Automating Differential Testing with Overappoximate Symbolic Execution

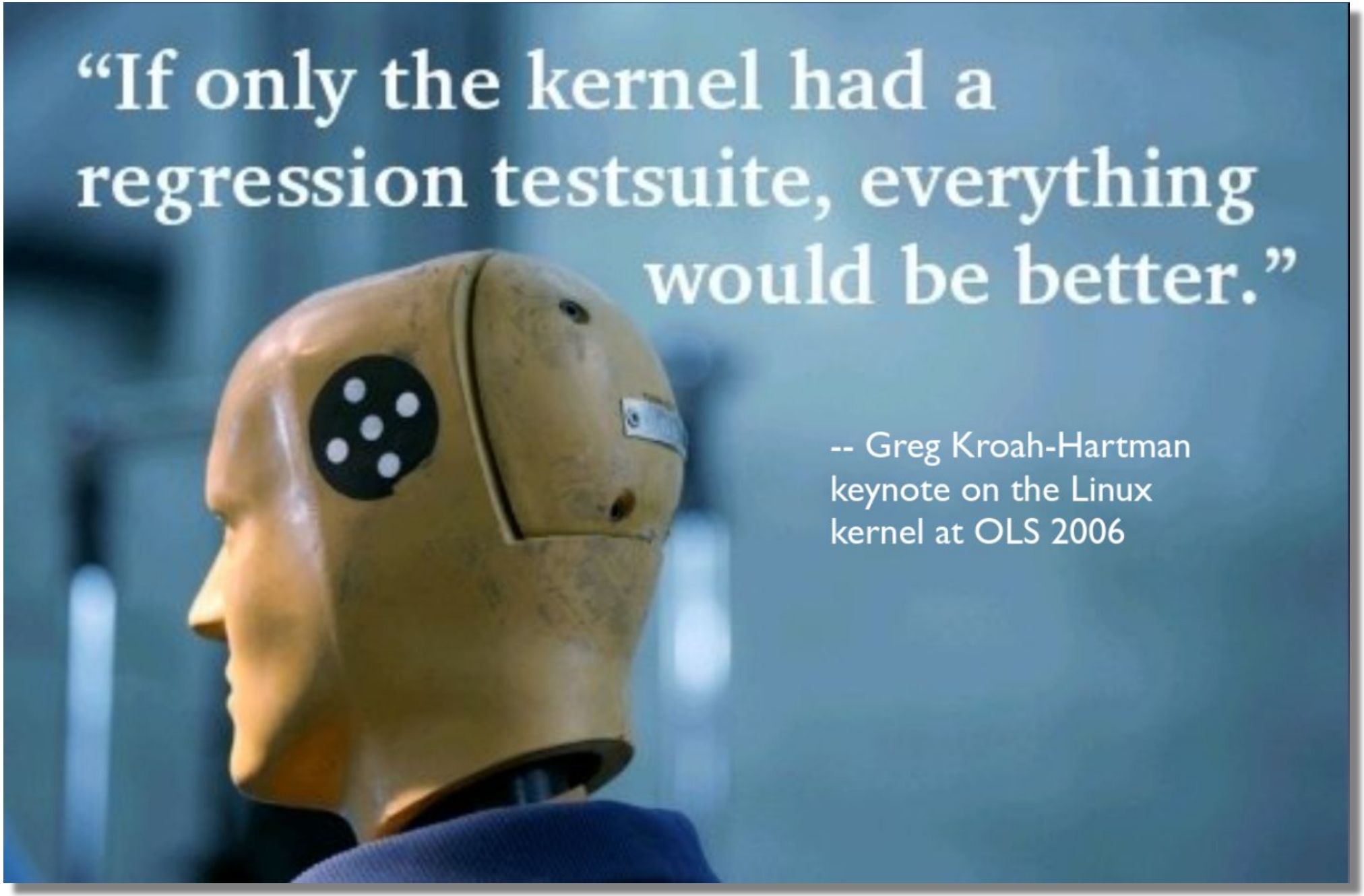
Richard Rutledge, Alessandro Orso

Auto

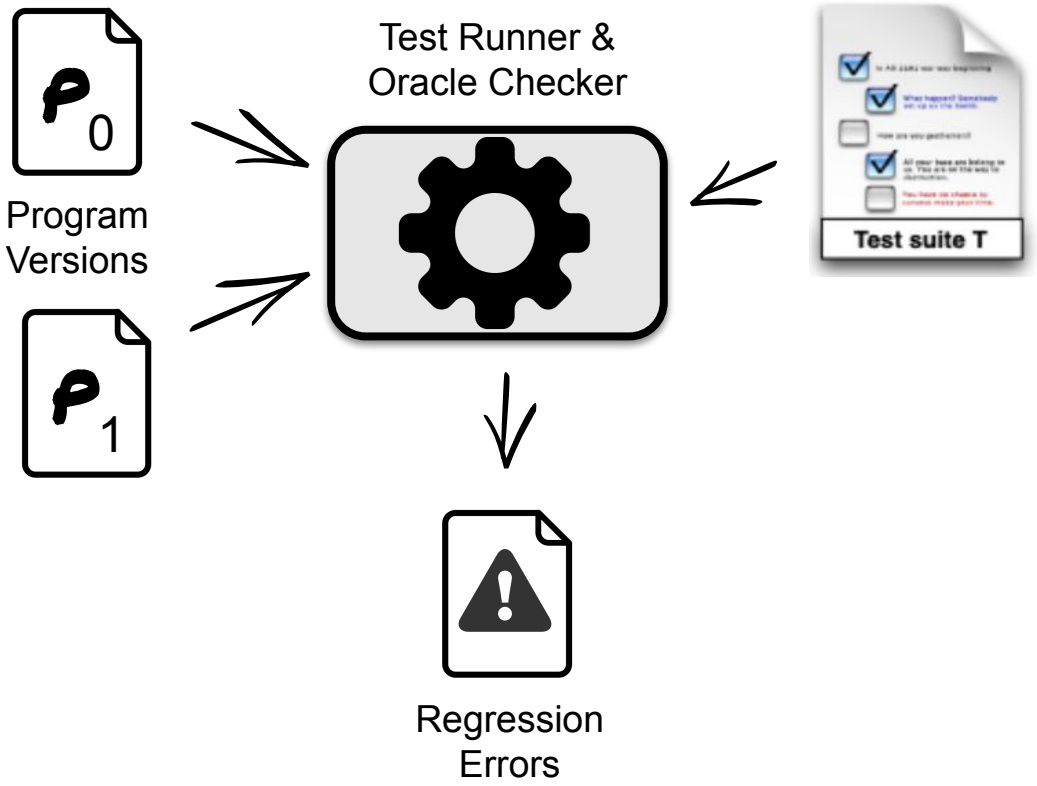
Over

with

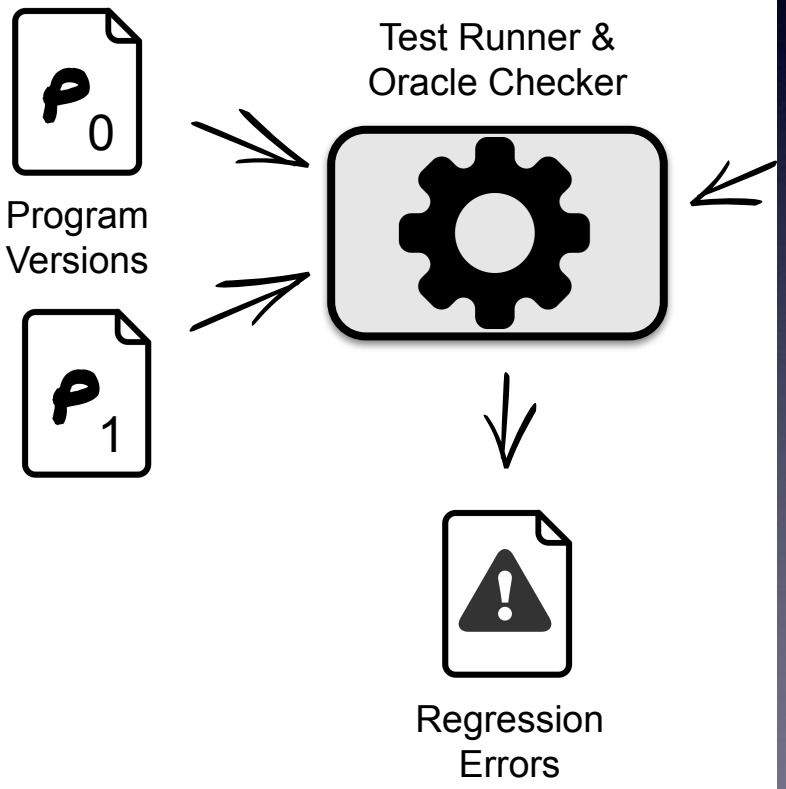
ution

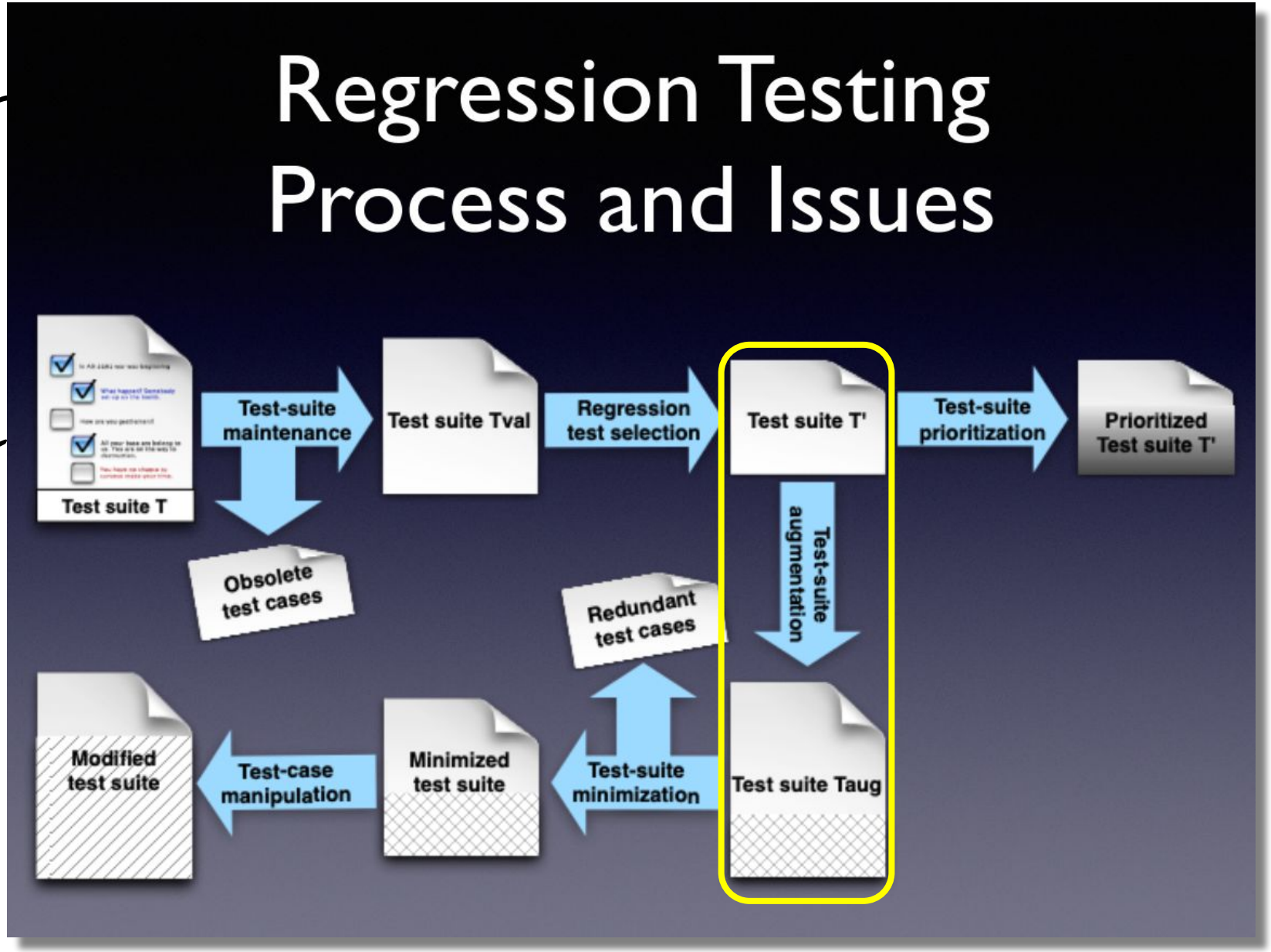

"If only the kernel had a regression testsuite, everything would be better."
-- Greg Kroah-Hartman keynote on the Linux kernel at OLS 2006

