Code-based test generation

David Honfi, Zoltan Micskei, Istvan Majzik

Budapest University of Technology and Economics
Fault Tolerant Systems Research Group

Main topics of the course

- Overview (1.5)
  - Introduction, V&V techniques
- Static techniques (1.5)
  - Specification, Verifying source code
- Dynamic techniques: Testing (7)
  - Testing overview, Test design techniques
  - **Test generation**, Automation
- System-level verification (3)
  - Verifying architecture, Dependability analysis
  - Runtime verification

Learning outcomes

- Explain the *basic ideas* of different code-based test generation techniques (K2)

- *Demonstrate the workflow* of symbolic execution on a method by *graphically representing the execution* using a symbolic execution tree (K3)

- Use different code-based test generator tools (K3)

Motivation

- **Given a barely tested software to test**
  - Availability: source code or binary
- **Developer testing**
  - Can be expensive, incomplete, etc.
- **Idea: generate tests somehow!**
  - Based on various criteria (e.g., coverage)

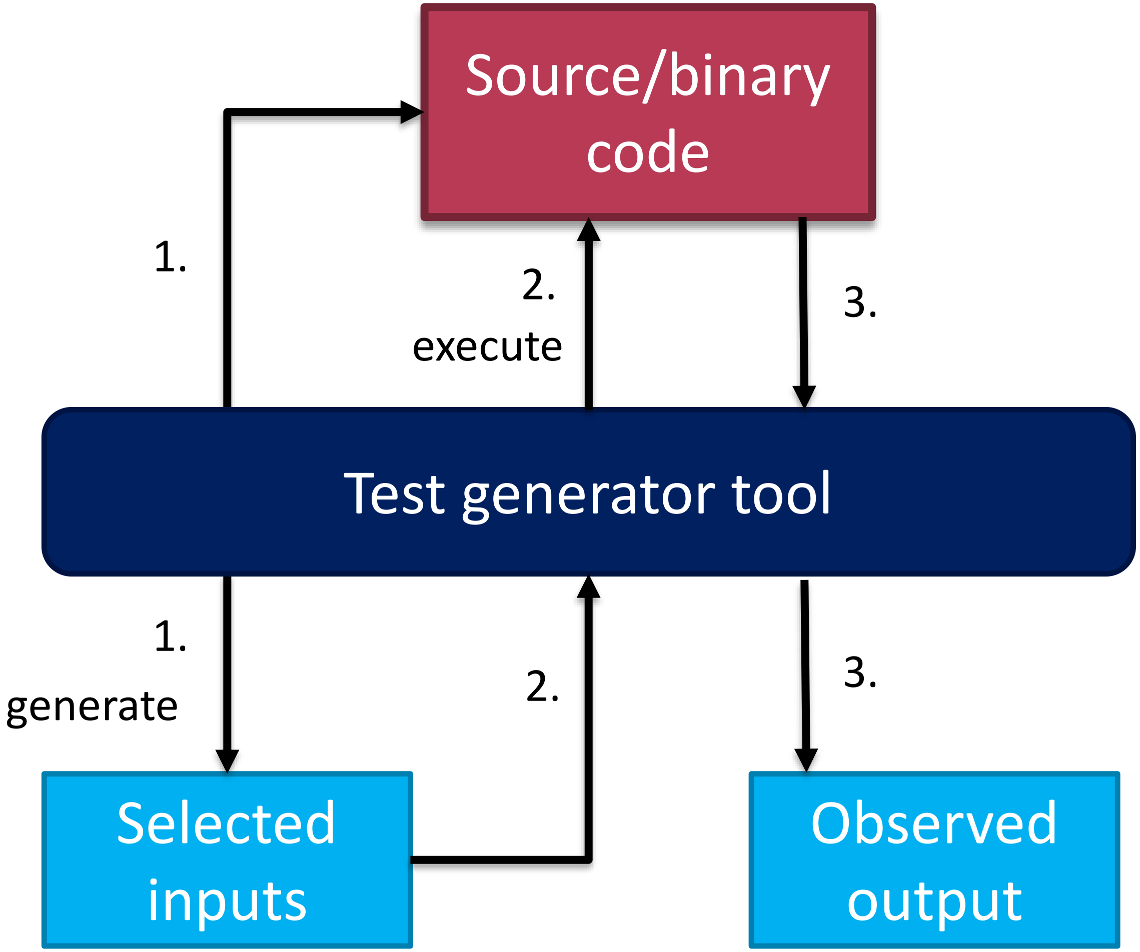
Test selection based on source code

```
  int fun1(int a, int b){
    if (a == 0){
1     printf(ERROR_MSG);
2     return -1;
    }
    if (b > a)
3     return b*a + 5;
    else
4    return (a+b) / 2;
  }
```

