CMPT 745
Software Engineering

An Overview of Software Testing

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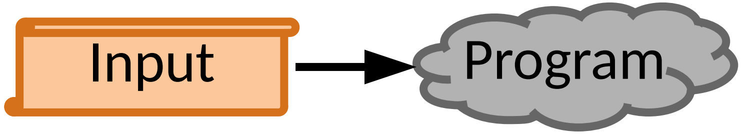
Software Testing

- The most common way of measuring and ensuring program correctness



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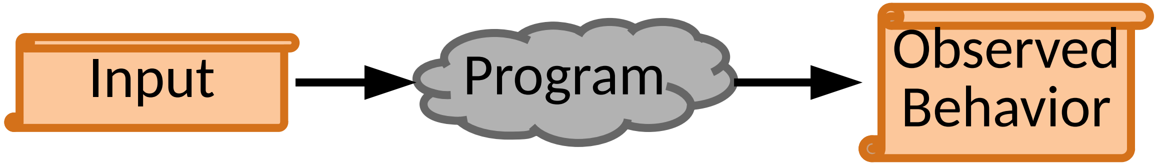

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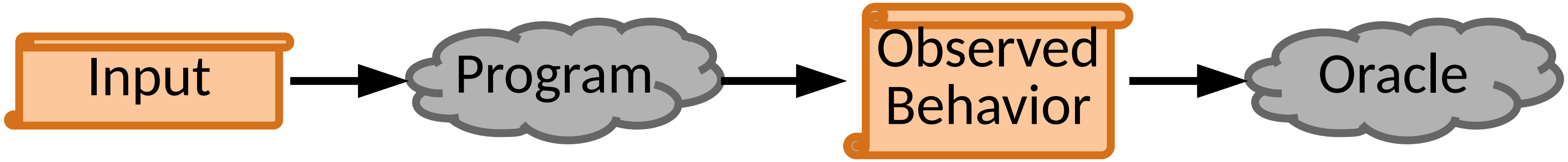

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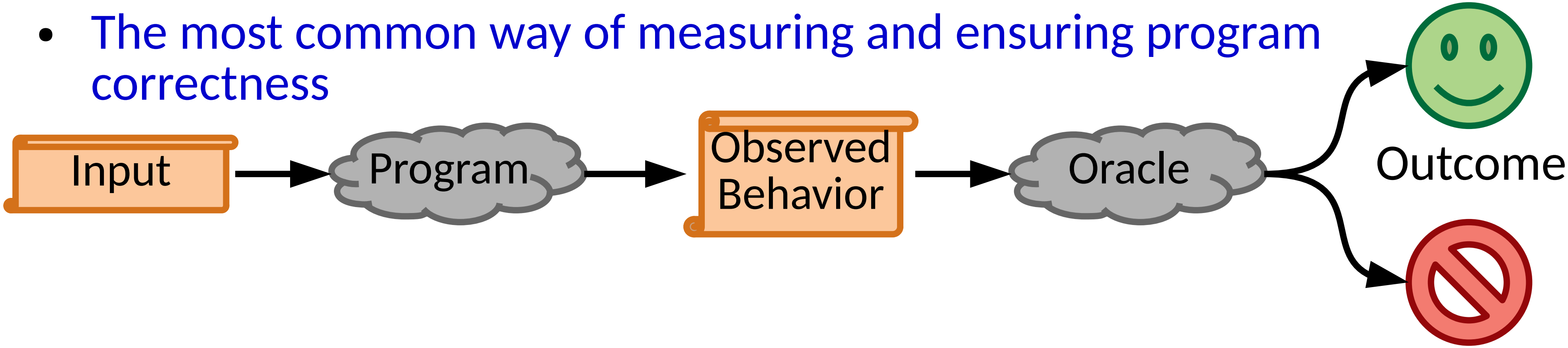

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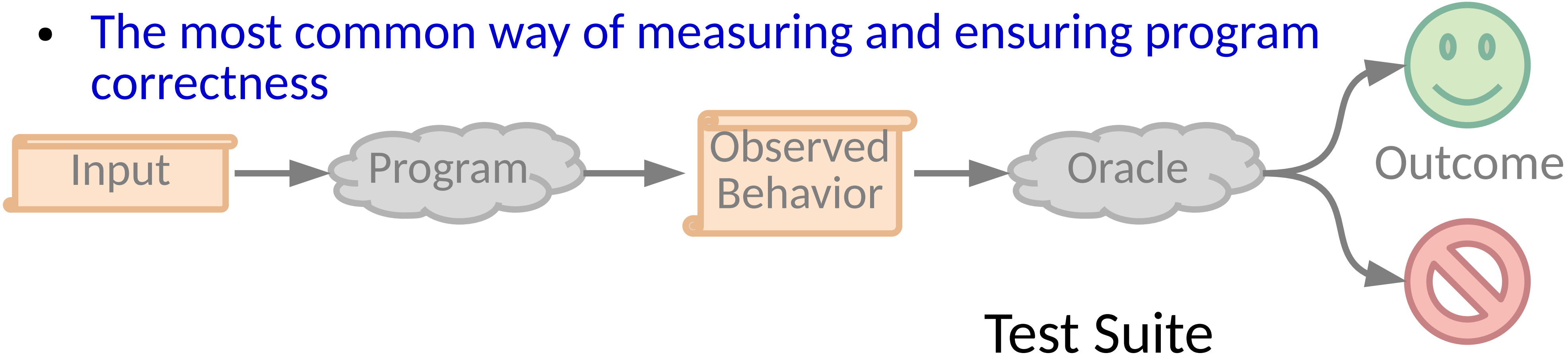

Test Suite

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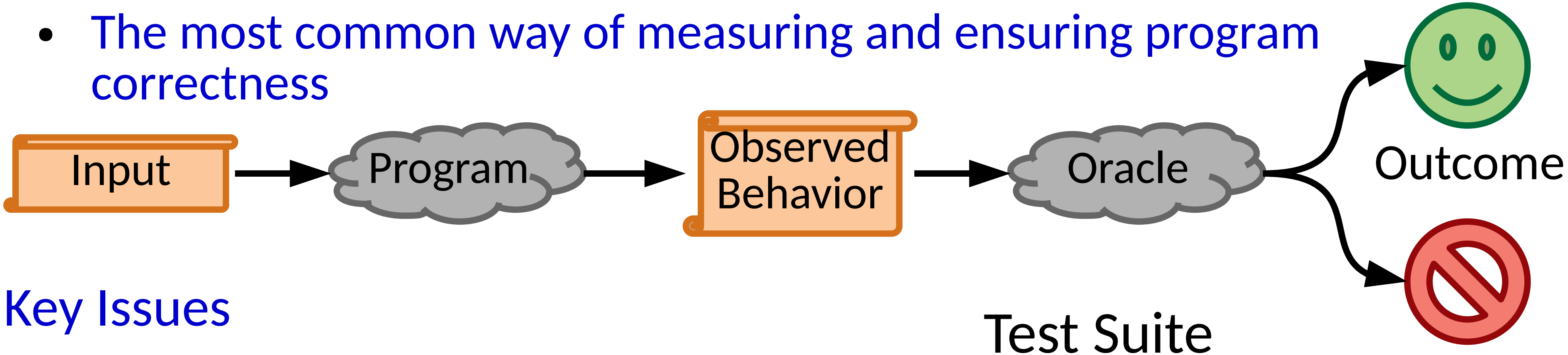

Key Issues

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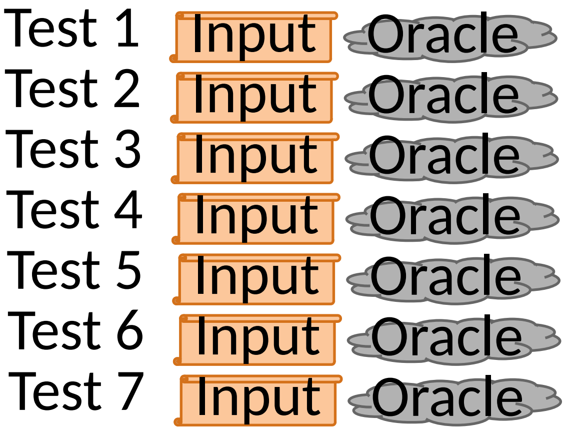

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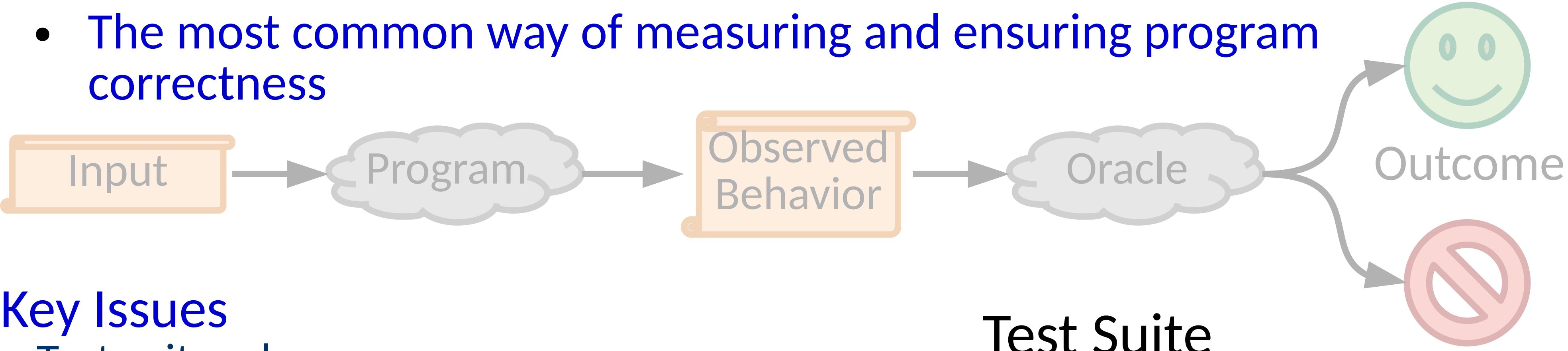

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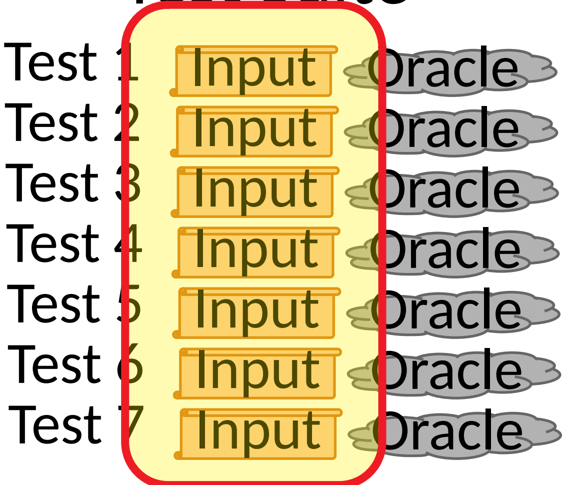

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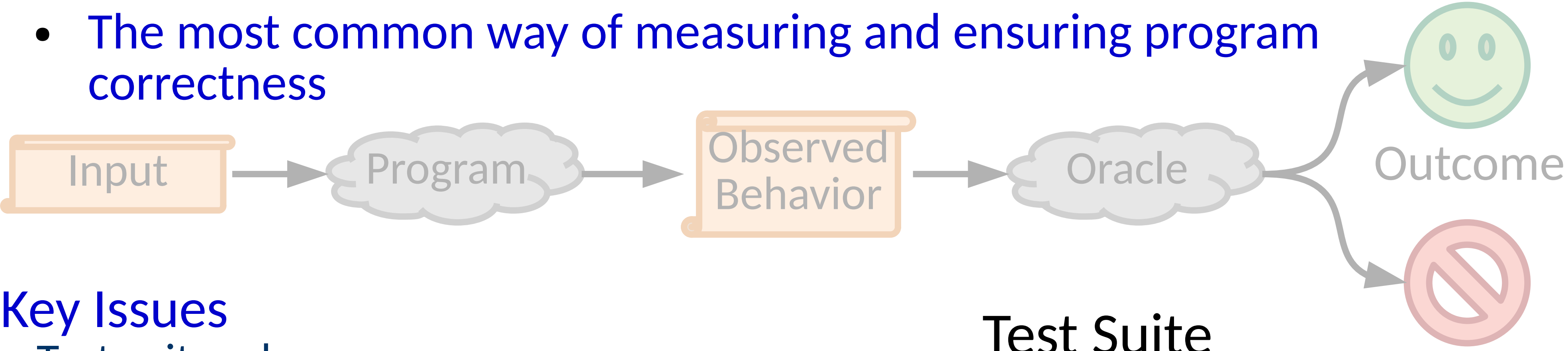

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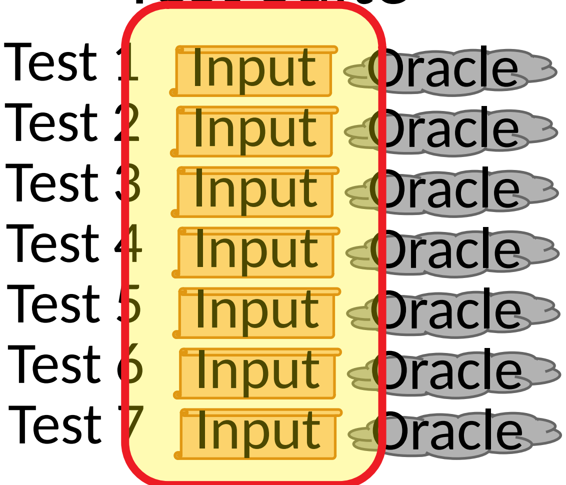
Testing is sampling.

How do we know whether we are sampling well?

Test Suite



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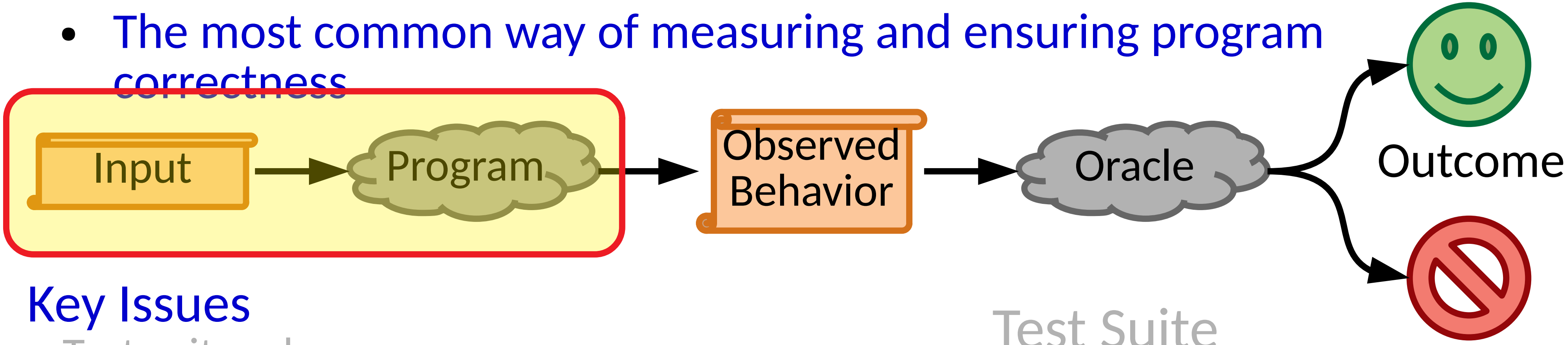

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- Automated input generation

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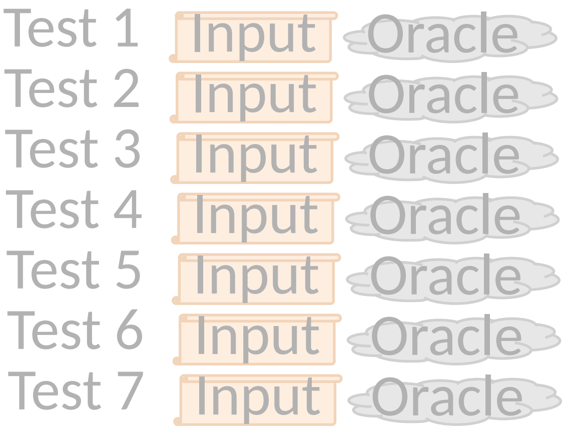

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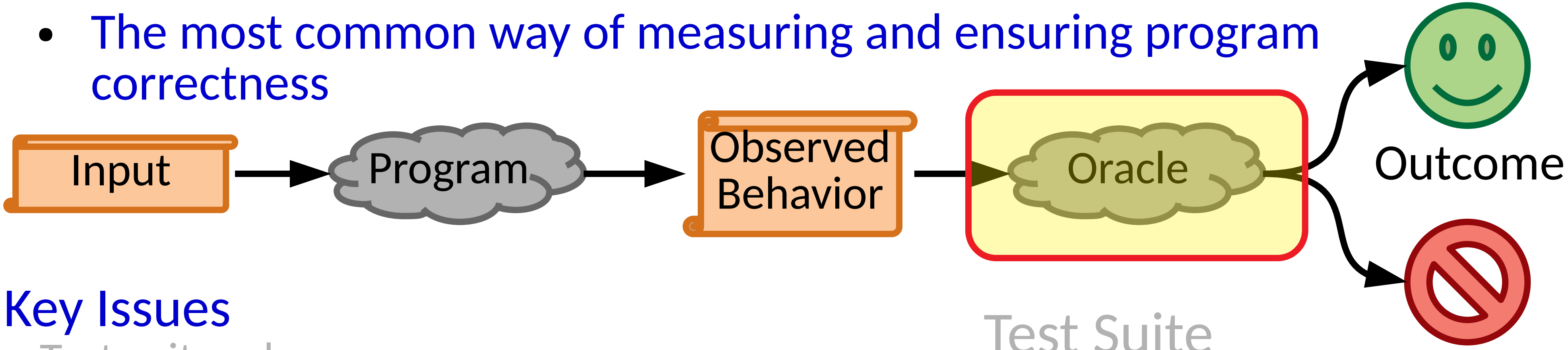

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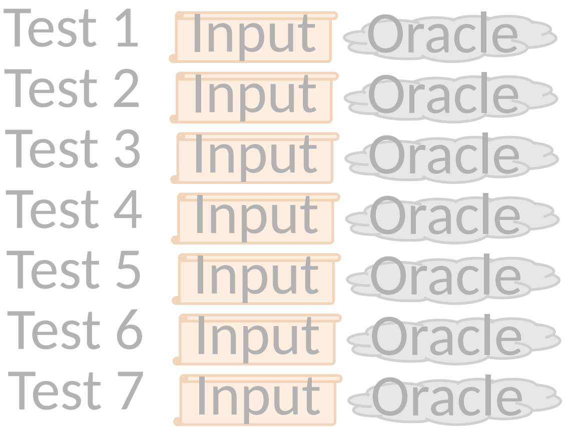

