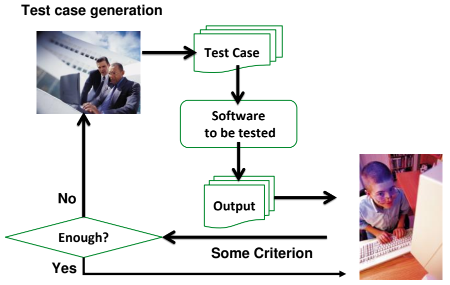
## Week 1

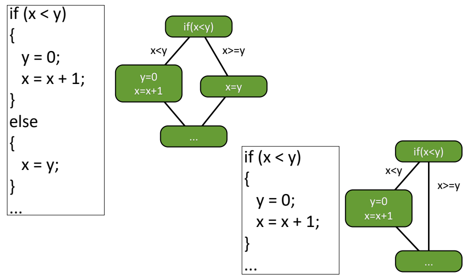
**Software testing**: process of executing program/system with intent of finding errors
**Fault**: incorrect portions of code (can be missing as well as incorrect)
**Failure**: observable correct behaviour of program
**Error**: cause of fault, something bad programmer did (conceptual, typo, etc)
**Bug**: informal term for fault
**Test case**: set of test inputs, execution conditions, expected results developed for particular objective, such as to exercise particular program path ot verify compliance with specific requirement

### A Typical Software Testing Process


Test case generation
Test Case
Software to be tested
Output
No
Enough?
Some Criterion
Yes

**Testing**: find inputs that cause failure of software, failure unknown, performed by testers
**Debugging**: process of finding & fixing fault given failure, failure is known, performed by devs
**Black-Box/Functional Testing**: identify functions & design test cases to check whether functions are correctly performed by software (formal & informal specs)
**Equivalence partitioning**: divide into partitions, select 1 test case from each partition, partitions must be disjointed (no input belongs to more than 1 partition) & all partitions must cover entire input domain
**Equivalence partitioning examples**: isEven then even & odd, password min 8 & max 12 characters then less than, valid, more than
**Boundary-Value analysis**: partition input domain, identify boundaries, select test data (for range $[R_1, R_2]$ less than $R_1$, equal to $R_1$, between, equal to $R_2$, greater than $R_2$, for unordered sets select in & not in, for equality select equal & not equal, for sets, lists select empty & not empty)
**White box/structural testing**: generate test cases based on program structure, abstract program to control flow graph (node is sequence of statements, edge is transfers of control)

### CFG : The if statement



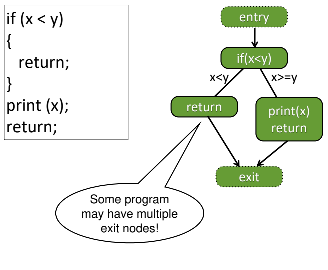
```
if (x < y)
{
  y = 0;
  x = x + 1;
}
else
{
  x = y;
}
...
```

if(x<y)
x<y
x>=y
y=0
x=x+1
x=y
...

```
if (x < y)
{
  y = 0;
  x = x + 1;
}
...
```

if(x<y)
x<y
x>=y
y=0
x=x+1
...

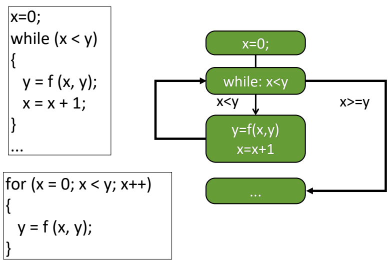
### CFG : The dummy nodes



```
if (x < y)
{
  return;
}
print (x);
return;
```

entry
if(x<y)
x<y
x>=y
return
print(x)
return
exit
Some program may have multiple exit nodes!

### CFG : while and for loops

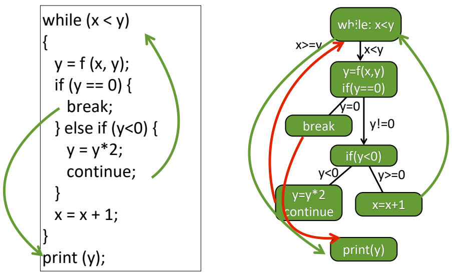


```
x=0;
while (x < y)
{
  y = f (x, y);
  x = x + 1;
}
...
```

```
for (x = 0; x < y; x++)
{
  y = f (x, y);
}
```

x=0;
while: x<y
x<y
x>=y
y=f(x,y)
x=x+1
...

