软件分析与测试
第三次课：白盒测试

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本次课的主要内容

- 白盒测试中的覆盖准则
- 基于覆盖准则测试用例生成和选择技术
- 白盒测试中的辅助技术

测试的要素

- 对被测软件行为的描述
- 对被测软件功能的正确性的描述（Oracle）
- 测试充分性—测试什么时候终止
  - →Coverage criteria

测试准则 Test Criterion

- **功能**
  - 作为测试可以结束的终止条件;
  - 作为软件质量的一个度量，一个测试集合代表了一个质量等级
  - 用于生成测试用例。如果两个测试集合符合相同的测试准则，我们称他们为等效的。
- **一般定义为某种覆盖（Coverage）**

黑盒测试中的准则

- **检查程序的接口和性能**
  - 尽可能少的测试用例集合来保证对系统的充分测试;
  - 检查所有功能点。
    部分错误不是白盒测试能解决的，如白盒测试不能发现功能缺失的错误。
- **边界值分析（Boundary Value Analysis）**
  - 主要目的是查找域错误 。
  - 先选取边界上一个点作为测试用例。如果这条边界在子域内，再选 一个外点（也就是“临近”边界，但是不在子域中的点）作为测试用例；否则选一个内点作为测试用例。

组合测试中的覆盖

- 按照如下目标设计测试用例

- 给定的一个小正整数 t（称为组合强度，一般为2或者3），测试用例应该覆盖任意 t 个参数的所有取值组合

控制流测试

图模型

- 软件工程（软件测试）中，最常用的模型
- 一些常见的图模型
  - 控制流图 CFG (Control Flow Graph)
    - statements & branches, methods & calls, etc.
  - 状态机 FSMs and statecharts
    - states and transitions
  - Use cases

有向图（Directed Graph）

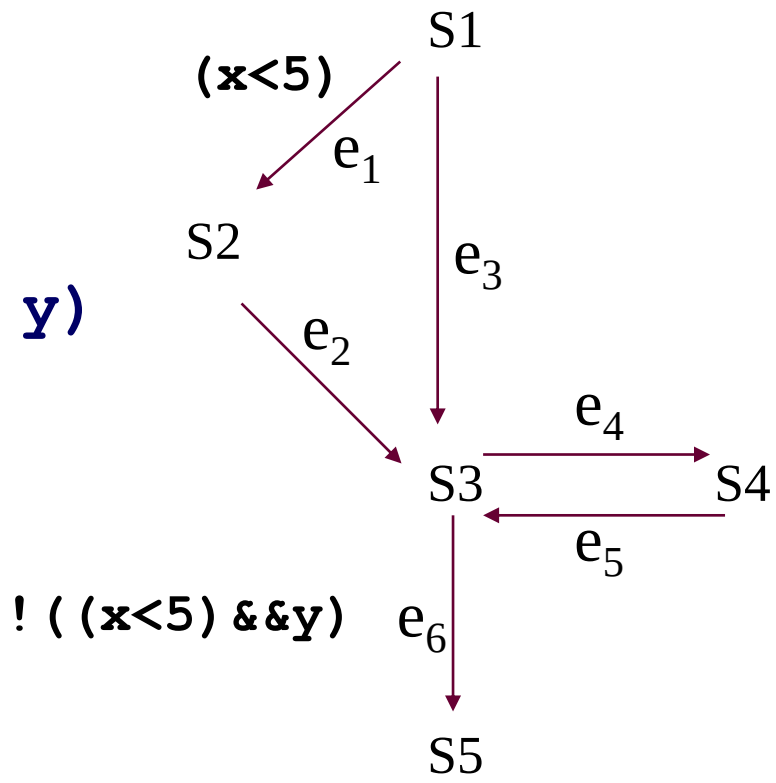
- A set N of nodes, N is not empty
- A set N_0 of initial nodes, N_0 is not empty
- A set N_f of final nodes, N_f is not empty
- A set E of edges, $E \subseteq N \times N$
- Path: A sequence of nodes $p = [n_1, n_2, \ldots, n_k]$
  - Each pair of nodes is an edge
  - Length: (k-1) - the number of edges
- Subpath: A subsequence of nodes in p
- *Reach*(n): Subgraph that can be reached from n

控制流图

- **控制流图（CFG）**
  - 图中每个点（基本块）代表程序中的一系列顺序运算
  - 每条边代表两个节点之间的一个转移
- **控制流图有三种基本结构**
  - 顺序结构
  - 分支结构（**if-then-else, switch-case**）
  - 循环结构（**while, do-while, for**）
- goto语句会破坏程序的结构
  - 程序中尽量避免使用break, continue 等

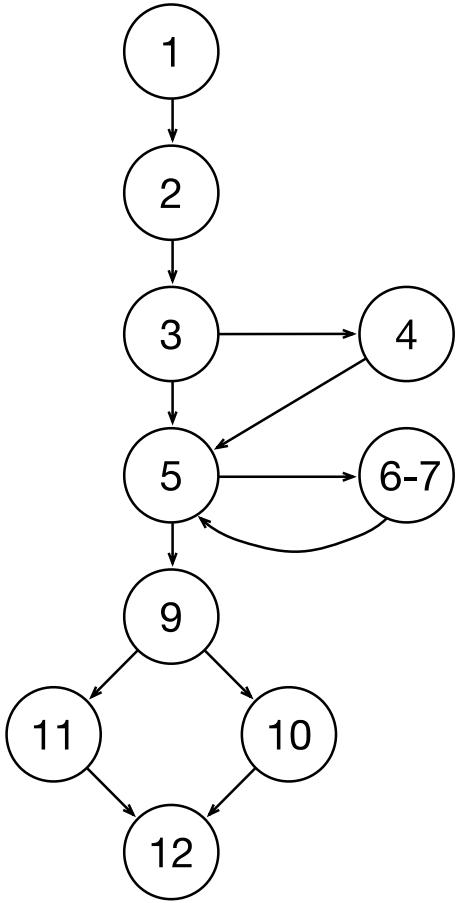
Example. A program and its flow graph

```
        int x, y;
/*S1*/  if (x < 5)
/*S2*/    y = 2;
/*S3*/  while ((x < 5) && y)
/*S4*/    { x++; y--; }
/*S5*/  return;
```



Another Example

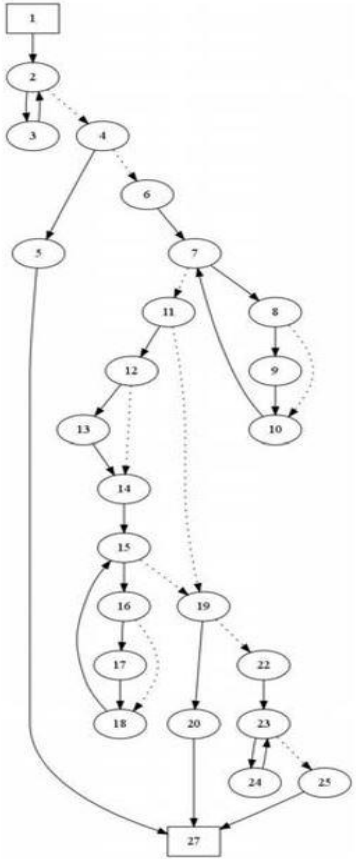
```
1 int maxsum (int maxint, value) {
2     int result = 0, i = 0 ;
3     IF (value < 0)
4     THEN value = - value ;
5     WHILE ((i < value)
        AND (result <= maxint))
6      {   i = i + 1 ;
7          result = result + i ;
8      }
9      IF (result <= maxint)
10    THEN OUTPUT (result);
11    ELSE OUTPUT ("too large");
12 }
```



Yet Another Example (real program)

```
int getop(s, lim)
    char s[];
    int  lim;
{
    int i, c;
    while ((c = getchar()) == ' ' || c == '\t' || c == '\n') ;
    if (c != '.' && (c < '0' || c > '9'))
        return(c);
    s[0] = c;
    for(i = 1; (c=getchar()) >= '0' && c <= '9'; i++)
        if (i < lim) s[i] = c;
    if (c == '.') {if (i < lim)    return(c); …}
    …
}
```

Test Paths




```
1:  c=getchar();
2:  !(((c==32 || c==9) || c==10))
3:  c=getchar();
4:  !((c!=46 && (c<48 || c>57)))
5:  RETURN: c;
6:  s[0]=c; c=getchar(); i=1;
7:  !((c>=48 && c<=57))
8:  !(i<lim)
9:  s[i]=c;
10: c=getchar(); _temp_var0=i; i=i+1;
11: !(c==46)
12: !(i<lim)
13: s[i]=c;
14: c=getchar(); _temp_var1=i; i=i+1;
15: !((c>=48 && c<=57))
16: !(i<lim)
17: s[i]=c;
18: c=getchar(); _temp_var2=i; i=i+1;
19: !(i<lim)
20: s[i]=0; RETURN: 1000;
22: NOP
23: !((c!=10 && c!=-1))
24: c=getchar();
25: _temp_var3=lim-1; s[_temp_var3]=0; RETURN: 9999;
27: END
```

Fig. 1. getop()

Selected paths from its flow graph

- **Path 1**

  1 → 2 → 4 → 5 → 27.

