Automatic Testing & Verification

Introduction

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About Us…

- Juan Pablo Galeotti
- Alessandra Gorla

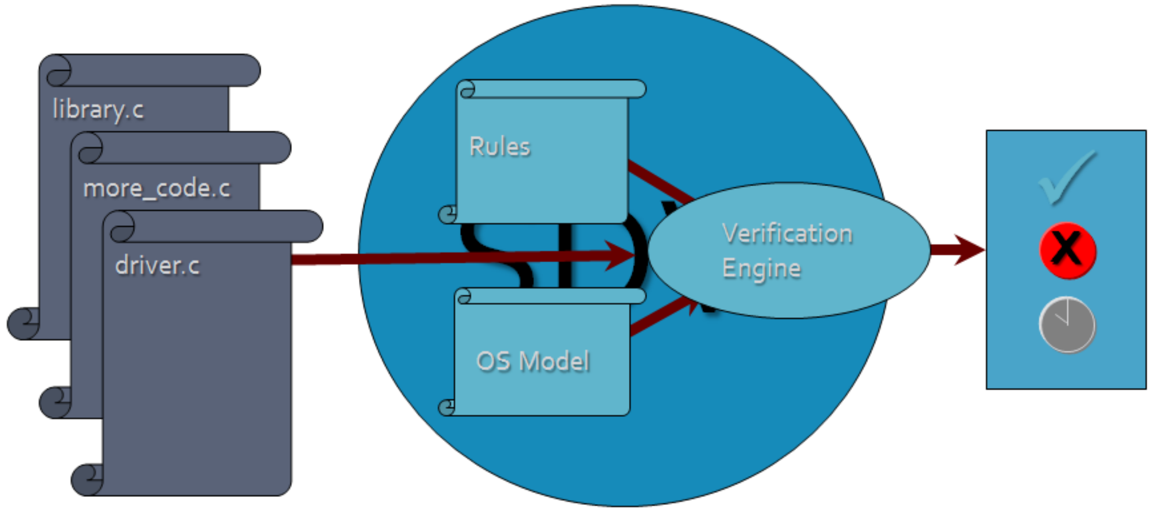
- http://www.st.cs.uni-saarland.de
  - Computer Science – Saarland University
  - Research on:
    - Mining software archives
    - Automated Debugging
    - Mutation Testing
    - Mining Models
  - Bachelor and Master students
    - Always welcome!

Motivation

- Automated analysis is rapidly gaining ground on all software development activities.
- **Industry**: Tools are more often used to enhance more traditional QA methodologies.
  - More results are obtained at a lower cost.

Impact on Industry

- "Static Analysis can reduce defects by up to a factor of six!"
  - (Capers Jones, Software Productivity Group)
- **Microsoft**
  - Code is automatically analyzed using automatic verifiers (PREfix, PREfast)
  - Visual Studio + Code Contracts: Static Analysis + Test Case Generation
  - Kit for verifying drivers is delivered to third-parties vendors.



Impact on Industry

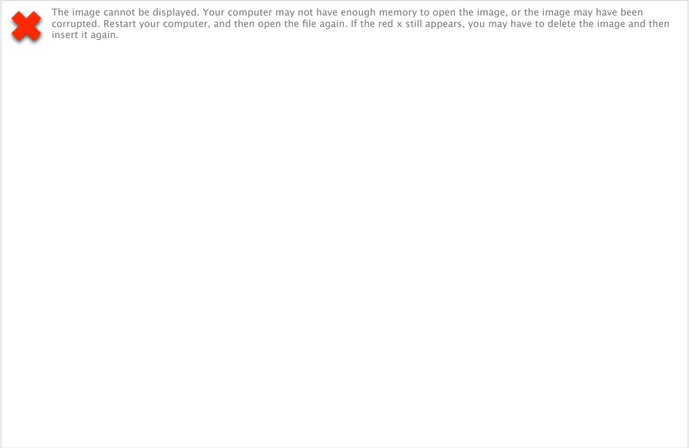
- **Java FindBugs**: > 1,5 million downloads
  - Actively used in Google, Sun, Ebay, etc.
  - It finds “mechanical” errors, error patterns
- Experience in **Google**:
  - >4000 problems in deployed code!
  - More than 80 infinite loops!

Motivation

- Automatic program analysis is increasily used in software engineering activities
- **Industry**: Tools are more often used to enhance traditional QA methodologies
  - Concrete results are obtained at lower cost.
- **Academia**: A lot of activity
  - Program analysis topics gain presence in more important conferences in software engineering, programming and systems
    - Hybrid approachs (static analysis + testing) .
    - Bug detection, Multicore (data races, automatic parallelization).
      - More precision, usability, scalability (no longer a bottleneck)
    - Security

Some disasters

- Therac 25:
  - Due to a bug, a radio therapy machine applied 100 times the radiation dose on patients
    - A *race condition* did not allow the machine to detect a change in the operation mode



- Ariane V Flight 501:
  - An arithmetic *overflow* in inertial computation
  - Exception badly handled
  - Reused code from Ariane 4

- http://en.wikipedia.org/wiki/List_of_software_bugs

Any mini-disaster at home?

