Lecture 3 – Coverage Criteria

AAA705: Software Testing and Quality Assurance

Jihyeok Park

PLRG

2026 Fall

Recall

- Random Testing (RT)
  - Geometric distribution – $E(X) = 1/p$, $1 - (1 - p)^n$
  - Residual risk – n clean runs only give $p < \ln(1/\delta)/n$
- Feedback-Directed Random Testing (Randoop)
- Adaptive Random Testing (ART)
  - Distance between inputs, and the 50% upper bound
- Fuzz Testing
  - Generation-based (grammars, Csmith) / mutation-based (bytes, ASTs)
  - **Coverage-guided** fuzzing, and directed fuzzing
  - Sanitizers as oracles, and crash triage

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- It turns that structure into a finite set of **test requirements**, so "how much have we tested?" becomes a **number**.
- And then the honest question: does a bigger number mean **better tests**? The same question comes back for neural networks.

Contents

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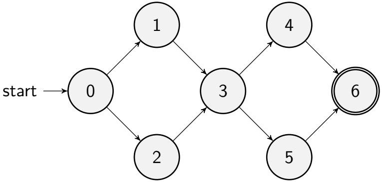
Programs Are Graphs

```
int f(int a, int b) {
  int x = 42;             // 0
  if (a > 0) g();         // 1
  else       h();         // 2
  int y;
  if (b > 0)              // 3
    y = x * 2;            // 4
  else
    y = x - 5;            // 5
  return y;               // 6
}
```



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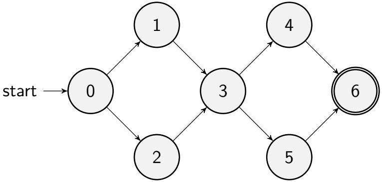

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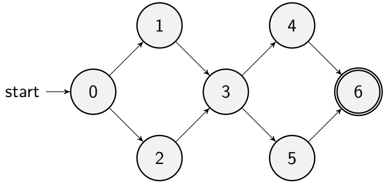

- A **control flow graph (CFG)** is one of many: **call graphs**, **finite state machines**, class hierarchies, spec structures.
- Define coverage **once** on graphs, and it applies to all of them.

Graphs and Paths

Definition (Graph)

A **graph** $G = (N, E, N_s, N_f)$ consists of a set of **nodes** N, a set of **edges** $E \subseteq N \times N$, a set of **start nodes** $N_s \subseteq N$, and a set of **final nodes** $N_f \subseteq N$.

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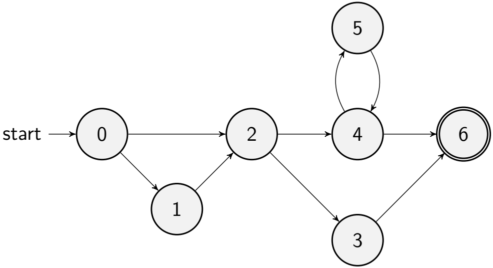
- A **subpath** $q \preceq p$ is a **contiguous** subsequence: $\exists 0 \leq i \leq j \leq k.\ q = (n_i, \ldots, n_j)$.
- A **test path** starts at a start node and ends at a final node ($n_0 \in N_s \wedge n_k \in N_f$) – it is what an **execution** of a test case looks like. We write path(t) for the test path of a test case t, and path(T) for those of a test suite T.

Paths – Example

Consider a path $p = [0, 2, 4, 5, 4, 6]$ in the graph G.

$G =$ 

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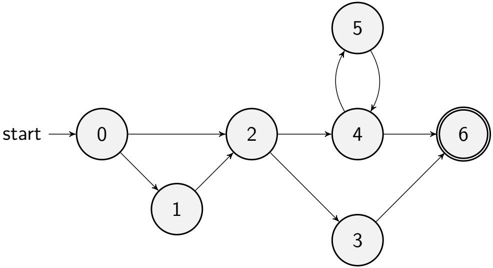

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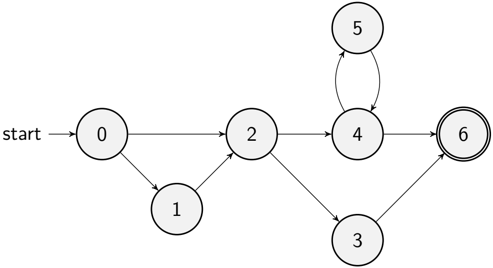
$G =$ 