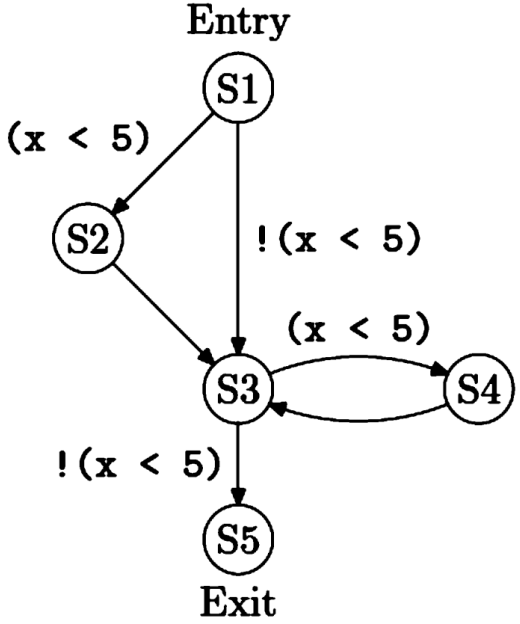
- **Path 2**

  1 → 2 → 4 → 6 → 7 → 11 → 19 → 20 → 27.

测试路径

- **CFG上的路径**
  - 完整路径：***A path that starts at an initial node and ends at a final node***
  - 例：**S1-S2-S3-S4-S3-S5**
- **不可行路径**
  - **S1-S3-S4-S3-S5**
- **不可达点（死代码）**
  - 所有从起点到该点的路径都是不可行的

```
void f(int x）{
/*S1*/ if (x < 5）
/*S2*/ y = 2;
/*S3*/ while (x < 5）
/*S4*/ x++;
/*S5*/ return;
}
```



基于控制流图的结构测试

- 找到一组测试用例（带有输入数据），以覆盖控制流图中的一些基本元素。

- Rationale: it is impossible to detect a fault in some piece of code by testing, if that code is never executed.

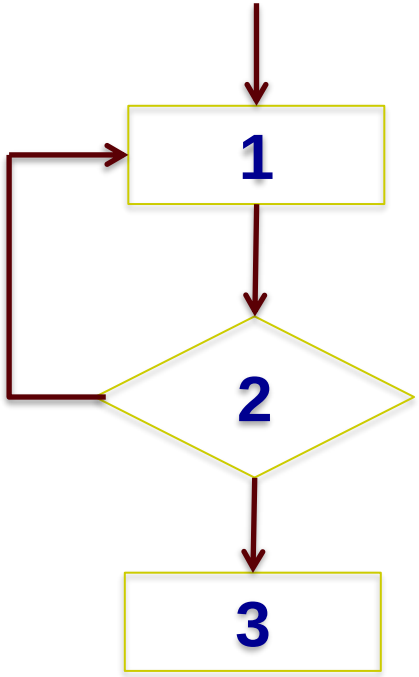
覆盖准则

- 语句覆盖（Statement Coverage）
  - 程序中的所有语句都被执行
  - 覆盖控制流图中所有的节点
- 分支覆盖（Branch Coverage）
  - 控制转移都得到了覆盖
  - 测试路径覆盖了控制流图中所有的边
  - 对应于迁移条件表达式的判定覆盖
- 路径覆盖（Path Coverage）
  - 覆盖控制流图中所有的完整路径
  - 进一步定义可行路径覆盖(Feasible Path Coverage)
  - （可行）路径数量可能是无限的

语句与分支覆盖

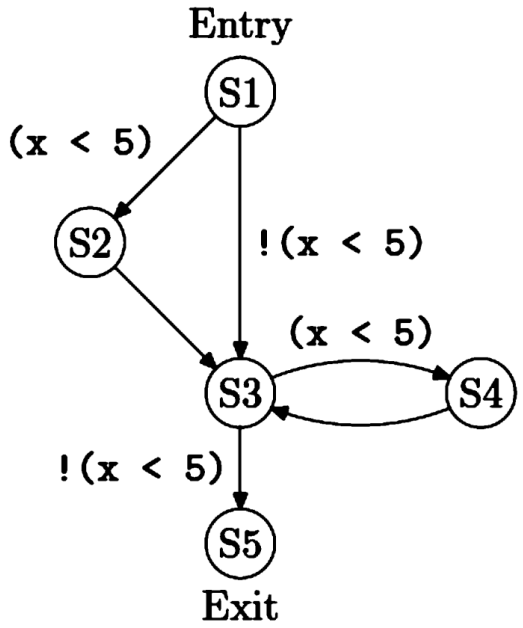
Statement coverage: Path 1, 2, 3

Branch coverage: Path 1, 2, 1, 2, 3

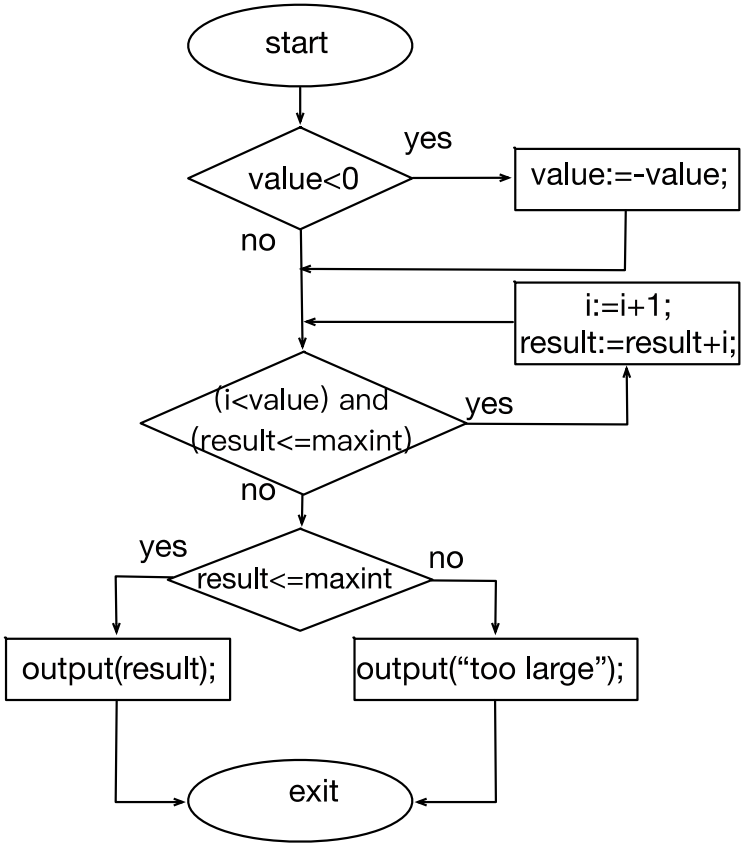


- 语句覆盖
  S1-S2-S3-S4-S3-S5

- 分支覆盖（两条路径）
  S1-S2-S3-S4-S3-S5
  S1-S3-S5



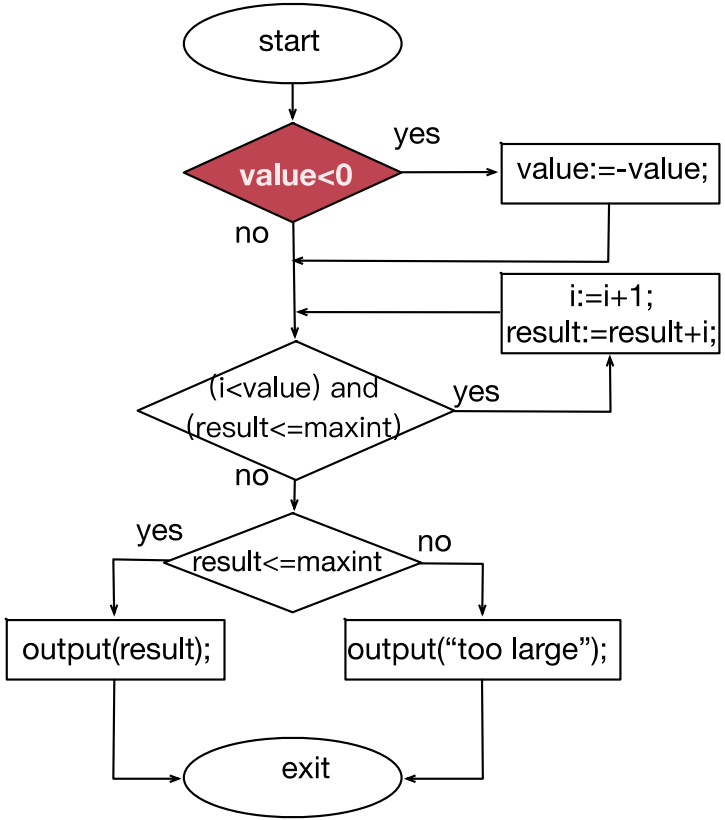
Example: Statement Coverage



Test cases for 100% statement coverage:

maxint	value
10	-1
0	-1

Example : Branch Coverage



Test cases for 100% branch coverage:

maxint	value
10	2
0	-1

路径覆盖准则

- **长度*n*准则（Length-*n*）**
  - 测试路径集合覆盖所有长度不超过***n*** 的子路径
  - **Length-0** 对应语句覆盖, **Length-1** 对应分支覆盖
- **简单路径覆盖（Simple Path Coverage）和初等路径覆盖（Elementary Path Coverage）**
  - **a path that has no repeated occurrence of any *edge* is called a simple path in graph theory**
  - **a path that has no repeated occurrences of any *node* is called an elementary path.**
- **Level-*i* 覆盖**
  - **The criterion starts with testing all elementary paths from the begin node to the end node. Then, if there is an elementary subpath or cycle that has not been exercised, the subpath is required to be checked at the next level. This process is repeated until all nodes and edges are covered by testing.**

循环体测试

- 循环 *K* 次准则
  - 最常用：0-1循环覆盖准则
- 循环体有三种:
  - 简单循环 (Simple Loops）
  - 嵌套循环 (Nested loops）
  - 串联循环 (Concatenated Loops）
- 对每个循环分别执行循环 *K* 次准则.

程序复杂度

- **Size:**
  - **length:**
    - **LOC: SLOC (source program length)、LLOC (logic)**
    - **#components: number of files, classes**
  - **Amount of functionality: functional points (specification-based)**
- **Structure:**
  - **Control flow -- McCabe's**
  - **Data flow**
  - **Modularity**

圈复杂度 (Cyclomatic Complexity)

- 欧拉公式：G是连通平面图，那么
  $\varphi = e - n + 2$
  φ 是图中不同区域的个数 – 圈
  e 是G中的边数
  n 是G中的节点数
- 图的圈复杂度由$V(G) = e - n + 2p$给出，其中
  e 是G中的边数
  n 是G中的节点数
  p 是G中的连通分量数

圈复杂度 (Cyclomatic Complexity)

- 程序的控制流图 → 圈复杂度
  - 增加一个分支，控制流图的区域数+1
  - 如果所有分支都是二叉的，那么 *V*(*G*)是判定节点数+1
- 圈复杂度代表了程序的逻辑复杂度
- 经验表明，程序中可能存在的Bug数和圈复杂度有着很大的相关性
- 测试应该和圈复杂度关联

基本路径测试

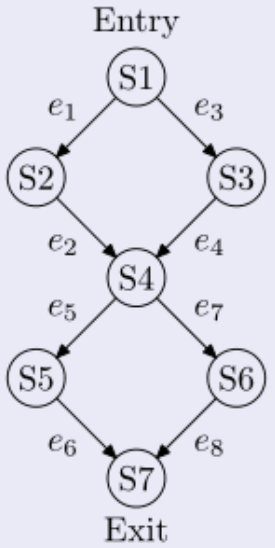
- 路径向量$A = \langle a_1, a_2, \ldots, a_k \rangle$ ， a_i 表示编号为 i 的有向边在路径 A 中出现的次数
- 路径B称为路径 $A_1, A_2, \ldots, A_n$ 的线性组合，如果存在常数 $\lambda_1, \lambda_2, \ldots, \lambda_n$ 使得 $B = \lambda_1 A_1 + \lambda_2 A_2 + \ldots + \lambda_n A_n$
- 对于一个测试路径集合来说，如果流图中的任意一个完整路径都是测试集合中路径的线性组合，那么这个测试集合满足基本路径覆盖（Basis Path Coverage）。

基本路径测试

- **最优测试集合**
  - 各条测试路径是线性无关的
  - 对应于线性空间的基(basis)
  - 含有 $V(G) = |E| - |N| + 2$ 条线性独立的完整路径

例

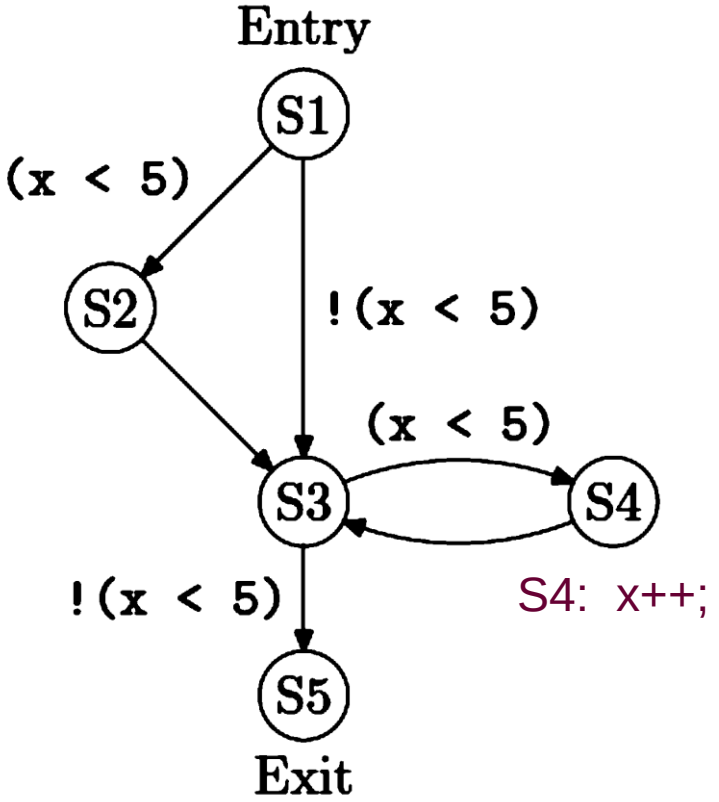
$$p_1 = e_1 e_2 e_5 e_6 = \langle 1, 1, 0, 0, 1, 1, 0, 0 \rangle$$
$$p_2 = e_1 e_2 e_7 e_8 = \langle 1, 1, 0, 0, 0, 0, 1, 1 \rangle$$
$$p_3 = e_3 e_4 e_5 e_6 = \langle 0, 0, 1, 1, 1, 1, 0, 0 \rangle$$
$$p_4 = e_3 e_4 e_7 e_8 = \langle 0, 0, 1, 1, 0, 0, 1, 1 \rangle$$



任意一条路径都可以由其他三条路径线性组合得出, 如

$$p_4 = -p_1 + p_2 + p_3$$

思考



- 左图中的程序，其基本路径集合是什么？

- S1-S3-S5
- S1-S2-S3-S4-S3-S5
- S1-S2-S3-S4-S3-S4-S3-S5

基于程序文本的测试

- **LCSAJ**
  - 线性代码序列与跳转（Linear Code Sequence And Jump）
  - 一组顺序执行的代码, 以控制流跳转为其结束点
  - 几个首尾相接, 且第一个 LCSAJ 起点为程序起点，最后一个 LCSAJ 终点为程序终点的 LCSAJ 串就组成了程序的一条路径.
- **TER$_n$**
  - 第一层n=1是语句覆盖;
  - 第二层是分支覆盖;
  - 第三层就是LCSAJ覆盖，即程序中的每一个LCSAJ都至少在测试中经历过一次;
  - 而TER$_{n+2}$要求每n个首尾相连的LCSAJ组合在测试中都要经历一次.