Why is so hard to build quality programs?

- In other fields,
  - Many failures, but unfrequent
    - A building, a bridge, or a car do not need weekly *patches*…
  - Well-defined techniques for quality assurance
  - Quality can be measured and predicted
  - Relatively simple parts, composition can be done.
- In software…
  - Systems fail everyday
  - It is very complex to determine quality and predict problems.
  - Building a failure-tolerant system is more complex than "concrete" engineering
    - Replicate components can lead to new problems…

Software Complexity

- A lot of functionality!
- Size:
  - Code millions lines length
    - Each line might be important!
  - State-explosion:
    - A single 32bits variable has 2^32 potential values!!!
- Complexities:
  - Arithmetic, concurrency, dynamic heap memory
  - Complex hardware, heterogenous
  - etc.

Program analysis

"Program analysis is the systematic examination of a software «artifact» to discover its properties"

- **Examination**:
  - Automatic vs. manual
- **Systematic**:
  - Coverage in testing, inspection checklist, exhaustive model checking, etc…
- **Artifact**:
  - Program, execution trace, test case, design, requirements document.
- **Properties**:
  - Functional: correction
  - Non-functional: memory consumption, performance, availability, security

Program Analysis

Analyze (infer/prove properties over) **programs**

- **Dynamic Analysis**:
  - Program analysis using the execution of the program
  - Characterizes some executions
  - Precise: it knows all concrete states
- **Static Analysis**:
  - The program is analysed without executing code.
  - Characterizes all possible executions
  - Conservative: it approximates concrete states

Verification, Validation, Synthesis, Inference

- Verification
  - Against a specification
    - It might be an implicit specification
- Validation
  - Does the system do what the user wants?
  - Failures in specifications
- Inference
  - Discover some interesting properties about the program
- Synthesis
  - Create a new program: optimize (compiler), control (scheduler)

We will focus on verification and inference

A problem has been detected and Windows has been shut down to prevent damage to your computer.

UNEXPECTED_KERNEL_MODE_TRAP

If this is the first time you've seen this Stop error screen, restart your computer. If this screen appears again, follow these steps:

Check to make sure that any new hardware or software is properly installed. If this is a new installation, ask your hardware or software manufacturer for any Windows updates you might need.

If problems continue, disable or remove any newly installed hardware or software. Disable BIOS memory options such as caching or shadowing. If you need to use Safe Mode to remove or disable components, restart your computer, press F8 to select Advanced Startup Options, and then select Safe Mode.

Technical information:

*** STOP: 0x0000007F (0x00000000,0xB9FC8E84,0x00000008,0xC0000000)

*** Beep.SYS - Address B9FC8E84 base at B9FC7000, DateStamp 36B04C16

Find the bug!

```
x := 8;
y := x;
z := 0;
while y > -1 do
    x := x / y;
    y := y-2;
    z := 5;
```

Division by zero!

Find the bug!

```
x := 8;
y := x;
z := 0;
while y > f(x,y,z) do
    x := x / y;
    y := y-2;
    z := 5;
```

Division by zero!

The BIG program

- Remove bugs from our programs.
  - As soon as possible (before deployment).

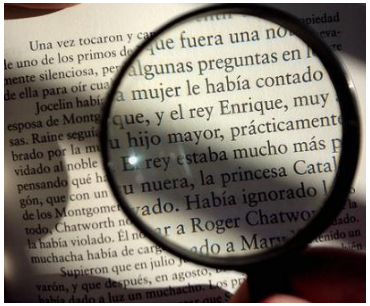
Classic techniques

- Remove bugs from our programs.
  - As soon as possible (mainly before deployment).
- **Testing**: Direct execution of a program in a controlled environment
  - Identify and localize faults: it does not guarantee absence
  - It may be too expensive

"*Program testing can be used to show the presence of bugs, but never to show their absence!*" -- Edsger Dijkstra

Classic Techniques

- Remove bugs from our programs.
  - As soon as possible (mainly before deployment).
- **Dynamic Analysis**: Tools for mining information from program executions
  - Find failures (memory)
  - Invariants
  - Precise but under approximates.



- **Inspections**: Human evaluation of artifacts.
  - Specifications, Designs, <u>Code</u>.
  - Important human effort: error prone,
    it can not be exhaustive due to scale of artifacts
  - Sometimes failures are “subtle”, they happen after a non-trivial sequence of events.

