

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: **undecidability**
 - ▶ many techniques allow to **compute semantic properties**
 - ▶ each comes with **advantages** and **drawbacks**
- 3 an introduction to the **theory of ordered sets** (though some terminology probably already known...)
 - ▶ **order relations** are pervasive in **semantics** and **verification**
 - ▶ **fixpoints** of operators are also very common

Outline

1 Introduction

2 Case studies

- Ariane 5, Flight 501 (1996)
- Patriot missile (anti-missile system), Dahran (1991)
- Dirty COW
- Need for semantics and verification

3 Approaches to verification

4 Orderings, lattices, fixpoints

5 Conclusion

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 !)

Full report available online:

<http://esamultimedia.esa.int/docs/esa-x-1819eng.pdf>

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
- an **unhandled arithmetic conversion overflow crashes the SRI**

From the root cause to the failure

A **not so trivial** sequence of events:

- 1 a **conversion from 64-bits float to 16-bits signed int** is performed and **causes an overflow**
- 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

Let us discuss **a few specific points**

A crash due to an unaddressed software case

Several solutions would have prevented this mishappening:

1 Deactivate interruptions on overflows:

- ▶ then, an overflow may happen, and produce wrong values 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. <= x && x <= 32767. )  
    i = (short) x;  
else  
    i = /* default value */;
```

- ▶ 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 few additional insights

The task that crashed was useless after lift off:

- purpose: re-calibration of gyroscopes in case of a launch delay obviously, no chance of this happening after ignition!
- implementation: shutdown 50 seconds into the flight failure at 36 seconds

Legacy software:

- due to positive experience in Ariane 4, many defensive guards were optimised away
- **but Ariane 5 is a lot more powerful than Ariane 4**

Note: **importance of assumptions** on the running environment

Failure of the redundant design:

- two versions of the SRI with distinct hardware
- but with **the same software**

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

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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:**

decimal value	sign	truncated value	fractional portion
2	0	00000000010	00000000000000000000
-5	1	00000000101	00000000000000000000
0.5	0	00000000000	10000000000000000000
-9.125	1	00000001001	00100000000000000000

- **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 $\frac{1}{2^i}$:

$$\begin{aligned} \frac{1}{10} &= \frac{1}{2} \cdot \frac{1}{5} \\ \frac{1}{5} &= \frac{1}{8} + \frac{1}{16} + \frac{1}{16} \cdot \frac{1}{5} = \frac{1}{8} + \frac{1}{16} + \frac{1}{16} \cdot \left(\frac{1}{8} + \frac{1}{16} + \frac{1}{16} \cdot \frac{1}{5} \right) = \dots \end{aligned}$$

- ▶ **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

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**: $T_c = 0.000110011001100110011001b \times_b T_d$!
- **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

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An exploit for Linux-based systems

Exploit principle:

- 1 be on a Linux system with kernel older than 4.4.26, 4.7.9, 4.8.3
- 2 find a file f owned by root, that is write-protected
- 3 run the exploit executable (compiled from a rather short C file) with f passed as an argument, as well as any string/sequence of bytes s
- 4 result: s gets written into f !
- 5 a bit more “work” gives root access...

More information at [CVE-2016-5195](#)

Consequences can be catastrophic, any file owned by root can be overwritten including system executable files, so one can completely take over the system.

History of DirtyCOW

History of the exploit and its fix:

- problem present in the kernel from version 2.x
- discovered in 2016
- patch provided very shortly, but wrong
- fixed properly by Linus Torvalds in 2017, but some systems remained vulnerable much later; e.g. Android impacted until 2018
- tied to subtle issues in memory management and IO, that we overview next

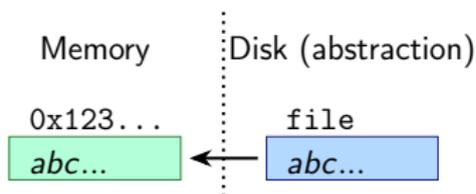
Comments by Linus Torvalds:

“[DirtyCOW] is an ancient bug that was actually attempted to be fixed once (badly) by me eleven years ago [...] but that was then undone due to problems on s390 by [another] commit”

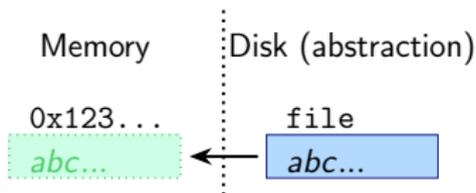
Memory/IO: mapping a file in memory (mmap)

Copying a file to memory:

- real copy:



- virtual copy:



- ▶ reading still from the disk version
- ▶ in case of write, the copy is made real

Copy on write: performed before writing into a virtual mmap region

Memory: advise to the kernel (madvise)

Generic mechanism to tell the kernel **information about a memory region**, e.g., created by `mmap`

Among possible options:

- **WILLNEED**:
region needed soon, read some pages ahead
- **DONTNEED**:
region not needed anytime soon, associated memory pages may be freed
- ...

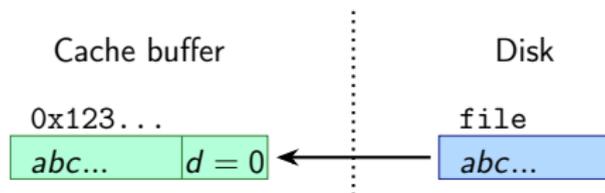
In the case of **DONTNEED**, further access will not fail but simply result in **reloading** (major slow-down)

IO: disk writing

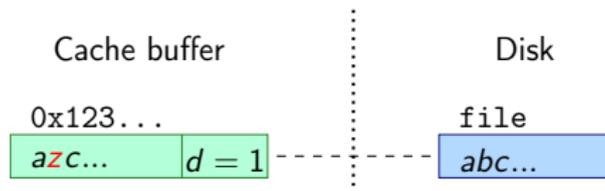
Caching of writes, for speed in case of an open in R/W mode:

- disk writes are not direct but through a cache buffer in memory
- buffers carry a **dirty bit**
 - turns to 1 when a write happens; remains 0 before that
- closing access will write back when dirty

Example, opening of a file R/W (assuming no virtual copy):



Example, writing a character, e.g. at position 2:



Exploit

A short program, repeating multiple actions:

```
mmap(file.txt, fptr, COPY_ON_WRITE)
fork and run two threads
```

```
repeat 1 000 000 times
  madvise(fptr, DONTNEED)
```

```
open(/proc/mem, p)
repeat 1 000 000 times
  seek(p, [mapped file position])
  write(p, string)
```

Actions:

- Thread 1 repeatedly tells the kernel to discard the mmaped area
- Thread 2 looks up the process memory directly, and repeatedly tries to write, causing re-synthesis of virtual copies and write; writes to disk cache and checks that should prevent permission violation

Data-race:

- quickly repeated sequence causes drop of kernel checks
- would never happen for a “slow” sequence of calls

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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:

- ❶ **Improper specification** or understanding of the environment, conditions of execution...
- ❷ **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
- ❸ **Incorrect understanding of the execution model**
e.g., generation of too imprecise results

Why do we need semantics ?

What do the C programs below do ?

When it is unclear, it means that we need more formal semantics...

P0.c

```
int x = 0
int f0( int y ){
    return x * y;
}
int f1( int y ){
    x = y;
    return 0;
}
void main( ){
    int z = f0( 10 ) +
            f1( 100 );
}
```

P1.c

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

P2.c

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

Need for semantics (1/2)

P0.c

```
int x = 0
int f0( int y ){
    return x * y;
}
int f1( int y ){
    x = y;
    return 0;
}
void main( ){
    int z = f0( 10 ) + f1
        ( 100 );
}
```

Execution order:

- **not specified in C**
- **specified in Java**
- if left to right, $z = 0$
- if right to left, $z = 1000$

Need for semantics (2/2)

P1.c

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

P2.c

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

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 ?

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**

Loose software specification: e.g., **machine learning**

- software may include **trained neural network**, loose specification

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)

Generally these methods are not rigorous enough to provide any guarantee on systems!

Formal methods:

- should have **sound mathematical foundations**
- should allow to **guarantee** programs 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

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: **undecidability**
- ▶ **several approaches**, that make various compromises around undecidability

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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 Pa such that:**

- ▶ Pa always terminates
 - ▶ $Pa(P, X) = 1$ **if P terminates** on input X
 - ▶ $Pa(P, X) = 0$ **if P does not terminate** on input X
- We consider the following program:

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

- **What is the return value of $Pa(P0, P0)$?**
i.e., **does P0 terminate on input P0 ?**

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 return 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 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