LCSAJ - Example

```
 1:#include <stdlib.h>
 2:#include <string.h>
 3:#include <math.h>
 4:#define MAXCOLUMNS 26
 5:#define MAXROWS 20
 6:#define MAXCOUNT 90
 7:#define ITERATIONS 750
 8:int main(void){
 9:   int count = 0, totals[MAXCOLUMNS], val = 0;
10:   memset(totals, 0, MAXCOLUMNS * sizeof(int));
11:   while(count < ITERATIONS){
12:     val = abs(rand()) % MAXCOLUMNS;
13:     totals[val] += 1;
14:     if(totals[val] > MAXCOUNT){
15:       totals[val] = MAXCOUNT;
16:     }
17:     count++;
18:   }
19:   return(0);
20:}
```

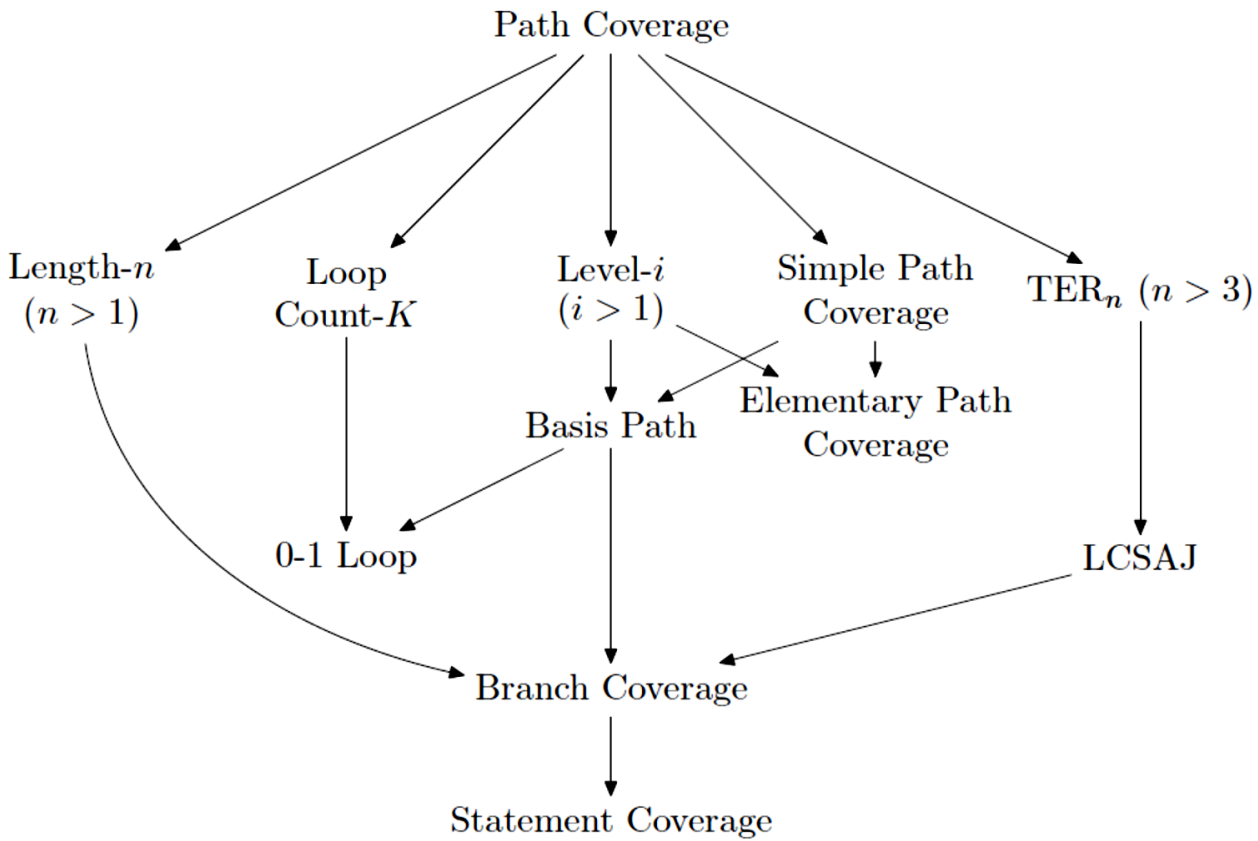
LCSAJ #	Start	End	Jump To
1	8	11	19
2	8	14	17
3	8	18	11
4	11	11	19
5	11	14	17
6	11	18	11
7	17	18	11
8	19	19	-1

覆盖准则之间的包含关系

- 一个准则 A 包含 (Subsume) 准则 B, 当且仅当满足 A 的测试数据集同时是满足 B 的测试数据集。

- 如果 A 包含 B , 那么测试准则 A 比 B 有更强的查错能力。

控制流测试准则之间的关系



- 条件表达式测试

Traffic Collision Avoidance System (TCAS)

```
bool Non_Crossing_Biased_Descend()
{
    int upward_preferred;
    bool result;

    upward_preferred = Inhibit_Biased_Climb() > Down_Separation;
    if (upward_preferred)  {
        result = Own_Below_Threat() && (Cur_Vertical_Sep >= MINSEP) &&
                 (Down_Separation >= ALIM());
    }
    else  {
        result = !(Own_Above_Threat()) || ((Own_Above_Threat()) &&
                 (Up_Separation >= ALIM()));
    }
    return result;
}
```

条件表达式

- （布尔）逻辑公式
- Decision 判定/判断
- Condition 条件

- 例： S = (x1∨x2) ∧ (x3∨x4)

  四个条件

Condition

- **NASA的定义**
  - **A decision without a Boolean operator is a condition. If a condition appears more than once in a decision, each occurrence is a distinct condition.**
  - **比如(A ∧ B) ∨ (A ∧ C)，实际上是4个condition，A(1), B, A(2), C**
  - **这个定义是不合适的，因为没法构造测试用例分别测试A(1)， A(2)**

Decision coverage and Condition coverage

- Decision coverage (DC) requires two test cases for each decision: one for a true outcome and another for a false outcome.

- Condition coverage (CC) requires that each condition in a decision take on all possible outcomes at least once.

条件表达式测试

- **判定覆盖DC**
  - 对于每个判断，至少有两个测试数据使其在运行中分别取真以及假
  - 两个测试用例

$S = (x1 \vee x2) \wedge (x3 \vee x4)$

判定覆盖测试集

x1	x2	x3	x4	S
0	0	0	0	0
1	0	1	0	1

- **条件覆盖CC**
  - 每个判断中的每个条件，至少有两个测试数据使其在运行中分别取真、假值
  - 两个测试用例

条件覆盖测试集

x1	x2	x3	x4	S
0	1	0	1	1
1	0	1	0	1

C/DC测试效果

- $S_0 = (x1 \vee x2) \wedge (x3 \vee x4)$
  满足CC，DC，C/DC的测试集

x1	x2	x3	x4	S
0	0	0	0	0
1	1	1	1	1

- 假定表达式误写为 $S_1 = (x1 \vee x2) \wedge (x3 \vee \neg x4)$
  - S_0 和S_1 的测试结果相同
  - 原因：没有测试每个条件独立对判定取值的影响

常见错误类型

- **ORF (Operator Reference Faults)**
  - 例如 **and** 写成 **or**
- **VNF (Variable Negation Faults)**
  - 变量误写为它的否定
- **ENF (Expression Negation Faults)**
  - 表达式误写为它的否定

MC/DC

- **MC/DC（Modified Condition/Decision Coverage，修正的判断条件覆盖）**
  - 测试用例要满足 **C/DC**
  - 每个条件要能够独立地影响判断的值：对于每个判断的每一个条件，至少有两个测试用例 --这个条件取不同的真假值，同时这个判断也取不同的值
  - **For the formula (A or B), we have test cases: (TF), (FT), and (FF).**
- **用于航空航天等安全关键软件的测试**

MC/DC – ex.1

```
bool x, y, z;
int example() {
  int w;
  if(x && (y || z))
    w = 0;
  else w = 1;
  if(w == 0) return 1;
  else return 0;
}
```

- **Test suite**

TABLE I: Outcomes of conditions and decisions

expression	t_1	t_2	t_3	t_4	t_5
x	F	T	F	T	T
y	T	T	T	F	F
z	T	F	F	T	F
$x \wedge (y \vee z)$	F	T	F	T	F

t2 and t3 → x;
t2 and t5 → y;
t4 and t5 → z.

