Introduction: Recap

Testing, Quality Assurance, and Maintenance
Winter 2018

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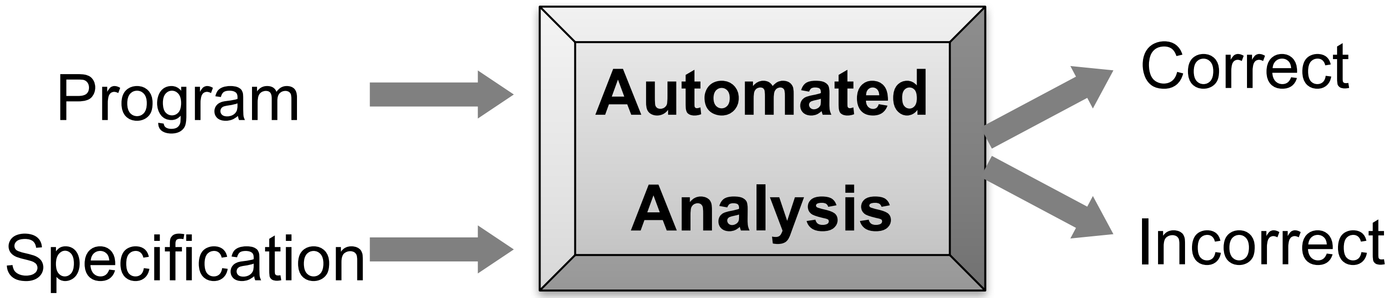
UNIVERSITY OF WATERLOO

Ultimate Goal: Static Program Analysis



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.

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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

Living with Undecidability

"Algorithms" that occasionally diverge

Limit programs that can be analyzed

- finite-state, loop-free

Partial (unsound) verification

Testing **Sym Exec**

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

Incomplete verification / Abstraction

Automated Verification

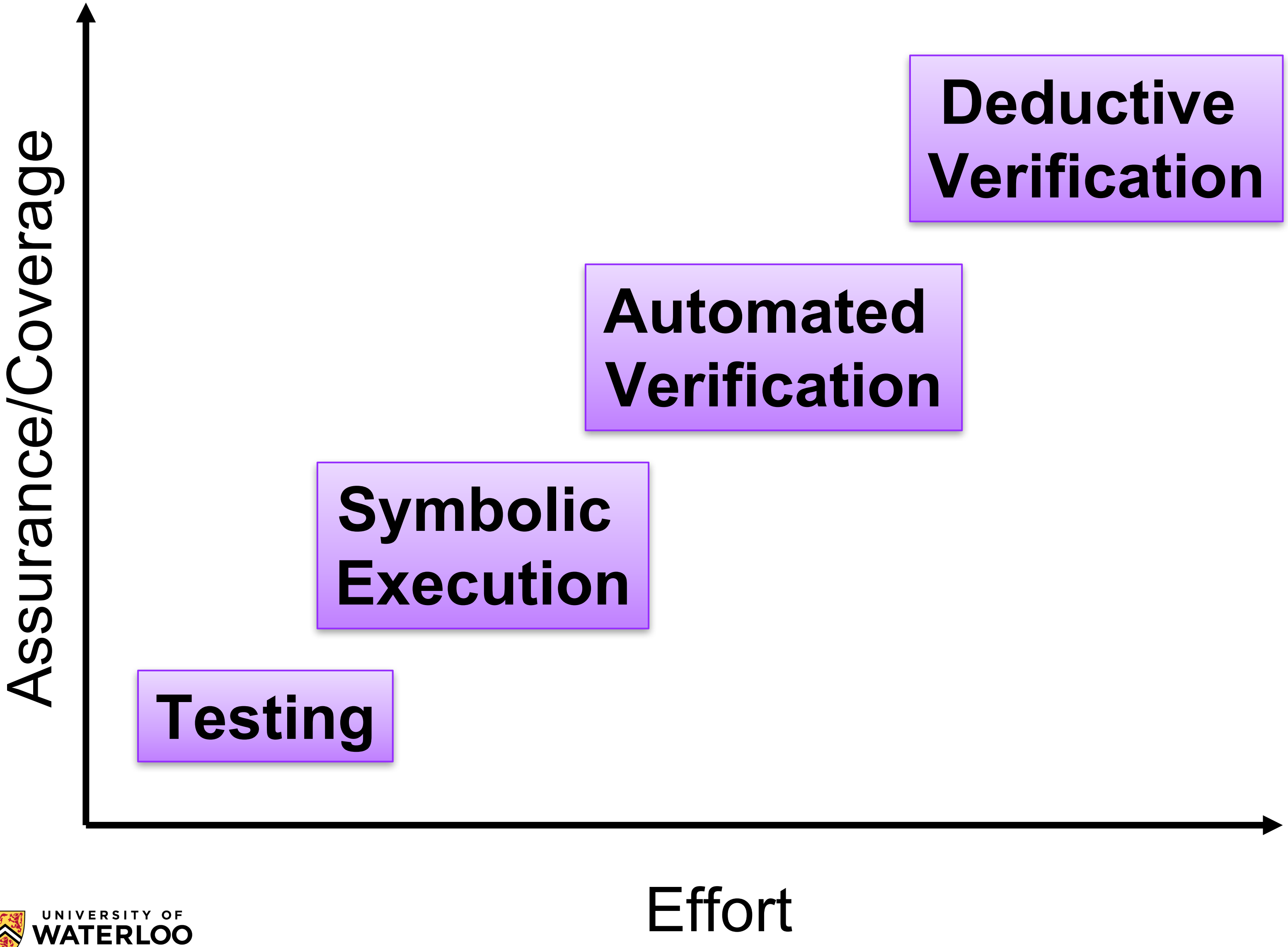
- analyze a superset of program executions