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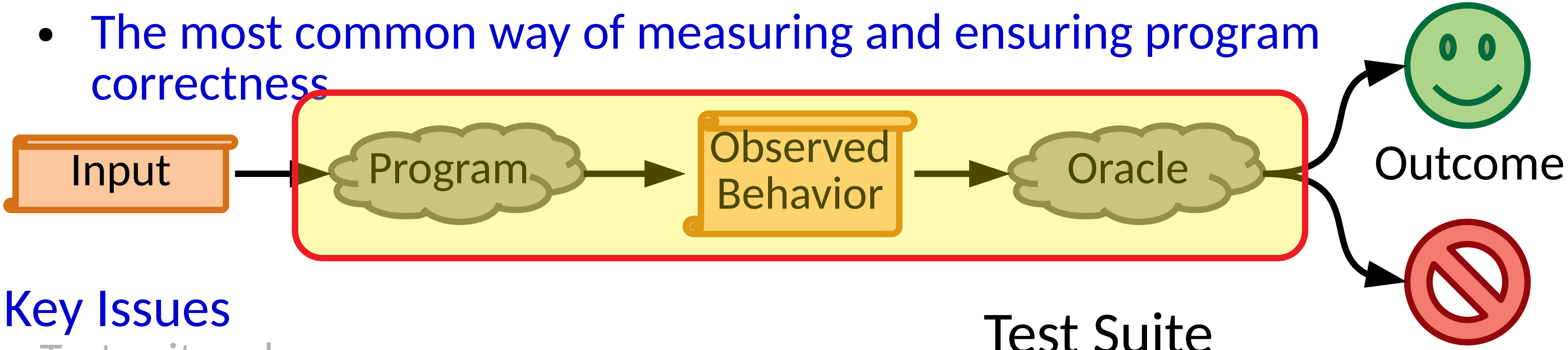

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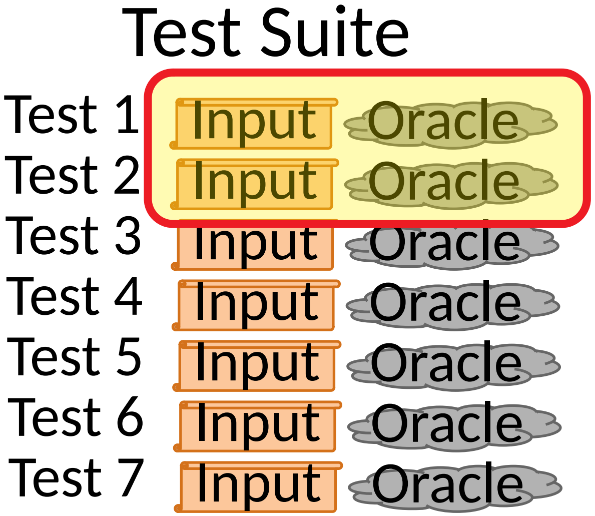

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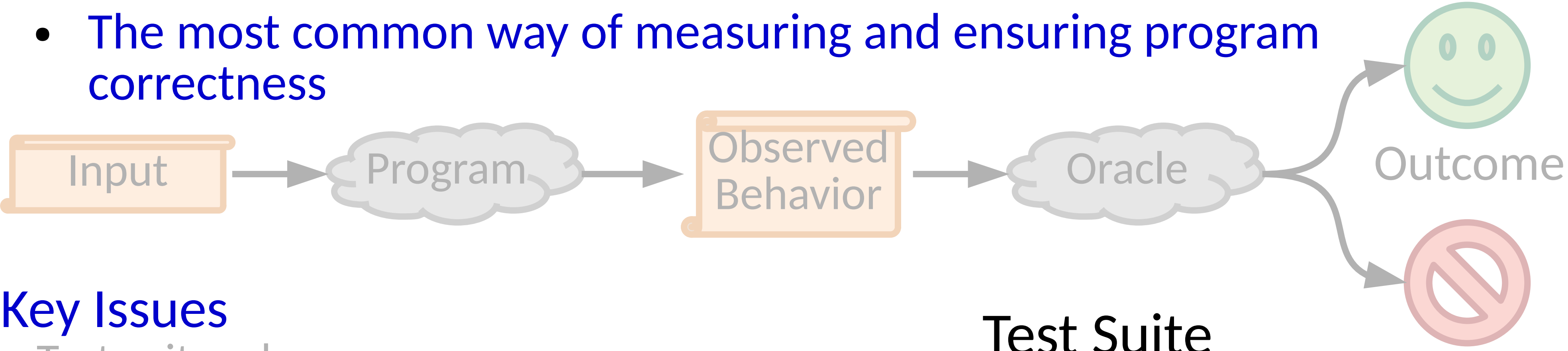

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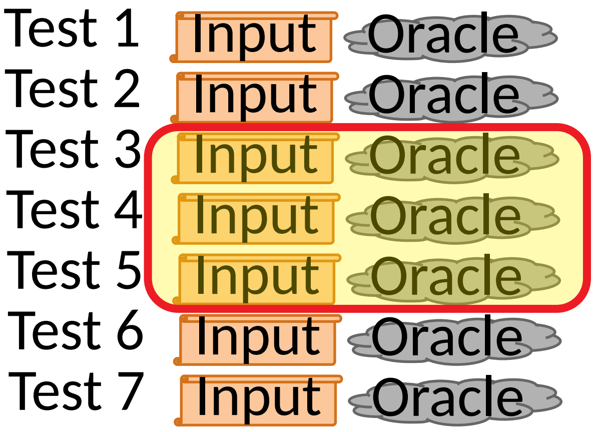

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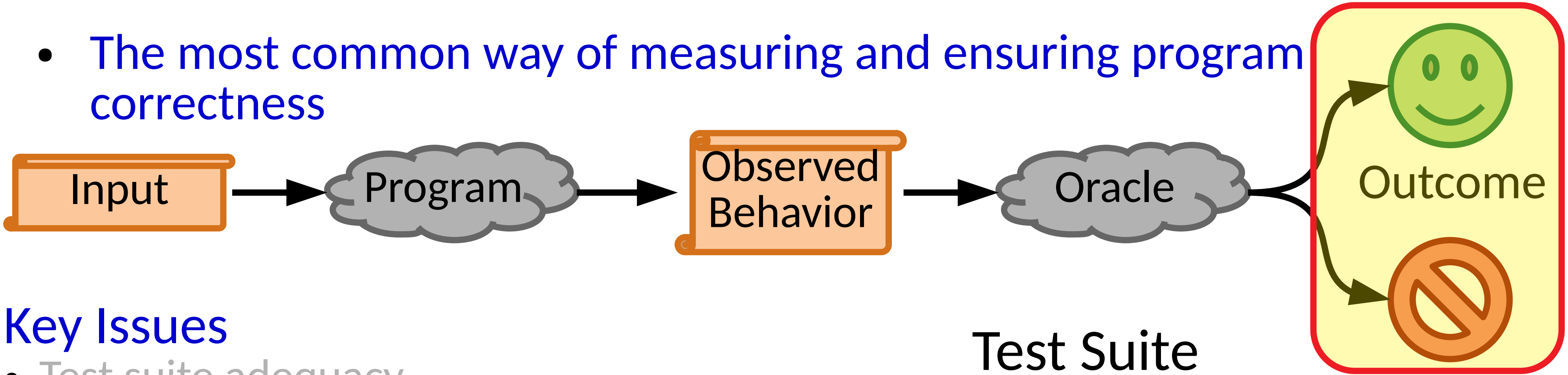

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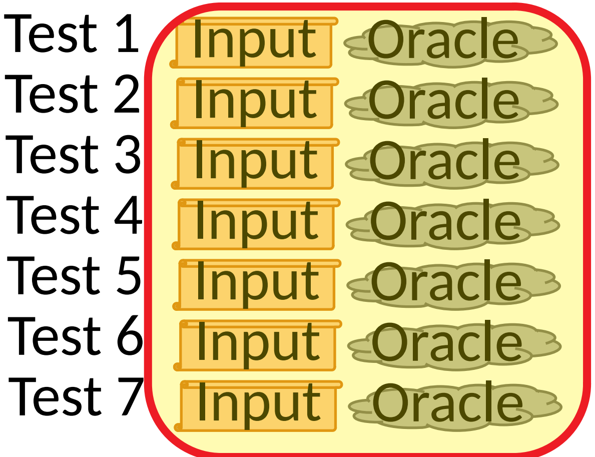

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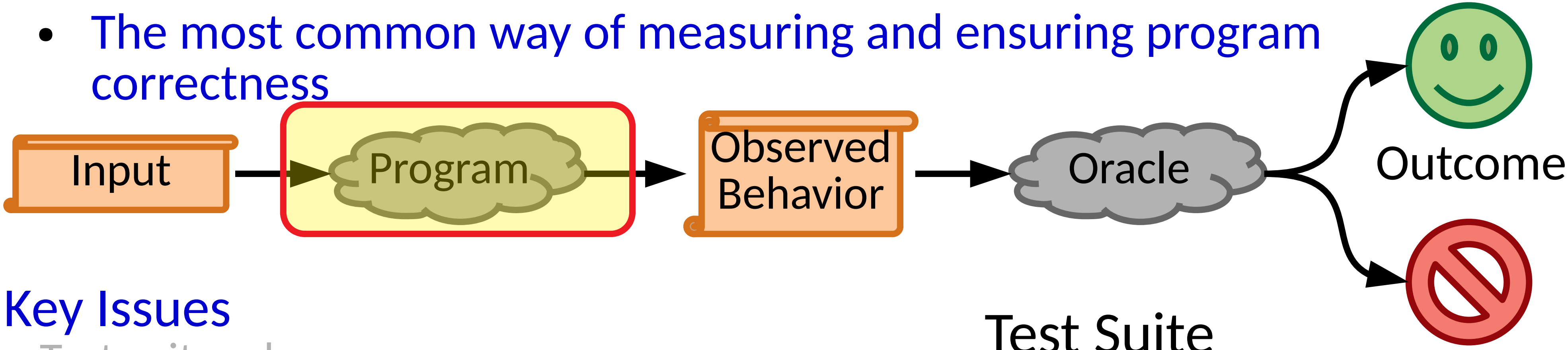

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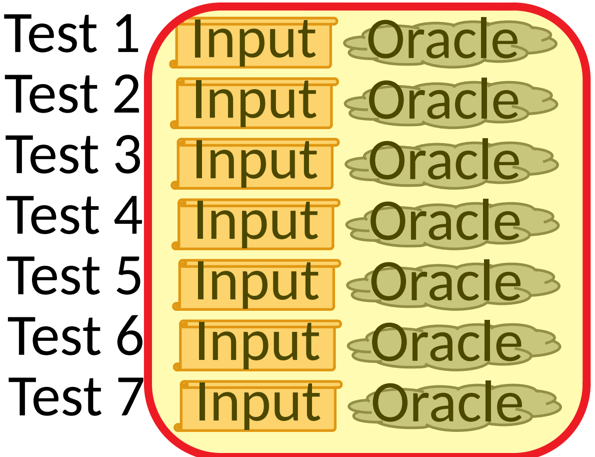

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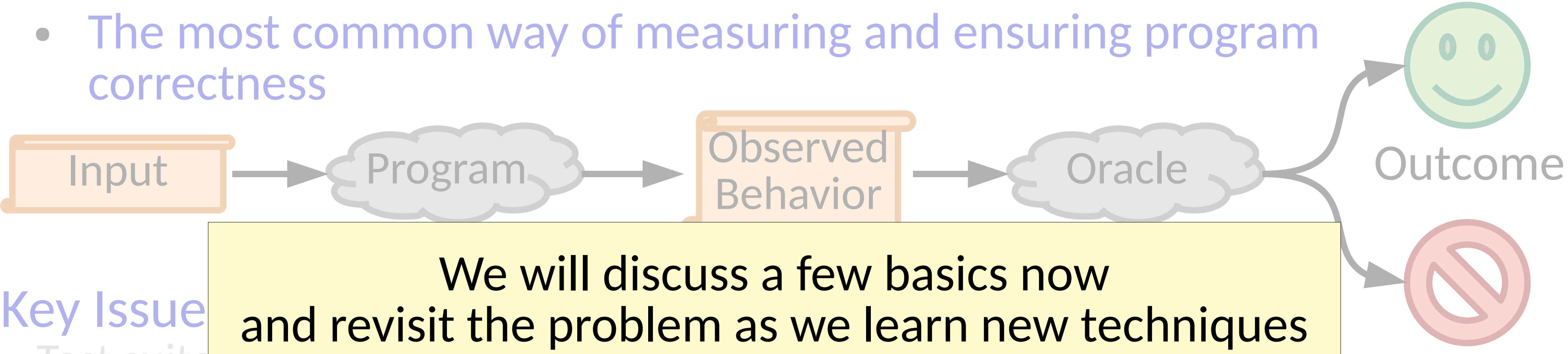

We will discuss a few basics now
and revisit the problem as we learn new techniques

Key Issue

- Test suite
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- Fault localization & automated debugging
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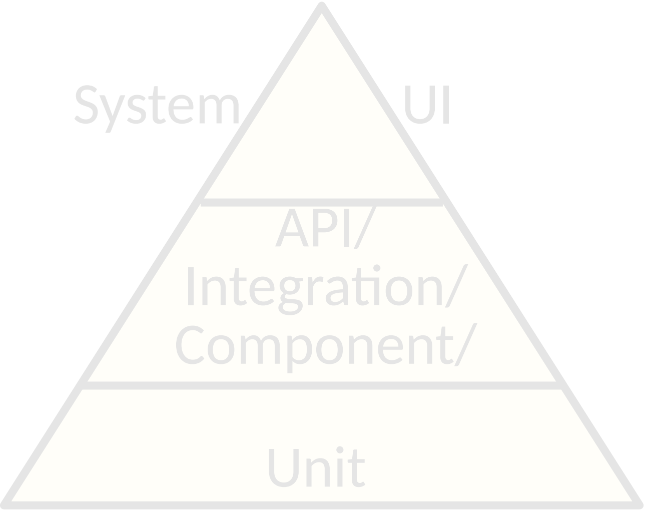

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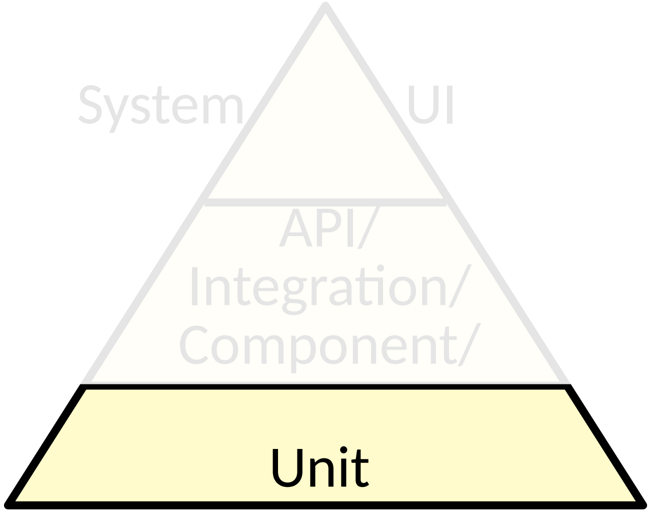

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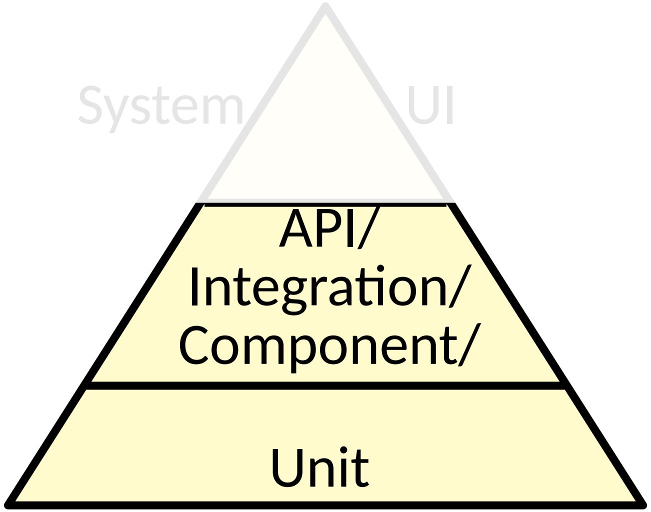

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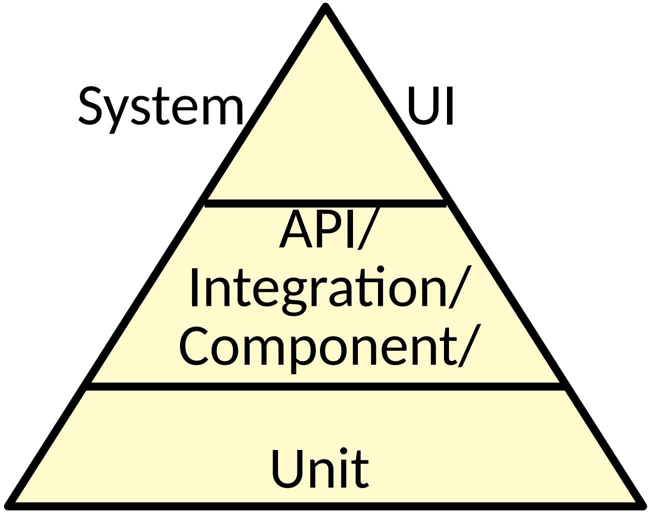

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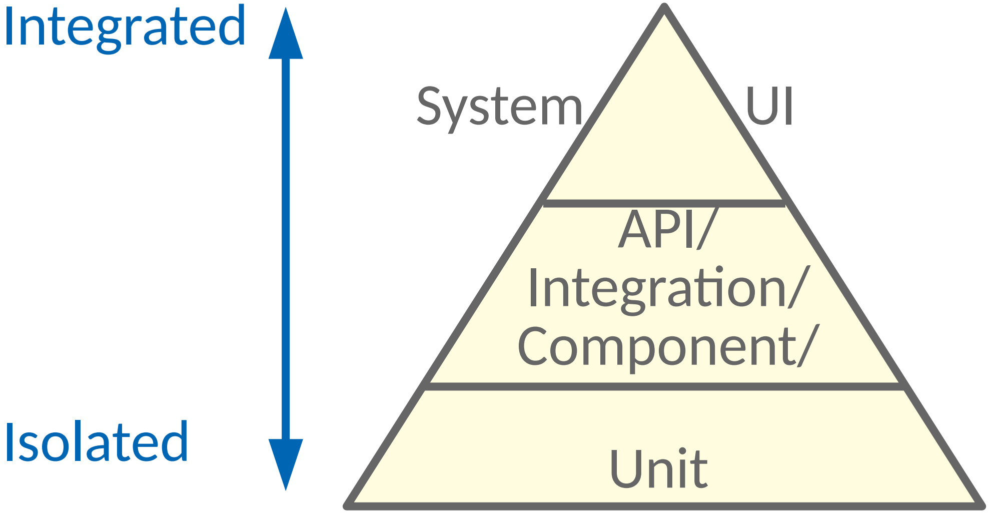