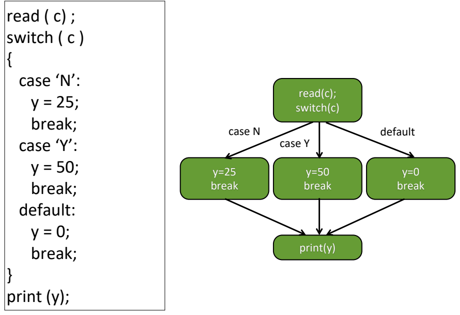
### CFG: break and continue



```
while (x < y)
{
  y = f (x, y);
  if (y == 0) {
    break;
  } else if (y<0) {
    y = y*2;
    continue;
  }
  x = x + 1;
}
print (y);
```

while: x<y
x>=y
x<y
y=f(x,y)
if(y==0)
y=0
y!=0
break
if(y<0)
y<0
y>=0
y=y*2
continue
x=x+1
print(y)

### CFG: switch



```
read ( c) ;
switch ( c )
{
  case 'N':
    y = 25;
    break;
  case 'Y':
    y = 50;
    break;
  default:
    y = 0;
    break;
}
print (y);
```

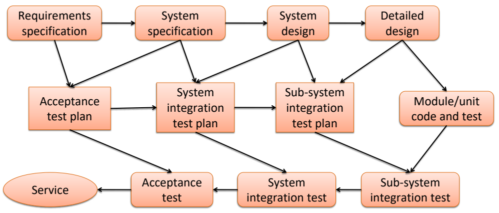
read(c);
switch(c)
case N
case Y
default
y=25
break
y=50
break
y=0
break
print(y)

**Coverage types**: statement, branch, path (infinite if loop exists), strictly subsumes all beforehand

## Week 2

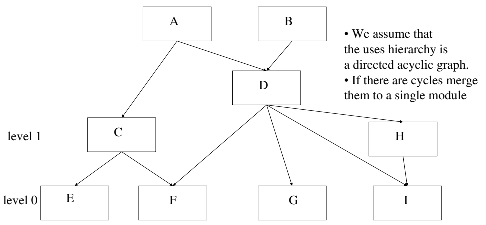
**Test oracle**: expected output of software for given input, part of test case
**Test driver**: software framework that can load collection of test cases or test suite
**Test suite**: collection of test cases

### The V-model of development


Requirements specification
System specification
System design
Detailed design
Acceptance test plan
System integration test plan
Sub-system integration test plan
Module/unit code and test
Service
Acceptance test
System integration test
Sub-system integration test

**Testing types**:
*Unit/Module*: test single module in isolated environment, use drivers & stubs for isolation
*Integration*: test parts of system by combining modules, integrated collection of modules tested as group or partial system
*System*: test system as a whole after integration phase
*Acceptance*: test system as a whole to find out if it satisfies requirements specifications
**Driver**: program that calls interface procedures of module being tested & reports results, simulates module that calls module currently being tested, also provides access to global variables for module under test
**Stub**: program that has same interface as module being used by module being tested but simpler, simulates module called by module being tested
**Mock objects**: create object that mimics behaviour needed for testing

### Module Structure


A
B
D
C
H
E
F
G
I
level 1
level 0

- We assume that the uses hierarchy is a directed acyclic graph.
- If there are cycles merge them to a single module

- A uses C and D; B uses D; C uses E and F; D uses F, G, H and I; H uses I
- Modules A and B are at level 3; Module D is at level 2
Modules C and H are at level 1; Modules E, F, G, I are at level 0
- level 0 components do not use any other components
- level *i* components use at least one component on level *i*-1 and no component at a level higher than *i*-1

**Integration types**:
*Bottom-Up*: only terminal modules tested in isolation, requires drivers but not stubs (since lower levels are tested already)
*Top-down*: modules tested in isolation are modules at highest level, requires stubs but not drivers
*Sandwich*: begin both bottom-up & top-down, meet at predetermined point in middle
*Big bang*: every module unit tested, then integrate all at once, no driver or stub needed but may be hard to isolate bugs
**System/Acceptance testing**: can construct test case based on requirements specifications, main purpose is to assure that system meets requirements, alpha testing performed within development organisation, beta testing performed by select group of friendly customers

