Failure Sketching: A Technique for Automated Root Cause Diagnosis of In-Production Failures

Baris Kasikci, Benjamin Schubert, Cristiano Pereira,
Gilles Pokam, George Candea

Debugging In-Production Software Failures Today

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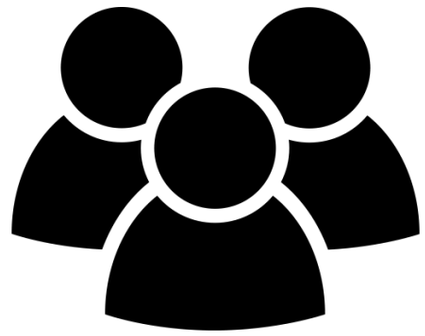

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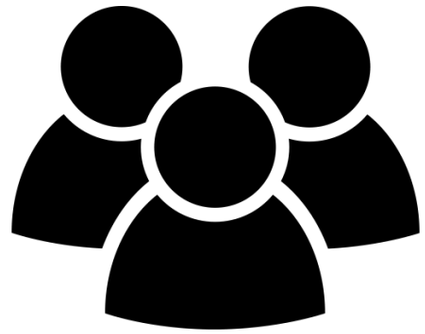

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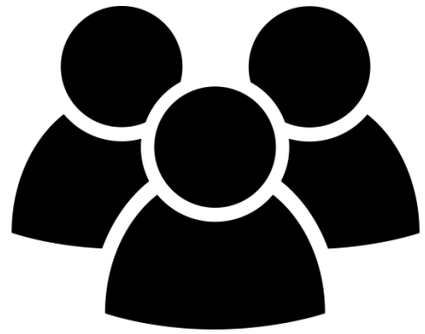

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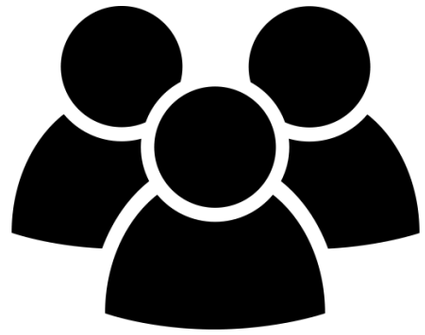

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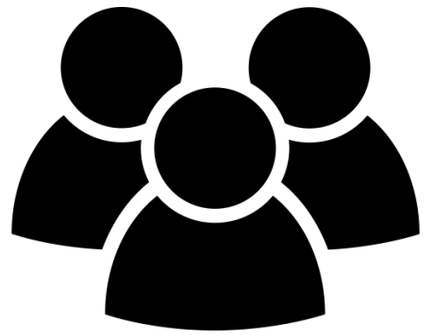

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Related Work

- Collaborative approaches
  - *WER [SOSP'09], CBI [PLDI'05], CCI [OOPSLA'10]*
- Identifying differences of failing and successful runs
  - *Delta debugging [TSE'02], Symbiosis [PLDI'15]*
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Contributions

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Goal: automate the manual detective work of debugging

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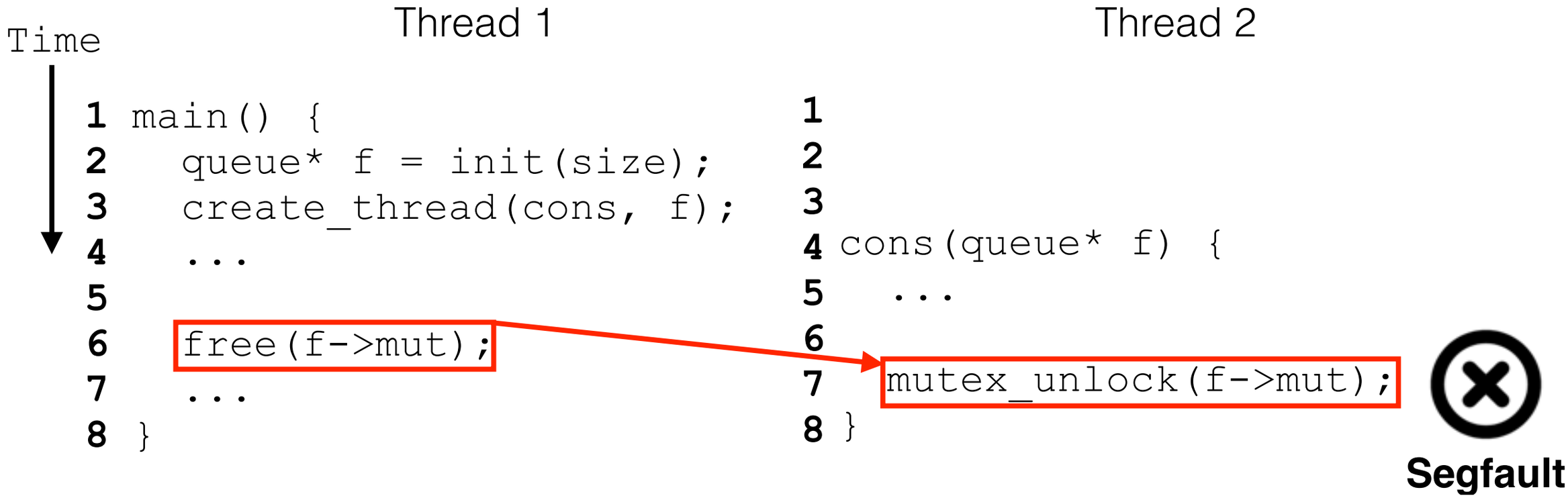
Failure sketching

Complements in-house static analysis with in-production dynamic analysis

Automatically and efficiently builds accurate failure sketches that show root causes of failures

Failure Sketch



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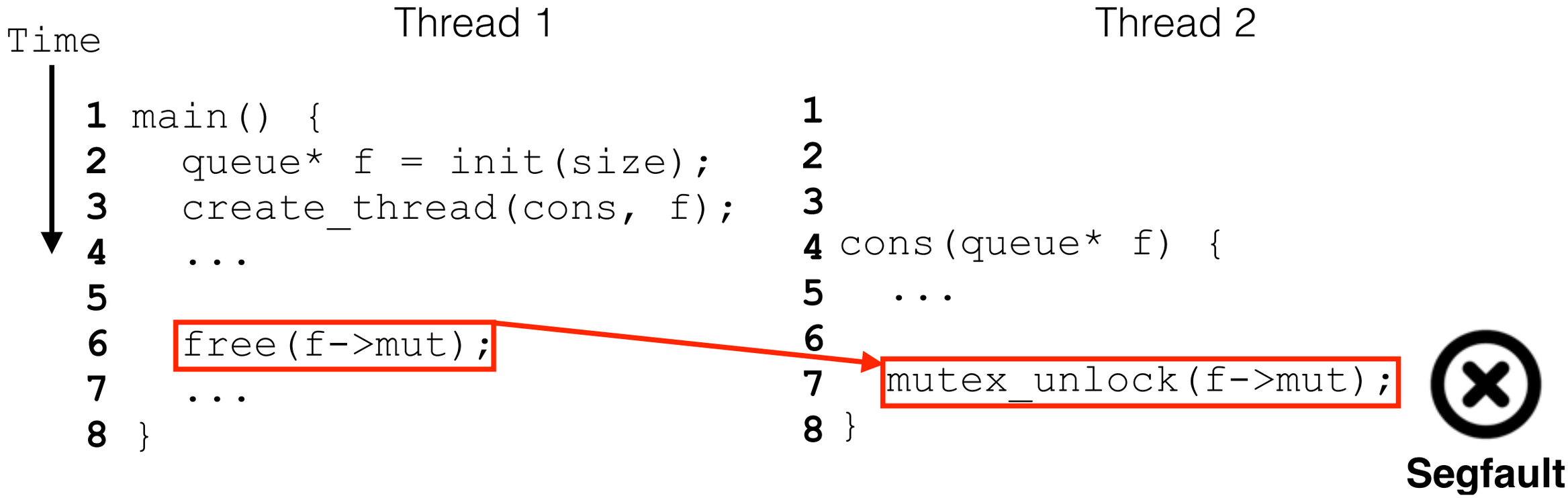

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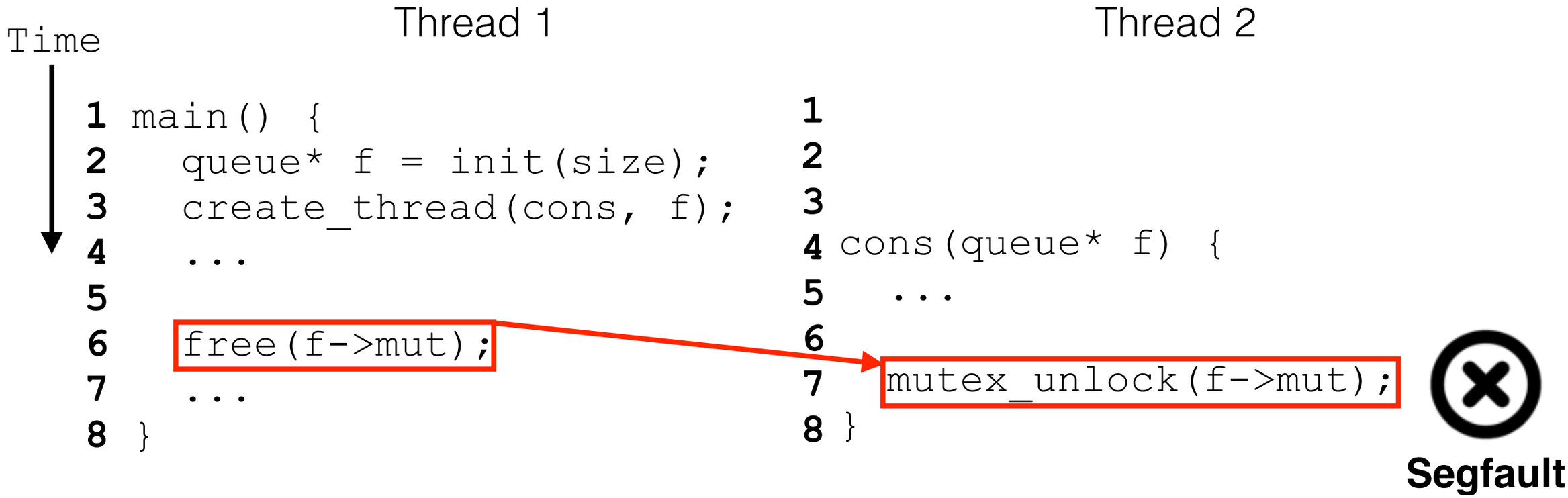


Failure Sketch

Time

Thread 1

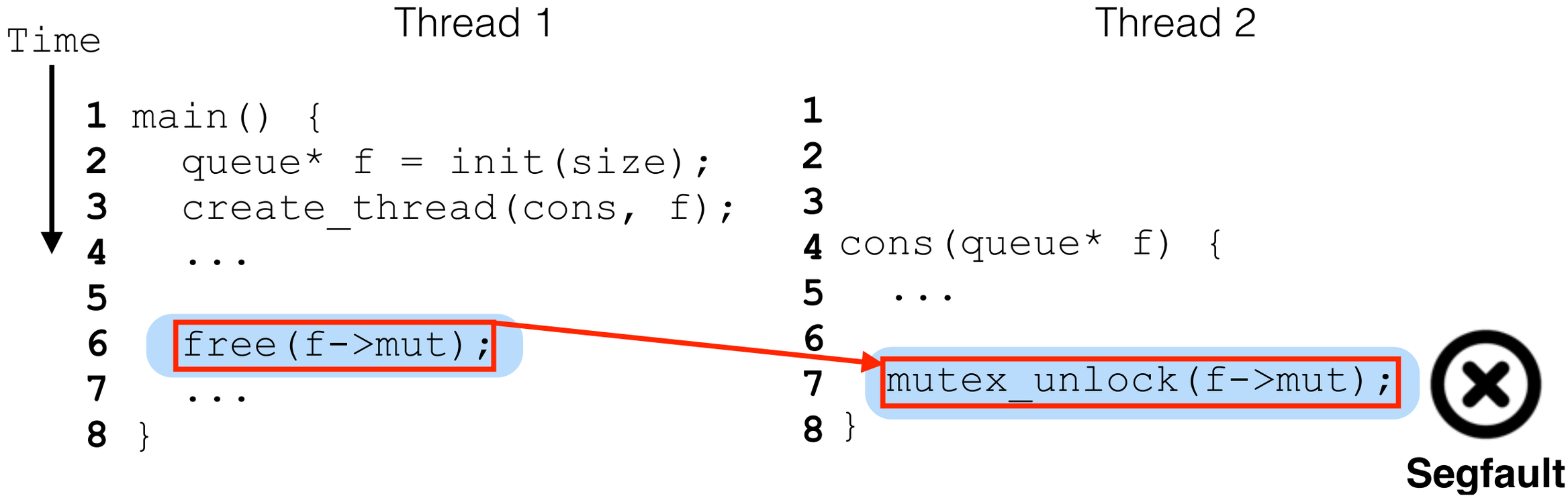
```
1 main() {
2   queue* f = init(size);
3   create_thread(cons, f);
4   ...
5
6   free(f->mut);
7   ...
8 }
```