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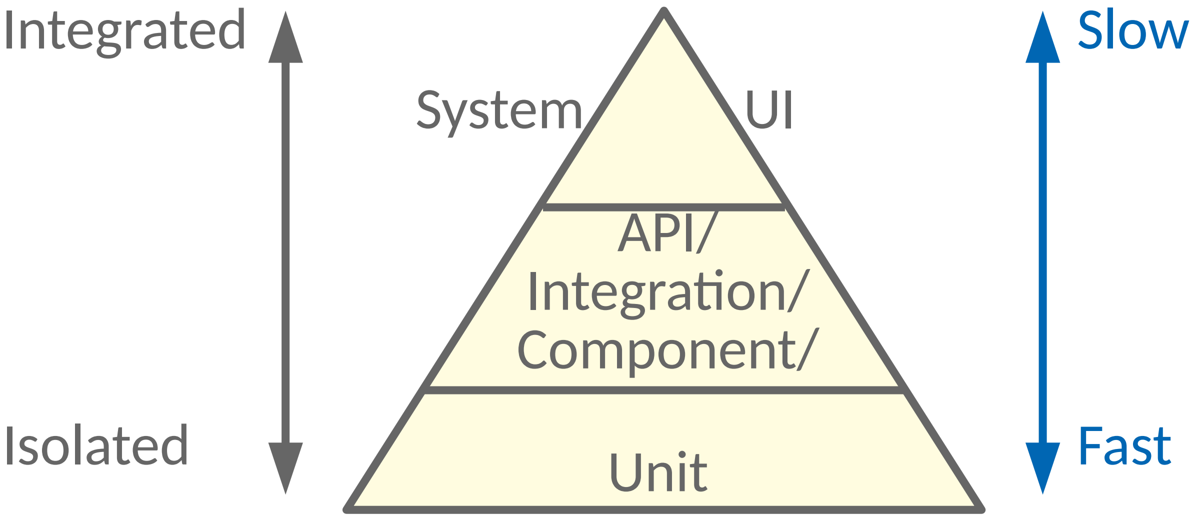

Designing a Unit Test

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TEST_CASE("empty") {
  Environment env;
  ExprTree tree;

  auto result = evaluate(tree, env);

  CHECK(!result.has_value());
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Set up a scenario

Designing a Unit Test

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Run the scenario

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Check the outcome

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- Tests should run in isolation

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  Frob()
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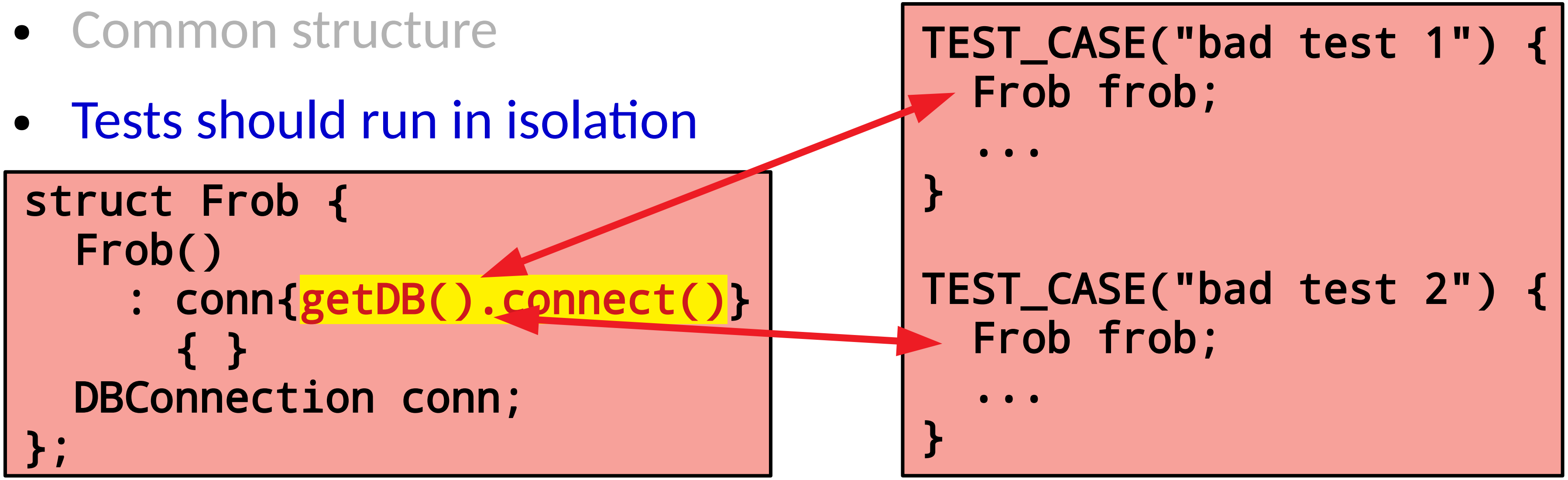

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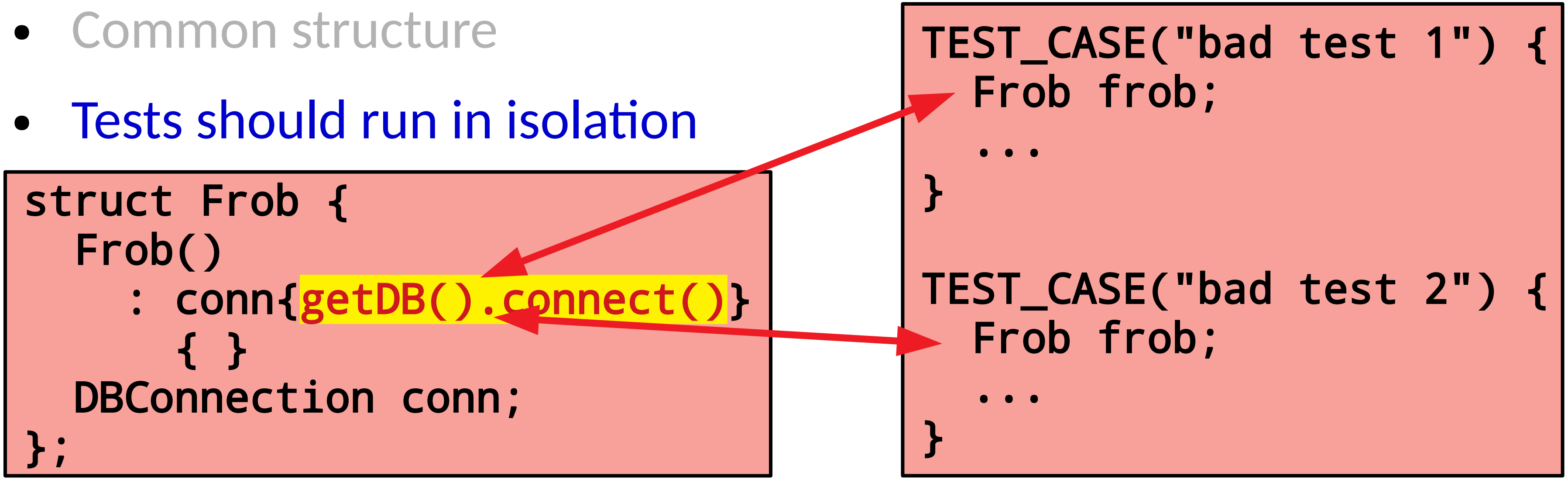

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A flaky DB can affect results!

Designing a Unit Test

- Common structure
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struct Frob {
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Dependency injection allows the user of a class to control its behavior

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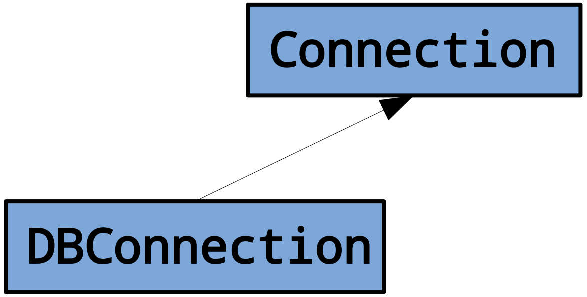

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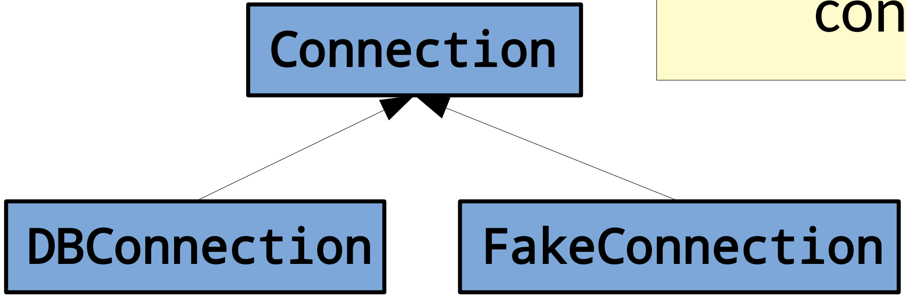

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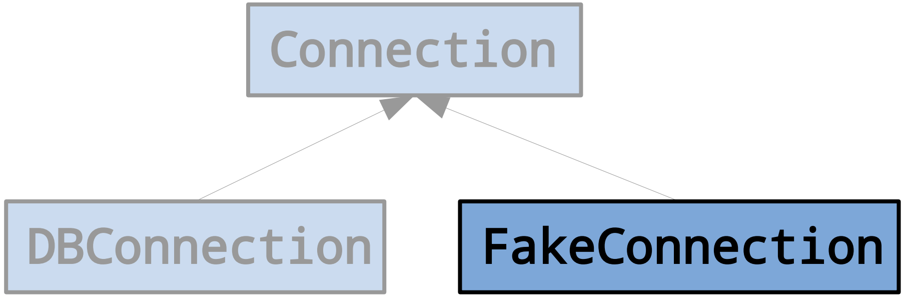

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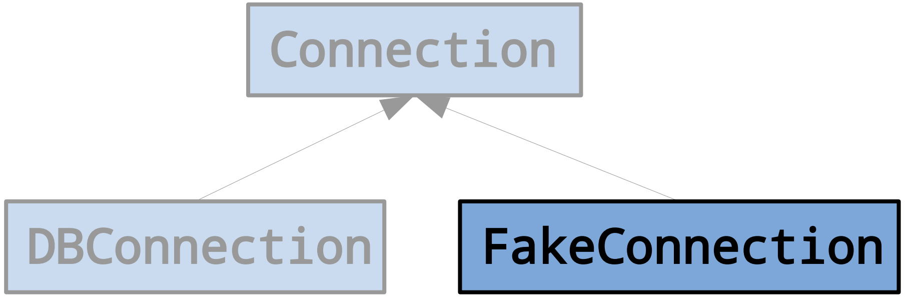


Connection

DBConnection

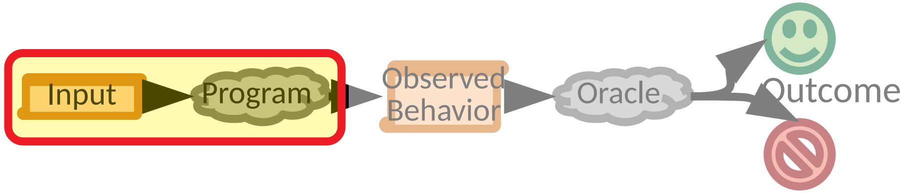
FakeConnection

Mocks & stubs isolate and examine how a component interacts with dependencies

Designing a Unit Test

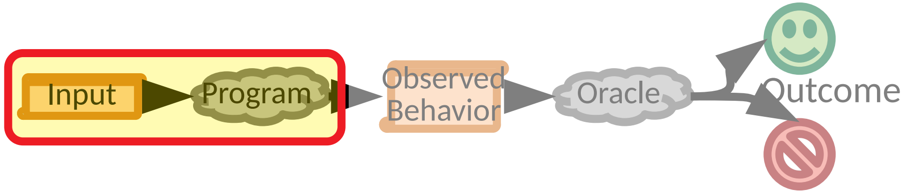
- Common structure
- Tests should run in isolation
- Key problem to resolve:
  - How do you define your inputs & oracles?

Selecting Inputs



- Two broad categories

Selecting Inputs



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  - ***Black box testing*** – treat the program as opaque/unknown

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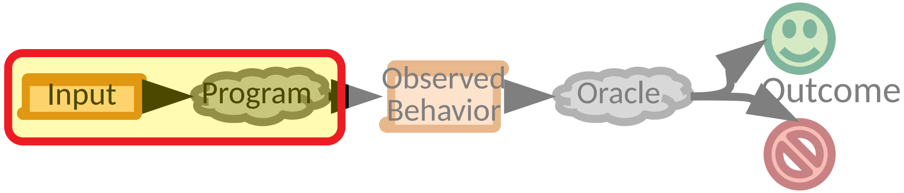

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specification based (BDD?)
model driven
naive fuzzing
boundary value analysis

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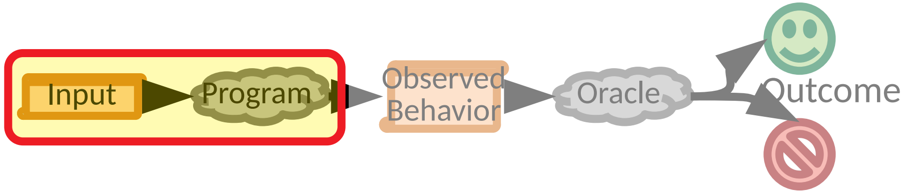

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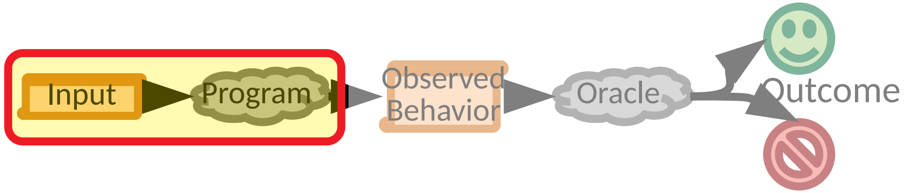

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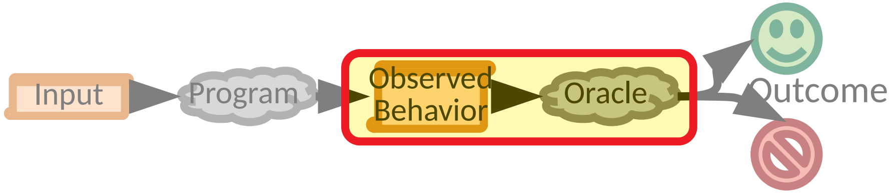
symbolic execution
call chain synthesis
grey/whitebox fuzzing

Designing Oracles



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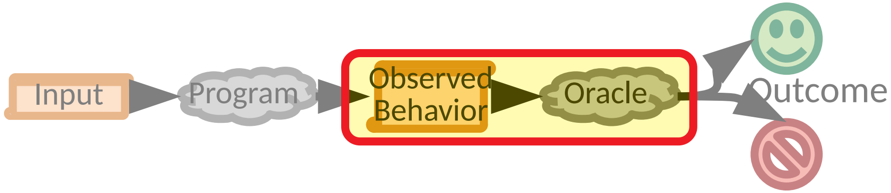
  - For a known scenario, a specific output is expected

Designing Oracles



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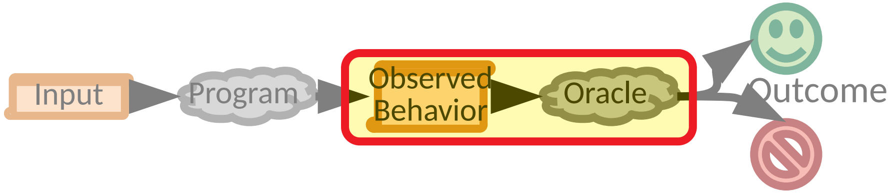
What about tasks like:
machine learning
simulation
…

Designing Oracles



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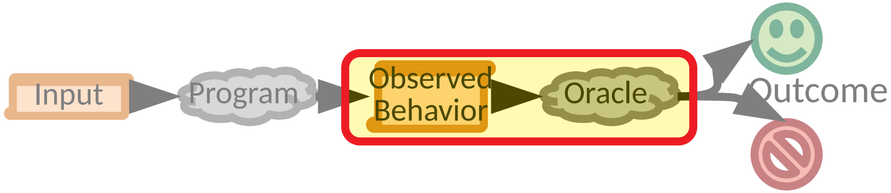

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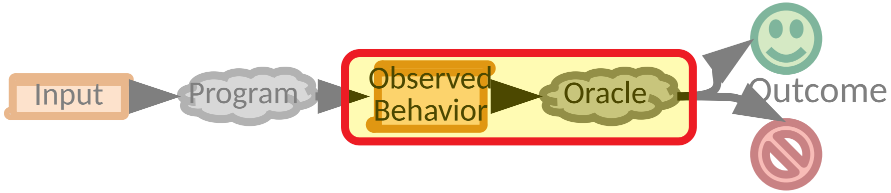

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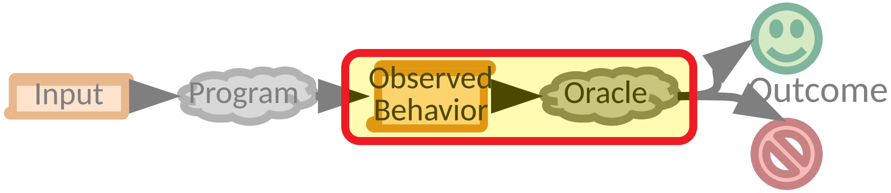

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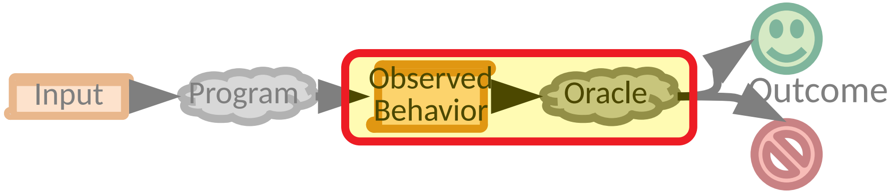
Metamorphic testing

Designing Oracles



- Sometimes it is simple
  - For a known scenario, a specific output is expected
- Invariants & properties are powerful
  - foo^{-1}(foo(x)) == x (e.g. archive & unarchive a file)
  - turn(360, direction) == direction
  - program1(x) == program2(x)

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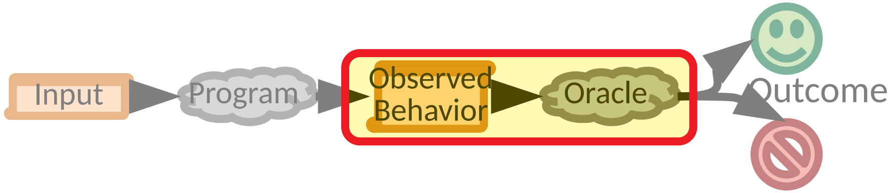

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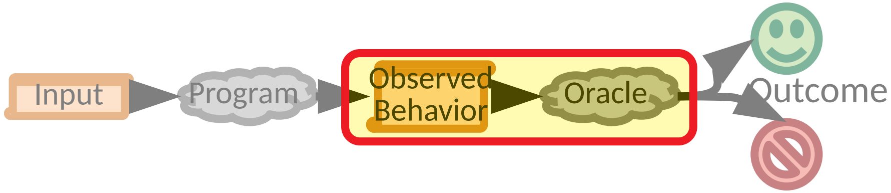
Differential testing



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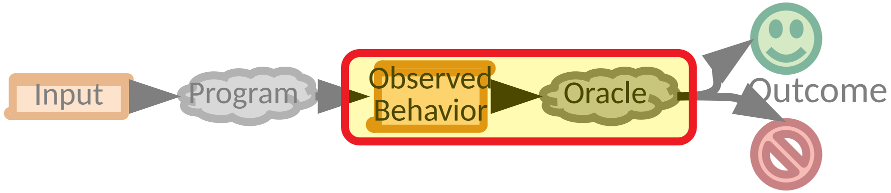
General invariants can be exploited in (semi)automated test generation (e.g. property based)

Designing Oracles



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- Fully automated tests benefit from fully automated oracles
  - But the problem is hard

Test Suite Adequacy

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  - Is a test suite good enough? (Will a higher score mean fewer defects?)

