Timing Analysis of Event-Driven Programs with Directed Testing

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Talk Outline

- Introduction
  - Toyota UA Case
  - Problem Definition and Previous Work
  - Review of Classic Directed Testing
  - Motivating Experiments
- Our Approach
  - Example
  - VICE: Algorithms and tools
- Experiment Results
- Conclusion
  - ***Event-Based Directed Testing*** improves the state-of-art

Aug. 28, 2009, San Diego CA, USA

- Toyota Lexus ES 350 sedan
  - UA Reached 100 mph+
- 911 Emergency Phone Call from passenger during event
  - All 4 occupants killed in crash
- Driver:
  Mark Saylor, 45 year old male.
  Off-duty California Highway Patrol Officer; vehicle inspector.
  - Crash was blamed on wrong floor mats causing pedal entrapment
  - Brake rotor damage indicated "endured braking"
- This event triggered escalation of investigations dating back to 2002 MY

The New York Times February 1, 2010

Gomez Law Firm

The wreckage of a Lexus ES 350 in which four people died in August after it accelerated out of control.

Recalls & Public Discussion

(*Brakes might not mitigate open throttle* – more later)

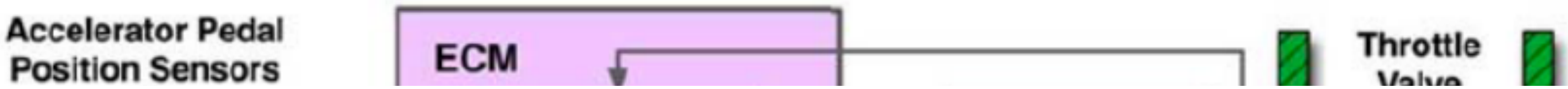
- Floor mat recalls
  - Sept. 2007 recall to fasten floor mats
  - Wider recall Oct./Nov. 2009 after Saylor mishap

- Sticky gas pedal recall
  - Jan. 2010 and onward

- Congressional investigation
  - Toyota President testifies to US Congress, Feb. 2010
  - April 2010: Economic loss class action venue selected

NASA Investigation

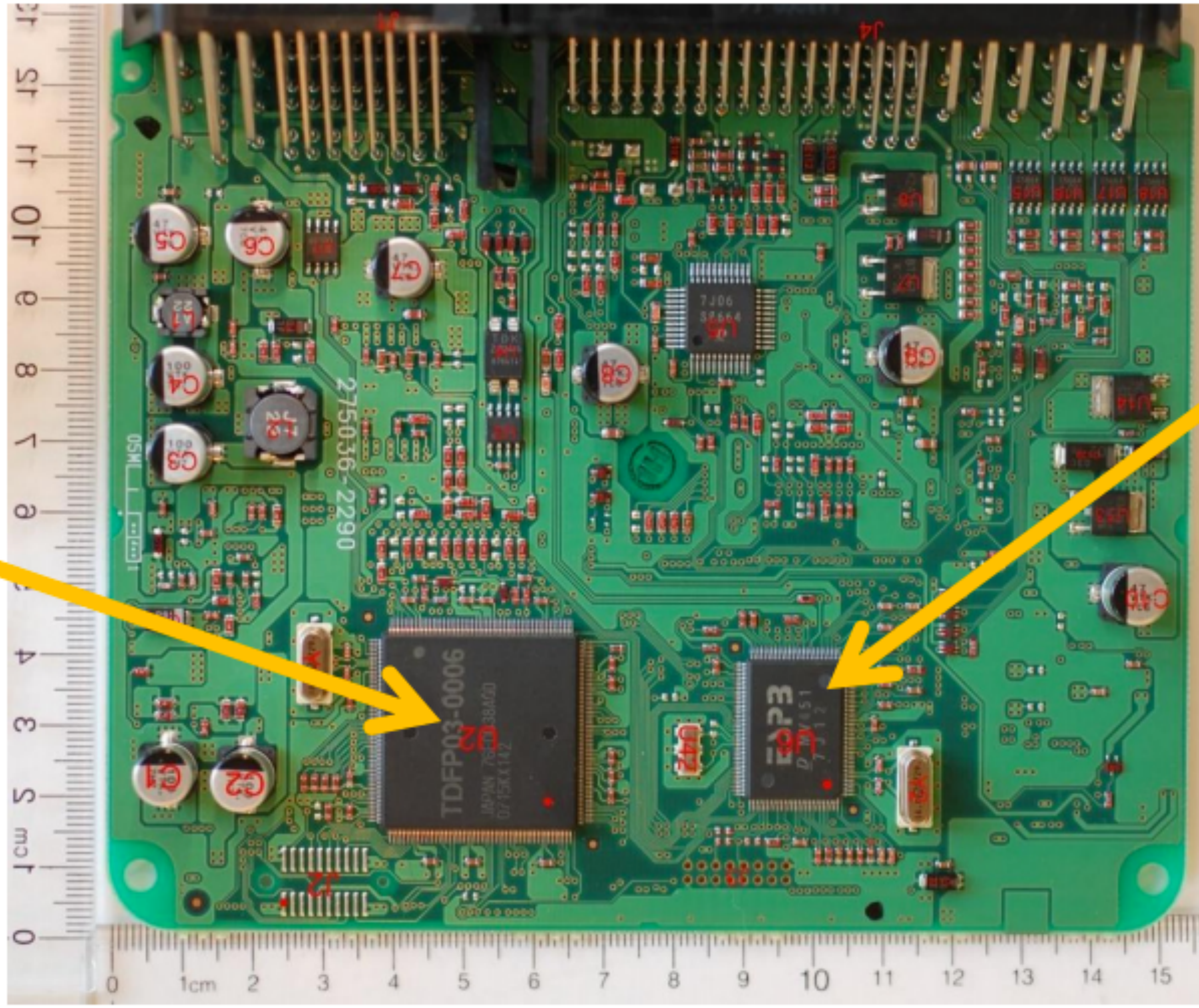
- NASA team investigates UA (2010-2011)
  - Including **Electronic Throttle Control System (ETCS)**
  - Controls air + fuel + spark ➔ engine power



- Timing analysis too difficult for NASA
  - Worst Case Execution Time difficult due to busy-wait loops, indirect recursion, etc. [NASA App. A pp. 120-133]
  - But, no deadline misses seen [NASA App. A. pp. 120-125]

Toyota 2008 ETCS – Two CPUs

Main CPU (Contains Software)



Monitor Chip (Contains Software)

http://m.eet.com/media/1201063/Toyota_ECM.jpg

$1.6B Economic Loss Class Action

- "Lawsuit pursues claims for breach of warranties, unjust enrichment, and violations of various state consumer protection statutes, among other claims."
  - https://www.toyotaelsettlement.com/
  - 2002 through 2010 models of Toyota vehicles
  - Toyota denies claims; settled for $1.6 Billion in Dec. 2012
  - Brake override firmware update for in some **recent** models

Please be advised that the Brake Override System installation is now available for the following make and model vehicles:

2008 - 2010 Toyota LandCruiser
2009 - 2010 Toyota Corolla
2009 - 2010 Toyota Corolla Matrix
2008 - 2010 Toyota Highlander
2006 - 2010 Toyota RAV4
2003 - 2009 Toyota 4Runner
2007 - 2010 Toyota Tundra
2008 - 2010 Lexus LX
2010 Lexus RX

https://www.toyotaelsettlement.com/
3 August 2014

Bookout/Schwarz Trial

[http://money.cnn.com/2013/10/25/news/companies/toyota-crash-verdict/]

- October 2013, Oklahoma
  - Fatal 2007 crash of a 2005 Toyota Camry
  - Neither floor mat nor sticky pedal recalls cover this MY; no "fixes" announced
- Toyota blamed driver error for crash
  - Mr. Arora (Exponent) testified as Toyota software expert
  - "[Toyota's counsel] theorized that Bookout mistakenly pumped the gas pedal instead of the brake, and by the time she realized her mistake and pressed the brake, it was too late to avoid the crash" [http://bigstory.ap.org/article/oklahoma-jury-considers-toyota-acceleration-case]
- Plaintiffs blamed ETCS
  - Dr. Koopman & Mr. Barr testified as software experts
  - Testified about defective safety architecture & software defects
  - 150 feet of skid marks implied open throttle while braking

WCET

- Controllers in safety time-critical embedded systems are expected to finish their tasks within reliable time bounds.
  - Underestimation causes missing deadlines and leads to bugs
  - Overestimation wastes process availability.
- *Question: what is the exact WCET across all inputs?*
  1. Program ***P***, ***K*** is the WCET of all executions of ***P***, if ***P***'s WCET never grows beyond ***K***.
  2. There is a possible schedule of events and an execution of the program ***P*** such that the WCET becomes ***K***.

