MUTATION TESTING

WHAT IS ADEQUACY?

- Consider a program P written to meet a set R of functional requirements. We notate such a P and R as (P, R). Let R contain n requirements labeled R1, R2,…, Rn .

- Suppose now that a set T containing k tests has been constructed to test P to determine whether or not it meets all the requirements in R . Also, P has been executed against each test in T and has produced correct behavior.

- We now ask: Is T good enough? This question can be stated differently as: Has P been tested thoroughly?, or as: Is T adequate?

WHAT IS PROGRAM MUTATION?

- Suppose that program P has been tested against a test set T and P has not failed on any test case in T. Now suppose we do the following:

$$P \xrightarrow{\text{Changed to}} P'$$

What behavior do you expect from P’ against tests in T?

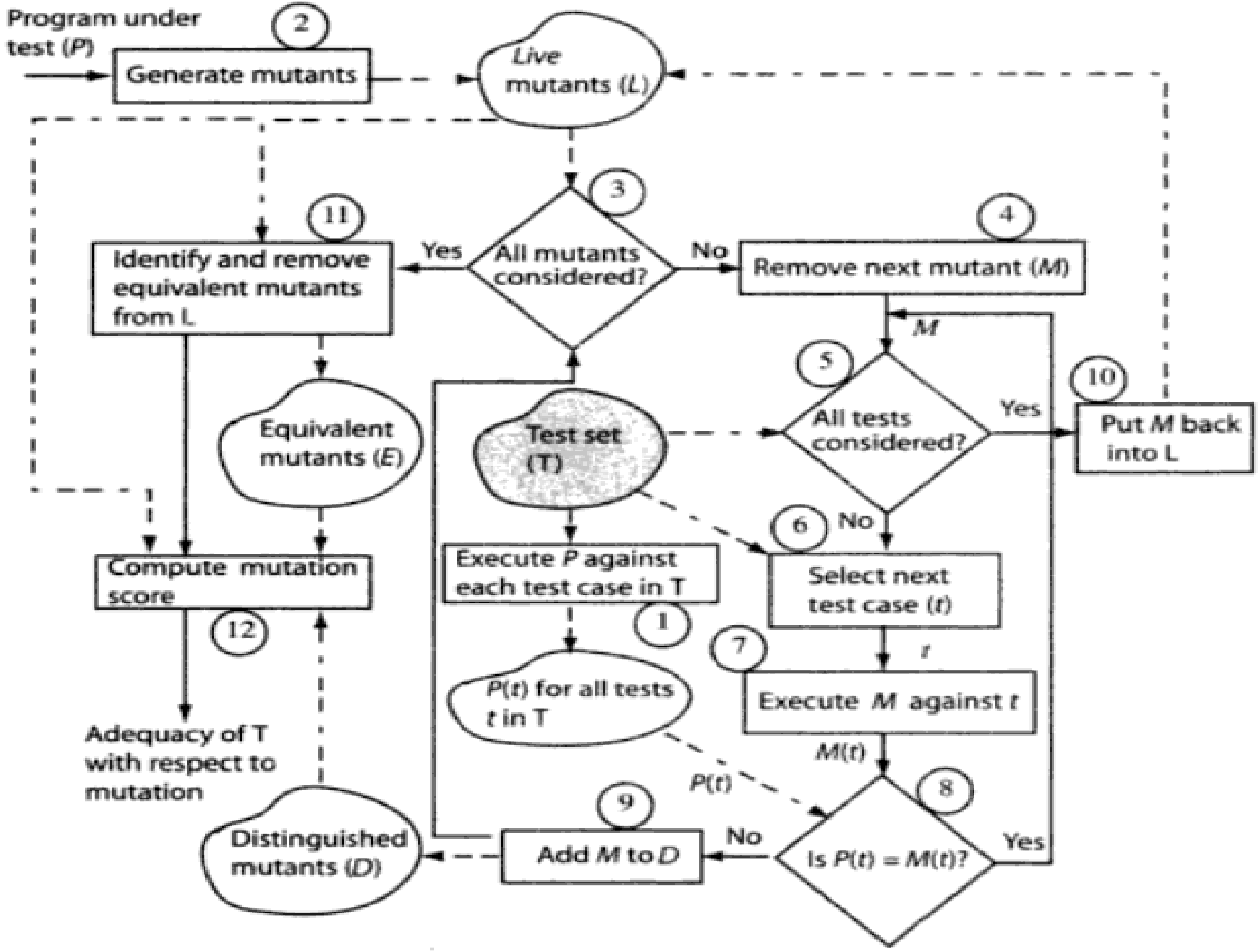
WHAT IS PROGRAM MUTATION? [2]