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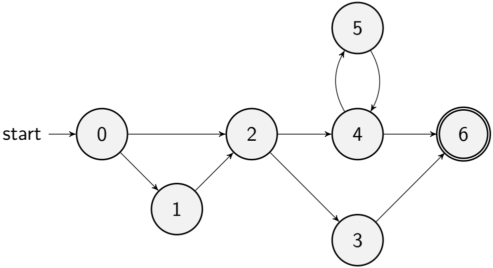
$G \quad =$ 

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- $[2, 4, 5] \preceq p$, but $[2, 4, 6] \not\preceq p$ – **contiguous**, not just in order
- p **visits** nodes 0, 2, 4, 5, 6 and edges $(0, 2)$, $(2, 4)$, $(4, 5)$, $(5, 4)$, $(4, 6)$

Graph Coverage Criterion

Definition (Graph Coverage Criterion)

A **graph coverage criterion** $C_G = (R_G, \sim)$ for a graph G is

- a set of **test requirements (TRs)** R_G, and
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- Everything below is a choice of R_G and $\sim$: **structural** criteria use only nodes, edges, and paths; **data-flow** criteria use a graph annotated with **variables**.

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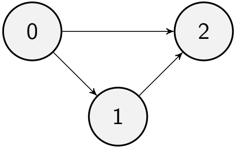
NC and EC differ only when there is **both** an edge and another subpath between a pair of nodes – an `if` without an `else` is the smallest case: $[0, 2]$ visits every node but misses $(0, 1)$.



Node and Edge Coverage – Example

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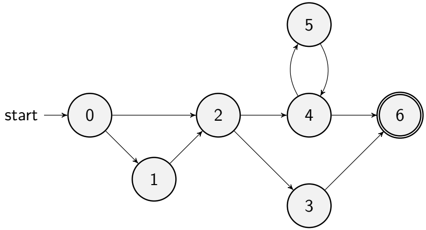

- **Node Coverage (NC)**

$$R_G = \{0, 1, 2, 3, 4, 5, 6\}$$
$$\text{Test Paths} = \{[0, 1, 2, 3, 6], [0, 1, 2, 4, 5, 4, 6]\}$$

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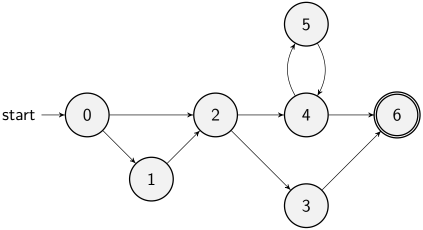

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- **Edge Coverage (EC)**

$$R_G = \{(0, 1), (0, 2), (1, 2), (2, 3), (2, 4), (3, 6), (4, 5), (5, 4), (4, 6)\}$$
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Node and Edge Coverage – Example

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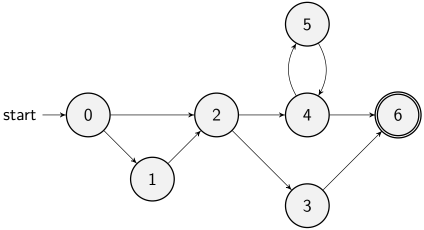

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- The NC suite is **not** EC-adequate: it never takes $(0, 2)$.

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- $R_G = \{p \in P_G \mid |p| \leq k\}$
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- The criteria we just defined are the small cases of this one:

$k = 0:$	paths of length $0 =$ **nodes**	**node coverage (NC)**
$k = 1:$	$+$ paths of length $1 =$ **edges**	**edge coverage (EC)**
$k = 2:$	$+$ pairs of adjacent edges	**edge-pair coverage (EPC)**
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- So k is a single **knob** trading cost for strength.

Edge-Pair Coverage – Example

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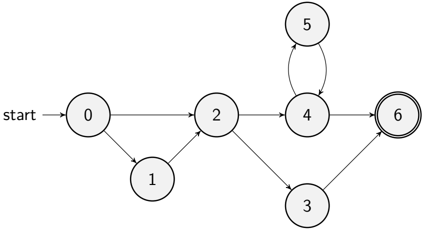

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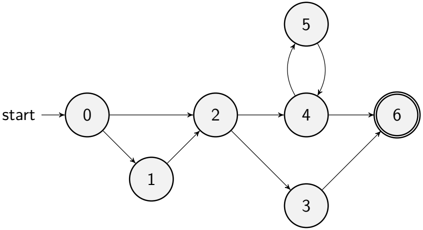

- **11** requirements of length 2 (plus the nodes and edges):

$$[0,1,2],\ [0,2,3],\ [0,2,4],\ [1,2,3],\ [1,2,4],\ [2,3,6],$$
$$[2,4,5],\ [2,4,6],\ [4,5,4],\ [5,4,5],\ [5,4,6]$$

