Fault, Error, and Failure

Testing, Quality Assurance, and Maintenance
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based on slides by Prof. Lin Tan and others

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Terminology

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!

- Let's look at an IEEE standard …

IEEE/ISO/IEC 24765-2017: Fault

2123031

fault

abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function

- Note 1 to entry: IEV 191-05-01 defines "fault" as a state characterized by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources.
- Note 2 to entry: fault: term and definition standardized by ISO/IEC [ISO/IEC 2382-14:1997].
- Note 3 to entry: 14.01.10 (2382)
- [SOURCE: ISO-IEC-2382-14 * 1997 * * *]

https://www.iso.org/obp/ui/#iso:std:iso-iec:2382:ed-1:v1:en

IEEE/ISO/IEC 24765-2017: Error

2123029

error

discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition

- Note 1 to entry: A slightly different wording is used in IEV 191-05-24.
- Note 2 to entry: The definition in ISO 2382-2 is the same.
- Note 3 to entry: error: term and definition standardized by ISO/IEC [ISO/IEC 2382-14:1997].
- Note 4 to entry: 14.01.08 (02.06.04) (2382)
- [SOURCE: ISO-IEC-2382-14 * 1997 * * *]

2124096

error

…

https://www.iso.org/obp/ui/#iso:std:iso-iec:2382:ed-1:v1:en

IEEE/ISO/IEC 24765-2017: Failure

2123032

failure

termination of the ability of a functional unit to perform a required function

- Note 1 to entry: The definition in IEV 191-04-01 is the same, with additional notes referring to a different meaning of the term "fault".
- Note 2 to entry: failure: term and definition standardized by ISO/IEC [ISO/IEC 2382-14:1997].
- Note 3 to entry: 14.01.11 (2382)
- [SOURCE: ISO-IEC-2382-14 * 1997 * * *]

https://www.iso.org/obp/ui/#iso:std:iso-iec:2382:ed-1:v1:en

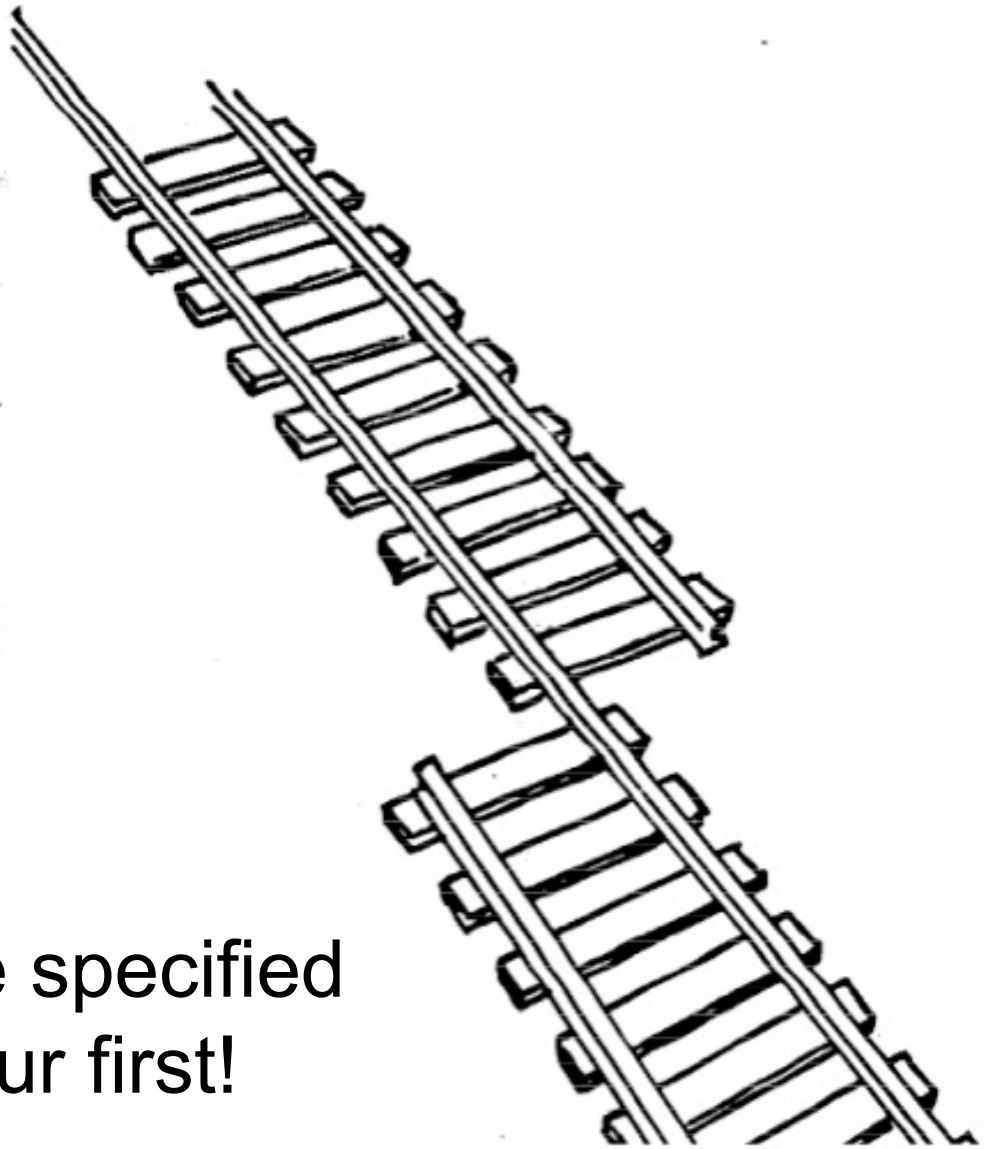
What is this?