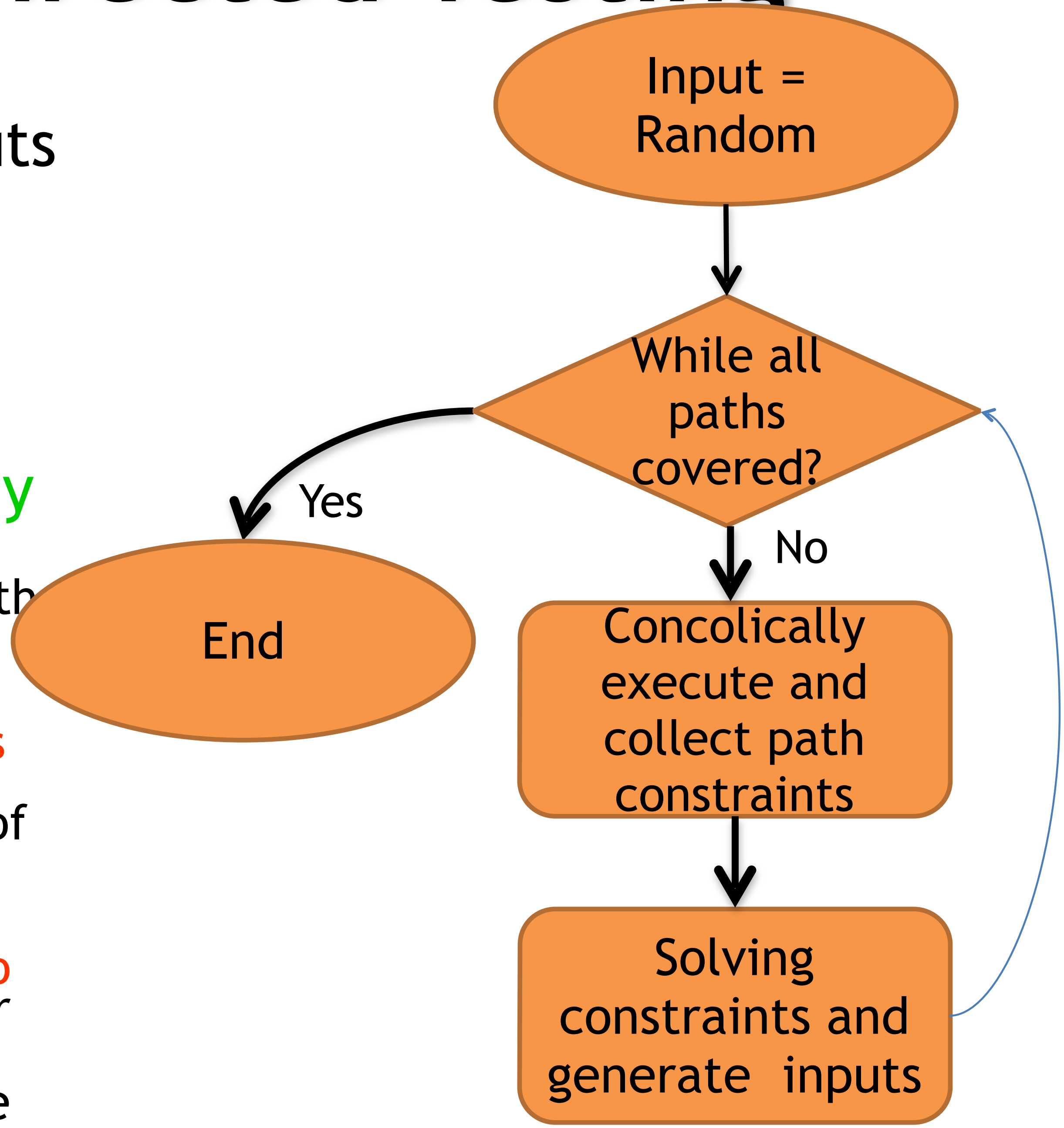
WCET in Literature

- Dynamic Analysis
  - Random Algorithms:
    - [Bernat et. Al., *RTSS'02*]
  - Genetic Algorithm:
    - [Atanassov et. Al., *EWDC'01*]
  - Classic Directed Testing:
    - [N. Williams and M.Roger, AST'09]
- Static Analysis
    - [Holsti et. Al., ESA'2000]
    - [C.Ferdinand, *BIS'04*]
    - [Gustafsson and Ermedahl, *RTSS'06*]

Classic Directed Testing

- Generate concrete inputs one by one
  - each input leads program along a different path

- On each input execute program both concretely and symbolically
  - concrete execution guides th symbolic execution
  - concrete execution enables symbolic execution to overcome incompleteness of theorem prover
  - symbolic execution helps to generate concrete input for next execution
    - increases coverage



Example

```
int double (int v) {
    return 2*v;
}

void testme (int x, int y) {
    z = double (y);
    if (z == x) {
        if (x > y+10) {
            ERROR;
        }
    }
}
```

Example

```
int double (int v) {
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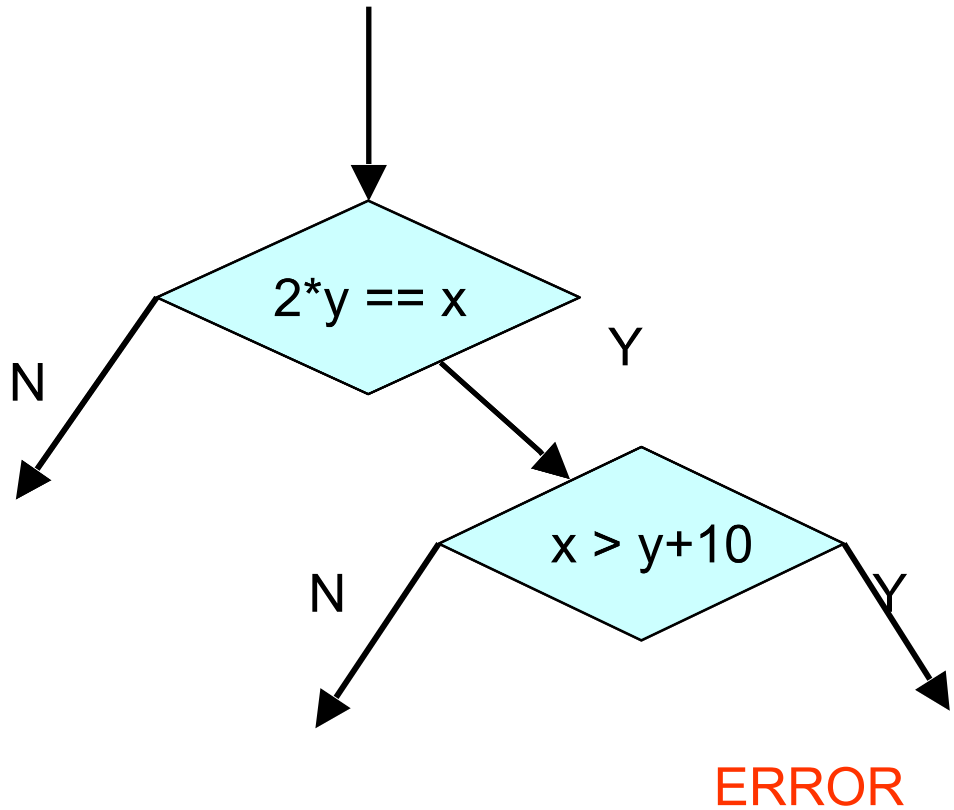

Directed Testing Approach