```
void P1( P ){
  if( Pc( P, P ) == 1 ){
    0 / 0; // deliberately crash
          (unsafe)
  } else {
    return; // do nothing
  }
}
```

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...

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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)
- **static analysis with abstraction: attempt at automatic correctness proofs** (yet, may fail to verify some correct programs)
- **bug-finding:** search for “patterns” indicating “likely errors” (may miss real program errors, and report non existing issues)

Safety verification method characteristics

Safety verification problem

- **Semantics** $\llbracket P \rrbracket$ of program P : set of behaviors of P (e.g., states)
- **Property to verify** \mathcal{S} : set of admissible behaviors (e.g., safe states)

Goal: establish $\llbracket P \rrbracket \subseteq \mathcal{S}$

- **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
- ▶ also for math: four colour theorem, Feith-Thomson theorem and vast adoption of Lean in the math community

- **Not fully automated**

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

- **Sound** and quasi-**complete** (in practice fine...)

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. Static analysis with abstraction (1/4)

Principle

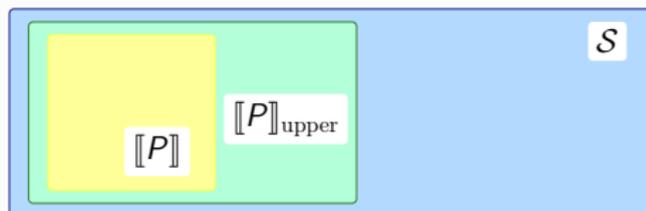
Use some approximation, but **always in a conservative manner**

- **Over-approximation** of the semantics: $\llbracket P \rrbracket \subseteq \llbracket P \rrbracket_{\text{upper}}$
- We may need to **under-approximation** of the target property:
i.e., $\mathcal{S}_{\text{under}} \subseteq \mathcal{S}$ (we assume this here this is not the case)
- We let an automatic static analyzer attempt to prove that:

$$\llbracket P \rrbracket_{\text{upper}} \subseteq \mathcal{S}$$

When this proof succeeds, $\llbracket P \rrbracket \subseteq \mathcal{S}$

- In practice, the static analyzer **computes** $\llbracket P \rrbracket_{\text{upper}}$



4. Static analysis with abstraction (2/4)

Soundness

The abstraction will catch **any incorrect program**

- If $\llbracket P \rrbracket \not\subseteq \mathcal{S}$, then $\llbracket P \rrbracket_{\text{upper}} \not\subseteq \mathcal{S}$
since $\llbracket P \rrbracket \subseteq \llbracket P \rrbracket_{\text{upper}}$

reachable dangerous configuration

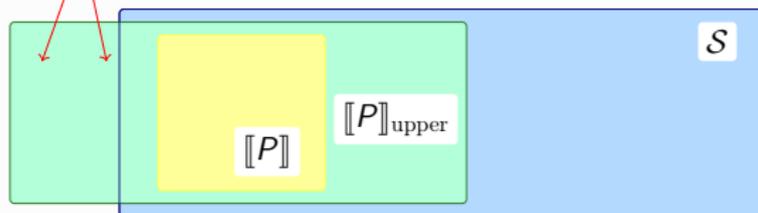


4. Static analysis with abstraction (3/4)

Incompleteness

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

dangerous configurations not ruled out by the abstract semantics



Case of a false alarm:

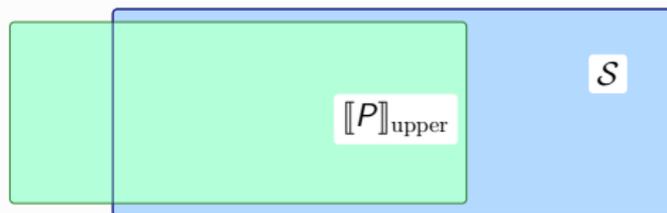
- program P is **correct**
- but the static analysis **fails**

4. 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**: $\llbracket P \rrbracket_{upper}$, S computed automatically
- **Sound**: reports any incorrect program
- **Incomplete**: may reject correct programs

5. “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

- Intuition: **model checking or static analysis made unsound**
- **Example**: Coverity
- **Automated**
- **Not complete**: may report false alarms
- **Not sound**: may accept false programs
thus **inadequate** for safety-critical systems

A summary of common verification techniques

	Automatic	Sound	Complete	Source level	Scalable
Simulation	Yes	No ¹	Yes	Yes	sometimes ²
Assisted proving	No	Yes	Almost	Partially	sometimes ³
Model-checking	Yes	Yes	Partially ⁴	No	sometimes
Static analysis	Yes	Yes	No	Yes	sometimes
Bug-finding	Yes	No	No	Yes	sometimes

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

¹unless full testing is doable

²full testing usually not possible except for small programs with finite state space

³quickly requires huge manpower

⁴only with respect to the finite models... but not with respect to infinite semantics