A fault?

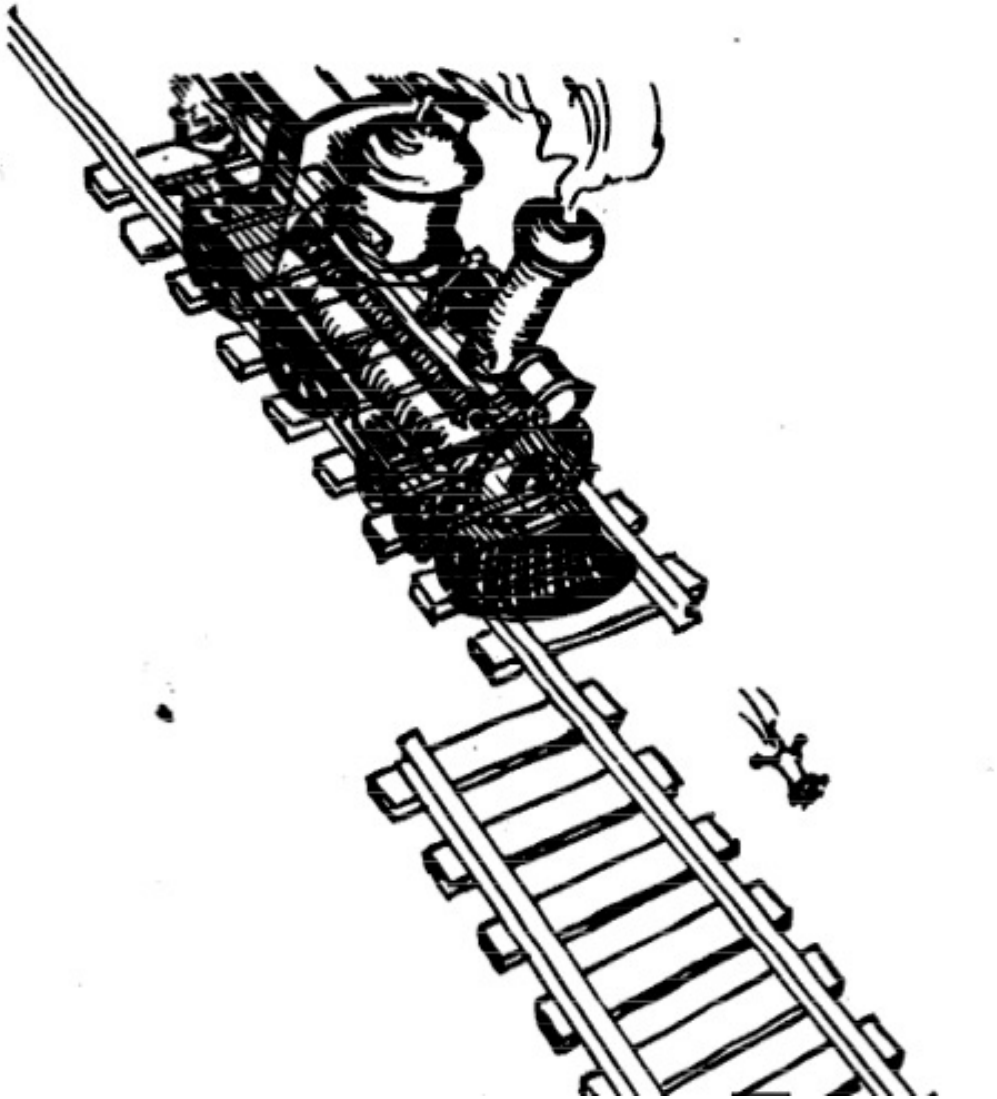
An error?