```
int double (int v) {
    return 2*v;
}

void testme (int x, int y) {
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}
```

Concrete Execution	Symbolic Execution	
concrete state	symbolic state	path condition
x = 22, y = 7	$x = x_0$, $y = y_0$	

Directed Testing Approach

```
int double (int v) {

    return 2*v;
}

void testme (int x, int y) {

    z = double (y);

    if (z == x) {

        if (x > y+10) {

            ERROR;
        }
    }

}
```

Concrete Execution	Symbolic Execution	
concrete state	symbolic state	path condition
x = 22, y = 7, z = 14	$x = x_0$, $y = y_0$, $z = 2*y_0$	

Directed Testing Approach

```
int double (int v) {
    return 2*v;
}

void testme (int x, int y) {
    z = double (y);
    if (z == x) {
        if (x > y+10) {
            ERROR;
        }
    }
}
```

	Concrete Execution	Symbolic Execution	
	concrete state	symbolic state	path condition
			$2*y_0 != x_0$
	$x = 22, y = 7, z = 14$	$x = x_0, y = y_0, z = 2*y_0$	

Directed Testing Approach

```
int double (int v) {
    return 2*v;
}

void testme (int x, int y) {
    z = double (y);
    if (z == x) {
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        }
    }
}
```

Concrete Execution | Symbolic Execution

concrete state | symbolic state | path condition

Solve: $2*y_0 == x_0$

Solution: $x_0 = 2, y_0 = 1$

$2*y_0 != x_0$

$x = 22, y = 7, z = 14$

$x = x_0, y = y_0, z = 2*y_0$

Directed Testing Approach

```
int double (int v) {
    return 2*v;
}

void testme (int x, int y) {
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Concrete Execution	Symbolic Execution	
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$x = 2, y = 1$	$x = x_0, y = y_0$	

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}
```

Concrete Execution	Symbolic Execution	
concrete state	symbolic state	path condition
$x = 2, y = 1,$ $z = 2$	$x = x_0, y = y_0,$ $z = 2*y_0$	

Directed Testing Approach

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int double (int v) {
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		$2*y_0 == x_0$
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	Concrete Execution	Symbolic Execution	
	concrete state	symbolic state	path condition
			$2*y_0 == x_0$
			$x_0 < y_0+10$
	$x = 2, y = 1, z = 2$	$x = x_0, y = y_0, z = 2*y_0$	

Directed Testing Approach

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        }
    }
}
```

Concrete Execution

Symbolic Execution

concrete state	symbolic state	path condition
$x = 2, y = 1, z = 2$	$x = x_0, y = y_0, z = 2^*y_0$	$2^*y_0 == x_0$
		$x_0 < y_0+10$