Static Analysis

- The program is analyzed without being **executed**.
- It is the systematic examination of an abstraction of the program states
- **Systematic**
  - We examine **all** program paths within one procedure
    - What about loops?
  - The exploration is **exhaustive**
- **Abstraction**
  - Keep **only** relevant information with regard to the property to infer
    - Variable sign (-,0,+)
    - Set of variables to be read in the future
    - Etc…

More known techniques

- **Deductive verification methods**
  - Formal proofs of correction against specifications.
  - Tool support :
    - Compilers+ theorem provers
    - Type checkers
    - Semi automatic or incomplete, often too costly.
  - They require annotations (**types** or **contracts**).

- **Model checking**
  - A formal model of a system is analyzed
  - Good for analyzing event interaction (protocols, concurrency, etc)
  - Expensive

- **Dataflow / Abs. Interpretation**
  - "**Mechanical**" Errors (difficult to exhibit through Testing or inspections):
    - Memory usage (null dereference, non initialized date).
    - Resource "Leaks" (memory, locks, files).
    - Vulnerabilities (buffers overruns, non validated data).
    - Non handled exceptions, concurrency (race conditions), etc.

- **Bug finding**
  - Search for common patterns
  - Good practice enforcement

Static Analysis: typical usage

- **To optimize code**
  - Detect unused variables;
  - Remove dead code
  - Detect more frequently used expressions.
  - Purity analysis.
  - Null dereference.
- **Verification**
  - Implicit or explicit contracts
  - Functional properties
  - “Mechanical” Errors
- **Program Understanding**
  - Type inference
  - Pre/post computation
  - Invariants
  - Memory requirements
  - Reverse engineering
    - Call graph of a OO program
    - Behavioral Models
    - Architectural view
    - …
- **Improve code quality/ readability**
  - It might check if a program satisfies established “good practices” patterns

Static Analyzer Glossary

Concepts that appear recurrently:

- Abstraction
- Approximation
  - May vs Must
- Correction vs Completeness
  - False positives
  - False negatives

- Inference vs. Checking
- Verification vs. Bug Finding

- Sensibility
  - Flow-sensitive
  - Path-sensitive
  - Context-sensitive
- Intra vs. Interprocedural

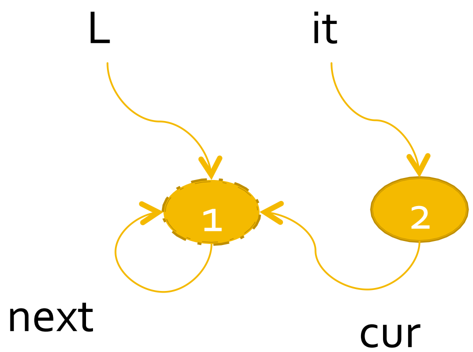
Abstraction

- Focus on property to analyze
- Which aspects of the problem are interesting?
  - Control aspects
    - e.g: event sequences, instruction sequences, concurrency, etc.
  - Data
    - Division by zero
    - Memory comsuption
  - Security
  - Functionality
- To what degree of precision?

Abstraction: example

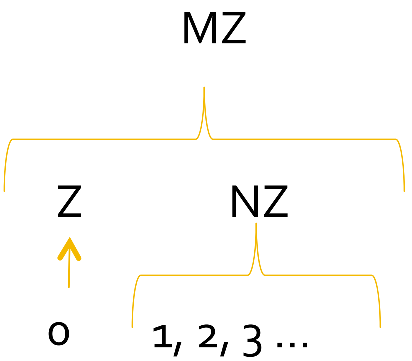
- I want to know about potential null dereferences
  - σ: Var → {**null**, **notNull**, **mayBeNull**}
- Division by Zero
  - σ: : Var →{**indef** , **Z**, **NZ**, **QZ**}
- Can I free memory used by the iterator on method exit?
  - σ: : **points-to graph**
  - Check reachability

```
float avg_List(List L)
{
  int c = 0, s = 0;
  Iterator itL = L.iterator();
  for(;itL.hasNext();)  {
      val = (Value)itL.next();
      s+=val.value();
      c++;
    }
  }
  return s/c;
}
```



Abstraction requires approximation

- Abstraction => handle an incomplete picture
  - We do not handle "concrete"/"real" information
- Examples: Positive integers
  - 3 – 3 = 0
  - Abs(3) = NZ
  - What is NZ – NZ?
    - Answer Z o NZ => MZ



MAY vs MUST Analysis

- We need to approximate and be conservative
  - We require to approximate from “above” (MAY) or from “below” (MUST)

Points-to analysis (e.g.: call graph)