## Week 3

**Basis Path Testing**: between branch & path coverage, fulfills branch testing & tests all independent paths that could be used to construct any arbitrary path through computer program
**Independent path**: includes some vertices/edges not covered in other path
**Cyclomatic complexity**: $e - n + 2p$, $e$ is edges, $n$ is nodes, $p$ is number of connected components, or $1 + d$, $d$ is loops or decision points, upper bound on number of test cases to guarantee coverage of all statements
**Decision Coverage**: executing true/false of decision
**Condition Coverage**: executing true/false of each condition
**Condition/Decision Coverage**: DC & CC, better than either
**Multiple Condition Coverage**: whether every possible combination of boolean sub-expressions occurs, test cases are truth table, $2^n$ test cases for $n$ conditions
**Modified C/DC**: for each basic condition $C$, 2 test cases, values of all evaluated conditions except $C$ are the same, compound decision as a whle evaluates to true for 1 & false for the other, subsumed by MCC & subsumes CC, DC, C/DC, stronger than statement & branch
**MC/DC coverage**: each entry & exit point invoked, each decision takes every possible outcome, each condition in a decision takes every possible outcome, each condition in decision is shown to independently affect outcome of decision, independence of condition is shown by proving that only one condition changes at a time

### MC/DC: linear complexity

- N+1 test cases for N basic conditions

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

| Test Case | a | b | c | d | e | outcome |
|---|---|---|---|---|---|---|
| (1) | $\underline{\text{true}}$ | -- | $\underline{\text{true}}$ | -- | $\underline{\text{true}}$ | true |
| (2) | false | $\underline{\text{true}}$ | true | -- | true | true |
| (3) | true | -- | false | $\underline{\text{true}}$ | true | true |
| (4) | true | -- | true | -- | $\underline{\text{false}}$ | false |
| (5) | true | -- | $\underline{\text{false}}$ | $\underline{\text{false}}$ | -- | false |
| (6) | $\underline{\text{false}}$ | $\underline{\text{false}}$ | -- | false | -- | false |

- Underlined values independently affect the output of the decision

Table 1. Types of Structural Coverage

| Coverage Criteria | Statement Coverage | Decision Coverage | Condition Coverage | Condition/ Decision Coverage | MC/DC | Multiple Condition Coverage |
|---|---|---|---|---|---|---|
| Every point of entry and exit in the program has been invoked at least once | | • | • | • | • | • |
| Every statement in the program has been invoked at least once | • | | | | | |
| Every decision in the program has taken all possible outcomes at least once | | • | | • | • | • |
| Every condition in a decision in the program has taken all possible outcomes at least once | | | • | • | • | • |
| Every condition in a decision has been shown to independently affect that decision's outcome | | | | | • | •[8] |
| Every combination of condition outcomes within a decision has been invoked at least once | | | | | | • |

## Week 4

**Dataflow Coverage**: considers how data gets accessed & modified in system & how it can get corrupted
**Common access-related bugs**: using unde

fined/uninitializsed variable, deallocating/reinitialising variable before constructed/initialised/used, deleting collection object leaving members unaccessible

**Variable definition**: defined whenever value modified (LHS of assignment, input statement, call-by-reference)

**Variable use**: used whenever value read (RHS of assignment, call-by-value, branch statement predicate)

**p-use**: use in predicate of branch statement

**c-use**: any other use

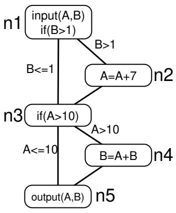
**Use & redefine in single statement**: both sides of assignment, call-by-reference

**du-pair**: with respect to variable $v$ is a pair $(d, u)$ such that $d$ is a node defining $v$, $u$ is a node/edge using $v$ (if p-use $u$ is outgoing edge of predicate), there is a def-clear path with respect to $v$ from $d$ to $u$

**Definition clear**: with respect to variable $v$ if no variable re-definition of $v$ on path

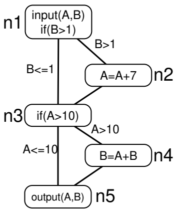
## Identifying du-pairs – variable **A**

| du-pair | path(s) |
|---|---|
| (1,2) | <1,2> |
| (1,4) | <1,3,4> |
| (1,5) | <1,3,4,5> |
|  | <1,3,5> |
| (1,<3,4>) | <1,3,4> |
| (1,<3,5>) | <1,3,5> |
| (2,4) | <2,3,4> |
| (2,5) | <2,3,4,5> |
|  | <2,3,5> |
| (2,<3,4>) | <2,3,4> |
| (2,<3,5>) | <2,3,5> |