Thread 2

```
1
2
3
4 cons(queue* f) {
5   ...
6
7   mutex_unlock(f->mut);
8 }
```

Segfault

Failure Sketch



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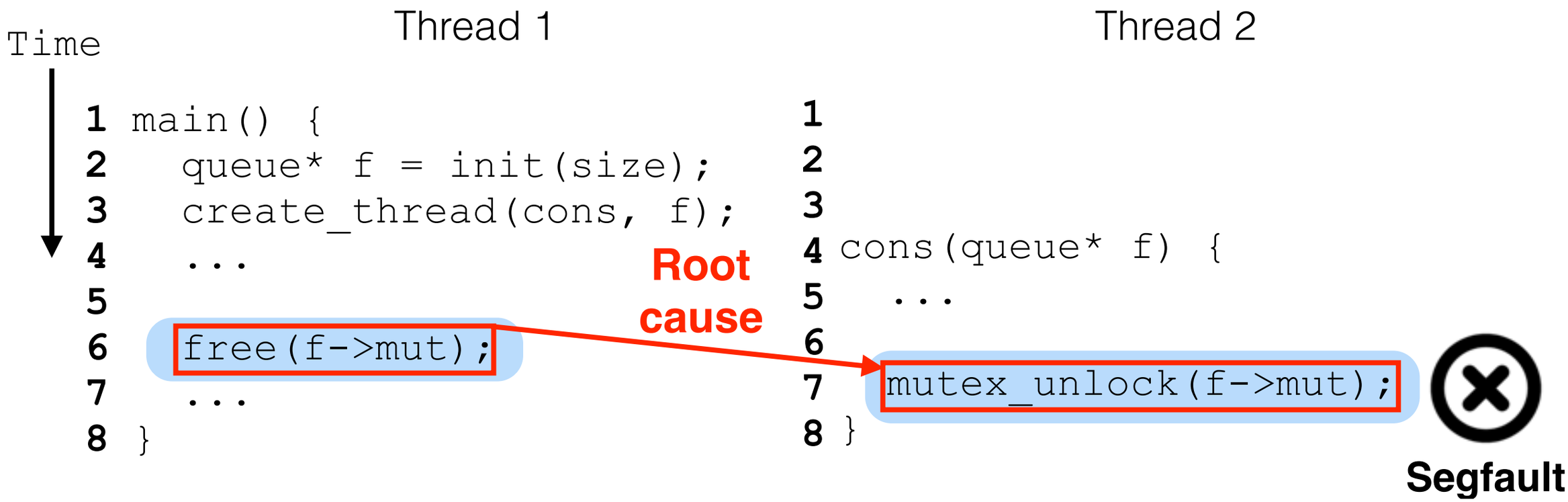

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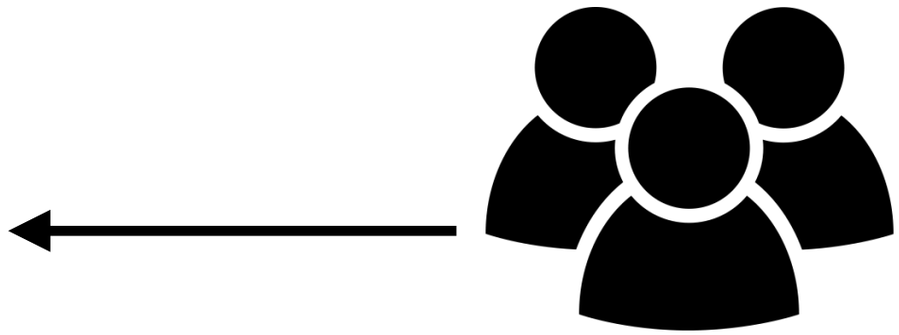

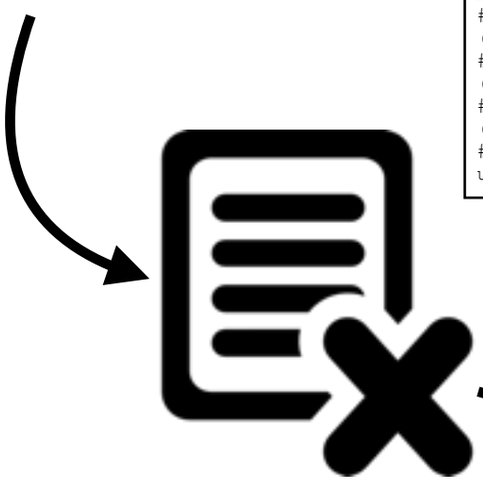

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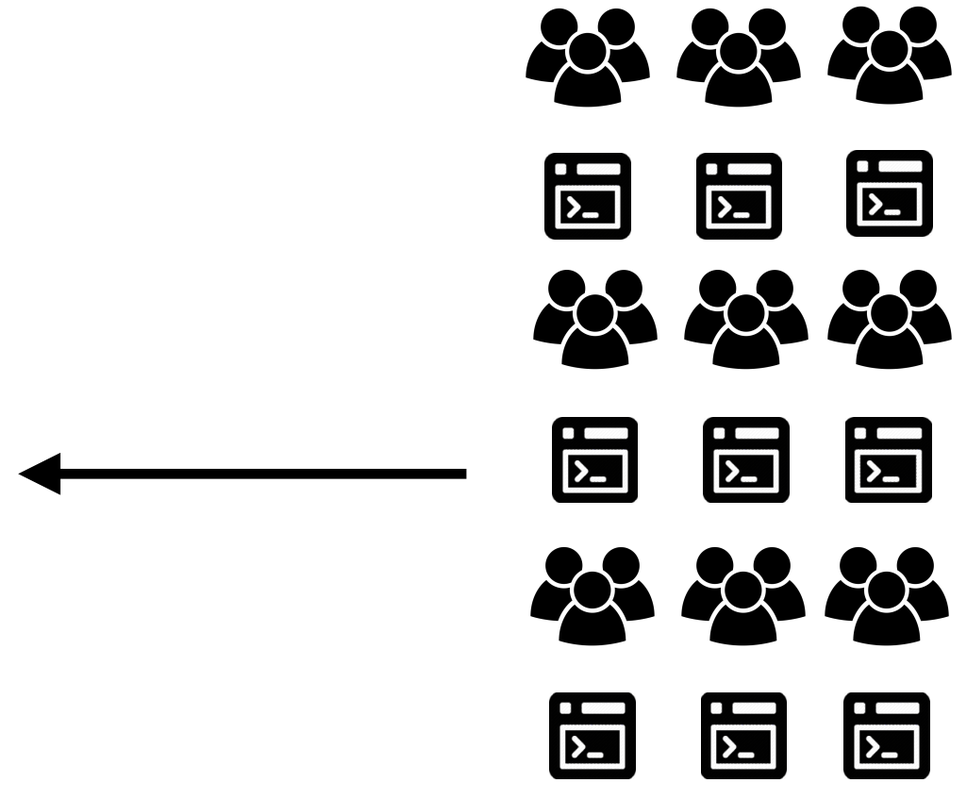

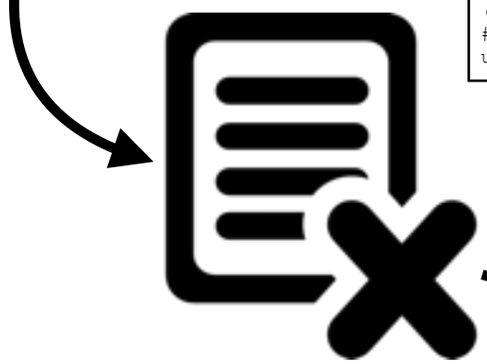

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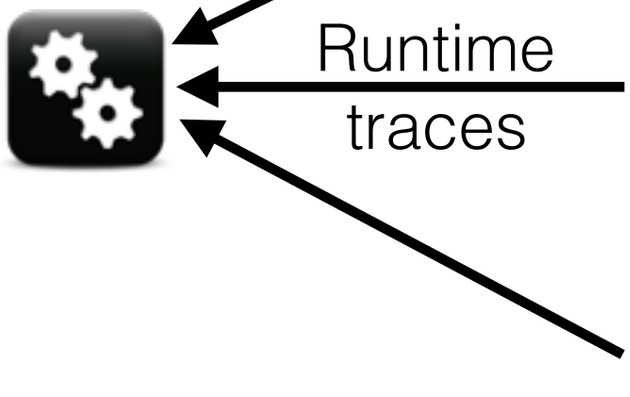
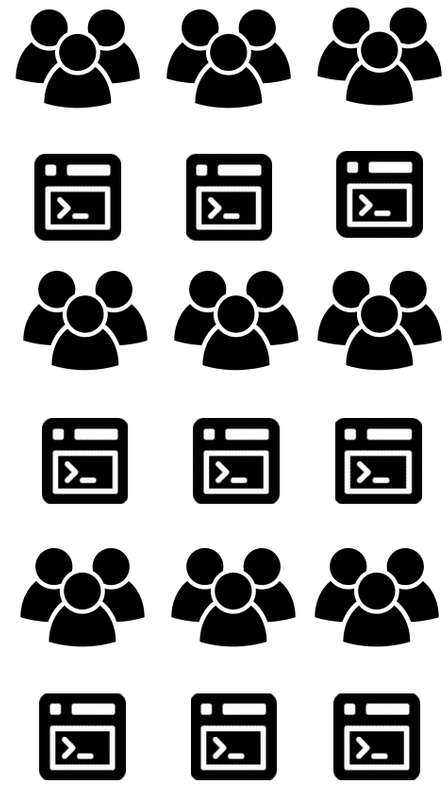
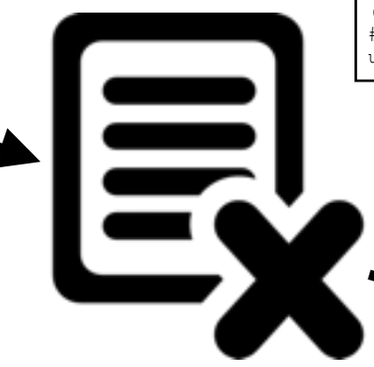


