Intro to Software Testing

chapter 9

Syntax Coverage & Mutation Testing

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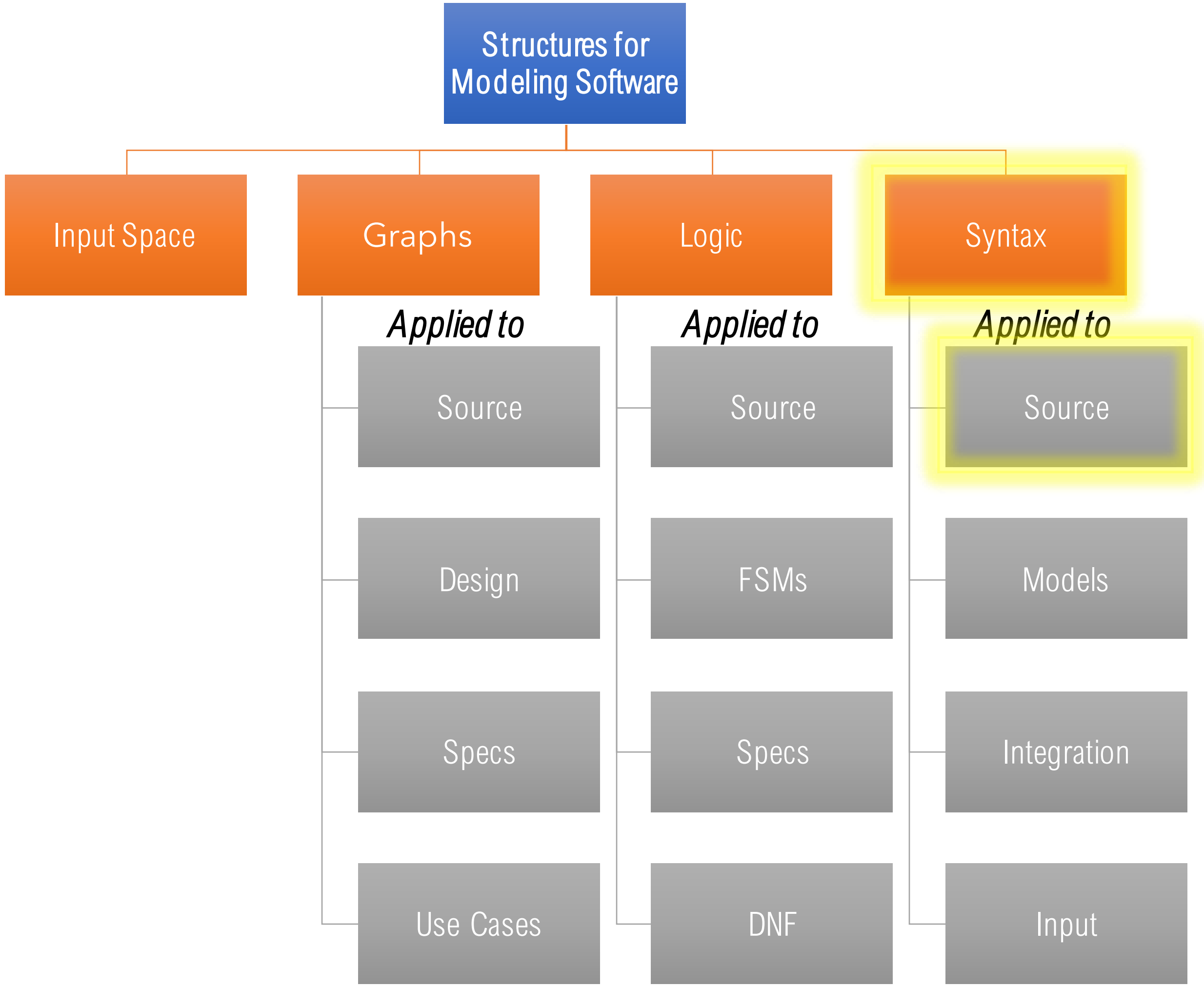
(Dr. B for short)

https://go.gmu.edu/SWE637

Adapted from slides by Jeff Offutt and Bob Kurtz

Logic Coverage



Structures for Modeling Software

Input Space

Graphs

Applied to

- Source
- Design
- Specs
- Use Cases

Logic

Applied to

- Source
- FSMs
- Specs
- DNF

Syntax

Applied to

- Source
- Models
- Integration
- Input

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)