Programmer Assistance

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

Deductive Verification

(User) Effort vs (Verification) Assurance



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, dataflow, and logic

Symbolic Execution

- using SMT solvers, constraints, path conditions, exploration strategies
- building a (toy) 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

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

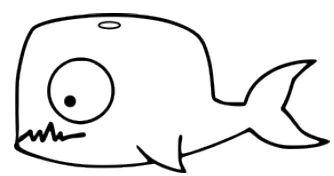
వింత

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

- parametric symbolic reachability – verifying safety properties of parametric systems
- automated verification of C
- …

Fault, Error, and Failure

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based on slides by Prof. Lin Tan and others

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Terminology, IEEE 610.12-1990

Fault -- often referred to as Bug [Avizienis'00]

- A static defect in software (incorrect lines of code)

Error

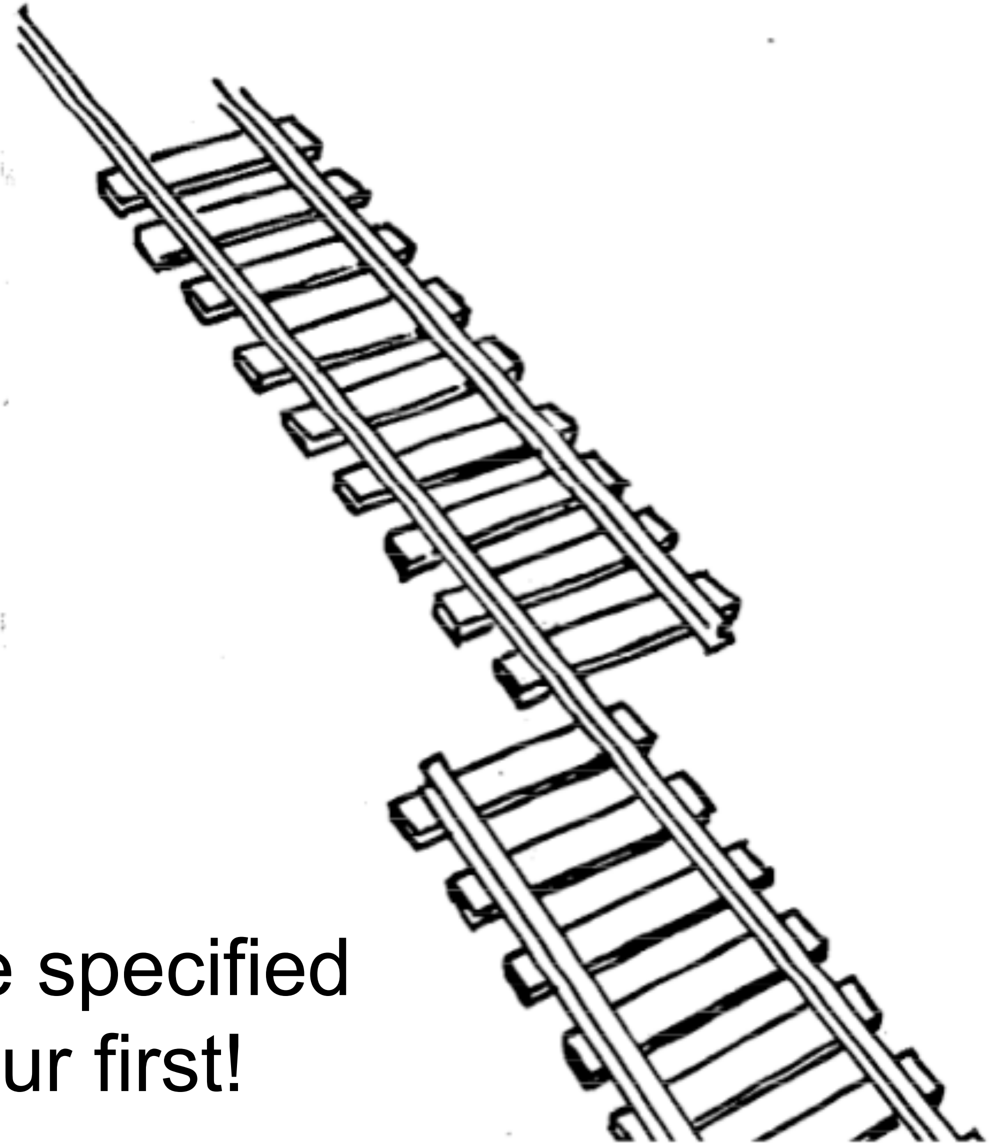
- An incorrect internal state (unobserved)

Failure

- External, incorrect behaviour with respect to the expected behaviour (observed)

Not used consistently in literature!