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  - Can we measure how likely a test suite is to measure what we want?
- High level decision making
  - Is a test suite good enough? (Will a higher score mean fewer defects?)
  - What parts of a program should be tested better?

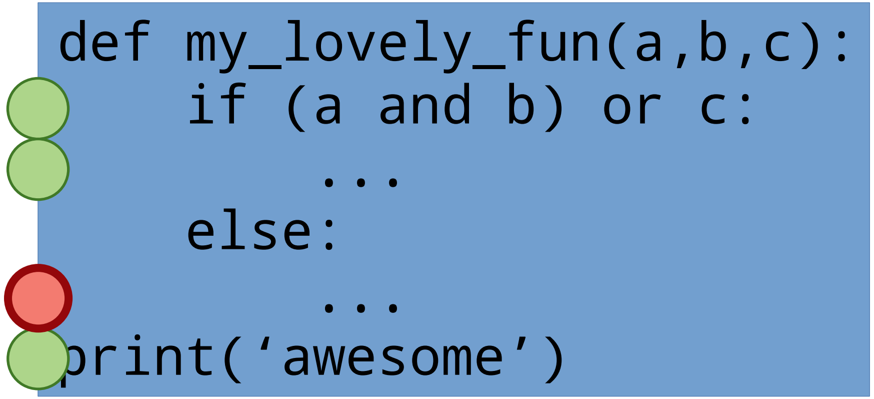
Test Suite Adequacy

- Metrics

Remember: A higher score ***should*** mean fewer defects

Test Suite Adequacy

- Metrics
  - Statement coverage



```
def my_lovely_fun(a,b,c):
    if (a and b) or c:
        ...
    else:
        ...
print('awesome')
```

Is each ***statement covered*** by at least one test in the test suite?

$$\text{score} = \frac{\#\ \text{covered}}{\#\ \text{statements}}$$

Test Suite Adequacy

- Metrics
  - Statement coverage
  - Branch coverage

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def my_lovely_fun(a,b,c):
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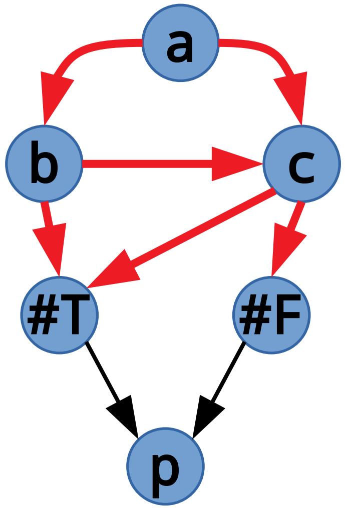
We will discuss
control flow graphs
again soon



$$\text{score} = \frac{\#\ \text{covered}}{\#\ \text{branches}}$$

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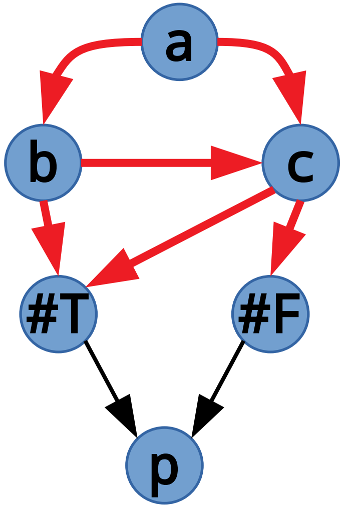

Is each ***branch covered*** by at least one test in the test suite?

$$\text{score} = \frac{\text{\# covered}}{\text{\# branches}}$$

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by at least one test
in the test suite?

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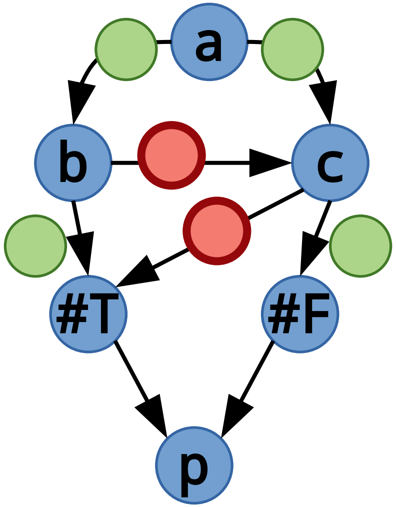

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It is widely agreed that statement/edge coverage are not good *measures*.

But they are *sanity checks*.

Test suite adequacy is complex.
[Groce 2014]

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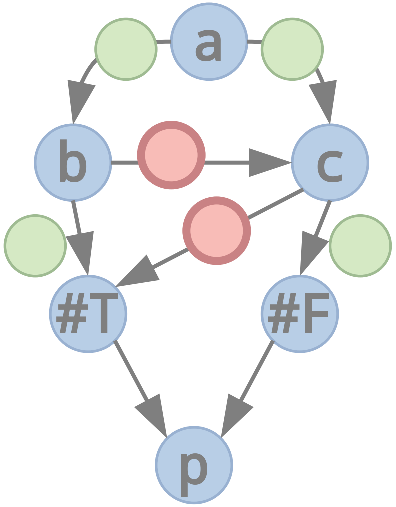

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  - **MC/DC coverage***

Does each ***term determine***
the outcome of at least one condition
in the test suite?

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a=#T	b=#T	c=#F	↦	#T
a=#F	b=#T	c=#F	↦	#F

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a in this condition
is covered by the test suite

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Required by regulation in (e.g.)
avionics, safety critical systems, automotive software

Test Suite Adequacy

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How many ***injected bugs***
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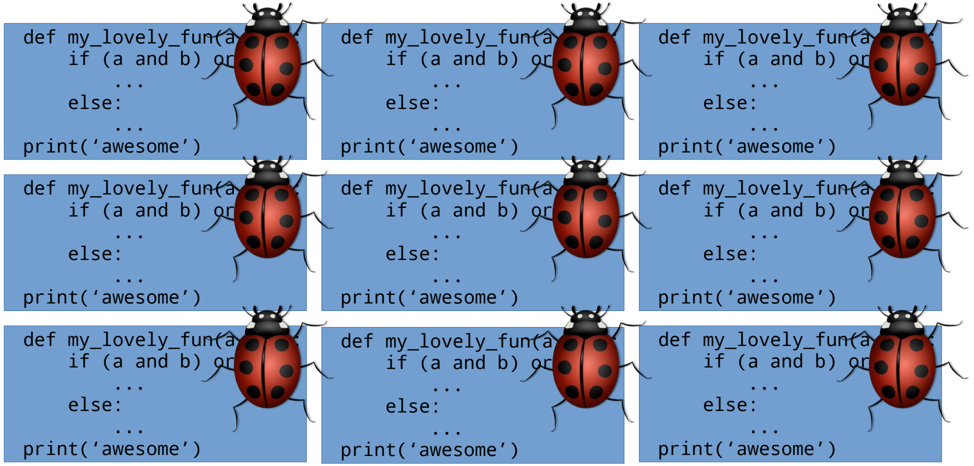

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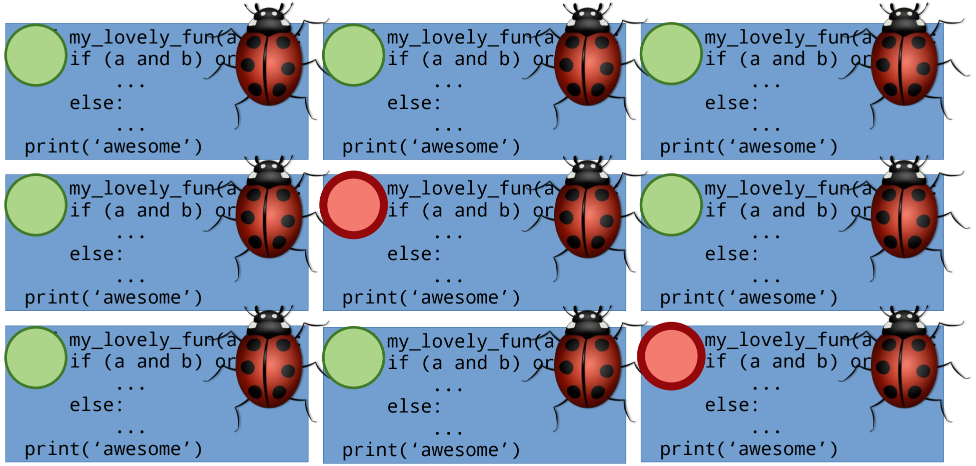

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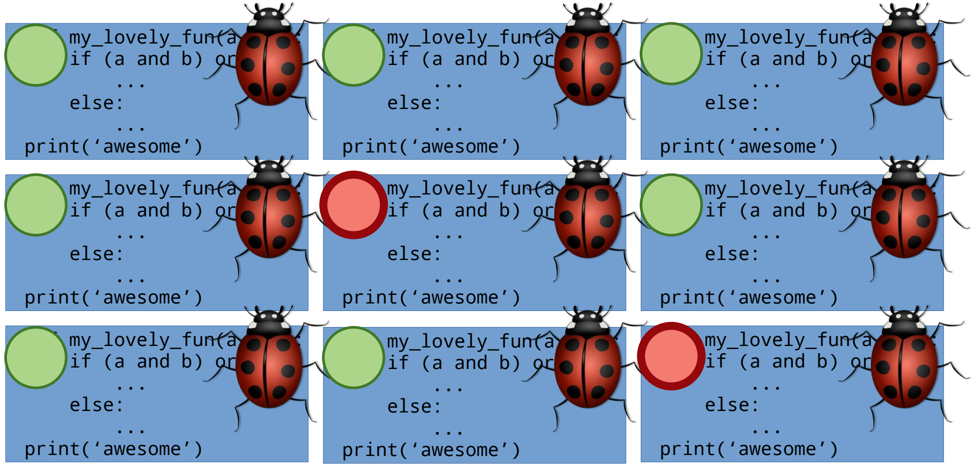
$$\text{score} = \frac{\text{\# covered/killed}}{\text{\# non-equivalent mutants}}$$



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Is each *path covered*
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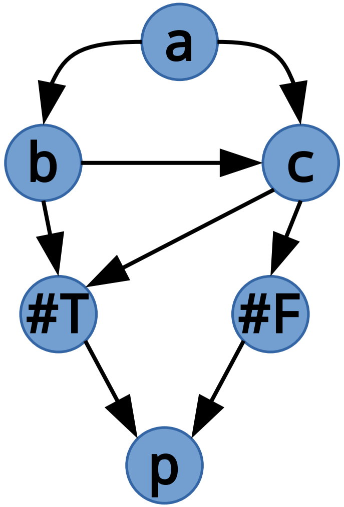

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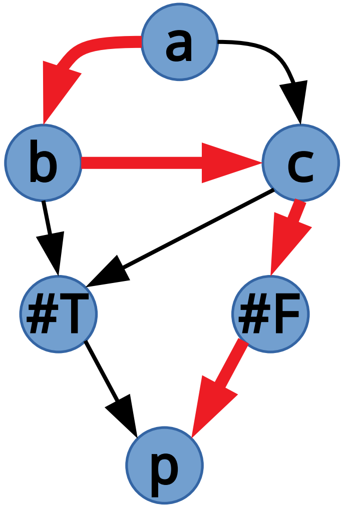
abT
abcT
abcF
acT
acF



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🟢 abT
🔴 abcT
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🟢 acT
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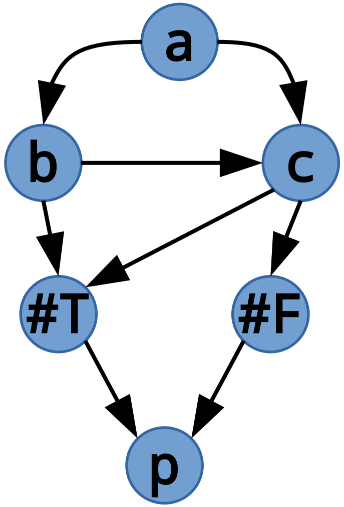

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But shrinking test suites while maintaining St, Br, MC/DC *decreases defect detection*.

There is more going on here.

[Rothermel 1998, Yoo 2012, Shi 2018]

MC/DC Testing

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MC/DC Coverage

- Logic & conditional behaviors are pervasive
- `if` statements are the most frequently fixed statements in bug fixes [Pan, ESE 2008]
- Safety critical systems often involve many complex conditions (avionics, medical, automotive, ...)
- We should place more effort/burden on ensuring correctness of conditions

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if (a | b) & (c | d):
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How does it do in these cases?

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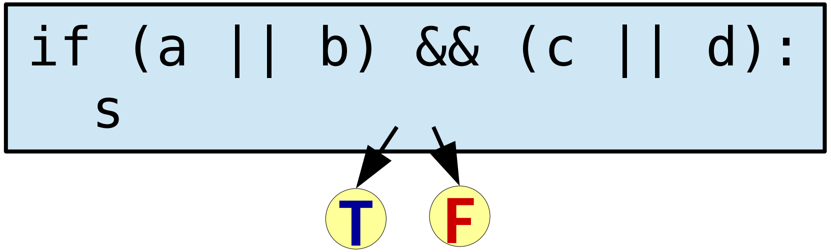

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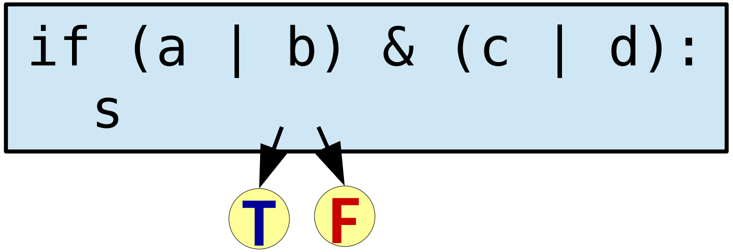

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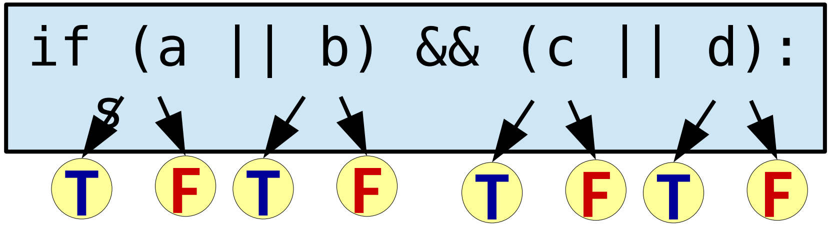

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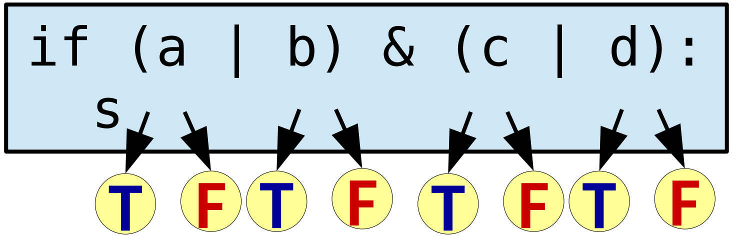

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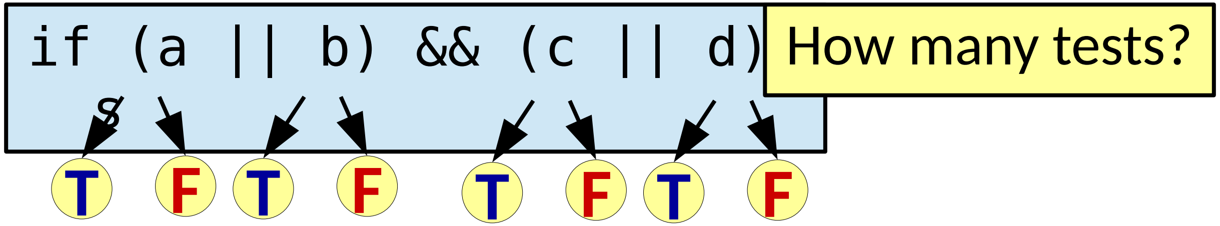

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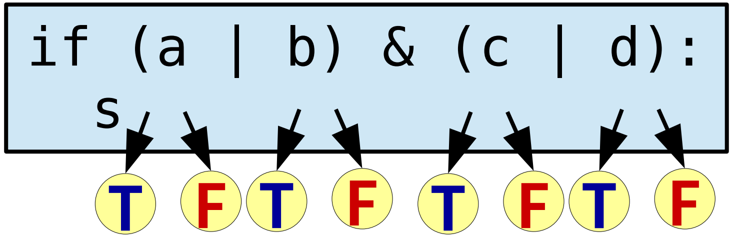

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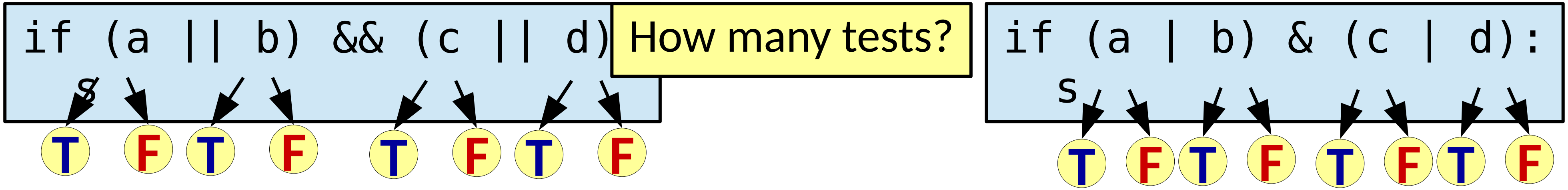

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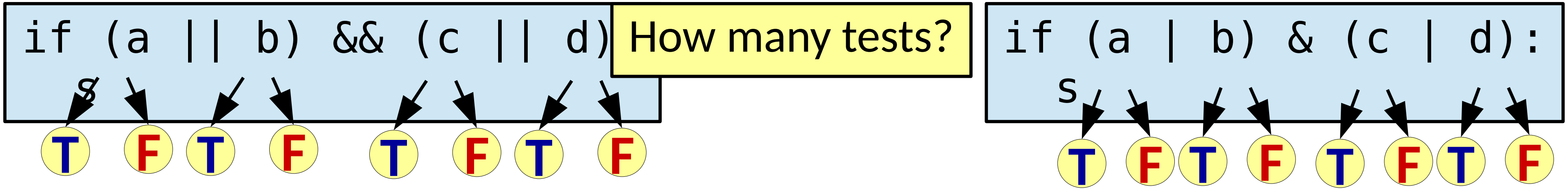

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How many tests?