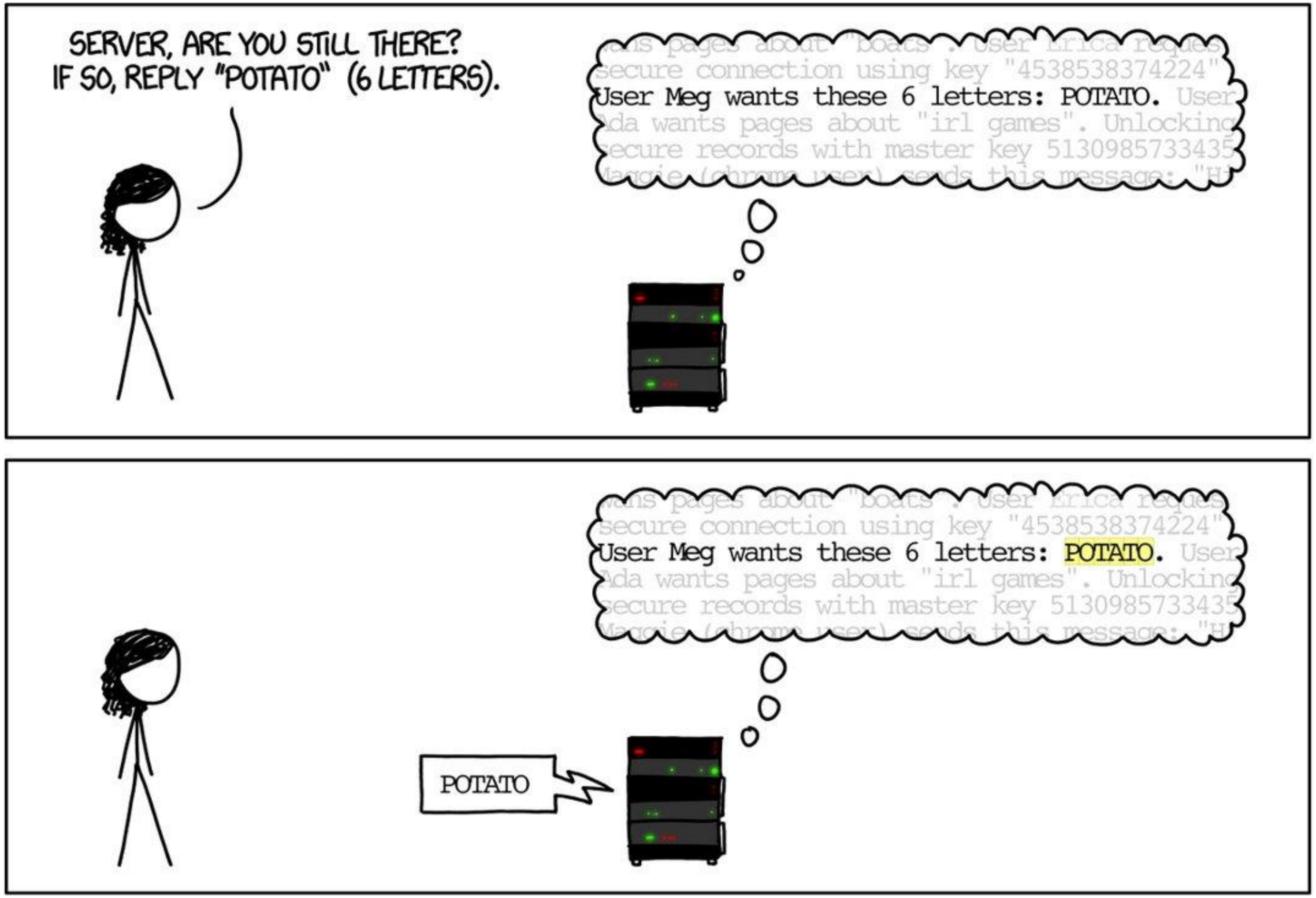
Fuzzing

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

- The objective it 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

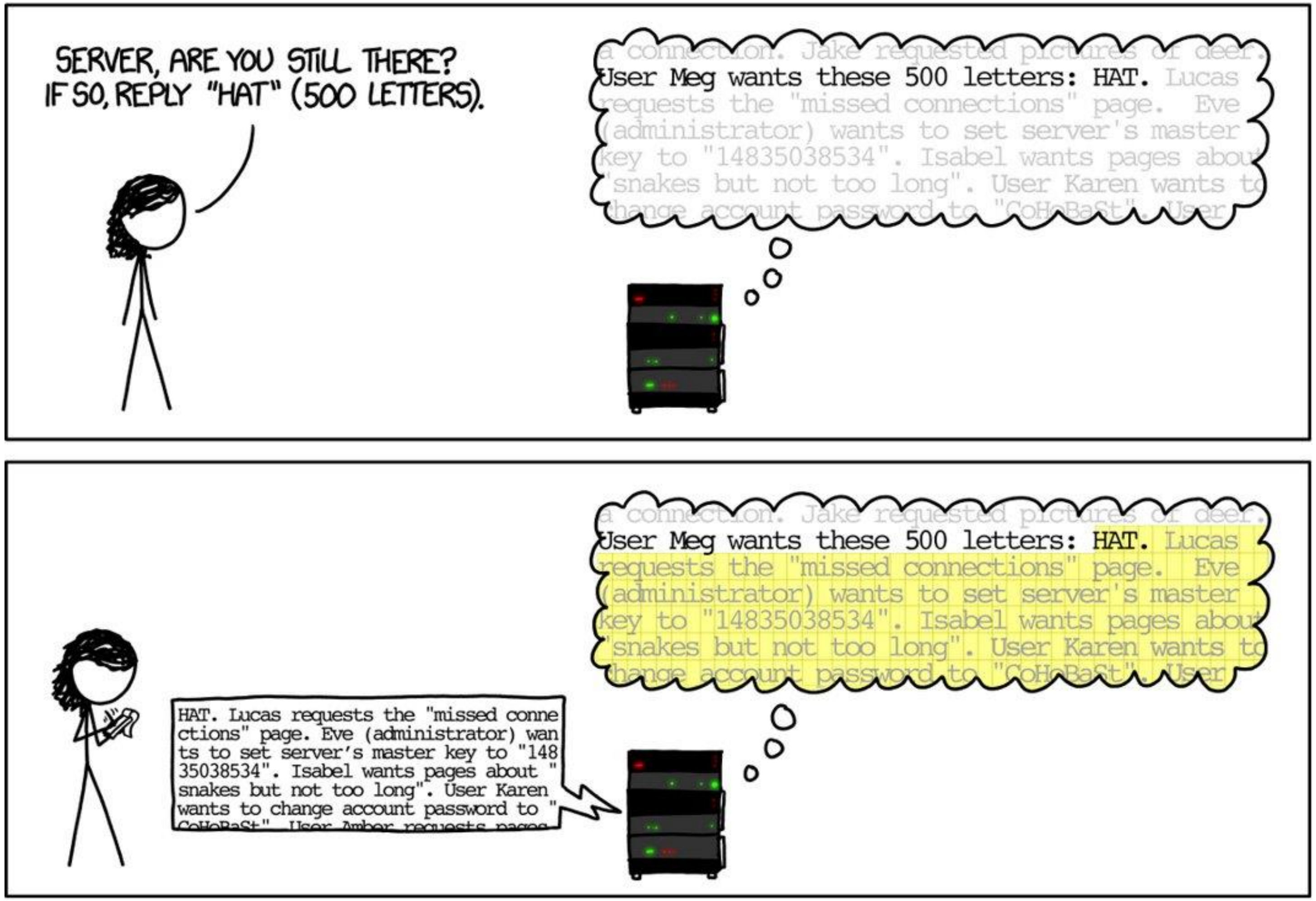
- Fuzzing may selectively modify the input grammar, or may use heuristics based on past experience, or may simply make randomized changes