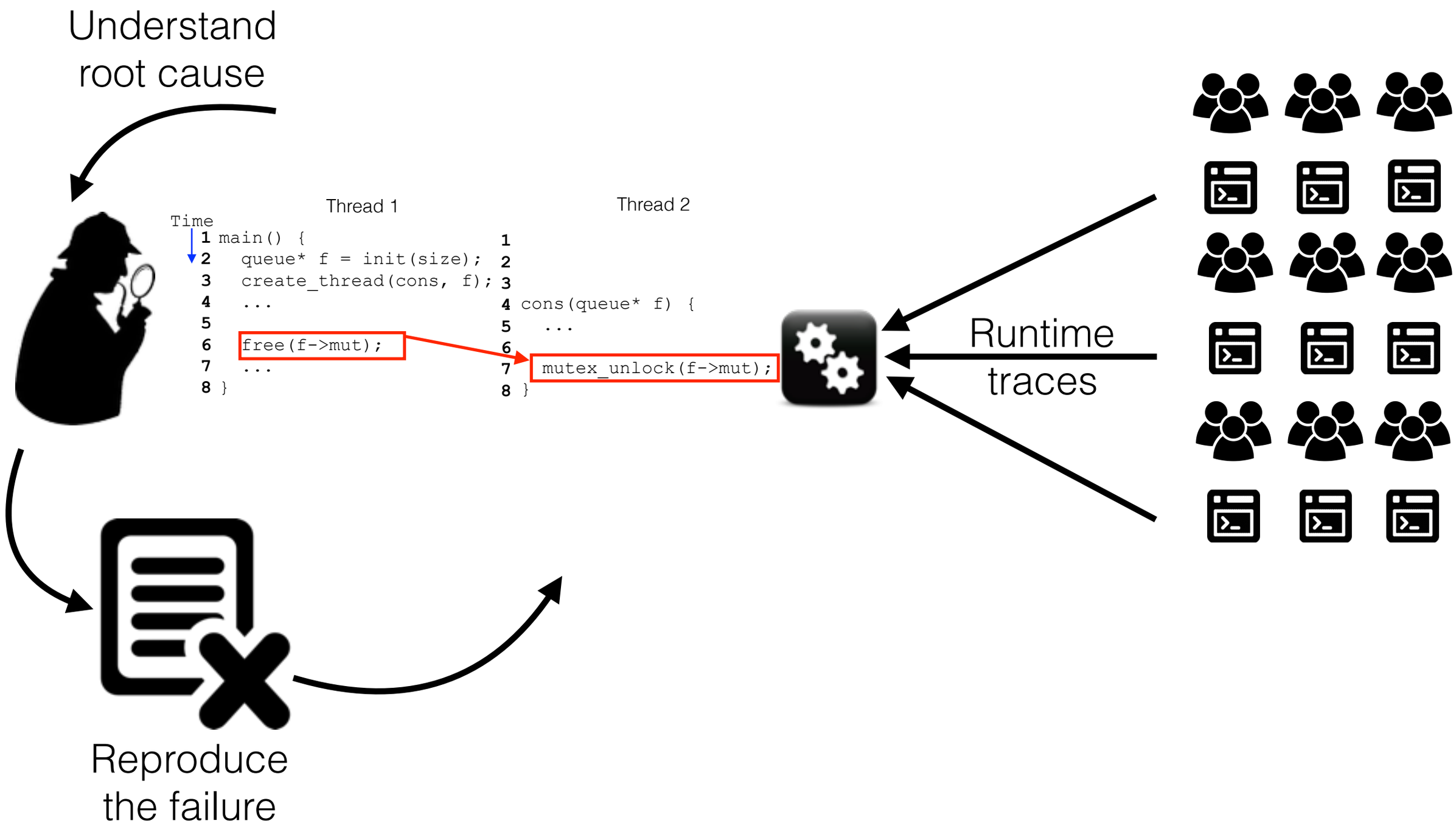
Runtime traces



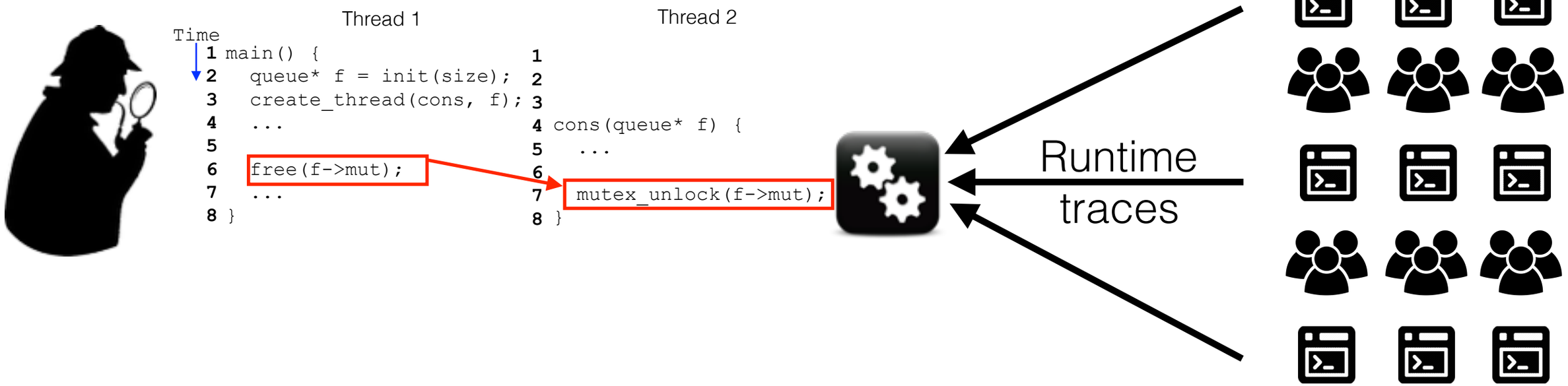


Reproduce the failure

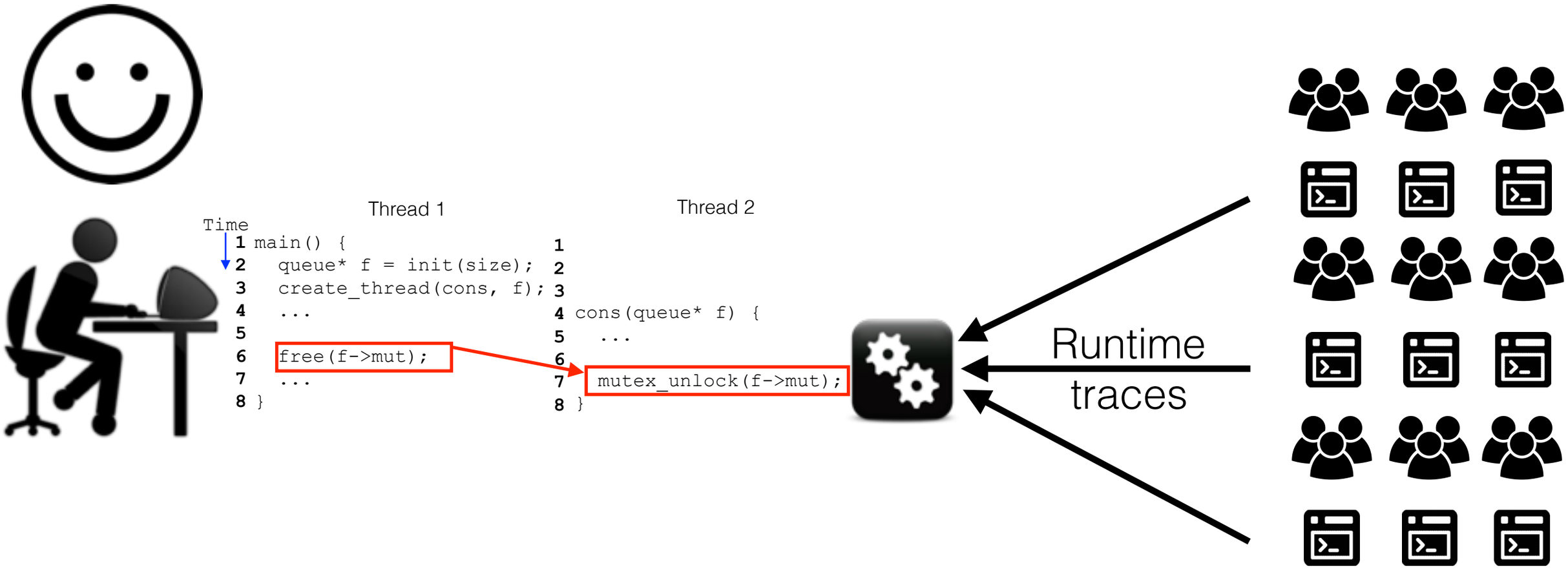
Failure Sketch Usage Model



Failure Sketch Usage Model



Failure Sketch Usage Model



Outline

- Challenges
- Design
- Evaluation

Outline

- Challenges
- Design
- Evaluation

Challenges of Building Failure Sketches

- Accuracy
  - *Exclude all irrelevant information, preserve all relevant one*
- Recurrence
  - *Gathering enough execution information from rare failures*
- Latency
  - *Achieve high accuracy after just a few recurrences*

Outline

- Challenges
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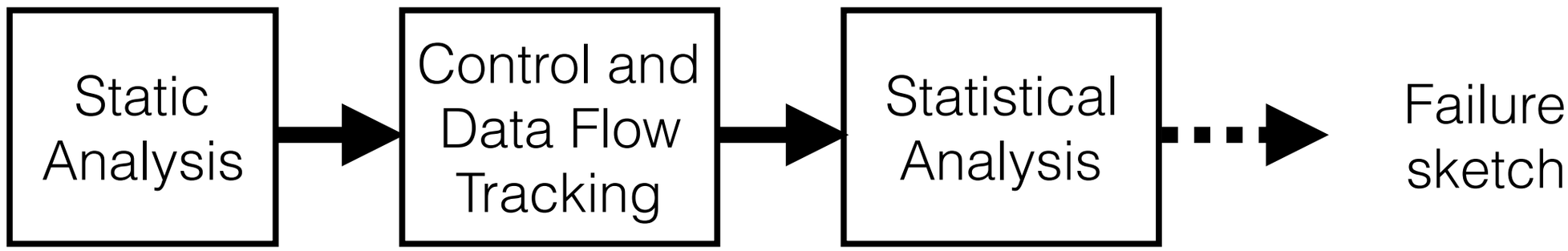
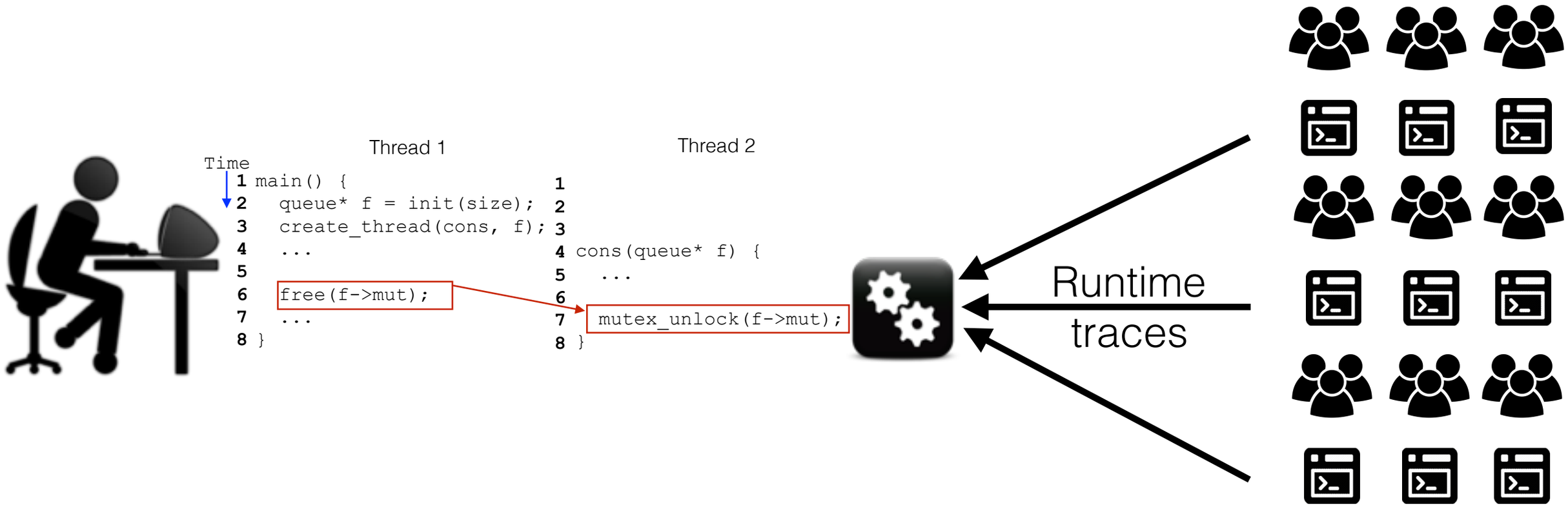
Outline

