Introduction: Software Testing and Quality Assurance

Software Testing, Quality Assurance, and Maintenance

Fall 2023

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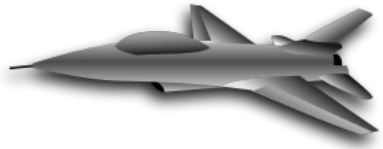
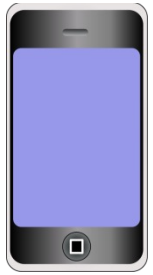
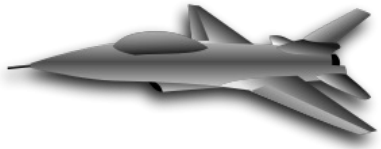
UNIVERSITY OF WATERLOO

Software is Everywhere





Software is Everywhere



"Software easily rates as the most poorly constructed, unreliable, and least maintainable technological artifacts invented by man"
Paul Strassman, former CIO of Xerox

Infamous Software Disasters

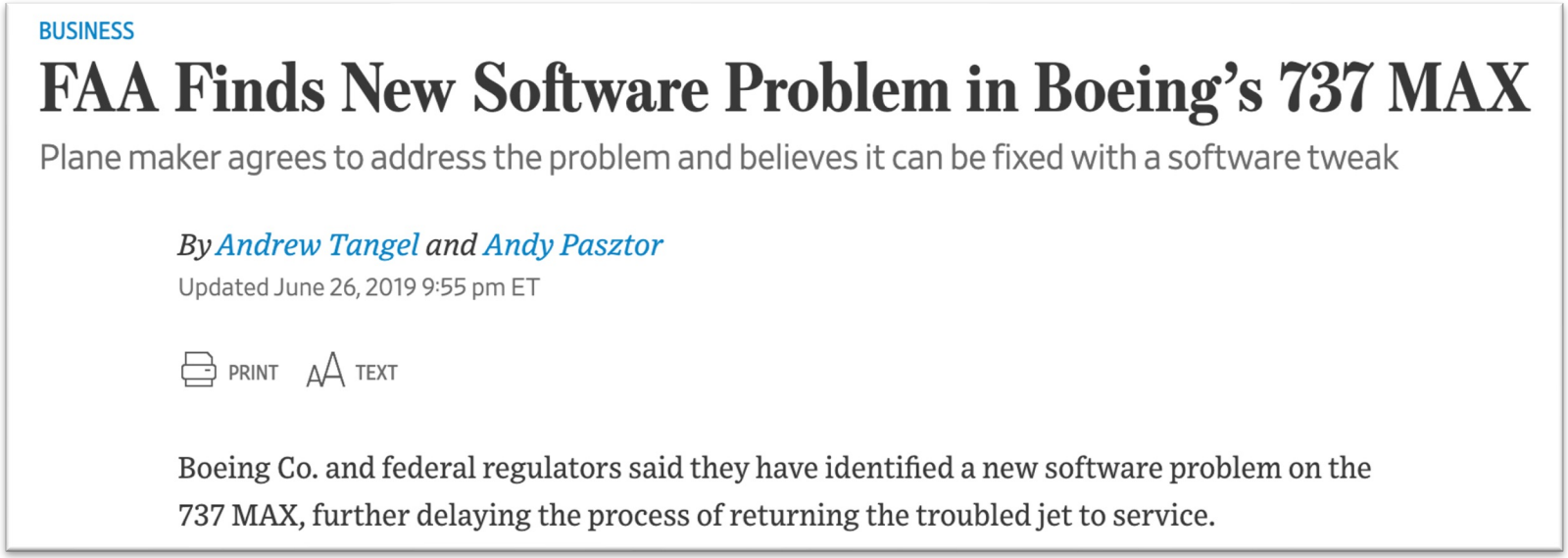
Between 1985 and 1987, **Therac-25** gave patients massive overdoses of radiation, approximately 100 times the intended dose. Three patients died as a direct consequence.

On February 25, 1991, during the Gulf War, an American **Patriot Missile** battery in Dharan, Saudi Arabia, failed to track and intercept an incoming Iraqi Scud missile. The Scud struck an American Army barracks, killing 28 soldiers and injuring around 100 other people.

On June 4, 1996 an unmanned **Ariane 5** rocket launched by the European Space Agency forty seconds after lift-off. The rocket was on its first voyage, after a decade of development costing $7 billion. The destroyed rocket and its cargo were valued at $500 million.

http://www5.in.tum.de/~huckle/bugse.html

Recent Software "Disasters"



BUSINESS

FAA Finds New Software Problem in Boeing's 737 MAX

Plane maker agrees to address the problem and believes it can be fixed with a software tweak

By *Andrew Tangel* and *Andy Pasztor*

Updated June 26, 2019 9:55 pm ET

PRINT TEXT

Boeing Co. and federal regulators said they have identified a new software problem on the 737 MAX, further delaying the process of returning the troubled jet to service.