- P’ is known as a mutant of P.
- There might be a test t in T such that P(t)≠P’(t). In this case we say that t distinguishes P’ from P. Or, that t has killed P’.
- There might be not be any test t in T such that P(t)≠P’(t). In this case we say that T is unable to distinguish P and P’. Hence P’ is considered live in the test process.

WHAT IS PROGRAM MUTATION? [3]

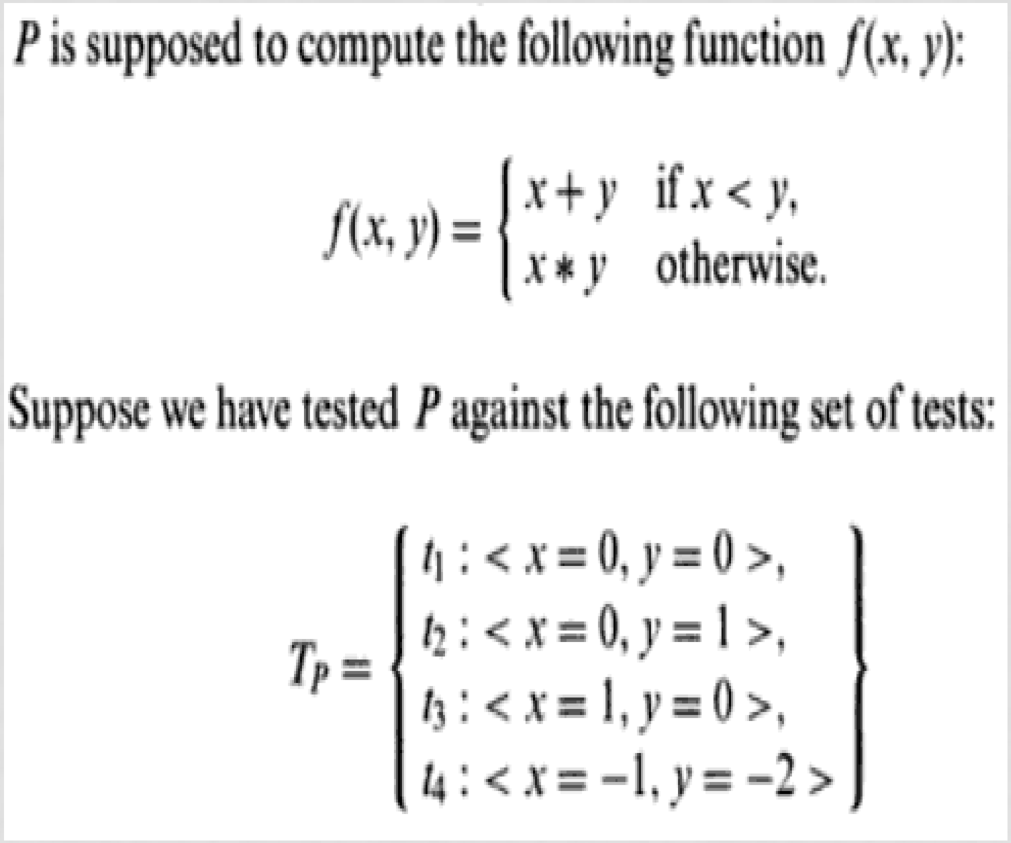
- If there does not exist any test case t in the input domain of P that distinguishes P from P’ then P’ is said to be equivalent to P.
- If P’ is not equivalent to P but no test in T is able to distinguish it from P then T is considered inadequate.
- A non-equivalent and live mutant offers the tester an opportunity to generate a new test case and hence enhance T.

We will refer to program mutation as mutation.



