Predicate-based Test Coverage and Generation

17-654/17-765
Analysis of Software Artifacts
Jonathan Aldrich

These slides prepared by Thomas Ball, with additional material from M. Young, A. Memon and MSR's FSE group. Used by permission.

MSIL **U**nit **T**est **T**ool

a hybrid helper

- Goal
  - capture developer knowledge ***ASAP***
  - via a ***strong*** set of unit tests
  - to form a ***specification*** of the code's behavior
- How
  - generate tests based on analysis of MSIL
  - symbolic execution + constraint satisfaction
  - runtime analysis to check complicated invariants
- Facets
  - complements specification-based test generation
  - positive feedback cycle with programmer

What criteria should guide unit test generation?

Predicate-complete Testing

- Predicates
  - relational expression such as (x<0)
  - the expression (x<0) || (y>0) has two predicates
  - predicates come from program and safe runtime semantics
- Consider a program with *m* statements and *n* predicates
  - predicates partition input domain
  - $m \times 2^n$ possible *observable* states S
- Goal of Predicate-complete Testing:
  - cover all *reachable* observable states $R \subseteq S$

PCT Coverage

L2: if (A || B) S else T
L3: if (C || D) U else V

- PCT requires covering all logical combinations over {A,B,C,D} at
  - L2 and L3
  - S, T, U and V
- Some combinations may not be reachable

PCT Coverage Subsumes Statement, Edge Coverage

- Statement coverage
  - Must cover all statements with all predicates
- Edge coverage
  - Must cover if statements with all predicates
  - Therefore touch both branches
- Path coverage
  - Must cover every path through program
  - Infinite number of them!

PCT Coverage does not imply Path Coverage

```
L1:  if (x<0)
L2:    skip;
     else
L3:    x = -2;
L4:  x = x + 1;
L5:  if (x<0)
L6:    A;
```

(L1, x<0) (L1, !(x<0))
(L2, x<0)
(L3, !(x<0))
(L4, x<0)
(L5, x<0) (L5, !(x<0))
(L6, x<0)

PCT Coverage does not imply Path Coverage

```
L1:  if (x<0)
L2:    skip;
     else
L3:    x = -2;
L4:  x = x + 1;
L5:  if (x<0)
L6:    A;
```

(L1, x<0) (L1, !(x<0))
(L2, x<0)
(L3, !(x<0))
(L4, x<0) → (L5, !(x<0))
(L5, x<0)
(L6, x<0)

Three tests

x → -1

PCT Coverage does not imply Path Coverage

```
L1:  if (x<0)
L2:    skip;
     else
L3:    x = -2;
L4:  x = x + 1;
L5:  if (x<0)
L6:    A;
```

(L1, x<0) (L1, !(x<0))
(L2, x<0)
(L3, !(x<0))
(L4, x<0) → (L5, !(x<0))
(L5, x<0)
(L6, x<0)

Three tests

x → -1 x → 2

PCT Coverage does not imply Path Coverage

```
L1:  if (x<0)
L2:    skip;
     else
L3:    x = -2;
L4:  x = x + 1;
L5:  if (x<0)
L6:    A;
```

(L1, x<0) (L1, !(x<0))
(L2, x<0)
(L3, !(x<0))
(L4, x<0) → (L5, !(x<0))
(L5, x<0)
(L6, x<0)

Three tests

x → -1 x → 2 x → -3

Path Coverage does not imply PCT Coverage

```
L1:  if (p)
L2:    if (q)
L3:      x=0;
L4:  y=p+q;
```

(L1, pq) (L1, p̄q) (L1, pq̄) (L1, p̄q̄)
(L2, pq) (L2, pq̄)
(L3, pq)
(L4, pq) (L4, p̄q) (L4, pq̄) (L4, p̄q̄)

path L1 L2 L3 L4

path L1 L2 L4

Path Coverage does not imply PCT Coverage

```
L1:  if (p)
L2:    if (q)
L3:      x=0;
L4:  y=p+q;
```