Outline

- 1 Introduction
- 2 Case studies
- 3 Approaches to verification
- 4 Orderings, lattices, fixpoints**
 - Basic definitions on orderings
 - Operators over a poset and fixpoints
- 5 Conclusion

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 proving termination

Definition: partially ordered set (poset)

Let a set \mathcal{S} and a binary relation $(\sqsubseteq) \subseteq \mathcal{S} \times \mathcal{S}$ over \mathcal{S} .

Then, \sqsubseteq is an **order relation** (and $(\mathcal{S}, \sqsubseteq)$ is called a **poset**) if and only if it is

- **reflexive**: $\forall x \in \mathcal{S}, x \sqsubseteq x$
- **transitive**: $\forall x, y, z \in \mathcal{S}, x \sqsubseteq y \wedge y \sqsubseteq z \implies x \sqsubseteq z$
- **antisymmetric**: $\forall x, y \in \mathcal{S}, x \sqsubseteq y \wedge y \sqsubseteq x \implies x = y$
- **notation**: $x \sqsubset y ::= (x \sqsubseteq y \wedge x \neq y)$

Graphical representation

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

Extensive definition:

- $\mathcal{S} = \{x_0, x_1, x_2, x_3, x_4\}$
- \sqsubseteq defined by:

$$x_0 \sqsubseteq x_1$$

$$x_1 \sqsubseteq x_2$$

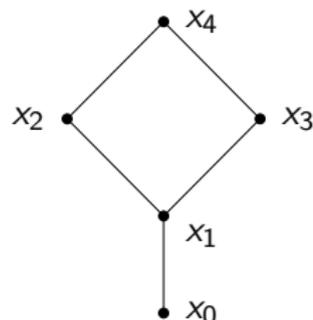
$$x_1 \sqsubseteq x_3$$

$$x_2 \sqsubseteq x_4$$

$$x_3 \sqsubseteq x_4$$

- By reflexivity, we have, e.g., $x_1 \sqsubseteq x_1$
- By transitivity, we have, e.g., $x_1 \sqsubseteq x_4$

Diagram:



Order relations are very useful in semantics...

Example: semantics of automata

In the following, we **illustrate order relations** and their **usefulness in semantics** using **word automata**.

We consider the classical notion of **finite word 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**

Semantics of an automaton

The set of words recognized by $\mathcal{A} = (Q, q_i, q_f, \rightarrow)$ is defined by:

$$\mathcal{L}[\mathcal{A}] = \{a_0 a_1 \dots a_n \mid \exists q_0 \dots q_{n-1} \in Q, q_i \xrightarrow{a_0} q_0 \xrightarrow{a_1} q_1 \dots q_{n-1} \xrightarrow{a_n} q_f\}$$

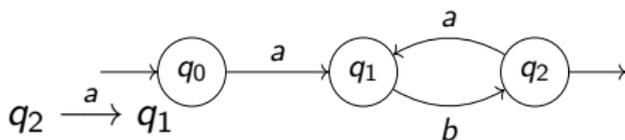
Example: automata and semantic properties

A simple automaton:

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

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

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



A few semantic properties:

- \mathcal{P}_0 : no recognized word contains two consecutive b

$$\mathcal{L}[\mathcal{A}] \subseteq L^* \setminus L^* bbL^*$$

- \mathcal{P}_1 : all recognized words contain at least one occurrence of a

$$\mathcal{L}[\mathcal{A}] \subseteq L^* aL^*$$

- \mathcal{P}_2 : recognized words do not contain b

$$\mathcal{L}[\mathcal{A}] \subseteq (L \setminus \{b\})^*$$

- we could also consider under-approximation properties (of the form $\mathcal{P}_3 \subseteq \mathcal{L}[\mathcal{A}]$), but do not in this lecture

Total ordering

Definition: total order relation

Order relation \sqsubseteq over \mathcal{S} is a **total** order if and only if

$$\forall x, y \in \mathcal{S}, x \sqsubseteq y \vee y \sqsubseteq x$$

Examples:

- **real numbers:**

(\mathbb{R}, \leq) is a total ordering

- **powerset:**

if set \mathcal{S} has at least two distinct elements x, y then its powerset

$(\mathcal{P}(\mathcal{S}), \subseteq)$ is **not** a total order

indeed $\{x\}, \{y\}$ cannot be compared

Most of the order relations we will use are **not be total**

indeed: very often, powerset or similar

Minimum and maximum elements

Definition: extremal elements

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

- **minimum element** of \mathcal{S}' if and only if $x \in \mathcal{S}' \wedge \forall y \in \mathcal{S}', x \sqsubseteq y$
- **maximum element** of \mathcal{S}' if and only if $x \in \mathcal{S}' \wedge \forall y \in \mathcal{S}', y \sqsubseteq x$

- maximum and minimum elements **may not exist**