a	b	statement
0	*	1, 2
a!=0	b > a	3
a!=0	b <= a	4

This can be (easily) automated!

Idea of white-box test generation



What is missing?

test case = input + *test oracle*

What can be checked without expectations?

- Basic, generic errors (exception, segfault…)
- Failing assert statement for different inputs
- Manually extending assertions can improve this
- Reuse of already existing outputs
  - Regression testing, different implementations

TECHNIQUES

Techniques

- Symbolic execution
- Random generation
- Annotation-based
- Search-based

Example: Static symbolic execution

```
  int fun1(int a, int b){
    if (a == 0){
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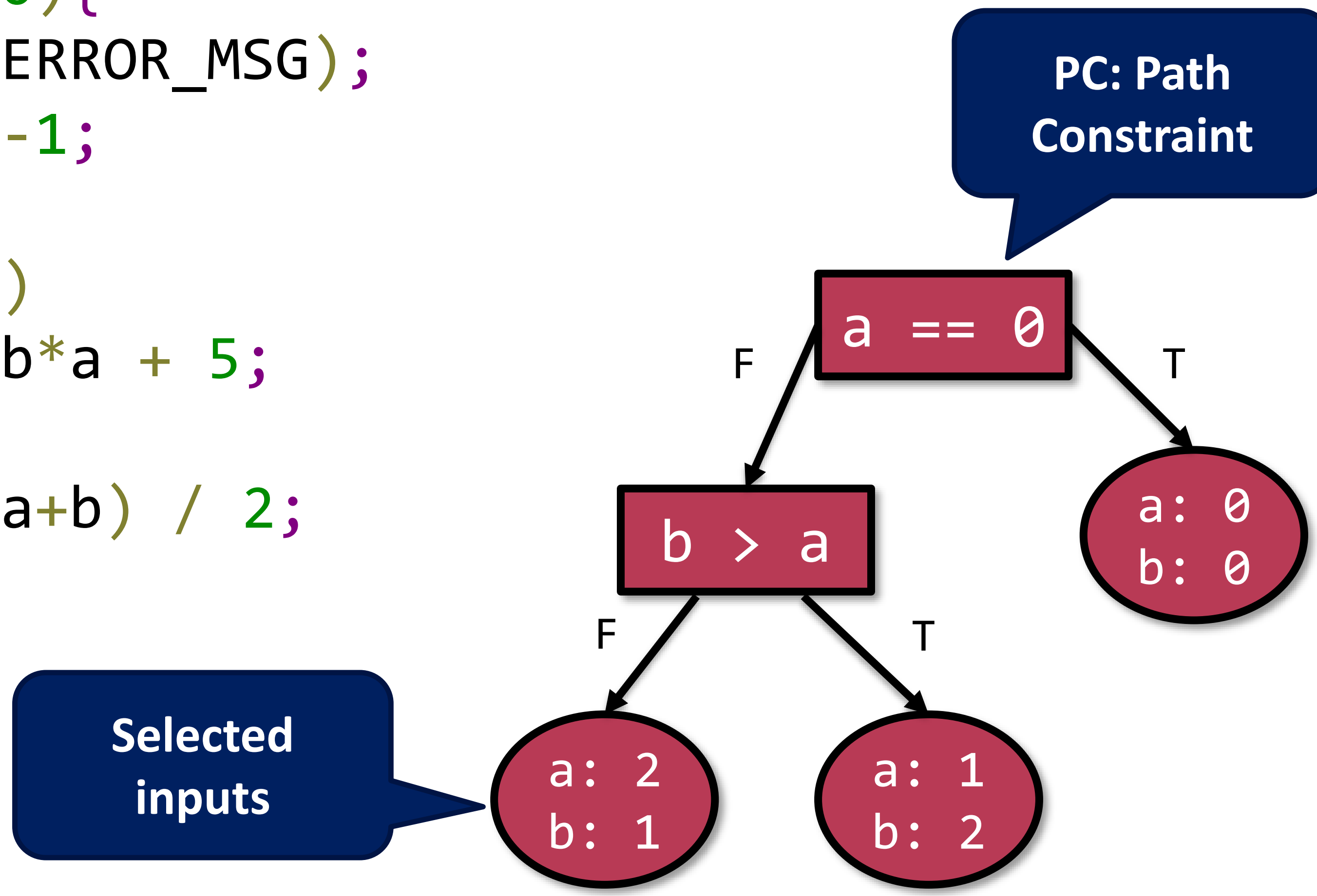


Symbolic execution: the idea

- **Static program analysis technique from the ’70s**
- **Application for test generation**