Program under test (P)
Generate mutants
2
Live mutants (L)
3
All mutants considered?
Yes
No
4
Remove next mutant (M)
11
Identify and remove equivalent mutants from L
M
5
All tests considered?
Yes
No
10
Put M back into L
Equivalent mutants (E)
Test set (T)
6
Select next test case (t)
Compute mutation score
12
Execute P against each test case in T
1
7
t
Execute M against t
P(t) for all tests t in T
M(t)
P(t)
Adequacy of T with respect to mutation
8
9
Distinguished mutants (D)
Add M to D
No
Is P(t) = M(t)?
Yes

1 - PROGRAM EXECUTION

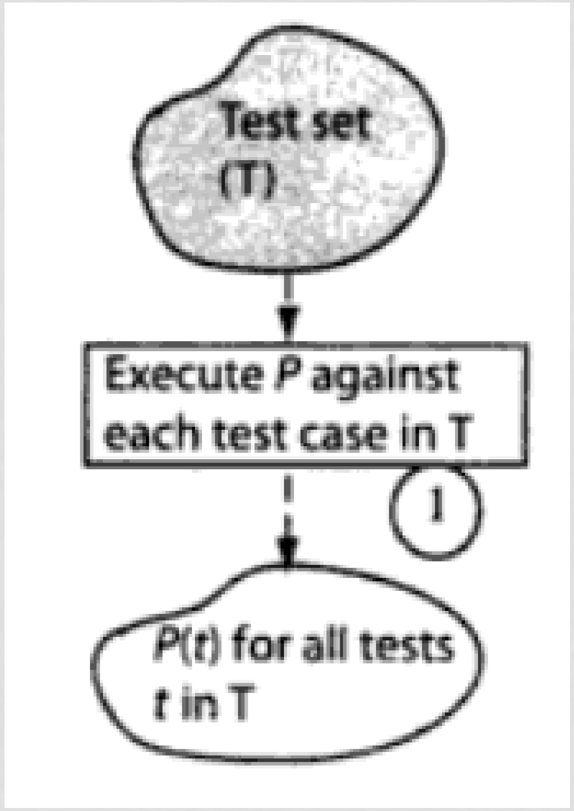


P is supposed to compute the following function $f(x, y)$:

$$f(x,y) = \begin{cases} x + y & \text{if } x < y, \\ x * y & \text{otherwise.} \end{cases}$$

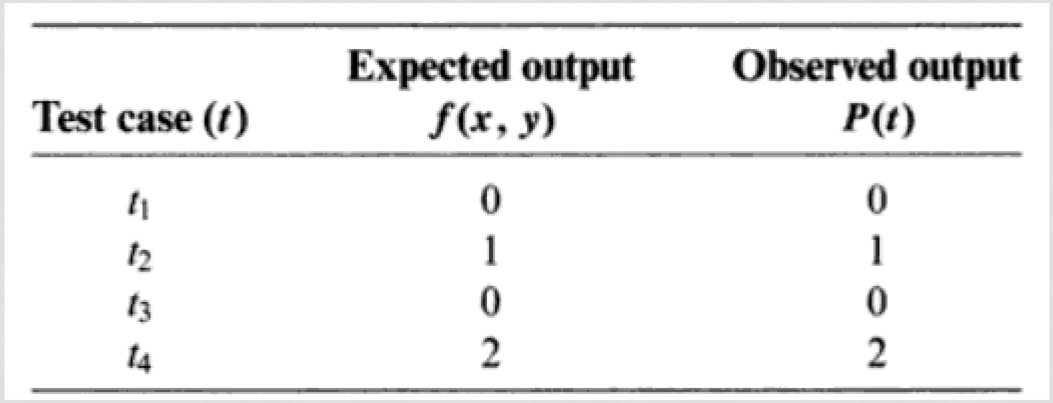
Suppose we have tested P against the following set of tests:

$$T_P = \left\{ \begin{array}{l} t_1 : < x = 0, y = 0 >, \\ t_2 : < x = 0, y = 1 >, \\ t_3 : < x = 1, y = 0 >, \\ t_4 : < x = -1, y = -2 > \end{array} \right\}$$


Test set (T)
Execute *P* against each test case in T
1
P(*t*) for all tests *t* in T