example: $\{\{x\}, \{y\}\}$ in the powerset, where $x \neq y$
- **infimum** \perp (“**bottom**”): minimum element of \mathcal{S}
- **supremum** \top (“**top**”): maximum element of \mathcal{S}

Exercise:

what are the logical interpretations of infimum / supremum elements ?

Upper bounds and least upper bound

Definition: bounds

Given poset $(\mathcal{S}, \sqsubseteq)$ and $\mathcal{S}' \subseteq \mathcal{S}$, then $x \in \mathcal{S}$ is

- an **upper bound** of \mathcal{S}' if

$$\forall y \in \mathcal{S}', y \sqsubseteq x$$

- the **least upper bound** (lub) of \mathcal{S}' (noted $\sqcup \mathcal{S}'$) if

$$\forall y \in \mathcal{S}', y \sqsubseteq x \wedge \forall z \in \mathcal{S}, (\forall y \in \mathcal{S}', y \sqsubseteq z) \implies x \sqsubseteq z$$

- if it exists, the least upper bound is **unique**: if x, y are least upper bounds of \mathcal{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 $\sqcap \mathcal{S}'$)

Exercise: logical interpretations ?

Duality principle

So far all definitions admit a symmetric counterpart

- **dual relation**: 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	maximum element
infimum	supremum
lower bound	upper bound
greatest lower bound	least upper bound

... more to follow

Complete lattice

Definition: complete lattice

A **complete lattice** is a tuple $(\mathcal{S}, \sqsubseteq, \perp, \top, \sqcup, \sqcap)$ where:

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

Properties:

- $\perp = \sqcup \emptyset = \sqcap \mathcal{S}$
- $\top = \sqcap \emptyset = \sqcup \mathcal{S}$

Example:

the **powerset** $(\mathcal{P}(\mathcal{S}), \subseteq, \emptyset, \mathcal{S}, \cup, \cap)$ of set \mathcal{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 $(\mathcal{S}, \sqsubseteq, \perp, \top, \sqcup, \sqcap)$ where:

- $(\mathcal{S}, \sqsubseteq)$ is a poset
 - \perp is the infimum of \mathcal{S}
 - \top is the supremum of \mathcal{S}
 - any **pair** $\{x, y\}$ of \mathcal{S} has a lub $x \sqcup y$ and a glb $x \sqcap y$
-
- let $\mathcal{Q} = \{q \in \mathbb{Q} \mid 0 \leq q \leq 1\}$;
then (\mathcal{Q}, \leq) is a **lattice** but **not a complete lattice**
indeed, $\{q \in \mathcal{Q} \mid q \leq \frac{\sqrt{2}}{2}\}$ has no lub in \mathcal{Q}
 - property: a **finite** lattice is also a complete lattice

Chains

Definition: increasing chain

Let $(\mathcal{S}, \sqsubseteq)$ be a poset and $\mathcal{C} \subseteq \mathcal{S}$.

It is an **increasing chain** if and only if

- it has an infimum (thus it is not empty)
- poset $(\mathcal{C}, \sqsubseteq)$ is total (i.e., any two elements can be compared)

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

$$\mathcal{C} = \{c_i \mid i \in \mathbb{N}\} \quad \text{where} \quad c_i = \{2^0, 2^2, \dots, 2^i\}$$

Definition: increasing chain condition

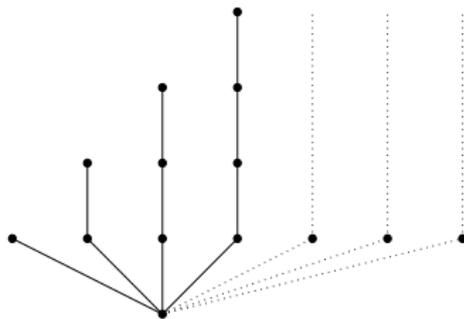
The poset $(\mathcal{S}, \sqsubseteq)$ **satisfies the increasing chain condition** if and only if any increasing chain $\mathcal{C} \subseteq \mathcal{S}$ is finite.

Complete partial orders

Definition: complete partial order

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

- clearly, any complete lattice is a cpo
- the opposite is not true:

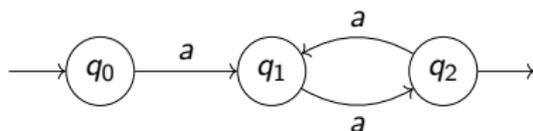


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How to (informally) prove semantic properties

Automaton:



Target property:

recognized words do not contain b

$$\mathcal{L}[\mathcal{A}] \subseteq (L \setminus \{b\})^*$$

Informal proof:

- ① processing of a word starts at q_0 , with ϵ
- ② then, processing may continue at q_1 , with an a
- ③ then, processing may continue at q_2 , with an a (may terminate)
- ④ then, processing may return to q_1 , with an a
- ⑤ ... **repeat the previous steps**

we want to do a proof by induction

Induction

- it is natural to **reason by induction** over executions