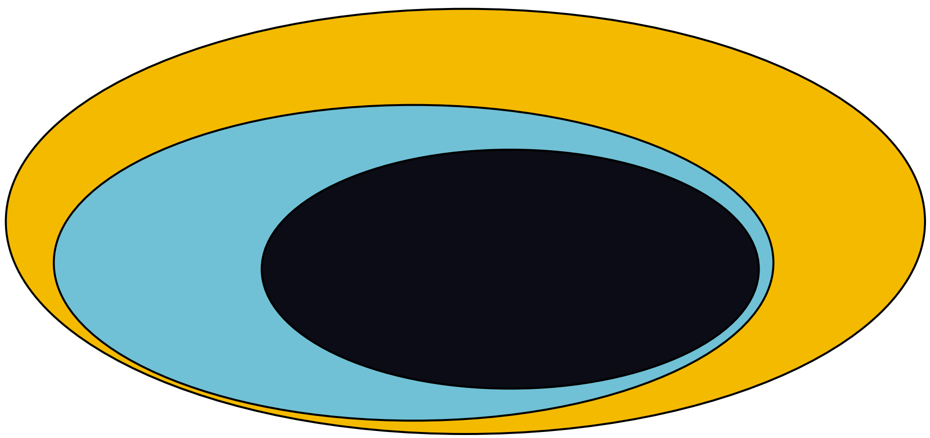
```
class  B extends A {};
...
  Object a;
   [a -> null]
  if(y<10) {
    a = new A();
    [a -> A]
  }
  else {
    a = new B()
    [a -> B]
  }
   [a -> A ó B]
  a.foo()
```

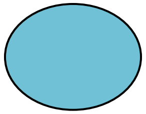
Available expressions (e.g.: remove redundant computation)

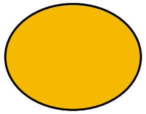
```
…
int c = b*b;
{b*b }
int d = c + 1;
{b*b, c+1}
int a = b*b;
{b*b, c+1}
c = 4;
{ b*b }
if(b < c) b = 2;
else a = b*4;
{}
return d;
```

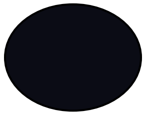
Soundness vs Completeness

- False positives vs. False negatives.



 = Real Bugs in the system

 = Bugs detected by a "**correct**" analysis

 = Bugs detected by a "**complete**" analysis (eg:testing)

Soundness and Completeness

Given an analysis A that checks certain property Q on a program Pr:

- **Soundness**
  - If program Pr satisfies Q, then analysis A can prove/find it
  - If analysis reports **no null dereference** => program **has no** null dereferences
- **Completness**
  - If analysis A reports property Q on program Pr, then property Q exists in program Pr.
  - If analysis reports **null dereference** => program **has** null dereference
- **Ideal** = Soundness+ Completeness

Inference vs Checking

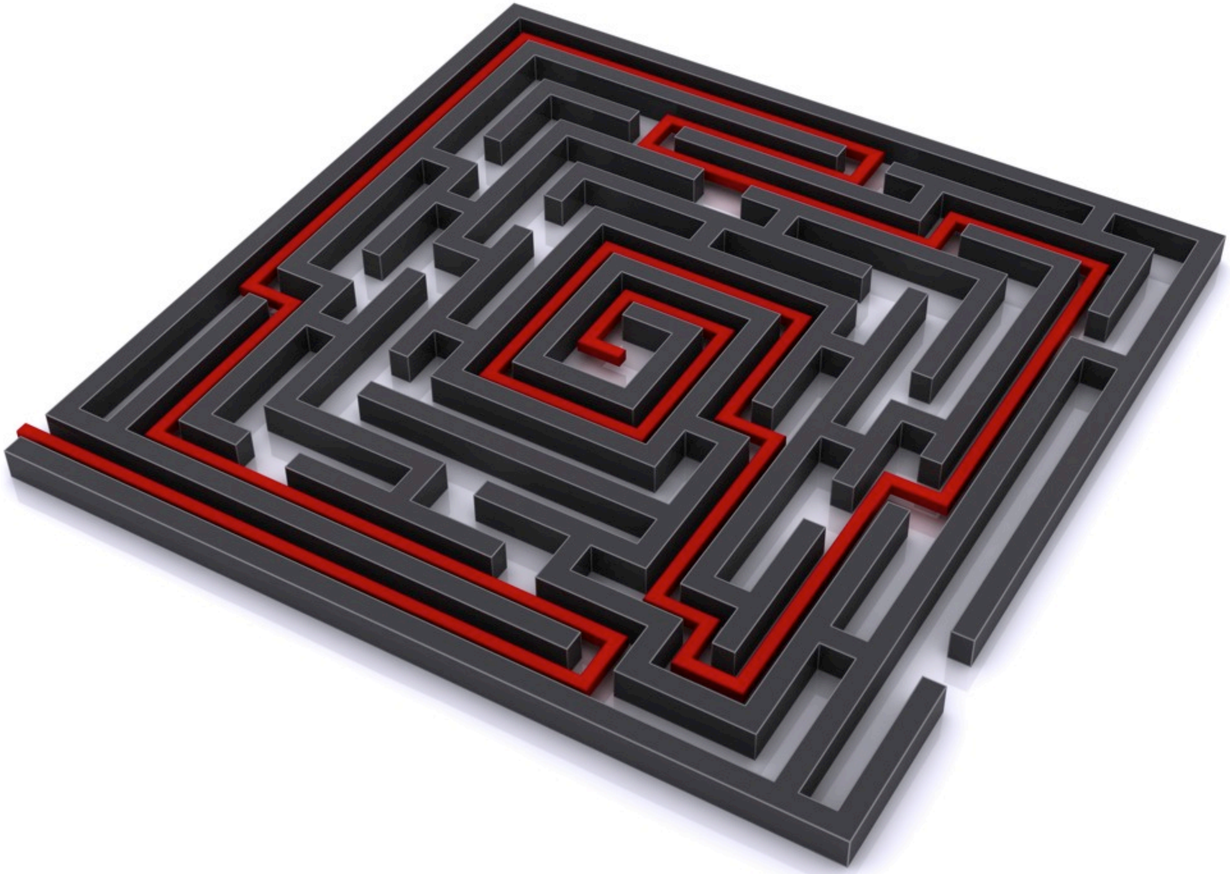
- **Type-Checking**:
  - Given a program and a set of annotations (property) check if the annotations are correct
- **Inference:**
  - Given a program infer annotations that exhibit a propety
- Checking is easier than infering!

```
int max(int[] a) {
1:   int i=0;
2:   int m = a[0];
3:   while (i < a.length) {
4:     if(a[i]> m)
5:        m = a[i];
6:     i++;
7:   }
8:   return m;
}
```