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Minimum of 2 tests

a=true, b=true, c=false, d=false
a=false, b=false, c=true, d=true

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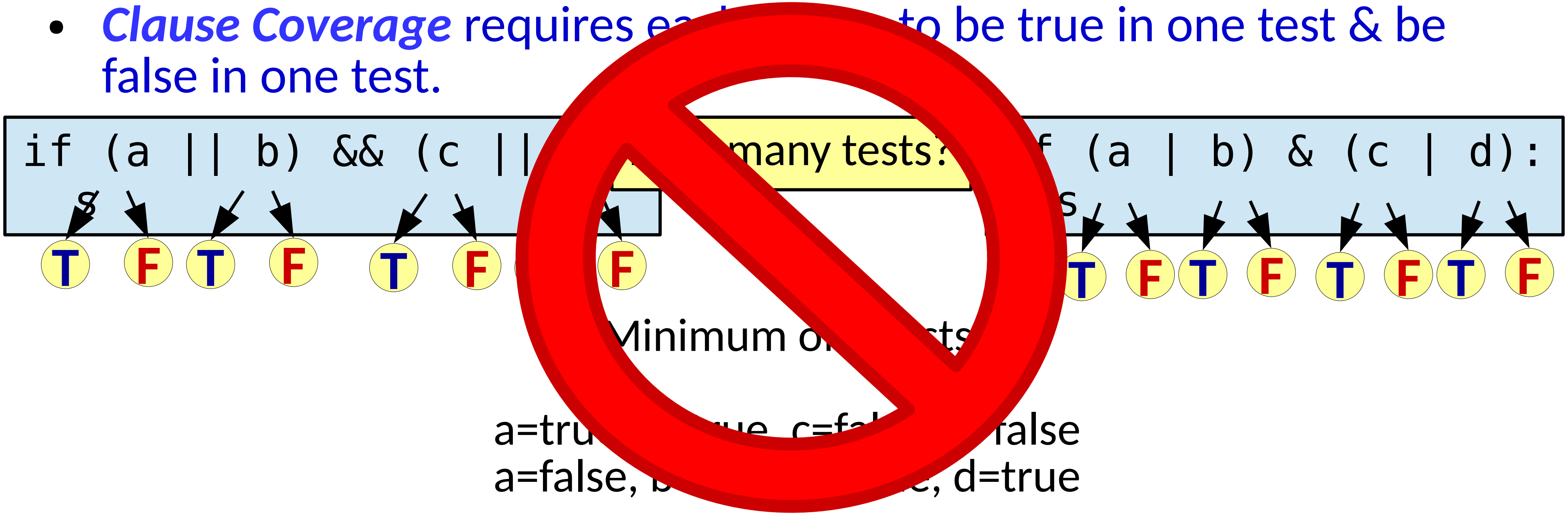

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```

Minimum o ts

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a=false, b e, d=true

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So far, this is clause coverage
w/o that pathological case

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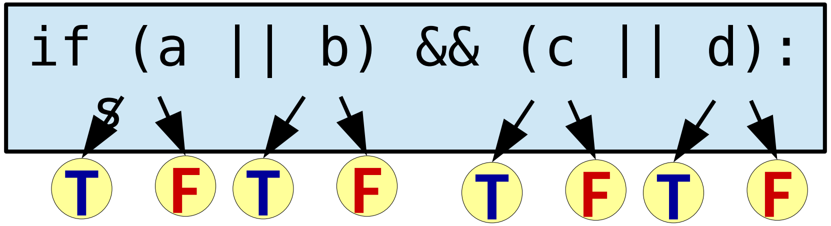

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Minimum of **2** tests

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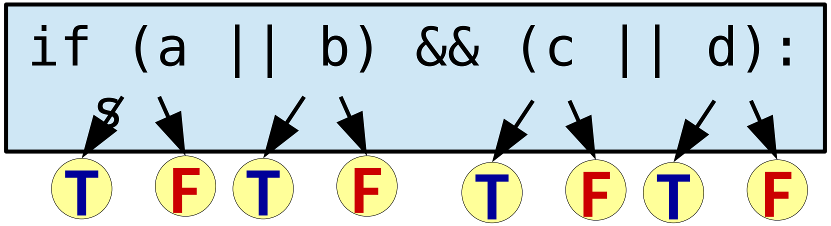

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Is this good?

Minimum of **2** tests

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Intuition:
Make sure that the tests for one clause are not *hidden* by *other* clauses

MC/DC Coverage

- *Modified Condition/Decision Coverage*
  1) Each entry & exit is used
  2) Each decision/branch takes every possible outcome
  3) Each clause takes every possible outcome
  4) Each clause independently impacts the the outcome
- Use in safety critical systems: avionics, spacecraft, …

MC/DC Coverage

- *Modified Condition/Decision Coverage*
  1) Each entry & exit is used
  2) Each decision/branch takes every possible outcome
  3) Each clause takes every possible outcome
  4) Each clause independently impacts the the outcome
- Use in safety critical systems: avionics, spacecraft, …
- Not only ensures that clauses are tested,
  but that each ***has an impact***

MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate

MC/DC Coverage

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```
def my_lovely_fun(a,b,c):
    if (a and b) or c:
        ...
    else:
        ...
print(‘awesome’)
```

a=#T b=#T c=#F ↦ #T

a=#F b=#T c=#F ↦ #F

MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate

$$\varphi(a,b,c) \neq \varphi(a,b,\neg c)$$

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```
(a || b && c)
```

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```
(a || b && c)
```

a=F

b=T

c=T

$$\underline{}$$

T

MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate

$$\varphi(a,b,c) \neq \varphi(a,b,\neg c)$$

```
(a || b && c)
```

a=F	a=F
b=T	b=T
c=T	c=F
T	F

MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate

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MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate

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```
(a || b && c)
```

a=F	a=F
b=T	b=T
c=T	c=F
T	F

This pair of tests shows the impact of `c`.

MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate
- The basic steps come from & and |

MC/DC Coverage

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a & b

If a=True, b determines
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MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate
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a & b
If a=True, b determines
the outcome.

a | b
If a=False, b determines
the outcome.

MC/DC Coverage

- A clause ***determines*** the outcome of a predicate when changing only the value of that clause changes the outcome of the predicate
- The basic steps come from & and |

a & b	a | b
If a=True, b determines the outcome.	If a=False, b determines the outcome.

- By definition, solve $\varphi_{c=true} \oplus \varphi_{c=false}$

MC/DC Coverage

- Given **a | (b & c)**, generate tests for a

a has impact ↔

MC/DC Coverage

- Given **a | (b & c)**, generate tests for a

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defines two different ways to test a

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defines two different ways to test a

Have b be #F

a=#T, b=#F, c=#T
a=#F, b=#F, c=#T

MC/DC Coverage

- Given **a | (b & c)**, generate tests for a

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defines two different ways to test a

Have b be #F

a=#T, b=#F, c=#T
a=#F, b=#F, c=#T

Have c be #F

a=#T, b=#T, c=#F
a=#F, b=#T, c=#F

MC/DC Coverage

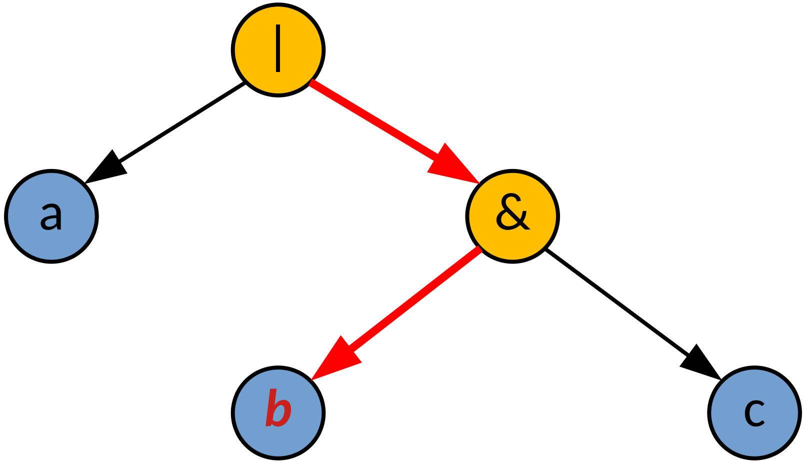
- Given **a | (b & c)**, generate tests for ***b***

  b has impact

MC/DC Coverage

- Given **a | (b & c)**, generate tests for ***b***

    b has impact



MC/DC Coverage

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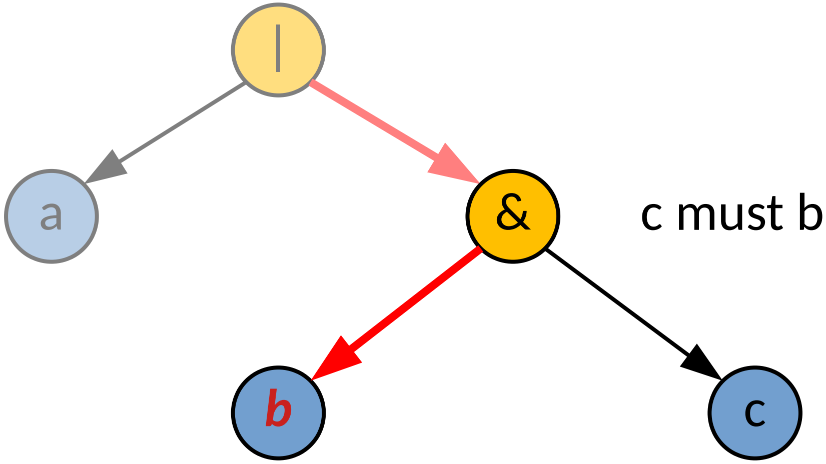


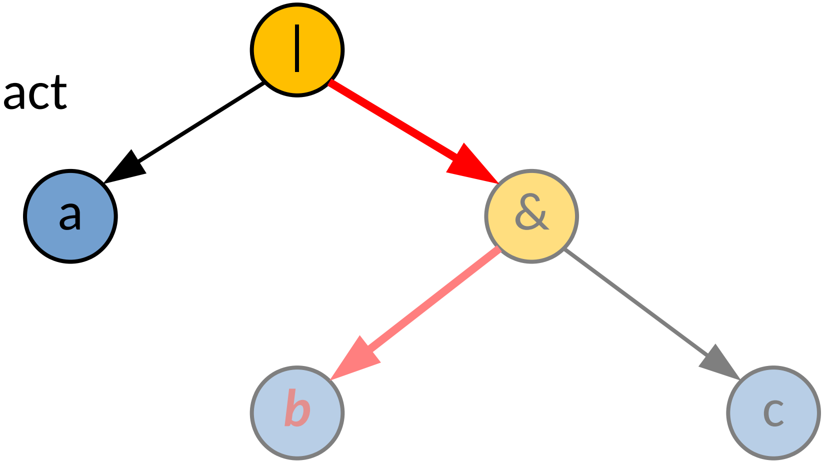
c must be true for impact

MC/DC Coverage

- Given **a | (b & c)**, generate tests for ***b***

b has impact

a must be false for impact



MC/DC Coverage

- Given **a | (b & c)**, generate tests for ***b***

b has impact ↔ a = #F & c = #T

MC/DC Coverage

- What about (a & b) | (a & ¬b)?
  - Can you show the impact of a?

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Lack of MC/DC coverage can also identify bugs.

MC/DC Coverage

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- BUT NASA recommended *not generating* MC/DC coverage.
  - Use MC/DC as a means of *evaluating* test suites generated by other means

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  - If you refactor the code, why does the coverage change?

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  - Use MC/DC as a means of *evaluating* test suites generated by other means
- In practice there are many pitfalls for getting value out of it
  - If you refactor the code, why does the coverage change?
  - How do you deal with short-circuiting operators?
  - …

Mutation Testing

Mutation Analysis

- Instead of covering program elements,
  estimate defect finding on a sample of representative bugs

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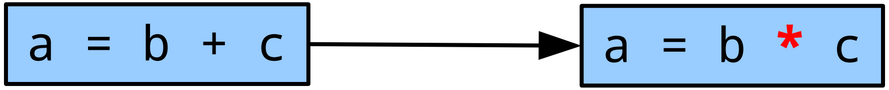

```
a = b + c
```

```
a = b * c
```

Mutation Analysis

- Instead of covering program elements,
  estimate defect finding on a sample of representative bugs
- Mutant
  - A valid program that behaves differently than the original
  - Consider small, local changes to programs
  - A test ***t*** kills a mutant ***m*** if ***t*** produces a different outcome on ***m*** than ***the original program***

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What does this mean?

Mutation Analysis

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- Systematically generate mutants separately from original program

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- The goal is to:
  - ***Mutation Analysis*** – Measure bug finding ability
  - ***Mutation Testing*** – create a test suite that kills a representative set of mutants

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- The goal is to:
  - ***Mutation Analysis*** – Measure bug finding ability
  - ***Mutation Testing*** – create a test suite that kills a representative set of mutants

Depending on the source, these may swap…

Mutation

- What are possible mutants?

```
int foo(int x, int y) {
  if (x > 5) {return x + y;}
  else {return x;}
}
```

Mutation

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- Once we have a test case that *kills* a mutant, the mutant itself is no longer useful.

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- Some are not generally useful:
  - (*Still Born*) Not compilable
  - (*Trivial*) Killed by most test cases
  - (*Equivalent*) Indistinguishable from original program
  - (*Redundant*) Indistinguishable from other mutants

Mutation

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```
int foo(int x, int y) {
  if (x > 5) {return x + y;}
  else {return x;}
}
```

- Once we have a test case that kills a mutant, the mutant itself is no longer useful.

- Some are not generally useful:
  - (*Still Born*) Not compilable
  - *Trivial*
  - *Equivalent*
  - *Redundant*

Filtering these out is *theoretically* impossible, yet it is an important & active area of research.

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

```
int min(int a, int b) {
  int minVal;
  minVal = a;

  if (b < a) {


    minVal = b;



  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

```
int min(int a, int b) {
  int minVal;
  minVal = a;
Mutant 1: minVal = b;
  if (b < a) {


    minVal = b;




  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

```
int min(int a, int b) {
  int minVal;
  minVal = a;
Mutant 1:  minVal = b;
  if (b < a) {
Mutant 2:  if (b > a) {

    minVal = b;




  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

```
      int min(int a, int b) {
        int minVal;
        minVal = a;
Mutant 1:  minVal = b;
        if (b < a) {
Mutant 2:  if (b > a) {
Mutant 3:  if (b < minVal) {
          minVal = b;



        }
        return minVal;
      }
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

```
int min(int a, int b) {
  int minVal;
  minVal = a;
Mutant 1:  minVal = b;
  if (b < a) {
Mutant 2:  if (b > a) {
Mutant 3:  if (b < minVal) {
    minVal = b;
Mutant 4:    BOMB();


  }
  return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

```
            int min(int a, int b) {
              int minVal;
              minVal = a;
Mutant 1:     minVal = b;
              if (b < a) {
Mutant 2:     if (b > a) {
Mutant 3:     if (b < minVal) {
                minVal = b;
Mutant 4:       BOMB();
Mutant 5:       minVal = a;

              }
              return minVal;
            }
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
   int minVal;
   minVal = a;
   if (b < a) {
      minVal = b;
   }
   return minVal;
}
```

```
int min(int a, int b) {
   int minVal;
   minVal = a;
Mutant 1:  minVal = b;
   if (b < a) {
Mutant 2:  if (b > a) {
Mutant 3:  if (b < minVal) {
      minVal = b;
Mutant 4:     BOMB();
Mutant 5:     minVal = a;
Mutant 6:     minVal = failOnZero(b);
   }
   return minVal;
}
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation

```
int min(int a, int b) {
  int minVal;
  minVal = a;
  if (b < a) {
    minVal = b;
  }
  return minVal;
}
```

What mimics statement coverage?

```
           int min(int a, int b) {
             int minVal;
             minVal = a;
Mutant 1:    minVal = b;
             if (b < a) {
Mutant 2:    if (b > a) {
Mutant 3:    if (b < minVal) {
               minVal = b;
Mutant 4:      BOMB();
Mutant 5:      minVal = a;
Mutant 6:      minVal = failOnZero(b);
             }
             return minVal;
           }
```

- Mimic mistakes
- Encode knowledge from other techniques

Mutation Analysis

Mutants

```
Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6
```

Mutation Analysis

Mutants

```
Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6
```

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Mutation Analysis

Mutants

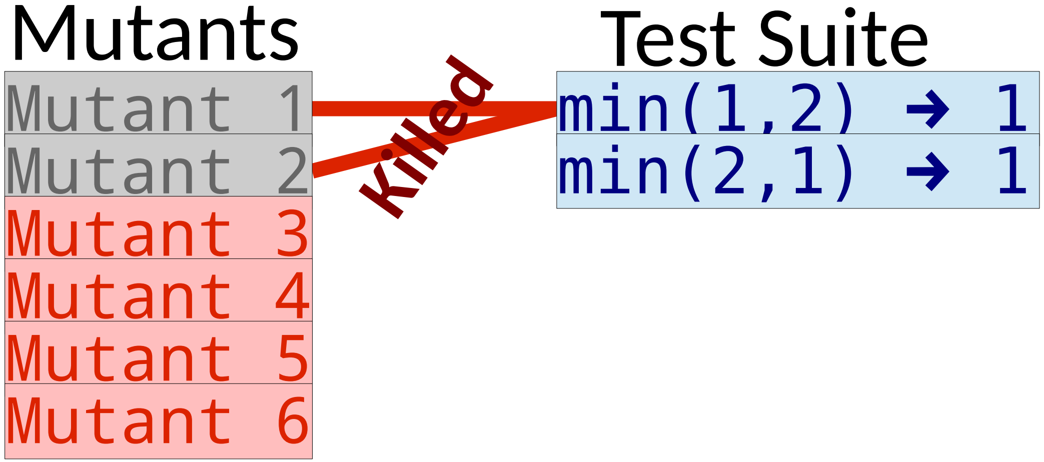
```
Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6
```

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Try every mutant on test 1.

Mutation Analysis



Mutants

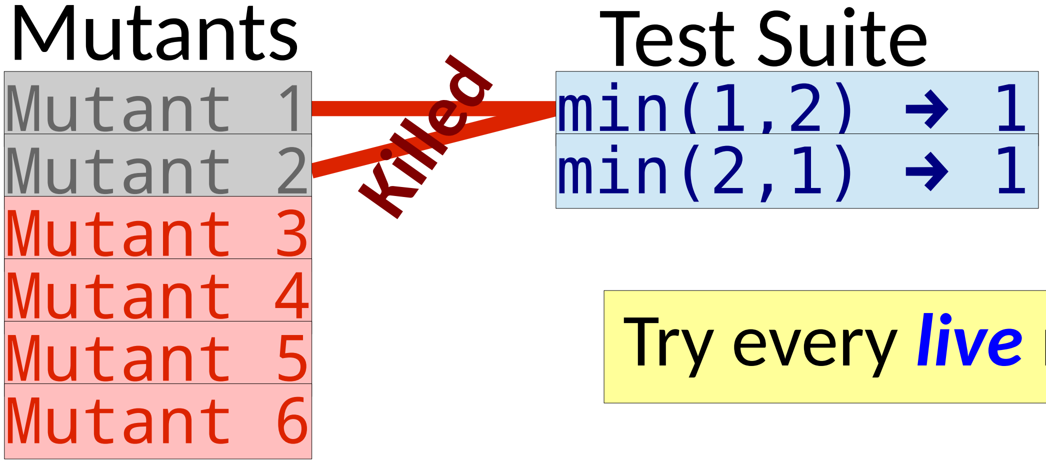
Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6

Killed

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Mutation Analysis



Mutants