(L1, pq) (L1, p̄q) (L1, pq̄) (L1, p̄q̄)
(L2, pq) (L2, pq̄)
(L3, pq)
(L4, pq) (L4, p̄q) (L4, pq̄) (L4, p̄q̄)

path L1 L2 L3 L4

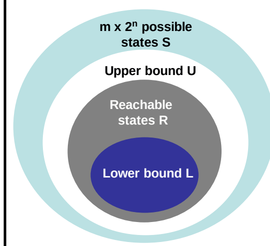
path L1 L2 L4

path L1 L4

Denominator Problem

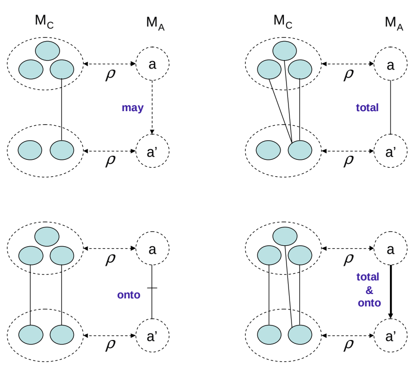
- Coverage metrics require a denominator
  - e.g. statements executed / total statements
- Easy to define for observable states
  - executed observable states / (m x 2^n)
- But (m x 2^n) is not a very good denominator!
  - most observable states will not be reachable
  - R <<< S

Upper and Lower Bounds

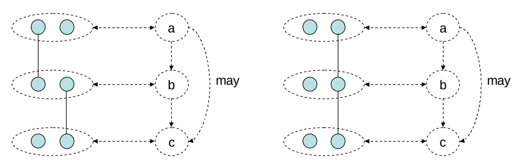


- Bound reachable observable states
  - modal transition systems and predicate abstraction
  - |L| / |U| defines "goodness" of abstraction
- Test generation using lower bound L
- Refinement to increase |L| / |U| ratio

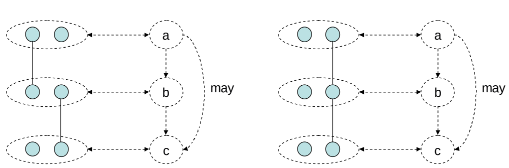
Abstraction Construction



Upper Bound: May-Reachability

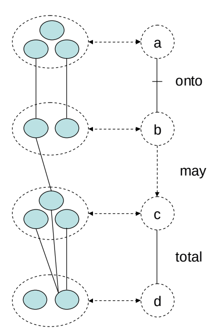


Upper Bound: May-Reachability

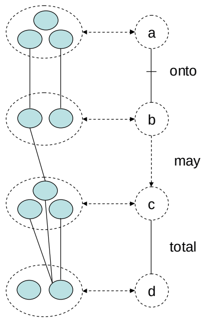


U = (may)*

Pessimistic Lower Bound



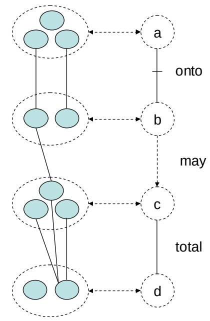
Pessimistic Lower Bound



(onto)* is onto

(total)* is total

Pessimistic Lower Bound



(onto)* is onto

(total)* is total

$L_p = (\text{onto})^* \text{ may? } (\text{total})^*$

Example

```
void partition(int a[]) {
  assume(a.length()>2);
  int pivot = a[0];
  int lo = 1;
  int hi = a.length()-1;
  while (lo<=hi) {
    while (a[lo]<=pivot)
      lo++;
    while (a[hi]>pivot)
      hi--;
    if (lo<hi)
      swap(a,lo,hi);
  }
}
```

Observation Vector

[lo<hi, lo<=hi, a[lo]<=pivot, a[hi]>pivot]

- lo<hi ⇒ lo<=hi
- ¬lo<hi ∧ lo<=hi ⇒ (a[lo]<=pivot ∧ ¬a[hi]>pivot)
  ∨ (¬a[lo]<=pivot ∧ a[hi]>pivot)

Only 10/16 observations possible

```
void partition(int a[]) {
  assume(a.length()>2);
  int pivot = a[0];
  int lo = 1;
  int hi = a.length()-1;

  L0: while (lo<=hi) {
  L1:   ;
  L2:   while (a[lo]<=pivot) {
  L3:     lo++;
  L4:   ;}
  L5:   while (a[hi]>pivot) {
  L6:     hi--;
  L7:   ;}
  L8:   if (lo<hi) {
  L9:     swap(a,lo,hi);
  LA:   ;}
  LB: ;}
  LC: ;
}
```

13 labels x 10 observations = 130 observable states

But, program constrains **reachable** observable states greatly.