Solve: $(2^*y_0 == x_0)$ Æ $(x_0 > y_0 + 10)$

Solution: $x_0 = 30, y_0 = 15$

Directed Testing Approach

```
int double (int v) {

    return 2*v;
}

void testme (int x, int y) {

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    if (z == x) {

        if (x > y+10) {

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Concrete Execution	Symbolic Execution	
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x = 30, y = 15	$x = x_0$, $y = y_0$	

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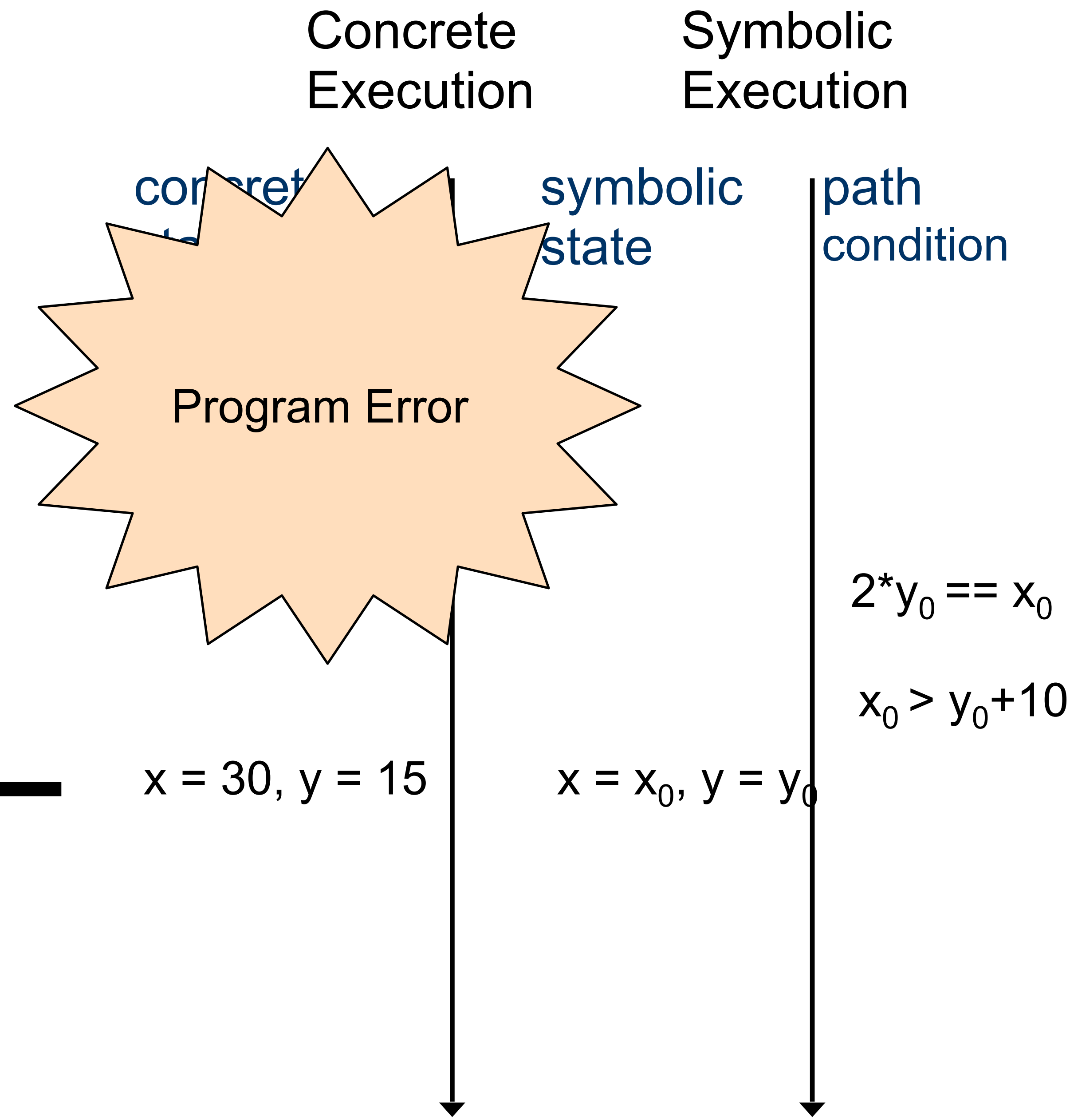
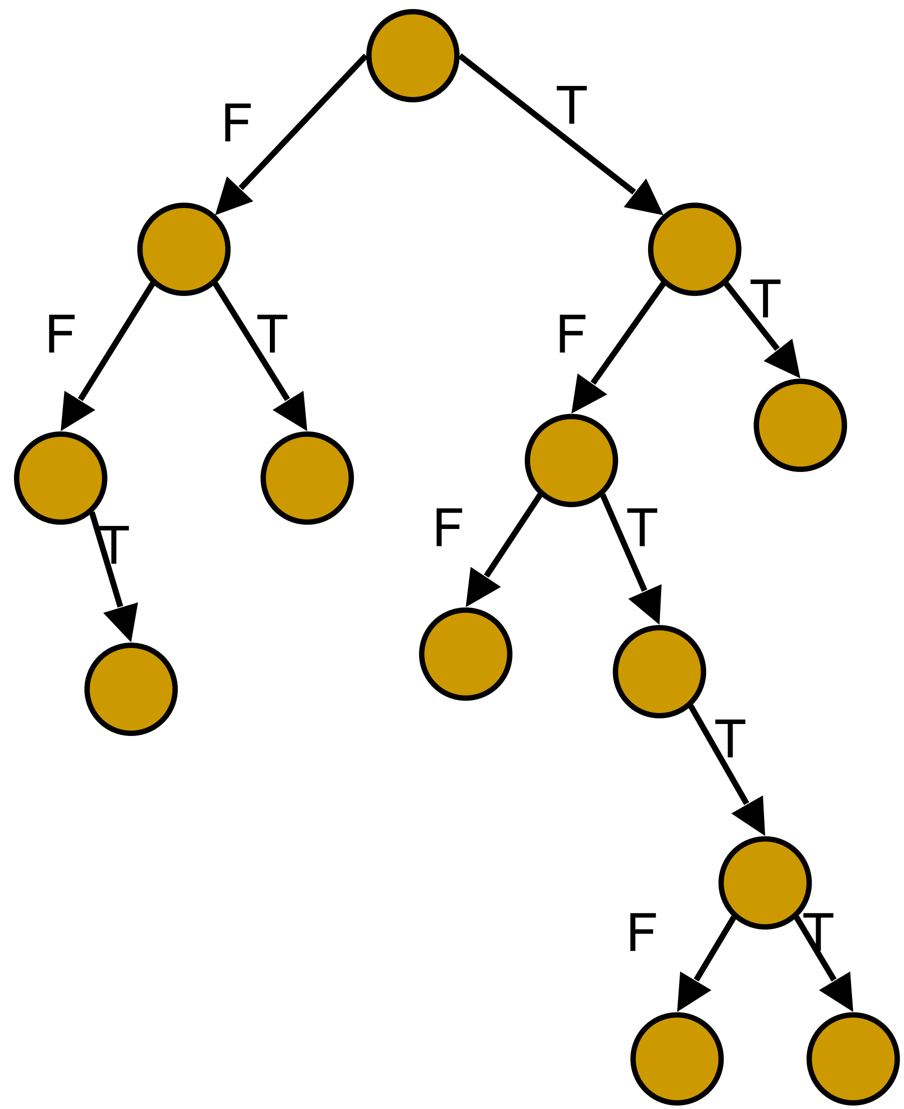


Explicit Path Model Checking