Regression Testing

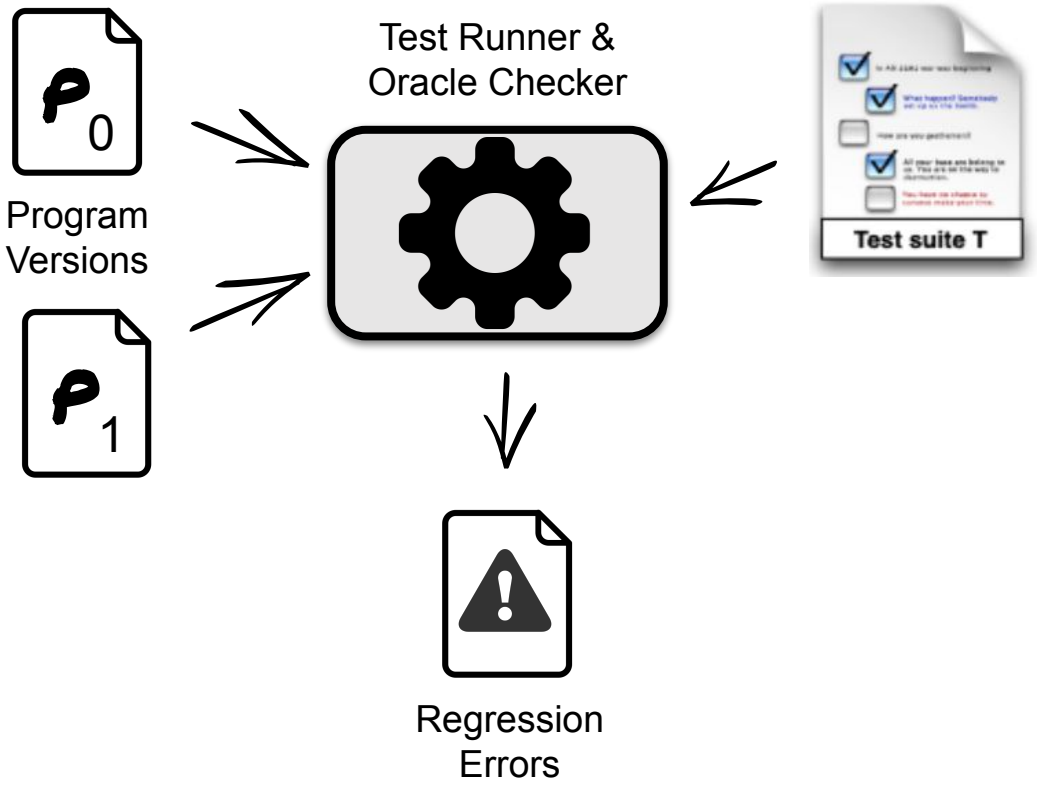


Regression Testin

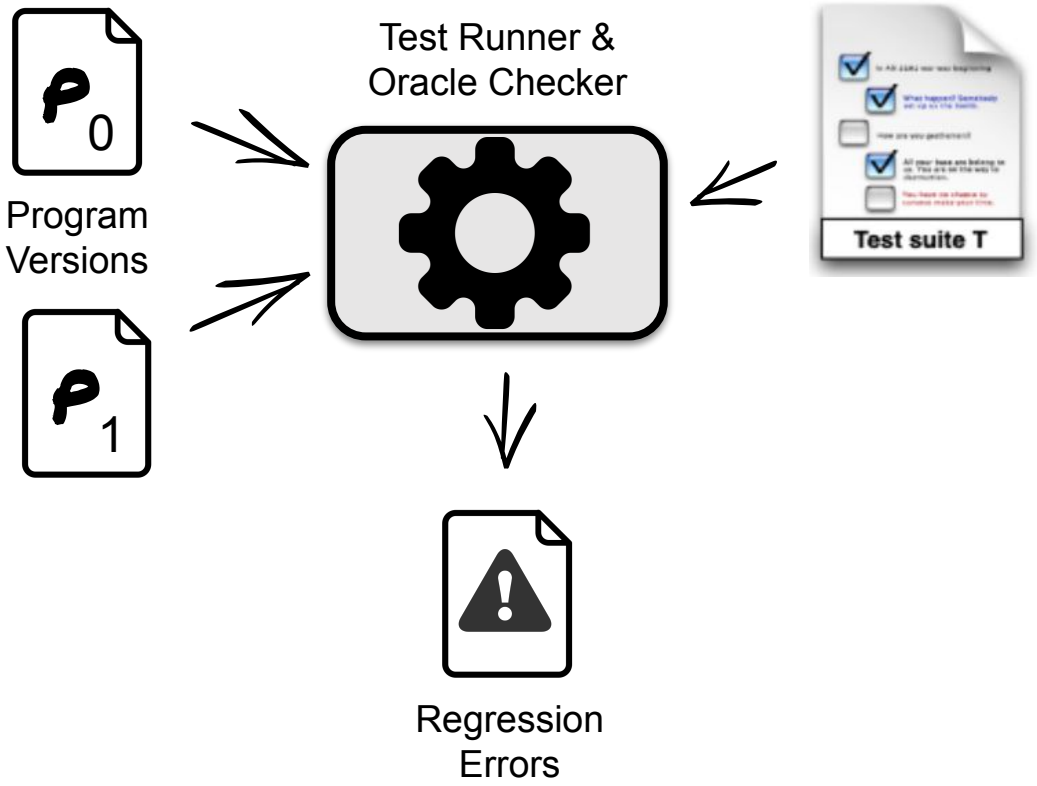




Regression Testing



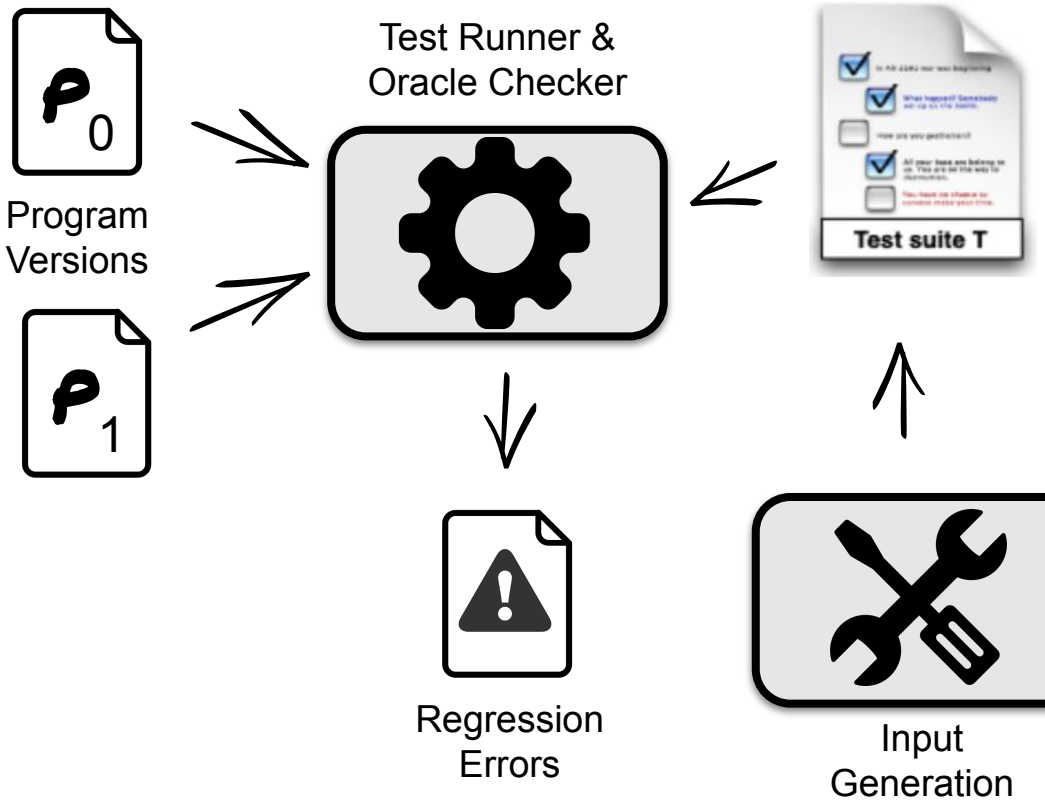
Regression Testing



Issues with regression test suites

- ➔ Focus on core behavior
- ➔ Provide limited coverage
- ➔ Use approximated oracles
- ➔ Sometimes not present at all

First "Intuition": Input Generation

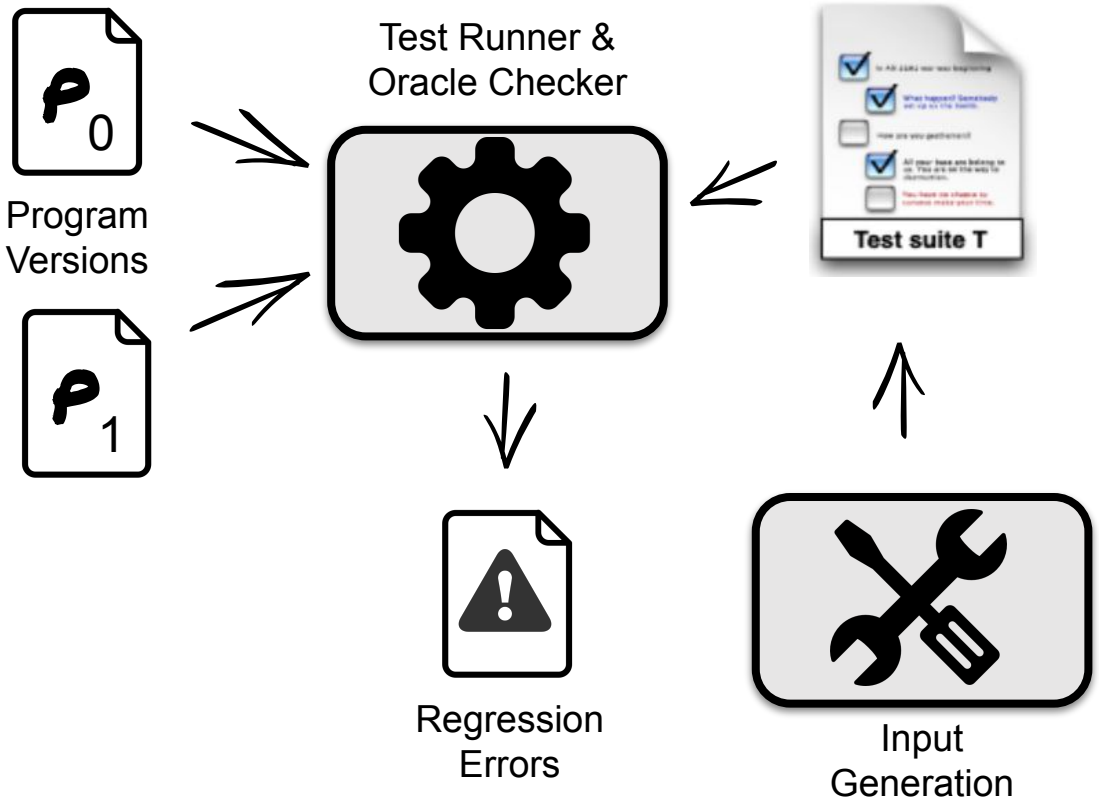


Issues with regression test suites

- ➔ Focus on core behavior
- ➔ Provide limited coverage
- ➔ Use approximated oracles
- ➔ Sometimes not present at all