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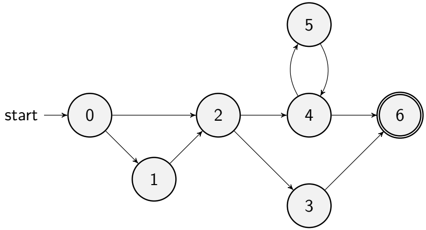

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$= \{[0,1,2,3,6],\ [0,1,2,4,6],\ [0,2,3,6],\ [0,2,4,5,4,5,4,6]\}$

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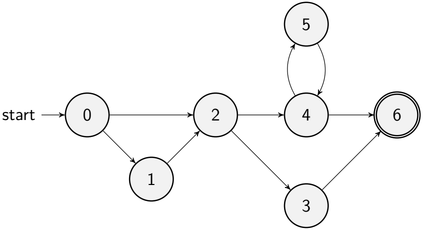
$G =$ 

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- Test Paths
  $= \{[0,1,2,3,6],\ [0,1,2,4,6],\ [0,2,3,6],\ [0,2,4,5,4,5,4,6]\}$
- Note $[5,4,5]$: covering it needs $4 \rightarrow 5 \rightarrow 4 \rightarrow 5$, so EPC forces the loop body **twice**.

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- One loop makes P_G **infinite**, so CPC is infeasible. Which finitely many paths should stand in for the infinitely many?

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- **Specified path coverage (SPC)** lets the tester list them – and makes the criterion depend on the tester's expertise.
- Four decades of answers:
  - 1970s: execute each cycle once ($[4, 5, 4]$ above)
  - 1980s: execute each loop exactly once
  - 1990s: execute each loop 0 times, once, more than once
  - 2000s: **prime paths** – get all three for free

Simple and Prime Paths

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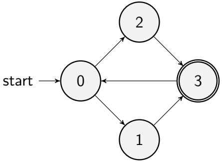

23 simple paths, of which **8** are prime:
$[0, 1, 3, 0]$, $[0, 2, 3, 0]$, $[1, 3, 0, 1]$, $[1, 3, 0, 2]$, $[2, 3, 0, 1]$, $[2, 3, 0, 2]$, $[3, 0, 1, 3]$, $[3, 0, 2, 3]$

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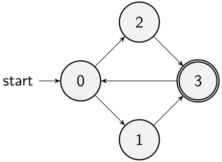

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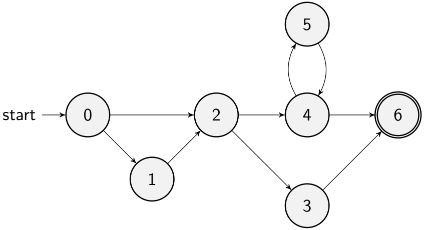
The other 15 are subpaths of these: $[0]$, $[0, 1]$, $[0, 1, 3]$, ...

Prime Paths Handle Loops



38 simple paths,	**9** prime:
[0, 1, 2, 3, 6]	[0, 2, 4, 5]
[0, 1, 2, 4, 5]	[0, 2, 4, 6]
[0, 1, 2, 4, 6]	[4, 5, 4]
[0, 2, 3, 6]	[5, 4, 5]
	[5, 4, 6]

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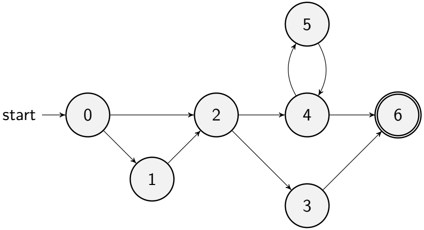

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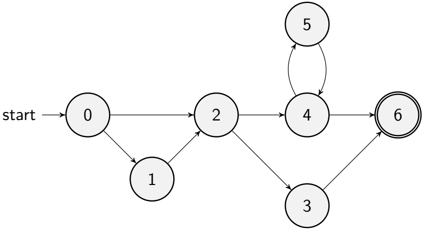

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[4, 5, 4] executes the loop **once**

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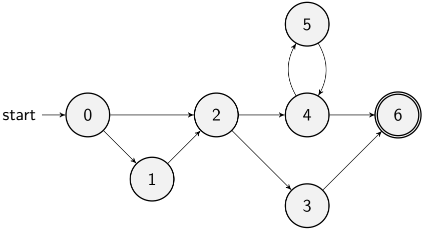

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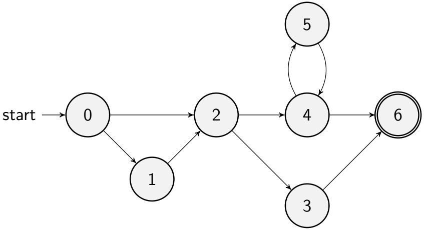
Prime Paths Handle Loops



38 simple paths,

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Prime path coverage needs all three, so it handles loops without a special rule.