Violating the Syntax - Heartbleed



https://xkcd.com/1354/

Violating the Syntax - Heartbleed



https://xkcd.com/1354/

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*

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?

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 <u>are not tests,</u> 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); the leading tool is probably PIT (https://pitest.org) though Google has established their own in-house capability

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 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 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

Categories of Mutants

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)

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;
  els
```

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

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

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;
}
```

```
   // 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;
   }
```

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

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* = assertTrue(isEven(-4))

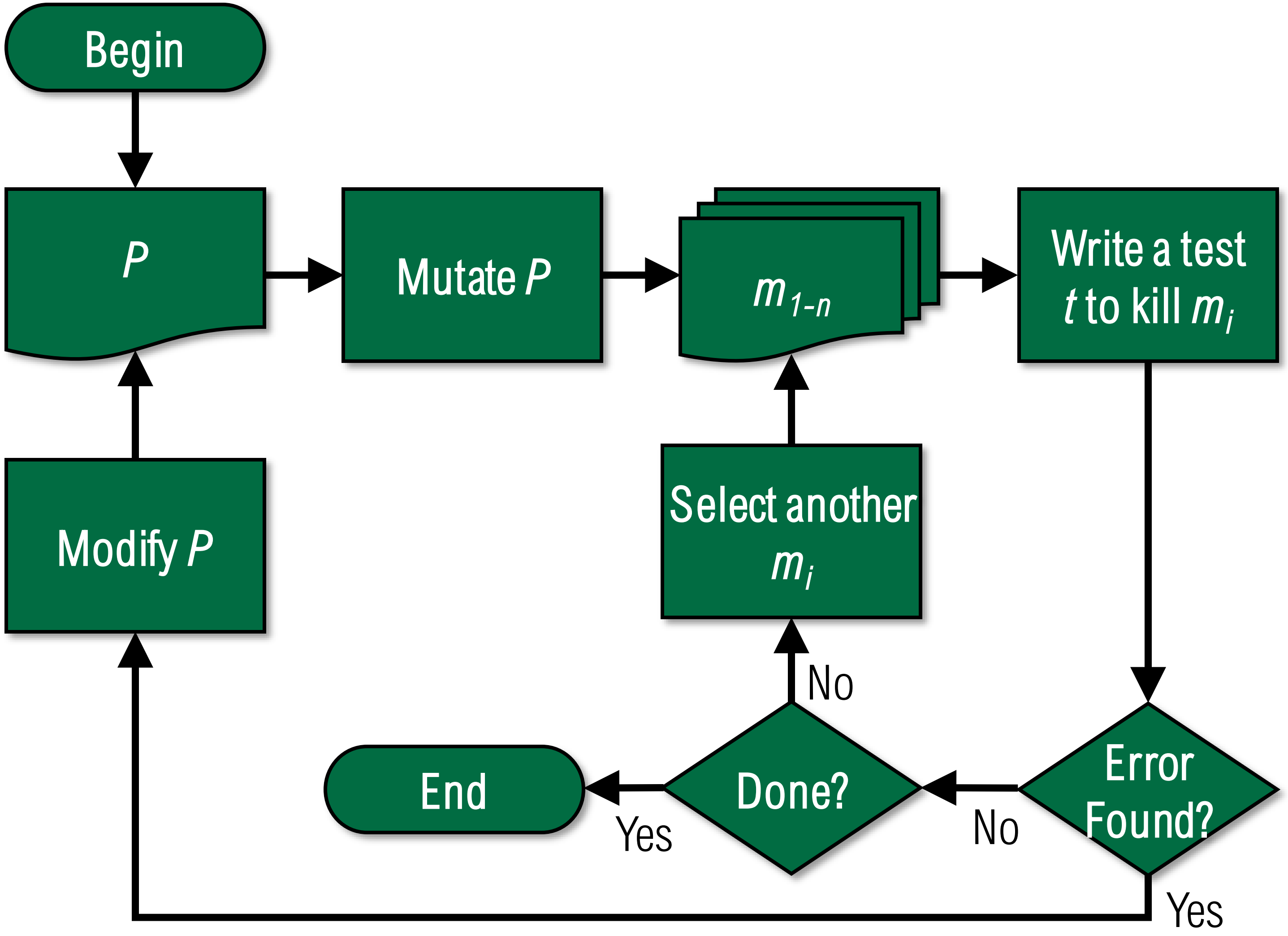
```
   boolean isEven (int i)
   {
     if (i < 0)
       i = 0 - i;
Δ1     i = 0 + i;
     if (i == ((i/2)*2))
       return true;
     else
       return false;
   }
```