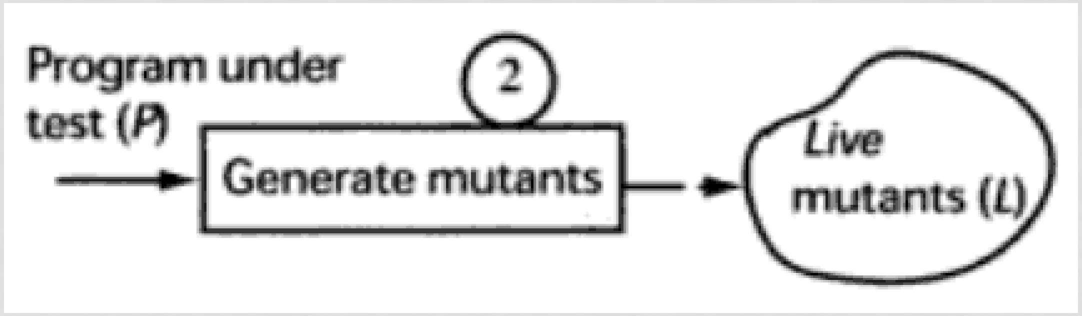
1 - PROGRAM EXECUTION

```
begin
        int x, y;
        input(x,y);
        if(x<y)
                output(x+y);
        else
                output(x*y);
end
```



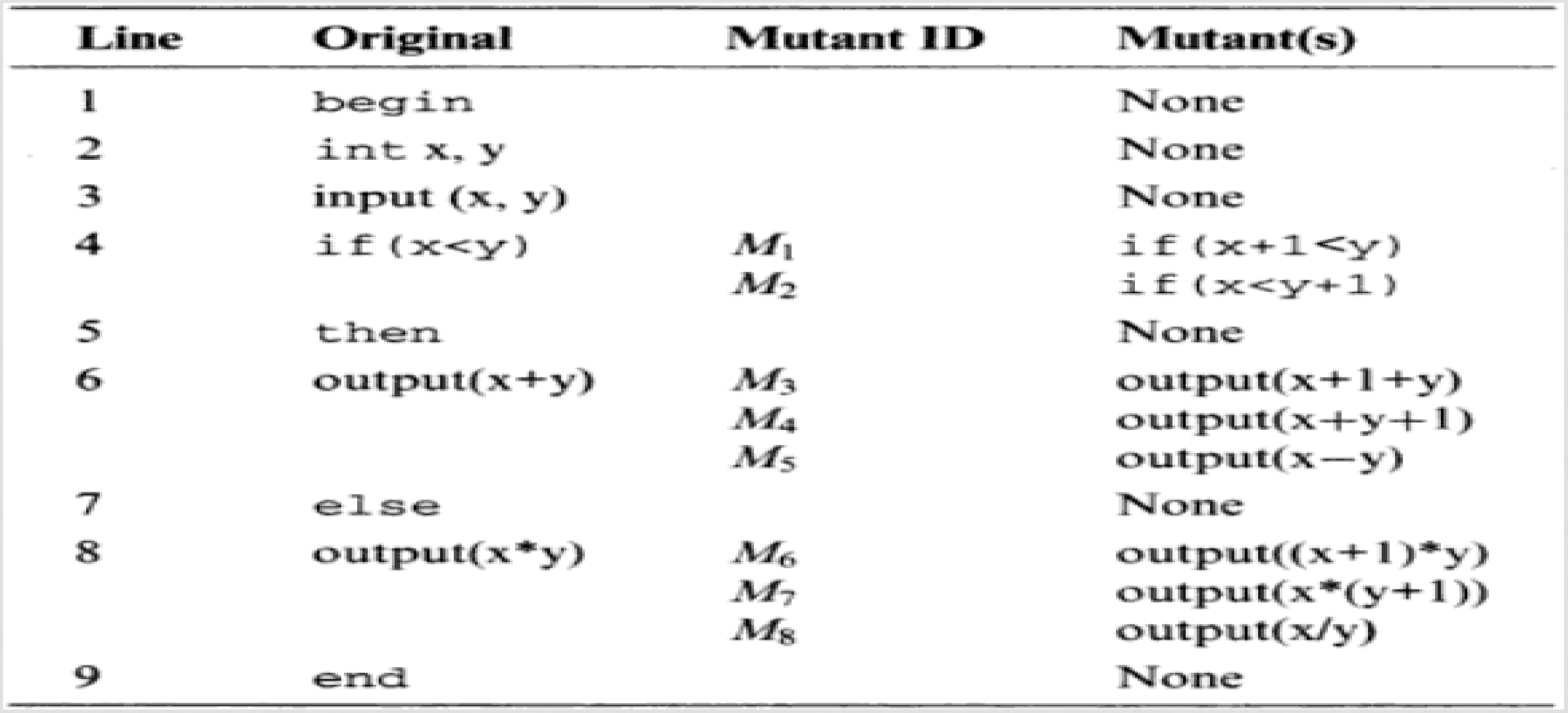
Test case (t)	Expected output $f(x, y)$	Observed output $P(t)$
t_1	0	0
t_2	1	1
t_3	0	0
t_4	2	2

