phi(x_0) \sqsubseteq y\) since \(\phi(y) \sqsubseteq y\), by definition of \(X\).

Therefore \(\phi(x_0) \sqsubseteq x_0\), since \(x_0 = \sqcap X\).
Tarski’s Theorem

We proved that $\phi(x_0) \subseteq x_0$. We derive from this that:

- $\phi(\phi(x_0)) \subseteq \phi(x_0)$ since $\phi$ is monotone;
- $\phi(x_0)$ is a post-fixpoint of $\phi$, thus $\phi(x_0) \in X$;
- $x_0 \sqsubseteq \phi(x_0)$ by definition of the greatest lower bound

We have established both inclusions so $\phi(x_0) = x_0$.

If $x_1$ is another fixpoint, then $x_1 \in X$, so $x_0 \sqsubseteq x_1$ Proof of point 2:
similar, by duality.

Proof of point 3:

- if $X$ is a set of fixpoints of $\phi$, we need to consider $\phi$ over
  \( \{y \in S \mid y \sqsubseteq S \cap X\} \) to establish the existence of a glb of $X$ in the poset of fixpoints
- the existence of least upper bounds in the poset of fixpoints follows by duality
Tarski’s theorem: example (1)

A function over the powerset:
We consider a set $\mathcal{E}$, and a subset $\mathcal{A} \subseteq \mathcal{E}$
We let:

$$f : \mathcal{P}(\mathcal{E}) \rightarrow \mathcal{P}(\mathcal{E})$$
$$X \mapsto X \cup \mathcal{A}$$

Exercise:
- apply Tarski’s theorem, characterize the least and greatest fixpoints
Tarski’s theorem: example (2)

Function:

\[ f : [1, 4\pi - 1] \rightarrow [1, 4\pi - 1] \]
\[ x \mapsto x + \sin x \]

Exercise:

- apply Tarski’s theorem, and derive the fixpoints of the function
Automata example, fixpoint definition

**Lattice:**
- \( S = Q \rightarrow \mathcal{P}(L^*) \)
- the ordering is the pointwise extension \( \sqsubseteq \) of \( \subseteq \)

**Operator:**
- we let \( \phi_0 : S \rightarrow S \) be defined by
  \[
  \phi_0(f) = \lambda(q \in Q) \cdot \bigcup_{q' \in Q} \{wa \mid w \in f(q') \land q' \xrightarrow{a} q\}
  \]
- we let \( \phi : S \rightarrow S \) by defined by
  \[
  \phi(f) = \lambda(q \in Q) \cdot \begin{cases} 
  f(q) \cup \phi_0(f)(q_i) \cup \{\epsilon\} & \text{if } q = q_i \\
  f(q) \cup \phi_0(f)(q) & \text{otherwise}
  \end{cases}
  \]

**Proof steps to complete:**
- the existence of \( \text{Lfp} \phi \) follows from Tarski’s theorem
- the equality \( \text{Lfp} \phi = [A] \) can be established by induction and double inclusion... but there is a simpler way
Kleene’s Theorem

Tarski’s theorem guarantees existence of an lfp, but is not constructive.

Theorem

Let \((S, \sqsubseteq, \perp)\) be a pointed cpo and \(\phi : S \to S\) be a continuous operator over \(S\). Then \(\phi\) has a least fixpoint, and

\[
\text{lfp } \phi = \bigsqcup_{n \in \mathbb{N}} \phi^n(\perp)
\]

First, we prove the existence of the lub:

Since \(\phi\) is continuous, it is also monotone. We can prove by induction over \(n\) that \(\{\phi^n(\perp) \mid n \in \mathbb{N}\}\) is a chain:

- \(\phi^0(\perp) = \perp \sqsubseteq \phi(\perp)\) by definition of the infimum;
- if \(\phi^n(\perp) \sqsubseteq \phi^{n+1}(\perp)\), then
  \[
  \phi^{n+1}(\perp) = \phi(\phi^n(\perp)) \sqsubseteq \phi(\phi^{n+1}(\perp)) = \phi^{n+2}(\perp)
  \]

By definition of the cpo structure, the lub exists. We let \(x_0\) denote it.
Kleene’s Theorem

Secondly, we prove that it is a fixpoint of $\phi$:

Since $\phi$ is continuous, $\{\phi^{n+1}(\bot) \mid n \in \mathbb{N}\}$ has a lub, and

$$
\phi(x_0) = \phi(\bigsqcup \{\phi^n(\bot) \mid n \in \mathbb{N}\}) \\
= \bigsqcup \{\phi^{n+1}(\bot) \mid n \in \mathbb{N}\} \quad \text{by continuity of } \phi \\
= \bot \bigsqcup (\bigsqcup \{\phi^{n+1}(\bot) \mid n \in \mathbb{N}\}) \quad \text{by definition of } \bot \\
= x_0 \quad \text{by simple rewrite}
$$

Last, we show that it is the least fixpoint:

Let $x_1$ denote another fixpoint of $\phi$. We show by induction over $n$ that $\phi^n(\bot) \sqsubseteq x_1$:

- $\phi^0(\bot) = \bot \sqsubseteq x_1$ by definition of $\bot$;
- if $\phi^n(\bot) \sqsubseteq x_1$, then $\phi^{n+1}(\bot) \sqsubseteq \phi(x_1) = x_1$ by monotony, and since $x_1$ is a fixpoint.