Prime Path and Round-Trip Coverage

Definition (Prime Path Coverage (PPC))

$R_G = \{p \in P_G \mid p \text{ is a prime path}\}$, and $p \sim q \iff q \preceq p$.

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- On a **CFG** a node is not a state you can inspect, so these buy nothing over prime paths.

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Touring, Sidetrips, and Detours

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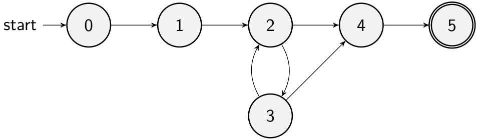

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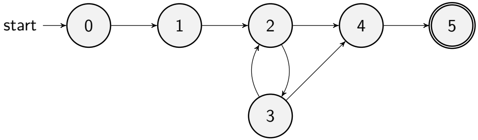

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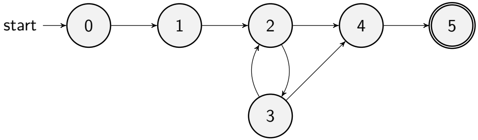

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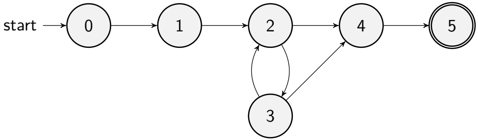

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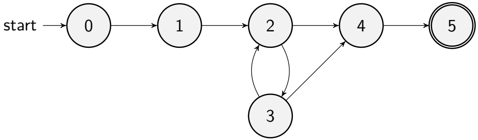

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- A detour may **skip the edge under test** – $(2, 4)$ is never taken above. That is why sidetrips are the usual compromise.

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- **In practice**: satisfy what you can **without** sidetrips, then **allow** sidetrips for the rest, then inspect the remainder by hand.

Definitions and Uses

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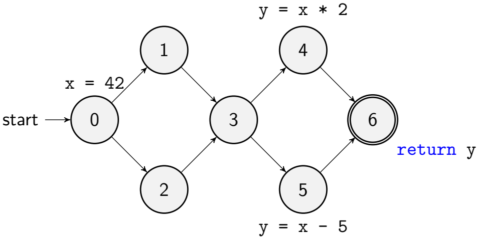

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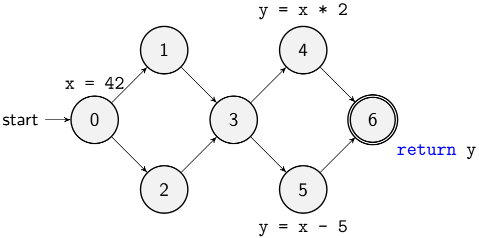

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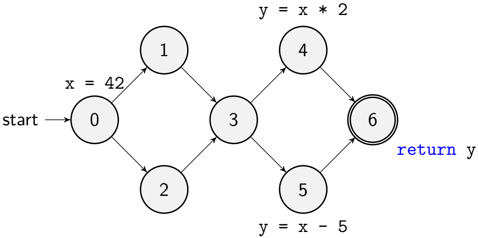

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- A **def** of a variable is a location where it is **assigned**; a **use** is a location where its value is **read**.
- Node coverage reaches node 4. It never checks that the 42 written at node 0 is the value node 4 reads.

DU-Pairs and DU-Paths

Definition (DU-Pair)

A **du-pair** for x is a pair of locations (l, l') such that x is defined at l and used at l'.

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PLRG

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- A test path **du-tours** a du-path if it tours it **and** the subpath taken stays def-clear – sidetrips are allowed only if they do not redefine x.

Three Data-Flow Criteria

One def, one use, and many paths between them. The three criteria differ exactly on **how many of those paths** you must take.

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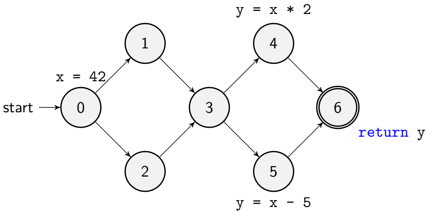
- ADC: every def reaches **some** use. AUC: every def reaches **every** use it can. ADUPC: and by **every route**.
- So ADUPC is the **strongest** of the three and ADC the **weakest**. When a tool says "data-flow coverage" it almost always means **AUC** – the other two are too weak and too expensive respectively.