- Inherent limitations
- Oracle problem

Second Intuition: Limited Scope and Differential Testing



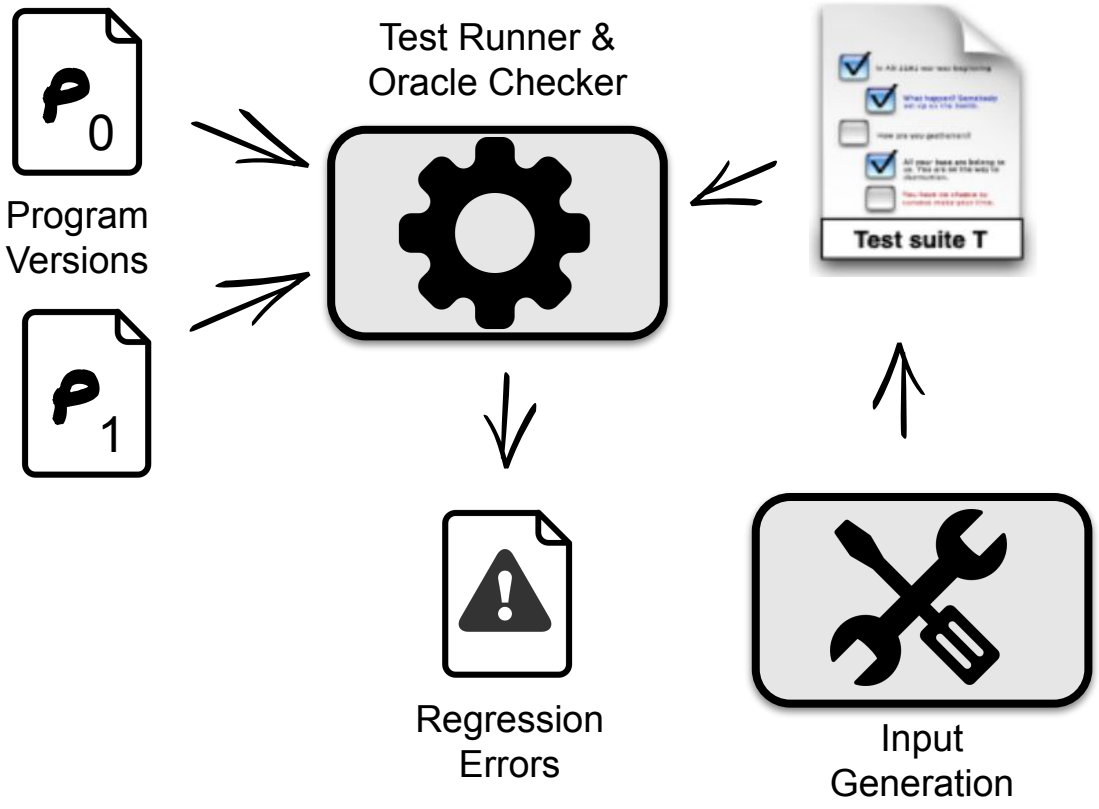
Focused input generation

+

P_0 as oracle

➔ focus on changed code
➔ thorough coverage
➔ no need for oracles

Second Intuition: Limited Scope and Differential Testing



Focused input generation

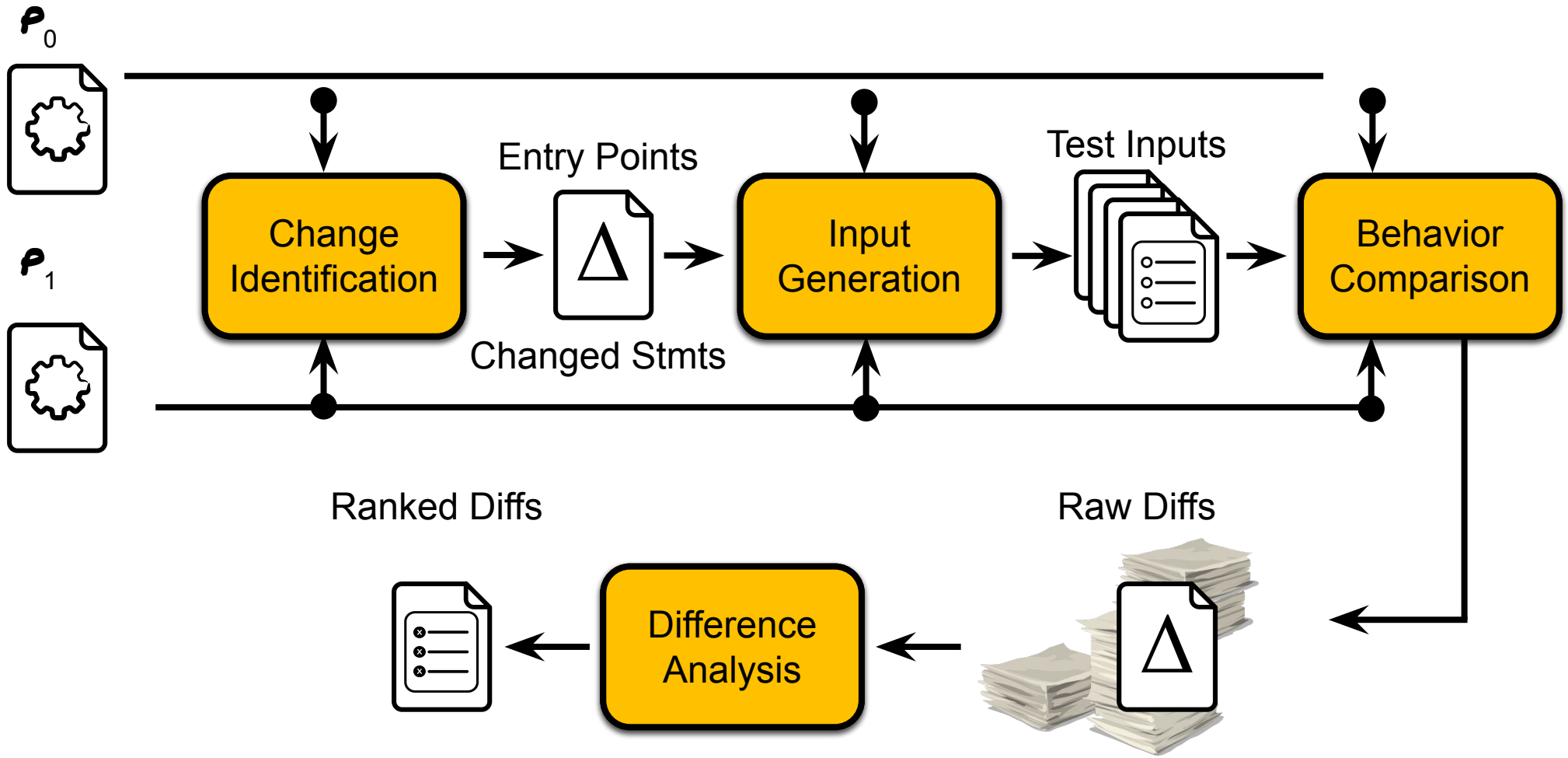
+

P_0 as oracle

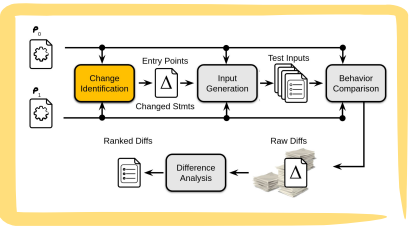
➔ focus on changed code
➔ thorough coverage
➔ no need for oracles

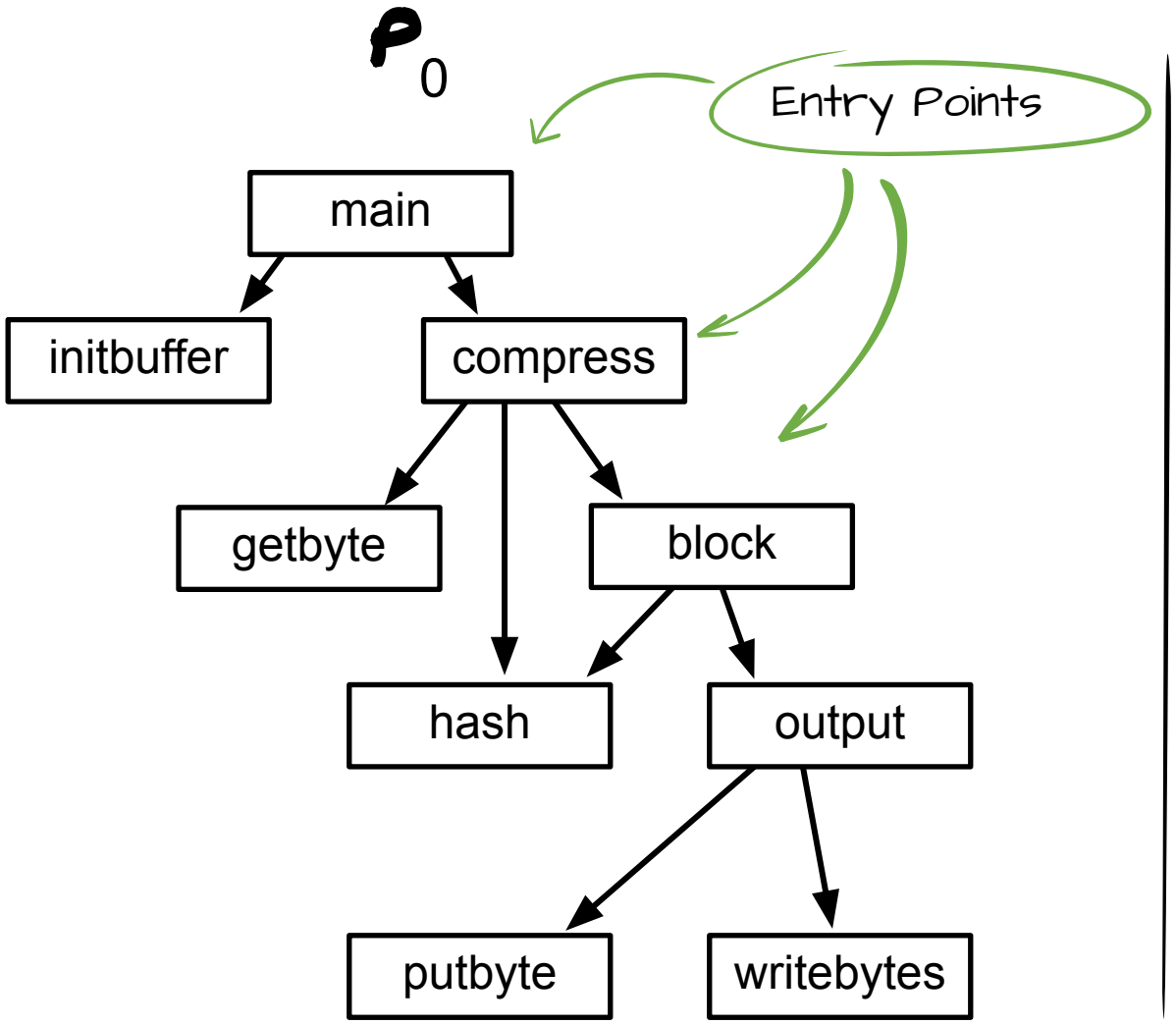
Usage scenario: frequent use (e.g., every save or before merge into release branch)