What is this?



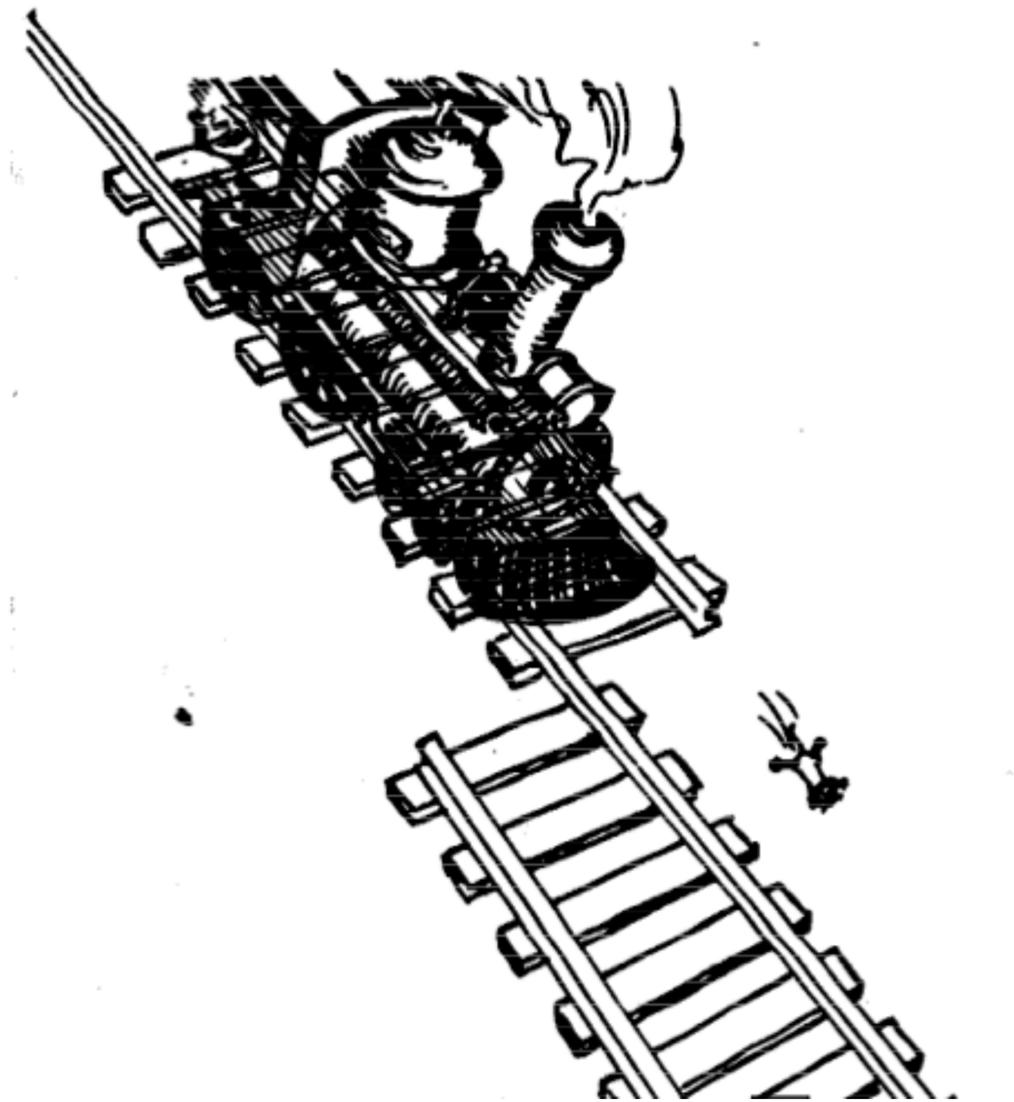
A fault?

An error?