Data-Flow Coverage – Example



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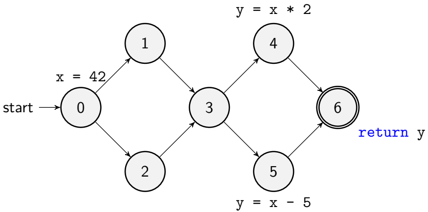

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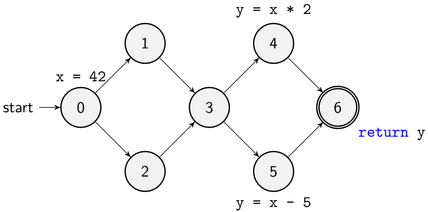

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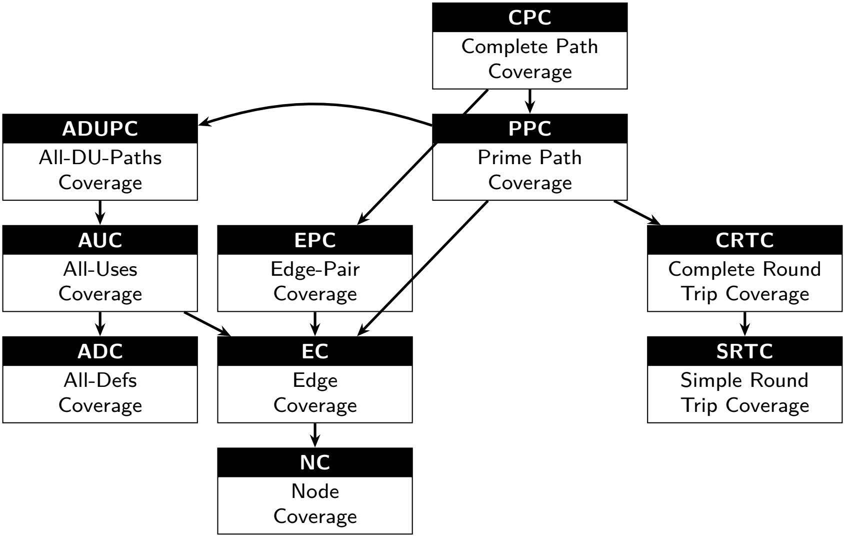
- CRTC and SRTC subsume neither – they see only loops.
- Subsumption is about **guarantees**, not about **finding bugs**. A PPC-adequate suite is not automatically better at detecting faults than an EC-adequate one. We come back to this later.

Subsumption Relationships



Contents

Predicates and Clauses

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- Operators: $\neg$, $\land$, $\lor$, $\oplus$, $\Rightarrow$, $\Leftrightarrow$.
- Node and edge coverage see **one bit** per `if` – which way it went. Logic coverage looks **inside** the condition.

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PLRG

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PC asks **two** questions per predicate; CC asks **two per clause**. Both are cheap, and neither implies the other.

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$$p = ((a < b) \vee D) \wedge (m \geq n \times o)$$

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PC

a	b	D	m	n	o	p
5	10	T	1	1	1	T
10	5	F	1	1	1	F

CC

a	b	D	m	n	o	$(a < b)$	D	$(m \geq n \times o)$
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10	5	T	1	2	2	F	T	F

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10	5	T	1	2	2	F	T	F

- Two tests each. This CC suite **happens** to satisfy PC as well (p is `true` then `false`) – but that is luck, not a guarantee.

Neither One Is Enough

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T	F	T
F	T	T

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- The simplest fix is to require **every combination**.

Combinatorial Coverage

Definition (Combinatorial Coverage (CoC))

For each $p \in P$, the TRs are **all combinations** of truth values of the clauses in C_p.

$$p = ((a < b) \vee D) \wedge (m \geq n \times o)$$

$(a < b)$	D	$(m \geq n \times o)$	p
T	T	T	T
T	T	F	F
T	F	T	T
T	F	F	F
F	T	T	T
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2^N tests for N clauses. We want CoC's **guarantee** at CC's **price**.

Determination

Definition (Determination)

A clause $c \in C_p$ – the **major clause** – **determines** p if the remaining **minor clauses** have values such that **changing the value of** c **changes the value of** p.

