

Introduction to Software Testing

Syntax Coverage & Mutation Testing (Ch. 9)

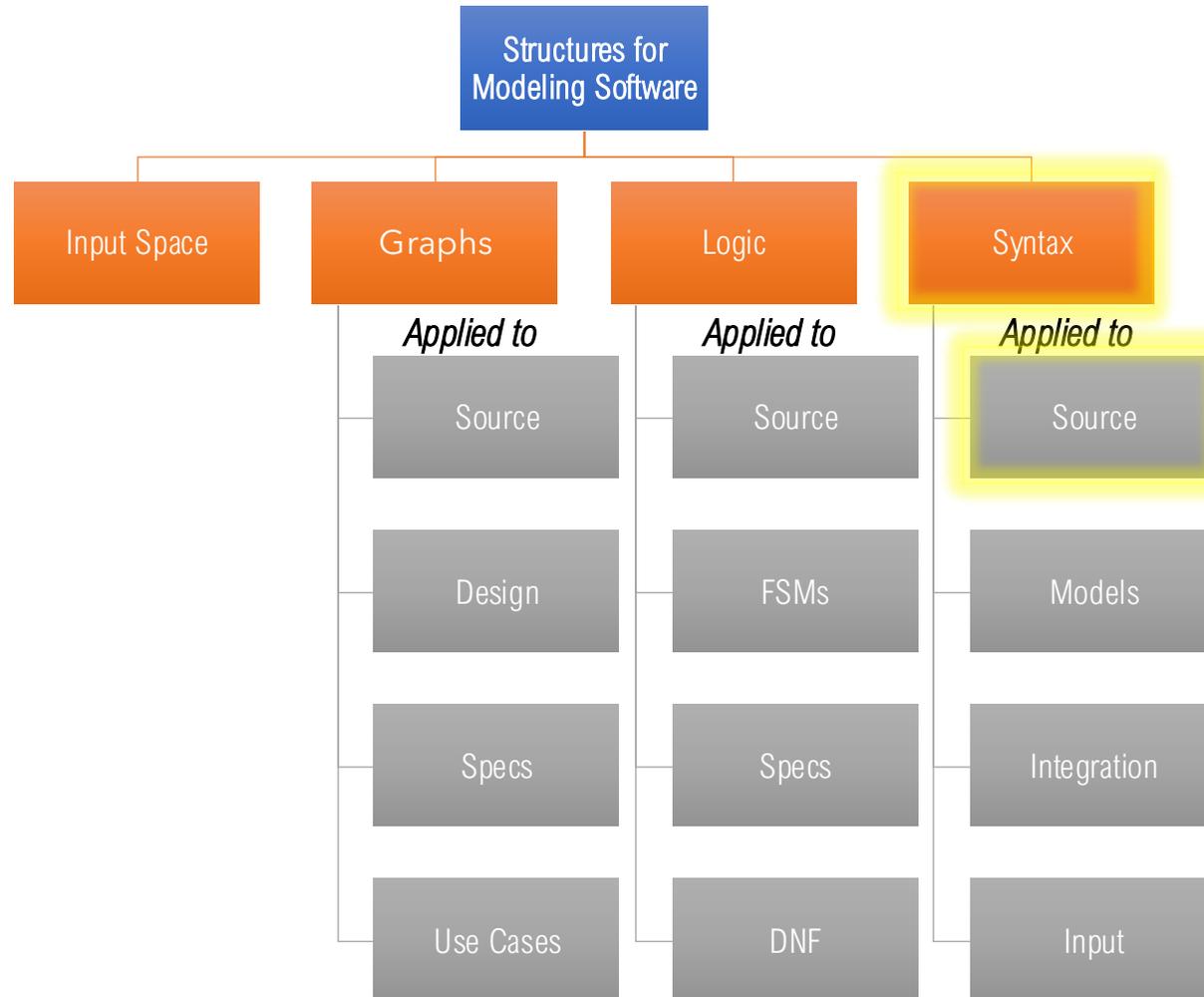
Software Testing & Maintenance

SWE 437/637

go.gmu.edu/SoftwareTestingFall24

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Syntax Coverage



Syntax-based Testing

Software artifacts often have **syntax rules**.

We can use two approaches when developing tests based on syntax

- Cover** the syntax in some way

- Violate** the syntax (to create invalid test cases)