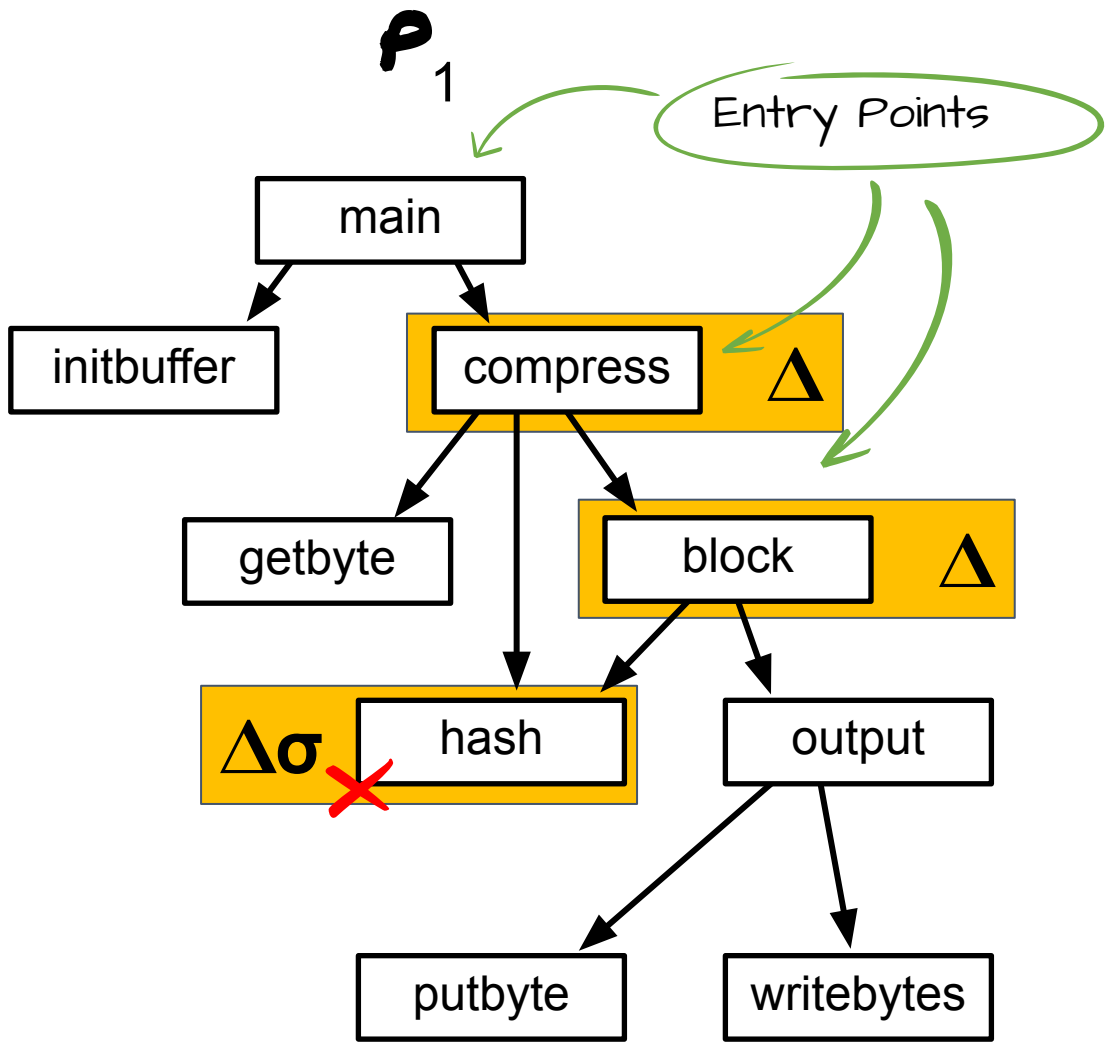
Overapproximate Differential Regression Testing (ODiT) Overview

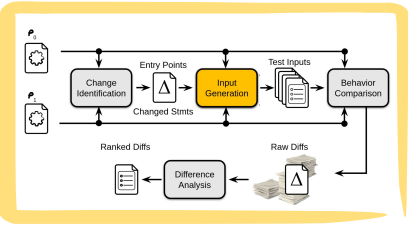


Change Identification

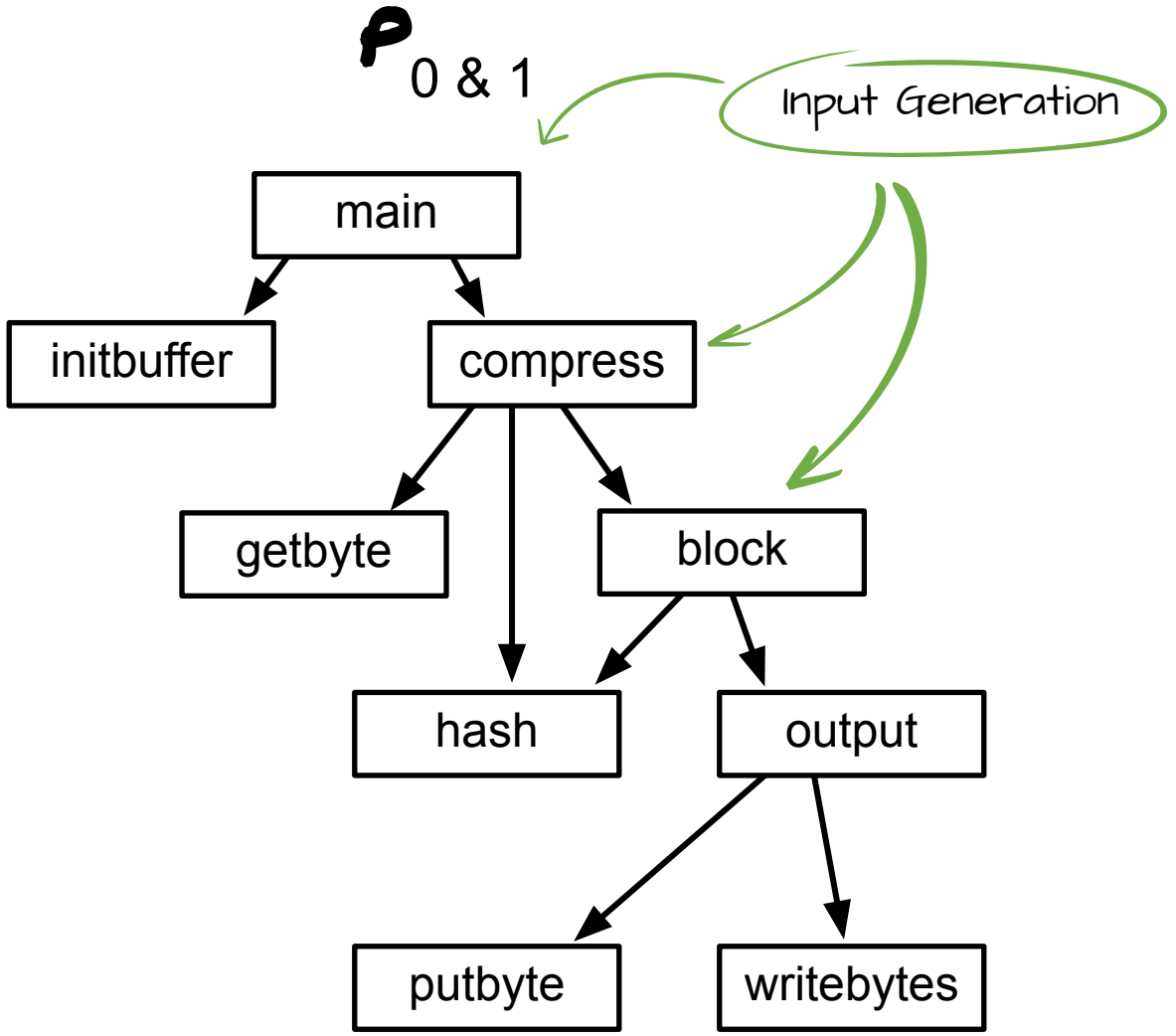


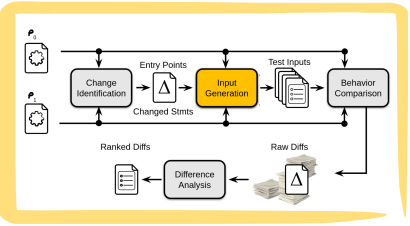






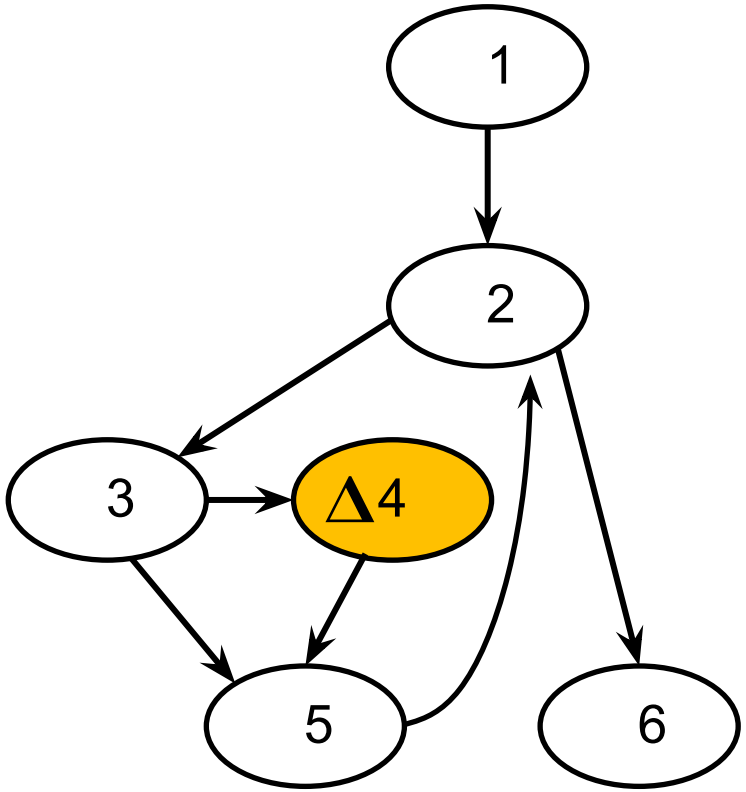
Input Generation: Underconstrained SymEx





Input Generation: Input Selection

`block` Control Flow Graph (CFG)