  - Symbolic variables instead of normal ones
  - Constraints forming for each path with symb. variables
  - Constraint solving (e.g., SMT solver)
  - A solution yields an input to execute a given path
- **New century, new progress:**
  - Enough computing power (e.g., for SMT solvers)
  - New ideas, extensions, algorithms and *tools*

Extending static symbolic execution

- **Static SE fails** in several cases, e.g.
  - Too long paths → too many constraints
  - Cannot decide if a path is really feasible or not
- **Idea:** mix symbolic with concrete executions
  - Dynamic Symbolic Execution (DSE) or
  - Concolic Testing

Dynamic symbolic execution

Negated condition

Choose next path

Solve

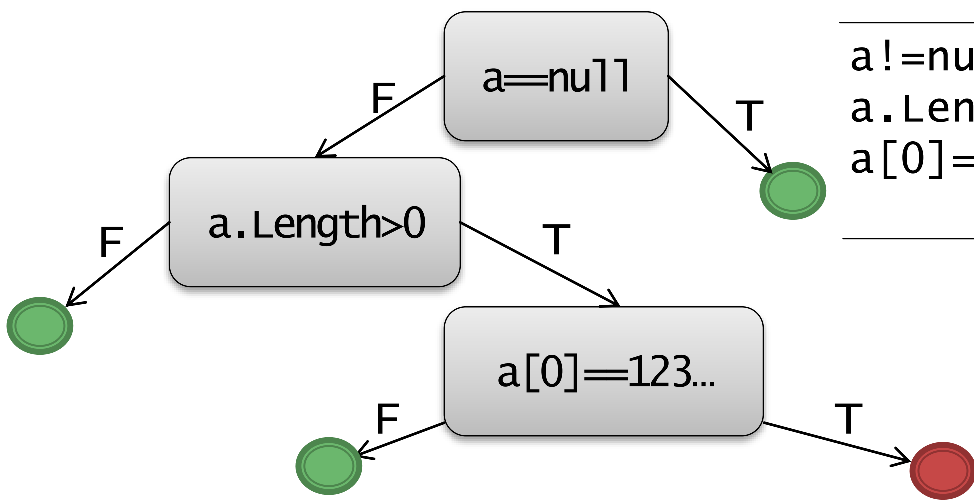
Execute&Monitor

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	int[] a	Observed constraints
	null	a==null