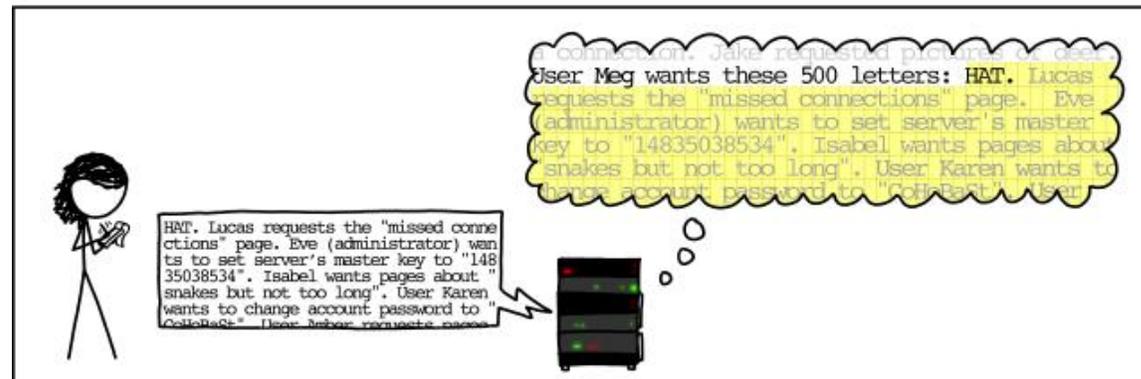
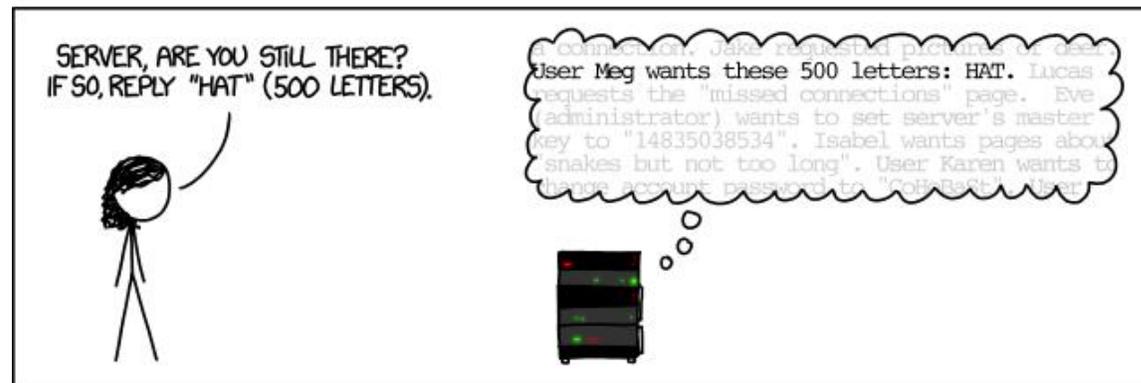
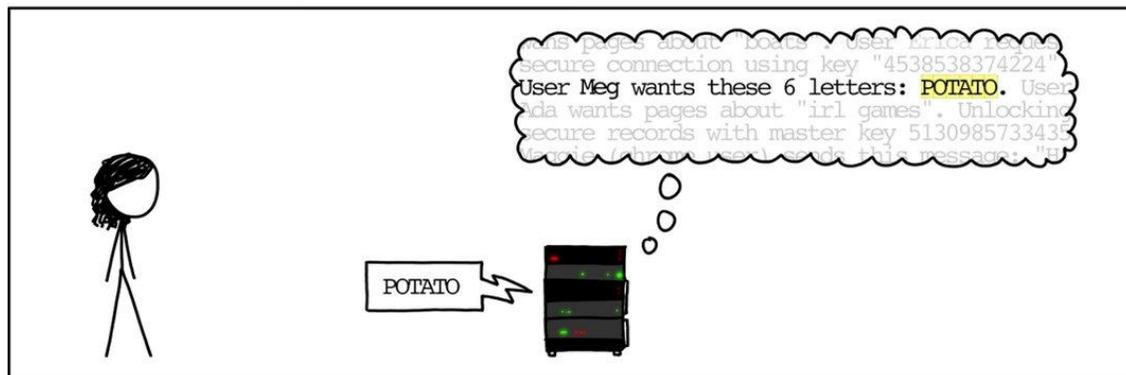
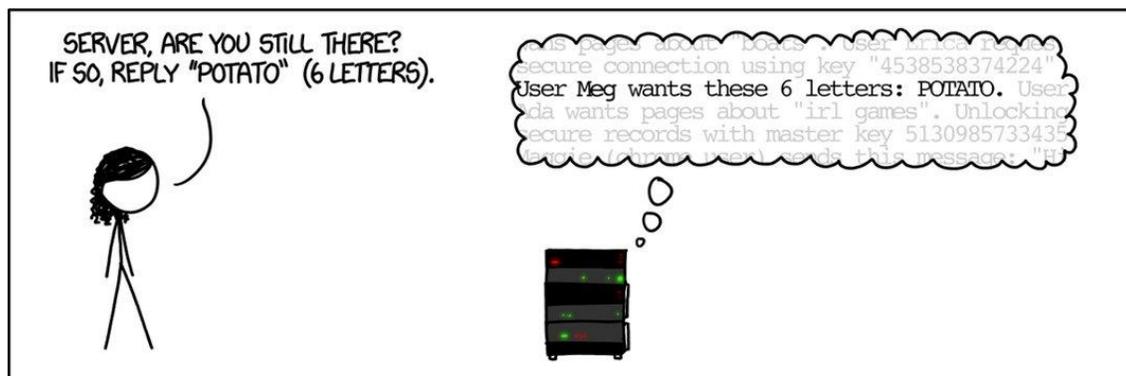
Fuzzing

One common use of syntax manipulation is **fuzzing** or **fuzz testing**

The objective is to provide inputs to the system that are *“correct enough”* to **pass any input validation**, but *“incorrect enough”* to **expose defects and/or unexpected behaviors**

Fuzzing may selectively **modify the input grammar**, or may use **heuristics based on past experience**, or may

Violating the Syntax -- Heartbleed



Defining Mutation

Mutation testing is a generalization of fuzzing.

In mutation testing, we

1. Take a *ground string* (a syntactically valid original artifact),
2. apply a *mutation operator* (a rule that governs how to modify the artifact),
3. to generate a *mutant* (a modified artifact) that is either in the grammar (valid) or very close to being in the grammar, then
4. determine whether the mutant exhibits different behavior than the ground string, which *detects* or *kills* the mutant

Mutation Testing

Mutation testing can be applied to:

- Input grammars (SQL, HTML, XML, etc.)

- Modeling languages (state charts, activity diagrams, etc.)

- Specification languages (Z, SMV, algebraic specifications, DNF)

- Program source code

Mutation Testing

Mutation testing can be applied to:

Input grammars (SQL, HTML, XML, etc.)

Modeling languages (state charts, activity diagrams, etc.)

Specification languages (Z, SMV, algebraic specifications, DNF)

Program source

This is the type of mutation testing we'll be talking about

Program Mutation

This is the **original** and **most widely-known** use of mutation, and is generally applied to *individual classes or methods*

Mutation operators are applied to the ground string (the original program) to produce a set of *mutants* (modified programs)

The resulting mutants are not tests, but can be used to develop or evaluate tests.

What's mutation testing for?

Mutation testing can be used in two complementary ways:

1. **Test development:** write tests to kill mutants
This is how software developers use mutation testing (when they use it at all)
2. **Test evaluation:** given a set of tests developed using some other criteria, how complete are those tests?
This is how software researchers tend to use mutation testing

Why does mutation testing work?