Boolean Program

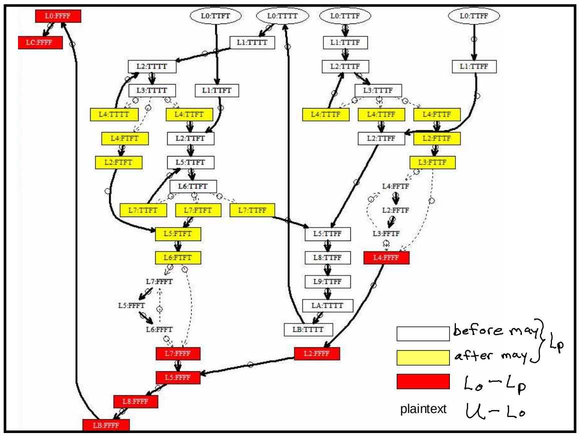
```
void partition() {
  decl lt, le, al, ah;
  enforce ( (lt=>le) &
            ((!lt&le)=>(al&!ah)|(!al&ah)) );
      lt,le,al,ah := T,T,*,*;
  L0: while (le) {
  L1:   ;
  L2:   while (al) {
  L3:     lt,le,al := (!lt ? F:*), lt, *;
  L4:   ;}
  L5:   while (ah) {
  L6:     lt,le,ah := (!lt ? F:*), lt, *;
  L7:   ;}
  L8:   if (lt) {
  L9:     al,ah := !ah,!al;
  LA:   ;}
  LB: ;}
  LC: ;
}
```

State Space of Boolean Program

[lo<hi, lo<=hi, a[lo]<=pivot, a[hi]>pivot]

	TTTT	TTTF	FTTF	FFTF	TTFT	FTFT	FFFT	TTFF	FFFF	FFTT
L0	x	x			x			x	x	
L1	x	x			x			x		
L2	x	x	x	x	x	x		x	x	
L3	x	x	x	x						
L4	x	x	x	x	x	x		x	x	
L5					x	x	x	x	x	
L6					x	x	x			
L7					x	x	x	x	x	
L8								x	x	
L9								x		
LA	x									
LB	x								x	
LC									x	

Upper Bound = 49 states



Test Generation

- DFS of L_p generates covering set of paths
- Symbolically execute paths to generate tests
- Run program on tests to find errors and compute coverage of observable states

Generated Inputs

```
void partition(int a[]) {
  assume(a.length()>2);
  int pivot = a[0];
  int lo = 1;
  int hi = a.length()-1;

  L0: while (lo<=hi) {
  L1:   ;
  L2:   while (a[lo]<=pivot) {
  L3:     lo++;
  L4:   ;}
  L5:   while (a[hi]>pivot) {
  L6:     hi--;
  L7:   ;}
  L8:   if (lo<hi) {
  L9:    swap(a,lo,hi);
  LA:   ;}
  LB: ;}
  LC: ;
}
```

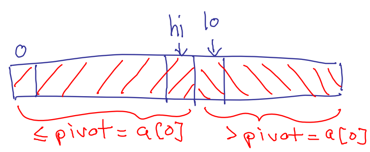
Array bounds violations

(L0:TTTT,L4:FTFT)	{ 0,-8,1 }
(L0:TTTT,L4:TTFT)	{ 0,-8,2,1 }
(L0:TTTT,L4:TTTT)	{ 0,-8,-8,1 }
(L0:TTTF,L4:TTFF)	{ 1,-7,3,0 }
(L0:TTTF,L4:FTTF)	{ 0,-7,-8 }
(L0:TTTF,L4:TTTF)	{ 1,-7,-7,0 }
(L0:TTFT,L7:TTFF)	{ 0,2,-8,1 }
(L0:TTFT,L7:FTFT)	{ 0,1,2 }
(L0:TTFT,L7:TTFT)	{ 0,3,1,2 }
(L0:TTFF,L0:TTTT)	{ 1,2,-1,0 }

Results

- Buggy partition function
  - U=49, L=43, Tested=42
- Fixed partition function
  - U=56, L=37, Tested=43
- What about the remaining 13 states?

Refinement



Existing predicates do not precisely track boundary condition

lo<hi, lo≤hi, a[lo]≤pivot, a[hi]>pivot

New Observation Vector

[lo<hi, lo<=hi, lo=hi+1,
a[lo]<=pivot, a[hi]>pivot,
a[lo-1]<=pivot, a[hi+1]>pivot
]

Only 48/128 observations possible

For this set of predicates, L_p = U

Conclusions

- PCT coverage
  - new form of state-based coverage
  - similar to path coverage but finite
- Upper and lower bounds
  - computed using predicate abstraction and modal transitions
  - use lower bound to guide test generation
  - refine bounds