## Identifying du-pairs – variable **B**

| du-pair | path(s) |
|---|---|
| (1,4) | <1,2,3,4> |
|  | <1,3,4> |
| (1,5) | <1,2,3,5> |
|  | <1,3,5> |
| (1,<1,2>) | <1,2> |
| (1,<1,3>) | <1,3> |
| (4,5) | <4,5> |



**Dataflow test coverage criteria**:

*All-Defs*: for every variable $v$, at least one def-clear path from every definition of $v$ to at least one c-use or p-use of $v$ must be covered

*All-P/C-Uses*: for every variable $v$, at least one def-clear path from every definition of $v$ to every p/c-use of $v$ must be covered

*All-Uses*: all du-pairs covered

**Notations**:

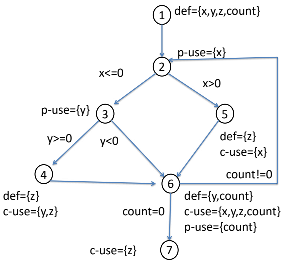
$d_1(x)$: definition of variable $x$ in node $i$

$u_i(x)$: use of variable $x$ in node $i$ $dcu(d_i(x)) = dcu(x, i)$: set of c-uses with respect to $d_1(x)$

$dpu(d_i(x)) = dpu(x, i)$: set of p-uses with respect to $d_1(x)$

## Another Example

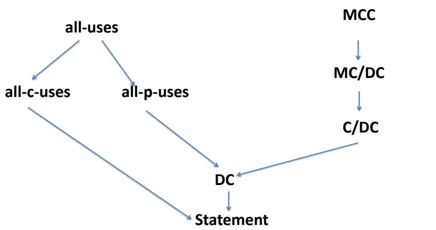
```
begin
   float x,y,z=0.0;
   int count;
   input(x,y,count);
   do{
     if(x≤0) {
       if(y≥0)  {
         z=y*z+1;
       }
     }
     else{
      z=1/x;
     }
     y=x*y+z;
     count=count-1;}
   while(count>0)
   output(z);
end
```



**All-C-Uses for above**: $dcu(x,1) + dcu(y,1) + dcu(y,6) + dcu(z,1) + dcu(z,4) + dcu(z,5) + dcu(count,1) + dcu(count,6) = 2+2+2+3+3+3+1+1 = 17$

**All-P-Uses for above**: $dpu(x,1) + dpu(y,1) + dpu(y,6) + dpu(z,1) + dpu(z,4) + dpu(z,5) + dpu(count,1) + dpu(count,6) = 2+2+2+0+0+0+2+2 = 10$ (note this includes using the initial count definition even though it will always be redefined (-1) before the comparison)

## Relationships among some of the coverage criteria



**Week 5**

**Program mutation**: create artificial bugs by injecting changes to statements of programs, simulate subtle bugs in real programs

**Mutation testing**: software testing technique based on program mutation, can be used to evaluate test effectiveness & enhance test suite, can be stronger than control/data-flow coverage, extremely costly since need to run whole test suite against each mutant

**Mutation testing steps**: applies artificial changes based on mutation operators to generate mutants (each mutant with ony one artificial bug), run test suite against each mutant (if any test fails mutant killed, else survives), compute mutation score

**Symbolic execution/evaluation**: analyse program to determine what inputs cause each part of program to execute, execute programs with symbols (track symbolic state rather than concrete input, when execute one path actually simulate many test inputs (since considering all inputs that can exercise same path))

**Problems with symbolic execution**:

*Path explosion*: $2^n$ paths for $n$ branches, infinite paths for unbounded loops, calculate constraints for all paths is infeasible for real software

*Constraint too complex*: especially for large programs, also it is NP-complete

**Input sub-domain**: set of inputs satisfying path condition

**Searching input to execute path**: equivalent to solving associated path condition

## Example

```
y = read();                y=s, s is a symbolic variable for input
p = 1;                    p = 1, y = s
while(y < 10){            p = 1, y = s
      y = y + 1;           s<10, y = s + 1, p = 1
      if y >2
        p = p + 1;           2 < s + 1< 10, y = s + 1, p = 2
       else
        p = p + 2;          s + 1<=2, y = s + 1, p = 3
 }
 print (p);
```

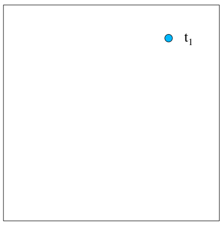
**Week 6**

**Random testing**: random number generator (monkeys) to generate test cases, also called fuzz testing, monkey testing, slelect tests from entire input domain (set of all possible inputs) randomly & independently, no guide towards failure-causing inputs

**Adaptive Random Testing**: achieve even spread of test cases

## Fixed Size Candidate Set ART

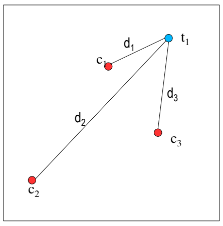
**Step 1.** Randomly select the first input, namely $t_1$, and store it in a list (called **T**)



T= {$t_1$} .