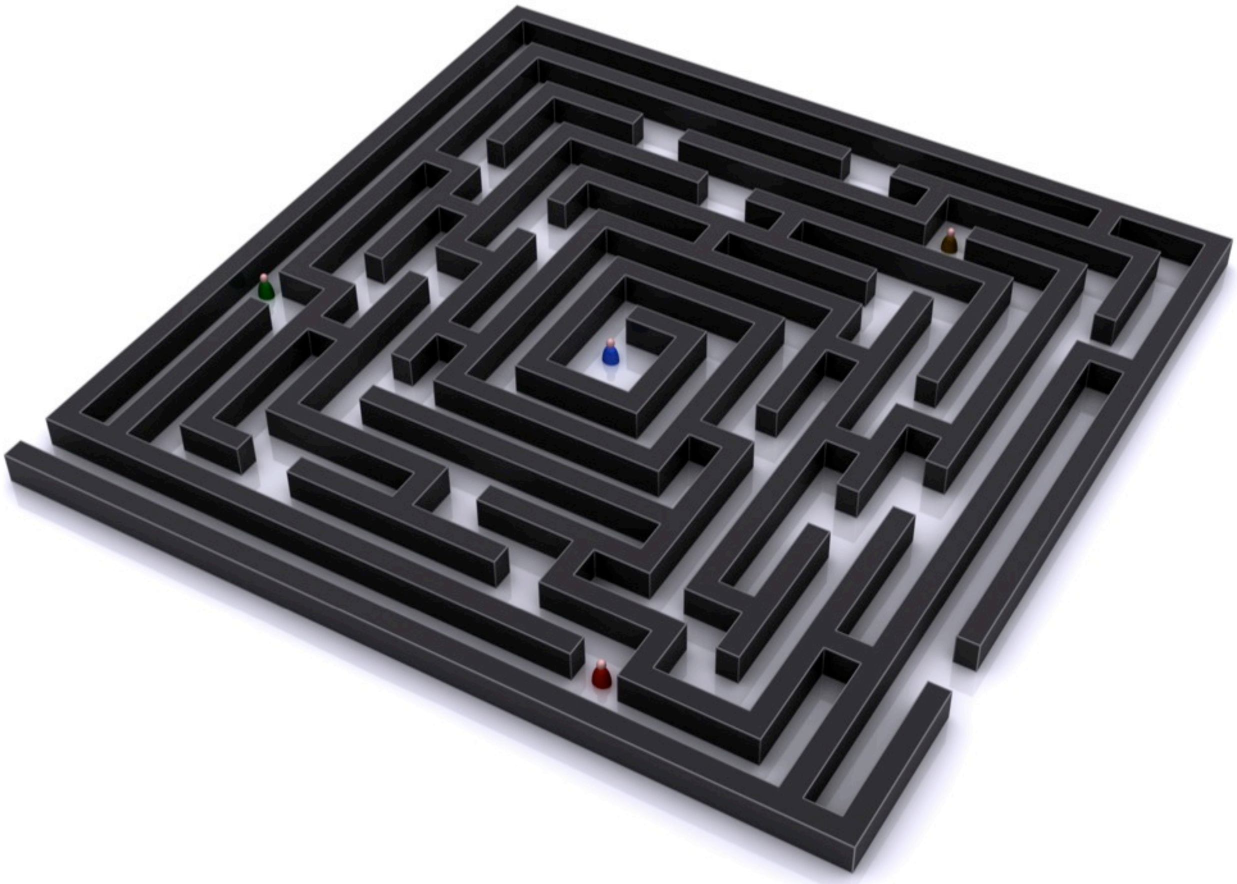
```
requires |a|>0;
ensures ∀j:[0,|a|)| res>=a[j];
```

```
1: assert i == 0;
2: assert m == a[0];
3: assert 0<=i<|a| && ∀j:[0,i)| m>=a[j];
4: assert 0<=i<|a| && ∀j:[0,i)| m>=a[j] && a[i]>m;
5: assert 0<=i<|a| && ∀j:[0,i)| m>=a[j] && m==a[i];
6: assert 0<i<=|a| && ∀j:[0,i]| m>=a[j];
7: assert i==|a| && ∀j:[0,i)| m>=a[j];
8: assert i==|a| && ∀j:[0,i)| res>=a[j];
```