- Challenges
- Design



- Evaluation

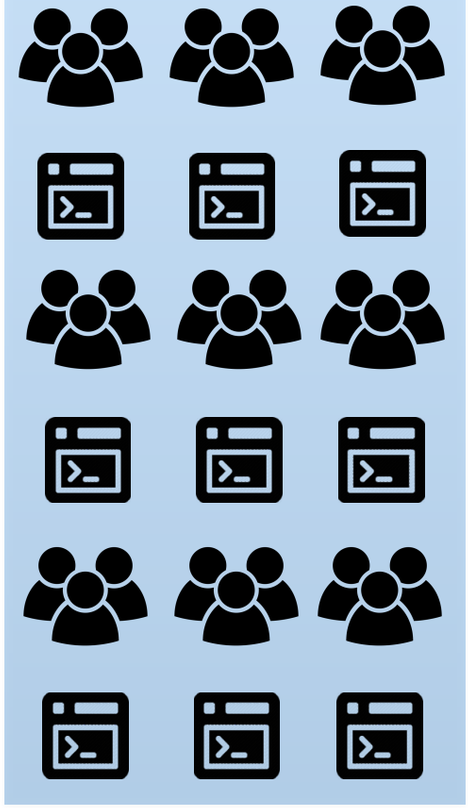
Gist System Architecture



Gist System Architecture

Server

Client



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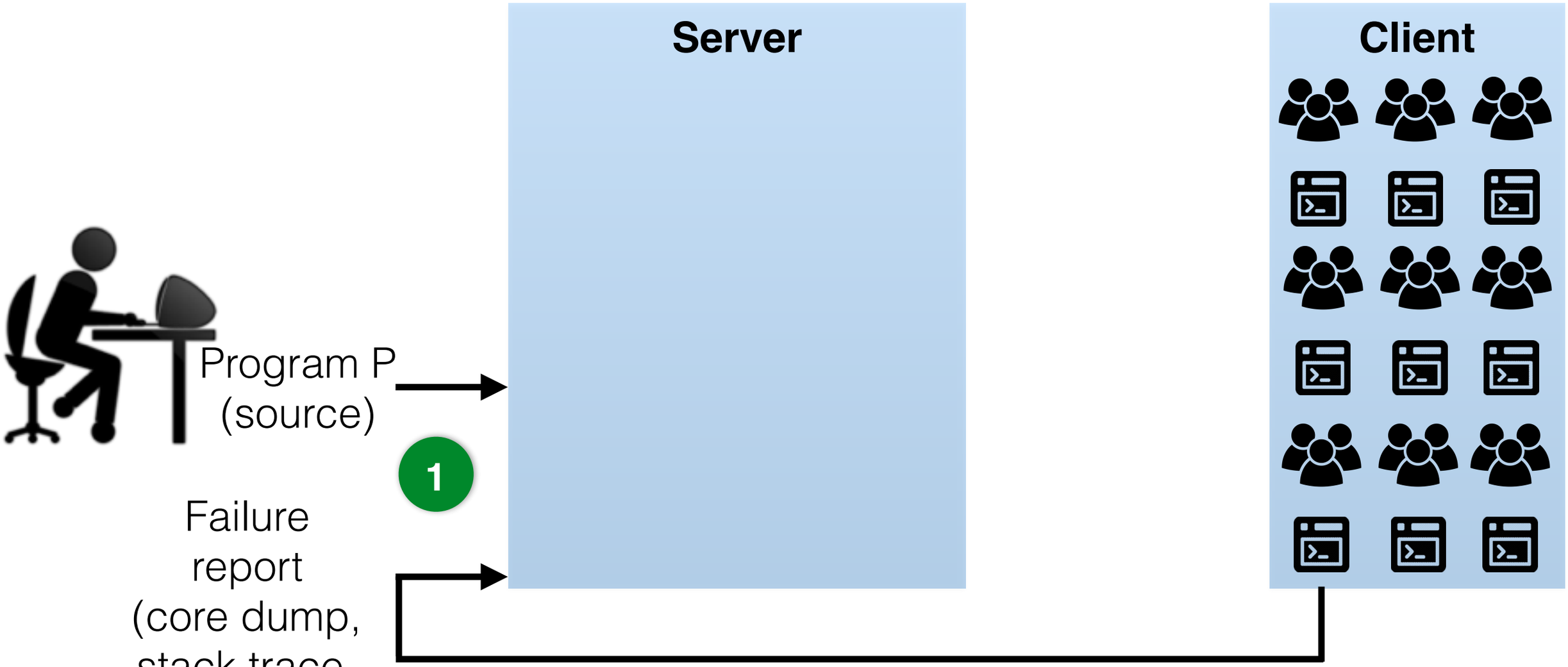
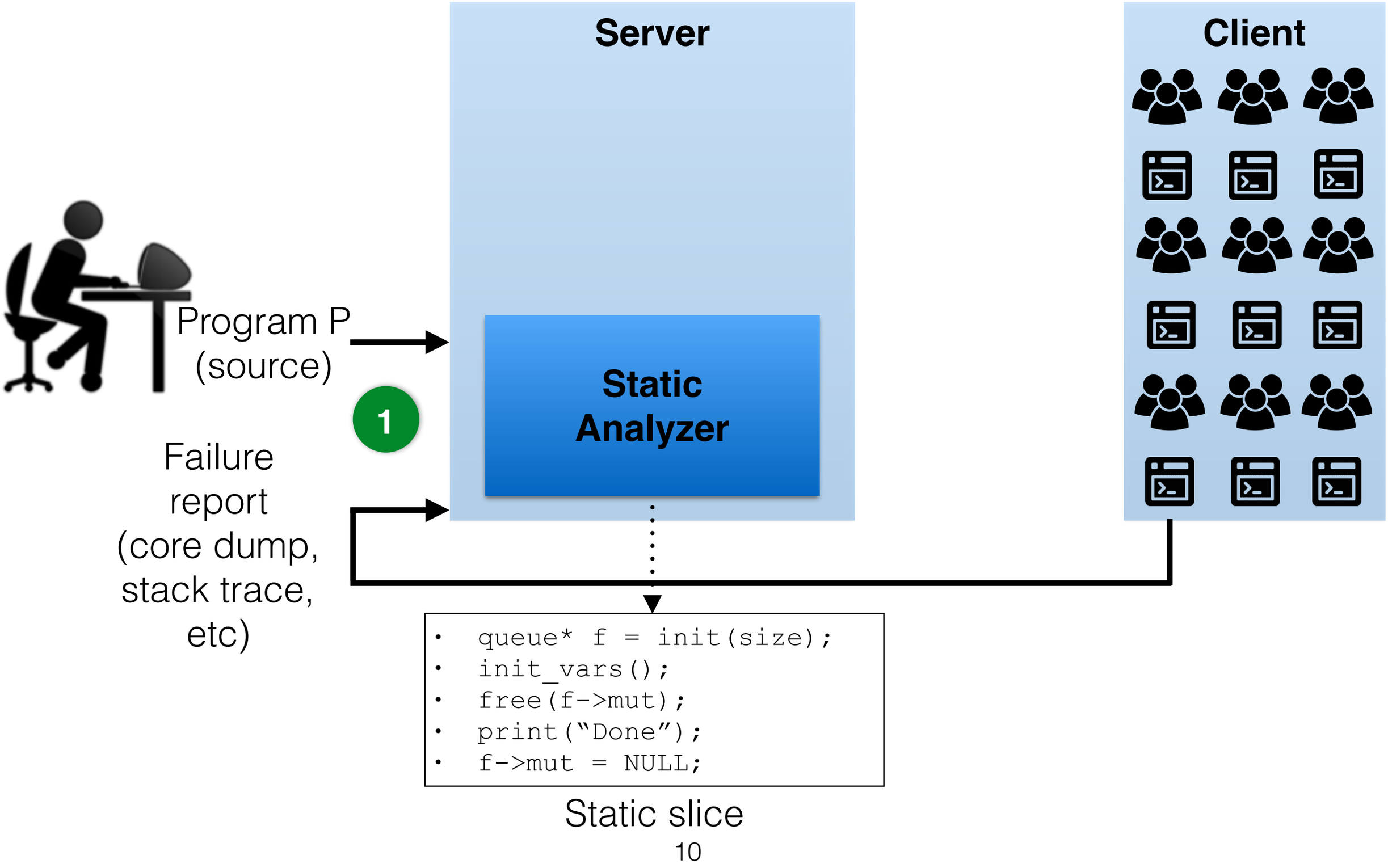


Gist System Architecture



Gist System Architecture

Program P
(source)

Failure
report
(core dump,
stack trace,
etc)

1

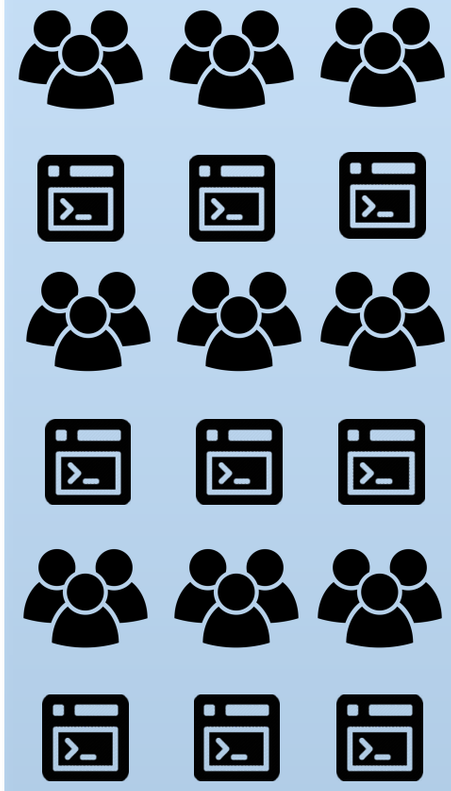
Server

Static Analyzer

2

Instrumentation

Client



Tracking
control and
data flow

```
•  queue* f = init(size);
•  init_vars();
•  free(f->mut);
•  print("Done");
•  f->mut = NULL;
```

Static slice

Gist System Architecture

Program P
(source)

Failure
report
(core dump,
stack trace,
etc)

1

Server

Static Analyzer

2

Instrumentation

3

Refinement with
runtime traces

Client

Tracking
control and
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Static slice

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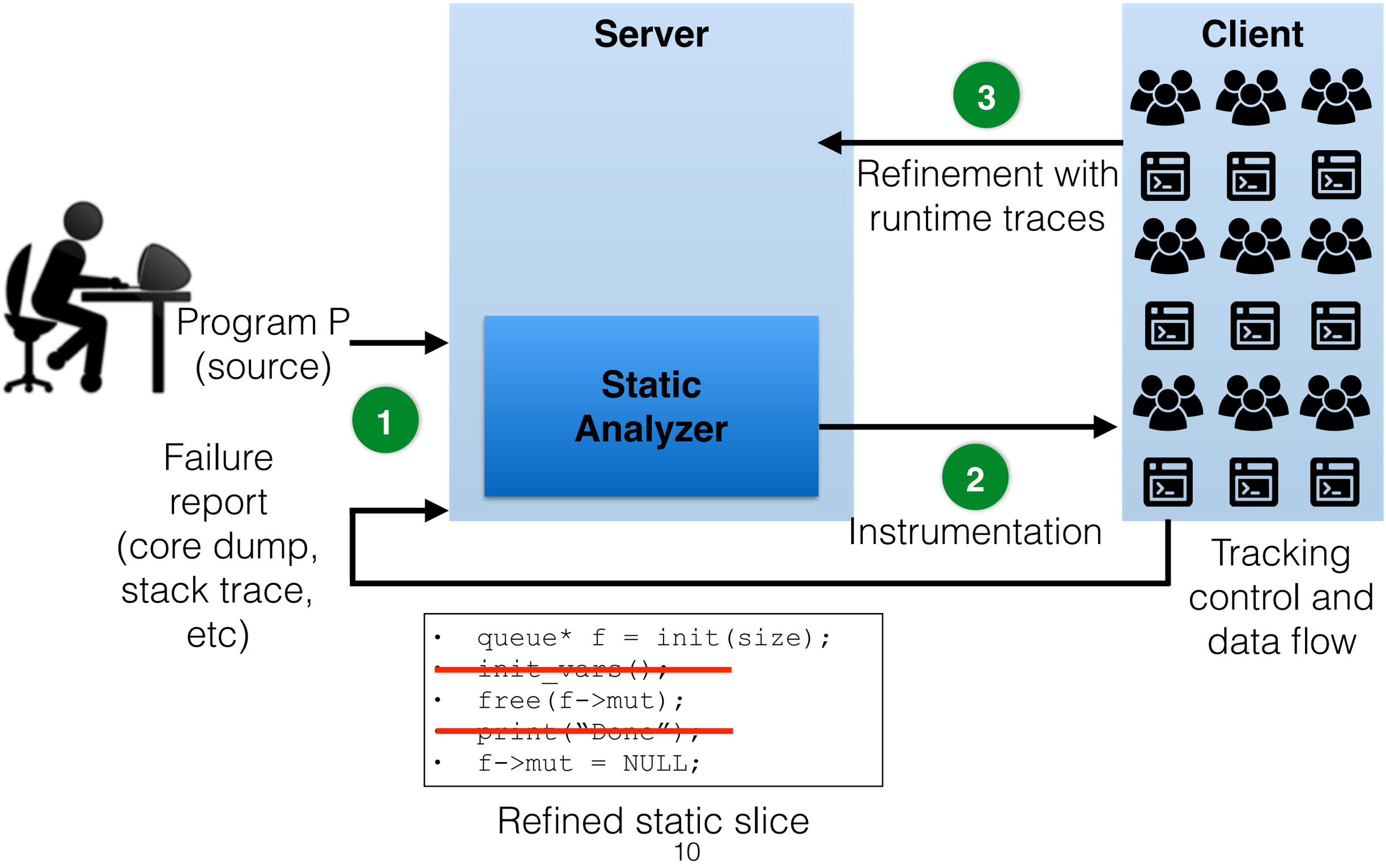