MC/DC – ex.2

- S = (x1∨x2) ∧ (x3∨x4)
- 5个测试用例
  - {t1, t3} 覆盖条件x1
  - {t1, t2} 覆盖条件x2
  - {t4, t5} 覆盖条件x3
  - {t2, t4} 覆盖条件x4
- 测试用例{t2, t4} 区分
  - S_0 = (x1∨x2) ∧ (x3∨x4)
  - S_1 = (x1∨x2) ∧ (x3∨ ¬x4)

用例	x1	x2	x3	x4	S
t1	0	0	0	1	0
t2	0	1	0	1	1
t3	1	0	0	1	1
t4	0	1	0	0	0
t5	0	1	1	0	1

MC/DC测试集大小

- 一般情况测试用例数[n+1, 2n]
- 对很多表达式，最优测试集大小就是n+1

Ling Yang, et al., Generating Minimal Test Set Satisfying MC/DC Criterion via SAT Based Approach. ACM SAC 2018

一种（常见的）特殊情况

- 对于一个只含有（与、或、非运算）的n变量布尔表达式，每个变量（条件）只出现一次，那么它的MC/DC最优测试集大小为n+1。

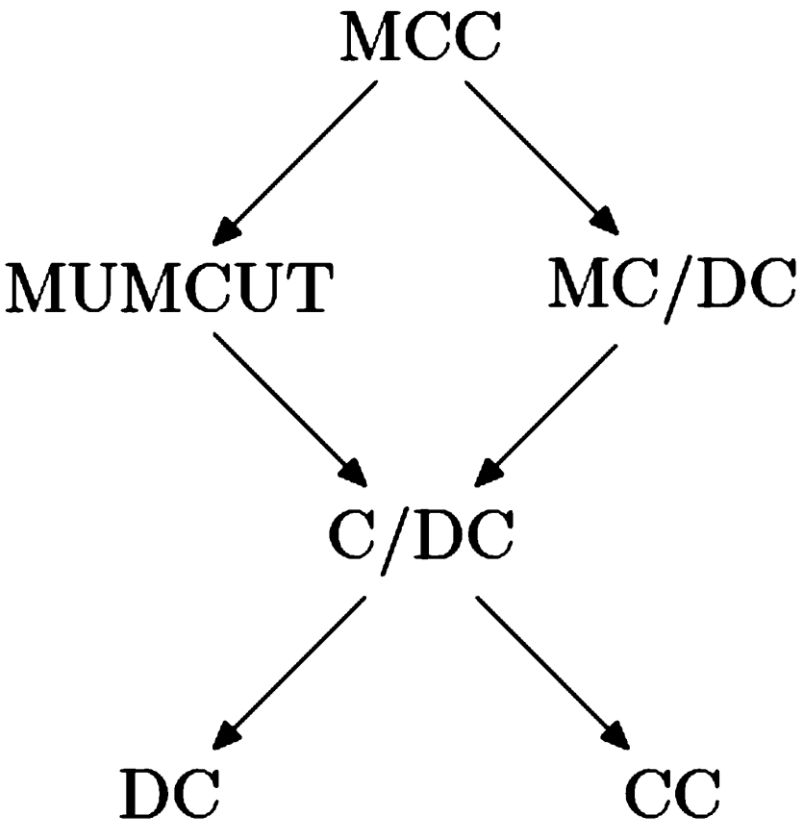
- 证明：（数学归纳法)
  - n=1 成立
  - 假设表达式$S_1(x_1,x_2,\ldots,x_j)$有大小为j+1的测试集
    $TS_1 = \{t_{1,1}, t_{1,2},\ldots, t_{1,j+1}\}$,
    表达式$S_2(x_{j+1},x_{j+2},\ldots,x_{j+k})$有大小为k+1的测试集
    $TS_2 = \{t_{2,1}, t_{2,2},\ldots, t_{2,k+1}\}$
  - 对于表达式$S= S_1 \wedge S_2$, 不妨假定$S_1(t_{1,1})=1$, $S_2(t_{2,1})=1$,构造集合
    $T_1 = \{t_{1,1}t_{2,1}, t_{1,2}t_{2,1}, \ldots, t_{1,j+1}t_{2,1}\}$
    $T_2 = \{t_{1,1}t_{2,1}, t_{1,1}t_{2,2}, \ldots, t_{1,1}t_{2,k+1}\}$
    显然集合T_1可以MC/DC 覆盖S的前j个参数，集合T_2可以MC/DC 覆盖S的后k个参数。那么 $T = T_1 \cup T_2$是表达式S的MC/DC测试集，它的大小为t+1+k+1-l = t+k+1 （有一个公共元素$t_{1,1}t_{2,1}$）。
  - 类似可以证明$S= S_1 \vee S_2$的情况。

MUMCUT

- 针对判断表达式中的更多错误设计，由三个子准则构成
  - MUTP (Multiple Unique True Point)
  - MNTP (Multiple Near False Point)
  - CUTPNFP (Corresponding Unique True Point and Near False Point Pair)
- 不足之处
  - 过于复杂，不易设计测试用例
  - 要求条件表达式具有特定的形式

条件表达式覆盖准则之间的关系

- 一个准则 A 包含 (Subsume) 准则 B, 当且仅当满足 A 的测试数据集同时是满足 B 的测试数据集.
- 如果 A 包含 B , 那么测试准则 A 比 B 有更强的查错能力.



其它测试准则

- 函数覆盖（Function Coverage）
- 面向对象程序测试
  - 方法覆盖（Method Coverage）
  - 类覆盖（Class Coverage）
- 集成测试中
  - 模块覆盖（Module Coverage）
  - 调用对覆盖（Call-Pair Coverage）
- …

- 数据流测试

数据流测试--基本概念

- 定义性出现（Definition Occurrence）
  y = x + z
  `scanf("%d %d", &x, &y)` 定义变量 x和y
- 引用性出现（Use Occurrence）
  - 计算性引用（c-use）
    y = x + z
  - 谓词性引用（p-use）
    if (x1 < x2)
- Def of a variable at line l_1 and its use at line l_2 constitute a def-use pair. (l_1 and l_2 can be the same.)
- 无定义的（Def-Clear）
- du-path：定义到引用之间是def-clear的

Rapps和Weyuker的数据流测试准则

- 定义覆盖准则（All-Defs Criterion） 存在一条测试路径覆盖从变量的定义性出现传递到某一个引用性出现
- 引用覆盖准则（All-Uses Criterion） 对于每一个变量的每一个定义性出现，每一个能够可行的传递到的引用，存在一条测试路径覆盖该传递和引用
- 定义-引用覆盖准则（All-DU-Paths Criterion） 所有的定义到引用的传递路径都检查 （在循环上使用0-1准则）。
- 计算性引用覆盖（All-C-Uses），谓词性引用覆盖（All-P-Uses）

Example 1

```
1.  begin
2.  int x,y; float z;
3.  input(x,y);
4.  z = 0;
5.  if (x != 0)
6.    z = z+y;
7.  else z = z-y;
8.  if (y != 0)
    // should be (y != 0 &&
    x != 0)
9.    z = z/x;
10. else z = z*x;
11. output(z);
12. end
```

满足分支覆盖的测试用例

	x	y	z
t1	0	0	0.0
t2	1	1	1.0

变量z的定义：4，6，7，9，10
变量z的使用：6，7，9，10

Example 1

```
1.  begin
2.  int x,y; float z;
3.  input(x,y);
4.  z = 0;
5.  if (x != 0)
6.    z = z+y;
7.  else z = z-y;
8.  if (y != 0)
9.    z = z/x;
10. else z = z*x;
11. output(z);
12. end
```

对于变量Z的du-path覆盖测试用例

	x	y	z	DU pairs covered
t_1	0	0	0.0	(4,7), (7,10)
t_2	1	1	1.0	(4,6), (6,9)
t_3	0	1	0.0	(4,7), (7,9)
t_4	1	0	1.0	(4,6), (6,10)

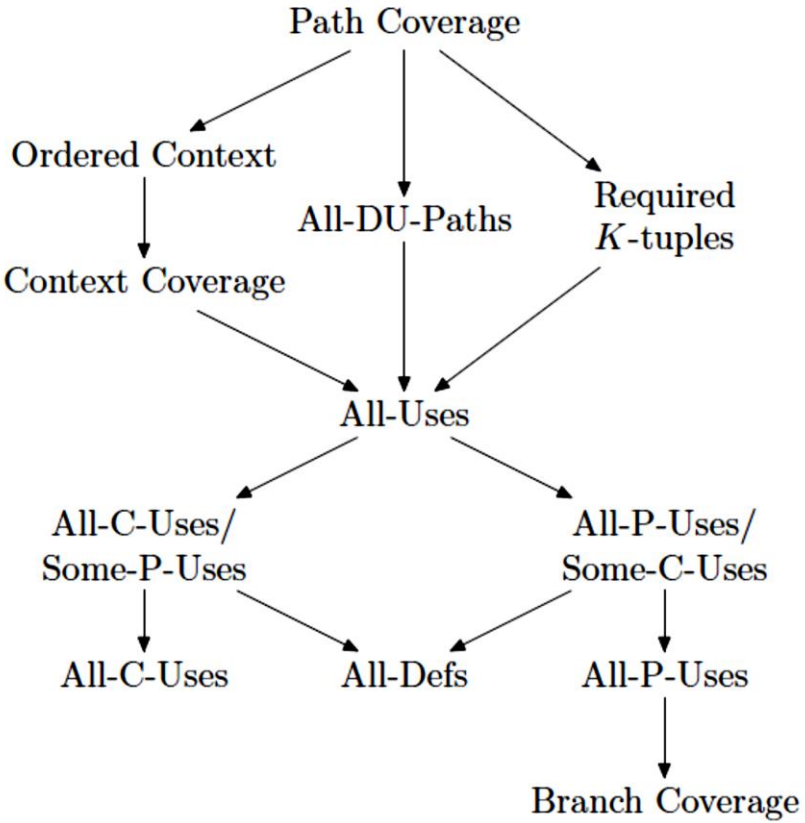
(l_1,l_2): z is defined in l_1 and used in l_2.