A failure?

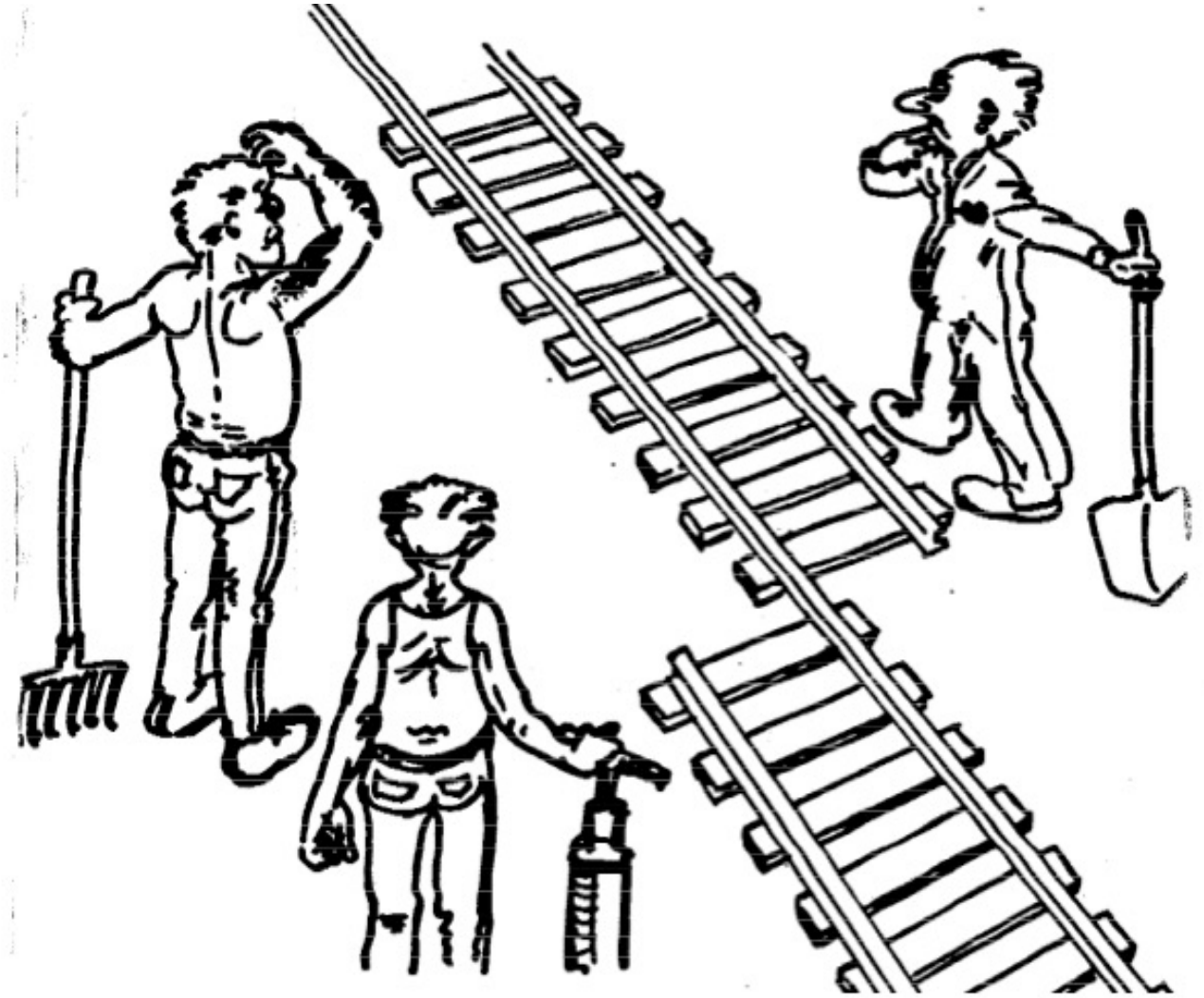
We need to describe specified and desired behaviour first!