By definition of the lub, $x_0 \sqsubseteq x_1$
Kleene’s theorem: example

Function:

\[ f : [1, 4\pi - 1] \rightarrow [1, 4\pi - 1] \]
\[ x \mapsto x + \sin x \]

Exercise:

- apply Kleene’s theorem and sketch the iterations
Automata: constructive semantics

We can now state a **constructive definition** of the automaton semantics. Operator $\phi$ is defined by

$$
\phi(f) = \lambda(q \in Q) \cdot \begin{cases} 
  f(x) \cup \phi_0(f)(q_i) \cup \{\epsilon\} & \text{if } q = q_i \\
  f(x) \cup \phi_0(f)(q) & \text{otherwise}
\end{cases}
$$

**Proof steps:**

- $\phi$ is continuous
- thus, Kleene’s theorem applies so $\text{lfp } \phi$ exists and
  $$
  \text{lfp } \phi = \bigcup_{n \in \mathbb{N}} \phi^n(\bot)\
  $$
  ... this actually saves the double inclusion proof to establish that
  $$
  \llbracket A \rrbracket = \text{lfp } \phi
  $$

Furthermore, $\llbracket A \rrbracket = \bigcup_{n \in \mathbb{N}} \phi^n(\bot)$.

This fixpoint definition will be very useful to infer or verify semantic properties.
Automata: constructive semantics iterates

A simple automaton:

$$L = \{a, b\} \quad Q = \{q_0, q_1, q_2\}$$

$$q_i = q_0 \quad q_f = q_2$$

$$q_0 \xrightarrow{a} q_1 \quad q_1 \xrightarrow{b} q_2 \quad q_2 \xrightarrow{a} q_1$$

Iterates of function $\phi$ from $\perp$:

<table>
<thead>
<tr>
<th>Iterate</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_0$</td>
<td>$\emptyset$</td>
<td>${\epsilon}$</td>
<td>${\epsilon}$</td>
<td>${\epsilon}$</td>
<td>${\epsilon}$</td>
<td>${\epsilon}$</td>
</tr>
<tr>
<td>$q_1$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>${a}$</td>
<td>${a}$</td>
<td>${a, aba}$</td>
<td>${a, aba}$</td>
</tr>
<tr>
<td>$q_2$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>${ab}$</td>
<td>${ab}$</td>
<td>${ab, abab}$</td>
</tr>
</tbody>
</table>
Duality principle

We can extend the duality notion:

- monotone  |  monotone
- anti-monotone  |  anti-monotone
- post-fixpoint  |  pre-fixpoint
- least fixpoint  |  greatest fixpoint
- increasing chain  |  decreasing chain

Furthermore both Tarski’s theorem and Kleene’s theorem have a dual version (Tarski’s theorem mostly encloses its own dual, except for the definition of the gfp).
On inductive reasoning

Formalizing inductive definitions:

Definition based on inference rules:

\[ \begin{array}{c}
    x_0 \in X \\
    x \in X \\
    f(x) \in X
\end{array} \]

Same property based on a least-fixpoint:

\[ \text{lfp}(Y \mapsto \{x_0\} \cup Y \cup \{f(x) \mid x \in Y\}) \]

Proving the inclusion of a fixpoint in a given set:

- Let \( \phi : S \rightarrow S \) be a continuous operator
- Let \( I \in S \) such that:
  \[ \forall x \in S, \ x \subseteq I \Rightarrow \phi(x) \subseteq I \]
  
  - We obviously have \( \bot \subseteq I \)
  - We can prove that \( \text{lfp} \phi \subseteq I \)
Exercise: language of a grammar

Language of a grammar as a least-fixpoint

Assumptions:

- Alphabet $A$, finite set of nodes $N$
- Finite set of rules $R \subseteq N \times (A \cup N)^*$
- Starting node $S \in N$

Questions:

- Define the set of words recognized by the grammar with inductive rules
- Do the same using a least-fixpoint

Hints:

- start with a function that maps each node into the set of words recognized by this node
- compute such a function by inductions
In the next lectures...

- Families of **semantics**, for a general model of programs
- Families of **semantic properties of programs**
- **Verification techniques:**
  - abstract interpretation based static analysis
  - machine assisted theorem proving
  - model checking

Next week: transition systems and operational semantics
Practical information about the course

The course will be taught by:

- **Sylvain Conchon** (LRI, Paris-Orsay)
- **Jérôme Feret** (DIENS)
- **Marie Peleau** (LIP 6)
- **Xavier Rival** (DIENS)

**Practical organization:**

- 1h30 Cours + 2h00 TD or TP depending on week

**Evaluation:**

\[ n = \frac{p + e}{2} \]

- **project** \( p \): several projects will be proposed in a few weeks
- **exam** \( e \): 2nd of June, 2017