- so we would like a **more suitable way to express the semantics**

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

$$\begin{aligned} \llbracket \mathcal{A} \rrbracket : Q &\longrightarrow \mathcal{P}(L^*) \\ q &\longmapsto \{w \in L^* \mid \exists n, w = a_0 a_1 \dots a_n \\ &\quad \exists q_0 \dots q_{n-1} \in Q, q_i \xrightarrow{a_0} q_0 \xrightarrow{a_1} \dots q_{n-1} \xrightarrow{a_n} q\} \end{aligned}$$

Observation 2: $\llbracket \mathcal{A} \rrbracket = \dot{\bigcup}_{n \in \mathbb{N}} \llbracket \mathcal{A} \rrbracket_n$ where

$$\begin{aligned} \llbracket \mathcal{A} \rrbracket_n : Q &\longrightarrow \mathcal{P}(L^*) \\ q &\longmapsto \{a_0 a_1 \dots a_{n-1} \mid \\ &\quad \exists q_0 \dots q_{n-2} \in Q, q_i \xrightarrow{a_0} q_0 \xrightarrow{a_1} \dots q_{n-1} \xrightarrow{a_{n-1}} q\} \end{aligned}$$

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

$$\llbracket \mathcal{A} \rrbracket_{n+1}(q) = \bigcup_{q' \in Q} \{w a \mid w \in \llbracket \mathcal{A} \rrbracket_n(q') \wedge q' \xrightarrow{a} q\}$$

Towards a constructive definition of the automata semantics

Alternate approach:

- 1 Let $\llbracket \mathcal{A} \rrbracket_n$ denote **recognized words of length at most n** :

$$\llbracket \mathcal{A} \rrbracket_n(q) ::= \{w \in \llbracket \mathcal{A} \rrbracket(q) \mid \text{length}(w) \leq n\}$$

- 2 Compute $\llbracket \mathcal{A} \rrbracket_{n+1}$ from $\llbracket \mathcal{A} \rrbracket_n$
- 3 Define the semantics of the automaton as the union of the iterates of this sequence:

$$\llbracket \mathcal{A} \rrbracket = \bigcup_{n \in \mathbb{N}} \llbracket \mathcal{A} \rrbracket_n$$

In the following, we **study such a way of defining semantics**, based on **general mathematical tools**, that we will use throughout the course

Operators over a poset

Definition: operators and orderings

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

- **monotone** if and only if $\forall x, y \in \mathcal{S}, x \sqsubseteq y \implies \phi(x) \sqsubseteq \phi(y)$
- **continuous** if and only if, for any chain $\mathcal{S}' \subseteq \mathcal{S}$ then:
 - $\left\{ \begin{array}{l} \text{if } \sqcup \mathcal{S}' \text{ exists, so does } \sqcup \{\phi(x) \mid x \in \mathcal{S}'\} \\ \text{and } \phi(\sqcup \mathcal{S}') = \sqcup \{\phi(x) \mid x \in \mathcal{S}'\} \end{array} \right.$
- **\sqcup -preserving** if and only if:
 - $\forall \mathcal{S}' \subseteq \mathcal{S}, \left\{ \begin{array}{l} \text{if } \sqcup \mathcal{S}' \text{ exists, then } \sqcup \{\phi(x) \mid x \in \mathcal{S}'\} \text{ exists} \\ \text{and } \phi(\sqcup \mathcal{S}') = \sqcup \{\phi(x) \mid x \in \mathcal{S}'\} \end{array} \right.$

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:

Continuity implies monotonicity

If ϕ is continuous, then it is also **monotone**

We assume ϕ is continuous, and $x, y \in \mathcal{S}$ 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 $\phi(x) \sqsubseteq \phi(y)$.

\sqcup -preserving implies monotonicity

If ϕ preserves \sqcup , then it is also **monotone**

Same argument.

Fixpoints

Definition: fixpoints

Let $(\mathcal{S}, \sqsubseteq)$ be a poset and $\phi : \mathcal{S} \rightarrow \mathcal{S}$ be an operator over \mathcal{S} .

- a **fixpoint** of ϕ is an element x such that $\phi(x) = x$
- a **pre-fixpoint** of ϕ is an element x such that $x \sqsubseteq \phi(x)$
- a **post-fixpoint** of ϕ is an element x such that $\phi(x) \sqsubseteq x$
- the **least fixpoint** $\text{lfp } \phi$ of ϕ (if it exists, it is unique) is the smallest fixpoint of ϕ
- the **greatest fixpoint** $\text{gfp } \phi$ of ϕ (if it exists, it is unique) is the greatest fixpoint of ϕ

Note: the existence of a least fixpoint, a greatest fixpoint or even a fixpoint is *not guaranteed*; we will see several theorems that establish their existence under specific assumptions...