Ntafos的数据流测试准则

考虑数据在程序中的传播过程

- *k*元数据交互链（*k-dr* interaction），交互路径 $n_1, n_2, \ldots, n_k$
  如果节点n_i上有变量x_i的定义，节点n_{i+1}上有x_i的引用性出现，该引用被用来计算赋予x_{i+1}的数据。从定义到引用，再定义到新的变量的过程不断重复，使得数据在变量之间传播。
- *k*元数据交互链覆盖准则（Required *k*-Tuples criterion）
- 2元数据交互链覆盖准则即为引用覆盖准则。

数据流测试准则之间的关系



- 关于覆盖率

Hierarchy (Aditya P. Mathur)

- 需求 (requirement)
- 函数 (function/method)
- 语句 (statement)
- 判定 (decision)
- 数据流 (data-flow)
- …

错误检测率与覆盖率增长的关系（Gittens）

- 经验研究
  - 商用软件，221,629行，221个模块，
  - 代码块覆盖
- 饱和效应
  - 在系统测试中，覆盖率达到51%-60%之前，错误检测率与覆盖率相关
  - 回归测试中，覆盖率达到61%-70%之前，错误检测率与覆盖率相关

覆盖率与找错

- 测试即使达到100%的语句/分支覆盖率，也可能会漏掉很多错误。
- 例.
  - int a[10], i, j;
  - INPUT(i);
  - if (i > 4) j = i-1;
  - else j = i+1;
  - a[j] = j; // 可能越界

两个测试用例
1. i = 4
2. i = 5

Example 2

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

T1:

<x= -2, y=2, count=2>

T2:

<x= 2, y=2, count=1>

这两个测试用例满足100%语句、分支、MC/DC覆盖

巧合正确性

- Coincidental Correctness
- 执行了语句/路径，但未发现其中的错误。

- 例：
  - y = x * 2;
  - y = x ^ 2;

    - 如果输入数据 x==2, …

参考文献

- Hong Zhu, Patrick A. V. Hall, and John H. R. May. 1997. Software unit test coverage and adequacy. ACM Comput. Surv. 29, 4 (December 1997), 366-427.
- 朱鸿、金凌紫，《软件质量保障与测试》，科学出版社，1997。
- A. P. Mathur, Foundations of Software Testing, 2008.
- Ting Su, Ke Wu, Weikai Miao, Geguang Pu, Jifeng He, Yuting Chen, Zhendong Su: A Survey on Data-Flow Testing. ACM Comput. Surv. 50(1): 5:1-5:35 (2017)

白盒测试用例生成与选择

Research problems

- **Test data/case generation: How can we generate a test suite to achieve 100% statement/branch/… coverage?** 测试生成

- **Does high coverage indicate better fault detection capability?** 发现错误的能力

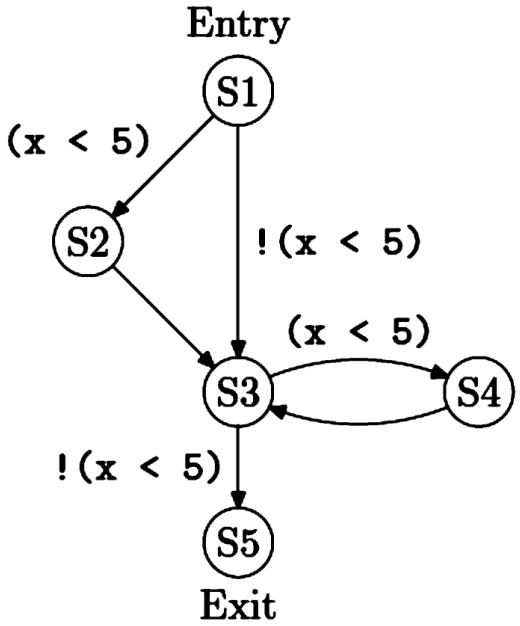
简单的测试生成

```
TS = EmptySet;
   do {
      产生测试数据 t;
      采用 t 执行程序，检查覆盖率;
      if (覆盖率增加)
            将 t 加入测试集TS;
   } while (覆盖率不达标);
   return TS;
```

测试路径

- **CFG上的路径**
  - 完整路径：***A path that starts at an initial node and ends at a final node***
  - 例：**S1-S2-S3-S4-S3-S5**
- **不可行路径**
  - **S1-S3-S4-S3-S5**

```
void f(int x）{
/*S1*/ if (x < 5）
/*S2*/ y = 2;
/*S3*/ while (x < 5）
/*S4*/ x++;
/*S5*/ return;
}
```



基于路径的测试生成过程

```
TS = EmptySet;
    do {
      生成一条对覆盖率有贡献的测试路径p;
      if (可从p产生测试数据t)
            将t加入测试集TS;
      根据p统计覆盖率;
   } while (覆盖率不达标);
   return TS;
```

Path Feasibility – Ex.

```
int  i, j;
bool good;
if ((i > 2) && (j > 3))
{
     j = j-1;
     if (i+2j < 5)
        good = FALSE;
     else  good = TRUE;
}
```

Two paths

- **Path 1:**

```
@((i > 2) && (j > 3))
   j = j-1;
@(i+2j < 5)
  good = FALSE;
```

- **Path 2:**

```
@((i > 2) && (j > 3))
   j = j-1;
@! (i+2j < 5)
  good = TRUE;
```

如何分析路径产生测试数据

- 符号执行
- 约束求解

测试集最小化

- **给定一组测试用例 *P*，选择其（最小）子集*Ps*，达到高覆盖度。**
- **(branch coverage)**

H. S. Wang, S. R. Hsu, and J. C. Lin. A generalized optimal path-selection model for structural program testing. Journal of Systems and Software, 10: 55-63, 1989.

路径的覆盖度矩阵

Branch

Path	Br_1	Br_2	…	Br_j	…
P_1	b_{11}	b_{12}	…	b_{1j}	…
P_2	b_{21}	b_{22}	…	b_{2j}	…
…					
P_i	b_{i1}	b_{i2}	…	b_{ij}	…
…					

b_{ij}: coverage frequency for path P_i over branch Br_j.

建模为优化问题

- Bool X_i = ITE(P_i is selected, 1, 0)
- 优化问题

  $min. \sum_i X_i$

  $s.t. \ \sum_i X_i b_{ij} \geq 1$ for all j

  （对每条边 Br_j）
- 整数规划/伪布尔优化

Branch Path Matrix

Path No.	branch No. / branch	1 a	2 b	3 c	4 d	5 e	6 f	7 g	8 h	9 i	10 j	11 k	12 l	13 m	14 n	15 o	16 p	17 q	18 r	19 s	20 t	P_BN
1>	ac	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
2>	bdedfghjkmprti	0	1	0	2	1	1	1	1	1	1	1	0	1	0	0	1	0	1	0	1	14
3>	bdedfghjkmqsti	0	1	0	2	1	1	1	1	1	1	1	0	1	0	0	0	1	0	1	1	14
4>	bdedfghjlnkmprti	0	1	0	2	1	1	1	1	1	1	1	1	1	1	0	1	0	1	0	1	16
5>	bdedfghjlnkmqsti	0	1	0	2	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1	16
6>	bdedfghjlnloprti	0	1	0	2	1	1	1	1	1	1	0	2	0	1	1	1	0	1	0	1	16
7>	bdedfghjlnloqsti	0	1	0	2	1	1	1	1	1	1	0	2	0	1	1	0	1	0	1	1	16
8>	bdedfghjloprti	0	1	0	2	1	1	1	1	1	1	0	1	0	0	1	1	0	1	0	1	14
9>	bdedfghjloqsti	0	1	0	2	1	1	1	1	1	1	0	1	0	0	1	0	1	0	1	1	14
10>	bdedfgi	0	1	0	2	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	7
11>	bdfghjkmprti	0	1	0	1	0	1	1	1	1	1	1	0	1	0	0	1	0	1	0	1	12
12>	bdfghjkmqsti	0	1	0	1	0	1	1	1	1	1	1	0	1	0	0	0	1	0	1	1	12
13>	bdfghjlnkmprti	0	1	0	1	0	1	1	1	1	1	1	1	1	1	0	1	0	1	0	1	14
14>	bdfghjlnkmqsti	0	1	0	1	0	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1	14
15>	bdfghjlnloprti	0	1	0	1	0	1	1	1	1	1	0	2	0	1	1	1	0	1	0	1	14
16>	bdfghjlnloqsti	0	1	0	1	0	1	1	1	1	1	0	2	0	1	1	0	1	0	1	1	14
17>	bdfghjloprti	0	1	0	1	0	1	1	1	1	1	0	1	0	0	1	1	0	1	0	1	12
18>	bdfghjloqsti	0	1	0	1	0	1	1	1	1	1	0	1	0	0	1	0	1	0	1	1	12
19>	bdfgi	0	1	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	5