Competent Programmer Hypothesis: programmers are generally competent and tend to write programs that are nearly correct

The small changes to programs introduced by mutation testing are considered to be reasonable approximations for the types of errors inadvertently injected by engineers

Why does mutation testing work?

Coupling Hypothesis: complex faults are coupled to simple faults in such a way that a test data set that detects all simple faults in a program will detect a high percentage of the complex faults

The faults generated by mutation testing are useful proxies for actual faults

Mutant Categories

Live: a mutant that has not been killed by a test

Killed (or **dead**): a mutant that has been killed by a test (its behavior is different than the original)

Defunct (*historically known as stillborn*): a syntactically invalid mutant that cannot be compiled or executed

Trivial: a mutant that is killed by every test that reaches the mutation, usually by exception

Equivalent: a mutant that behaves identically to the ground string, such that no test can kill it

This seems counter-intuitive but is quite common

Mutation Coverage

DEFINITION

Mutation Coverage (MC) – For each mutant m in the set of mutants M , TR contains exactly one requirement: to kill m .

A test t kills a mutant m if and only if the behavior of m while executing t differs from the behavior of the ground string while executing t

The mutation coverage metric is based on the proportion of mutants killed, also known as the *mutation score*

Mutation Example

```
// Ground string
// (original program)
int max (int i, int j)
{
    if (i >= j)
        return i;
    else
        return j;
}
```

```
// Mutant m1
// (modified program)
int max (int i, int j)
{
    if (i <= j)
        return i;
    else
```

**Mutate a
relational
operator**

A test for m_1 :

```
assertEquals(2, max(1, 2));
```

Mutant m_1 is *killed* (returns 1 instead of 2)

Mutation Example

```
// Ground string
// (original program)
int max (int i, int j)
{
    if (i >= j)
        return i;
    else
        return j;
}
```

```
// Mutant m2
// (modified program)
int max (int i, int j)
{
    if (i >= j)
        return i;
    else
        return i;
}
```

Mutate a variable

A test for m_2 :

```
assertEquals(2, max(1, 2));
```

Mutant m_2 is *killed* (returns 1 instead of 2)

Mutation Example

```
// Ground string
// (original program)
int max (int i, int j)
{
    if (i >= j)
        return i;
    else
        return j;
}
```

```
// Mutant m3
// (modified program)
int max (int i, int j)
{
    if (i >= j)
        trap();
    else
        return j;
}
```

**Crash the
program
whenever the
mutation is
reached**

A test for m_3 :

```
assertEquals(2, max(1, 2));
```

Mutant m_3 is *killed* and *trivial* - it is killed by any test that reaches it

Mutation Example

```
// Ground string
// (original program)
int max (int i, int j)
{
    if (i >= j)
        return i;
    else
        return j;
}
```

```
// Mutant m4
// (modified program)
int max (int i, int j)
{
    if (i > j)
        return i;
    else
```

Mutate a relational
operator

A test for m_4 :

```
assertEquals(2, max(1, 2));
```

Mutant m_4 is *equivalent* - no test exists that can kill it

Mutation Notation

```
// Ground string
// (original program)
int max (int i, int j)
{
    if (i >= j)
        return i;
    else
        return j;
}
```

Mutants are often shown in a single consolidated listing, with **deltas** marking

```
// Mutant m4
// (modified program)
int max (int i, int j)
{
    if (i >= j)
        Δ1 if (i <= j)
        Δ4 if (i > j)
            return i;
        Δ3 trap();
    else
        return j;
        Δ2 return i;
}
```

Mutation Coverage Revisited

DEFINITION

Mutation Coverage (MC) – For each mutant m in the set of mutants M , TR contains exactly one requirement: to kill m .

Consider the **RIPR model**

Program execution must *reach* the fault

The fault must *infect* the program state with an error

The error must *propagate* to an output

The error must be *revealed* to the tester

This suggests two definitions for *kill*

Strong and Weak Mutation

Strong mutation: given a mutant $m \in M$ for a program P and a test t , t *strongly kills* m if and only if the output of t on P is different from the output of t on m .

Strong mutation requires reachability, infection, propagation, and revealability

Weak mutation: given a mutant $m \in M$ that modifies a location l in program P and a test t , t *weakly kills* m if and only if the state of execution of t on P is different from the state of execution of t on m immediately after l .

Weak mutation requires only reachability and infection

Strong and Weak Mutation

It is easier to weakly kill mutants than to strongly kill them.

However, it can be difficult to determine whether a mutant has been weakly killed.

Some mutants can be weakly killed but not strongly killed (the error does not propagate or is not revealed).

Studies have found that tests that weakly kill mutants also tend to strongly kill them