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A	B	$A \wedge B$
T	T	T
T	F	F
F	T	F
F	F	F

A	B	$A \oplus B$
T	T	F
T	F	T
F	T	T
F	F	F

A	B	$A \Leftrightarrow B$
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T	F	F
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A	B	$A \Leftrightarrow B$
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F	F	T

- A determines $A \vee B$ only when $B = \texttt{false}$, and $A \wedge B$ only when $B = \texttt{true}$.
- A **always** determines $A \oplus B$ and $A \Leftrightarrow B$ – the minor clause cannot mask it.

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For each $p \in P$ and each major clause $c \in C_p$, the TRs are the minor values that make c **determine** p, paired with $c = \texttt{true}$ and $c = \texttt{false}$.

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- For $p = A \vee B$:
  1. $A = \texttt{true}$, $B = \texttt{false}$ (A determines p)
  2. $A = \texttt{false}$, $B = \texttt{false}$ (A determines p)
  3. $A = \texttt{false}$, $B = \texttt{true}$ (B determines p)
  4. ~~$A = \texttt{false}$, $B = \texttt{false}$~~ (same row as 2)

  $N + 1$ tests instead of 2^N: **three** rows, not four.

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- ACC is better known as **modified condition/decision coverage (MC/DC)**. It is the criterion regulators require for the software that **flies aircraft**.[2]

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One Definition, Three Criteria

Ambiguity: must the **minor** clauses keep the **same values** when the major clause flips?

$$p = A \vee (B \wedge C), \quad \text{major clause } A$$

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is $C =$ `false` allowed here?

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- **General** active clause coverage (GACC)
- **Restricted** active clause coverage (RACC)
- **Correlated** active clause coverage (CACC)

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- GACC was meant to be **stronger** than predicate coverage. It is not even as strong. So we need a different rule.

RACC vs. CACC

RACC

A	B	C	$A \wedge (B \vee C)$
T	T	T	T
F	T	T	F
T	T	F	T
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RACC vs. CACC

PLRG

RACC

A	B	C	$A \land (B \lor C)$
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- **CACC** (*correlated*) only requires p to flip, so **any** top row pairs with **any** bottom row – **nine** choices.
- **RACC** is what the aviation industry adopted. **CACC** is the later reading: weaker, easier to satisfy, and still enough to subsume predicate coverage.

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For each $p \in P$ and each major clause $c \in C_p$, the TRs are the minor values that make c **not determine** p, paired with $c =$ `true` and $c =$ `false`.

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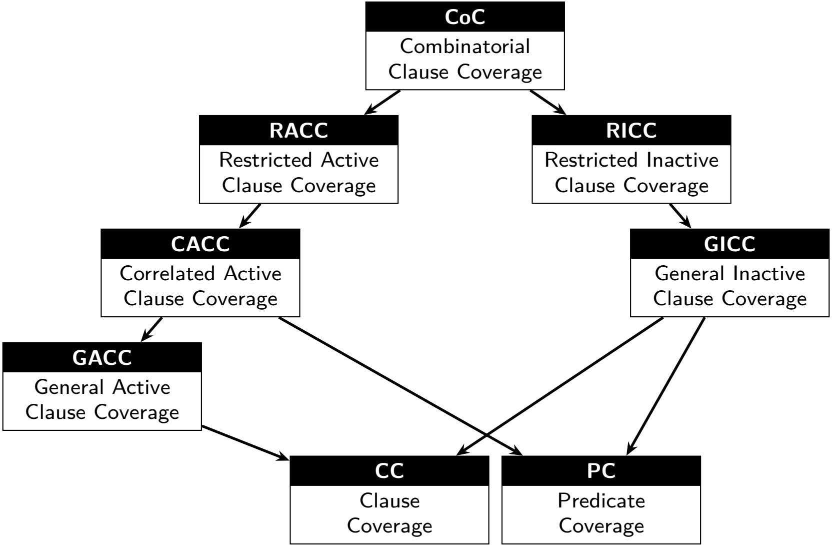
- Same ambiguity: **GICC** / **RICC**. No “correlated” variant – CACC asks the minor clauses to make p **flip** with c, and under ICC p never flips.

Subsumption Relationships



Contents

From a Criterion to a Number

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- The denominator is **not stable**: adding a line changes $|R_G|$, so the percentage moves without anyone writing a test.
- Three questions remain: **where** do the numbers come from, **what** do real tools count, and **what does the number mean**?