Opinion
Technology

The millennium bug was real – and 20 years later we face the same threats

Martyn Thomas

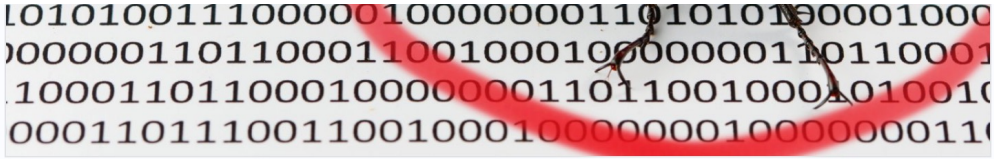
Tue 31 Dec 2019 09.00 GMT

The Y2K problem is now seen as a bit of a joke – but only a fool would be complacent about the vulnerability of IT systems

https://www.computerworld.com/article/3412197/top-software-failures-in-recent-history.html#slide1

“Smart” Contracts Disasters

https://news.bitcoin.com/25-of-all-smart-contracts-contain-critical-bugs/



25% of All Smart Contracts Contain Critical Bugs

13,732 views | Jul 10, 2018, 11:38pm

Blockchain Smart Contracts: More Trouble Than They Are Worth?

Sherman Lee Contributor ⓘ
Asia
I write about deep tech, crypto, and artificial intelligence.

Proving that Android's, Java's and Python's sorting algorithm is broken (and showing how to fix it)

February 24, 2015 Envisage Written by Stijn de Gouw. $s

Tim Peters developed the Timsort hybrid sorting algorithm in 2002. It is a clever combination of ideas from merge sort and insertion sort, and designed to perform well on real world data. TimSort was first developed for Python, but later ported to Java (where it appears as java.util.Collections.sort and java.util.Arrays.sort) by Joshua Bloch (the designer of Java Collections who also pointed out that most binary search algorithms were broken). TimSort is today used as the default sorting algorithm for Android SDK, Sun's JDK and OpenJDK. Given the popularity of these platforms this means that the number of computers, cloud services and mobile phones that use TimSort for sorting is well into the billions.

http://envisage-project.eu/proving-android-java-and-python-sorting-algorithm-is-broken-and-how-to-fix-it/

Why so many bugs?

Software Engineering is very complex

- Complicated algorithms
- Many interconnected components
- Legacy systems
- Huge programming APIs
- …

Software Engineers need better tools to deal with this complexity!

What Software Engineers Need Are …

Tools that give better confidence than *ad-hoc* testing while remaining easy to use

And at the same time, are

- … fully automatic
- … (reasonably) easy to use
- … provide (measurable) guarantees
- … come with guidelines and methodologies to apply effectively
- … apply to real software systems

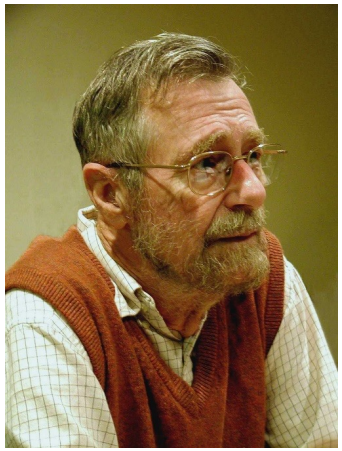
Testing

Software validation the “old-fashioned” way:

- Create a test suite (set of test cases)
- Run the test suite
- Fix the software if test suite fails
- Ship the software if test suite passes

“Program testing can be a very effective way to show the presence of bugs, but is hopelessly inadequate for showing their absence.”

Edsger W. Dijkstra



Very hard to test the portion inside the “if" statement!

```
x = read();
if (hash(x) == 10) {
    ...
}
```