Weak vs. Strong Example

Given $t = \text{assertTrue}(\text{isEven}(-4))$

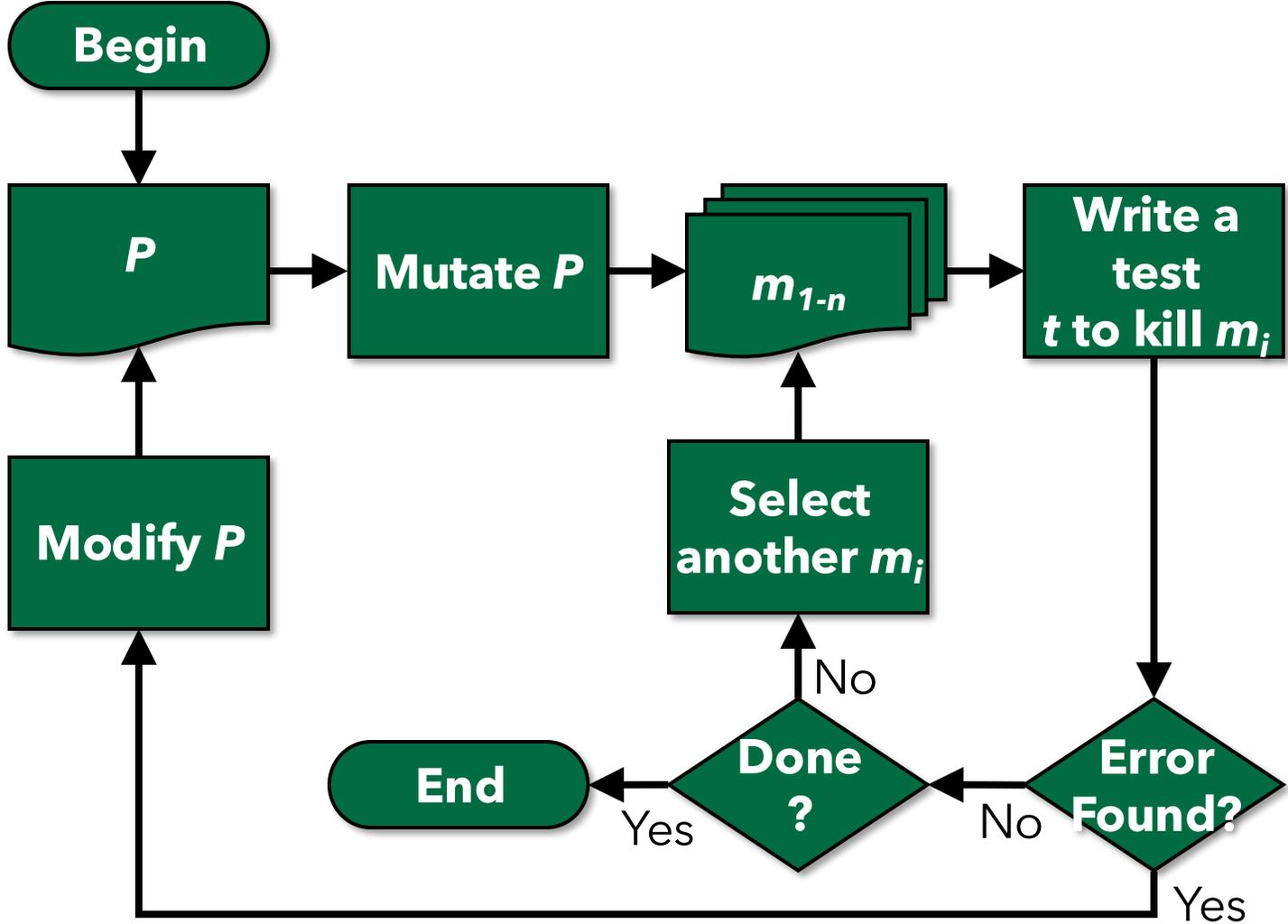
```
boolean isEven (int i)
{
  if (i < 0)
    i = 0 - i;
  Δ1  i = 0 + i;
  if (i == ((i/2)*2))
    return true;
  else
    return false;
}
```