Checking



Inference



Verification vs Bug Finding

- Verification: prove that a program obeys a specification
  - Specification could be implicit
  - Analysis is usually conservative

- Bug finding
  - Focus in *some* classes of errors with "real" impact.
    - Misusage of equals,hash
    - Null pointers
    - Synchronization
  - Apply several techniques on these errors
    - Dataflow, syntactic, statistical, etc.
  - Practical: it may miss bugs

Sensibility

- Sensibility: which code aspects will be considered?
  - Statement order? Flow sensitive
  - Call Stack? Context sensitive
  - Conditional branches? Path sentivive

Analysis	Sensibility
Type-checking	Insensible
Dataflow	Flow-sensitive
Model Checking	Flow-sensitive and Path-sensitive
Points-to	C :Flow-sensitive Java: Context-sensitive

Static Analysis limitations

- Why we need to approximate the static analysis?
  - Because of performance issues?
  - Because of shortage of resources?

- Because of indecibility of the analysis!
  - In general there is no program capable of computing precisely the properties of arbitrary.
  - This leads us to the Halting problem
    - "Has program P property X?" ≡ "Program P can reach a state where X holds?"

About this course

- Objetives
  - Present techniques for analyzing programs
    - Static and dynamic techniques
  - Learn their foundamentals:
    - In order to evaluate them, compare them
    - Pros & Cons.
    - Challenges
  - Promote using automatic tools for testing and program analysis

Outline

Verification and Analysis

- Design by contract
- Verification using automatic theorem provers
- Static verification, dynamic verification, bounded verification
- Typestates
- nullness, inmutability analysis
- Intraprocedural / Interprocedural Dataflow
- Dynamic Symbolic Execution

Testing

- Test case generation
- Structural and functional testing
- Search based testing
- Regression testing
- Mutation testing
- Model based testing
- Web applications testing
- GUI testing

Tools, tools, tools, demos, demos, tools, demos!