Tarski's Theorem

Theorem

Let $(\mathcal{S}, \sqsubseteq, \perp, \top, \sqcup, \sqcap)$ be a complete lattice and $\phi : \mathcal{S} \rightarrow \mathcal{S}$ be a monotone operator over \mathcal{S} . Then:

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

Proof of point 1:

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

For all $y \in X$, we remark that:

- $x_0 \sqsubseteq y$ by definition of the glb;
- thus, since ϕ 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 $x_0 = \sqcap X$ and $\phi(x_0)$ is a lower bound.

Tarski's Theorem

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

- $\phi(\phi(x_0)) \sqsubseteq \phi(x_0)$ since ϕ is monotone;
- $\phi(x_0)$ is a post-fixpoint of ϕ , 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 ϕ , we need to consider ϕ over $\{y \in \mathcal{S} \mid y \sqsubseteq_{\mathcal{S}} \sqcap X\}$ 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:

$$\begin{aligned} f : \mathcal{P}(\mathcal{E}) &\longrightarrow \mathcal{P}(\mathcal{E}) \\ X &\longmapsto X \cup \mathcal{A} \end{aligned}$$

Exercise:

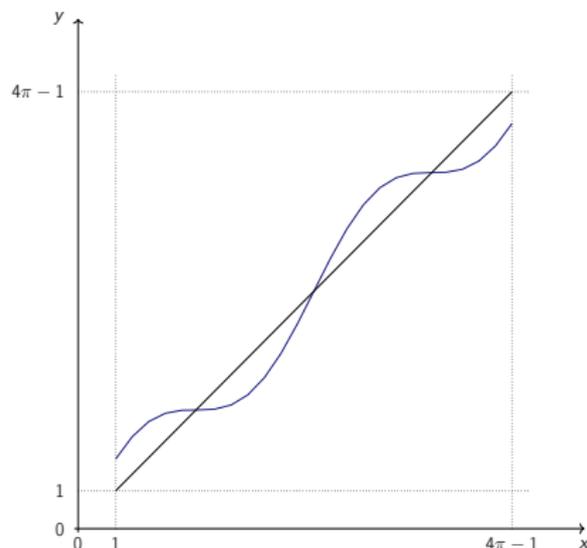
- apply Tarski's theorem, characterize the least and greatest fixpoints

Tarski's theorem: example (2)

Function:

$$f : [1, 4\pi - 1] \longrightarrow [1, 4\pi - 1]$$

$$x \longmapsto x + \sin x$$



Exercise:

- apply Tarski's theorem, and derive the fixpoints of the function

Automata example, fixpoint definition

Lattice:

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

Operator:

- we let $\phi_0 : \mathcal{S} \rightarrow \mathcal{S}$ be defined by

$$\phi_0(f) = \lambda(q \in Q) \cdot \bigcup_{q' \in Q} \{wa \mid w \in f(q') \wedge q' \xrightarrow{a} q\}$$
- we let $\phi : \mathcal{S} \rightarrow \mathcal{S}$ be defined by

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

Proof steps to complete:

- **the existence of $\text{lfp } \phi$** follows from Tarski's theorem
- **the equality $\text{lfp } \phi = \llbracket \mathcal{A} \rrbracket$** 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 $(\mathcal{S}, \sqsubseteq, \perp)$ be a pointed cpo and $\phi : \mathcal{S} \rightarrow \mathcal{S}$ be a continuous operator over \mathcal{S} . Then ϕ 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 ϕ 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 ϕ** :

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

$$\begin{aligned}
 \phi(x_0) &= \phi(\bigsqcup\{\phi^n(\perp) \mid n \in \mathbb{N}\}) \\
 &= \bigsqcup\{\phi^{n+1}(\perp) \mid n \in \mathbb{N}\} && \text{by continuity of } \phi \\
 &= \perp \bigsqcup (\bigsqcup\{\phi^{n+1}(\perp) \mid n \in \mathbb{N}\}) && \text{by definition of } \perp \\
 &= x_0 && \text{by simple rewrite}
 \end{aligned}$$

Last, we show that it is the **least** fixpoint:

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

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

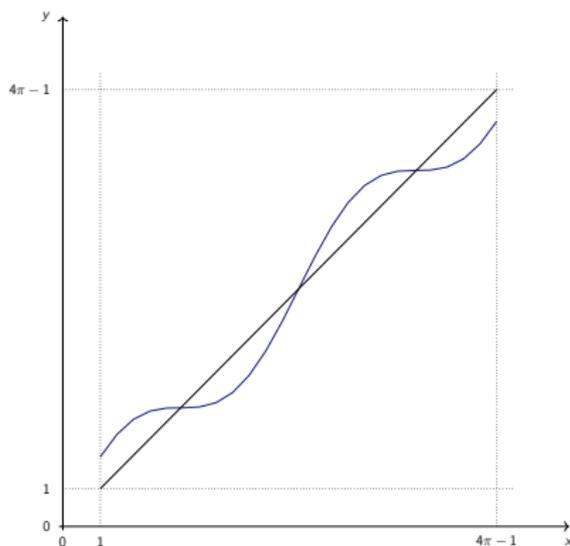
By definition of the lub, $x_0 \sqsubseteq x_1$

Kleene's theorem: example

Function:

$$f : [1, 4\pi - 1] \longrightarrow [1, 4\pi - 1]$$

$$x \longmapsto x + \sin x$$



Exercise:

- apply Kleene's theorem and sketch the iterations

Automata: constructive semantics

We can now state a **constructive definition** of the automaton semantics.
Operator ϕ is 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:

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

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

This fixpoint definition will be very useful to infer or verify semantic properties.

Automata: constructive semantics iterates

A simple automaton:

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

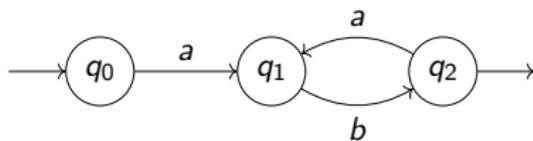
$$q_i = q_0$$

$$q_f = q_2$$

$$q_0 \xrightarrow{a} q_1$$