2 - MUTANT GENERATION



- Replace ‘+’ with ‘–’
- Replace ‘*’ with ‘/’
- Replace variable ’v’ with ‘v+1’

2 - MUTANT GENERATION

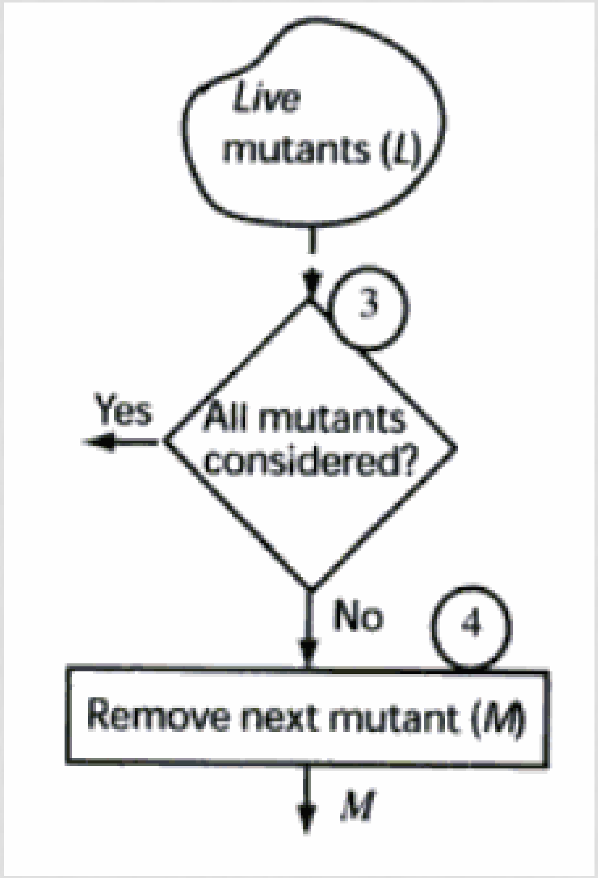


Line	Original	Mutant ID	Mutant(s)
1	`begin`		None
2	`int x, y`		None
3	input (x, y)		None
4	`if(x<y)`	M_1	`if(x+1<y)`
		M_2	`if(x<y+1)`
5	`then`		None
6	output(x+y)	M_3	output(x+1+y)
		M_4	output(x+y+1)
		M_5	output(x−y)
7	`else`		None
8	output(x*y)	M_6	output((x+1)*y)
		M_7	output(x*(y+1))
		M_8	output(x/y)
9	`end`		None