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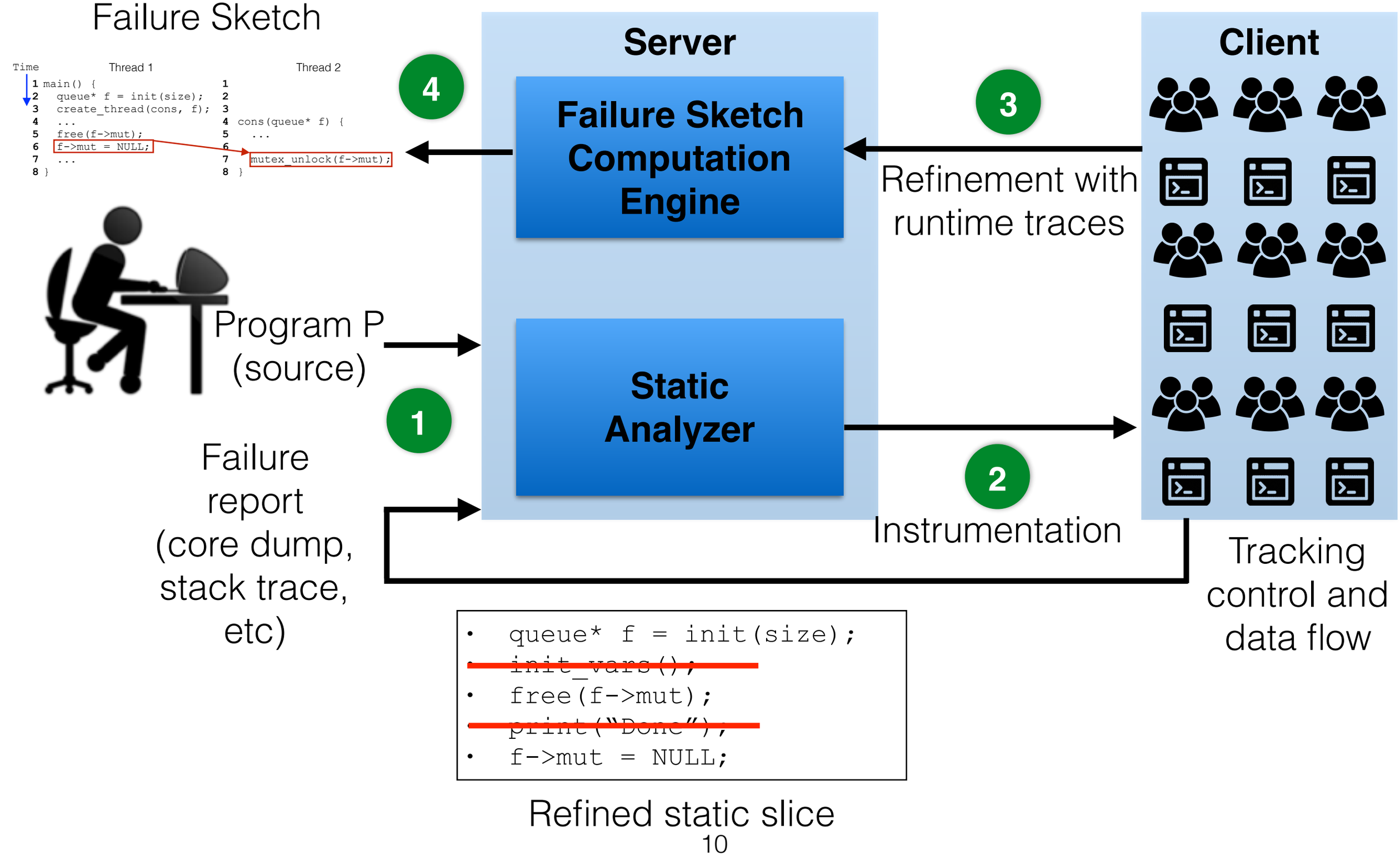
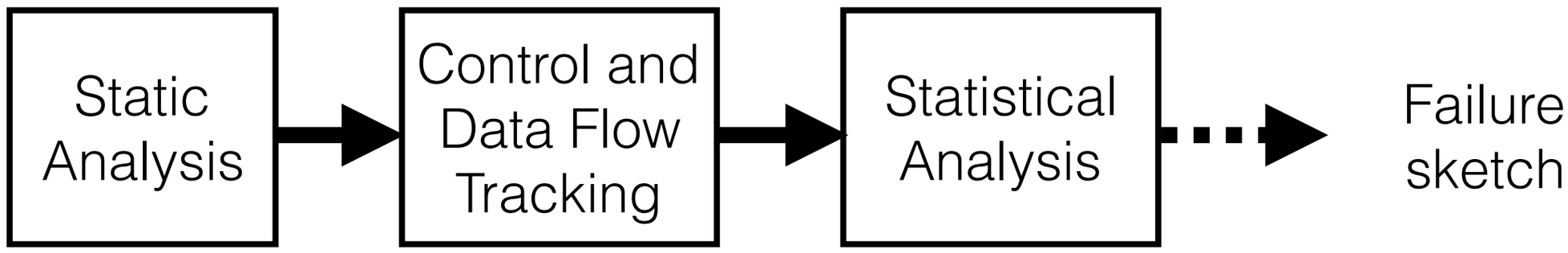


Outline

- Challenges
- Design



- Evaluation

Outline

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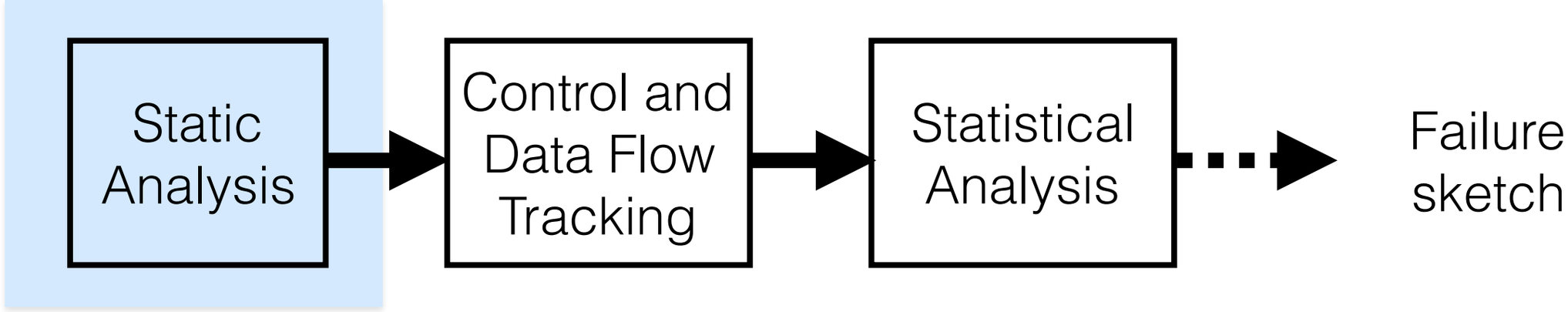

- Evaluation

Static Analysis to Reduce the Overhead

- Computes backward slices
  - *Includes statements with dependencies to the failure*
  - *Excludes all other statements*
- Inter-procedural
  - *Identify dependencies across functions*

Static Analysis to Reduce the Overhead

- Computes backward slices
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  - *Excludes all other statements*
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Static analysis reduces subsequent runtime tracking (20x)

Example

```
void cleanup(State* s) {
  log("Func:cleanup");
  if(verbose)
    log("Cleaning up %p", s);
  delete s;
}

void display_size(State* s) {
  log("Func:display_size");
  log("State: %u", s->size);
}
```

Example

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void cleanup(State* s) {
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Segfault

Example

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```

Segfault

Example: Static Backward Slicing

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void cleanup(State* s) {
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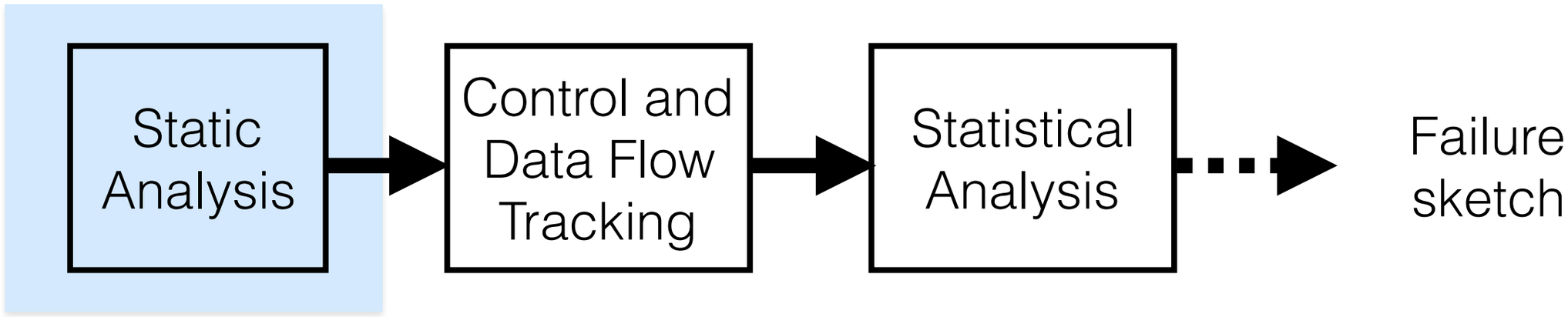
Segfault

Outline

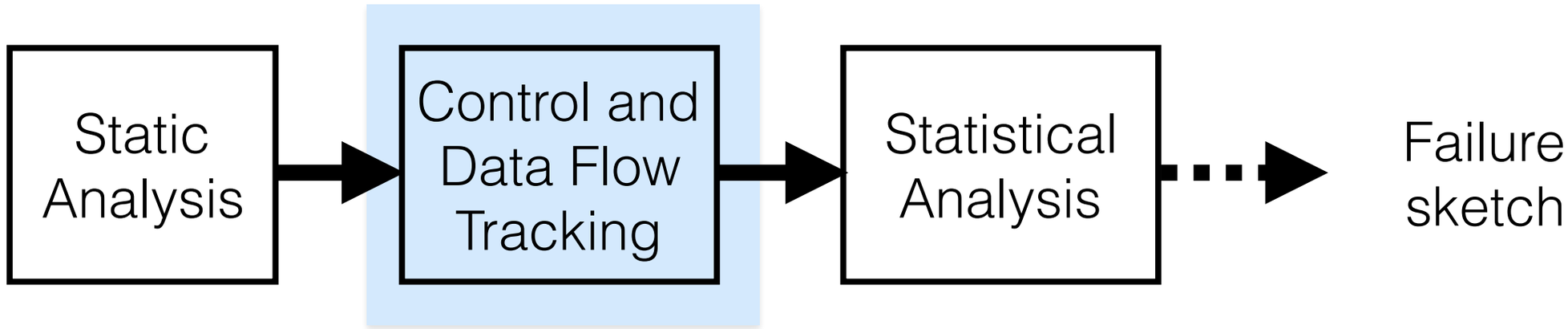
- Challenges
- Design



- Evaluation

Outline

- Challenges
- Design



- Evaluation

Low-Overhead Control Flow Tracking

- Software-based tracking is expensive (up to 15x)
- Hardware-based tracking is more efficient
  - *Intel PT: new feature in Intel CPUs (~40%)*
- Gist combines static analysis and hardware-based control flow tracking
  - *Low overhead (~2%)*