For ***P***, i=4

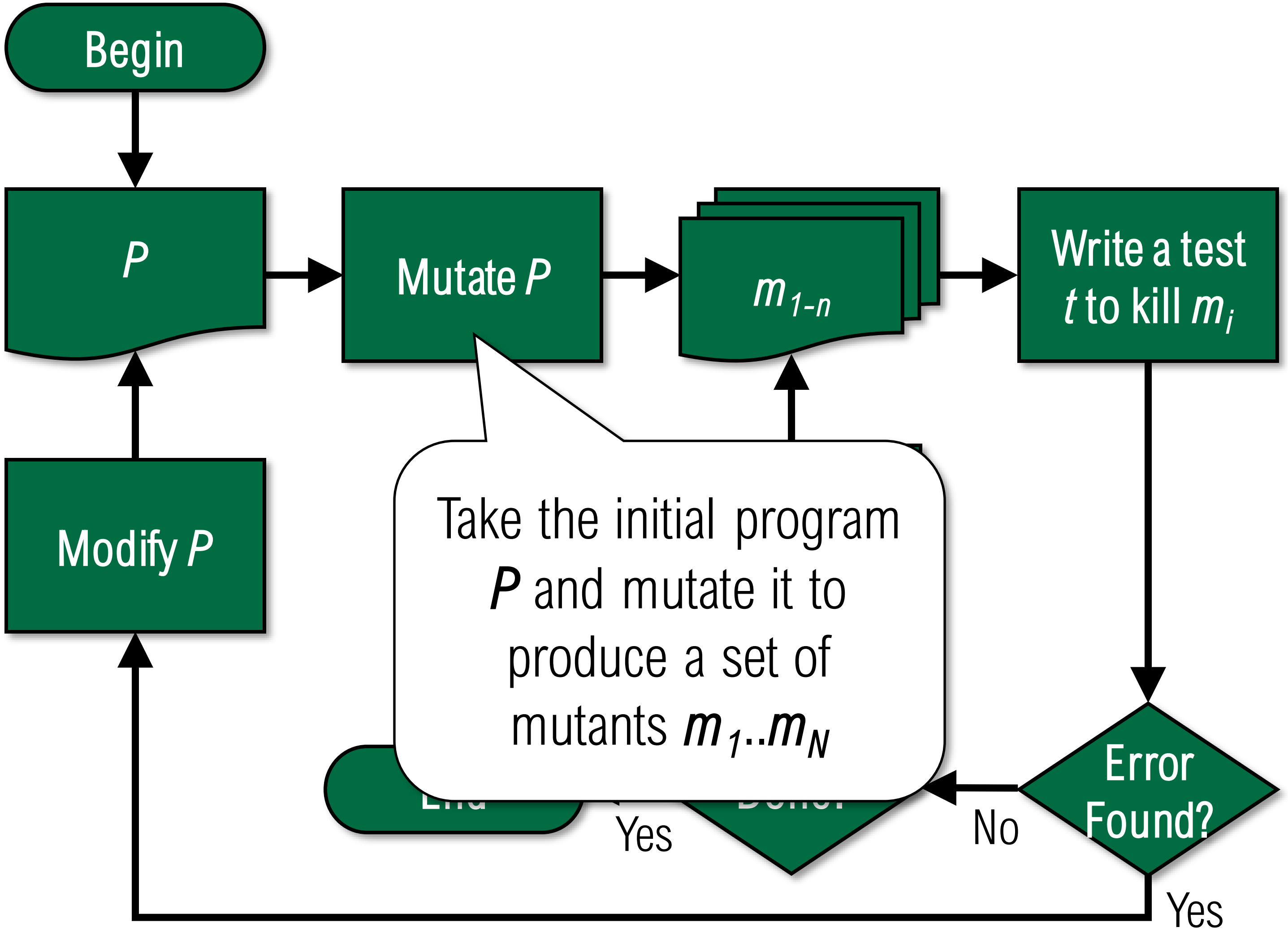
For ***m***, i=-4
thus ***t*** weakly kills ***m***