`Input execution paths:`

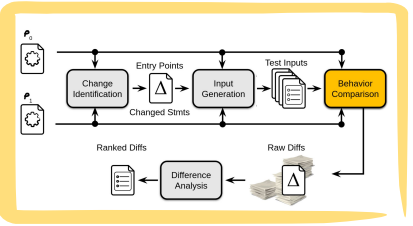
1, 2, 3, 5, 2, 6

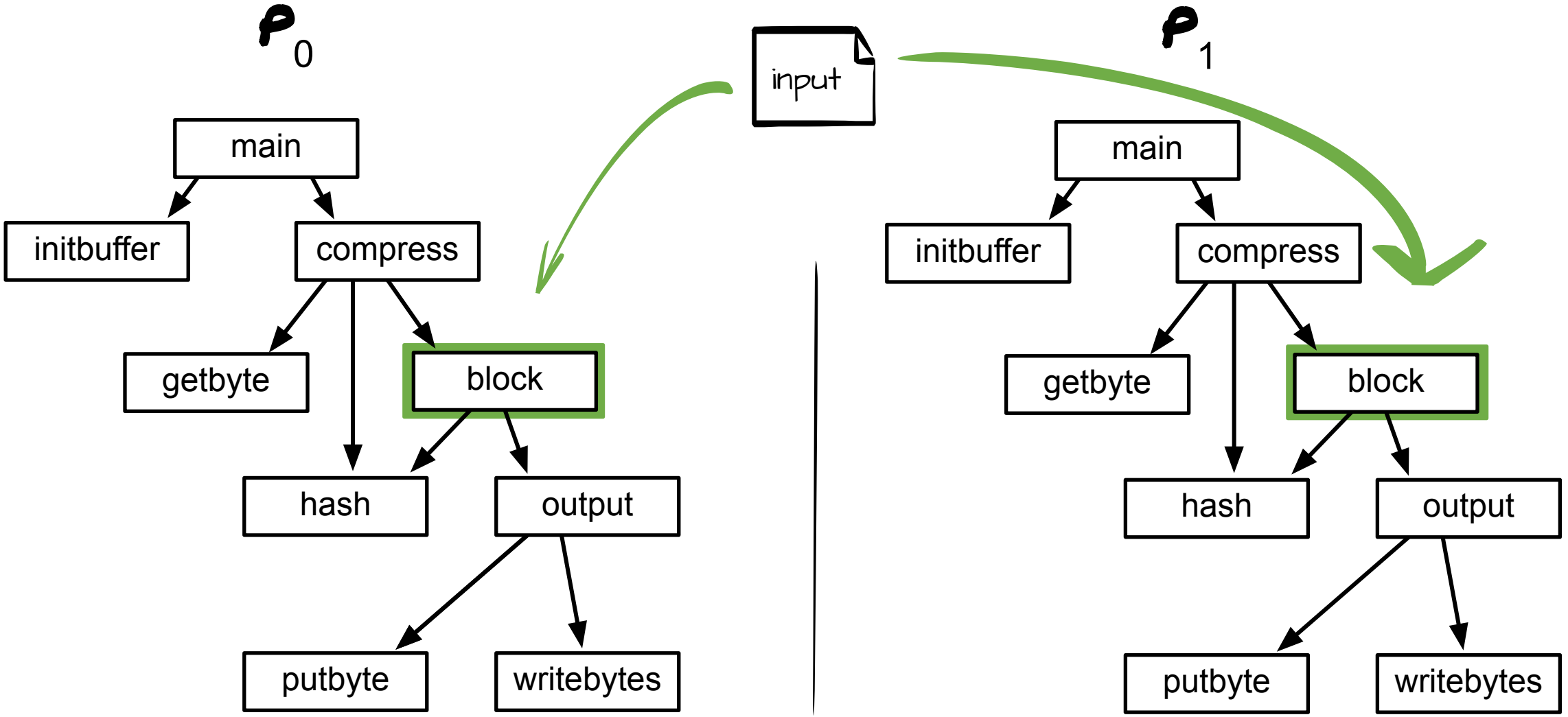
1, 2, 3, 4, 5, 2, 6

1, 2, 3, 5, 2, 3, 4, 5, 2, 6

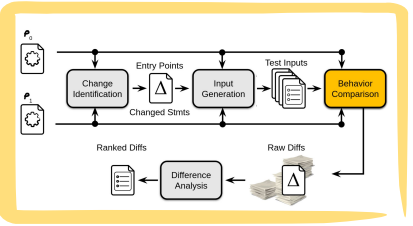
1, 2, 6

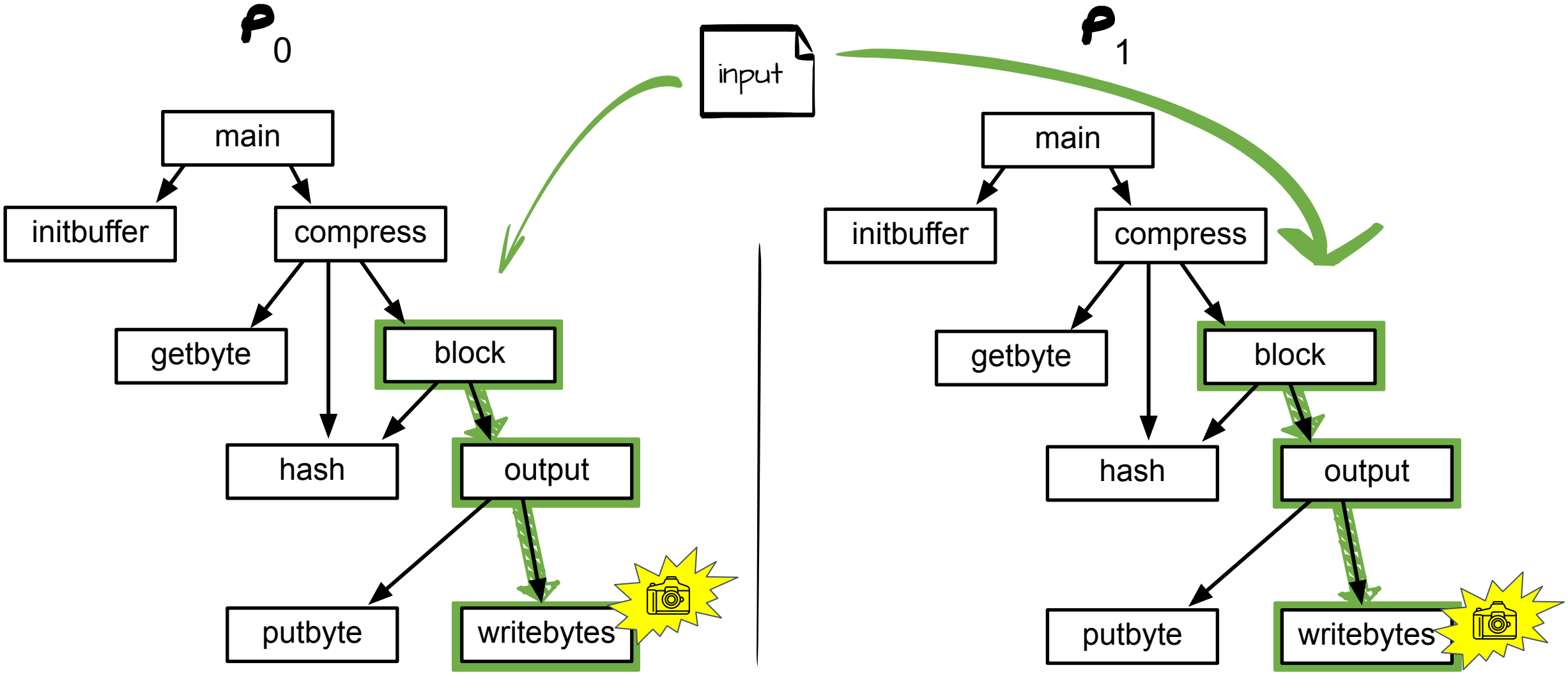
Behavior Comparison: Replay

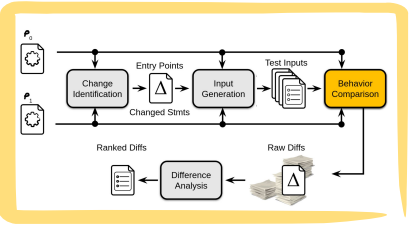




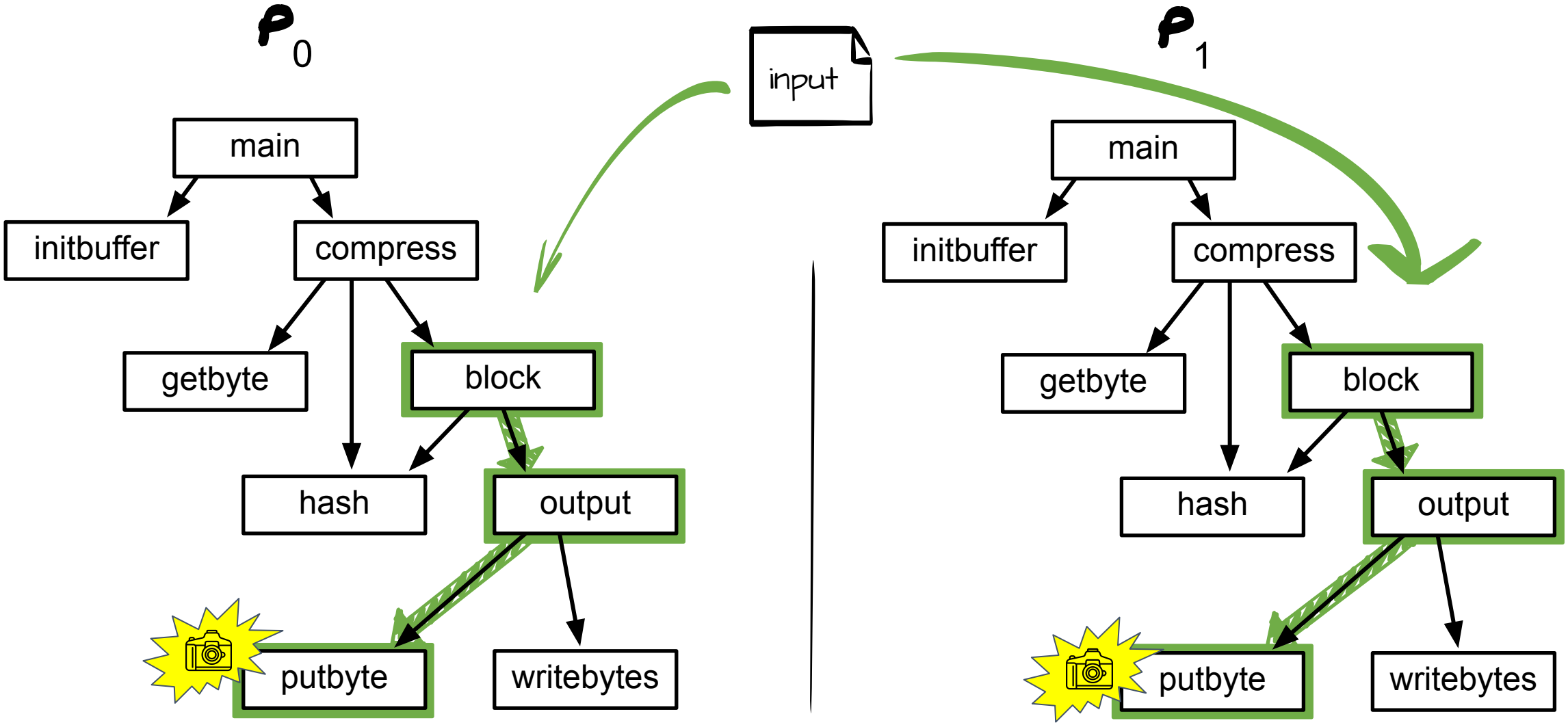
Behavior Comparison: Replay



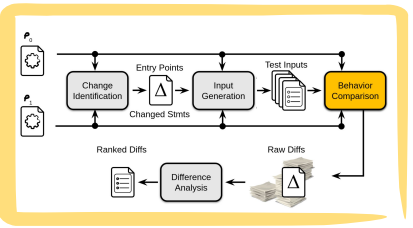


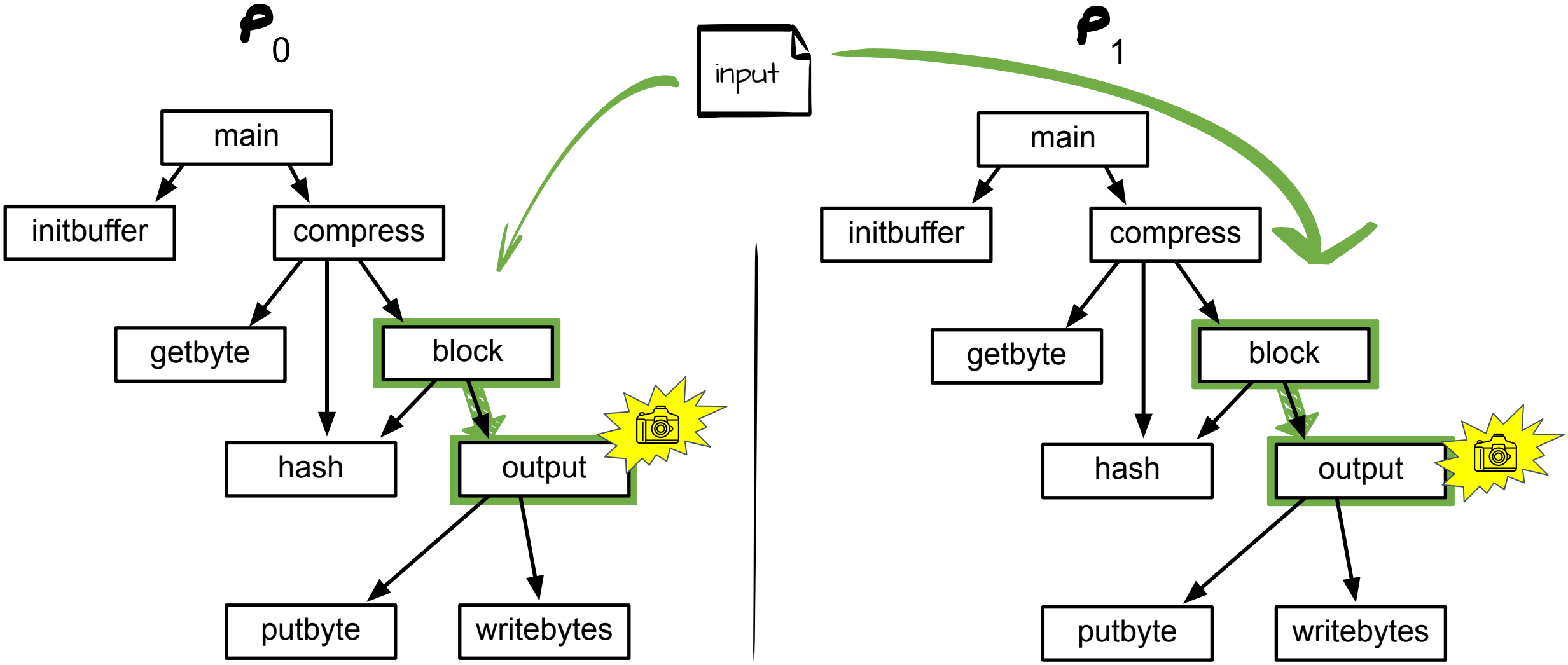


Behavior Comparison: Replay



Behavior Comparison: Replay





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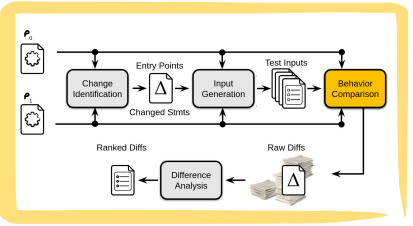
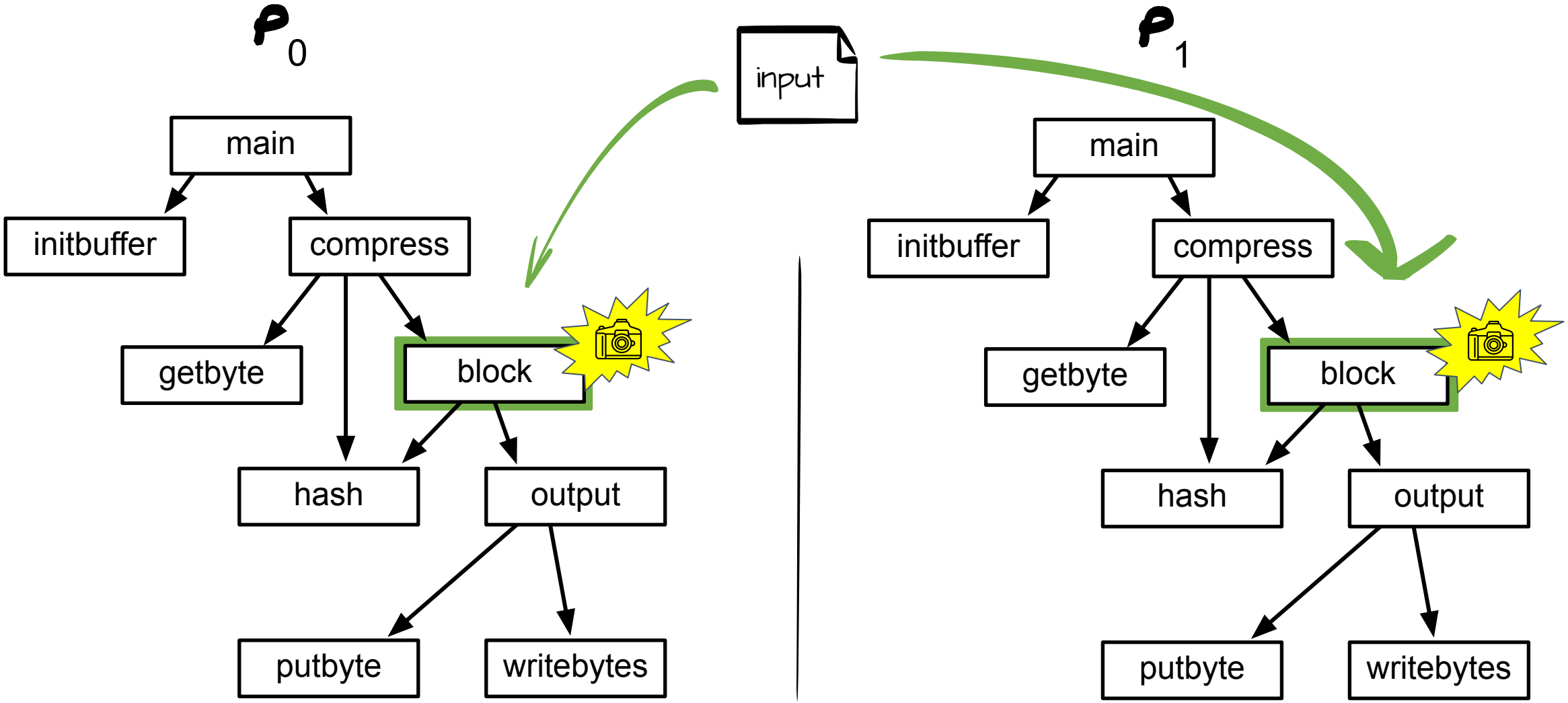
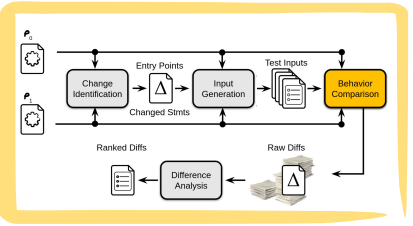
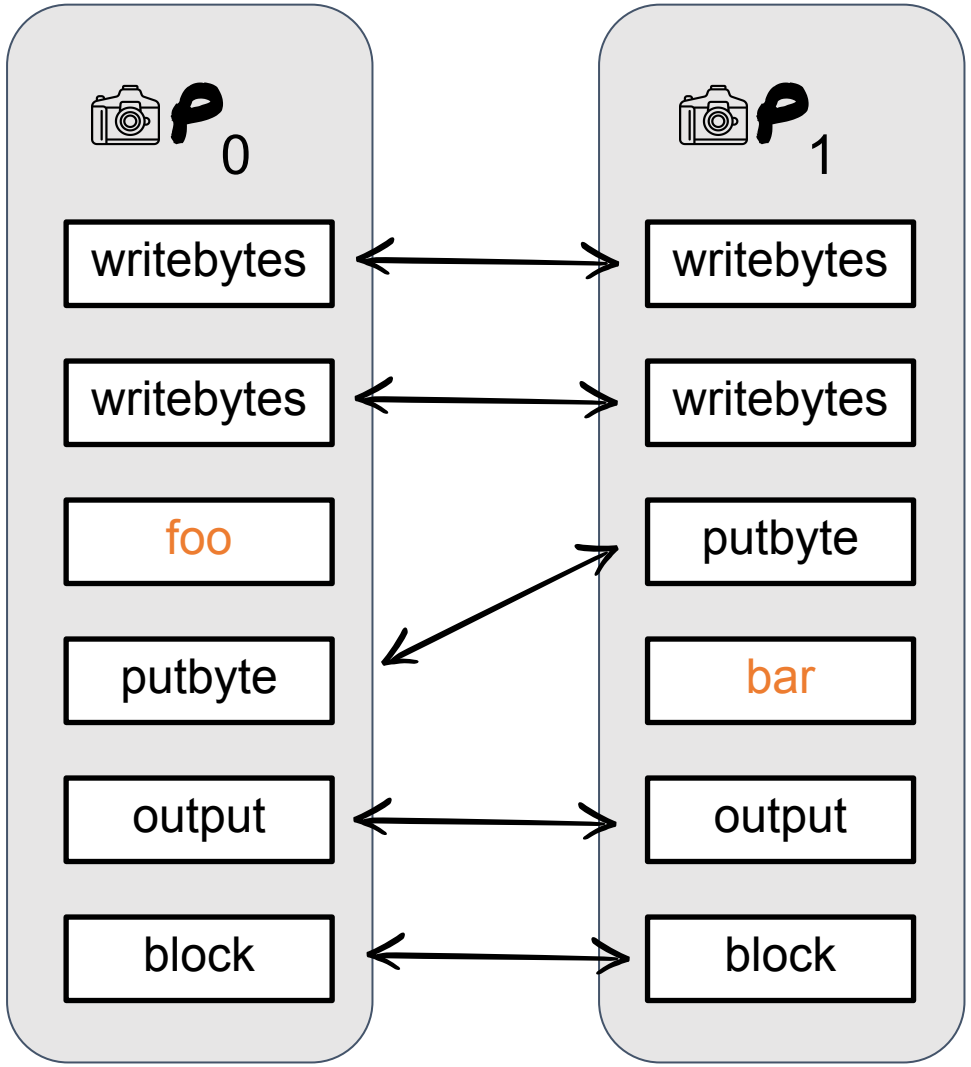






Behavior Comparison: Alignment and State

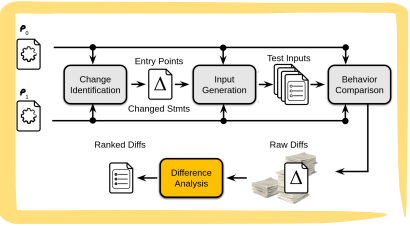


Alignment

- algorithm based on longest common subsequences

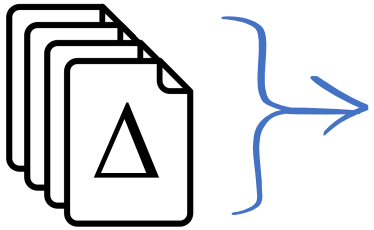
Address space elements compared:

- termination
- returning function value
- global variables
- output streams
- output parameters



Difference Analysis

- Group differences by Δ program elements



Δ return value of foo()

- Dependent differences based on co-occurrence

Δ x → Δ ret foo()

```
int x;
int bar() {
  x = foo();
}
```

root difference = Δ ret foo()