$$q_1 \xrightarrow{b} q_2$$

$$q_2 \xrightarrow{a} q_1$$

Iterates of function ϕ from \perp :

Iterate	0	1	2	3	4	5
q_0	\emptyset	$\{\epsilon\}$	$\{\epsilon\}$	$\{\epsilon\}$	$\{\epsilon\}$	$\{\epsilon\}$
q_1	\emptyset	\emptyset	$\{a\}$	$\{a\}$	$\{a, aba\}$	$\{a, aba\}$
q_2	\emptyset	\emptyset	\emptyset	$\{ab\}$	$\{ab\}$	$\{ab, abab\}$

Duality principle

We can **extend the duality notion to fixpoints**:

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 is its own dual).

On the topic of inductive reasoning...

Formalizing inductive definitions:

Definition based on
inference rules:

$$\frac{}{x_0 \in \mathcal{X}} \quad \frac{x \in \mathcal{X}}{f(x) \in \mathcal{X}}$$

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 $\phi : \mathcal{S} \rightarrow \mathcal{S}$ be a continuous operator
- Let $\mathcal{I} \in \mathcal{S}$ such that:

$$\forall x \in \mathcal{S}, x \sqsubseteq \mathcal{I} \implies \phi(x) \sqsubseteq \mathcal{I}$$

- We obviously have $\perp \sqsubseteq \mathcal{I}$
- We can prove that $\text{lfp } \phi \sqsubseteq \mathcal{I}$

Exercise: language of a grammar

Language of a grammar as a least-fixpoint

Assumptions:

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

Questions:

- 1 Define the set of words recognized by the grammar with inductive rules
- 2 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 induction

Exercise: transfinite iteration

A generalisation of Kleene's theorem

We let $(\mathcal{S}, \sqsubseteq, \perp)$ be a pointed cpo and $\phi : \mathcal{S} \rightarrow \mathcal{S}$ be a monotone over \mathcal{S} .

- 1 Propose a notion of **transfinite iteration sequence of ϕ** , indexed with **ordinals**
- 2 Prove that this sequence is well-defined and is a **chain**
- 3 Prove that this sequence is **stationary**
- 4 Prove that its limit is a **fixpoint** of ϕ
- 5 Derive an extension of Kleene's theorem

Hints:

- transfinite iterations generalise iteration sequences to ordinals (definition recalled on the next slide)
- note that it provides a constructive generalisation of the theorem of Tarski

Ordinal numbers

Definition

Inductive construction of ordinal numbers in set theory:

- $0 ::= \emptyset$ is an ordinal;
- if k is an ordinal, then so is its successor $Sk ::= k \cup \{k\}$;
- if E is a set of ordinals, then so is $\sup E = \bigcup E$

Application:

- $0, S0$ noted 1 , etc
- $\omega = \{0, 1, \dots$ is the first **limit ordinal**
- next limit ordinals are $2\omega, 3\omega, \dots, \omega^2$

Transfinite induction

Let P a predicate over ordinal numbers. We assume that, for all ordinal k , if for all $k' < k$, $P(k')$ holds, then so does $P(k)$.

Then P holds for all ordinal numbers.

Outline

- 1 Introduction
- 2 Case studies
- 3 Approaches to verification
- 4 Orderings, lattices, fixpoints
- 5 Conclusion**

Main points to remember

Foundations:

- **program semantics**: express program behaviors
- **target semantic property**: express proof goal
- **conservative approximation** usually required due to undecidability

Order relations:

- **counterpart for logical implication** (among other)
- will be pervasive in this course

Fixpoints and induction:

- **encode general iteration**
- will also be pervasive in this course

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

Course (1h30) + **TD or TP** (2h00)

Schedule: **Friday morning** 8h30–12h15

Location: Room É Noether (also known as “U ou V”)

Course teachers:

- Charles De Haro: lab sessions
- Jérôme Feret: semantics, typing, abstract interpretation
- Xavier Rival: semantics, program properties, Rocq proof assistant, abstract interpretation

Webpage with class material:

<https://www.di.ens.fr/~rival/semverif-2026>
material (e.g., video if a class is online) also on Moodle

Evaluation: 50 % project + 50 % final exam (or homework, TBC)