```
Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6
```

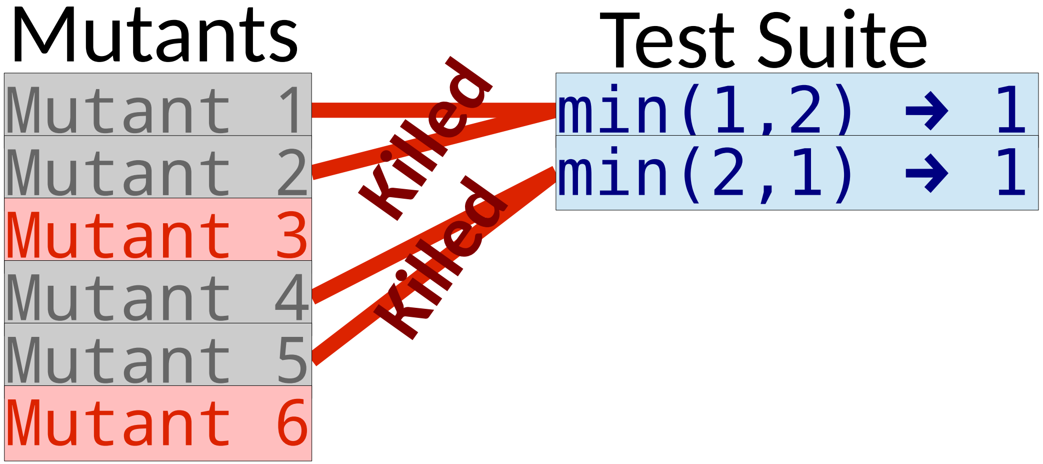
Killed

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Try every ***live*** mutant on test 2.

Mutation Analysis



Mutants

Mutant 1

Mutant 2

Mutant 3

Mutant 4

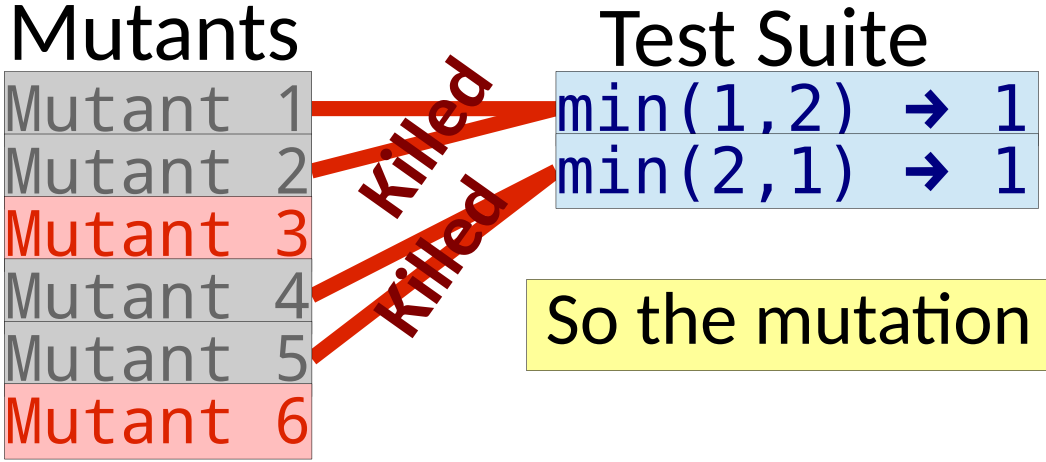
Mutant 5

Mutant 6

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

Mutation Analysis



Mutants

```
Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6
```

Killed

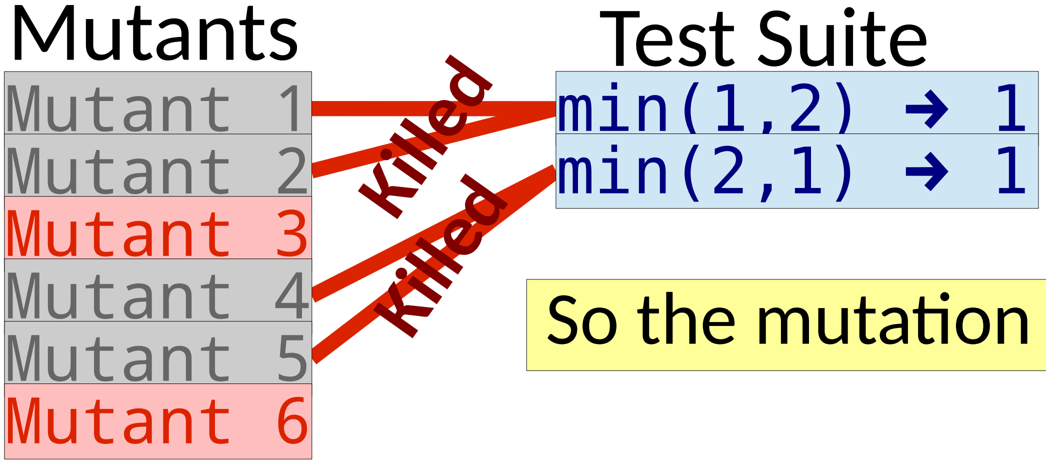
Killed

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

So the mutation score is…

Mutation Analysis



Mutants

Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6

Killed

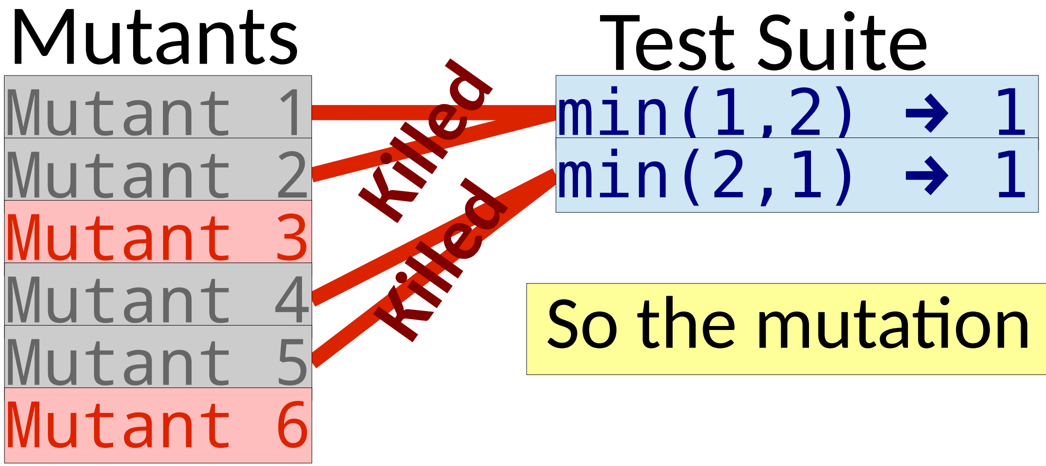
Killed

Test Suite

```
min(1,2) → 1
min(2,1) → 1
```

So the mutation score is... **4/5**. *Why?*

Mutation Analysis



Mutants

Mutant 1
Mutant 2
Mutant 3
Mutant 4
Mutant 5
Mutant 6

Killed

Killed

Test Suite

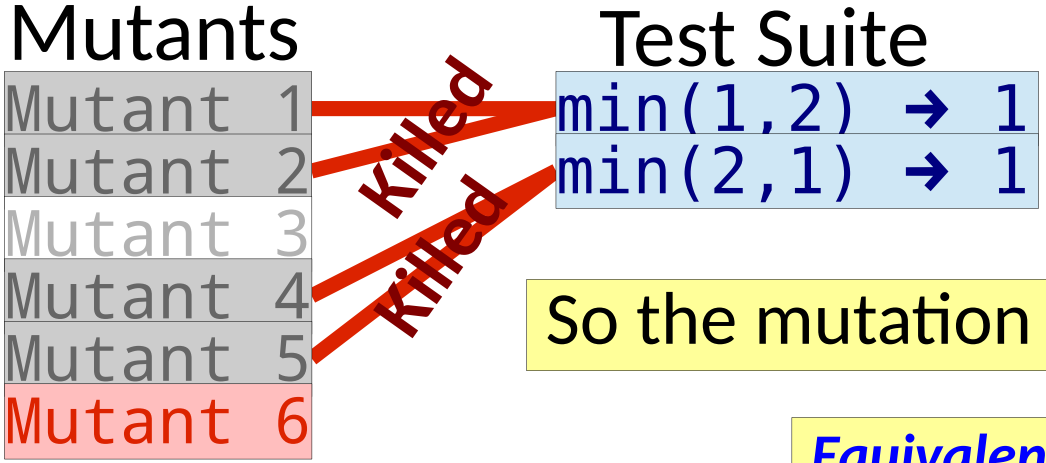
min(1,2) → 1
min(2,1) → 1

So the mutation score is... **4/5**. *Why?*

```
min3(int a, int b):
   int minVal;
   minVal = a;
   if (b < minVal)
     minVal = b;
   return minVal;
```

```
min6(int a, int b):
   int minVal;
   minVal = a;
   if (b < a)
     minVal = failOnZero(b);
   return minVal;
```

Mutation Analysis



Mutants

Mutant 1

Mutant 2

Mutant 3

Mutant 4

Mutant 5

Mutant 6

Test Suite

min(1,2) → 1

min(2,1) → 1

So the mutation score is… **4/5**. *Why?*

```
min3(int a, int b):
  int minVal;
  minVal = a;
  if (b < minVal)
    minVal = b;
  return minVal;
```

Equivalent to the original!
There is no injected bug.

```
  int minVal;
  minVal = a;
  if (b < a)
    minVal = failOnZero(b);
  return minVal;
```

Equivalent Mutants

- Equivalent mutants are not bugs and should not be counted

Equivalent Mutants

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- New Mutation Score:

Equivalent Mutants

- Equivalent mutants are not bugs and should not be counted
- New Mutation Score:

$$\frac{\#Killed}{\#Mutants}$$

Start with the simplest score from *fault seeding*

Equivalent Mutants

- Equivalent mutants are not bugs and should not be counted
- New Mutation Score:

$$\frac{\#\text{Killed}}{\#\text{Mutants} - \#\text{Equivalent}}$$

Traditional mutation score from literature

Equivalent Mutants

- Equivalent mutants are not bugs and should not be counted
- New Mutation Score:

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Updated for handling of duplicate & equivalent mutants

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- So why are they equivalent?

Reachability **I**nfection **P**ropagation

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```
min3(int a, int b):
  int minVal;
  minVal = a;
  if (b < minVal)
    minVal = b;
  return minVal;
```

Requires reasoning about why the result was the same.

Mutation Operators

- Are the mutants representative of all bugs?
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Ideas? Why? Why not?

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Ideas? Why? Why not?

2 Key ideas are missing....

Competent Programmer *Hypothesis*

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- So *most* of the time simple mutations should reflect the real bugs.

Coupling Effect

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  - By casting a fine enough net, we'll catch the big fish, too (sorry dolphins)

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  - Better abstractions (source level, IR level, complex faults) [Hariri 2019, Wong 2020]
  - Better execution strategies (distributed, parallel, maximizing 1 run info) [Tokumoto 2016, Gopinath 2016, Just 2014]

Mutation Testing

- How is it *currently* used in practice?
  - Google can integrate results into the code review workflow [Petrovic 2018]
  - Facebook can use ML to guide the mutant process but not widely [Beller 2021]
  - Mutant sampling is still prevalent despite shortcomings [Petrovic 2018]
  - Tools are available across languages, but data for smaller firms is challenging

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What if you change |T|?

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So is that it?
Can we just do mutation
testing & be done?

Regression Testing

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- Regression tests further enable making changes

Why Use Regression Testing

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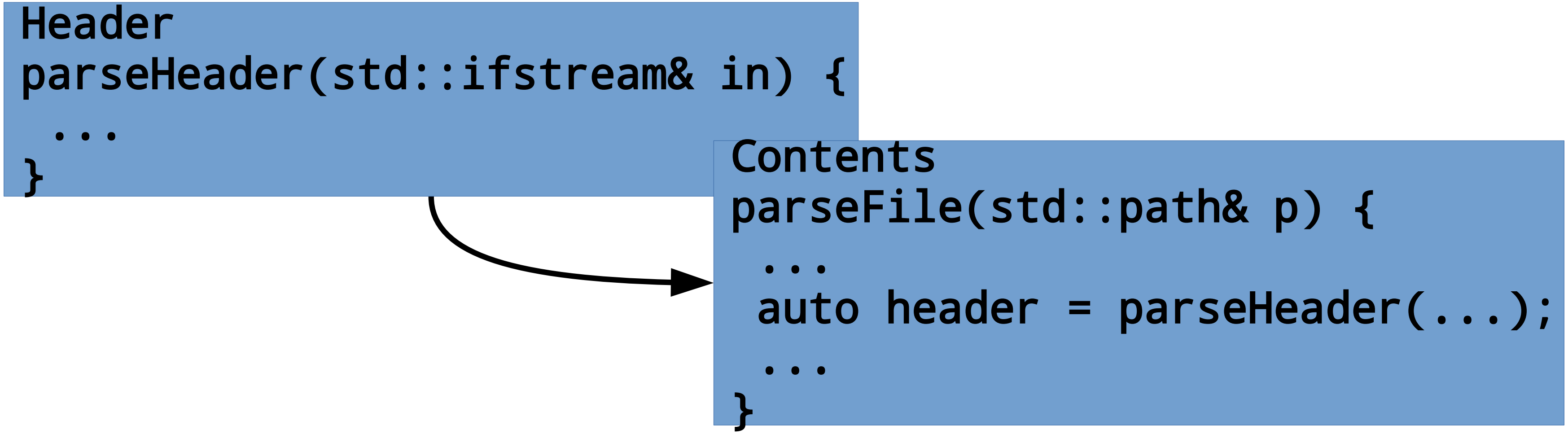

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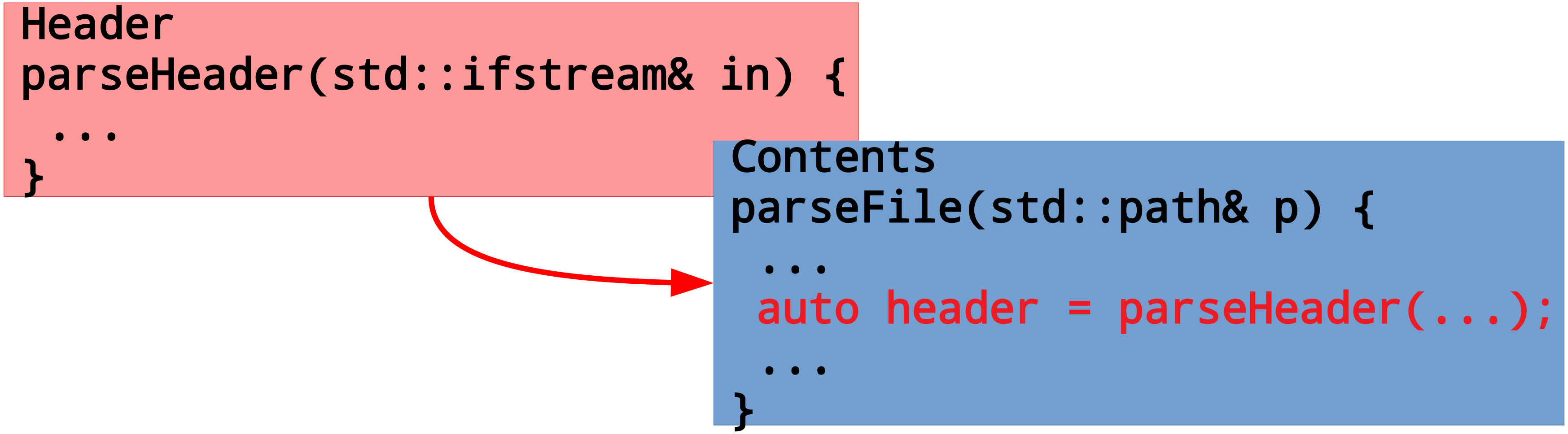

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  - New environments can introduce unexpected behavior in components that originally work.
- **Most testing is regression testing**
- Ensuring previous functionality can require large test suites.
  Are they always realistic?

Limiting Regression Suites

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But this is more or less where we started…

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These mostly validate the build process & core behaviors.

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- We may further reduce work using information about the change….

Limiting Regression Testing

- Can we be smarter about which test we run & when?

What else could we do?

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  - Identify *how* changes affect the rest of software

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Is the cheap approach *enough*?

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In practice, tools can assist in finding out which tests need to be run

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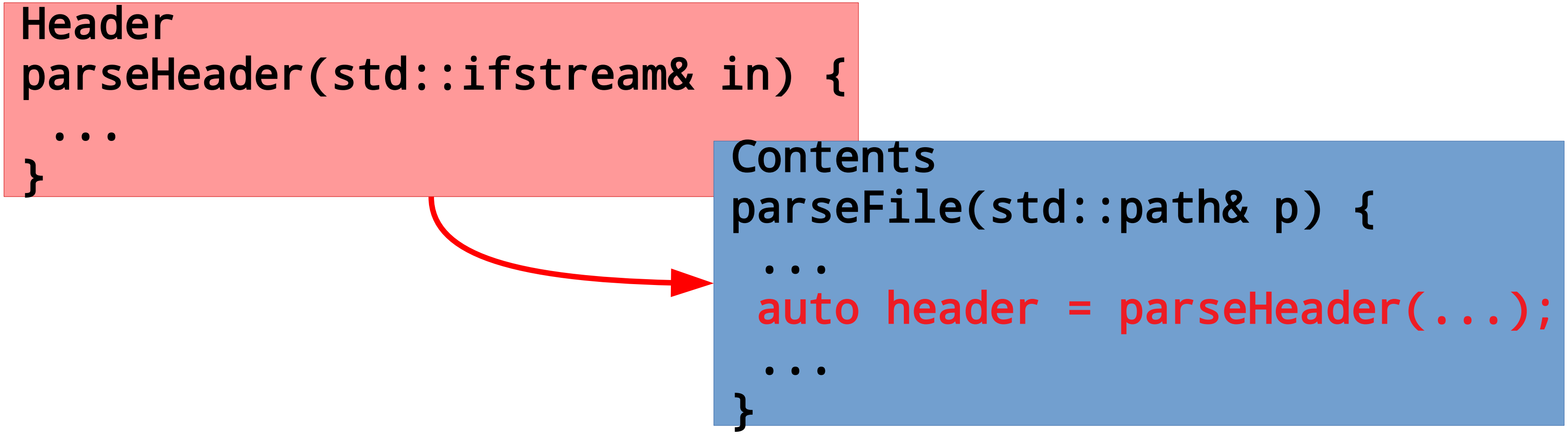

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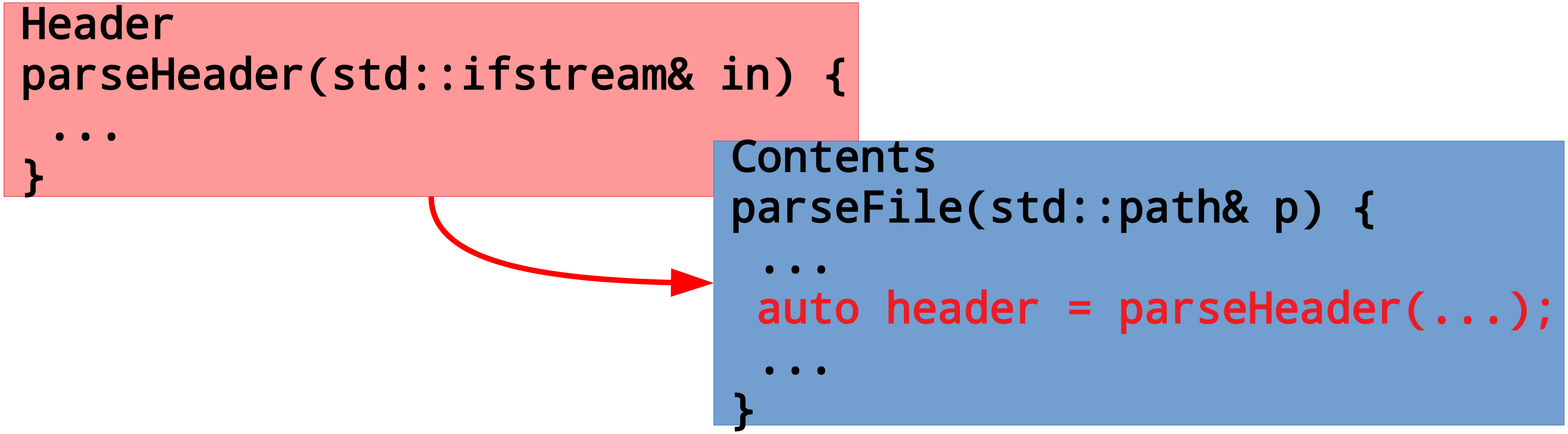