- Rank by distance from changed code in the dynamic call sequence.

foo() modified

1: foo() → Δ x

2: foo(), $same_1()$, $same_2()$, $same_3()$, … , $same_N()$ → Δ y

Rank

1. Δ y
2. Δ x

Evaluation: Implementation and Research Questions

Implementation

- Program analysis and differencing: clang & llvm
- Symbolic execution engine: forked from KLEE 1.3

Research Questions

- RQ1: Can ODiT detect and effectively rank regressions?
- RQ2: How does ODiT, which overapproximates behavior, compare to a tool that underapproximates behavior?
- RQ3: How does ODiT perform on refactored code?

Evaluation: Setup and Benchmarks

RQ1

- CoREBench: coreutils, find, and grep
- Bug oracles to compute TPs and FPs

RQ3

- Redis

program	CoREBench IDs	LOC
rm	1	1044
cut	3, 6, 12, 17, 21	519
tail	4, 5, 16	1039
seq	7, 8, 9, 18, 19, 20	254
cp	10	2498
ls	13, 14	3106
du	15	624
expr	22	583
find	23 - 37	8,738
grep	38 - 52	6,153
redis	N/A	121,989

CoREBench Selection

We considered the 70 CoREBench regressions, omitting those

- requiring 32-bit compilation
- using unsupported multibyte locales
- redundantly resulting from the same defect

=> this eliminated 9 of the 70 regressions)

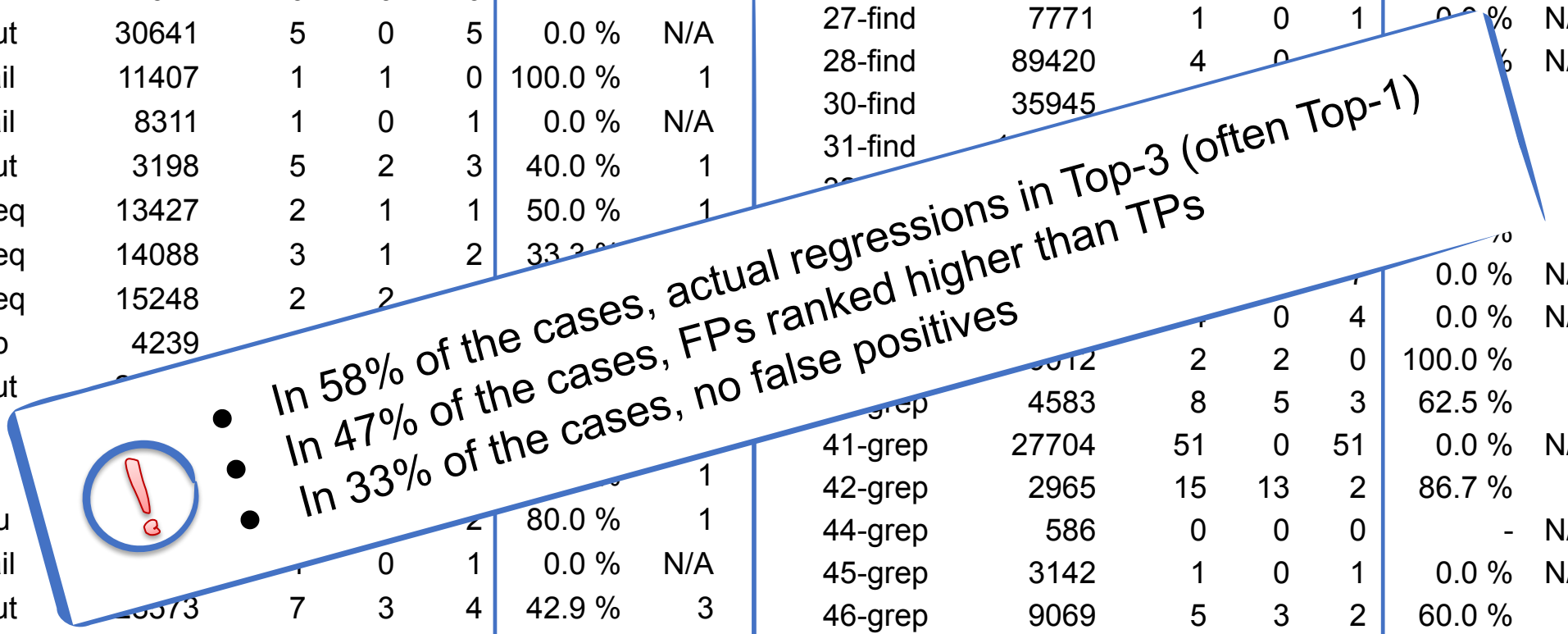
We then analyzed the remaining 61 regressions to identify those for which we could reliably define a ground truth (bug oracle)