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  - *Low overhead (~2%)*

Static analysis → Low-overhead control flow tracking

Example: Control Flow Tracking (Step 1)

```
void cleanup(State* s) {
  log("Func:cleanup");
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    log("Cleaning up %p", s);
  delete s;
}

void display_size(State* s) {
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```

Segfault

Example: Control Flow Tracking (Step 2)

```
void cleanup(State* s) {
  log("Func:cleanup");
  if(verbose)
    log("Cleaning up %p", s);
  delete s;
}

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```

Segfault

Example: Control Flow Tracking (Step 2)

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void cleanup(State* s) {
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  log("Func:display_size");
  log("State: %u", s->size);
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```

Segfault

Static analysis + control flow tracking shorten the sketch

Data Flow Tracking to Increase Accuracy

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- Data flow information
  - *Variable values & total order of memory accesses*

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  - *Allow tracking reads and writes with low overhead*
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- Monitor multiple clients when run out of watchpoints

Data Flow Tracking to Increase Accuracy

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Precise ordering information → High accuracy

Example: Data Flow Tracking

```
void cleanup(State* s) {
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Segfault

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Segfault

Watch &s

Example: Data Flow Tracking

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Segfault

Watch &s

Example: Data Flow Tracking

Thread 1

```
void display_size(State* s) {
  log("Func:display_size");
  log("State: %u", s->size);
}
```

Thread 2

```
void cleanup(State* s) {
  log("Func:cleanup");
  if(verbose)
    log("Cleaning up %p", s);
  delete s;
}
```

Success

Example: Data Flow Tracking

Thread 1

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void display_size(State* s) {
  log("Func:display_size");
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}
```

Thread 2

```
void cleanup(State* s) {
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  if(verbose)
    log("Cleaning up %p", s);
  delete s;
}
```

Success

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void cleanup(State* s) {
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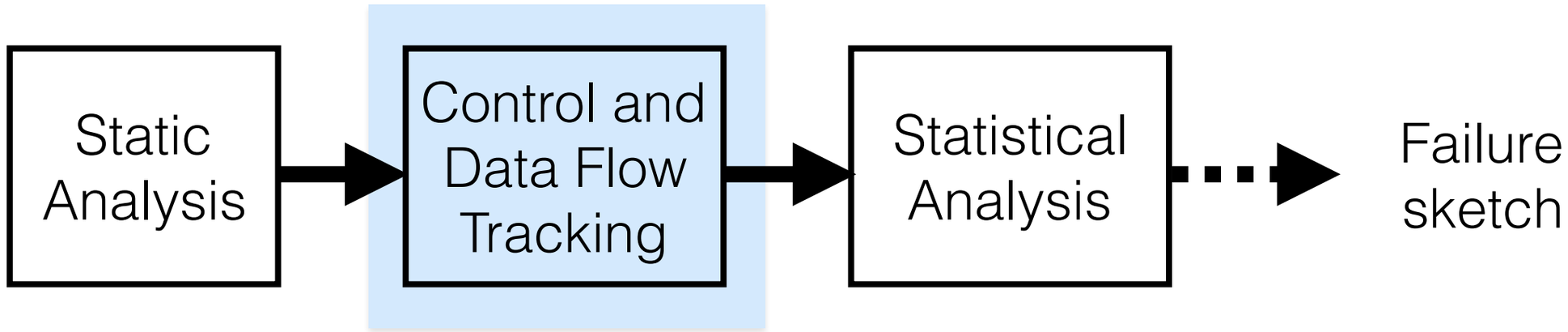
Failure

Outline

- Challenges
- Design



- Evaluation

Outline

- Challenges
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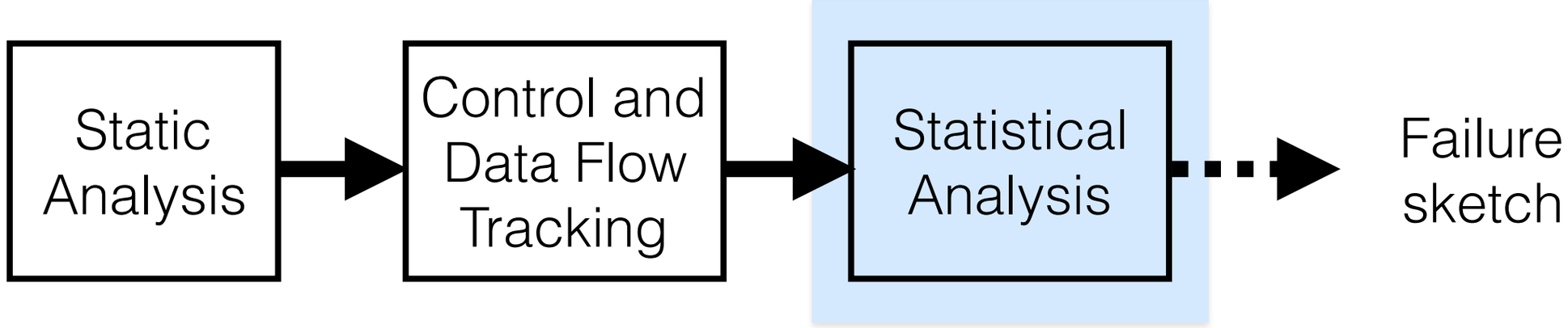

- Evaluation

Statistical Analysis

Statistical Analysis

- Identification of failure predictors[1]
  - *A good predictor portends a failure with high probability (e.g., data races, atomicity violations)*

[1] Liblit, B. et al. Scalable statistical bug isolation. PLDI 2005

Statistical Analysis

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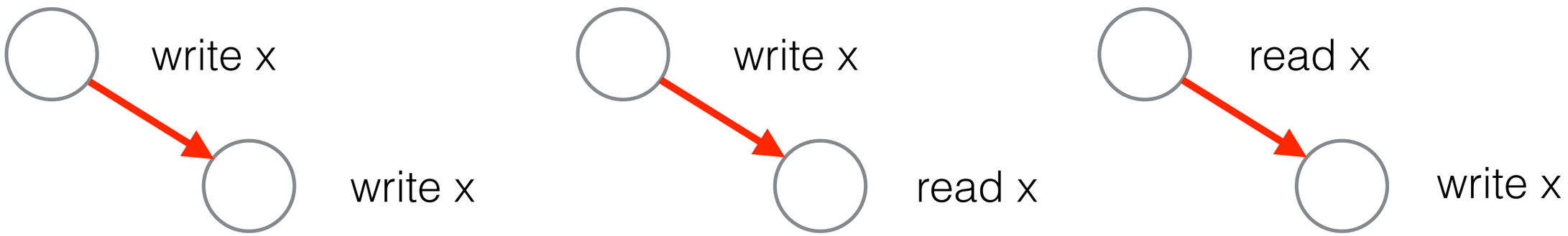

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Statistical Analysis

- Identification of failure predictors[1]
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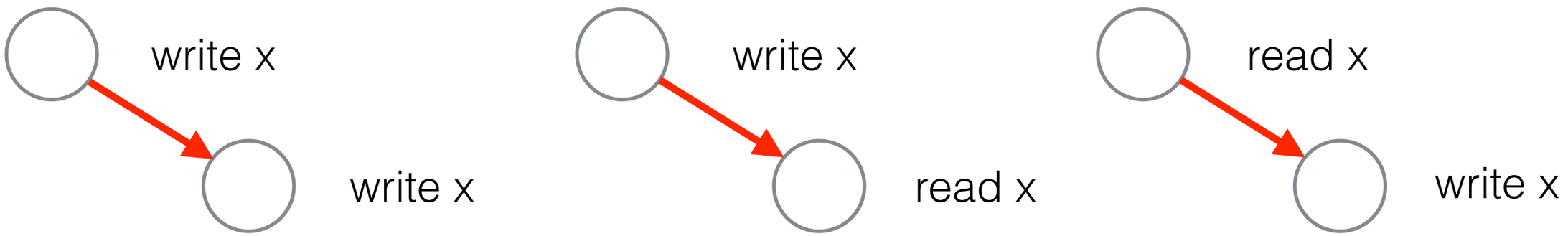

Failure predictors across multiple executions

[1] Liblit, B. et al. Scalable statistical bug isolation. PLDI 2005

Example: Statistical Analysis

```
void display_size(State* s) {
  log("Func:display_size");
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}
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void cleanup(State* s) {
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Success

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                                delete s;
                              }
```

Success

```
void display_size(State* s) {
  log("Func:display_size");
  log("State: %u", s->size);
}
                              void cleanup(State* s) {
                                log("Func:cleanup");
                                if(verbose)
                                  log("Cleaning up %p", s);
                                delete s;
                              }
```

Success

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  delete s;
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                              }
```

Failure

Example: Statistical Analysis

```
void display_size(State* s) {
  log(“Func:display_size”);
  log(“State: %u”, s->size);
}
                              void cleanup(State* s) {
                                log(“Func:cleanup”);
                                if(verbose)
                                  log(“Cleaning up %p”, s);
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Success

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}
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                                log(“State: %u”, s->size);
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Failure

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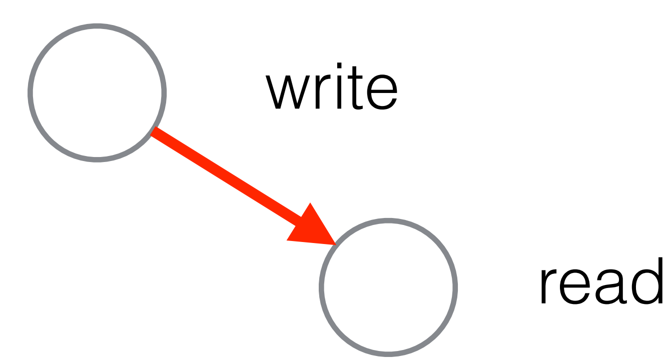
                                log(“State: %u”, s->size);
                              }
```

Failure



Example: Statistical Analysis

```
void display_size(State* s) {
  log("Func:display_size");
  log("State: %u", s->size);
}
                     void cleanup(State* s) {
                       log("Func:cleanup");
                       if(verbose)
                         log("Cleaning up %p", s);
                       delete s;
                     }
```

Success

```
void cleanup(State* s) {
  log("Func:cleanup");
  if(verbose)
    log("Cleaning up %p", s);
  delete s;
}
                     void display_size(State* s) {
                       log("Func:display_size");
                       log("State: %u", s->size);
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Failure

```
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  delete s;
}
                     void display_size(State* s) {
                       log("Func:display_size");
                       log("State: %u", s->size);
                     }
```
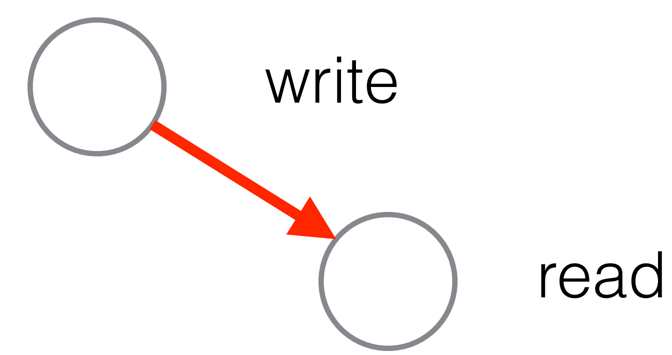
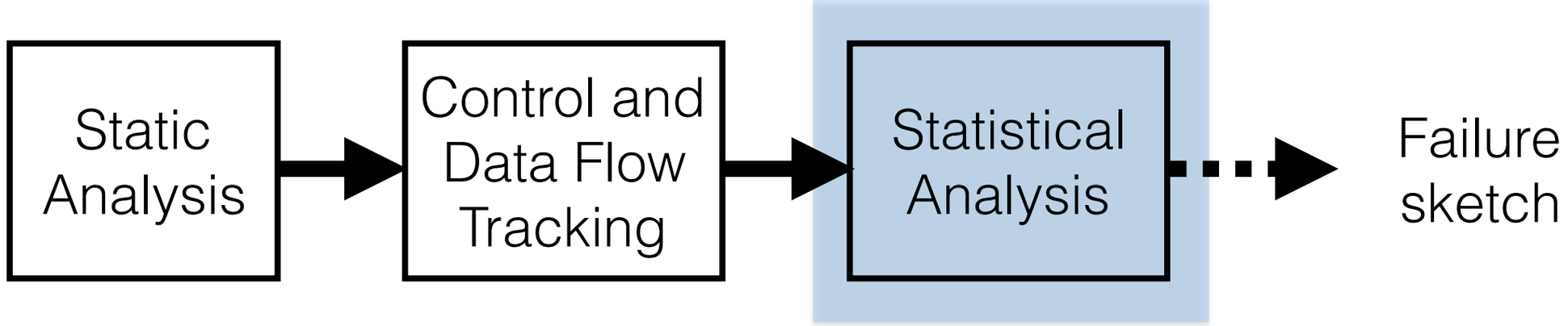

Failure



Static analysis + cooperative dynamic analysis

Outline

- Challenges
- Design



- Evaluation

Outline

- Challenges
- Design
- Evaluation
  - *Does Gist help developers do root cause diagnosis?*
  - *Is Gist efficient?*
  - *Is Gist accurate?*

Experimental Setup

- Client side executions are analyzed in the lab
- Real world server and desktop programs

Do Failure Sketches Help Developers?