For P , $i=4$

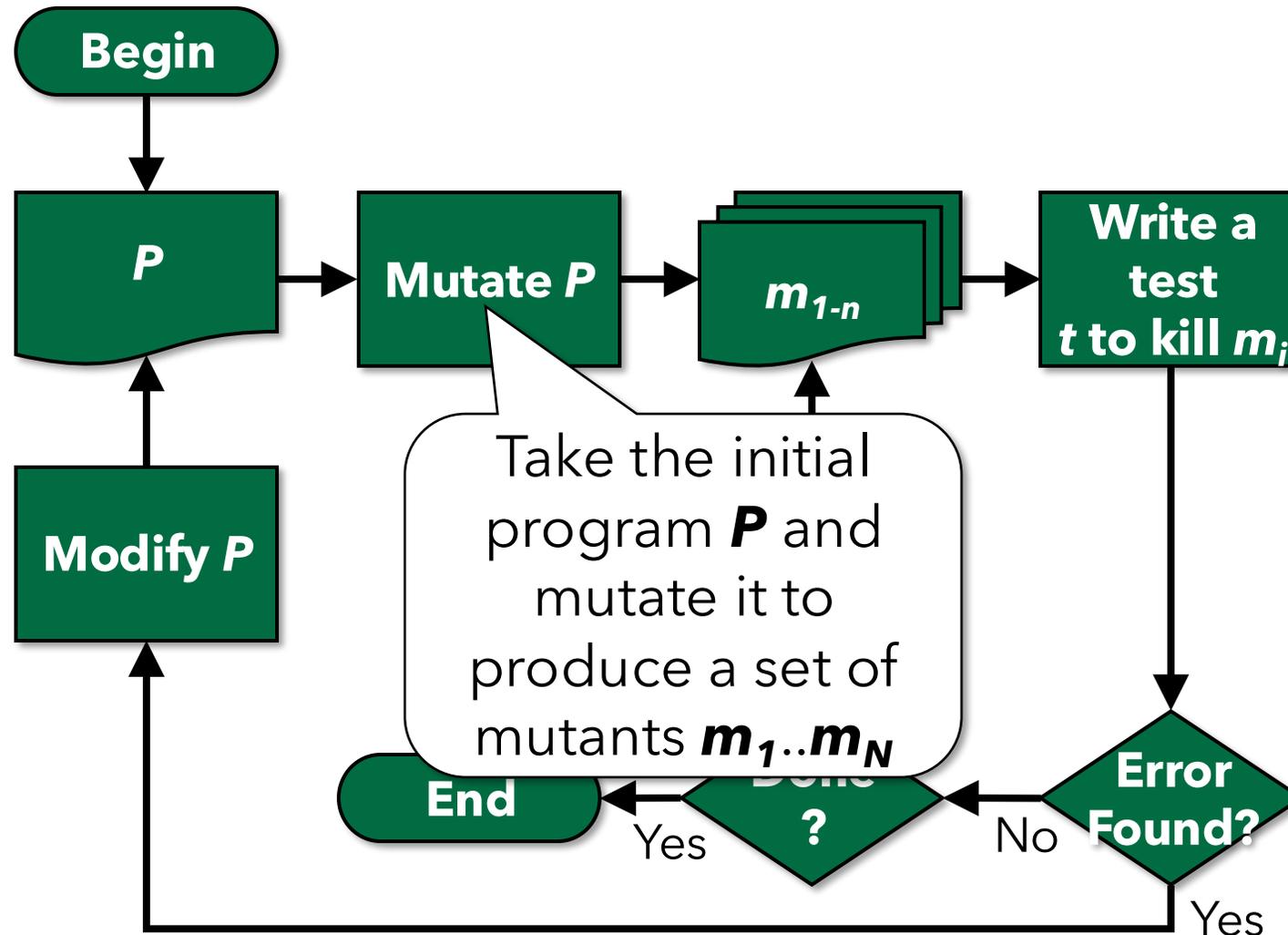
For m , $i=-4$
thus t weakly kills
 m

P and m both
return true, so t
does not strongly
kill m

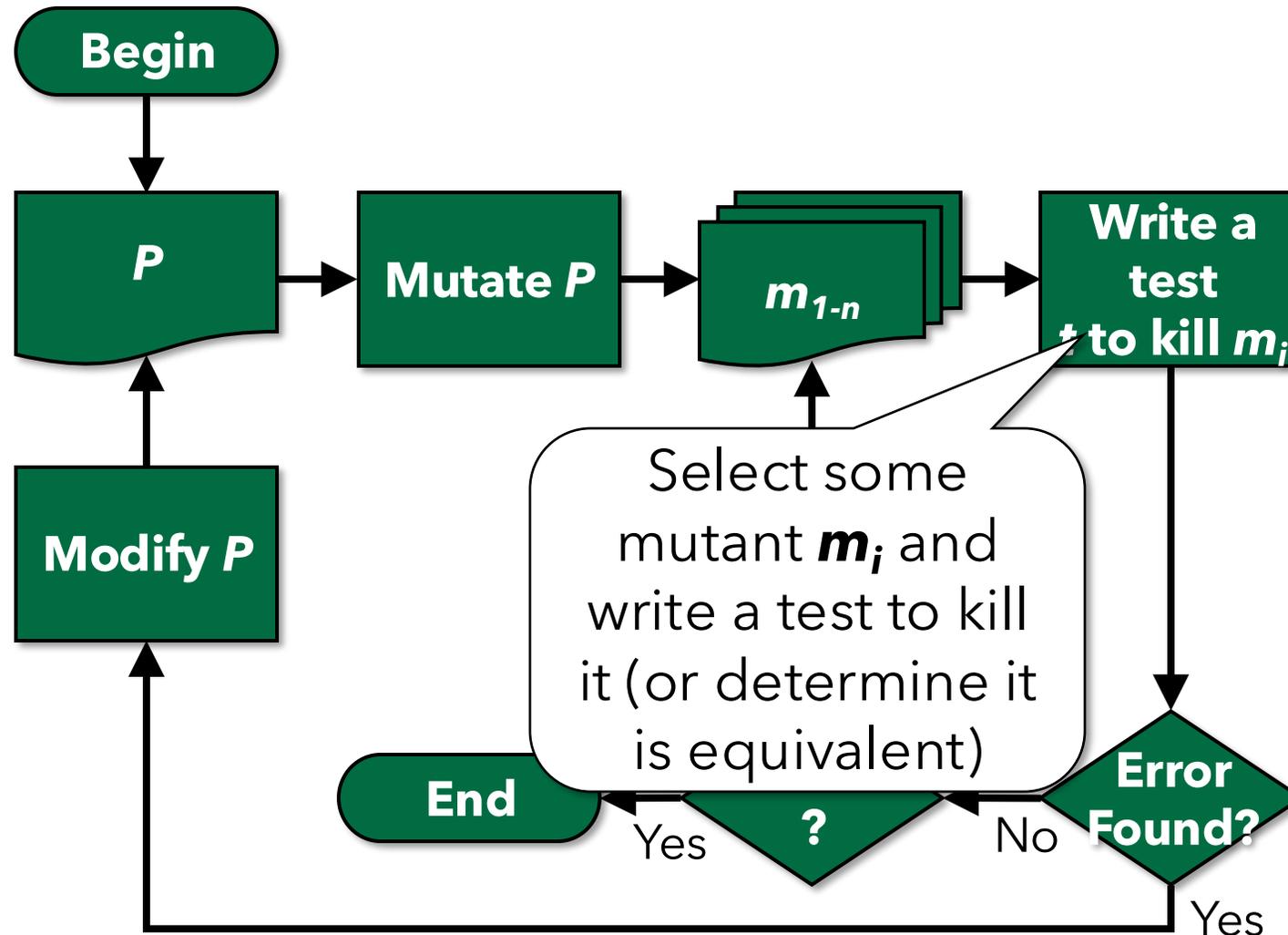
Mutation Test Development



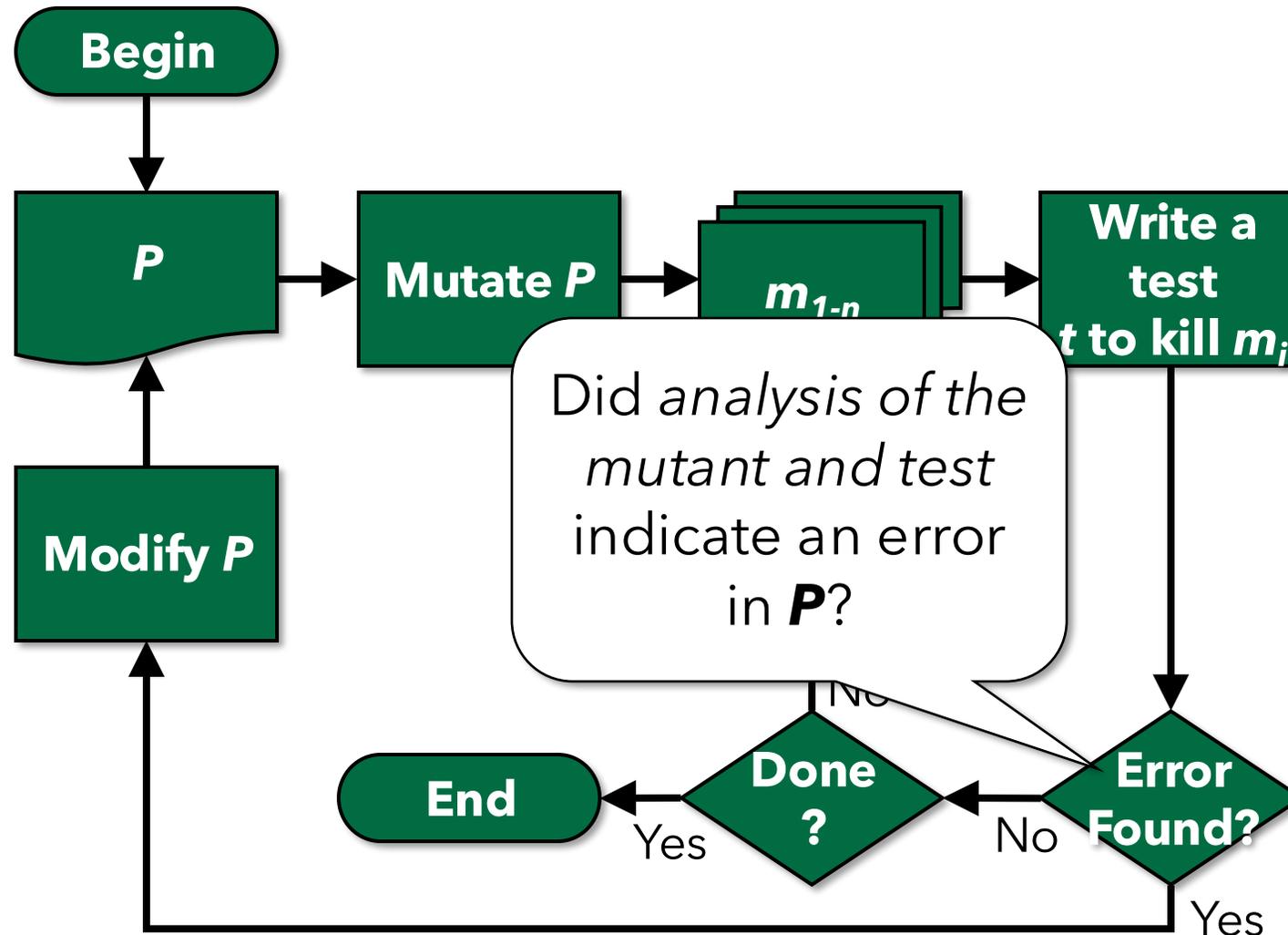
Mutation Test Development



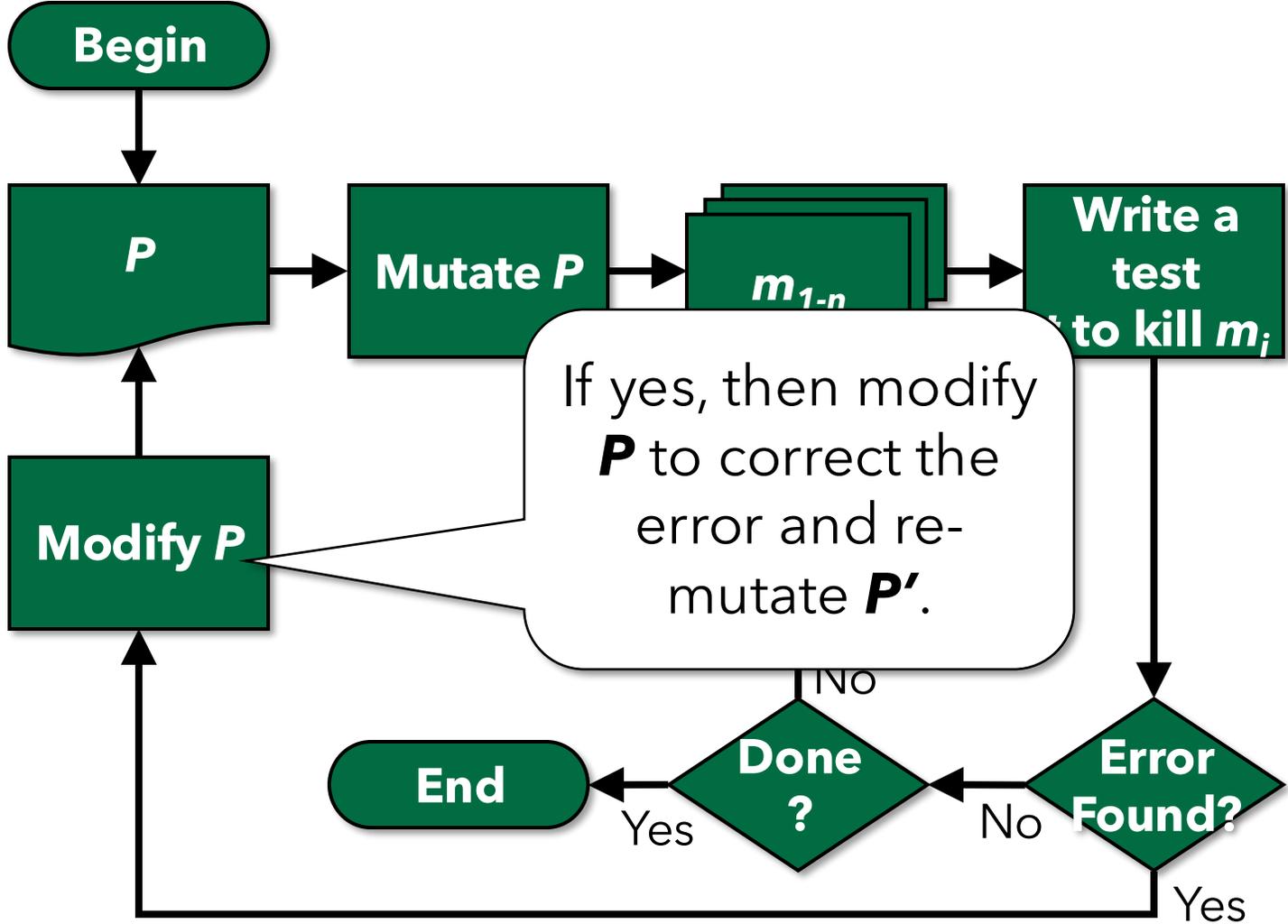
Mutation Test Development



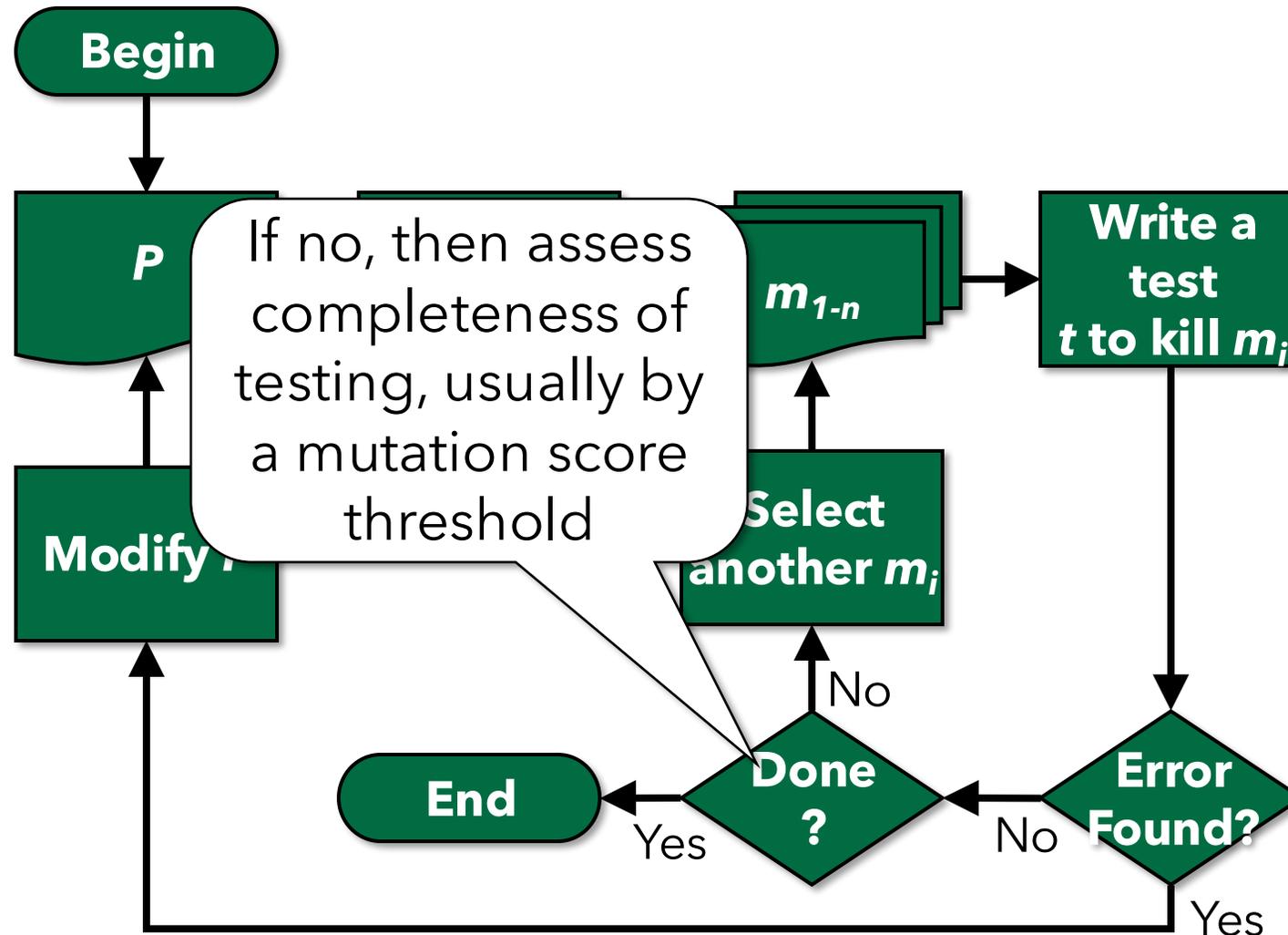
Mutation Test Development



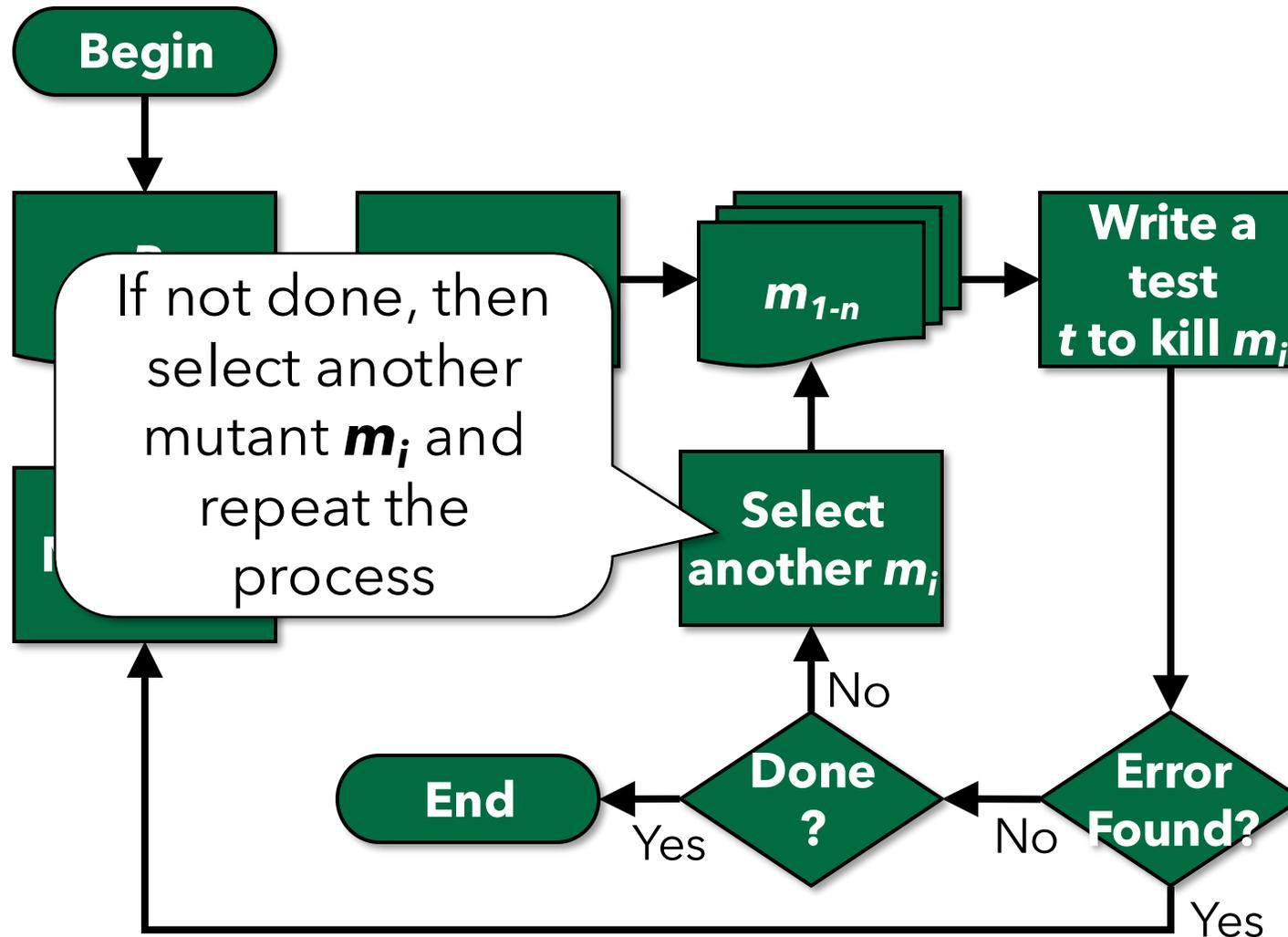
Mutation Test Development



Mutation Test Development



Mutation Test Development



Mutation Test Development

This process is **extremely labor-intensive** and thus expensive.

The outcome of the process is a very strong set of tests, *if the mutation operators are well-designed.*

Designing Mutation Operators

A good mutation operator...

- Creates mutants that are similar to programmer errors

- Creates mutants that tend to elicit effective tests

Researchers design lots of operators, then empirically determine which are effective.