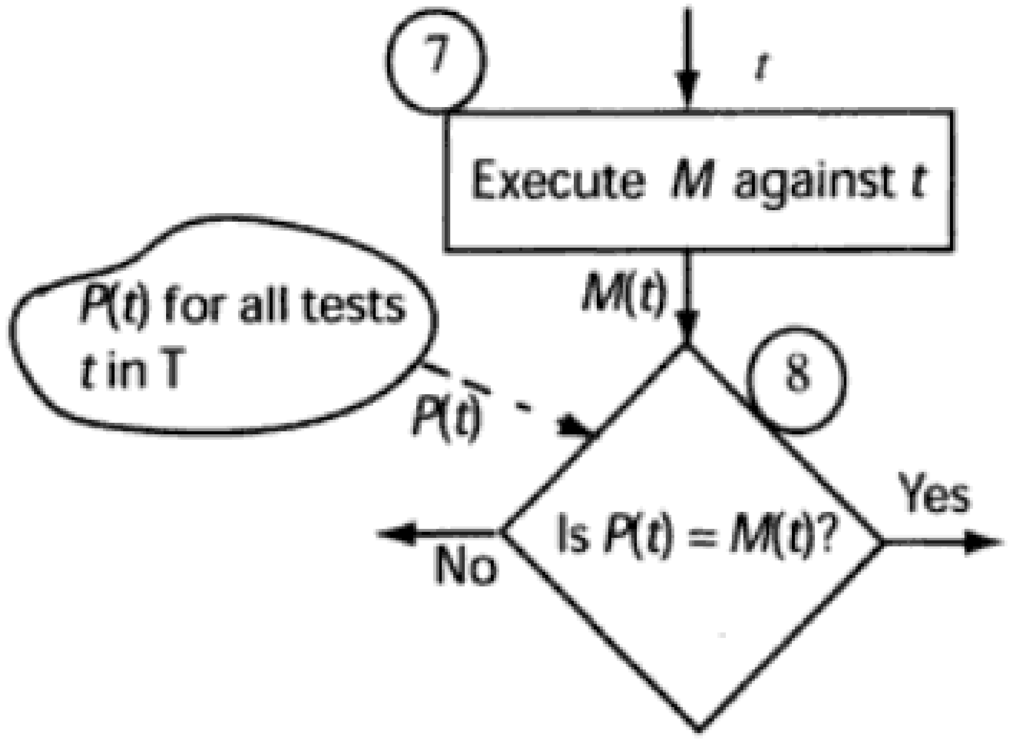
L = {M1, M2, M3,M4,M5, M6,M7,M8}

3 & 4 - SELECT NEXT MUTANT

L = {M1, M2, M3,M4,M5,M6,M7,M8}



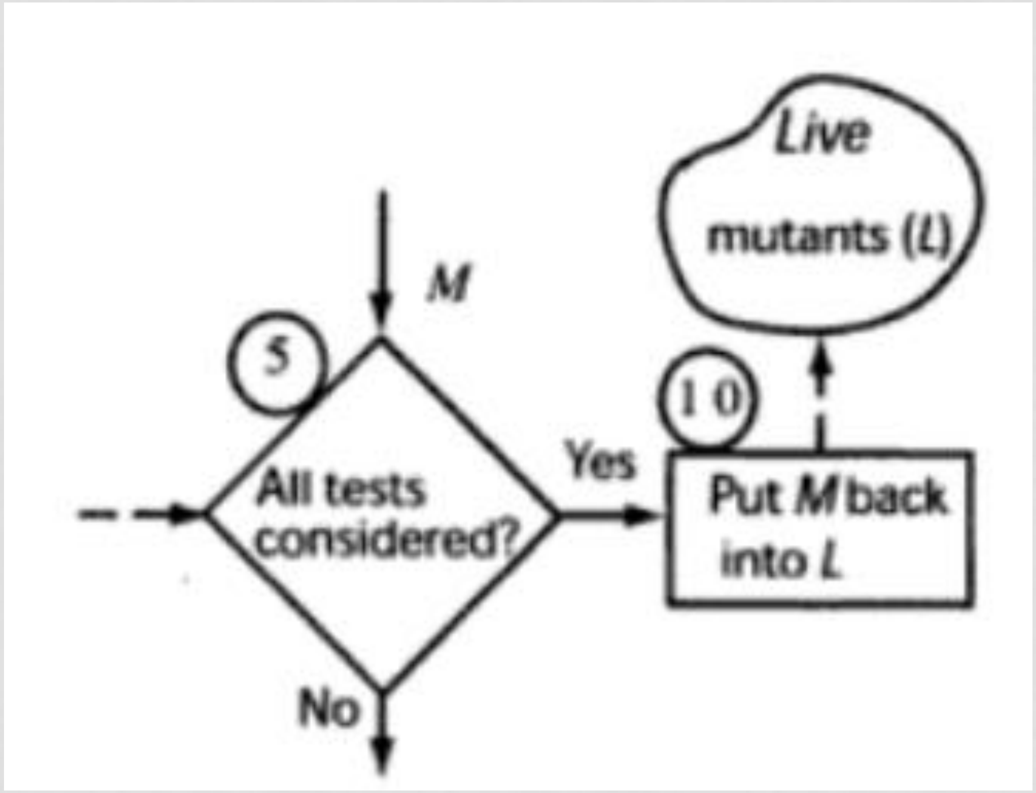
7, 8 & 9 – MUTANT EXECUTION AND CLASSIFICATION