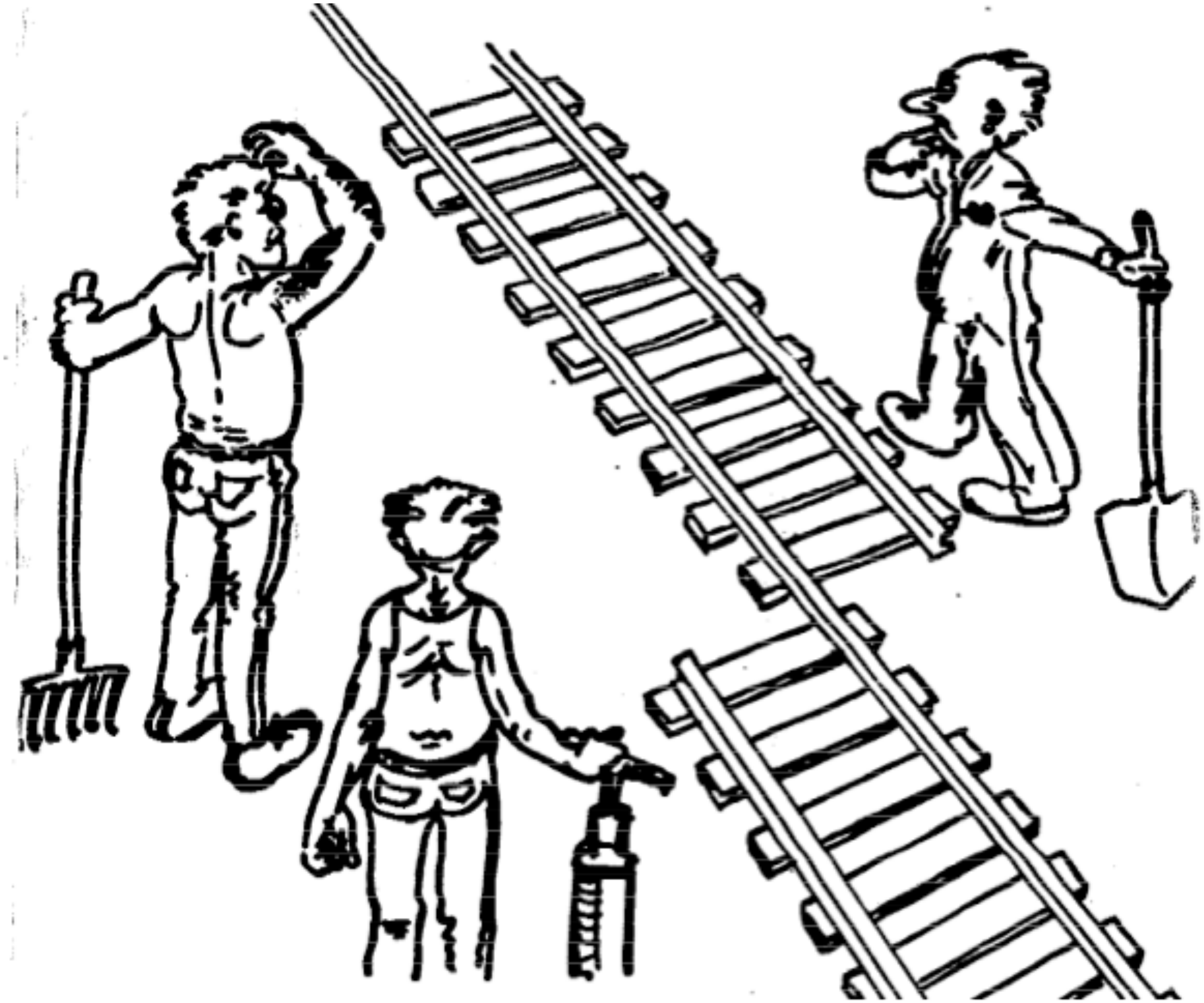
A failure?

We need to describe specified and desired behaviour first!

Erroneous State (“Error”)



Design Fault



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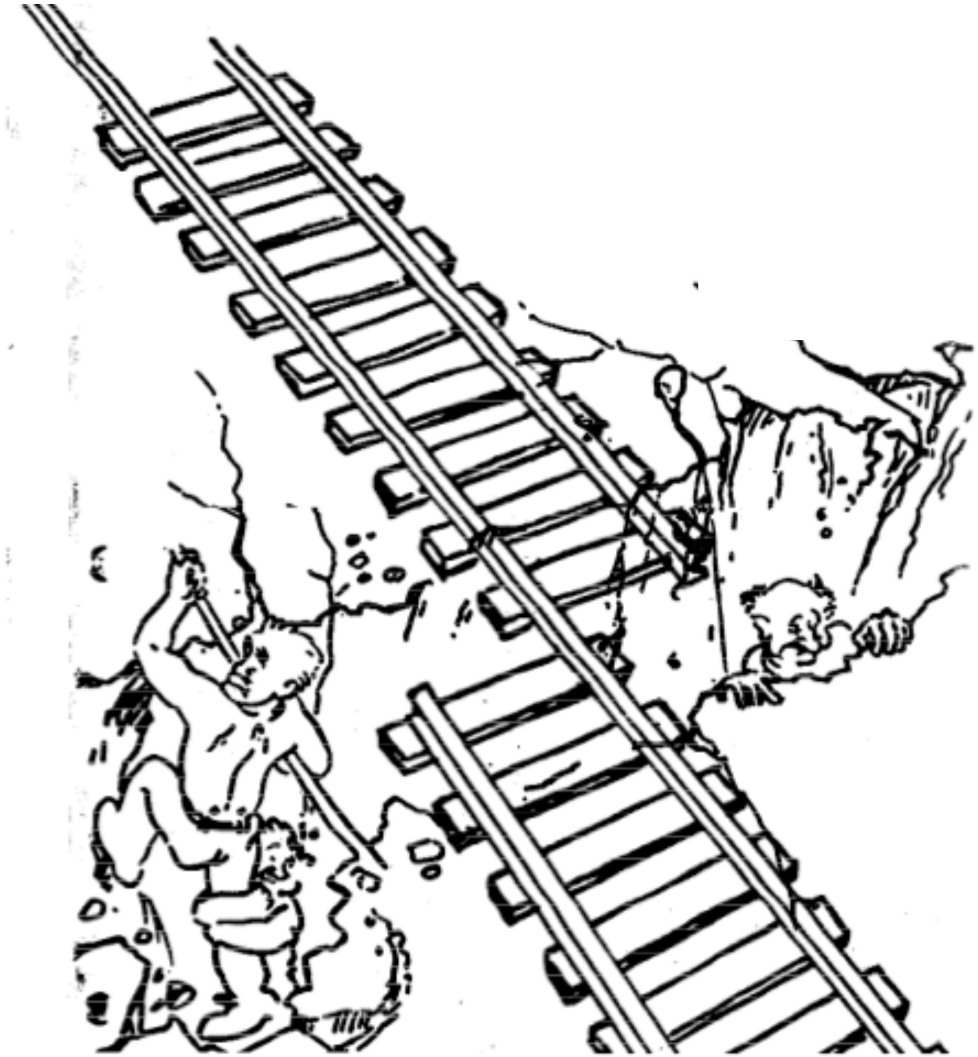
Mechanical Fault