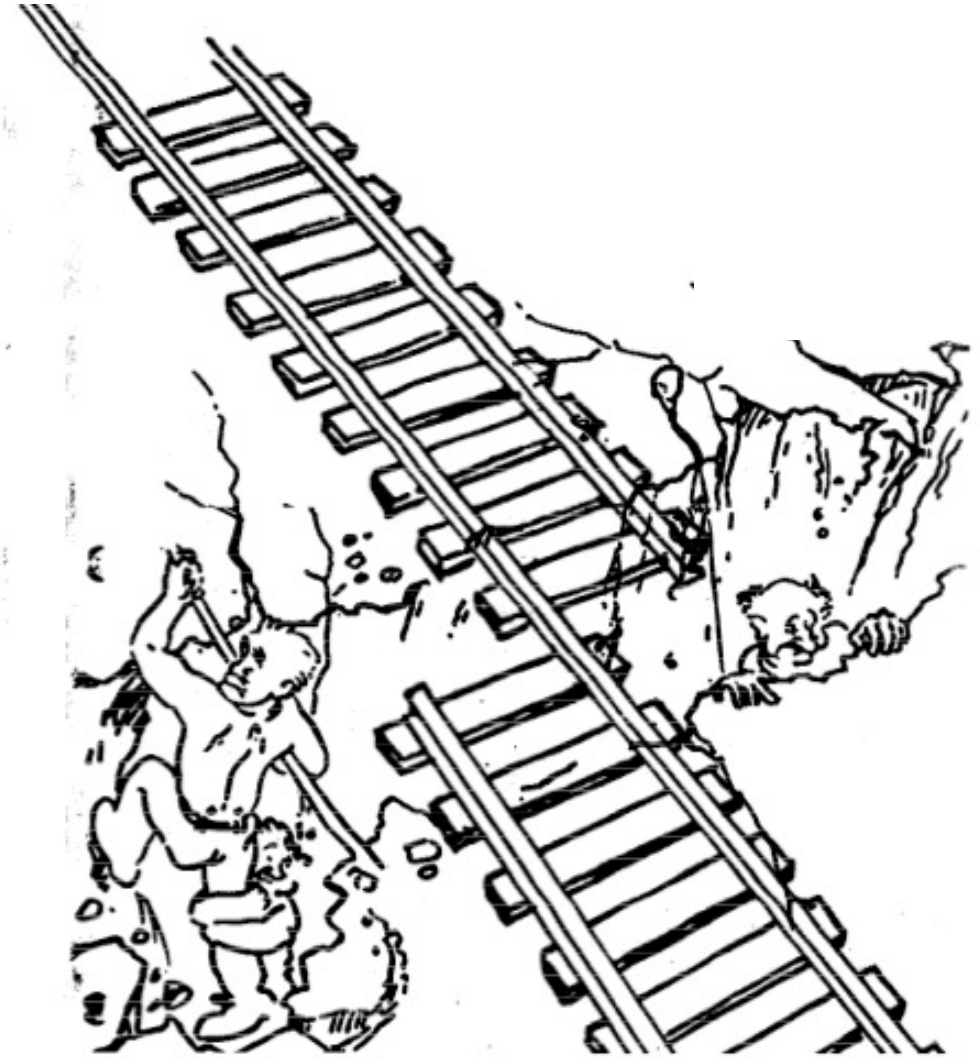
Erroneous State (“Error”)