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

Mutation Test Development

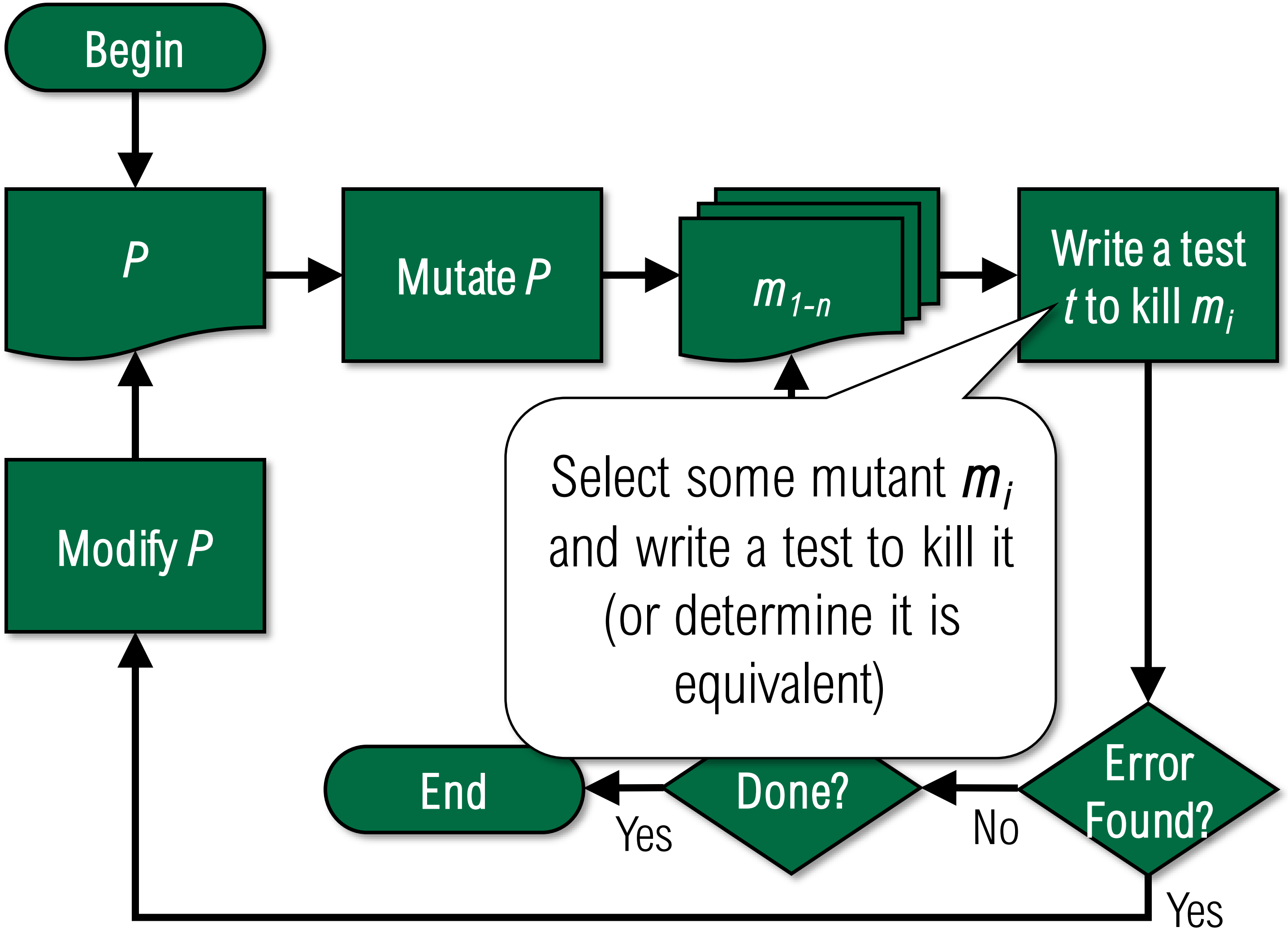


Mutation Test Development



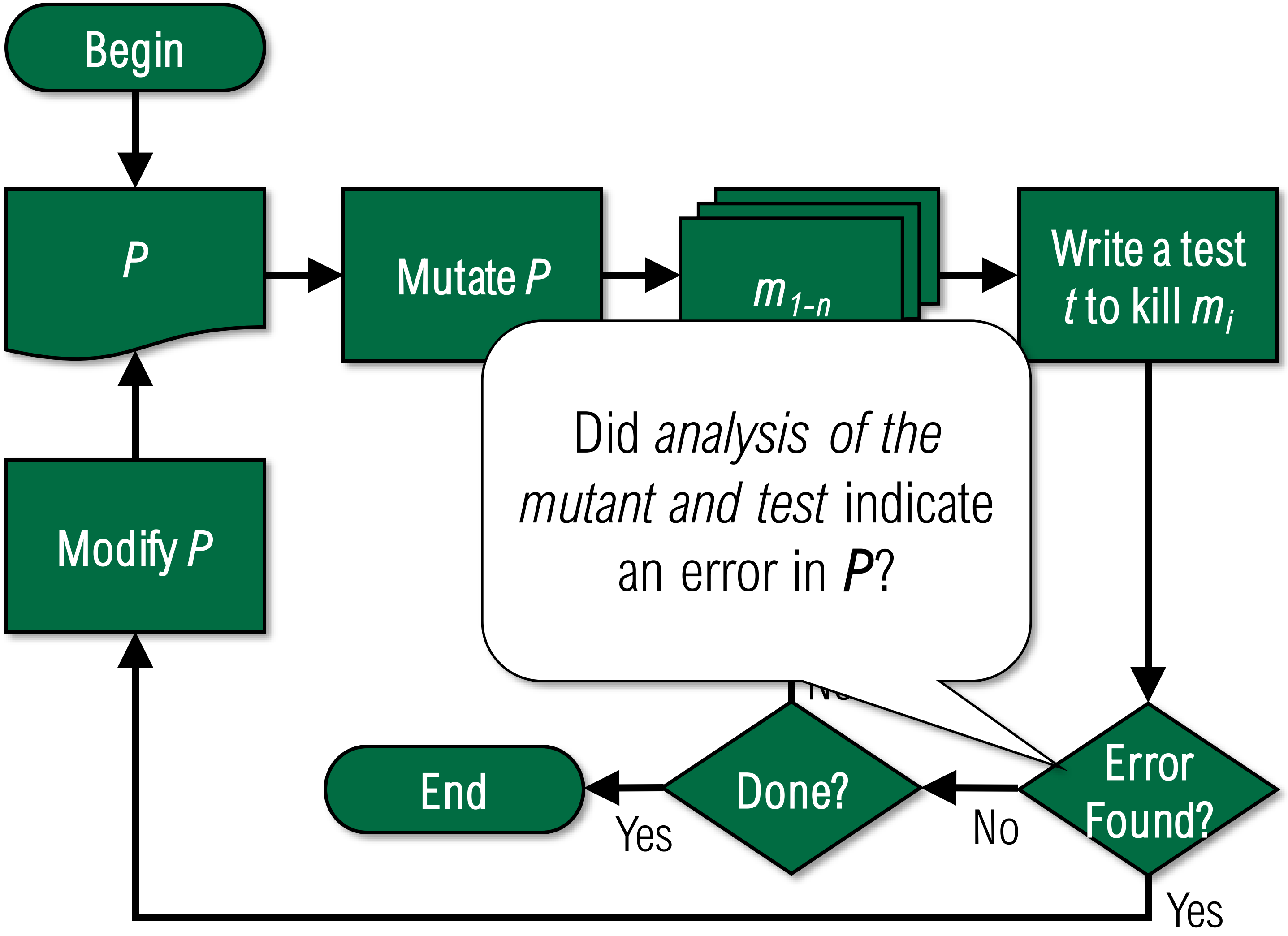