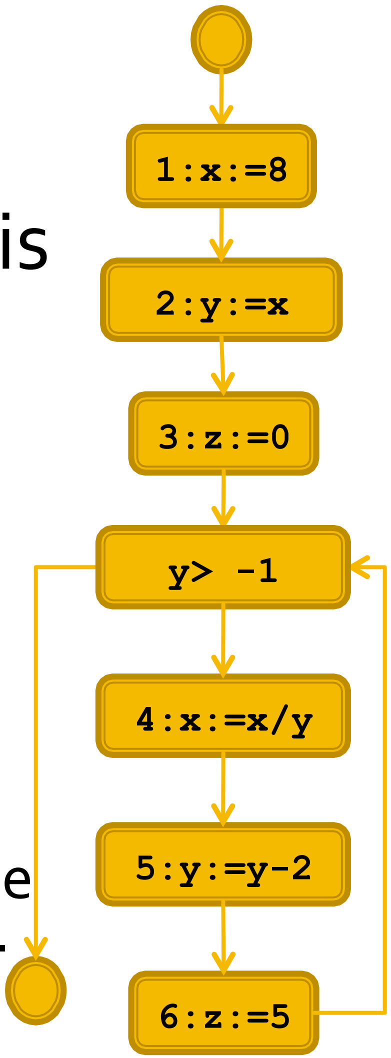
Course Organization

- 3 lectures every 2 weeks
- 1 lab session every 2 weeks

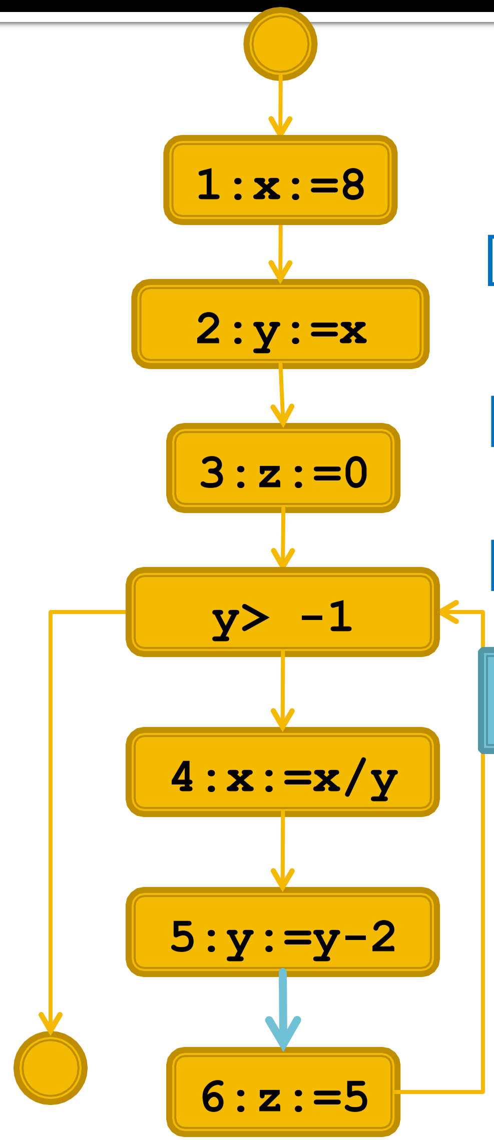
- 3 student projects
- Final written exam

Inferring properties

- Dataflow analysis
- It is the most heavily used static analysis technique.
- Purpose: Infer **automatically** interesting properties of a given program
- Principle: Model the execution of a program as the solution of a set of equations. The equations describe the flow of values through the program instructions.



An example



σ = []

[x→ NZ]

[x→ NZ, y → NZ]

[x→ NZ, y → NZ, z → Z]

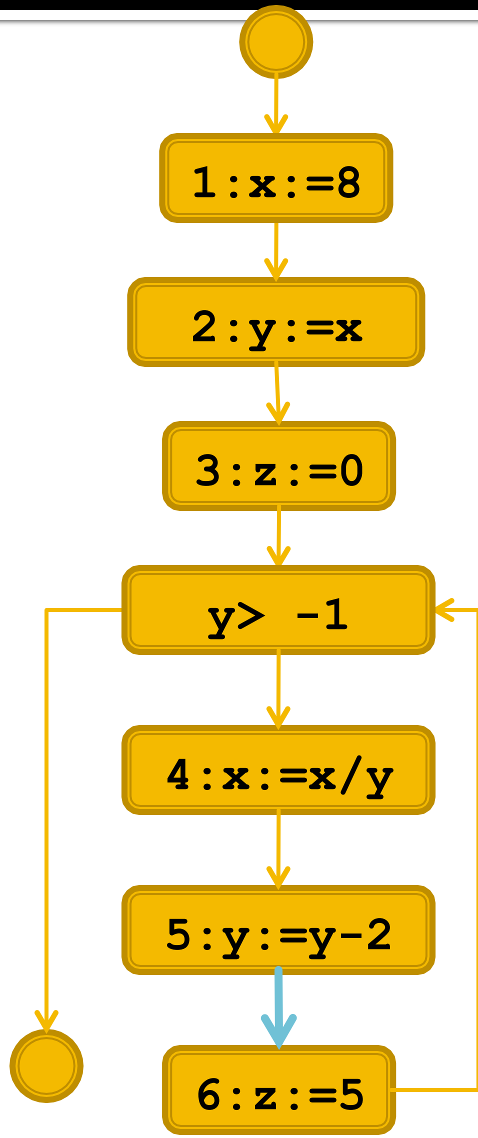
[x→ NZ, y → MZ, z → MZ]

[x→ NZ, y → NZ, z → Z]

[x→ NZ, y → MZ, z → Z]

[x→ NZ, y → MZ, z → NZ]

An example



σ = []

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[x → NZ, y → MZ, z → MZ]

[x → NZ, y → MZ, z → MZ]

[x → NZ, y → MZ, z → NZ]

An Example: Using the results

```
σ = []
x := 8;
σ = [x→ NZ]
y := x;
σ = [x→ NZ, y→ NZ]
z := 0;
σ = [x→ NZ, y→ NZ, z→ Z]
while y > -1 do
    σ = [x→ NZ, y→ MZ, z→ MZ]
    x := x / y;
    σ = [x→ NZ, y→ MZ, z→ MZ]
    y := y-2;
    σ = [x→ NZ, y→ MZ, z→ MZ]
    z := 5;
    σ = [x→ NZ, y→ MZ, z→ NZ]
```

Warning: This program ***may*** try to divide a number by zero

Contract Verification

- Basic Idea: Translate the program (and also the contract) into a logical formula.
  - Prove that the contract holds in the formula
    - We may use a automatic theorem prover (SMT or SAT solvers)

Example: Using Dijsktra Weakest Precondition

```
returns c
requires true
ensures c = a || b
```

```
bool P(bool a, bool b) {
  if (a)
    c:=true
  else
     c:=b
}
```

WP(P, c=a||b) = a => WP(c:=true,c=a||b) && !a => WP(c:=b,c=a||b) = (a=> true=a||b) && !a => b=a||b)

- Conjecture to prove: **true**=>**(a=> true=a||b) && !a => b=a||b)**

Modelling using type-states

```
class C {

   D f;

   C() {
      if (bluemoon()) {
        f = new D();
      }
   }

  C(D x) {
    f = x;
  }

  void m() {
       f.q();
  }
}
```

was *f* really initialized?