- Traverse all execution paths one by one to detect errors
  - assertion violations
  - program crash
  - uncaught exceptions



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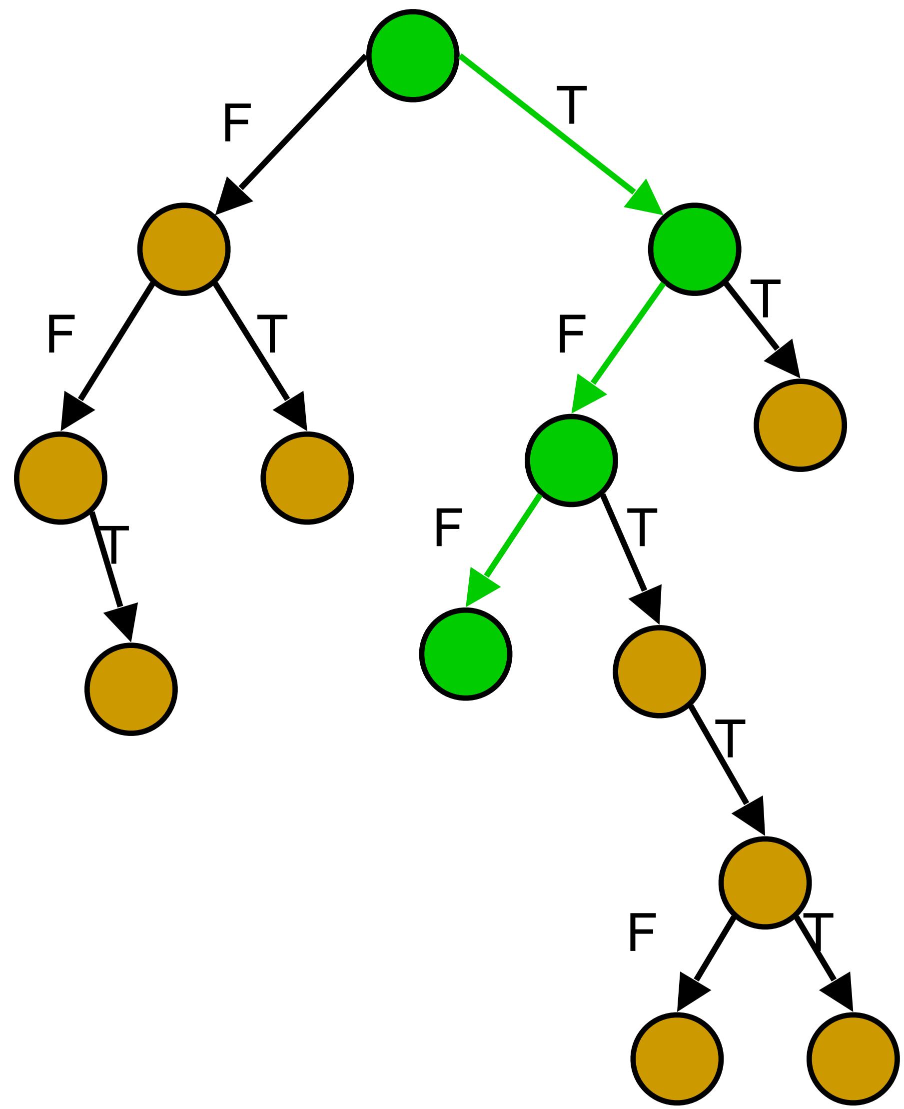

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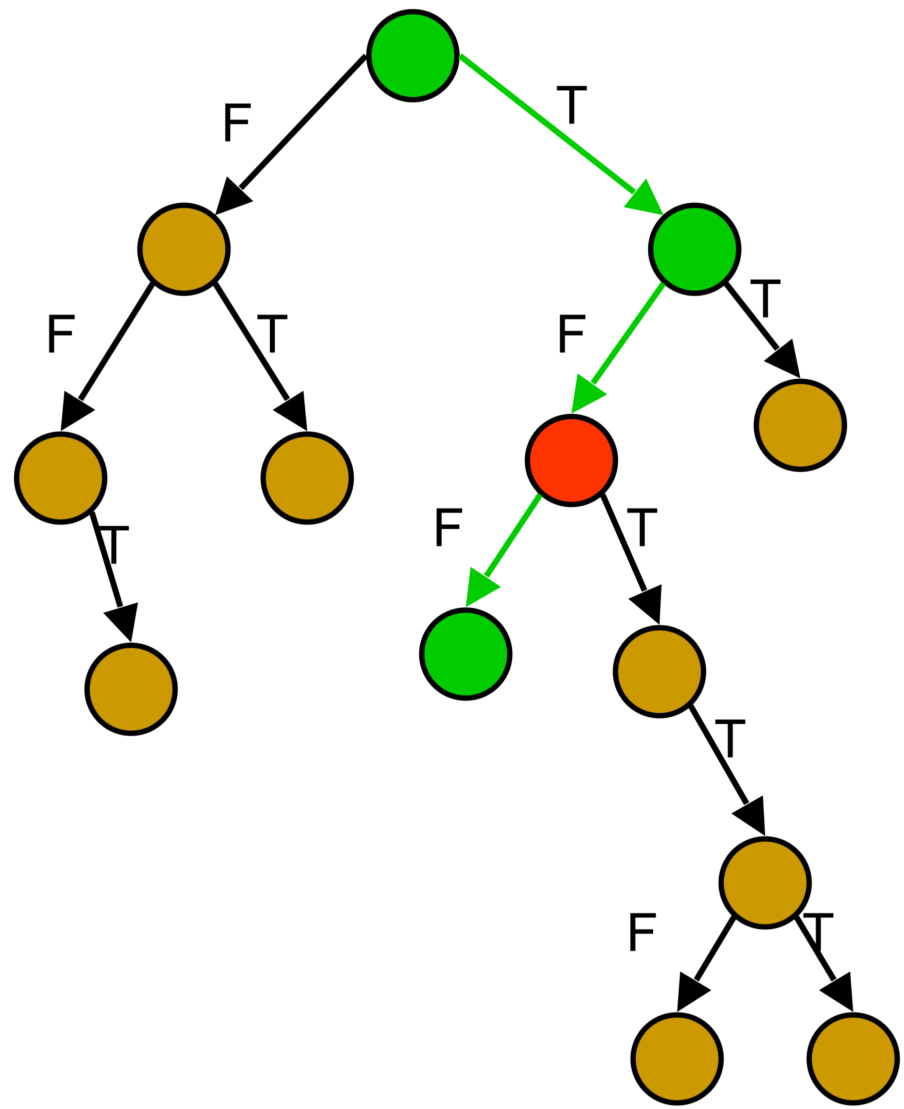

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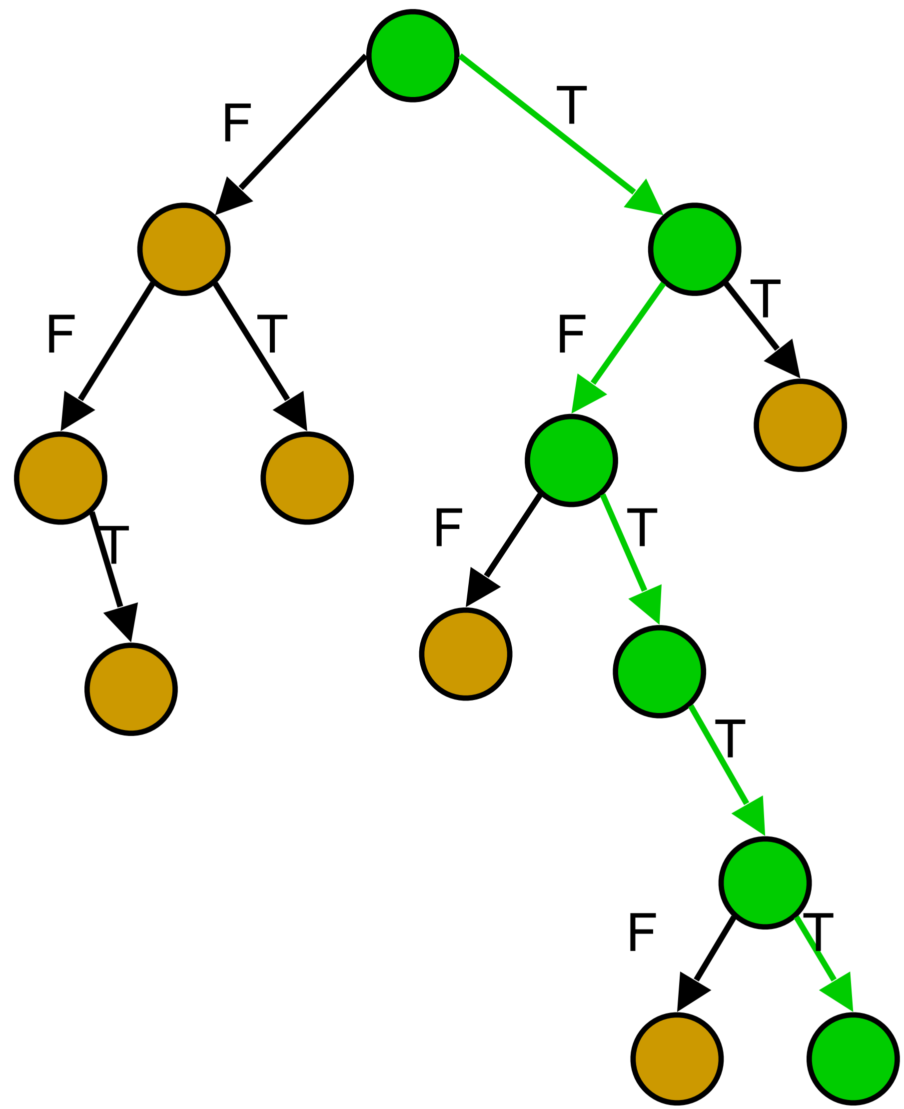

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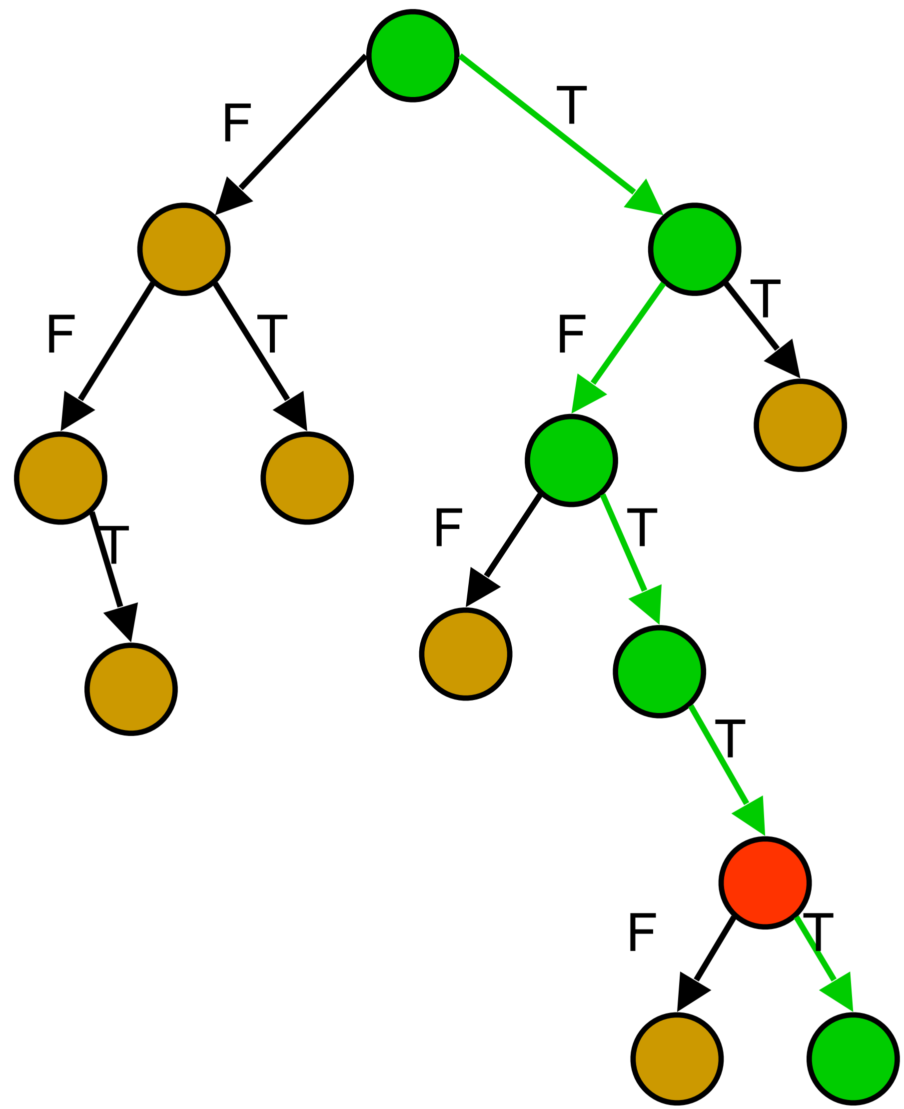

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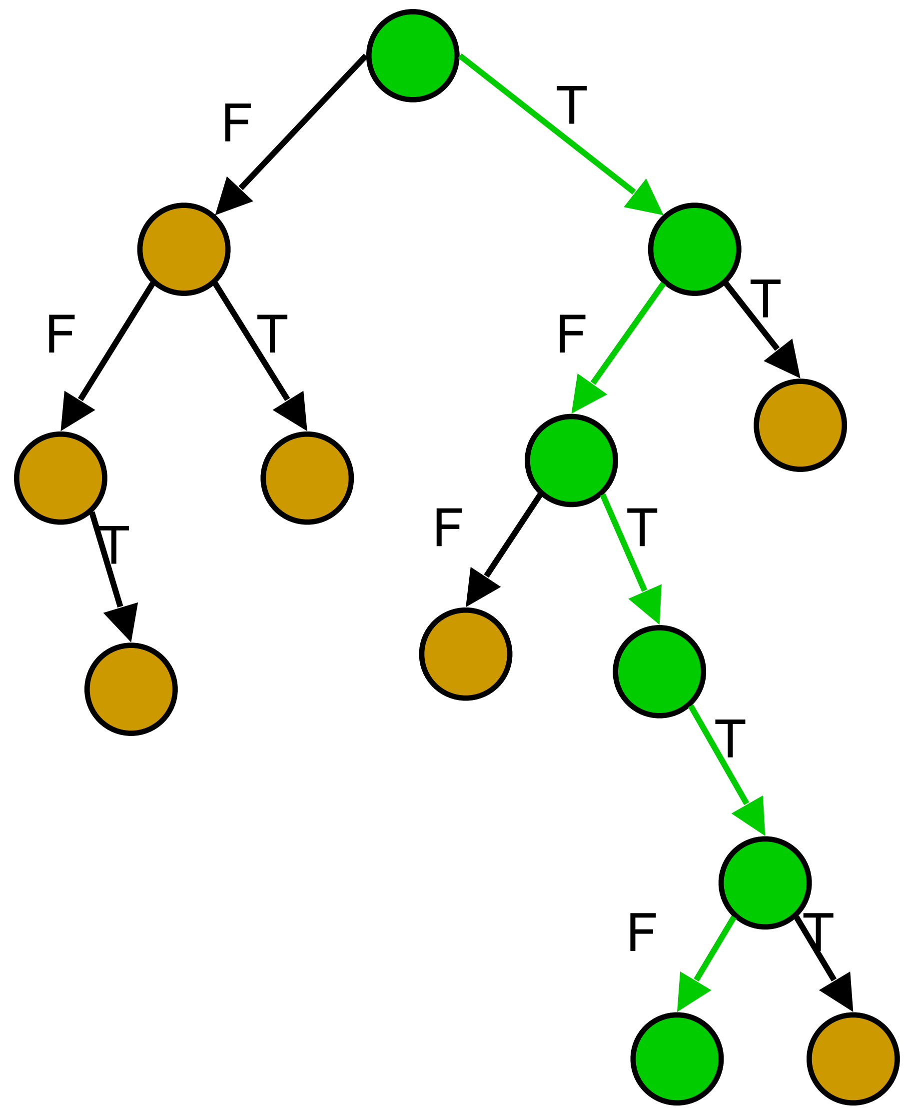
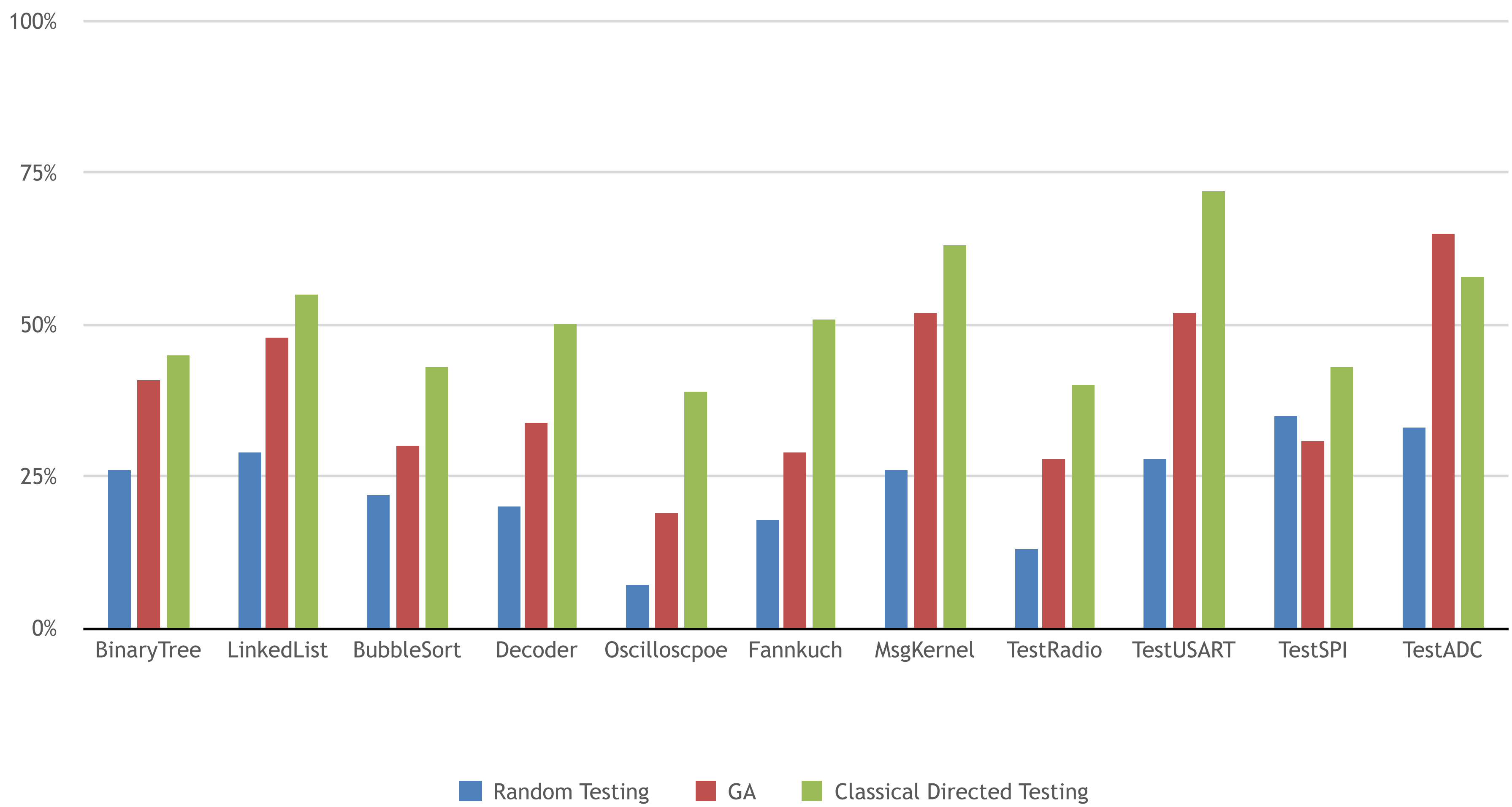