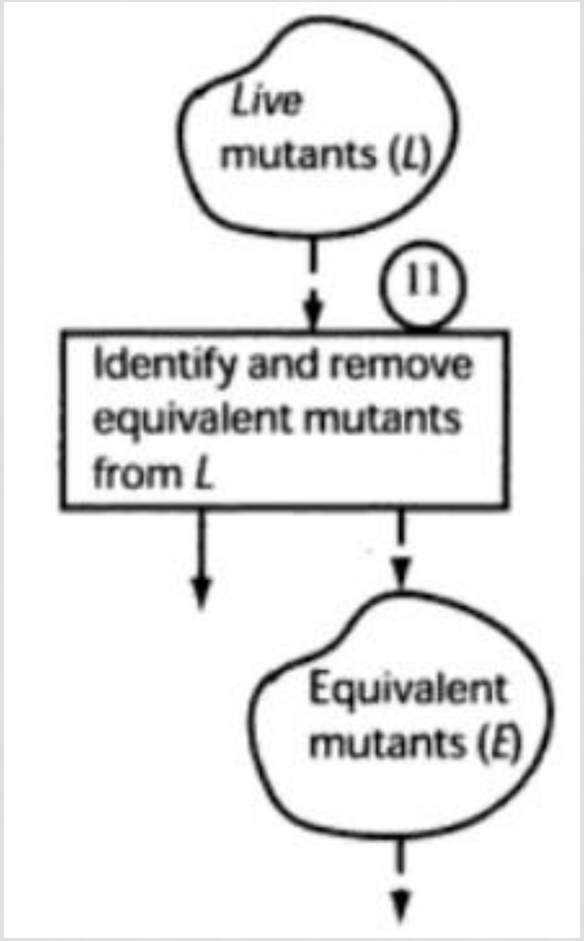
7, 8 & 9 – MUTANT EXECUTION AND CLASSIFICATION

Program	**t1**	**t2**	**t3**	**t4**	**D**
P(t)	0	1	0	2	{}
Mutant					
M1(t)	0	0*	NE	NE	{M1}
M2(t)	0	1	0	2	{}
M3(t)	0	2*	NE	NE	{M1, M3, M4}
M4(t)	0	2*	NE	NE	{M1, M3, M4, M5}
M5(t)	0	-1*	NE	NE	{M1, M3}
M6(t)	0	1	0	0*	{M1, M3, M4, M5, M6, M7}
M7(t)	0	1	1*	NE	{M1, M3, M4, M5, M6, M7, M8}
M8(t)	U*	NE	NE	NE	{M1, M3, M4, M5, M6}

10 - LIVE MUTANTS



11 – CHECK IF EQUIVALENT MUTANT



$$f_P(x, y) = \begin{cases} x + y & \text{if } x < y, \\ x * y & \text{otherwise.} \end{cases}$$

$$g_{M_2} P(x, y) = \begin{cases} x + y & \text{if } x < y + 1, \\ x * y & \text{otherwise.} \end{cases}$$

Not a equivalent mutant because we can add an extra test case such that Mutant can be distinguished.

$$t :< x = 1, y = 1 >$$

EQUIVALENT MUTANT EXAMPLE

Sample Program P

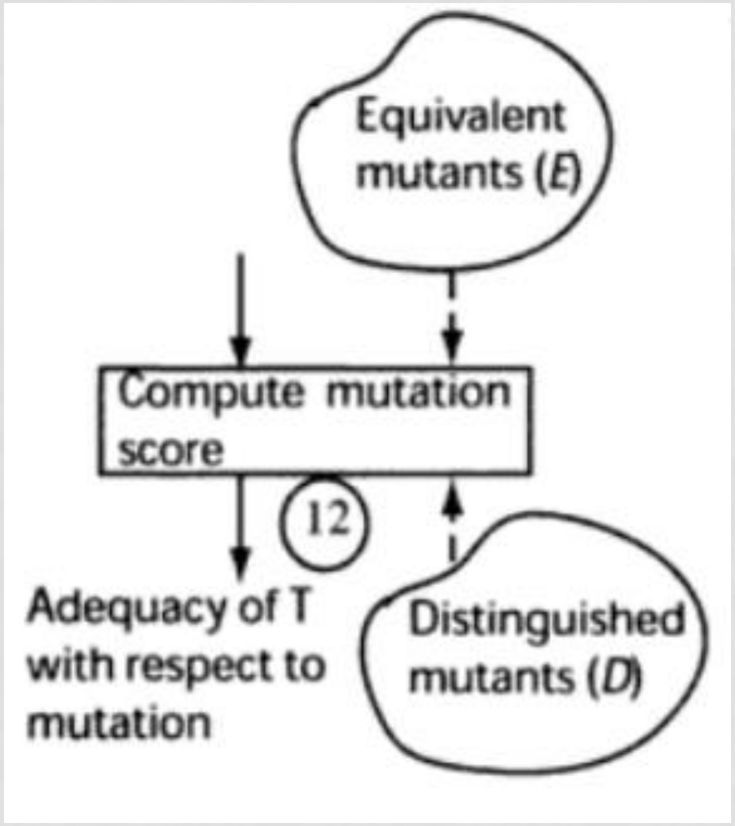
```
……
……
if(x == 2 && y == 2)
 z = x + y;
……
```