- We manually analyzed the usefulness of Gist for 11 failures
- Gist-identified failure predictors point to root causes
- *Developers eliminated those root causes to fix the bugs*
- *Average number of statements to look at: 7*

Do Failure Sketches Help Developers?

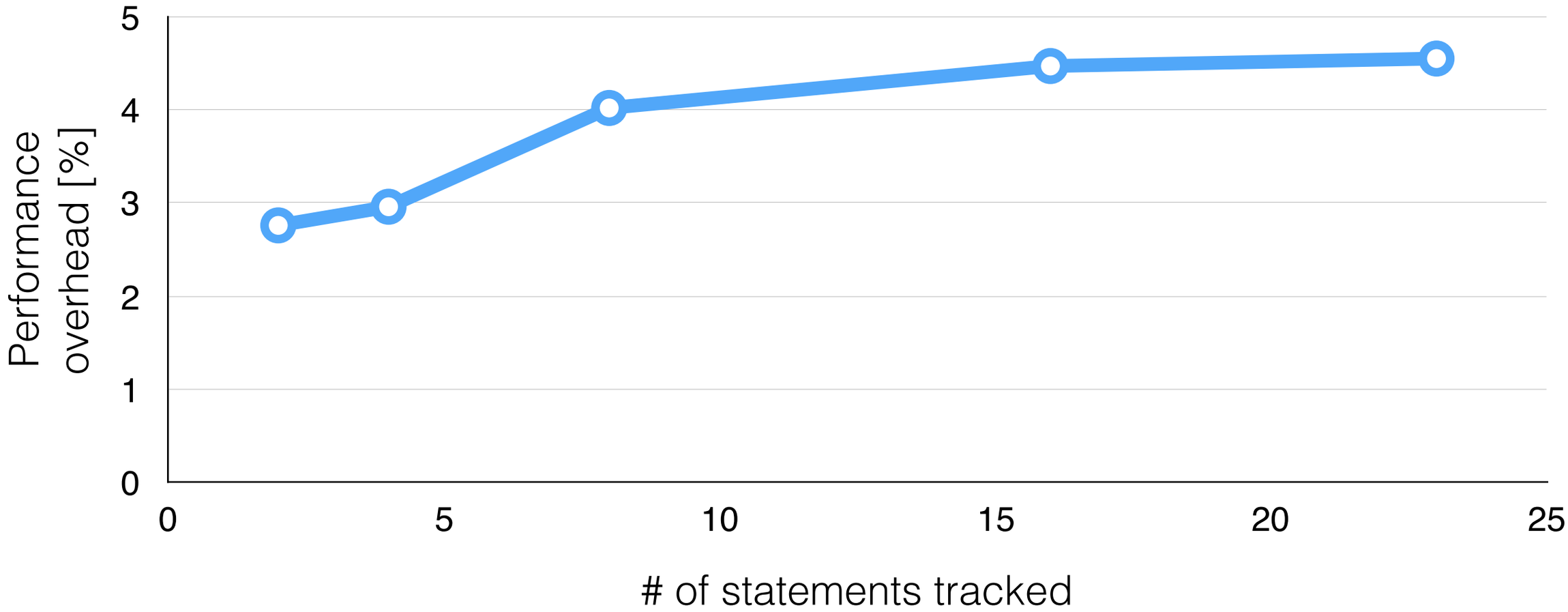
- We manually analyzed the usefulness of Gist for 11 failures

- Gist-identified failure predictors point to root causes
  - *Developers eliminated those root causes to fix the bugs*
  - *Average number of statements to look at: 7*

Gist points developers to the root causes of failures

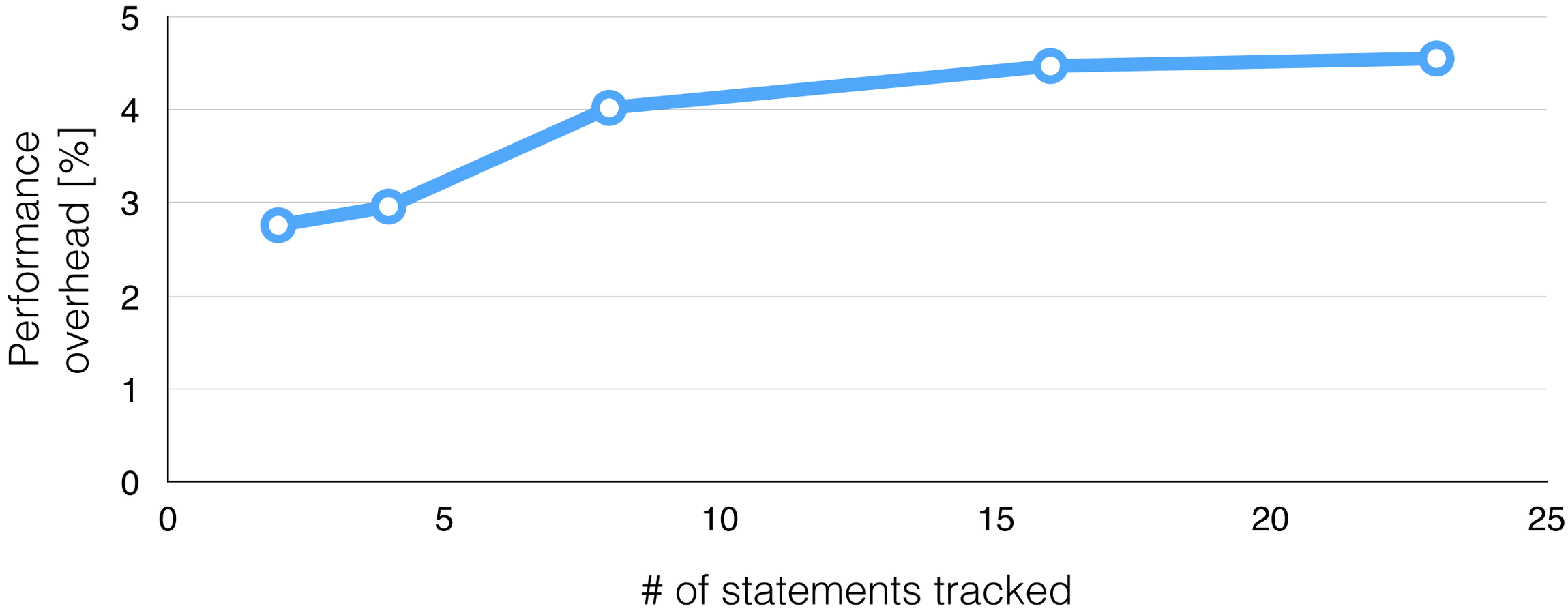
Efficiency

(Control & data flow tracking)



Efficiency

(Control & data flow tracking)



Gist has low average overhead (always below 5%)

Accuracy [%]