Instrumentation

To know that node 4 ran, the program must **say so**. Insert probes:

```
int f(int a, int b) {
  cov[0] = 1;  int x = 42;
  if (a > 0) { cov[1] = 1; g(); }
  else       { cov[2] = 1; h(); }
  cov[3] = 1;  int y;
  if (b > 0) { cov[4] = 1; y = x * 2; }
  else       { cov[5] = 1; y = x - 5; }
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- You do not need a probe on every node. If node 6 **post-dominates** node 3, one probe tells you about both.
- Coverage asks **whether** a block ran, not how often – so a probe can be **removed** once it fires.[4]

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What Real Tools Count

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- A fuzzer goes further: AFL **hashes** edges into 64K buckets, so two edges can share one. It wants a **fast** signal, not an exact one – the criterion follows from the **purpose**.

Contents

100% Coverage Is Not Correctness

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- **Necessary, not sufficient.** So how much does the necessary condition buy?

Then What Is It Good For?

- Bigger suites cover more **and** find more. Control for suite size and the correlation with fault detection is **weak** – and the studies still argue about how weak.[5]

  Low coverage is reliable bad news; high coverage is weak good news.

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- **As a search gradient.** Last week's fuzzer, and techniques still to come. Nobody reports the percentage; it is only a signal.

- **Not as a quality measure.** For that, seed faults and count kills – **mutation score**, which we take up later.

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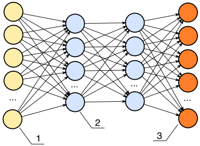
Contents

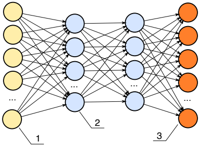
A Program With No Branches



- A DNN classifier is a function $f_\theta : X \to Y$ whose behavior lives in the **weights**, not in control flow. There is nothing to branch on – so cover the **neurons** instead. Write $f_\theta(n, x)$ for the output of neuron n on input x; the neuron is **activated** when that exceeds a threshold t.

[7] **[SOSP'17]** K. Pei, Y. Cao, J. Yang, S. Jana. "*DeepXplore.*" **[ASE'18]** L. Ma et al. "*DeepGauge.*"

A Program With No Branches



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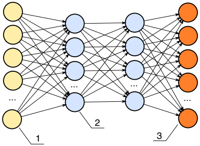

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Plain NC **saturates**, so it was refined by splitting each neuron's training range into k sections (**KMNC**), or looking outside that range (**NBC**), or taking the top k per layer (**TKNC**) – **the same k knob again**.[7]

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Does Neuron Coverage Work?

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- A better-founded alternative measures **surprise**: how far an input's activation trace is from the traces seen during training. It correlates with misclassification and gives a usable sampling target.[10]
- Same story as code coverage: **a criterion has to be validated, not just defined.**

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The Spec Is a Program

PLRG