Take the initial program *P* and mutate it to produce a set of mutants $m_1..m_N$

Mutation Test Development



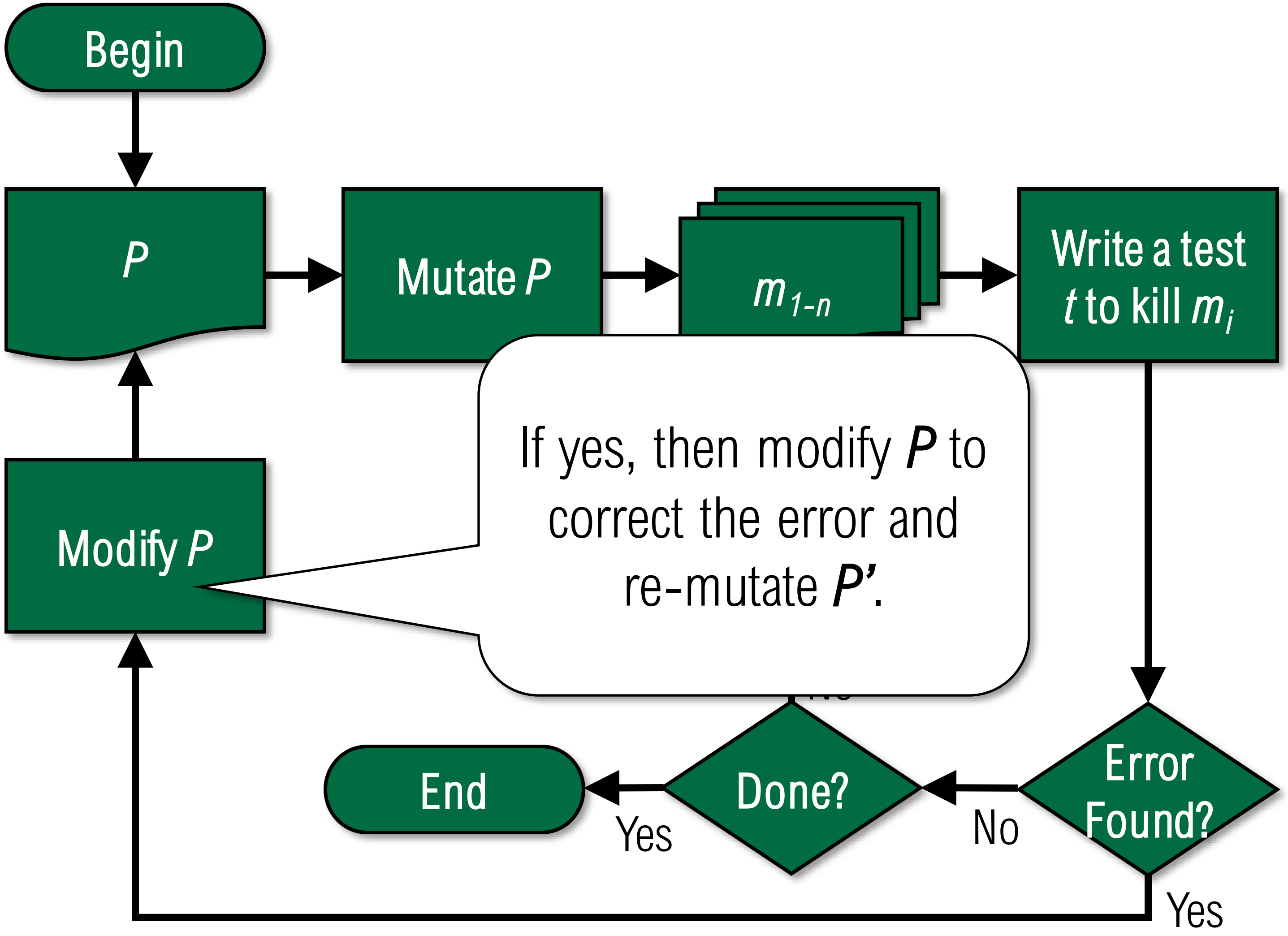
Select some mutant m_i and write a test to kill it (or determine it is equivalent)