=> 43 regressions

RQ1: Detection and Ranking

benchmark	inputs	diffs	TP	FP	precision	rank
01-rm	671	0	0	0	-	N/A
03-cut	30641	5	0	5	0.0 %	N/A
04-tail	11407	1	1	0	100.0 %	1
05-tail	8311	1	0	1	0.0 %	N/A
06-cut	3198	5	2	3	40.0 %	1
07-seq	13427	2	1	1	50.0 %	1
08-seq	14088	3	1	2	33.3 %	
09-seq	15248	2	2			
10-cp	4239					
12-cut						
13-ls						
14-ls						1
15-du			2		80.0 %	1
16-tail		1	0	1	0.0 %	N/A
17-cut	23573	7	3	4	42.9 %	3
18-seq	15248	2	2	0	100.0 %	1
19-seq	8533	3	1	2	33.3 %	3
20-seq	15250	2	2	0	100.0 %	1
21-cut	18841	11	11	0	100.0 %	1
22-expr	2644	1	1	0	100.0 %	1

benchmark	inputs	diffs	TP	FP	precision	rank
23-find	2552	67	1	66	1.5 %	67
24-find	22994	3	0	3	0.0 %	N/A
26-find	180975	65	10	55	15.4 %	1
27-find	7771	1	0	1	0.0 %	N/A
28-find	89420	4	0		%	N/A
30-find	35945					1
31-find						1
						1
						1
					0.0 %	N/A
			0	4	0.0 %	N/A
		2	2	0	100.0 %	1
grep	4583	8	5	3	62.5 %	2
41-grep	27704	51	0	51	0.0 %	N/A
42-grep	2965	15	13	2	86.7 %	1
44-grep	586	0	0	0	-	N/A
45-grep	3142	1	0	1	0.0 %	N/A
46-grep	9069	5	3	2	60.0 %	2
47-grep	25758	22	0	22	0.0 %	N/A
48-grep	25918	16	0	16	0.0 %	N/A
49-grep	58	0	0	0	-	N/A
51-grep	168	13	0	13	0.0 %	N/A
52-grep	2012	3	3	0	100.0 %	1



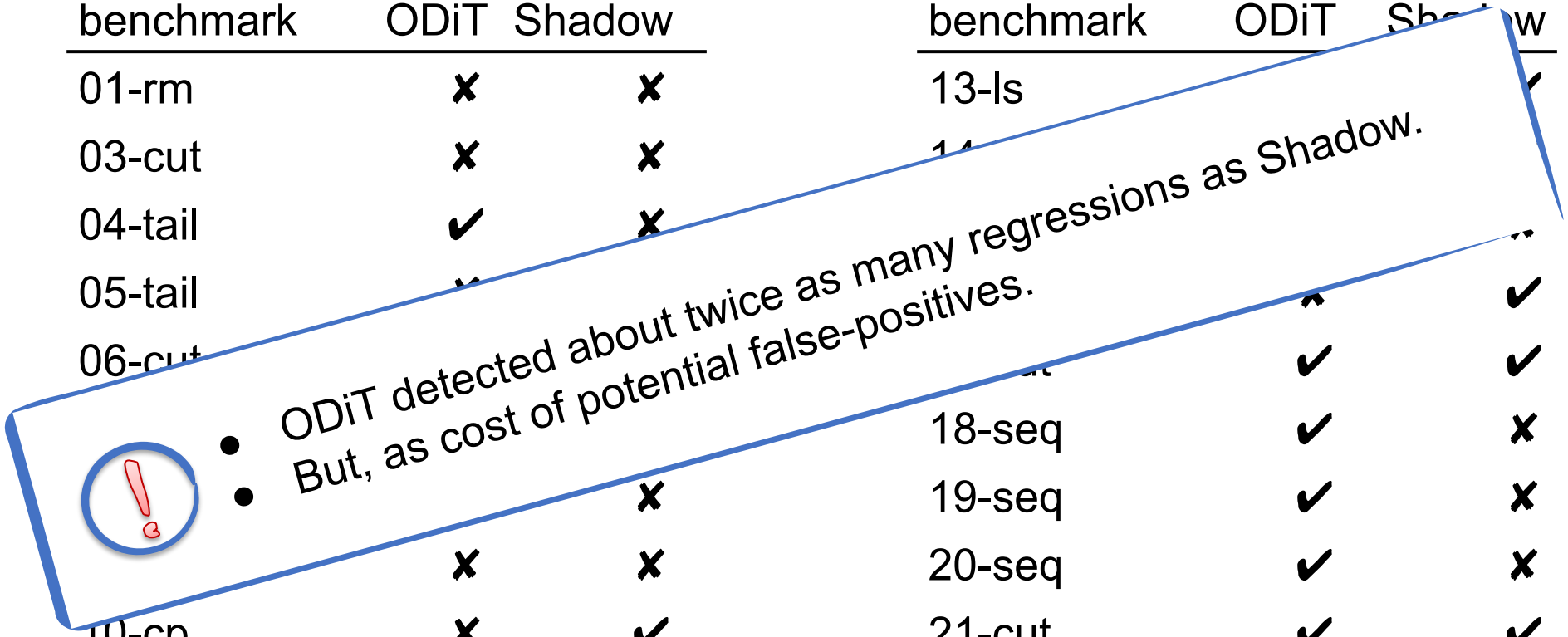
RQ1: Detection and Ranking

benchmark	inputs	diffs	TP	FP	precision	rank
01-rm	671	0	0	0	-	N/A
03-cut	30641	5	0	5	0.0 %	N/A
04-tail	11407	1	1	0	100.0 %	1
05-tail	8311	1	0	1	0.0 %	N/A
06-cut	3198	5	2	3	40.0 %	1
07-seq	13427	2	1	1	50.0 %	1
08-seq	14088	3	1	2	33.3 %	2
09-seq	15248	2	2	0	100.0 %	1
10-cp	4239	0	0	0	-	N/A
12-cut	28606	7	3	4	42.9 %	3
13-ls	13062	3	2	1	66.7 %	1
14-ls	10186	10	10	0	100.0 %	1
15-du	1402	10	8	2	80.0 %	1
16-tail	8296	1	0	1	0.0 %	N/A
17-cut	28573	7	3	4	42.9 %	3
18-seq	15248	2	2	0	100.0 %	1
19-seq	8533	3	1	2	33.3 %	3
20-seq	15250	2	2	0	100.0 %	1
21-cut	18841	11	11	0	100.0 %	1
22-expr	2644	1	1	0	100.0 %	1
23-find	2552	67	1	66	1.5 %	67
24-find	22994	3	0	3	0.0 %	N/A
26-find	180975	65	10	55	15.4 %	1
27-find	7771	1	0	1	0.0 %	N/A
28-find	89420	4	0	4	0.0 %	N/A
30-find	35945	7	7	0	100.0 %	1
31-find	180873	64	10	54	15.6 %	1
32-find	52459	9	2	7	22.2 %	1
33-find	52268	9	2	7	22.2 %	1
34-find	34835	7	0	7	0.0 %	N/A
36-find	68074	4	0	4	0.0 %	N/A
37-find	89012	2	2	0	100.0 %	1
38-grep	4583	8	5	3	62.5 %	2
41-grep	27704	51	0	51	0.0 %	N/A
42-grep	2965	15	13	2	86.7 %	1
44-grep	586	0	0	0	-	N/A
45-grep	3142	1	0	1	0.0 %	N/A
46-grep	9069	5	3	2	60.0 %	2
47-grep	25758	22	0	22	0.0 %	N/A
48-grep	25918	16	0	16	0.0 %	N/A
49-grep	58	0	0	0	-	N/A
51-grep	168	13	0	13	0.0 %	N/A
52-grep	2012	3	3	0	100.0 %	1

RQ2: Compare with Shadow

benchmark	ODiT	Shadow
01-rm	✘	✘
03-cut	✘	✘
04-tail	✔	✘
05-tail	✘	✔
06-cut	✔	✔
08-ls	✔	✘
09-ls	✘	✘
10-cp	✘	✔
12-cut	✔	✔

benchmark	ODiT	Shadow
13-ls	✘	✔
18-seq	✔	✘
19-seq	✔	✘
20-seq	✔	✘
21-cut	✔	✔
22-expr	✔	✘



RQ2: Compare with Shadow

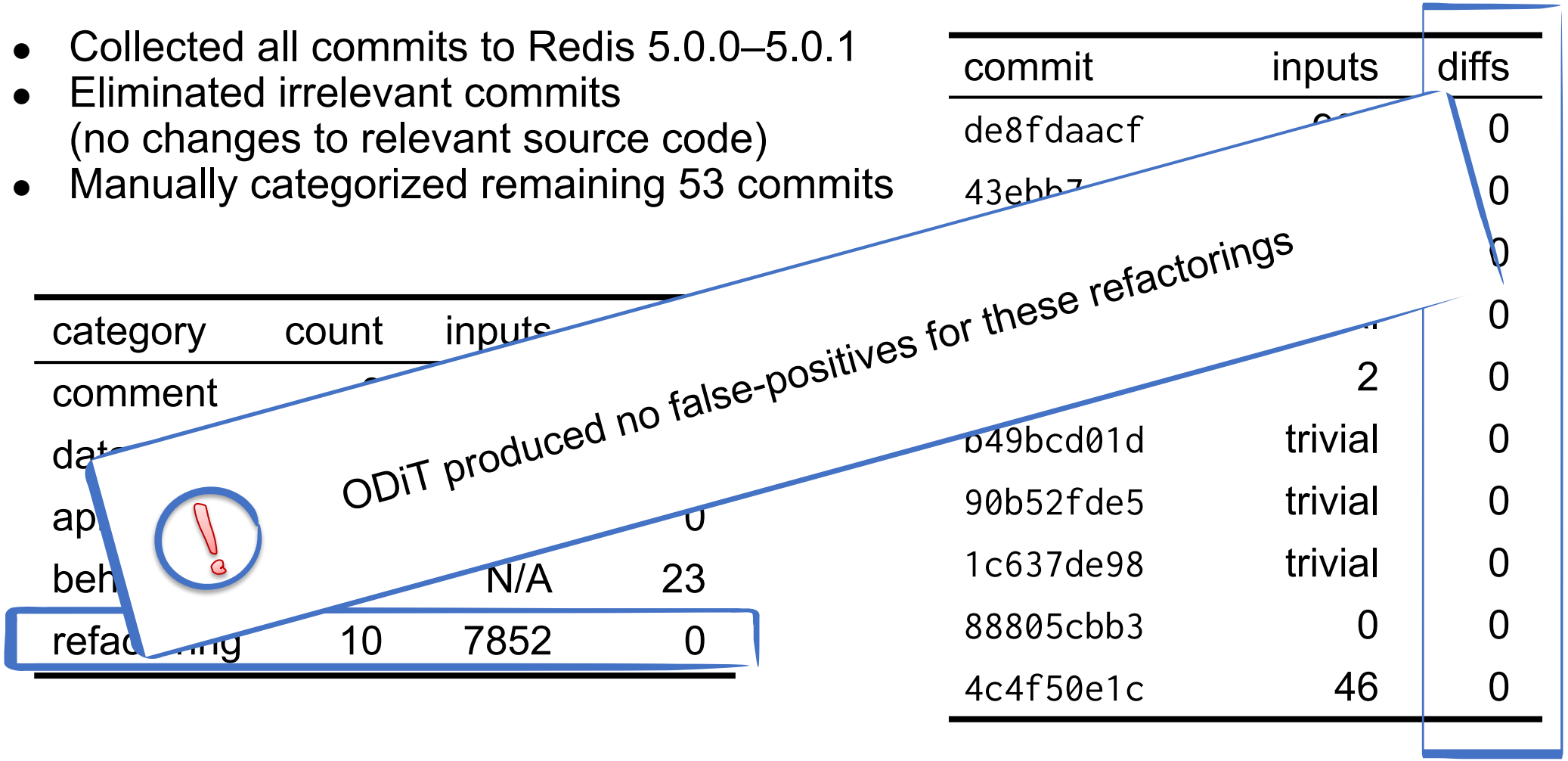
benchmark	ODiT	Shadow
01-rm	✘	✘
03-cut	✘	✘
04-tail	✔	✘
05-tail	✘	✔
06-cut	✔	✔
07-seq	✔	✘
08-seq	✔	✘
09-seq	✘	✘
10-cp	✘	✔
12-cut	✔	✔

benchmark	ODiT	Shadow
13-ls	✔	✔
14-ls	✔	✘
15-du	✔	✘
16-tail	✘	✔
17-cut	✔	✔
18-seq	✔	✘
19-seq	✔	✘
20-seq	✔	✘
21-cut	✔	✔
22-expr	✔	✘