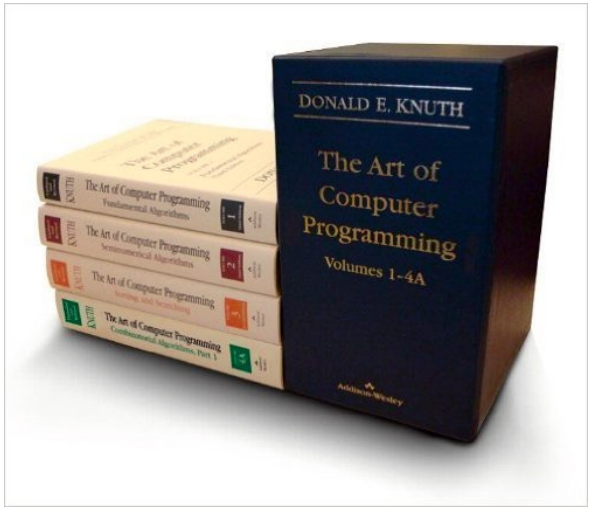
Hypothetical program

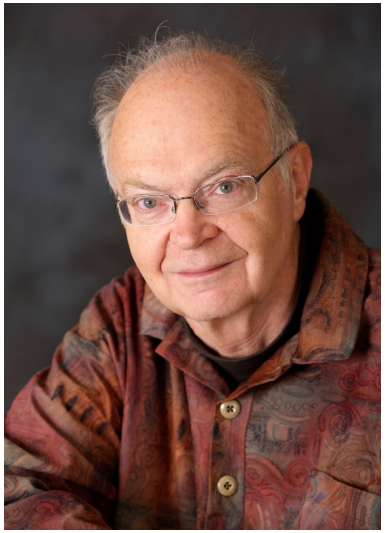
“Beware of bugs in the above code; I have only proved it correct, not tried it.”

Donald Knuth

You can only verify what you have specified.

Testing is still important, but can we make it less impromptu?





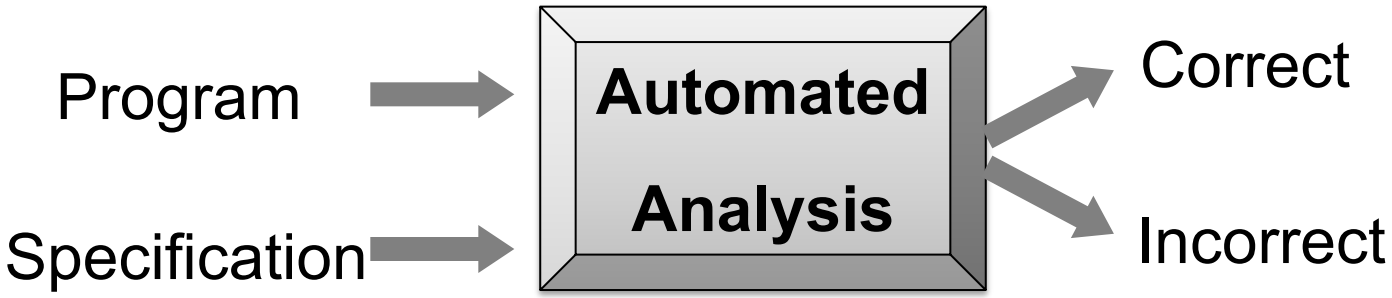
Verification / Quality Assurance

Verification: formally prove that a computing system satisfies its specifications

- **Rigor**: well established mathematical foundations
- **Exhaustiveness**: considers all possible behaviors of the system, i.e., finds all errors
- **Automation**: uses computers to build reliable computers

Formal Methods: general area of research related to program specification and verification

Ultimate Goal: Static Program Verification



Reasoning statically about behavior of a program without executing it

- compile-time analysis
- exhaustive, considers all possible executions under all possible environments and inputs

The *algorithmic* discovery of *properties* of program by *inspection* of the *source text*

Manna and Pnueli

Also known as *static analysis*, *program verification*, *formal methods*, etc.

Turing, 1936: “undecidable”

Undecidability

A problem is undecidable if there does not exists a Turing machine that can solve it