Mutation Test Development



Did *analysis of the mutant and test* indicate an error in *P*?

Mutation Test Development



Begin

P

Mutate *P*

$m_{1\text{-}n}$

Write a test t to kill m_i

Error Found?

No

Yes

Done?

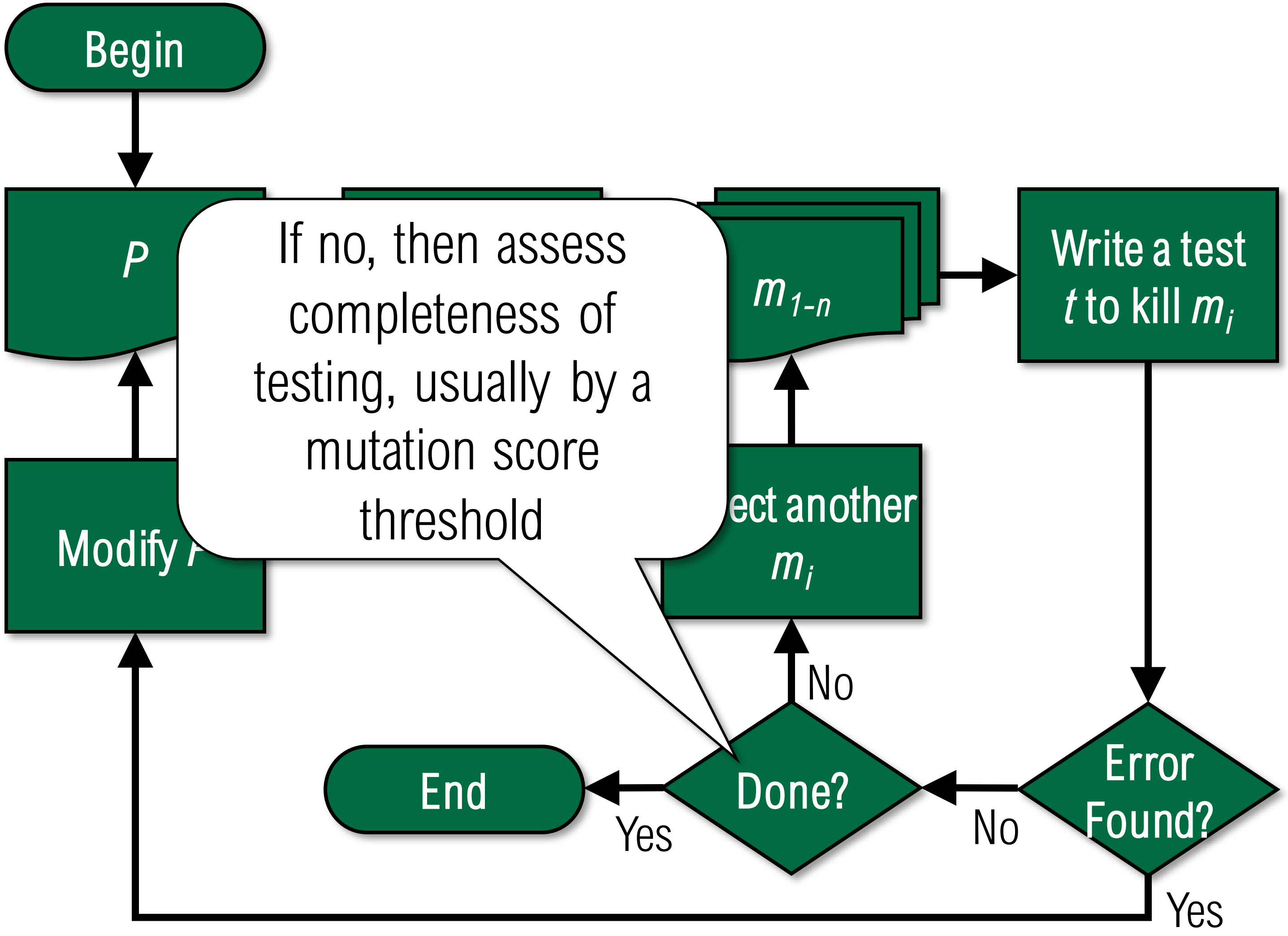
Yes

End

Modify *P*

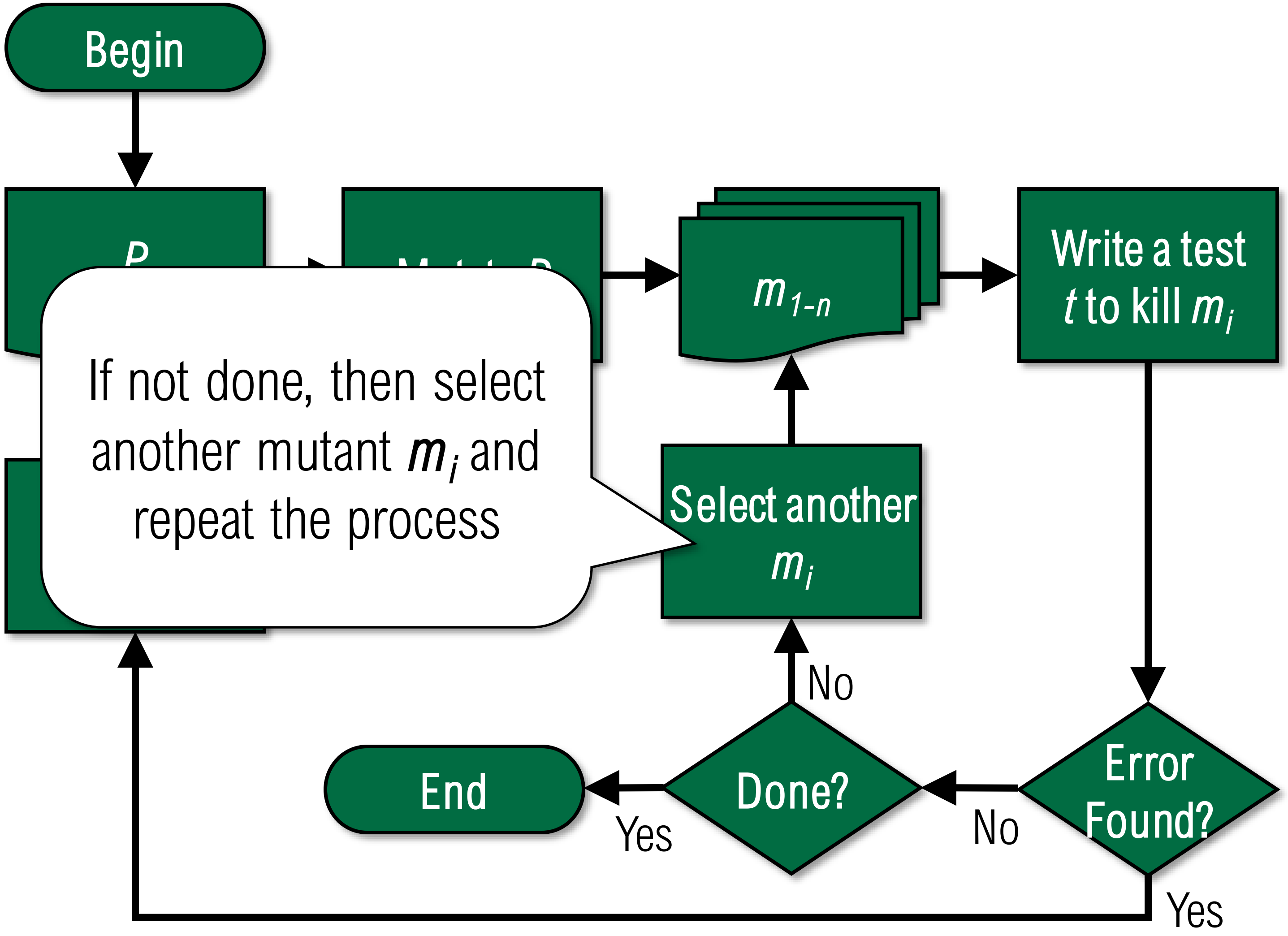
If yes, then modify *P* to correct the error and re-mutate *P'*.

Mutation Test Development



If no, then assess completeness of testing, usually by a mutation score threshold

Mutation Test Development



If not done, then select another mutant m_i and repeat the process

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
COR – conditional operator replacement
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
Δ1 a = ~~b +~~ c
Δ2 a = b ~~+ c~~

AOI – arithmetic operator insertion

a = b + c
Δ1 a = -b + c
Δ2 a = b + c++

AOR – arithmetic operator replacement

a = b + c
Δ1 a = b - c
Δ2 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

LOD – logical operator deletion

a = b | c
Δ1 a = b ~~| c~~
Δ2 a = ~~b |~~ c

LOI – logical operator insertion

a = b | c
Δ1 a = ~b | c
Δ2 a = b | ~c

LOR – logical operator replacement

a = b | c
Δ1 a = b & c
Δ2 a = b ^ 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

$$MS = \frac{mutants_{killed}}{mutants_{total} - mutants_{equivalent}}$$

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