Design Fault



Mechanical Fault



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;

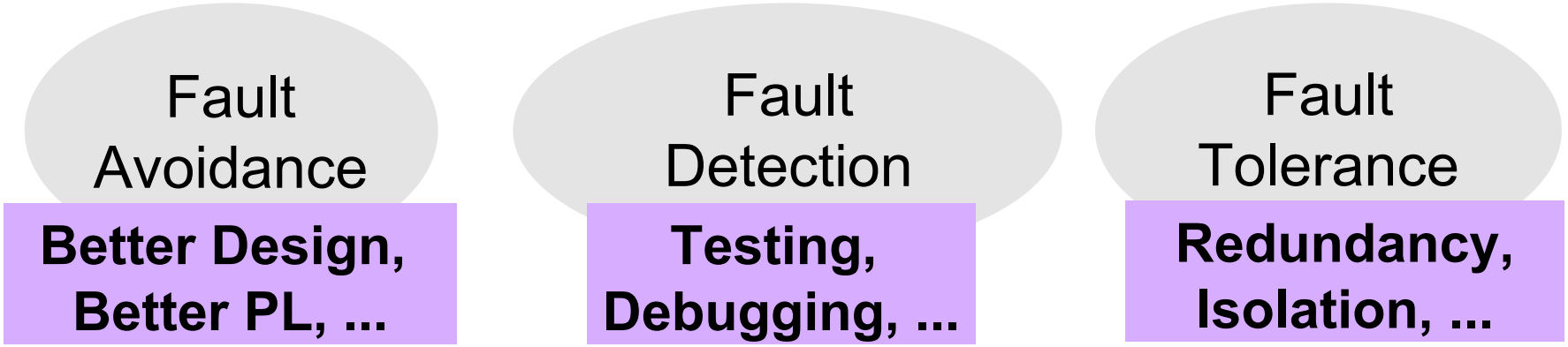
RIP Model

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

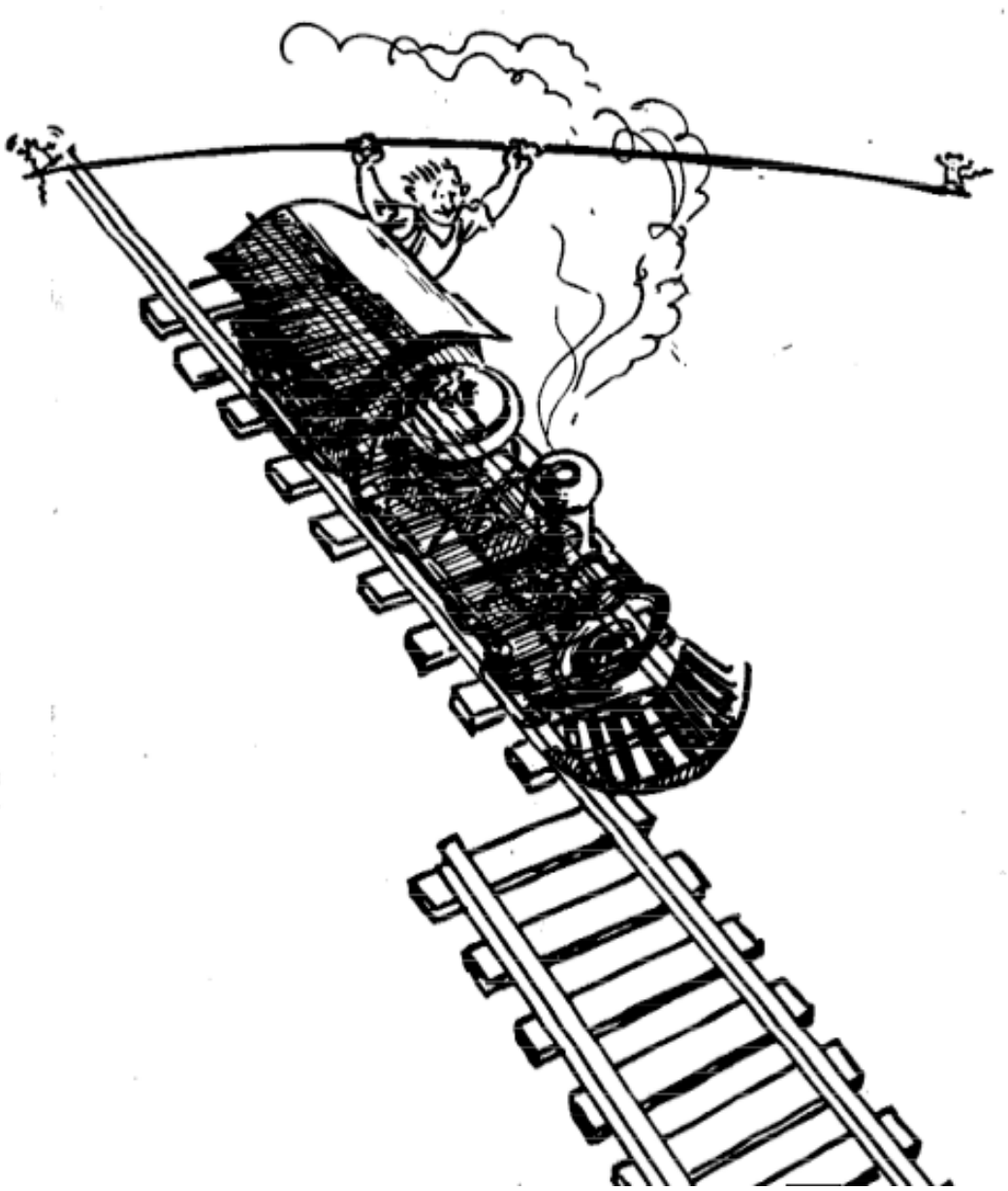
- Reachability: the location or locations in the program that contain the fault must be reached.
- Infection: After executing the location, the state of the program must be incorrect.
- Propagation: The infected state must propagate to cause some output of the program to be incorrect.