a!=null	{}	a!=null && !(a.Length>0)
a!=null && a.Length>0	{0}	a!=null && a.Length>0 && a[0]!=1234567890
a!=null && a.Length>0 && a[0]==1234567890	{123..}	a!=null && a.Length>0 && a[0]==1234567890

Done: There is no path left.



Source: T. Xie, N. Tillmann, P. Lakshman: Advances in Unit Testing: Theory and Practice

Tools available

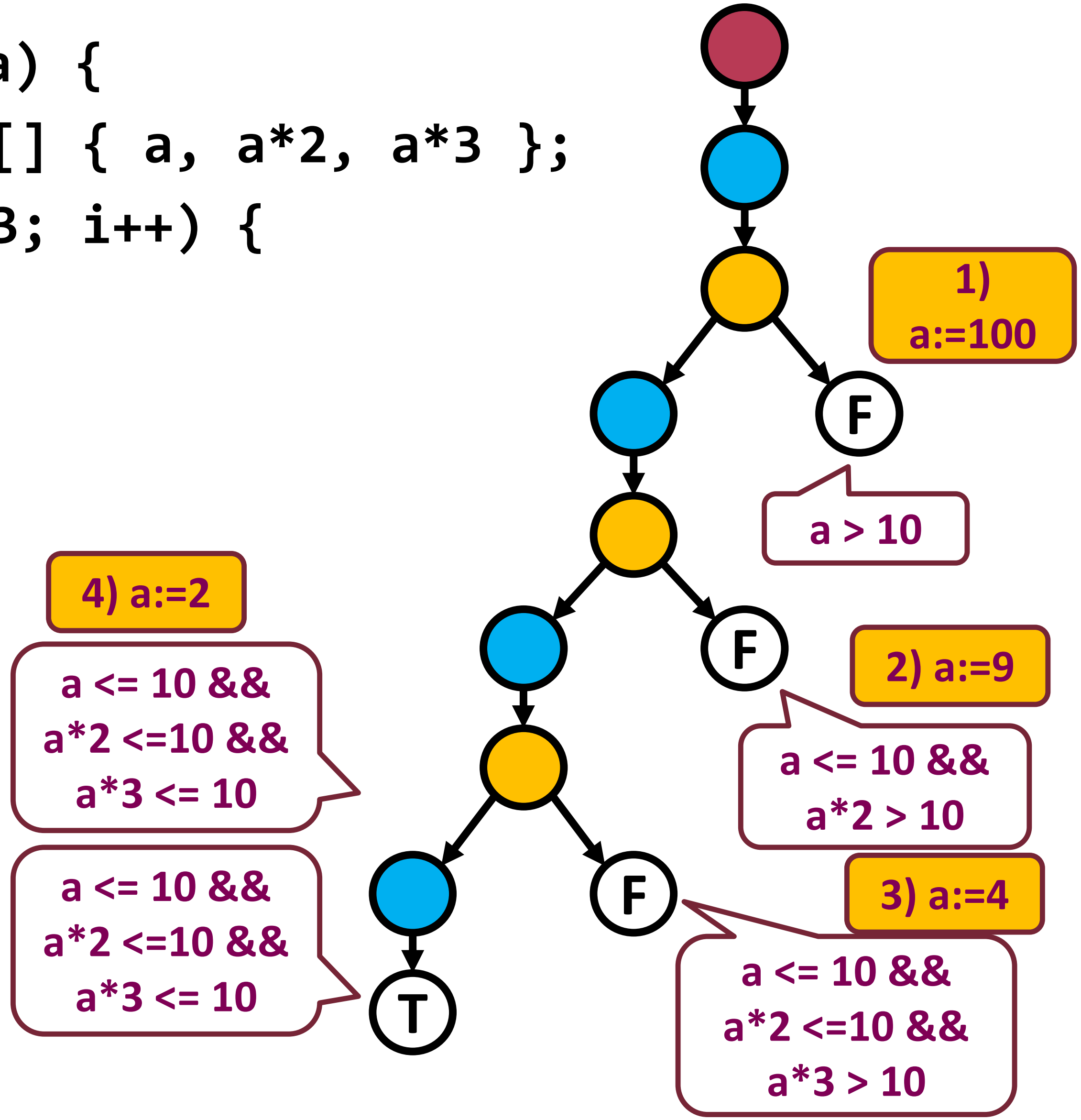
Name	Platform	Language	Notes
KLEE	Linux	C (LLVM bitcode)	
Pex	Windows	.NET assembly	Included in Visual Studio (IntelliTest)
SAGE	Windows	x86 binary	Security testing, SaaS model
Jalangi	-	JavaScript	
Symbolic PathFinder	-	Java	

Other (discontinued) tools:
CATG, CREST, CUTE, Euclide, EXE, jCUTE, jFuzz, LCT, Palus, PET, etc.

More tools: http://mit.bme.hu/~micskeiz/pages/cbtg.html

EXERCISE Building a SE tree

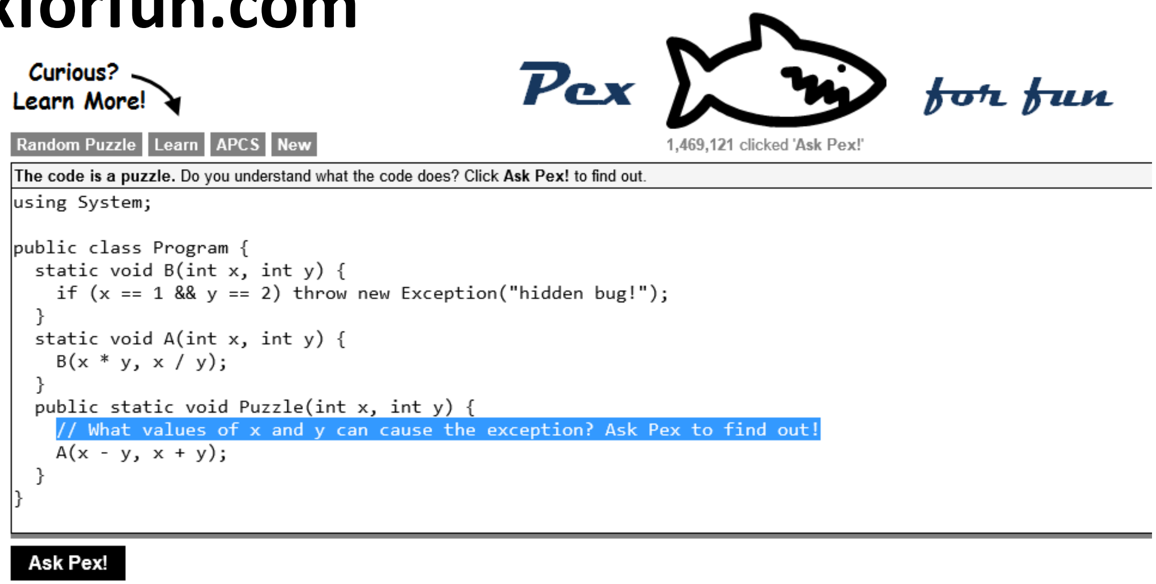
```
public bool fun2(int a) {