Mutant P’

```
……
……
if(x == 2 && y == 2)
 z = x * y;
……
```

The value of Z will be equal to 4; any test set will be unable to determine any faults with this program because the value will always be equal to 4.

12 – COMPUTATION OF MUTATION SCORE



Equivalent mutants (E)
Compute mutation score
12
Adequacy of T with respect to mutation
Distinguished mutants (D)

If no equivalent mutants

$$MS = \frac{|D|}{|D| + |L|}$$

With equivalent mutants

$$MS = \frac{|D|}{|M| - |E|}$$

HIGH COST MUTATION TESTING

- The main drawback of mutation testing is the high cost of running vast number of mutants against the set of test cases.
- The number of mutants generated for a program is proportional to the product of the number of data references and the number of data objects.
- This number is large for even small programs.

ERROR DETECTION USING MUTATION

- Consider the following function foo that is required to return the sum of two integers x and y. Clearly foo is incorrect.

```
int foo(int x, y){
return (x-y);          ←——    This should be return (x+y)
}
```

ERROR DETECTION USING MUTATION

- Now suppose that foo has been tested using a test set T that contains two tests:

T={ t1: <x=1, y=0>, t2: <x=-1, y=0>}

- First note that foo behaves perfectly fine on each test in, i.e. foo returns the expected value for each test case in T. Also, T is adequate with respect to all control and data flow based test adequacy criteria.

ERROR DETECTION USING MUTATION

Let us evaluate the adequacy of T using mutation. Suppose that the following three mutants are generated from foo.

M1:
```
int foo(int x, y){
return (x+y);
}
```

M2:
```
int foo(int x, y){
return (x-0);
}
```

M3:
```
int foo(int x, y){
return (0+y);
}
```

- Note that M1 is obtained by replacing the - operator by a + operator, M2 by replacing y by 0, and M3 by replacing x by 0.

ERROR DETECTION USING MUTATION

Next we execute each mutant against tests in T until the mutant is distinguished or we have exhausted all tests. Here is what we get.

T={ t1: <x=1, y=0>, t2: <x=-1, y=0>}

Test (t)	foo(t)	M1(t)	M2(t)	M3(t)
t1	1	1	1	0
t2	-1	-1	-1	0
		Live	Live	Killed

ERROR DETECTION USING MUTATION

After executing all three mutants we find that two are live and one is distinguished. Computation of mutation score requires us to determine of any of the live mutants is equivalent.

Determine whether or not the two live mutants are equivalent to foo and compute the mutation score of T.

ERROR DETECTION USING MUTATION

Let us examine the following two live mutants.

M1:
```
int foo(int x, y){
return (x+y);
}
```

M2:
```
int foo(int x, y){
return (x-0);
}
```

Let us focus on M1. A test that distinguishes M1 from foo must satisfy the following condition:

$x-y \neq x+y$ implies $y \neq 0$.

Hence we get t3: <x=1, y=1>

ERROR DETECTION USING MUTATION [7]

Executing foo on t3 gives us foo(t3)=0. However, according to the requirements we must get foo(t3)=2. Thus t3 distinguishes M1 from foo and also reveals the error. Correct the error and restart mutation testing from step 1

M1:
```
int foo(int x, y){
return (x+y);
}
```

M2:
```
int foo(int x, y){
return (x-0);
}
```