- i.e., not solvable by a computer program

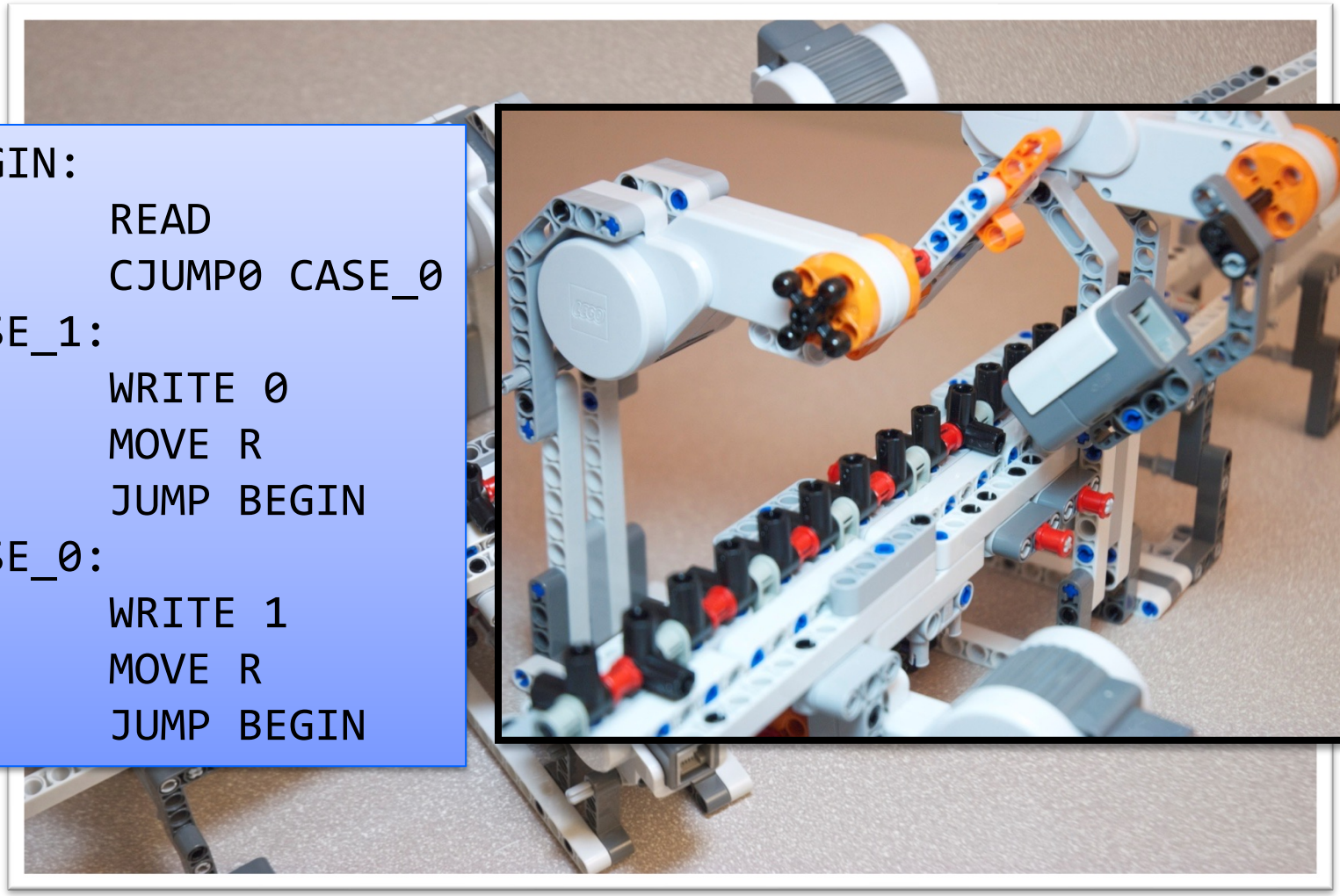
The halting problem

- does a program P terminates on input I
- proved undecidable by Alan Turing in 1936
- https://en.wikipedia.org/wiki/Halting_problem

Rice's Theorem

- for any non-trivial property of partial functions, no general and effective method can decide whether an algorithm computes a partial function with that property
- in practice, this means that there is no machine that can always decide whether the language of a given Turing machine has a particular nontrivial property
- https://en.wikipedia.org/wiki/Rice%27s_theorem

LEGO Turing Machine



```
BEGIN:
        READ
        CJUMP0 CASE_0
CASE_1:
        WRITE 0
        MOVE R
        JUMP BEGIN
CASE_0:
        WRITE 1
        MOVE R
        JUMP BEGIN
```

by Soonho Kong. See http://www.cs.cmu.edu/~soonhok for building instructions.