- It depends on the condition

May field *f* be null?

Modelling using type-states

```
class C {

   D! f;

   C() {
      if (bluemoon()) {
        f = new D();
      }
   }

  C(D x) {
    f = x;
  }

  void m() {
       f.q();
  }
}
```

Field *f* is non null !

Erros are now explicit

1. There are executions which do not initialize *f*
2. *x* can not be assigned to *f* because they do not share the same type!

Now, if a program typechecks, it means there are no null dereferences

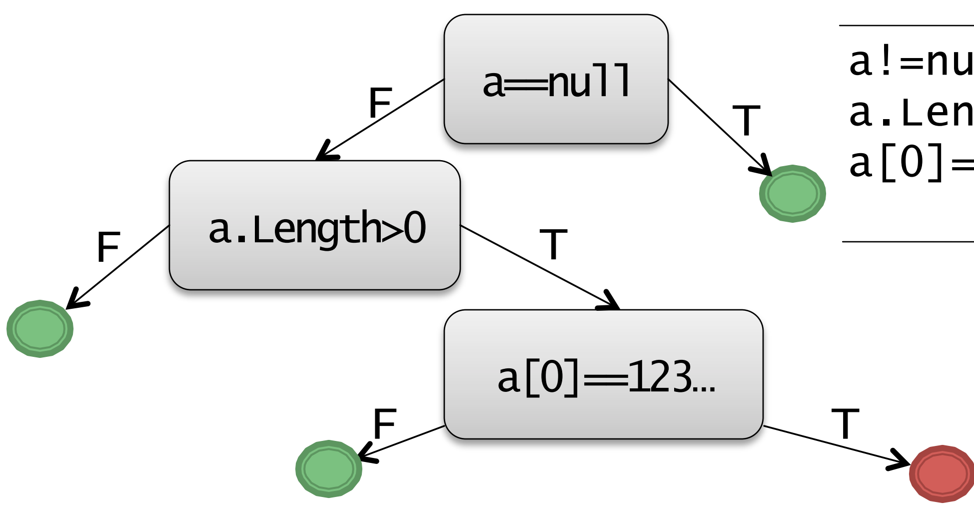
Automatic test case generation (using DSE)

Code to generate inputs for:

```
void CoverMe(int[] a)
{
  if (a == null) return;
  if (a.Length > 0)
    if (a[0] == 1234567890)
      throw new Exception("bug");
}
```

Constraints to solve	Data	Observed constraints
	null	a==null
a!=null	{}	a!=null && !(a.Length>0)
a!=null & a.Length>		& 90
a!=null && a.Length>0 && a[0]==1234567890	{123..}	a!=null && a.Length>0 && a[0]==1234567890

Negated condition



Done: There is no path left.

Bug finders

Apache Ant 1.6.2
org.apache.tools.ant.taskdefs.optional.metamata.MAudit

```
if (out == null) {
   try {  out.close(); }
   catch (IOException e) { }
}
```

J2SE version 1.5 build 63 (released version),
java.lang.annotation.AnnotationTypeMismatchException

```
public String foundType() {
     return this.foundType();
}
```

Eclipse 3.0.1,
org.eclipse.jdt.internal.debug.ui.JDIModelPresentation

```
if (sig != null || sig.length() == 1) {
   return sig;
}
```

Less harmful….

```
String dateString = getHeaderField(name);
dateString.trim();
```

- Specialized tools in finding Bugs
  - Search for recurrent patterns
    - Syntactically
    - Using dataflow analysis
    - Bug databases

Some tools

- Contract verification
  - Automatic :
    - Spec#, ESC-Java, HAVOC: SMT solvers
    - Code Contracs: Int Abs.
    - JForge, F-Soft, Siriam, TACO
  - Semi-automatic: Jahob, Krakatoa
  - Typestates: Plural, JSR, JavaRI
- Bug finding
  - FindBugs, Jlint, PMD, Astreé
  - Check'Crash, DSD
- Inference
  - Daikon, DySy
  - JConsume
- ModelCheckers:
  - JPF, Bandera,...
- Abstract refinement
  - Blast, SLAM
- Test Case generation
  - Pex, Randoop,...
  - Sage
- Validation/ Understanding
  - Contractor
  - CodeCity: Metrics
  - Eclipse: Navegation

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