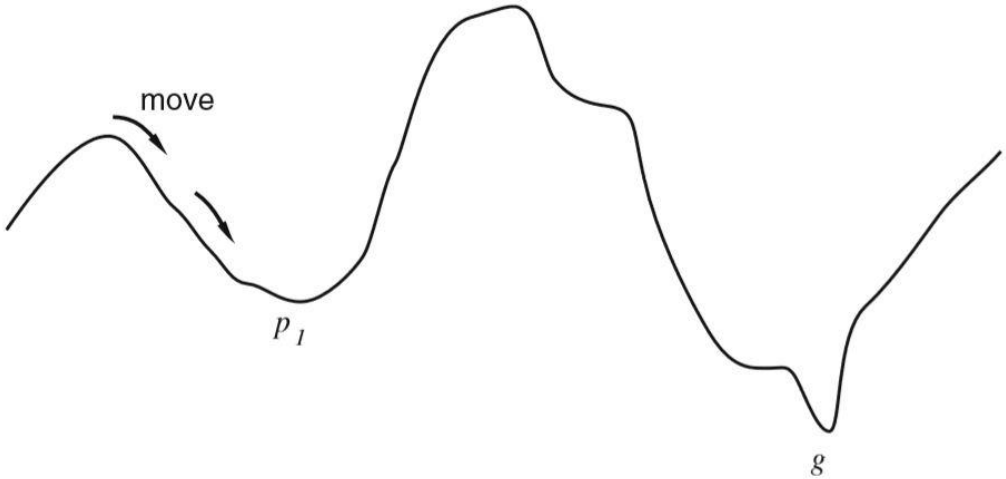
BRANCH PATH MATRIX

```
   *** STATEMENT-TESTING test path recommendation ***

 testpath set  1 , the min. path number=3
       path no.  1    12F
       path no.  4    134345678A89BCE6F
       path no.  9    134345678ABDE6F


   *** BRANCH-TESTING test path recommendation ***

 testpath set  1 , the min. path number=3
       path no.  1    ac
       path no.  4    bdedfghjlnkmprti
       path no.  7    bdedfghjlnloqsti
```

常用优化算法

- 部分完备算法
  - LP
  - Max-SAT
  - SMT-OPT
- 贪心
- 元启发式搜索

局部最优 vs 全局优化



复杂约束下的优化问题

- 单目标优化

$$min\ f(x)$$

$$s.t.\ constraints$$

- 多目标优化

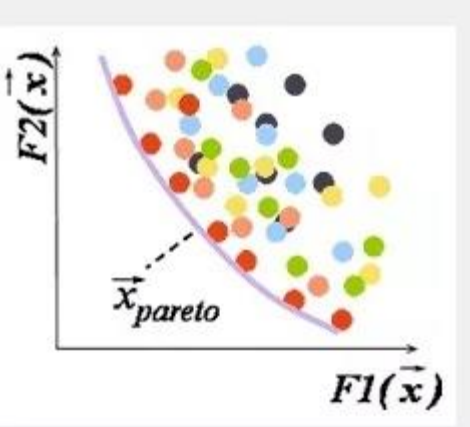
$$min\ f_1(x), f_2(x), \ldots, f_k(x)$$

$$s.t.\ constraints$$

多目标优化

- x是搜索空间中一点，说 x为Pareto最优解，当且仅当不存在 x' (在搜索空间可行性域中)使得 $f_k(x') \leq f_k(x)$成立

- 它的解并非唯一，而是存在一组由众多 Pareto最优解组成的最优解集合，集合中的各个元素称为Pareto最优解或非劣最优解。



多目标优化

- **自动化测试辅助工具**
  - 测试执行工具
  - 覆盖度统计工具

Unit Testing Frameworks

- https://en.wikipedia.org/wiki/List_of_unit_testing_frameworks
- **A test automation framework**
  - integrates the function libraries, test data sources, object details and various reusable modules
  - has the advantage of low maintenance cost.
- This page is a list of tables of code-driven unit testing frameworks for various programming languages. Some but not all of these are based on xUnit.

Testing frameworks for various PLs

Contents [hide]

Testing tools for C

C [edit]

Name	xUnit	Fixtures	Group fixtures	Generators	Source	License	Remarks
libcbdd	Yes	Yes	Yes		[24]	Apache License	libcbdd is a block-based Behavior-driven development library which allows for very readable tests. Tests are written inside main functions.
AceUnit	Yes	Yes			[25]	BSD License	AceUnit is JUnit 4.x style, easy, modular and flexible. AceUnit can be used in resource constraint environments, e.g. embedded software development, as well as on PCs, Workstations and Servers (Windows and UNIX).
API Sanity Checker	Yes	Yes (spectypes)	Yes (spectypes)	Yes	[26]	LGPL	Unit test generator for C/C++ libraries. Can automatically generate reasonable input data for every API function.
Automated Testing Framework					[27]	BSD	Originally developed for the NetBSD operating system but works well in most Unix-like platforms. Ability to install tests as part of a release.
Autounit (GNU)					[28]	LGPL	In beta/under construction
BDD-for-C					[29]	MIT	Single header file.
Parasoft C/C++test	Yes	Yes	Yes	Yes	[30]	Proprietary	Automated unit/component test generation and execution on host or embedded systems with code coverage and runtime error detection. Also provides static analysis and peer code review.
QA Systems Cantata	No	Yes	Yes	Yes	[31]	Proprietary	Automated unit and integration testing tool for C. Certified testing for host or embedded systems. Code coverage and unique call interface control to simulate and intercept calls.
Catsrunner					[32]	GPL	Unit testing framework for cross-platform embedded development.
cfix	Yes				[33]		Specialized for Windows development—both Win32 and NT kernel mode. Compatible to WinUnit.
Cgreen		Yes			[34][35]	ISC	Unit test framework including strict and loose mocks, reflective runner discovering tests automatically, suites, BDD-style Concept Under Test notation, test protected against exceptions, natural language out, extensible reporter, learning mocks...
CHEAT					[36][37]	BSD	Header-only unit testing framework. Multi-platform. Supports running each test in a separate process. Works without needing to "register" test cases.
Check	Yes	Yes	Yes		[38]	LGPL	Check features a simple interface for defining unit tests, putting little in the way of the developer. Tests are run in a separate process, so Check can catch both assertion failures and code errors that cause segmentation faults or other signals. The output from unit tests can be used within source code editors and IDEs. Check is supported on Linux, OS X, Windows, and probably others. Can output to multiple formats, like the TAP format, JUnit XML or SubUnit. Supported on Linux, OS X, FreeBSD, and Windows.
Cmocka	Yes	Yes	Yes		[39]	Apache License 2.0	CMocka is a test framework for C with support for mock objects. It's easy to use and setup.CMocka is the successor of cmockery, which was developed by Google but has been unmaintained for some time. So, CMocka was forked and will be maintained in the future. Can output to multiple formats, like the TAP format, JUnit XML or SubUnit.
Cmockery	Yes				[40]	Apache License 2.0	Google sponsored project.