Living with Undecidability

"Algorithms" that occasionally diverge

Limit programs that can be analyzed

- finite-state, loop-free

Partial (unsound) verification

- analyze only some executions up-to a fixed number of steps

Testing **Sym Exec**

Incomplete verification / Abstraction

- analyze a superset of program executions

Automated Verification

Programmer Assistance

- annotations, pre-, post-conditions, inductive invariants

Deductive Verification

Formal Software Analysis

J. McCarthy, "*A basis for mathematical theory of computation*", 1963.

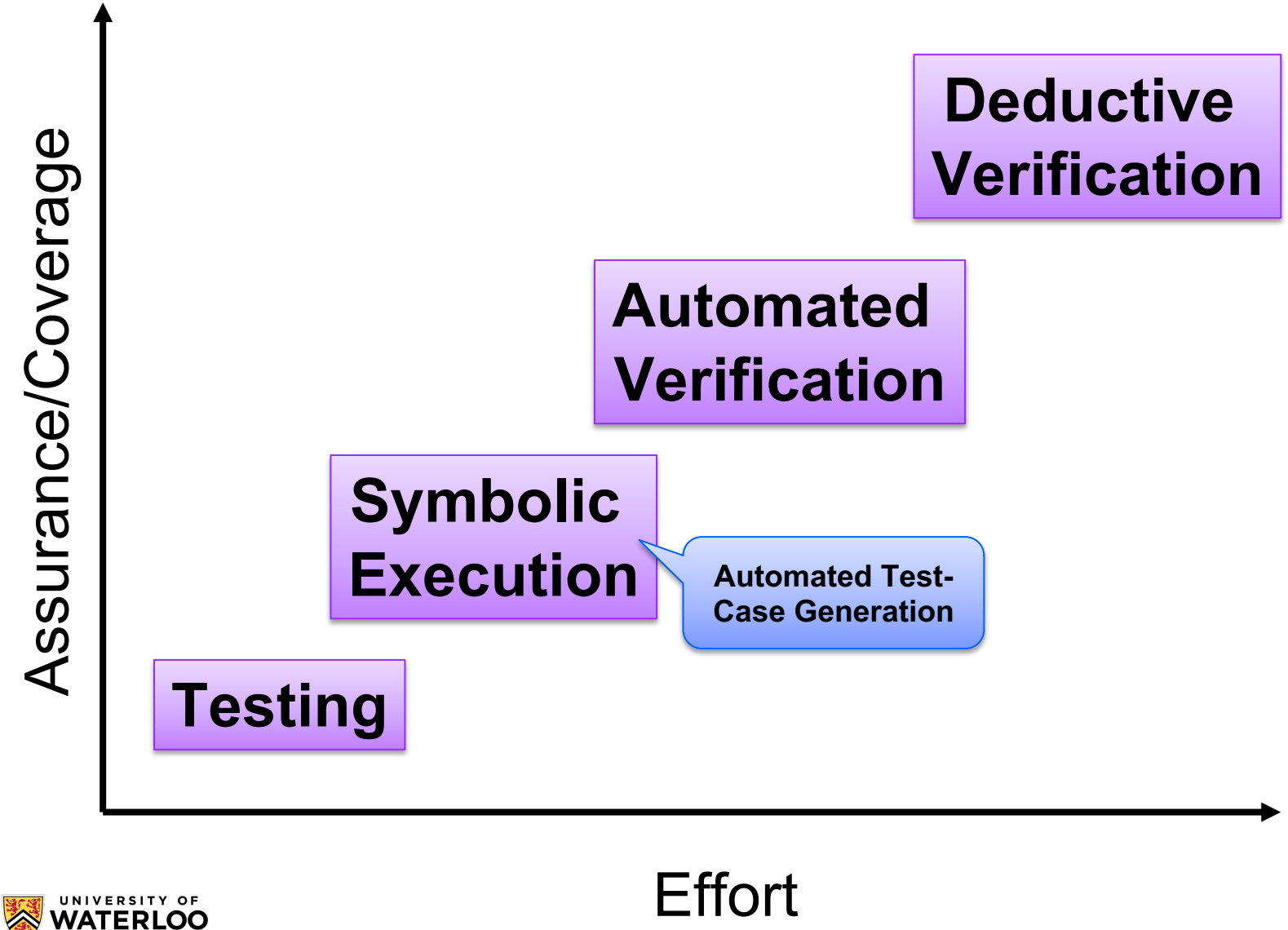
P. Naur, "*Proof of algorithms by general snapshots*", 1966.

R. W. Floyd, "*Assigning meaning to programs*", 1967.

C.A.R Hoare, "*An axiomatic basis for computer programming*", 1969.

E. W. Dijkstra: "*Guarded Commands, Nondeterminacy and Formal derivation* ", 1975.

(User) Effort vs (Verification) Assurance



Why are Testing and Verification Necessary

Why Test?

Why Verify?