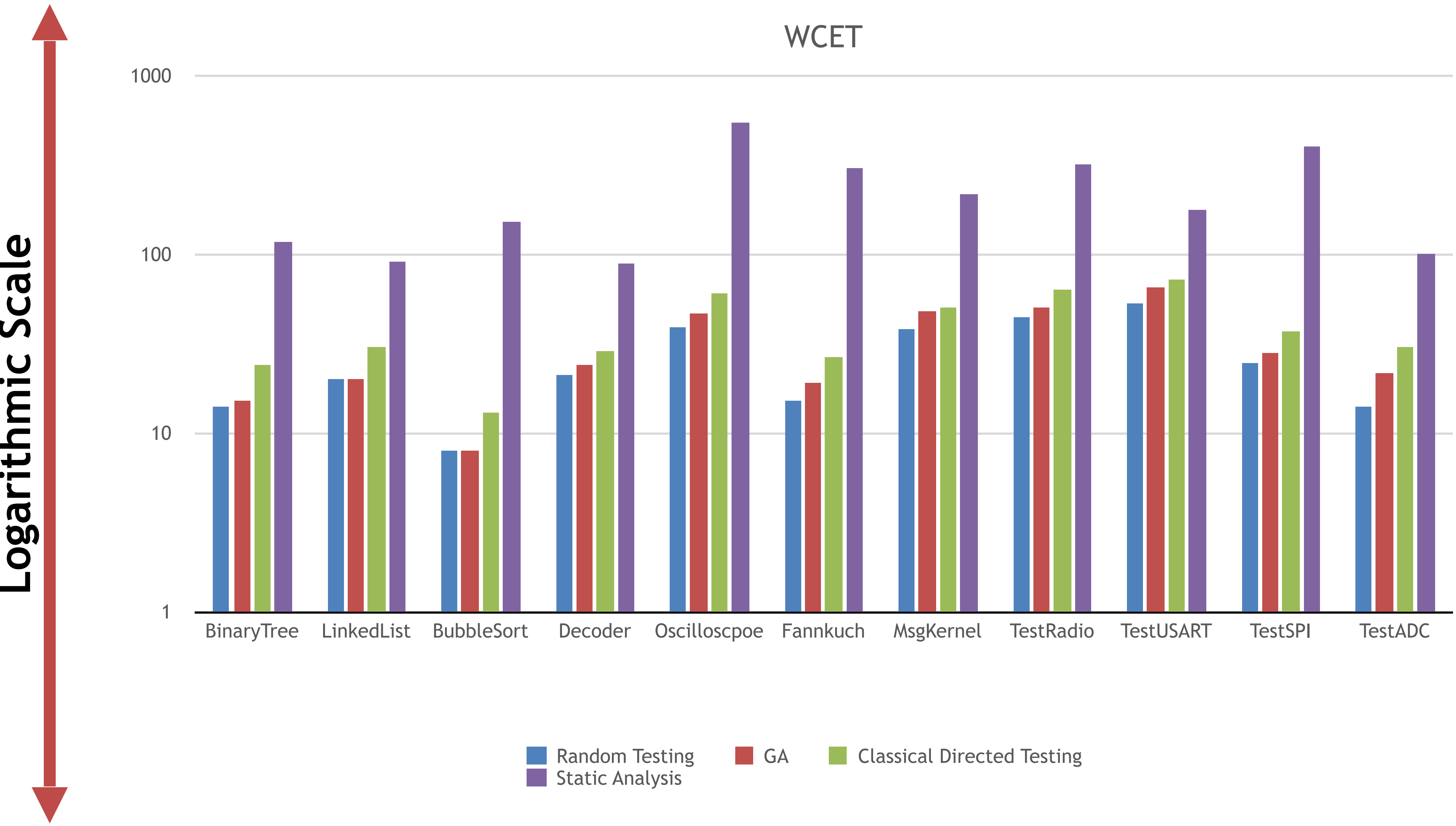
Motivating Experiments

branch coverage across testing techniques



Motivating Experiments

Testing VS Static Analysis of WCET



Testing Event Driven Software

- Classical software:
  - tester only devices a suite of single inputs.
- Event-Driven software (with real-time behavior):
  - tester must device a suite of *event sequences*.
    - In each sequence: # of events, types of events, values associated with the events e.g. registers' value, and timing of events.
- **Challenge**: Quickly generate a small number of challenging event sequences to improve branch coverage.

VICE Example