CppUTest	Yes	Yes	No	Yes	[41]		Limited C++ set by design to keep usage easy and allow it to work on embedded platforms. C++ is buried in macros so the learning curve for C programmers is minimal. Ported to Symbian. Has a mocking support library CppUMock
Criterion	Yes	Yes	Yes	Yes	[42]	MIT	Unit testing framework with automatic test registration. Supports theories and parameterized tests. Each test is run in its own process, so signals and crashes can be reported. Can output to multiple formats, like the TAP format or JUnit XML. Supported on Linux, OS X, FreeBSD, and Windows.
CU					[43]	LGPL	CU is a simple unit testing framework for handling automated tests in C.
CTest	Yes	Yes	Yes		[44]	Apache License 2.0	Ctest is a framework with some special features: formatted output for easy parsing, easy to use.
CUnit	Yes				[45]	LGPL	OS independent (Windows, Linux, Mac OS X, Solaris, HP-UX, AIX and probably others)
CUnit (CUnity Fork)	Yes				[46]	LGPL	Forked from CUnit in 2018 to provide ongoing development and support. OS independent (Windows, Linux, Mac OS X, Solaris, HP-UX, AIX and probably others). Also supports output compatible with JUnit and in most cases can be a drop in replacement for CUnit.
CUnitWin32	Yes				[47]	LGPL	For Win32. Minimalistic framework. Executes each test as a separate process.
CUT	No				[48]	BSD	
CuTest	Yes				[49]	zlib	Simple, straightforward, fast. Single .c file. Used in the Apache Portable Runtime Library.
Cutter	Yes				[50]	LGPL	A Unit Testing Framework for C.
EmbeddedUnit	Yes	Yes			[51]	MIT	Embedded C
Embunit	No				[52]	Proprietary	Create unit tests for C/C++ and Embedded C++
FCTX	Yes				[53]	BSD	Fast and complete unit testing framework all in one header. Declare and write your functions in one step. No dependencies. Cross-platform.
GLib Testing	Yes	Yes			[54]		Part of GLib
GUnit					[55]		for GNOME
Icut	Yes	Yes	Yes		[56]	Apache License 2.0	a Lightweight C Unit Testing framework, including mock support
LibU	Yes	No			[57]	BSD	multiplatform (Unixes and Windows); explicit test case/suite dependencies; parallel and sandboxed execution; xml, txt and customizable report formatting.
MinUnit					[58]	as-is	extreme minimalist unit testing using 2 C macros
Mut	No	No	No	No	[59]	MIT	Another minimalistic framework for C and Unix. Single header file.
NovaProva	Yes	Yes	No	Yes	[60]	Apache License 2.0	Unit testing framework with automatic test registration. Supports mocking and stubbing. Each test is run in parallel with valgrind in its own process, so memory errors and signals can be caught. Supported on Linux.
Opmock	Yes	Yes	Yes	Yes	[61]	GPLv3	Stubbing and mocking framework for C and C++ based on code generation from headers. Can check call parameters, call sequence, handle multiple implementations of a mock, and more. Includes as well a small unit testing framework, with JUnit compatible XML output, but works also with any unit testing framework.
RapiTest	No	Yes	Yes		[62]	Proprietary	Focus is safety-critical/aerospace/DO-178C software, runs on embedded targets and on-host, has code coverage.

JUnit

- JUnit: a unit testing framework for Java
- It provides
  - annotations to identify test methods.
  - assertions for checking expected results.
  - test runners for running tests.
- JUnit tests can be run automatically and they check their own results.

Example: MessageUtil.java

```
public class MessageUtil {
   private String message;
   //Constructor
   //@param message to be printed
   public MessageUtil(String message){
      this.message = message;
   }
   // prints the message
   public String printMessage(){
      System.out.println(message);
      return message;
   }
}
```

Example： TestJunit.java

```
import org.junit.Test;
import static org.junit.Assert.assertEquals;

public class TestJunit {

   String message = "Hello World";
   MessageUtil messageUtil = new MessageUtil(message);

   @Test
   public void testPrintMessage() {
      assertEquals(message, messageUtil.printMessage());
   }
}
```

Example： TestRunner.java

```
import org.junit.runner.JUnitCore;
import org.junit.runner.Result;
import org.junit.runner.notification.Failure;

public class TestRunner {
   public static void main(String[] args) {
      Result result = JUnitCore.runClasses(TestJunit.class);

      for (Failure failure : result.getFailures()) {
         System.out.println(failure.toString());
      }
      System.out.println(result.wasSuccessful());
   }
}
```

案例-JUSTIN工具

- 自动生成Java单元测试数据的工具
  - 以Java字节码为输入
  - 以public方法为测试单元
  - 生成单元测试源码
  - 生成结果可在JUnit框架下编译执行
- 所需环境
  - JDK 1.8
  - Junit
  - 命令行
- 测试数据生成方法
  - 随机测试，模糊测试，……

- 方法参数的自动生成
  - 基本类型
    - 包含 int | short | byte | long | float | double | char | Boolean
    - String 类型的常量生成
  - 自定义类
    - 支持复杂对象参数的生成
  - 数组
    - 支持多维数组
    - 支持元素为基本类型和自定义类
    - 数组中自动添加元素
- 方法调用

Justin产生的测试用例

- 源代码

```
package cn.ios.test;
public class GasStation {
    public int canCompleteCircuit(int[] gas, int[] cost) {
        int [] rest = new int [gas.length];

        int res = 0;

        for(int i = 0; i < gas.length; ++i){
            rest[i] = gas[i] - cost[i];
            res += rest[i];
        }

        if(res < 0)
            return -1;
        int len = rest.length;
        for(int i = 0; i < rest.length; ++i){
            int start = (i+1)%len;
            int end = i;
            int total = rest[i];
            if(total < 0)
                continue;
            while(start != end){
                total += rest[start];
                if(total < 0)
                    break;
                start = (start + 1)%len;
            }
            if(total >= 0)
                return i;
            else
                continue;
        }
        return -1;

    }
}
```

- 生成的测试代码

```
package cn.ios.test;

import org.junit.Test;

public class GasStation_Test {

  @Test
  public void test_GasStation_canCompleteCircuit_0(){

      int[] intArray1 = {-1852899294, -27147850, -1423120474};
      int[] intArray2 = {1513584829};
      cn.ios.test.GasStation gasStation0 = new cn.ios.test.GasStation();
      gasStation0.canCompleteCircuit(intArray1, intArray2);

  }


}
```

发现的bug（Justin-str，ISSRE2022）

JDK 开发者确认或修复的Bug 信息

Bug 类型：	ArrayIndexOutOfBoundsException (2)
Issue ID：	I4MWI1 (Commit ID), 8279422
Bug 类型：	StringIndexOutOfBoundsException (14)
Issue ID：	8278186, 8279128, 8279129, 8279198, 8279218, 8279336, 8279341, 8279342, 8279362, 8279423, **21212bd18(Commit ID), 8279424, **411a404a9(Commit ID), **8baba7d11(Commit ID)
Bug 类型：	Infinite Loop (1)
Issue ID：	8278993

GUnit

https://github.com/cpp-testing/GUnit

- **Based on GoogleTest/GoogleMock**

Google Test (Google's C++ testing framework), by Zhanyong Wan

Gunit

http://googletesting.blogspot.com/2012/10/why-are-there-so-many-c-testing.html

- 系统的可扩展性
- C++应用太广。很难写一个在各种环境下都能工作的 C++ 测试框架。
- Google had a huge number of C++ projects that got compiled on various operating systems (Linux, Windows, Mac OS X, and later Android, among others) with different compilers and all kinds of compiler flags, and we needed a framework that worked well in all these environments and could handle many different types and sizes of projects.

覆盖率统计工具：llvm-cov

- 编译
  - clang -fprofile-instr-generate -fcoverage-mapping test.cc -o test
- 运行
  - LLVM_PROFILE_FILE=“test.profraw" ./test
- 对profraw文件索引
  - llvm-profdata merge -sparse test.profraw -o test.profdata
- 生成覆盖率报告
  - llvm-cov show ./test -instr-profile=test.profdata
  - llvm-cov report -show-region-summary=false ./test -instr-profile=test.profdata

覆盖率报告

- 第一列为程序的行号
- 第二列为该行代码被覆盖的次数
- Branch (line : column) 标记了分支的位置
- [True:10 , False:1]表示满足条件和不满足条件的覆盖次数
- 标红的行表示未被测试用例覆盖

```
  1|       |#include <stdio.h>
  2|       |
  3|       |int main(void)
  4|      1|{
  5|      1|    int i,total;
  6|      1|    total = 0;
  7|     11|    for(i=0;i<10;i++)
------------------
|  Branch (7:13): [True: 10, False: 1]
------------------
  8|     10|        total += i;
  9|      1|    if(total != 45)
------------------
|  Branch (9:8): [True: 0, False: 1]
------------------
 10|      0|        printf("Failure\n");
 11|      1|    else
 12|      1|        printf("Success\n");
 13|       |    /*else
 14|       |        printf("just test\n");*/
 15|      1|    return 0;
 16|      1|}
 17|       |
```

覆盖率总结

- Functions为程序中所含函数数量
- Missed Functions 为未被覆盖的函数
- Executed 为函数覆盖率
- Lines 代码总行数
- Missed Lines 未被覆盖的行的数量
- Cover 行覆盖率
- Branches 条件总数
- - Missed Branches 未被覆盖了条件的数量

Filename	Functions	Missed Functions	Executed	Lines	Missed Lines	Cover	Branches	Missed Branches	Cover
/home/hurx/test/test.c	1	0	100.00%	11	1	90.91%	4	1	75.00%
TOTAL	1	0	100.00%	11	1	90.91%	4	1	75.00%

覆盖率总结报告