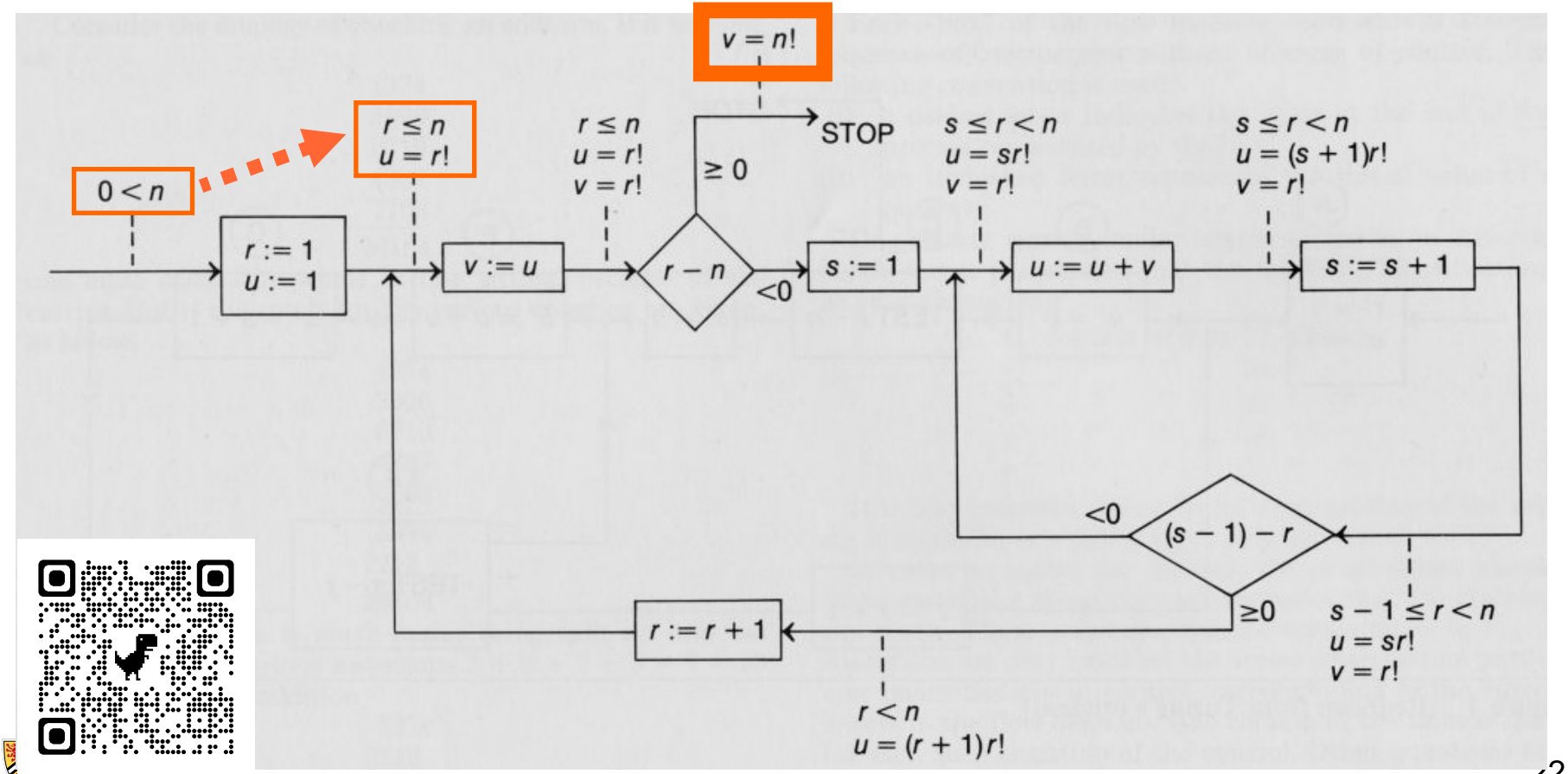
What is Verification? How is it different from Testing?

Turing, 1949

Alan M. Turing. “Checking a large routine”, 1949

How can one check a routine in the sense of making sure that it is right?

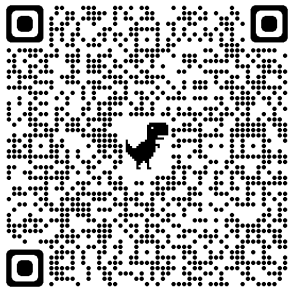
programmer should make a number of definite assertions which can be checked individually, and from which the correctness of the whole programme easily follows.



22

```
method factorial_turing (n: int) returns (v: int)
{
  var r := 1;
  var u := 1;

  while (true)
  {
    v := u;
    if (r - n ≥ 0)
    { return v; }
    var s := 1;
    while (true)
    {
      u := u + v;
      s := s + 1;
      if ((s - (r + 1)) ≥ 0)
      {break;}
    }
    r := r + 1;
  }
}
```



```
method factorial (n: int) returns (v:int)
{
  v := 1;
  if (n == 1) { return v; }
  var i := 2;
  while (i <= n)
  {
    v := i * v;
    i := i + 1;
  }
  return v;
}
```

```
method factorial (n: int) returns (v:int)
  requires n >= 0;
  ensures v = fact(n);
{
  v := 1;
  if (n <= 1) { return v; }
  var i := 2;
  while (i <= n)
    invariant i <= n + 1
    invariant v = fact(i - 1)
  {
    v := i * v;
    i := i + 1;
  }
  return v;
}
```