```
program Sample { entrypoint main = antenna.main, alt = antenna.alt; }
component test_antenna {
   field sending:bool = false;
   method main(data_1:int):void { dispatch_data(data_1); // code... }
   method alt(data_2:int):void { dispatch_data(data_2); }
   method dispatch_data(msg:int):void {
      local res:int, tmp:int = random(100)
      if (sending) return; else sending = true;
      if (-2048 < msg && msg < 1024) res = check_and_send(msg,tmp);
      sending = false;
      return;
   }
   method check_and_send(s:int, t:int):int {
      if (s==512)
          return 1;
      // send...
      return 0;
   }
}
```

Round 1

[<main,(723452)>,<alt1,(−10038)>,<main,_>,<alt1, _>]

Constraints: $data\_1 = msg \wedge data2 = msg \wedge -2048 < msg \wedge msg < 1024$

Branch Coverage: *50% (3/6)*

VICE Example

```
program Sample { entrypoint main = antenna.main, alt = antenna.alt; }
component test_antenna {
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   method main(data_1:int):void { dispatch_data(data_1); // code... }
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     if (-2048 < msg && msg < 1024) res = check_and_send(msg,tmp);
     sending = false;
     return;
   }
   method check_and_send(s:int, t:int):int {
     if (s==512)
         return 1;
     // send...
     return 0;
   }
}
```

Round 2

[<main,(-338)>,<alt1,(1001)>,<alt2,(6)>,<main, _>]

Constraints: $msg = s \wedge tmp = t \wedge s = 512$

Branch Coverage: *83% (5/6)*

VICE Example

```
program Sample { entrypoint main = antenna.main, alt = antenna.alt; }
component test_antenna {
   field sending:bool = false;
   method main(data_1:int):void { dispatch_data(data_1); // code... }
   method alt(data_2:int):void { dispatch_data(data_2); }
   method dispatch_data(msg:int):void {
     local res:int, tmp:int = random(100)
     if (sending) return; else sending = true;
     if (-2048 < msg && msg < 1024) res = check_and_send(msg,tmp);
     sending = false;
     return;
   }
   method check_and_send(s:int, t:int):int {
     if (s==512)
         return 1;
     // send...
     return 0;
   }
}
```

Round 3

[<main,(-338)>,<alt1,(1001)>,<alt2,(6)>,<main, _>]

Constraints: *data1 = data2 = msg = s = 512*

Branch Coverage: *83% (5/6)*

VICE Example