    int[] arr = new int[] { a, a*2, a*3 };
    for(int i = 0; i < 3; i++) {
      if(arr[i] > 10) {
        return false;
      }
    }
    return true;
}
```



Build the SE tree of this method

Pex for fun / Code Hunt

http://pexforfun.com



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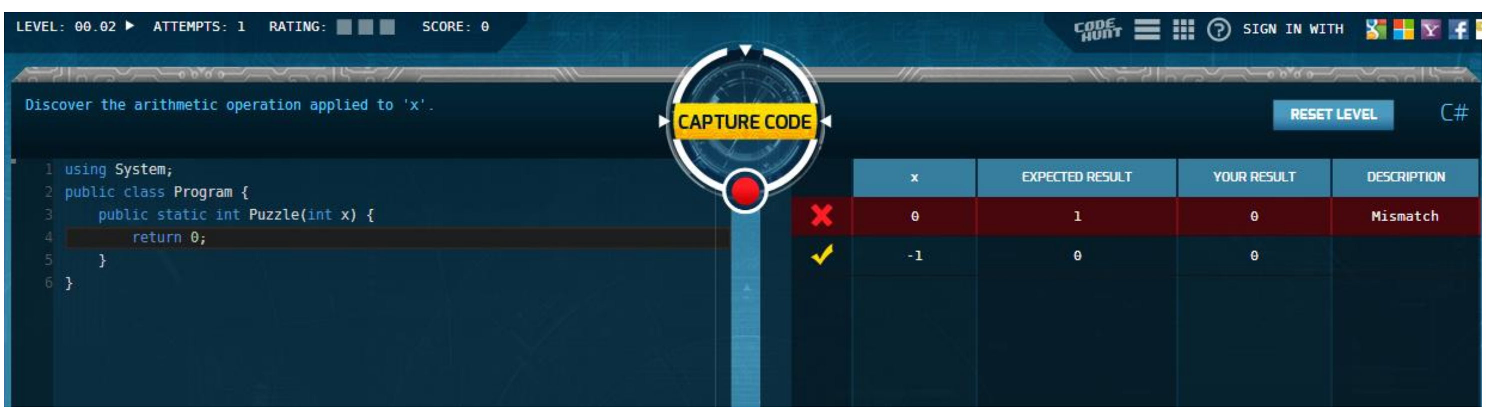

Parameterized Unit Testing

- **Idea: Using tests as specifications**
  - Easy to understand, easy to check, etc.
  - *But:* too specific (used for a code unit), verbose, etc.
- **Parameterized Unit Test (PUT)**
  - Wrapper method for method/unit under test
  - Main elements
    - Inputs of the unit
    - Assumptions for input space restriction
    - Call to the unit
    - Assertions for expected results
  - Serves as a **specification** → Test generators can use it

Example: Parameterized Unit Testing