## Fixed Size Candidate Set ART (cont.)

**Step 2.** Construct ***k*** random inputs to form a **candidate set C** = {$c_1$, $c_2$, …, $c_k$}, and measure their distance to $t_1$.

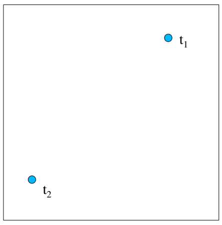


In this example, let set ***k*** = 3.

**C**= {$c_1$, $c_2$, $c_3$} .

## Fixed Size Candidate Set ART (cont.)

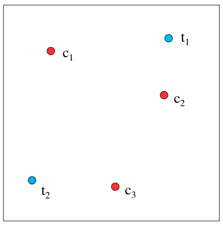
**Step 3.** Select the candidate which is the farthest away from $t_1$ to be the next test case. We name it $t_2$ and store it in **T**.



T= {$t_1$ , $t_2$} .

## Fixed Size Candidate Set ART (cont.)

**Step 4.** Re-construct another **candidate set C** with ***k*** random inputs.

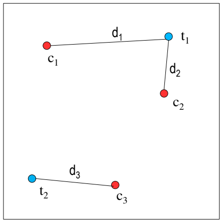


***k*** = 3. Another **C**= {$c_1$, $c_2$, $c_3$} will be constructed

## Fixed Size Candidate Set ART (cont.)

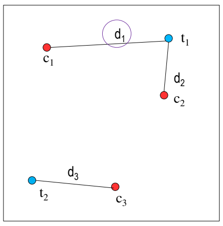
**Step 5.** For each candidate $c_j$ in **C**, do the following

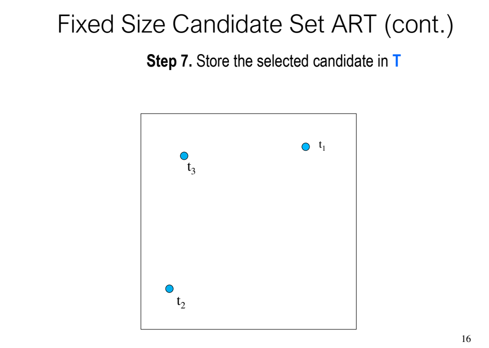
1. find which test case in **T** is the nearest neighbour of $c_j$
2. calculate the distance between $c_j$ and its nearest neighbour.



## Fixed Size Candidate Set ART (cont.)

**Step 6.** Select the candidate with the longest distance to its nearest neighbour.

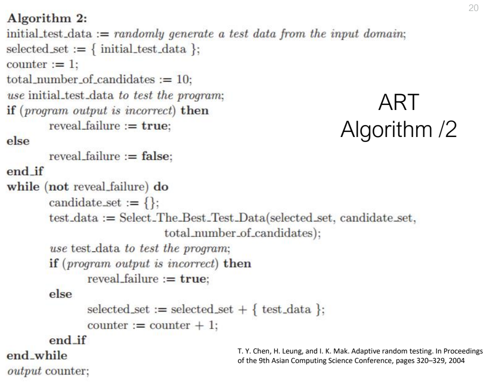




## Fixed Size Candidate Set ART (cont.)

**Step 7.** Store the selected candidate in T

**Distance in ART**: can use Euclidean distance, if $p = (p_1, p_2, \ldots, P_n)$ & $q = (q_1, q_2, \ldots, q_n)$ are 2 points in $n$-dimensional space, $d(p,q) = d(q,p) = \sqrt{(q_1 - p_1)^2 + (q_2 - p_2)^2 + \cdots + (q_n - p_n)^2} = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2}$