- If tests created to kill mutants generated by one operator also tend to kill mutants developed by other operators, than that operator is effective

Some Java Mutation Operators

AOD - arithmetic operator deletion

AOI - arithmetic operator insertion

AOR - arithmetic operator replacement

COD - conditional operator deletion

COI - conditional operator insertion

LOD - logical operator deletion

LOI - logical operator insertion

LOR - logical operator replacement

ROR - relational operator replacement

SDL - statement deletion

SOR - shift operator replacement

Mutation Operator Examples

AOD – arithmetic operator deletion

$a = b + c$
 $\Delta 1$ $a = b \text{---} + c$
 $\Delta 2$ $a = b + \text{---} c$

AOI – arithmetic operator insertion

$a = b + c$
 $\Delta 1$ $a = -b + c$
 $\Delta 2$ $a = b + c \text{++}$

AOR – arithmetic operator replacement

$a = b + c$
 $\Delta 1$ $a = b - c$
 $\Delta 2$ $a = b \% c$

Mutation Operator Examples

COD - conditional operator deletion

```
    if (a && !b)
Δ1  if (a && !b)
Δ2  if (a && !b)
```

COI - conditional operator insertion

```
    if (a && b)
Δ1  if (! (a && b))
Δ2  if (a && b || true)
```

COR - conditional operator replacement

```
    if (a && b)
Δ1  if (a || b)
Δ2  if (false)
```

Mutation Operator Examples

COD - conditional operator deletion

```
    if (a && !b)
Δ1  if (a && !b)
Δ2  if (a &&!b)
```

COI - conditional operator insertion

```
    if (a && b)
Δ1  if (!(a && b))
Δ2  if (a && b || true)
```

COR - conditional operator replacement

```
    if (a && b)
Δ1  if (a && b)
Δ2  if (if b)
```

Mutation Operator Examples

LOD - logical operator deletion

$a = b \mid c$
 $\Delta 1 \quad a = b \text{ ~~| c~~ }$
 $\Delta 2 \quad a = \text{ ~~b |~~ } c$

LOI - logical operator insertion

$a = b \mid c$
 $\Delta 1 \quad a = \sim b \mid c$
 $\Delta 2 \quad a = b \mid \sim c$

LOR - logical operator replacement

$a = b \mid c$
 $\Delta 1 \quad a = b \ \& \ c$
 $\Delta 2 \quad a = b \ \wedge \ c$

Mutation Operator Examples

ROR - relational operator replacement

```
    if (a < b)
Δ1  if (a > b)
Δ2  if (true)
```

SDL - statement deletion

```
    if (a && b) { c = true }
Δ1  if (a && b) { c = true }
Δ2  if (a && b) { c = true }
Δ3  if (a && b) { c = true }
```

SOR - shift operator replacement

```
    a = b >> c
Δ1  a = b << c
Δ2  a = b >>> c
```

The Mutation Score Problem

Mutation score measures the coverage with respect to the mutation criterion.

$$MS = \frac{\textit{mutants}_{killed}}{\textit{mutants}_{total} - \textit{mutants}_{equivalent}}$$

The problem is that we can't know how many mutants are equivalent until we've evaluated all of them, thus *we can't know the mutation score until it's 100%*!

Summary

Mutation testing can be used to develop tests or to evaluate tests.

Mutation testing is very powerful, but very expensive

As a result, it currently remains primarily a research tool.