RQ3: Refactored Code

- Collected all commits to Redis 5.0.0–5.0.1
- Eliminated irrelevant commits
  (no changes to relevant source code)
- Manually categorized remaining 53 commits

category	count	inputs	
comment			
dat			
ap			0
beh		N/A	23
refac ring	10	7852	0



commit	inputs	diffs
de8fdaacf		0
43ebb7		0
		0
		0
	2	0
b49bcd01d	trivial	0
90b52fde5	trivial	0
1c637de98	trivial	0
88805cbb3	0	0
4c4f50e1c	46	0

RQ3: Refactored Code

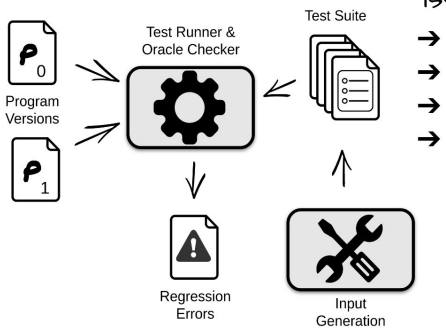
- 53 updates to Redis, from prior to 5.0.0 through 5.0.1
- Building commits that changed a program source file
- Manual inspection to categorize each commit

category	count	inputs	diffs
comment	8	N/A	0
data	5	unsupp	0
api	2	0	0
behavior	28	N/A	23
refactoring	10	7852	0

commit	inputs	diffs
de8fdaacf	906	0
43ebb7ee0	0	0
edc47a3ad	6898	0
3761582ff	trivial	0
50222af5f	2	0
b49bcd01d	trivial	0
90b52fde5	trivial	0
1c637de98	trivial	0
88805cbb3	0	0
4c4f50e1c	46	0

Conclusion

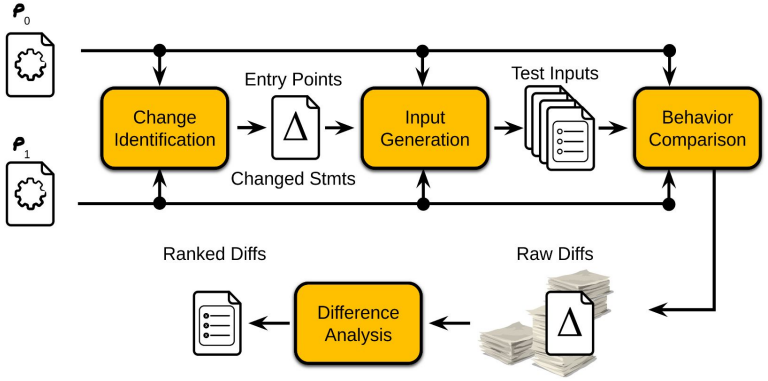
Regression Testing



Issues with regression test suites:

- Focus on core behavior
- Provide haphazard coverage
- Use approximated oracles
- Sometimes not present at all

Overapproximate Differential Regression Testing (ODiT) Overview



Evaluation: Implementation and Research Questions

Implementation:

- Program analysis and differencing: clang & llvm
- Symbolic execution engine: forked from KLEE 1.3

Research Questions:

- RQ1: Can ODiT detect and effectively rank regressions?
- RQ2: How does ODiT, which overapproximates behavior, compare to a tool that underapproximates behavior?
- RQ3: How does ODiT perform on refactored code?

RQ1: Detection and Ranking

benchmark	inputs	diffs	TP	FP	precision	rank
01-rm	671	0	0	0	-	N/A
03-cut	30641	5	0	5	0.0 %	N/A
04-tail	11407	1	1	0	100.0 %	1
05-tail	8311	1	0	1	0.0 %	N/A
06-cut	3198	5	2	3	40.0 %	1
07-seq	13427	2	1	1	50.0 %	1
08-seq	14088	3	1	2	33.3 %	3
09-seq	15248	2	2			
10-cp	4239					
12-cut						
13-ls						
14-ls						1
15-du			2		80.0 %	1
16-tail			0	1	0.0 %	N/A
17-cut		7	3	4	42.9 %	3
18-seq	15248	2	2	0	100.0 %	1
19-seq	8533	3	1	2	33.3 %	3
20-seq	15250	2	2	0	100.0 %	1
21-cut	18841	11	11	0	100.0 %	1
22-expr	2644	1	1	0	100.0 %	1

benchmark	inputs	diffs	TP	FP	precision	rank
23-find	2552	67	1	66	1.5 %	67
24-find	22994	3	0	3	0.0 %	N/A
26-find	180975	65	10	55	15.4 %	1
27-find	7771	1	0	1	0.0 %	N/A
28-find	89420	4	0			N/A
30-find	35945					1
31-find						1
						1
						1
					0.0 %	N/A
				0	4	0.0 %	N/A
		2	2	0	100.0 %	1
	4583	8	5	3	62.5 %	2
41-grep	27704	51	0	51	0.0 %	N/A
42-grep	2965	15	13	2	86.7 %	1
44-grep	586	0	0	0	-	N/A
45-grep	3142	1	0	1	0.0 %	N/A
46-grep	9069	5	3	2	60.0 %	2
47-grep	25758	22	0	22	0.0 %	N/A
48-grep	25918	16	0	16	0.0 %	N/A
49-grep	58	0	0	0	-	N/A
51-grep	168	13	0	13	0.0 %	N/A
52-grep	2012	3	3	0	100.0 %	1

- In 58% of the cases, actual regressions in Top-3 (often Top-1)
- In 42% of the cases, FPs ranked higher than TPs
- In 33% of the cases, no false positives

Results

bench mark	regression detection inputs	diffs	+o	PPV	-o	FDR	rank	cmp bklee	cmp shdw
01-rm	671	0	0	-	0	-	N/A	✗	✗
03-cut	30641	5	0	0.0%	5	100.0%	N/A	✗	✗
04-tail	11407	1	1	100.0%	0	0.0%	1	✓	✗
05-tail	83								
06-cut	31								
07-seq	134								
08-seq	140								
09-seq	152								
10-cp	4239	0	0	-	0	-	N/A	✗	✓
12-cut	28606	7	3	42.9%	4	57.1%	3	✓	✓[2]
13-ls	13062	3	2	66.7%	1	33.3%	1	✓	✓
14-ls	10186	10	10	100.0%	0	0.0%	1	✓	✗
15-du	1402	10	8	80.0%	2	20.0%	1	✓	✗
16-tail	8296	1	0	0.0%	1	100.0%	N/A	✗	✓[1]
17-cut	28573	7	3	42.9%	4	57.1%	3	✓	✓[2]
18-seq	15248	2	2	100.0%	0	0.0%	1	✓	✗
19-seq	8533	3	1	33.3%	2	66.7%	3	✓	✗
20-seq	15250	2	2	100.0%	0	0.0%	1	✓	✗
21-cut	18841	11	11	100.0%	0	0.0%	1	✓	✓
22-expr	2644	1	1	100.0%	0	0.0%	1	✓	✗

- Automatically identified >50% known regressions
- Reported higher ranked FP in only 18/43 cases

bench mark	regression detection inputs	diffs	+o	PPV	-o	FDR	rank	bklee
23-find	2552	67	1	1.5%	66	98.5%	67	✓
24-find	22994	3	0	0.0%	3	100.0%	N/A	✗
26-find	180975	65	10	15.4%	55	84.6%	1	✓
27-find	7771	1	0	0.0%	1	100.0%	N/A	✗
28-find	89420	4	0	0.0%	4	100.0%	N/A	✗
30-find	35945	7	7	100.0%	0	0.0%	1	✓
						84.4%	1	✓
						77.8%	1	✓
						77.8%	1	✓
						00.0%	N/A	✗
						100.0%	N/A	✗
37-find	89012	2	2	100.0%	0	0.0%	1	✓
38-grep	4583	8	5	62.5%	3	37.5%	2	✓
41-grep	27704	51	0	0.0%	51	100.0%	N/A	✗
42-grep	2965	15	13	86.7%	2	13.3%	1	✓
44-grep	586	0	0	-	0	-	N/A	✗
45-grep	3142	1	0	0.0%	1	100.0%	N/A	✗
46-grep	9069	5	3	60.0%	2	40.0%	2	✓
47-grep	25758	22	0	0.0%	22	100.0%	N/A	✗
48-grep	25918	16	0	0.0%	16	100.0%	N/A	✗
49-grep	58	0	0	-	0	-	N/A	✗
51-grep	168	13	0	0.0%	13	100.0%	N/A	✗
52-grep	2012	3	3	100.0%	0	0.0%	1	✓

Results

bench mark	regression detection inputs	diffs	+o	PPV	-o	FDR	rank	cmp bklee	cmp shdw
01-rm	671	0	0	-	0	-	N/A	✗	✗
03-cut	30641	5	0	0.0%	5	100.0%	N/A	✗	✗
04-tail	11407	1	1	100.0%					
05-tail	8311	1	0	0.0%					
06-cut	3198	5	2	40.0%					
07-seq	13427	2	1	50.0%					
08-seq	14088	3	1	33.3%					
09-seq	15248	2	2	100.0%	0	0.0%	1	✗	✗
10-cp	4239	0	0	-	0	-	N/A	✗	✓
12-cut	28606	7	3	42.9%	4	57.1%	3	✓	✓[2]
13-ls	13062	3	2	66.7%	1	33.3%	1	✓	✓
14-ls	10186	10	10	100.0%	0	0.0%	1	✓	✗
15-du	1402	10	8	80.0%	2	20.0%	1	✓	✗
16-tail	8296	1	0	0.0%	1	100.0%	N/A	✗	✓[1]
17-cut	28573	7	3	42.9%	4	57.1%	3	✓	✓[2]
18-seq	15248	2	2	100.0%	0	0.0%	1	✓	✗
19-seq	8533	3	1	33.3%	2	66.7%	3	✓	✗
20-seq	15250	2	2	100.0%	0	0.0%	1	✓	✗
21-cut	18841	11	11	100.0%	0	0.0%	1	✓	✓
22-expr	2644	1	1	100.0%	0	0.0%	1	✓	✗

Outperformed state-of-the-art technique used as a baseline.

bench mark	regression detection inputs	diffs	+o	PPV	-o	FDR	rank	bklee
23-find	2552	67	1	1.5%	66	98.5%	67	✓
24-find	22994	3	0	0.0%	3	100.0%	N/A	✗
26-find	180975	65	10	15.4%	55	84.6%	1	✓
27-find	7771	1	0	0.0%	1	100.0%	N/A	✗
28-find	89420	4	0	0.0%	4	100.0%	N/A	✗
				100.0%	0	0.0%	1	✓
				15.6%	54	84.4%	1	✓
				22.2%	7	77.8%	1	✓
				22.2%	7	77.8%	1	✓
				0.0%	7	100.0%	N/A	✗
36-find	68074	4	0	0.0%	4	100.0%	N/A	✗
37-find	89012	2	2	100.0%	0	0.0%	1	✓
38-grep	4583	8	5	62.5%	3	37.5%	2	✓
41-grep	27704	51	0	0.0%	51	100.0%	N/A	✗
42-grep	2965	15	13	86.7%	2	13.3%	1	✓
44-grep	586	0	0	-	0	-	N/A	✗
45-grep	3142	1	0	0.0%	1	100.0%	N/A	✗
46-grep	9069	5	3	60.0%	2	40.0%	2	✓
47-grep	25758	22	0	0.0%	22	100.0%	N/A	✗
48-grep	25918	16	0	0.0%	16	100.0%	N/A	✗
49-grep	58	0	0	-	0	-	N/A	✗
51-grep	168	13	0	0.0%	13	100.0%	N/A	✗
52-grep	2012	3	3	100.0%	0	0.0%	1	✓