```
/// The method reduces the quantity of the specified
/// product. The product is known to be NOT null, also
/// the sold amount is always more than zero. The method
/// has effects on the database, and returns the new
/// quantity of the product. If the quantity would be
/// negative, the method reduces the quantity to zero.
int ReduceQuantity(Product prod, int soldCount) { … }
```

```
void ReduceQuantityPUT(Product prod, int soldCount) {
    // Assumptions
    Assume.IsTrue(prod != null);
    Assume.IsTrue(soldCount > 0);
    // Calling the UUT
    int newQuantity = StorageManager.ReduceQuantity(prod,soldCount);
    // Assertions
    Assert.IsTrue(newQuantity >= 0);
    int oldQuantity = StorageManager.GetQuantityFor(prod);
    Assert.IsTrue(newQuantity < oldQuantity);
}
```

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Techniques

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- Random generation
- Annotation-based
- Search-based

Random test generation

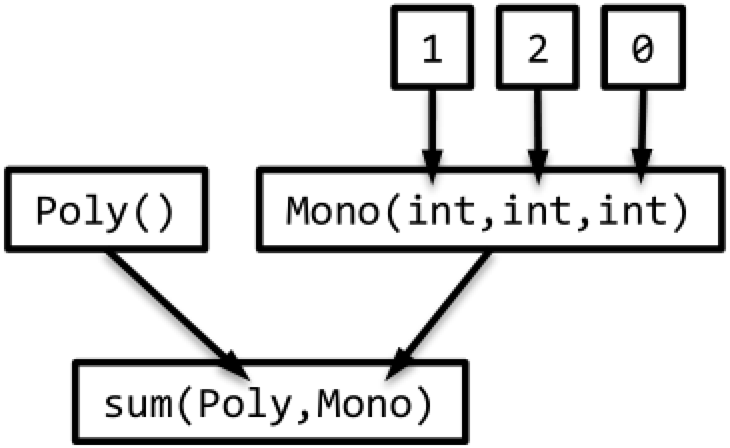
Random selection from input domain

- Advantage:
  - Very fast
  - Very cheap
- Ideas:
  - If no error found: trying different parts of domain
  - Selection based on: ”diff”, ”distance”, etc.

- Tool for Java:

Randoop: feedback-driven generation

- Generation of method sequence calls
- Compound objects:



- Heuristics:
  - Execution of selected case
  - Throwing away invalid, redundant cases

Cases studies of robustness testing

- **Robustness testing**
  - Fuzz: random inputs for console programs
    - Unix (1990), Unix (1995), MacOS (2007)
  - NASA: flash file system
    - Simulating HW errors, comparison with references
    - (Model checking did not scale well)
- **Randoop**
  - JDK, .NET libraries: checks for basic attributes (e.g.: `o.equals(o) returns true`)
  - Comparison of JDK 1.5 and 1.6
  - Was able to found bugs in well-tested components

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Using annotations for test generation

- If the code contains:
  - pre- and post-conditions (e.g.: design by contract)
  - other annotations
- These are able to guide test generation