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Example: Fault, Error, Failure

```
public static int numZero (int[] x) {
//Effects: if x==null throw NullPointerException
//         else return the number of occurrences of 0 in x
   int count = 0;
   for (int i = 1; i <x.length; i++) {
      if (x[i]==0) {
         count++;
      }
   }
   return count;
```

Error State:
x = [2,7,0]
i =1
count =0
PC=first iteration **for**

Expected State:
x = [2,7,0]
i =0
count =0
PC=first iteration **for**

Fix: `for(int i=0; i<x.length; i++)`

x = [2,7,0], fault executed, error, no failure

x = [0,7,2], fault executed, error, failure

State of the program: x, i, count, PC

Exercise: The Program

```
/* Effect: if x==null throw NullPointerException.
   Otherwise, return the index of the last element
   in the array 'x' that equals integer 'y'.
   Return -1 if no such element exists.        */

public int findLast (int[] x, int y) {
for (int i=x.length-1; i>0; i--) {
     if (x[i] == y) { return i; }
  }
  return -1;
}

/* test 1: x=[2,3,5], y=2;
   expect: findLast(x,y) == 0
   test 2: x=[2,3,5,2], y=2;
   expect: findLast(x,y) == 3 */
```

Exercise: The Problem

Read this faulty program, which includes a test case that results in failure. Answer the following questions.

- (a) Identify the fault, and fix the fault.
- (b) If possible, identify a test case that does not execute the fault.
- (c) If possible, identify a test case that executes the fault, but does not result in an error state.
- (d) If possible identify a test case that results in an error, but not a failure. Hint: Don't forget about the program counter.
- (e) For the given test case 'test1', identify the first error state. Be sure to describe the complete state.

States

State 0:

- x = [2,3,5]
- y = 2
- i = undefined
- PC = findLast(...)

- State 1:
  - x = [2,3,5]
  - y = 2
  - i = undefined
  - PC = before i =x.length-1;

- State 2:
  - x = [2,3,5]
  - y = 2
  - i = 2
  - PC = after i =x.length-1;

- State 3:
  - x = [2,3,5]
  - y = 2
  - i = 2
  - PC = i>0;

States

- State 3:
  - x = [2,3,5]
  - y = 2
  - i = 2
  - PC = i>0;

- State 4:
  - x = [2,3,5]
  - y = 2
  - i = 2
  - PC = if (x[i] ==y);

- State 5:
  - x = [2,3,5]
  - y = 2
  - i = 1
  - PC = i--;

- State 6:
  - x = [2,3,5]
  - y = 2
  - i = 1
  - PC = i>0;

- State 7:
  - x = [2,3,5]
  - y = 2
  - i = 1
  - PC = if (x[i] ==y);

- State 8:
  - x = [2,3,5]
  - y = 2
  - i = 0
  - PC = i--;

States

Incorrect Program

- State 8:
  - x = [2,3,5]
  - y = 2
  - i = 0
  - PC = i--;

- State 9:
  - x = [2,3,5]
  - y = 2
  - i = 0
  - PC = i>0;

- State 10:
  - x = [2,3,5]
  - y = 2
  - i = 0 (undefined)
  - PC = return -1;

Correct Program

- State 10:
  - x = [2,3,5]
  - y = 2
  - i = 0
  - PC = if (x[i]==y);

Exercise: Solutions (1/2)

(a) The for-loop should include the 0 index:

- for (int i=x.length-1; i >= 0; i--)

(b) The null value for x will result in a NullPointerException before the loop test is evaluated, hence no execution of the fault.