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

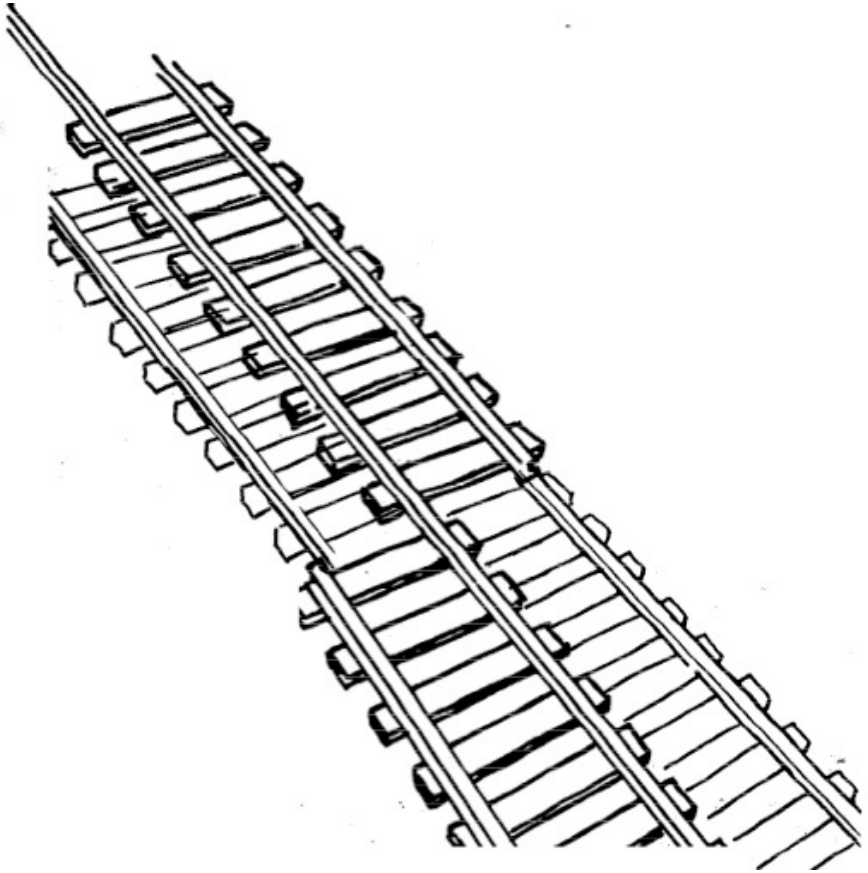
Addressing Faults at Different Stages



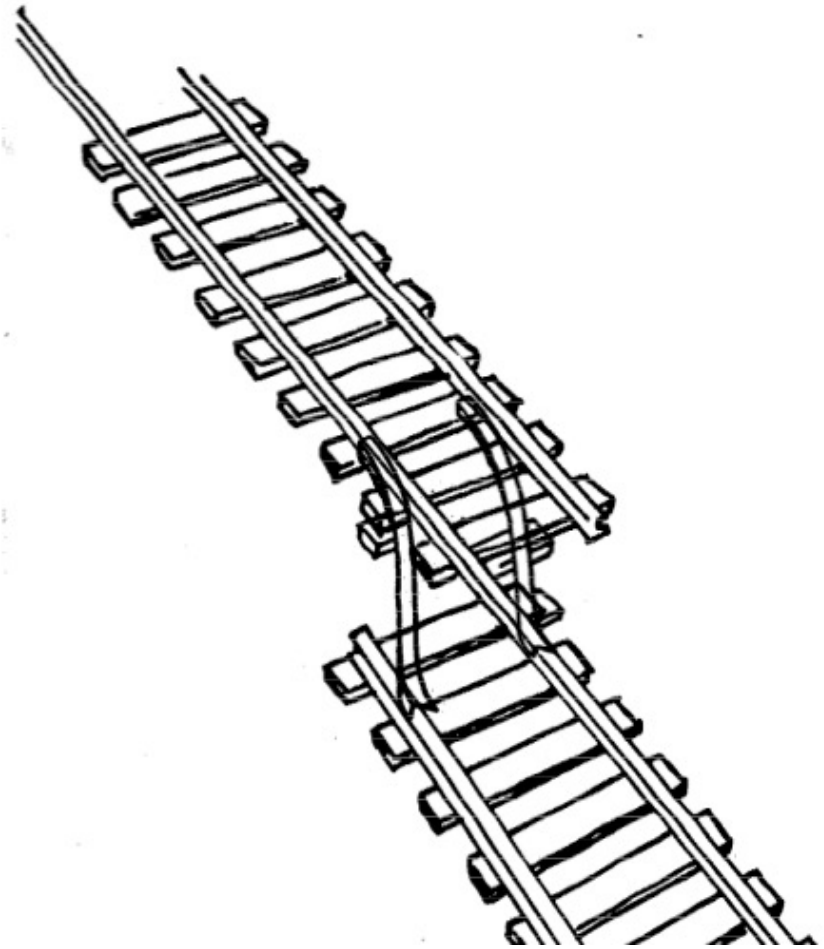
Declaring the Bug as a Feature



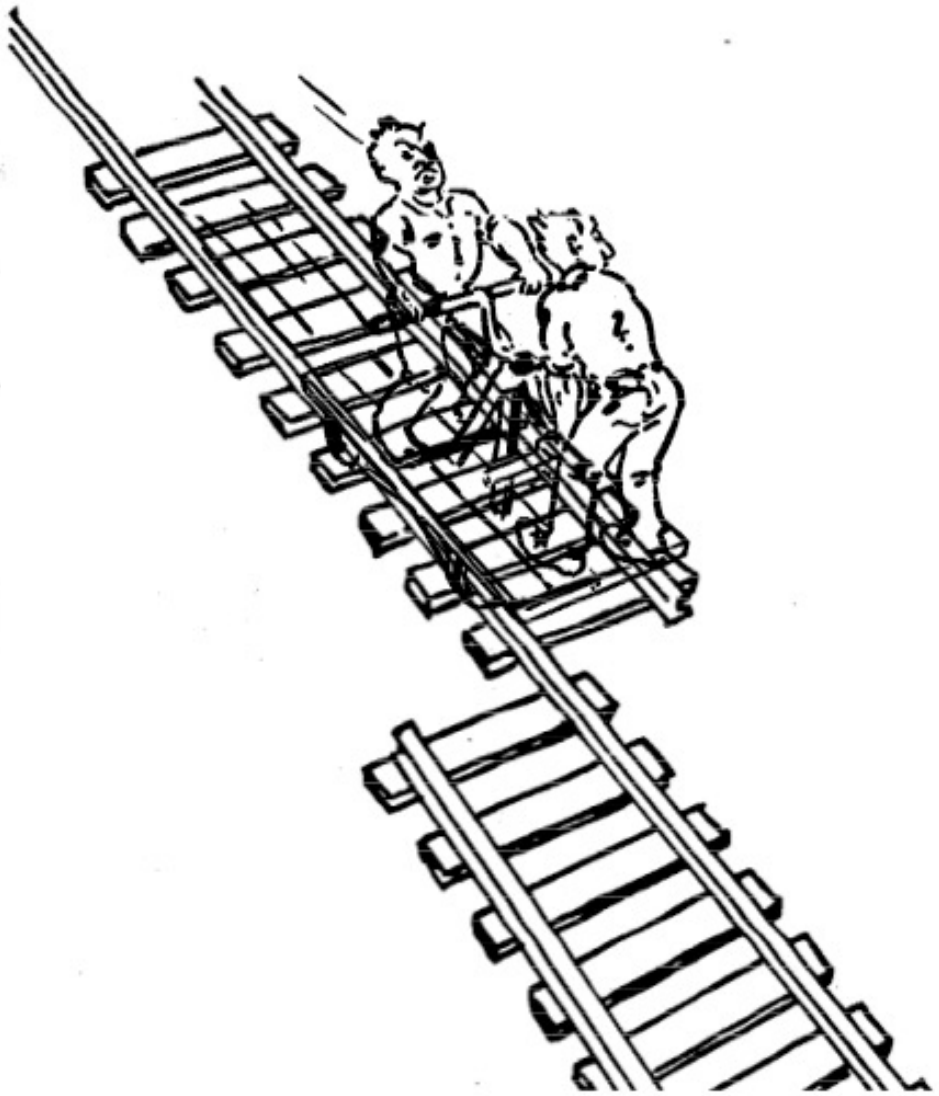
Modular Redundancy: Fault Tolerance



Patching: Fixing the Fault



Testing: Fault Detection



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?

- $1 / 2^{64}$

Exercise: The Problem

```
1  def pos_odd (x):
2      """Ensures: returns the number of positive odd elements in the list x
3         or throws an exception if x is not a list of numbers"""
4      cnt = 0
5      i = 0
6      while i < len (x):
7          if x[i] % 2 == 1:
8              cnt = cnt + 1
9          i = i + 1
10
11     return cnt
12
13 # x = [-10,-9,0,99,100]
14 # r = pos_odd(x)
15 # assert (r == 1)
```

a) What is the fault in this program

b) Identify a test case that does not execute the fault

c) Identify a test case that results in an error but does not cause failure

d) Identify a test case that causes a failure but no error

e) For the test case `x = [-10, -9, 0, 99, 100]` the expected output is 1. Identify the first error state

Exercise: Solution

a) Fault is at line 7. Negative numbers are not considered. Fixed by

```
if x[i] > 0 and x[i] % 2 == 1
```

b) Any input that does not execute line 7. For example, `x = 7` (not a list of numbers), `x=[]` (empty list), etc.

c) Any list that contains numbers and not-numbers. At a non-number, an exception is thrown (which is expected and is not a failure) even though an error has occurred before. For example, `x = [-1, 'hey']`

d) This situation is impossible. Fault is required for error, error is required for failure. It is possible to have fault without an error, and error without a failure, but not the other way around

e) The first error state is:

```
x = [-10, -9, 0, 99, 100]  i = 1
cnt = 0                    pc = at line 8
```

process counter