```
program Sample { entrypoint main = antenna.main, alt = antenna.alt; }
component test_antenna {
   field sending:bool = false;
   method main(data_1:int):void { dispatch_data(data_1); // code... }
   method alt(data_2:int):void { dispatch_data(data_2); }
   method dispatch_data(msg:int):void {
     local res:int, tmp:int = random(100)
     if (sending) return; else sending = true;
     if (-2048 < msg && msg < 1024) res = check_and_send(msg,tmp);
     sending = false;
     return;
   }
   method check_and_send(s:int, t:int):int {
     if (s==512)
         return 1;
     // send...
     return 0;
   }
}
```

Round 4

[<main,(512)>,<alt1,(512)>,<main,_>,<alt1, _>]

Constraints: -

Branch Coverage: *100% (6/6)*

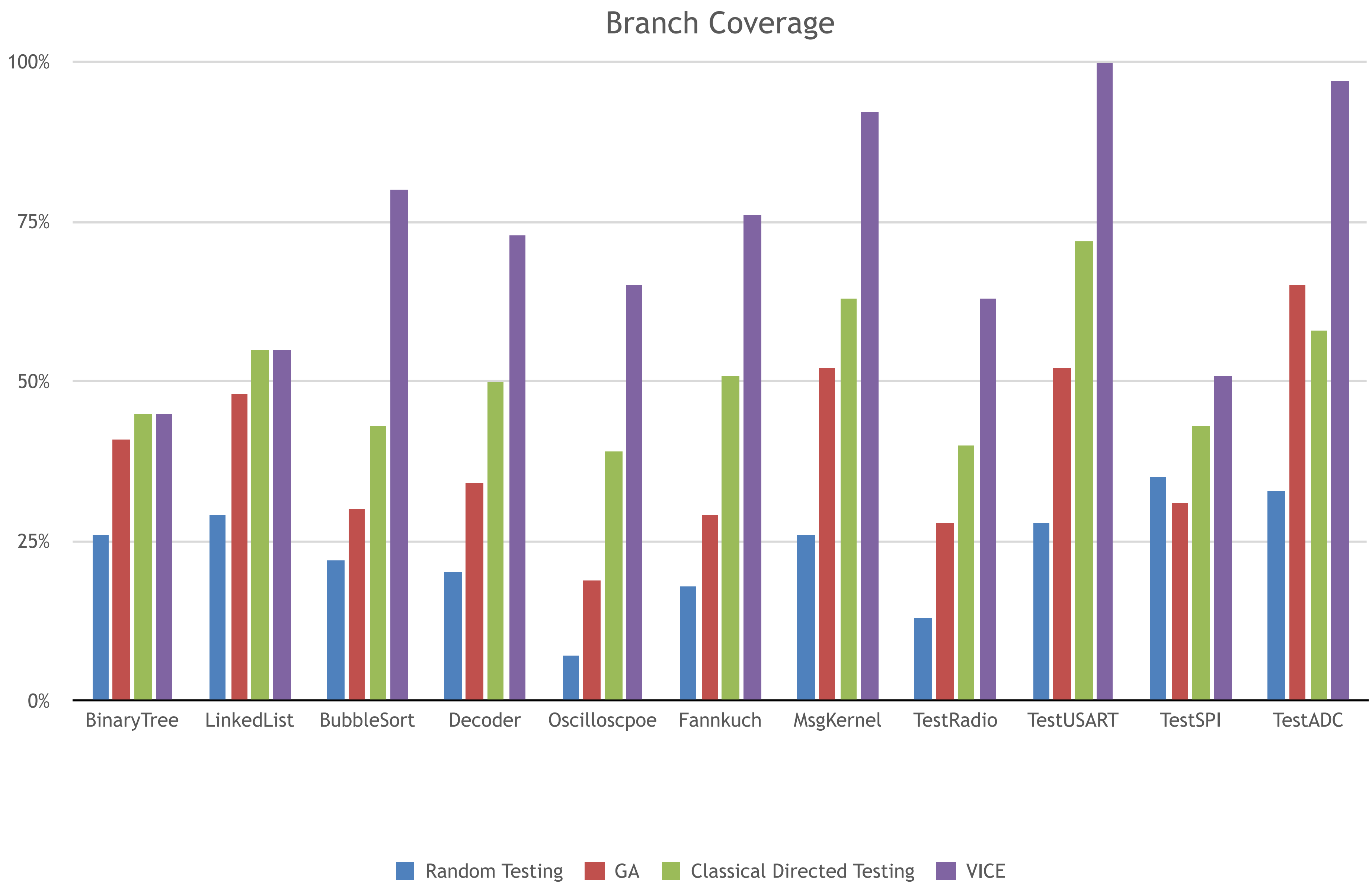
Event Based Directed Testing (EBDT)

- **compiler:**
  VirgilProgram → machineCode
- **avrora :**
  machineCode × eventSequence → wcet
- **random:**
  () → eventSequence
- **timeoutCombos:**
  eventSequence → (eventSequence list)
- **concolic:**
  (Virgil program × eventSeequence →
  (wcet × branchCoverage × constraints)
- **solver:**
  constraints → solution
- **generator:**
  solution → eventSequence

Algorithm

Input:	p: VirgilProgram
Output:	wcet $\times$ branchCoverage $\times$ eventSequence
Local:	a: machineCode = compiler(p), s: state = (0, 0.0, ( ), 0) , $roundId$: int = 0
	$seqs$: eventSequence = timeoutCombos(random())
Method:	while ($s.noChange < 2$) {
	foreach (seq in $seqs$) {
	let ($wcet$, bc, c) = concolic(p, seq) in
	s = update(s, $wcet$, bc, c, $roundId$)
	}
	$roundId$++
	$seqs$ = timeoutCombos(generator(solver($s.constraints$)))
	}
	return ($s.wcet$, $s.coverage$, $s.eventSeq$)

Experiment Results



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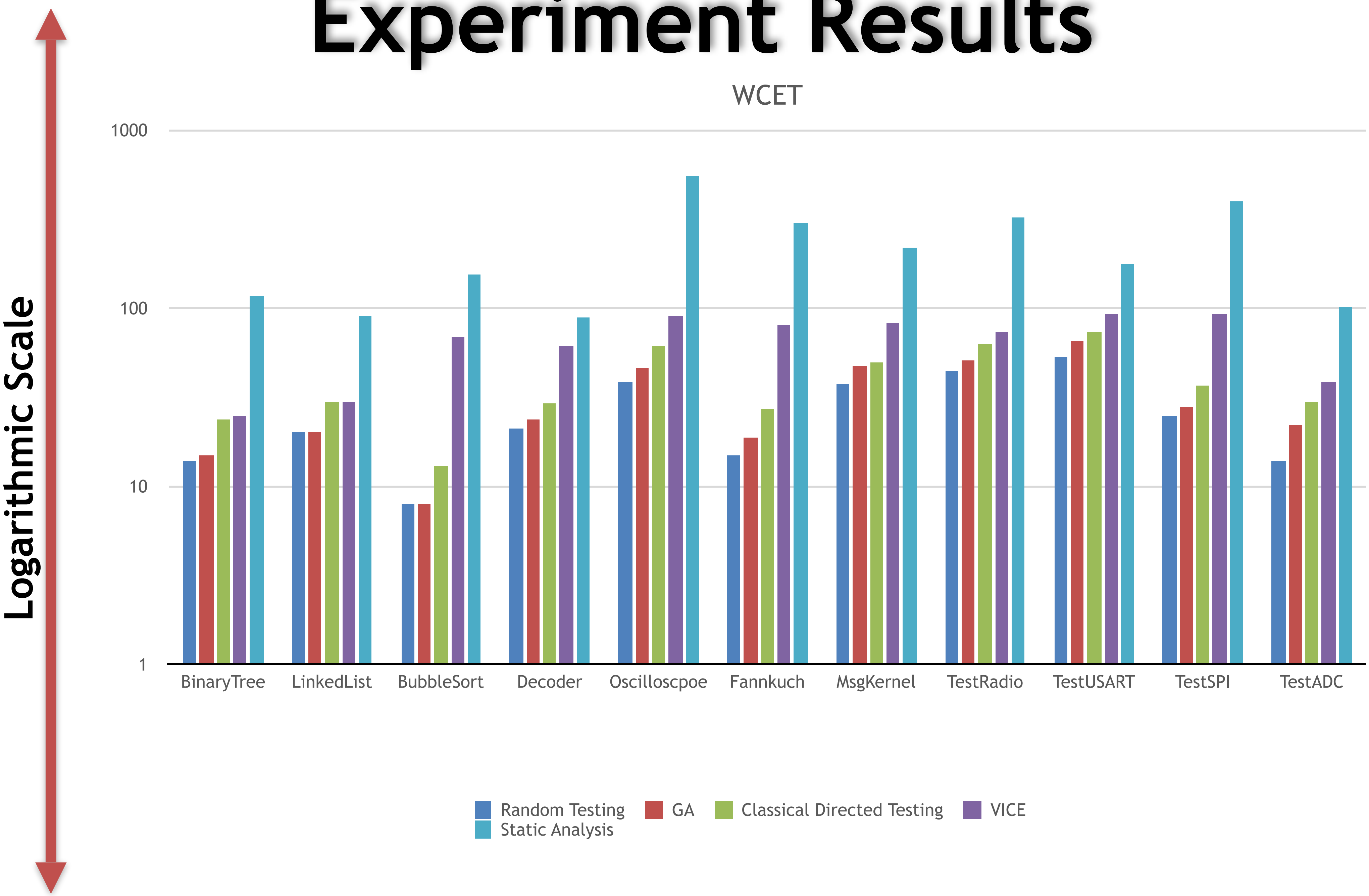

Future Works

- Formulating timeouts symbolically
- Using some static information
  - Locate places where wcet happens, and direct execution towards candidates
  - Replace random event generation with a IMR-certified model checker.