- Input: x = null; y = 3
- Expected Output: NullPointerException
- Actual Output: NullPointerException

(c) For any input where y appears in a position that is not position 0, there is no error. Also, if x is empty, there is no error.

- Input: x = [2, 3, 5]; y = 3;
- Expected Output: 1
- Actual Output: 1

Exercise: Solutions (2/2)

(d) For an input where y is not in x, the missing path (i.e. an incorrect PC on the final loop that is not taken, normally i = 2, 1, 0, but this one has only i = 2, 1,) is an error, but there is no failure.

- Input: x = [2, 3, 5]; y = 7;
- Expected Output: -1
- Actual Output: -1

(e) Note that the key aspect of the error state is that the PC is outside the loop (following the false evaluation of the 0>0 test. In a correct program, the PC should be at the if-test, with index i==0.

- Input: x = [2, 3, 5]; y = 2;
- Expected Output: 0
- Actual Output: -1
- First Error State:
  - x = [2, 3, 5]
  - y = 2;
  - i = 0 (or undefined);
  - PC = return -1;

RIP Model

Three conditions must be present for an error to be observed (i.e., failure to happen):

- Reachability: the location or locations in the program that contain the fault must be reached.
- Infection: After executing the location, the state of the program must be incorrect.
- Propagation: The infected state must propagate to cause some output of the program to be incorrect.

HOW DO WE DEAL WITH FAULTS, ERRORS, AND FAILURES?

Addressing Faults at Different Stages

Fault Avoidance

Better Design, Better PL, ...

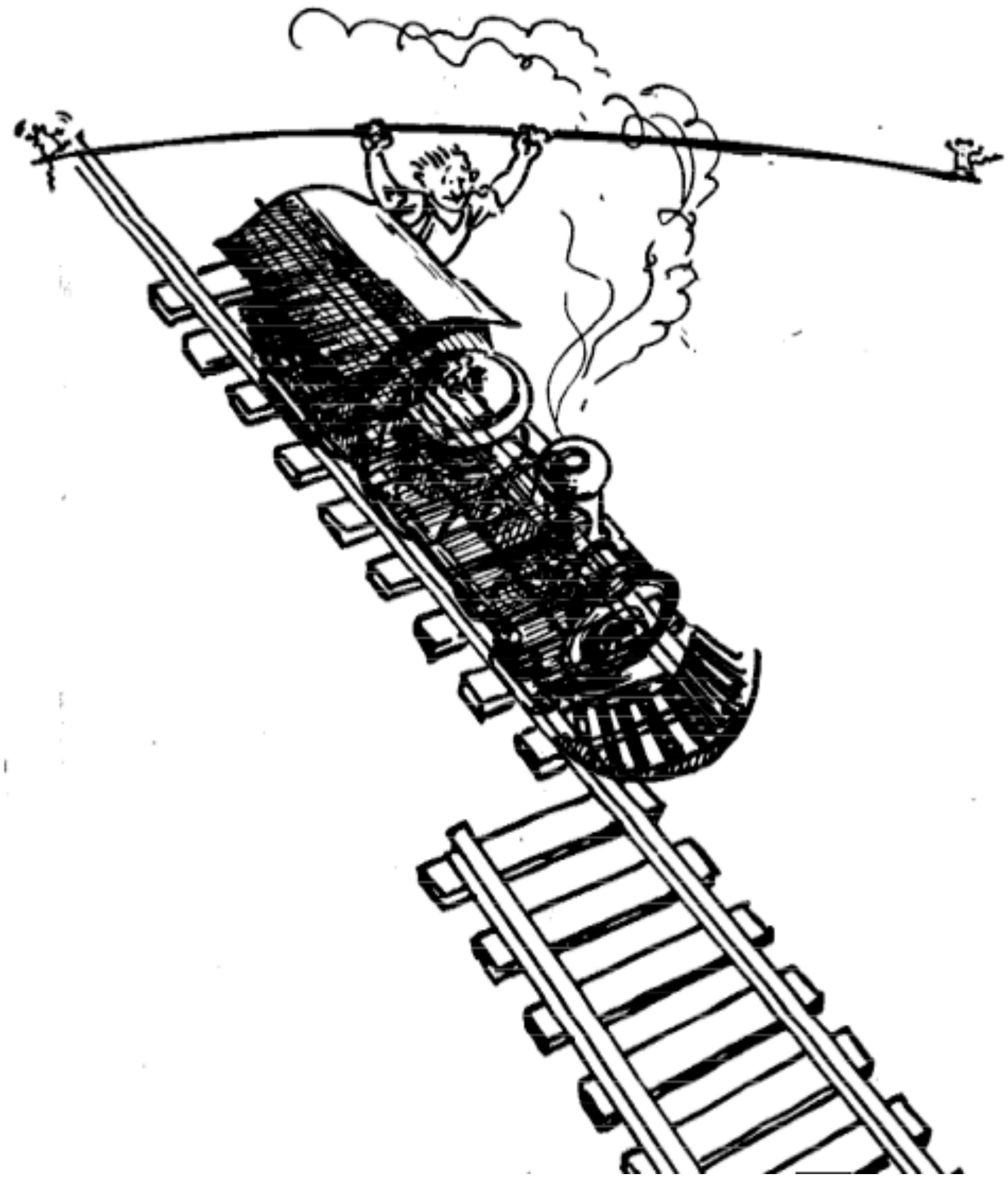
Fault Detection

Testing, Debugging, ...