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```
void
foo() {
  ...
  out = fopen(“channel.txt”,”w”);
  fwrite(out, ...);
}
```

```
void
bar() {
 ...
 in = fopen(“channel.txt”, “r”);
 fread(in, ...);
}
```

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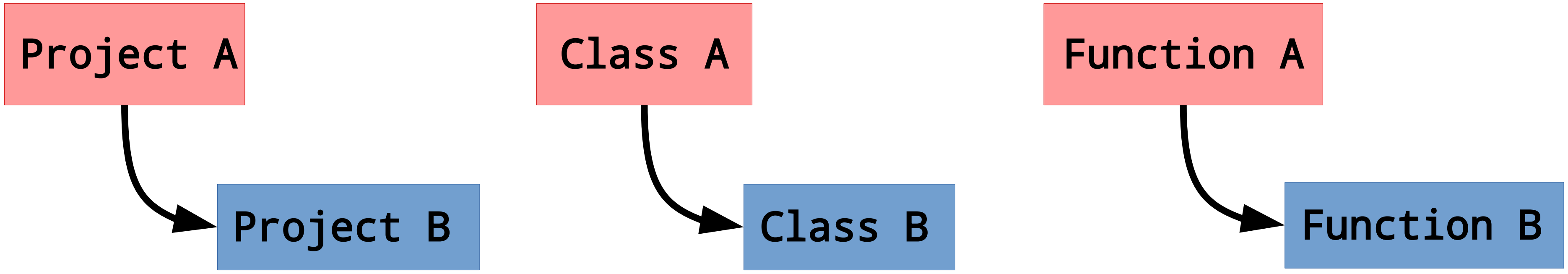

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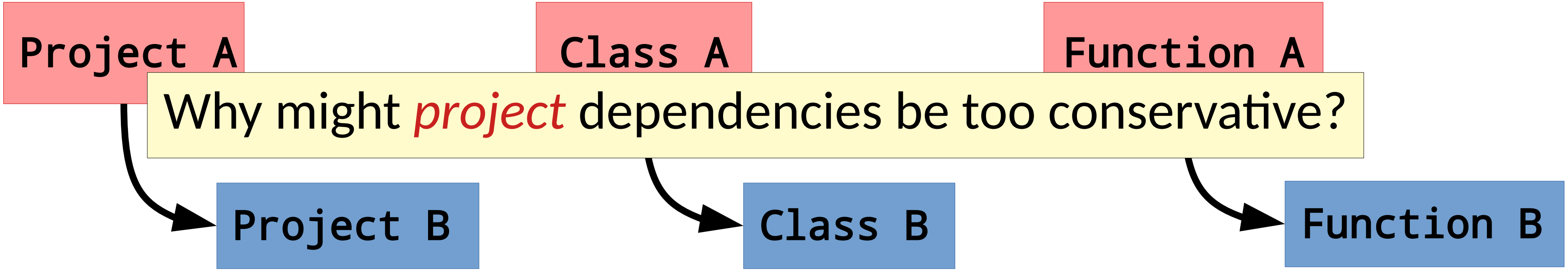

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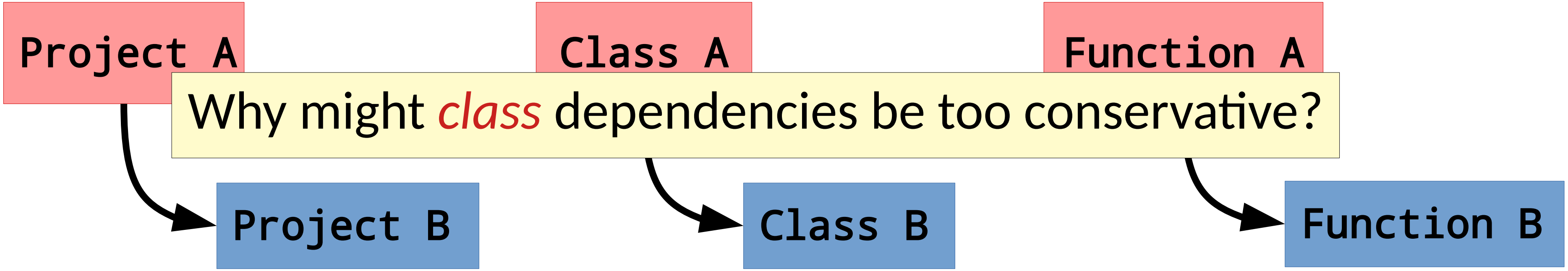

Why might *class* dependencies be too conservative?

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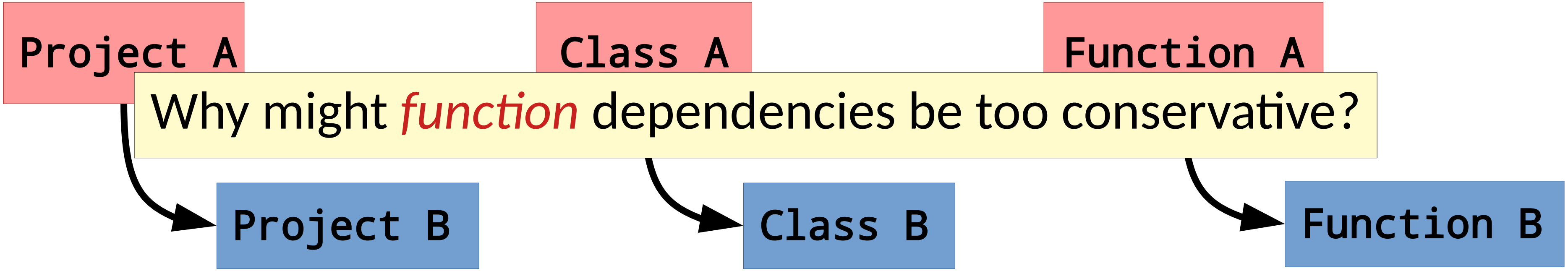

Why might *function* dependencies be too conservative?

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- We will discuss the techniques underneath this as
  static & dynamic program analysis

Additional Strategies for Speeding Up Testing

- Test Case Prioritization
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- Bug Prediction
  - Can we mine properties of a repository to predict where bugs will likely be?
  - Evidence indicated a mismatch between techniques & outcomes [Lewis 2013]
  - But advances are ongoing [Nam 2017]

Using Test Suites
For Other Purposes

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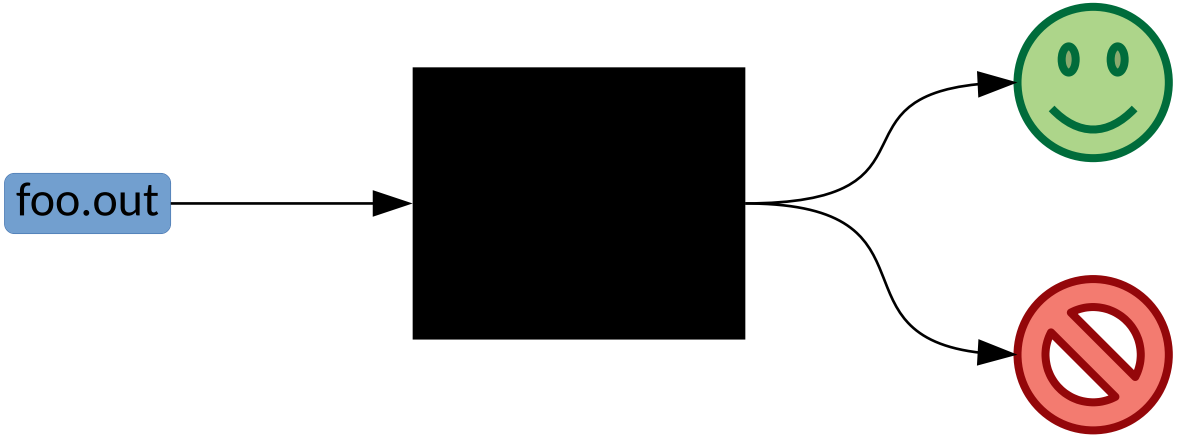

Is foo.out correct?

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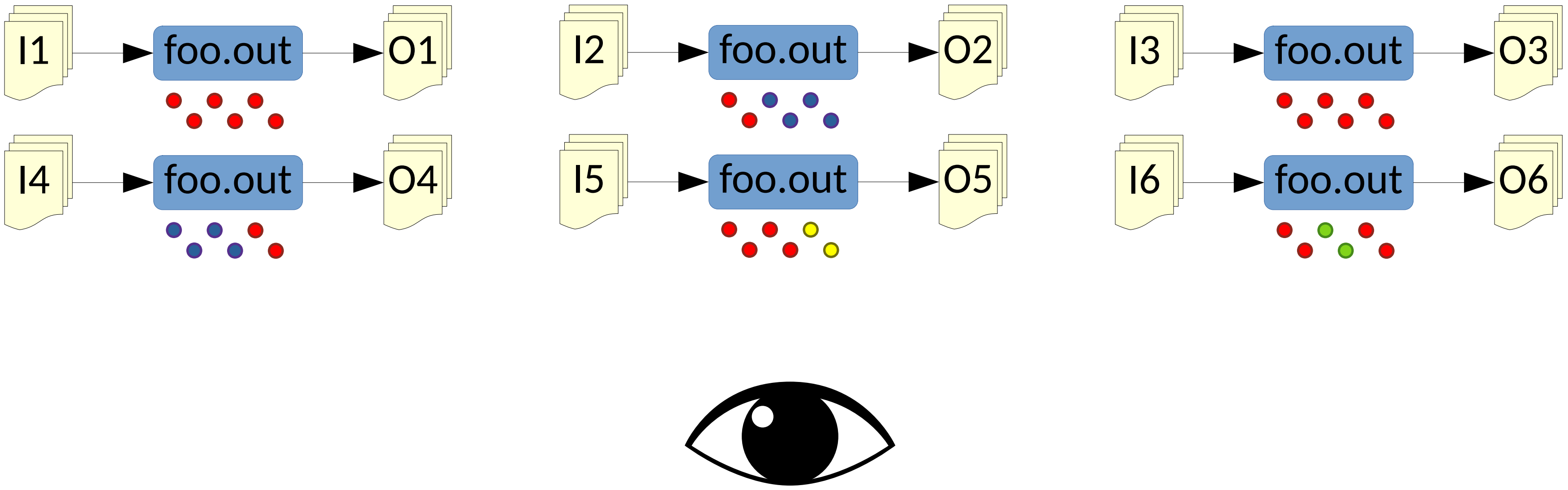
  - Observable information about *program behavior during tests*



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- Interesting questions:
  - What occurs in tests that pass?
  - What occurs in tests that fail?
  - Can I search for X that is part of a correct program?
  - Can I search for X that is part of a buggy program?
  - …

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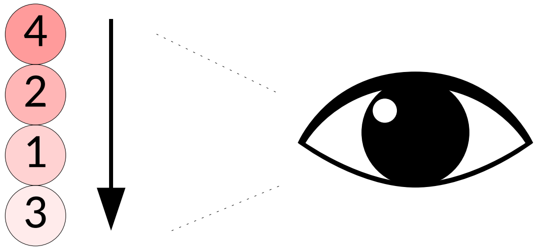

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  - Failing tests $f \subset \{t_i\}$
  - Observable criteria $c(t_i) = c_i$
- Produce
  - A ranked list of locations $[l_i]$ for a developer to consider
- Measures
  - Top-1 is ideal. Outside of Top-10 is not useful for *manual* analysis.

Fault Localization

- Suppose that a bug at a statement causes some tests to fail
  - The test suite embeds information that can aid our search for the bug
  - ***Fault localization*** ranks the locations in a program to consider
- Given
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  - Failing tests f ⊂{ti}
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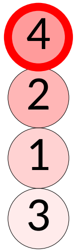

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- A lot of classic techniques focus on, e.g., statement coverage

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  x = a + b
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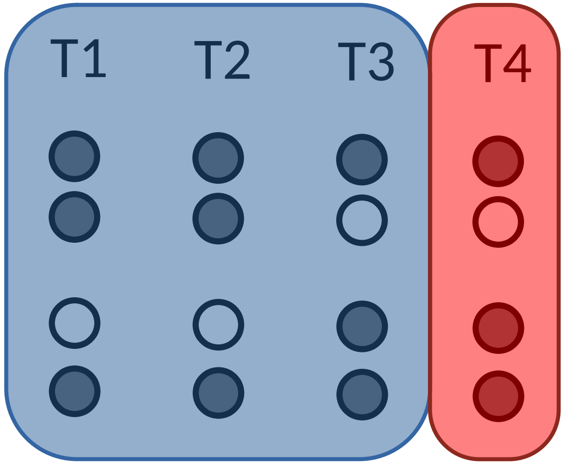

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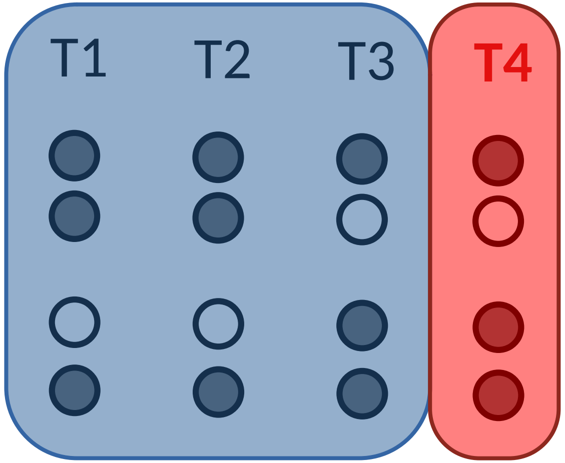

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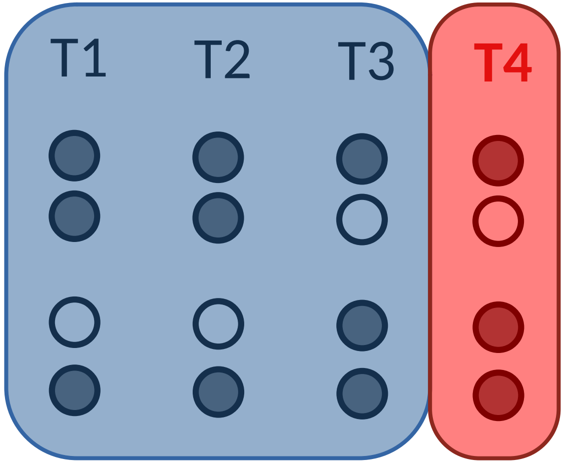

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  - Statistical [Landberg 2018]
  - ML based [Li 2019]
  - Hybrid models [Zou 2019]
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- Perhaps we can push this further….

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```
loop:
  patch = generatePatch()
  if apply(patch,P) passes T:
    return patch
```

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- For a given possibly buggy location
  - Enumerative search
  - Constraint guided search
  - ML (e.g. sequence-to-sequence)

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- But… it is now a part of the possible workflow at big companies
  - Google
  - Microsoft
  - Facebook
  - Bloomberg
  - Samsung
  - …

Testing Challenging Software

Revisiting the Oracle Problem

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How would you test software for modeling Covid-19?

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  - A test suite is unlikely to expose specific pathological combinations.
- We again need additional leverage
  - Additional implementations?
  - Knowledge about the domain

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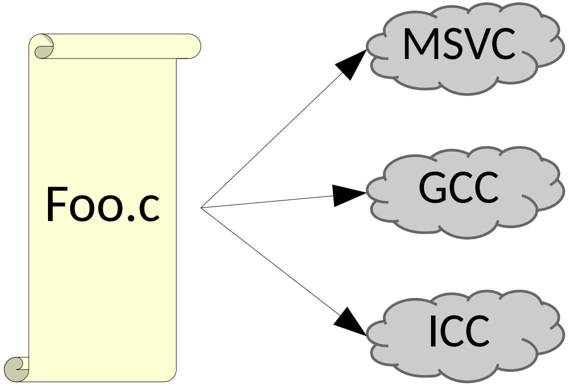

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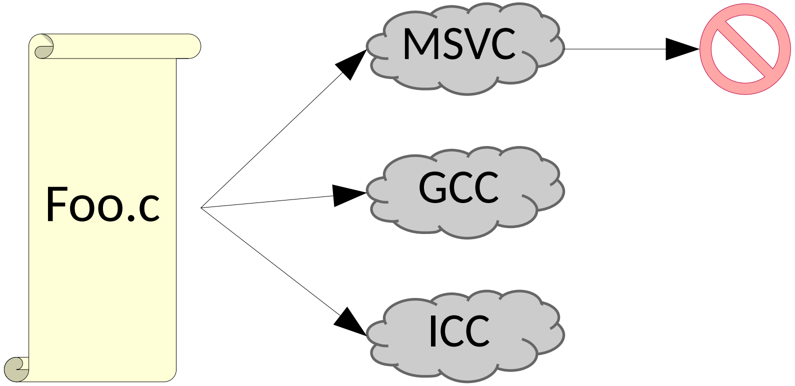

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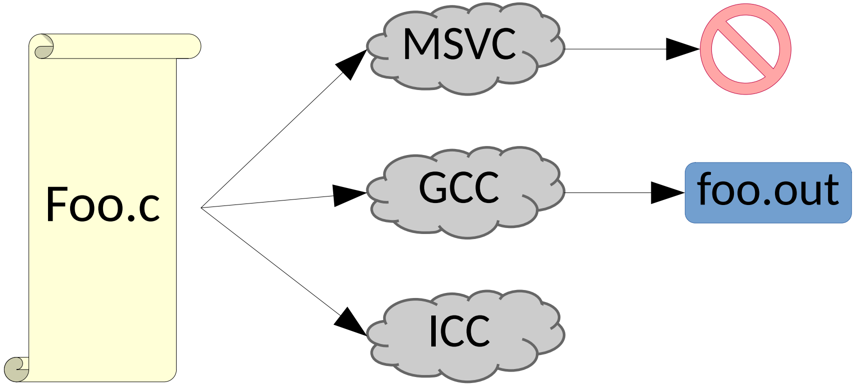

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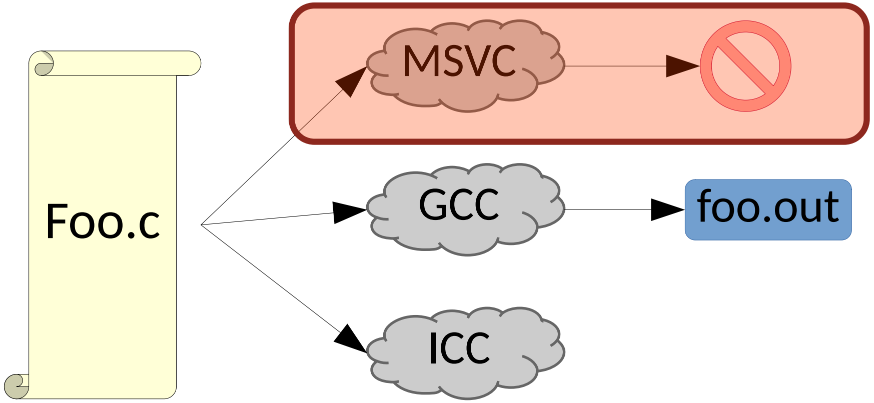