```
/*@ requires amt > 0 && amt <= acc.bal;
    @ assignable bal, acc.bal;
    @ ensures bal == \old(bal) + amt
    @   && acc.bal == \old(acc.bal - amt); @*/
  public void transfer(int amt, Account acc) {
    acc.withdraw(amt);
    deposit(amt);

  }
```

Tools for annotation-based test generation

- **AutoTest**
  - Eiffel language, Design by Contract
  - Input: „object pool”, random generation
    - Idea: Include inputs that satisfy preconditions.
  - Expected output: contracts

AutoTest: Bertrand Meyer et al., "Programs that Test Themselves", IEEE Computer 42:9, 2009.

Tools for property-based test generation

- **QuickCheck**
  - Goal: replace manual values with generated ones
  - Tries to cover laws of input domains

Methods to tests:

byte[] encrypt(byte[] plaintext, Key key)
byte[] decrypt(byte[] ciphertext, Key key)

Property:

```
@Property public decryptReversesEncrypt(String plaintext, Key key){
  Crypto.encrypt(plaintext.getBytes("US-ASCII"), key);
  assertEquals(plaintext,
               new String(Crypto.decrypt(ciphertext, key)));
}
```

Claessen et al. "QuickCheck: a lightweight tool for random testing of Haskell programs"
ACM Sigplan Notices 46.4 (2011): 53-64

Techniques

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Search-based techniques

Search-based Software Engineering (SBSE)

- Metaheuristic algorithms
  - genetic alg., simulated annealing, hill climbing…
- Representing a problem as a search:
  - Search space:
    program structure + possible inputs
  - Objective function: reaching a test goal
    (e.g., covering all branches of decisions)

A tool for search-based test generation

EVOSUITE

- „Whole test suite generation”
  - All test goals are taken into account
  - Searches based on multiple metrics
    - E.g., high coverage with minimal test suite
- Specialties:
  - Minimizes test code, maintains readability
  - Uses sandbox for environment interaction

EVALUATIONS

Applying these techniques on real code?

- SF100 benchmark (Java)
  - 100 projects selected from SourceForge
  - EvoSuite reaches branch coverage of 48%
  - Large deviations among projects

G. Fraser and A. Arcuri, “Sound Empirical Evidence in Software Testing,” ICSE 2013

- A large-scale embedded system (C)
  - Execution of CREST and KLEE on a project of ABB
  - ~60% branch coverage reached
  - Fails and issues in several cases

X. Qu, B. Robinson: A Case Study of Concolic Testing Tools and Their Limitations, ESEM 2011

Are these techniques really that good?

- Does it help software developers?
  - 49 participants wrote and generated tests
  - Generated tests with high code coverage did not discover more injected failures

G. Fraser et al., "Does Automated White-Box Test Generation Really Help Software Testers?," ISSTA 2013

- Finding real faults
  - Defects4J: database of 357 issues from 5 projects
  - Tools evaluated: EvoSuite, Randoop, Agitar
  - Only found 55% of faults

S. Shamshiri et al., „Do automatically generated unit tests find real faults? An empirical study of effectiveness and challenges." ASE 2015

Comparison of test generator tools

- Various source code snippets to execute
  - Covering most important features of languages
- 363 Java/.NET snippets
  - Executed on 6 different tools
- Experience:
  - Huge difference in tools
  - Some snippets challenging for all tools

L. Cseppentő, Z. Micskei: „Evaluating code-based test input generator tools," STVR 2017

Comparison of test generator tools

Current challenges

- Complex arithmetic operations (e.g., logarithms)
- Floating point numbers (e.g., equality)
- Non-trivial string operations
- Environment calls (e.g., files, native, external libs)
- Multithreading
- Compound data structures
- Pointer operations
- …

Summary

- Tests generation is possible based on code
- Various different techniques available
- Can find bugs in real-world software
- Further challenges (active research topic):
  - Scalability
  - Test oracle production
  - etc.