Specification

Inductive Invariant

Inductive Loop Invariants

An inductive loop invariant is a formula Inv (i.e., a conditional, a Boolean statement, a mathematical expression) such that

- Inv is true before the loop is executed for the first time
- Inv is true when the loop is executed for the second time
- Inv is true when the loop is executed for the third time
- …
- Inv is true when the loop is exited

We say that Inv summarizes the execution of a loop

Inductive means provable using principle of induction

- **Assume** Inv is true before SOME execution of the loop
- **Prove** that Inv must be true at the end of that execution

Proving inductive invariants

The main step is to show that the invariant is preserved by one execution of the loop

```
assume(i <= n + 1);
assume(v == fact(i - 1));
assume(i <= n);
v := i * v;
i := i + 1;
assert(i <= n + 1);
assert(v == fact(i - 1));
```

Correctness of a loop-free program can (often) be decided by a Theorem Prover or a Satisfiability Modulo Theory (SMT) solver.

Proving inductive invariants

The main step is to show that the invariant is preserved by one execution of the loop

```
(i0 <= n0+1)       &&
(v0 == (i0-1)!)    &&
(i0 <= n0)         &&
(v1 = i0 * v0)     &&
(i1 = i0 + 1)
➔
((i1 <= n0+1)      &&
(v1 == (i1-1)!))
```

```
assume(i <= n+1);
assume(v == fact(i-1));
assume(i <= n);
v := i*v;
i := i+1;

assert(i<=n+1);
assert(v == fact(i-1));
```

Correctness of a loop-free program can (often) be decided by a Theorem Prover or a Satisfiability Modulo Theory (SMT) solver.

Available Tools

Testing

- many tools actively used in industry. We will use Python **unittest**

Symbolic Execution / Automated Test-Case Generation

- mostly academic tools with emerging industrial applications
- Random Testing (fuzzing): AFL, LibFuzzer
- Symbolic: **KLEE**, S2E, jDART, Pex (now Microsoft IntelliTest)

Automated Verification

- built into compilers, may lightweight static analyzers
  - clang analyzer, Facebook Infer, Coverity, …
- academic pushing the coverage/automation boundary
  - SeaHorn (my tool), JayHorn, CPAChecker, SMACK, T2, …

(Automated) Deductive Verification

- academic, still rather hard to use, we'll experience in class ☺
- **Dafny**/Boogie (Microsoft), Viper, Why3, KeY, ...

Automated Reasoning at Amazon

AUTOMATED REASONING

amazon | science

A gentle introduction to automated reasoning

Meet Amazon Science's newest research area.

By Byron Cook

December 01, 2021

This week, Amazon Science added *automated reasoning* to its list of research areas. We made this change because of the impact that automated reasoning is having here at Amazon. For example, Amazon Web Services' customers now have direct access to automated-reasoning-based features such as IAM Access Analyzer, S3 Block Public Access, or VPC Reachability Analyzer. We also see Amazon

https://www.amazon.science/blog/a-gentle-introduction-to-automated-reasoning

Automated Reasoning at Amazon

AUTOMATED REASONING

amazon | science

A gentle introduction to auto

Meet Amazo

By Byron Cook

December 01, 202

This week, Ar
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Reachability A

What's interesting about testing, and something we often forget, is that it's doing much more than just telling us about the C or Python source code. It's also testing the compiler, the runtime, the interpreter, the microprocessor, etc. A test failure could be rooted in any of those tools in the stack.