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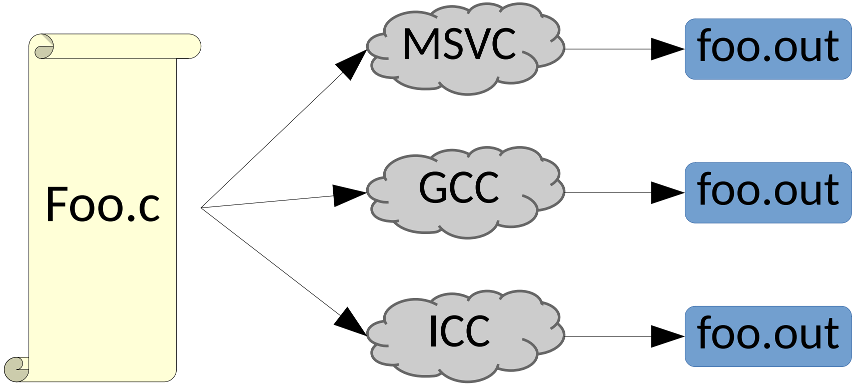

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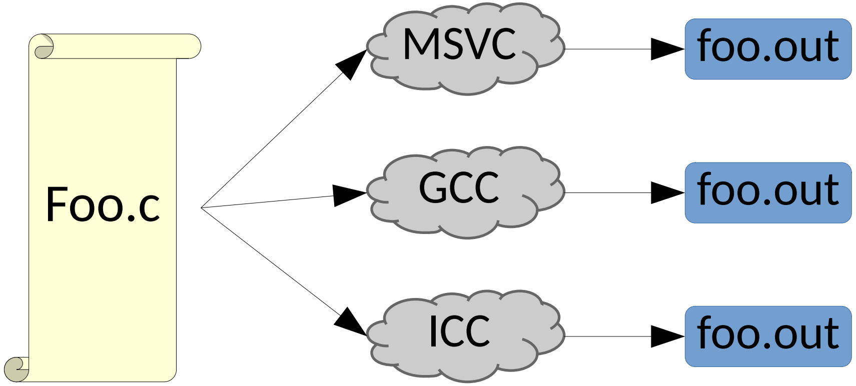

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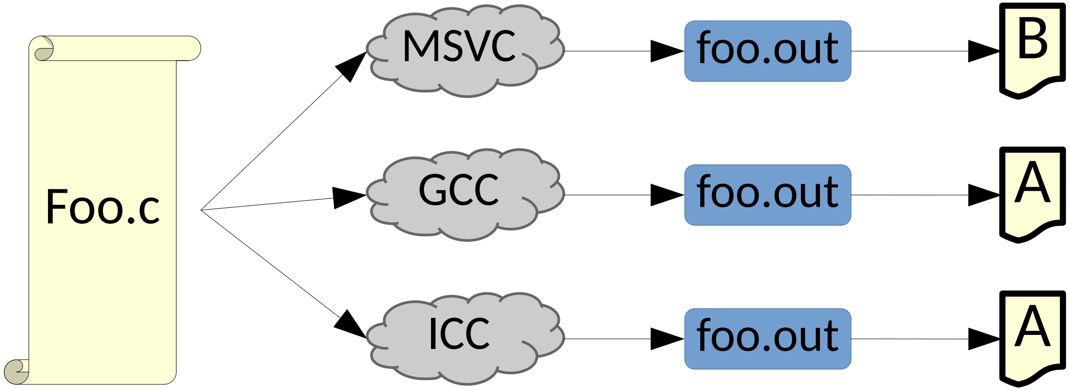

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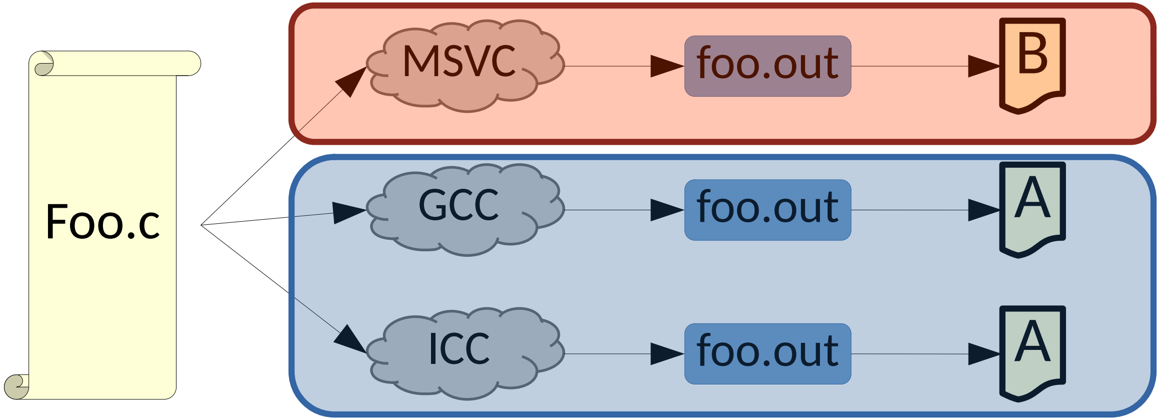

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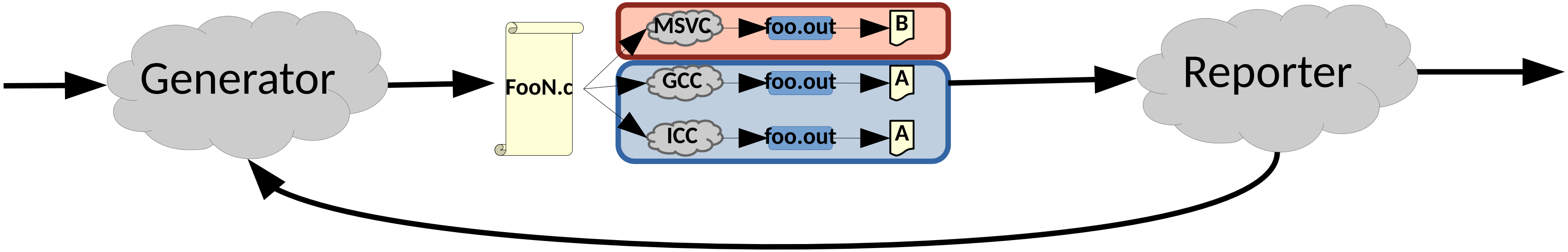

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int x = 5;
while (x) {
  if (x%2) {
    x = x + 1;
  } else {
    x = x - 1;
  }
}
printf(“%d”, x);
```

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- How might this fit into the compiler test cases?

Metamorphic Testing for Compilers

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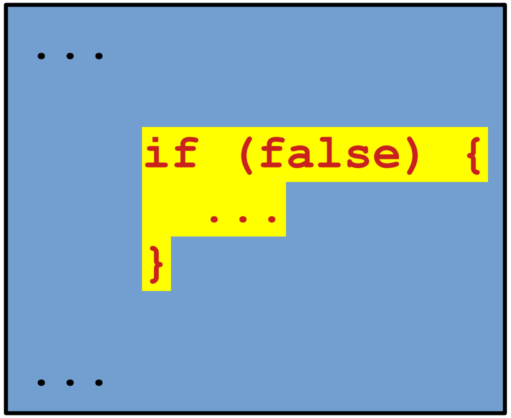

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```

- This may seem simple, but it provides a great deal of value today
  - GCC, Clang, MSVC, ICC
  - Vulcan & OpenGL shaders
  - ...

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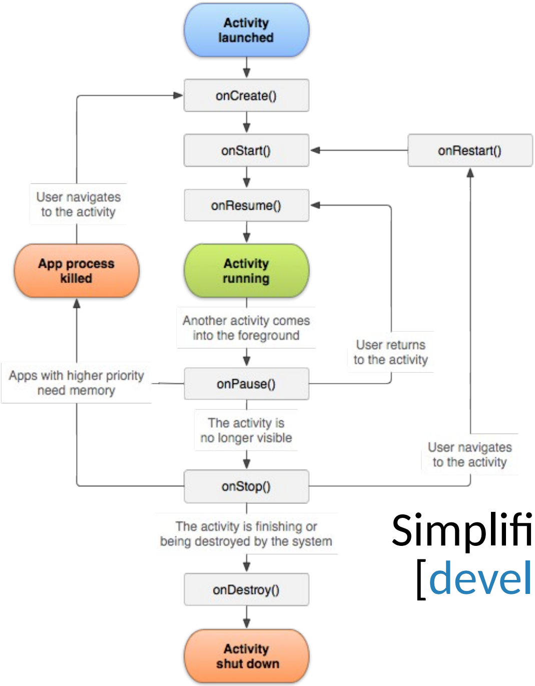
Activity launched
onCreate()
onStart()
onRestart()
User navigates to the activity
onResume()
App process killed
Activity running
Another activity comes into the foreground
User returns to the activity
Apps with higher priority need memory
onPause()
The activity is no longer visible
User navigates to the activity
onStop()
The activity is finishing or being destroyed by the system
onDestroy()
Activity shut down

Simplified Activity Lifecycle
[developer.android.com]

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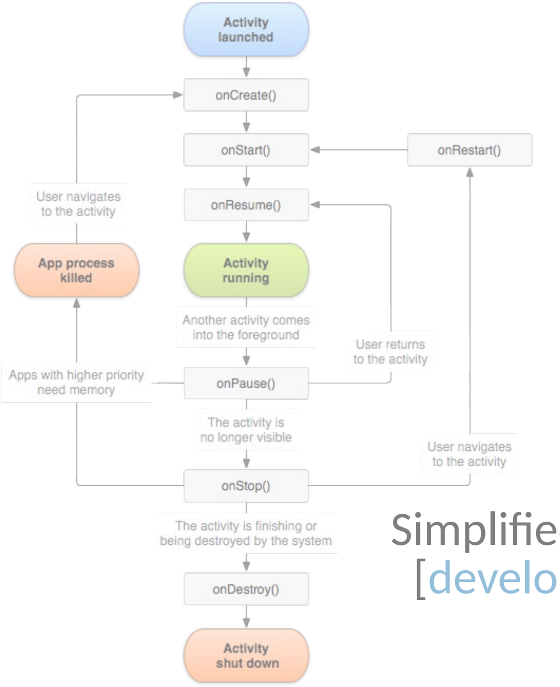

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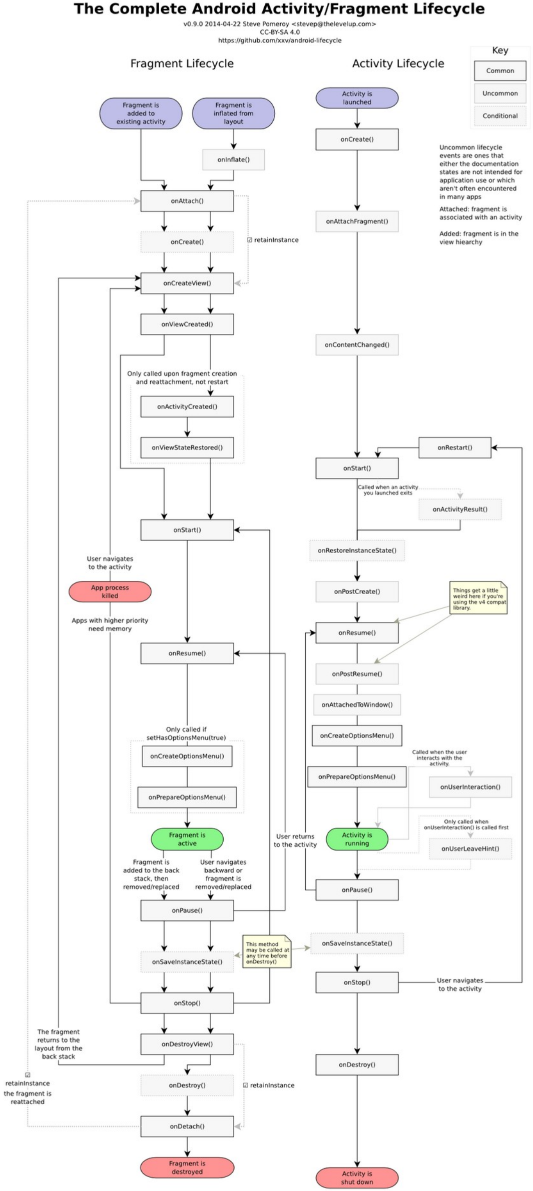
onResume()
App process killed
Activity running
Another activity comes into the foreground
User returns to the activity
Apps with higher priority need memory
onPause()
The activity is no longer visible
User navigates to the activity
onStop()
The activity is finishing or being destroyed by the system
onDestroy()
Activity shut down

Fragment/Activity Lifecycle
[Pomeroy 2014]

Simplified Activity Lifecycle
[developer.android.com]



The Complete Android Activity/Fragment Lifecycle
v0.9.0 2014-04-22 Steve Pomeroy <stevep@thelevelup.com>
CC-BY-SA 4.0
https://github.com/xxv/android-lifecycle
Fragment Lifecycle
Activity Lifecycle
Key
Common
Uncommon
Conditional
Fragment is added to existing activity
Fragment is inflated from layout
onInflate()
onAttach()
onCreate()
☑ retainInstance
onCreateView()
onViewCreated()
Only called upon fragment creation and reattachment, not restart
onActivityCreated()
onViewStateRestored()
onStart()
User navigates to the activity
App process killed
Apps with higher priority need memory
onResume()
Only called if setHasOptionsMenu(true)
onCreateOptionsMenu()
onPrepareOptionsMenu()
Fragment is active
Fragment is added to the back stack, then removed/replaced
User navigates backward or fragment is removed/replaced
User returns to the activity
onPause()
onSaveInstanceState()
This method may be called at any time before onDestroy()
onStop()
The fragment returns to the layout from the back stack
onDestroyView()
☑ retainInstance the fragment is reattached
onDestroy()
☑ retainInstance
onDetach()
Fragment is destroyed
Activity is launched
onCreate()
Uncommon lifecycle events are ones that either the documentation states are not intended for application use or which aren't often encountered in many apps
Attached: fragment is associated with an activity
Added: fragment is in the view hiearchy
onAttachFragment()
onContentChanged()
onRestart()
onStart()
Called when an activity you launched exits
onActivityResult()
onRestoreInstanceState()
onPostCreate()
Things get a little weird here if you're using the v4 compat library.
onResume()
onPostResume()
onAttachedToWindow()
onCreateOptionsMenu()
Called when the user interacts with the activity.
onPrepareOptionsMenu()
onUserInteraction()
Activity is running
Only called when onUserInteraction() is called first
onUserLeaveHint()
onPause()
onSaveInstanceState()
onStop()
User navigates to the activity
onDestroy()
Activity is shut down

Other Examples of Metamorphic Testing

- Android apps have complex life cycles and often experience UI glitches
  - Events come in from the framework
  - Apps need to respond consistently & intuitively
  - Handling events poorly leads to:
    - Crashes
    - Non-responsiveness
    - Unexpected UI changes
    - …

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Again, metamorphic testing makes this simpler.
Ideas?

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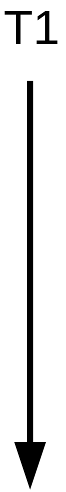

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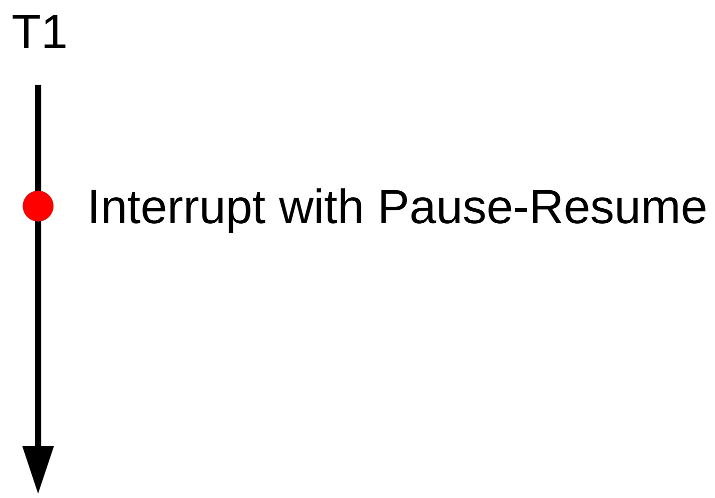

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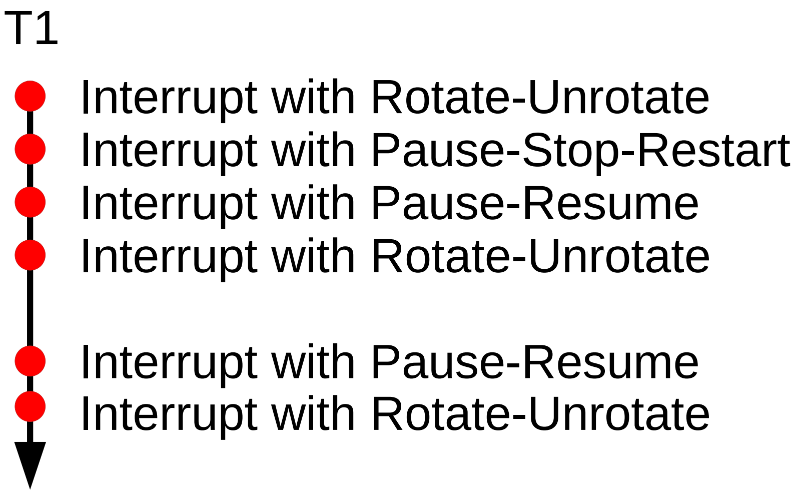

T1
Interrupt with Rotate-Unrotate
Interrupt with Pause-Stop-Restart
Interrupt with Pause-Resume
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Interrupt with Rotate-Unrotate

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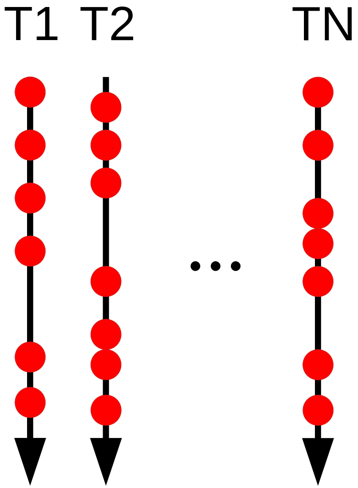

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"I like the movie"

expresses a mild positive opinion

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enjoyed
liked
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Why isn’t Santa Claus in jail?
Why isn’t the Tooth Fairy in jail?

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- Basic metamorphic testing tripled the bug discovery rate of ML testers. [Ribeiro 2020]

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  - *Measuring* whether you are testing well
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  - Measuring whether you are testing well
  - Managing testing over software evolution
- We have seen how to address challenging to test systems
  - Differential & metamorphic testing provide some guidance
- We have seen how test suites can be leveraged for further value
  - Localization
  - Repair
  - There are many more opportunities, too!