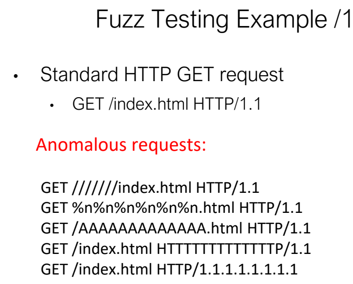


```
Algorithm 2:
initial_test_data := randomly generate a test data from the input domain;
selected_set := { initial_test_data };
counter := 1;
total_number_of_candidates := 10;
use initial_test_data to test the program;
if (program output is incorrect) then
        reveal_failure := true;
else
        reveal_failure := false;
end_if
while (not reveal_failure) do
        candidate_set := {};
        test_data := Select_The_Best_Test_Data(selected_set, candidate_set,
                              total_number_of_candidates);
        use test_data to test the program;
        if (program output is incorrect) then
                reveal_failure := true;
        else
                selected_set := selected_set + { test_data };
                counter := counter + 1;
        end_if
end_while
output counter;
```

ART
Algorithm /2

T. Y. Chen, H. Leung, and I. K. Mak. Adaptive random testing. In Proceedings of the 9th Asian Computing Science Conference, pages 320–329, 2004

**Random white-box testing**: generate random method invocations & random parameters
**Fuzz testing**: random testing technique that involves providing invalid, unexpected or random data as inputs to program, commonly used to discover coding errors & unknown vulnerabilities in software, OS or networks by inputting massive amounts of random data (fuzz) to system in attempt to make it crash, cost-effective alternative to more systematic testing techniques



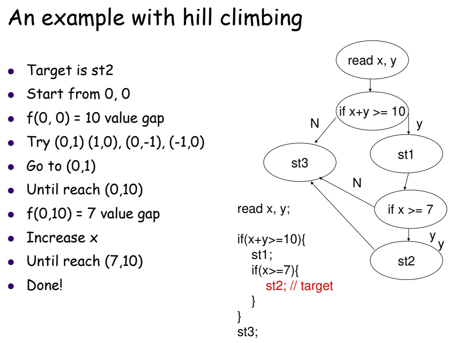
## Fuzz Testing Example /1

- Standard HTTP GET request
  - GET /index.html HTTP/1.1

Anomalous requests:

```
GET ///////index.html HTTP/1.1
GET %n%n%n%n%n%n.html HTTP/1.1
GET /AAAAAAAAAAAAA.html HTTP/1.1
GET /index.html HTTTTTTTTTTTTTP/1.1
GET /index.html HTTP/1.1.1.1.1.1.1.1
```

**Ways to generate inputs**:
*Mutation based/dumb fuzzing*: little/no knowledge of input sctructure assumed, anomalies added to existing valid inputs, may be completely random of follow heuristics (remove NL, shift char forward), get inputs, optionally mutate them, feed it to program, record if it crached & input causing it
*Generation based smart fuzzing*: test cases generated from some description fo format (RFC, docs, etc), anomalies added to each possible spot in inputs, knowledge of protocol should give better results than random fuzzing
**Fuzzing rules of thumb**: protocol specific knowledge very helpful (generational tends to beat mutation, better specs make better fuzzers), more fuzzers better (each implementation varies different fuzzers find different bugs), the longer it runs the more bugs found, best results come from guiding process (notice where get stuck, use profiling), code coverage useful for guiding process
**Fuzz testing +/-**: intuitively simple, but need to figure out how to check the output, corner faults might escape detection, debugging with randomly generated input is challenging
**Search-based testing**: deem test case generation as search problem, based on random testing & focus on input domains, use code coverage as guidance (try to generate test case that covers certain code element such as method, statement, branch)
**Metaheuristic search**:
*Hill climbing*: start from random point, try all neighboring points, go to point with highest value until all neighboring points have value lower than current point, easy to find local optimal
*Annealing simulation*: adaptation of hill climbing, has probability to move after reached local peak, probability drops as time goes by
*Genetic algorithm*: simualte process of evolution, start with random points, select number of best points, combine & mutate points until no more improvements can be made
**Transform testing to search**: list of random test cases as start point, each test case is point in input domain, use various metaheuristic search algorithms to find test cases, measure how well we have solved the problem (use simeple fitness function, how fat is already covered elements from target code elements, try to make it 0)



## An example with hill climbing

- Target is st2
- Start from 0, 0
- f(0, 0) = 10 value gap
- Try (0,1) (1,0), (0,-1), (-1,0)
- Go to (0,1)
- Until reach (0,10)
- f(0,10) = 7 value gap
- Increase x
- Until reach (7,10)
- Done!

```
read x, y;

if(x+y>=10){
    st1;
    if(x>=7){
        st2; // target
    }
}
st3;
```