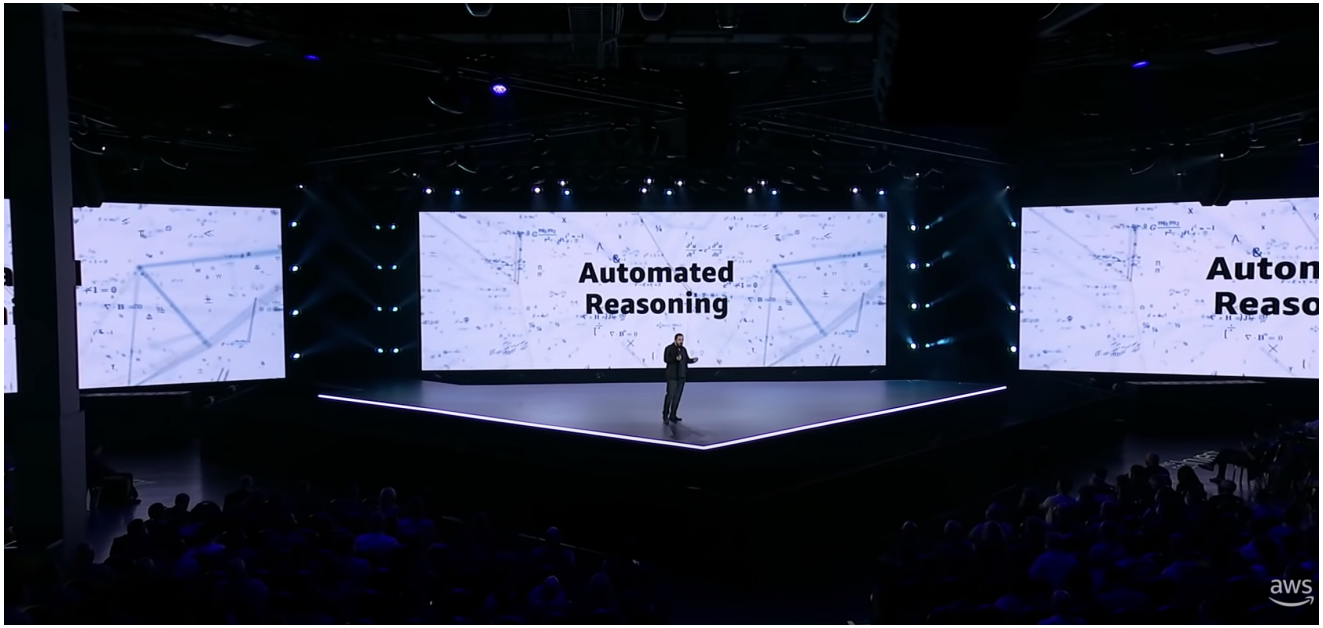
Automated reasoning, in contrast, is usually applied to just one layer of that stack — the source code itself, or sometimes the compiler or the microprocessor. What we find so valuable about reasoning is it allows us to clearly define both what we *do* know and what we *do not* know about the layer under inspection.

Furthermore, the models of the surrounding environment (e.g., the compiler or the procedure calling our procedure) used by the automated-reasoning tool make our assumptions *very* precise. Separating the layers of the computational stack helps make better use of our time, energy, and money and the capabilities of the tools today and tomorrow.

https://www.amazon.science/blog/a-gentle-introduction-to-automated-reasoning

Formal Methods at AWS re:Invent 2021

Peter DeSantis, Senior VP, AWS Utility Computing talked at AWS re:Invent 2021 about how AWS is using lightweight formal methods to quickly develop safe software systems



We will learn Dafny in the last part of this course

https://youtu.be/9NEQbFLtDmg?t=870

Key Challenges

Testing

- Coverage

Symbolic Execution and Automated Verification

- Scalability

Deductive Verification

- Usability

Common Challenge

- Specification / Oracle

Topics Covered in the Course

Foundations

- syntax, semantics, abstract syntax trees, visitors, control flow graphs

Testing

- coverage: structural

Symbolic Execution / Automated Test-Case Generation

- using SMT solvers, constraints, path conditions, exploration strategies
- building a (small) symbolic execution engine

Deductive Verification

- Hoare Logic, weakest pre-condition calculus, verification condition generation
- verifying algorithm using Dafny, building a small verification engine

Automated Verification

- (basics of) software model checking

Frequently Asked Questions

Is this course practical?

Is this course easy / hard?

What knowledge from the course is applicable to a developer?

Is it a compilers course?

Is it a logic course?

Do I have to attend the lectures?

What are most useful skills learned in the course?

- Foundations of testing and verification
- State-of-the-art tools and technique to automate testing and reasoning
- Understanding the difference between wishful thinking (I hope it works) and a strong argument (I know it works, here is why…)

A little about me

2007, PhD University of Toronto

2006-2016, Principle Researcher at Software Engineering Institute, Carnegie Mellon University

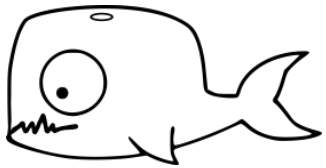
Sep 2016, Associate Professor, University of Waterloo

UFO

FrankenBit

SPACER

Avy



SeaHorn

Interests and Tools

Interests

- Software Model Checking, Program Verification, Decision Procedures, Abstract Interpretation, SMT, Horn Clauses, …

Active Tools

- SeaHorn – Algorithmic Logic-Based Verification framework for C
- AVY – Hardware Model Checker with Interpolating PDR
- SPACER – Horn Clause Solver based on Z3 GPDR
- for more, see http://arieg.bitbucket.org/tools.html

Current Work

- automated verification of C
- verification of Smart Contracts
- Decision procedures for verification (Constrained Horn Clauses, etc.)
- …