```
a = [10, 20, 30];
a.at(-1); // 30
a.at(5);  // undefined
```

23.1.3.1 Array.prototype.at (*index*)

1. Let *O* be ? ToObject(*this* value).
2. Let *len* be ? LengthOfArrayLike(*O*).
3. Let *relativeIndex* be ? ToIntegerOrInfinity(*index*).
4. If *relativeIndex* ≥ 0, then
   a. Let *k* be *relativeIndex*.
5. Else,
   a. Let *k* be *len* + *relativeIndex*.
6. If $k < 0$ or $k \geq len$, return **undefined**.
7. Return ? Get(*O*, ! ToString($\mathbb{F}$(*k*))).

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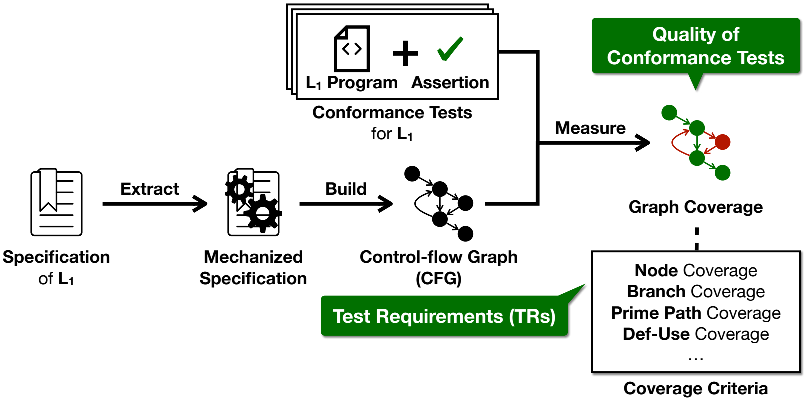
- ECMA-262 defines JavaScript as **pseudocode algorithms**. The two calls take **different paths** through this one: `at(-1)` runs $5 \to 7$, `at(5)` runs $4 \to 6$.

Covering the Specification



[11] **[ICSE'21]** J. Park, S. An, D. Youn, G. Kim, S. Ryu. "*JEST: N+1-Version Differential Testing of Both JavaScript Engines and Specification.*"

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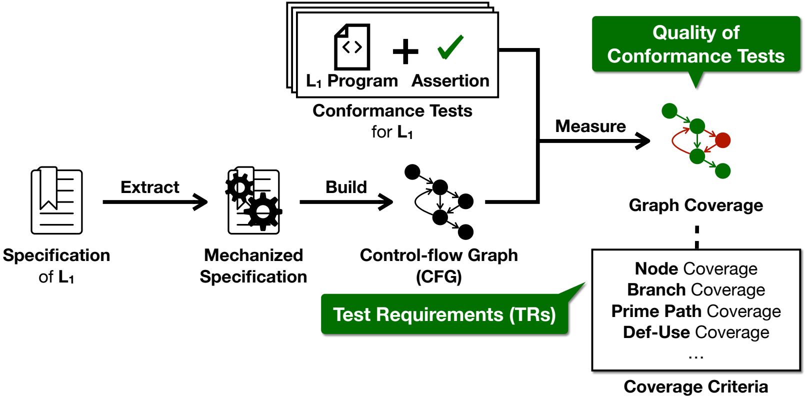

- **JEST**: 1,700 programs, **87.70%** of ES11 semantics – **44 engine bugs, 27 spec bugs**.[11]

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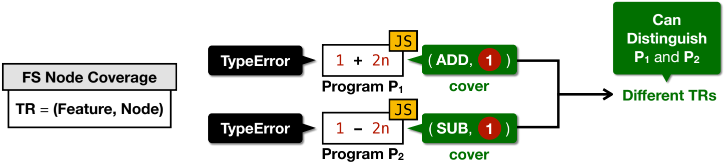
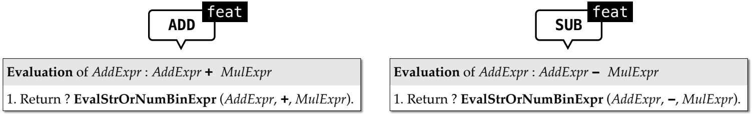
Feature-Sensitive Coverage



- **Feature-Sensitive (FS)** coverage criterion **divides** the given TRs with the **innermost enclosing** language **features**

FS Coverage

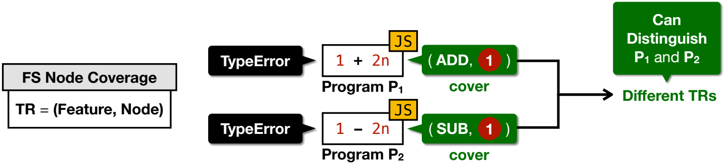
TR = (Feature, given TR)



[12] **[PLDI'23]** J. Park, D. Youn, K. Lee, S. Ryu. "*Feature-Sensitive Coverage for Conformance Testing of Programming Language Implementations.*"

[13] **[TOSEM'26]** K. Lee, S. Kim, J. Park, S. Ryu. "*Selective Feature-Sensitive Coverage for Conformance Testing of Programming Language Implementations.*"

Feature-Sensitive Coverage



- Feature-Sensitive (FS) coverage criterion **divides** the given TRs with the **innermost enclosing** language **features**

FS Coverage

TR = (Feature, given TR)

ADD feat

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **+**, *MulExpr*).

SUB feat

Evaluation of *AddExpr* : *AddExpr* **–** *MulExpr*

1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **–**, *MulExpr*).

- **143** bugs in eight implementations.[12] Selective FS: **70.7%** fewer tests but preserves 53 of 57 bugs.[13]

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Summary

1. Graph Coverage
    - Structural Coverage
    - Data-Flow Coverage
    - Subsumption Relationships
2. Logic Coverage
    - Simple Logic Expression Coverage
    - Active Clause Coverage
    - Inactive Clause Coverage
    - Subsumption Relationships
3. Measuring Coverage
4. Is Coverage a Good Criterion?
5. Coverage Beyond Code
    - Neuron Coverage
    - Feature-Sensitive Coverage

Homework #1 – Coverage Measurement

PLRG

- Build a **coverage profiler** that measures which parts of a program are executed by a test suite.
- Please see this document on GitHub:

  `https://github.com/ku-plrg-classroom/js-cov`

- The due date is **23:59 on September 21 (Mon.)**, and please submit it to **LMS**.

Next Lecture

- Search Based Software Testing (SBST)

Jihyeok Park
jihyeok_park@korea.ac.kr
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