Fault Tolerance

Redundancy, Isolation, ...

Declaring the Bug as a Feature



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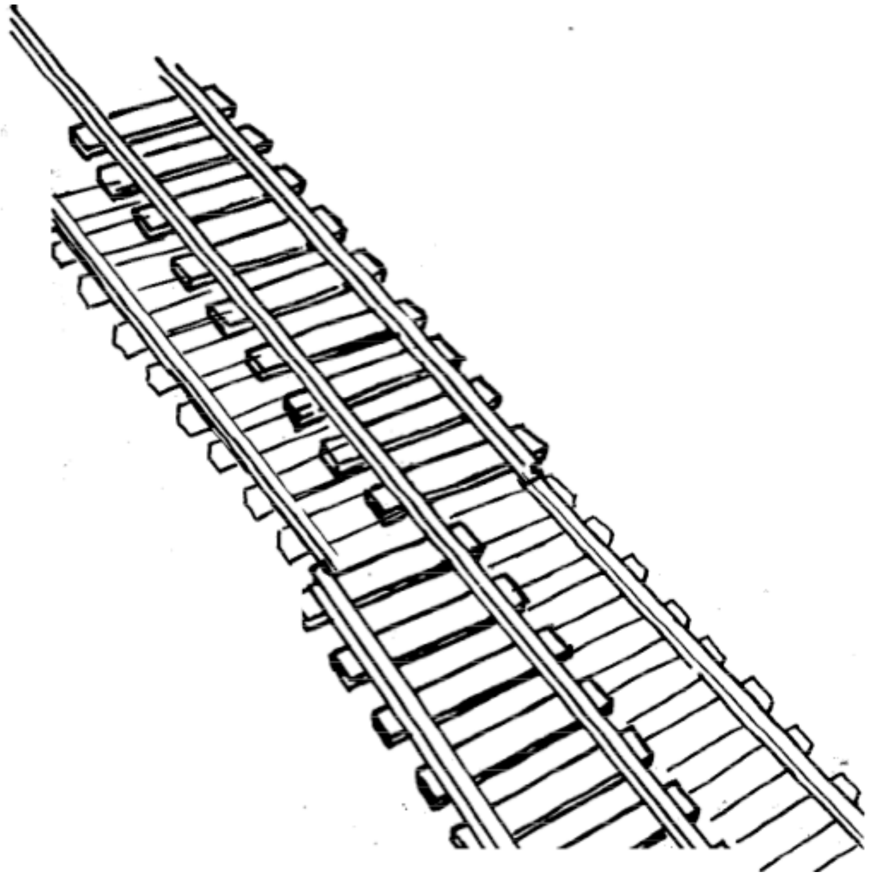
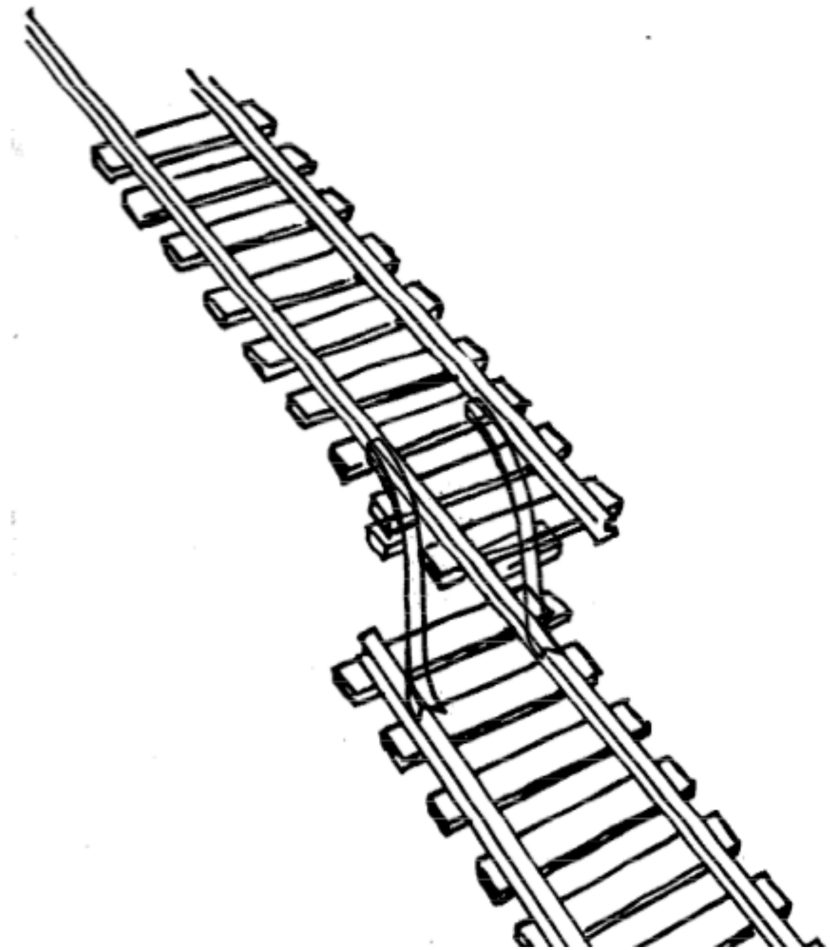
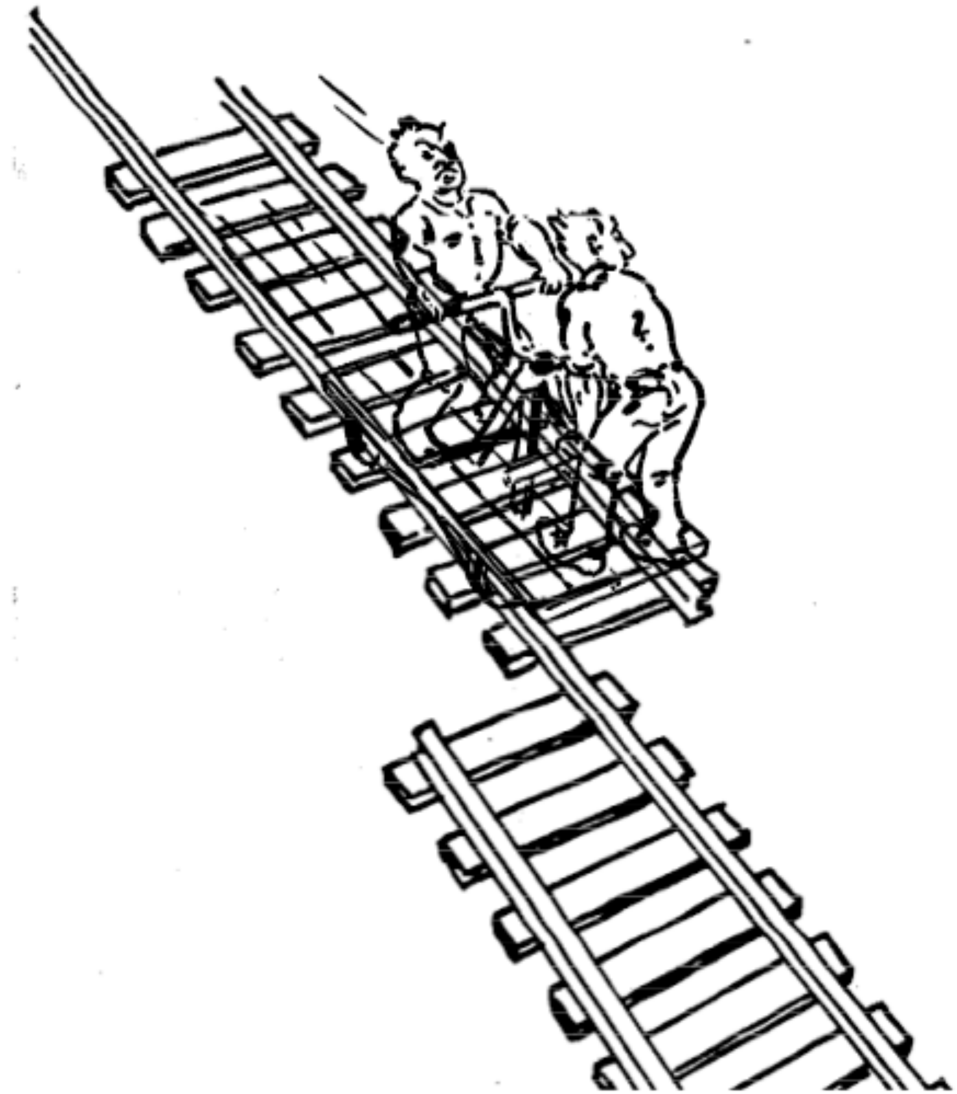
Modular Redundancy: Fault Tolerance



Patching: Fixing the Fault



Testing: Fault Detection



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Testing vs. Debugging

Testing: Evaluating software by observing its execution

Debugging: The process of finding a fault given a failure

Testing is hard:

- Often, only specific inputs will trigger the fault into creating a failure.

Debugging is hard:

- Given a failure, it is often difficult to know the fault.

Testing is hard

```
if ( x - 100 <= 0 )
  if ( y - 100 <= 0 )
    if ( x + y - 200 == 0 )
      crash();
```

Only input `x=100 & y=100` triggers the crash

If x and y are 32-bit integers, what is the probability of a crash?

- $1 / 2^{64}$

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