Apache-1

Apache-2

Apache-3

Apache-4

Cppcheck-1

Cppcheck-2

Curl

Transmission

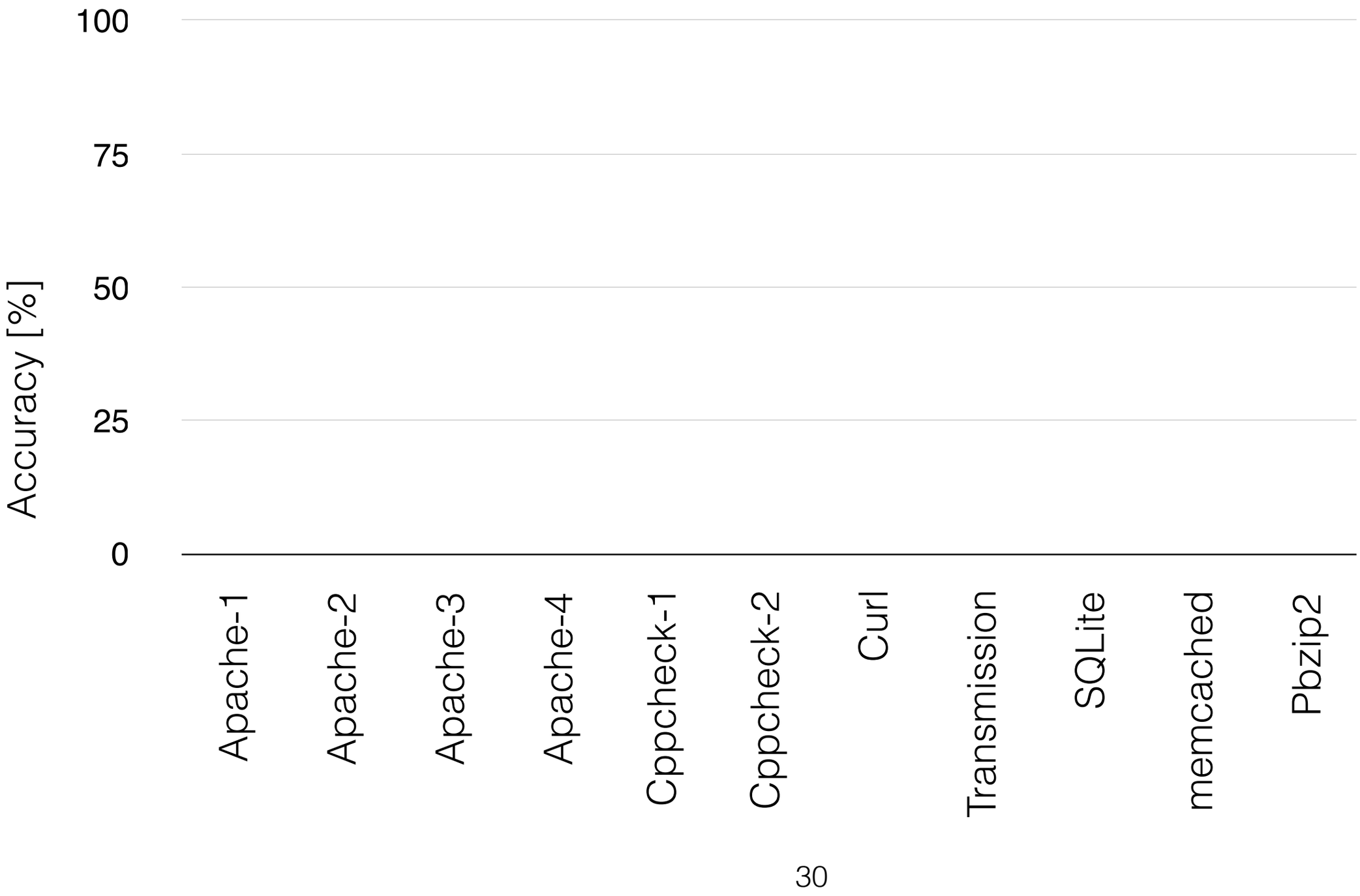
SQLite

memcached

Pbzip2

Accuracy

Accuracy


100
75
50
25
0
Accuracy [%]
Apache-1
Apache-2
Apache-3
Apache-4
Cppcheck-1
Cppcheck-2
Curl
Transmission
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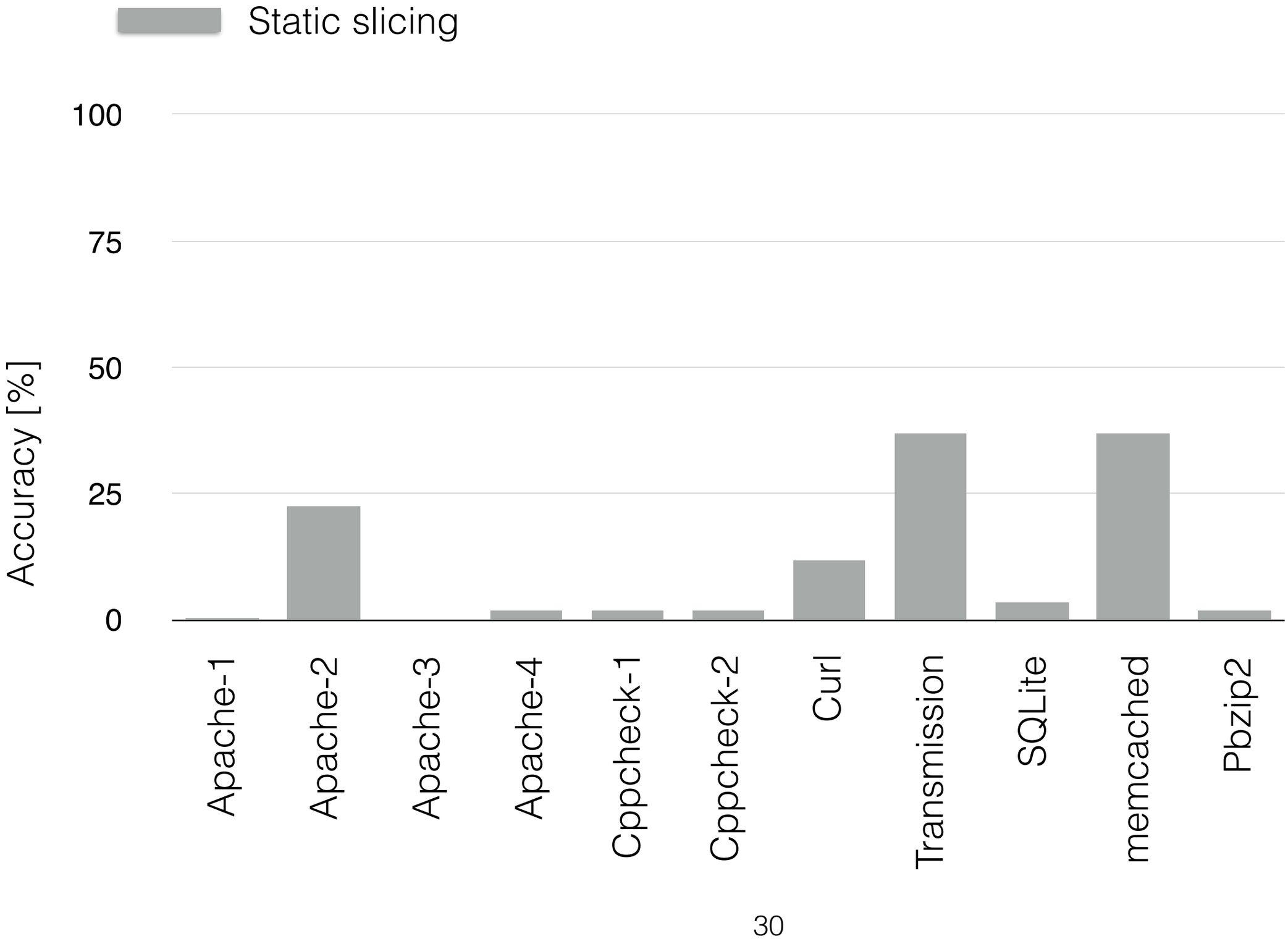
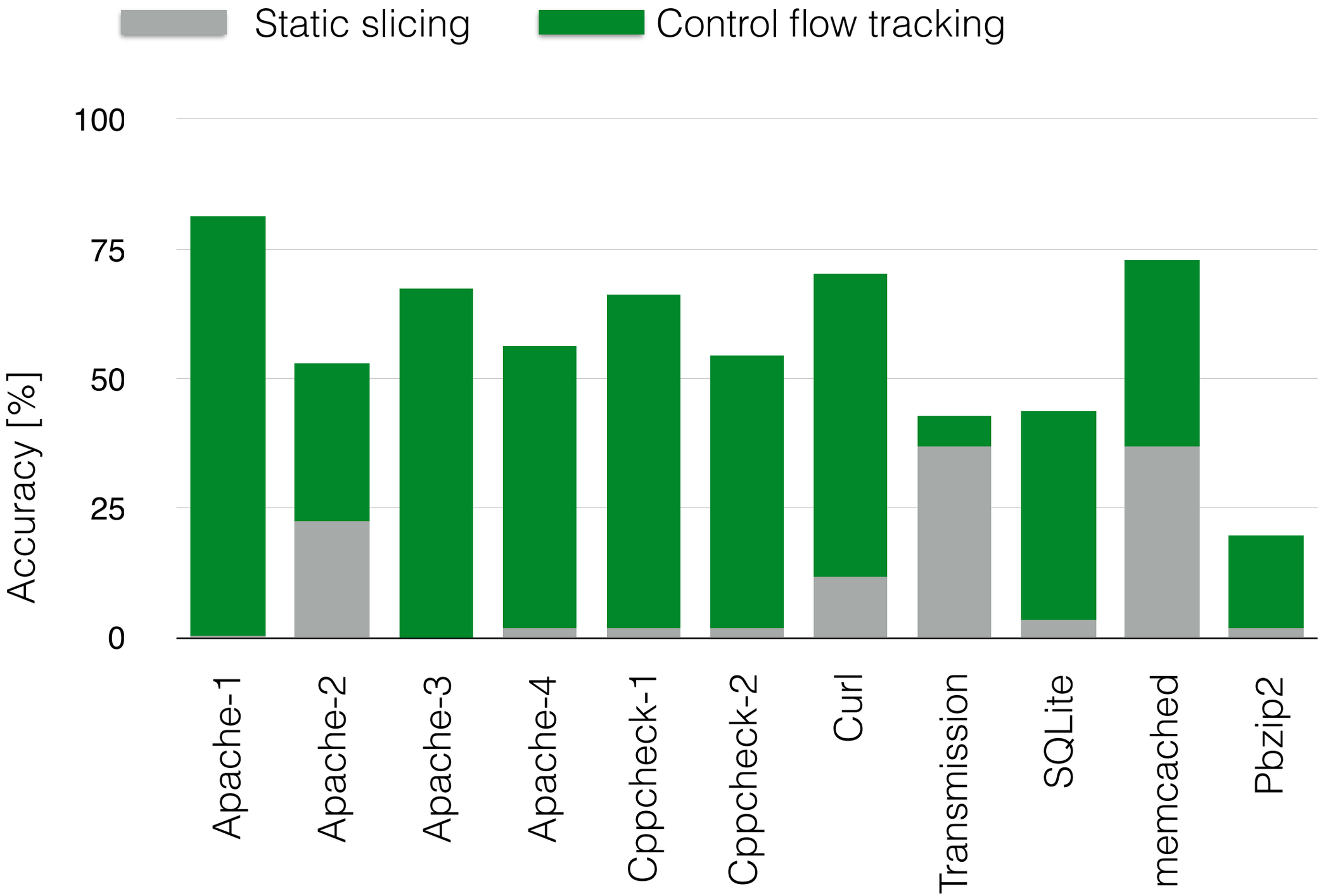
memcached
Pbzip2

Accuracy


Static slicing
100
75
50
25
0
Accuracy [%]
Apache-1
Apache-2
Apache-3
Apache-4
Cppcheck-1
Cppcheck-2
Curl
Transmission
SQLite
memcached
Pbzip2

Accuracy


Static slicing
Control flow tracking
100
75
50
25
0
Accuracy [%]
Apache-1
Apache-2
Apache-3
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Cppcheck-1
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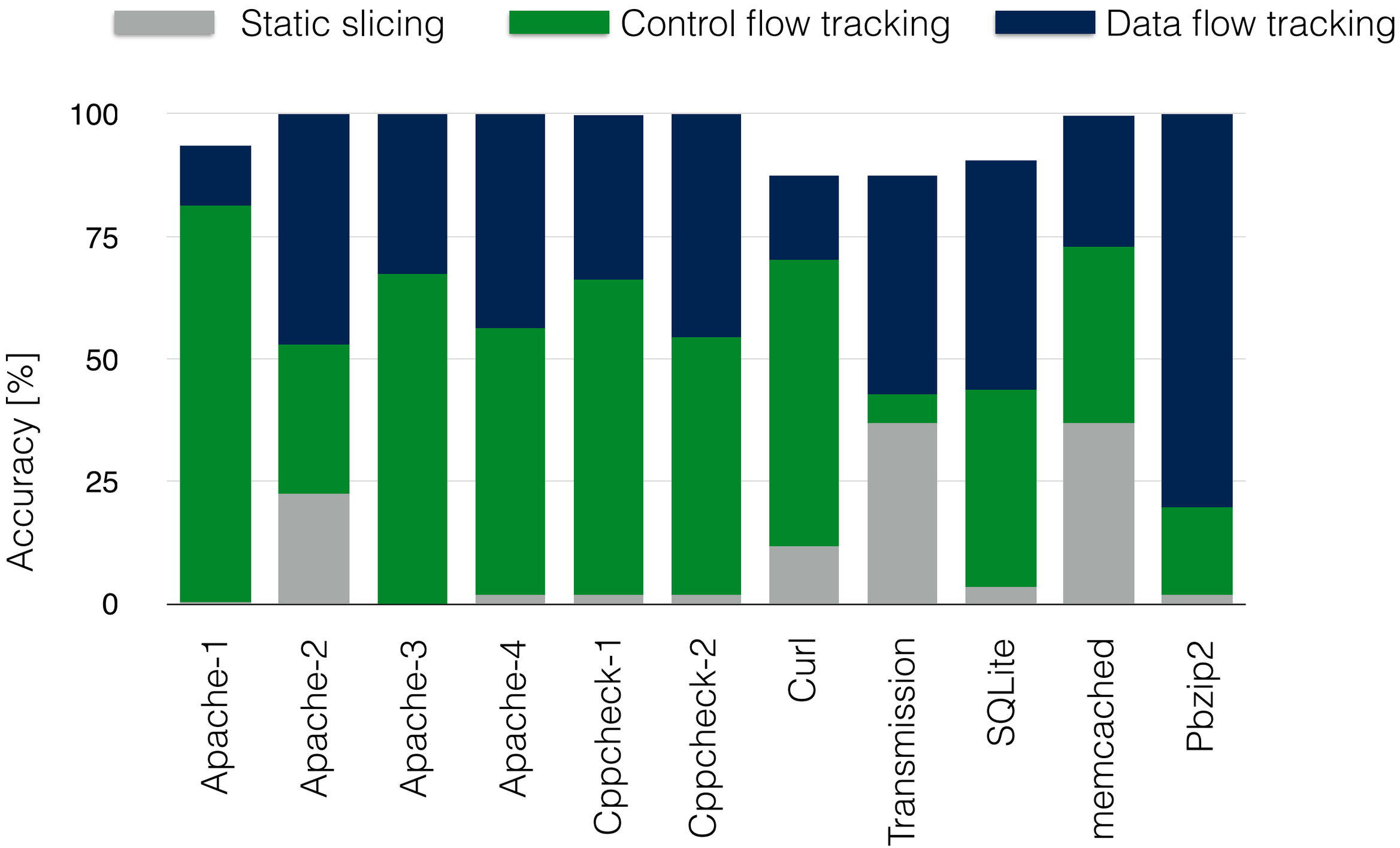
Accuracy


Static slicing
Control flow tracking
Data flow tracking
Accuracy [%]
100
75
50
25
0
Apache-1
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Apache-4
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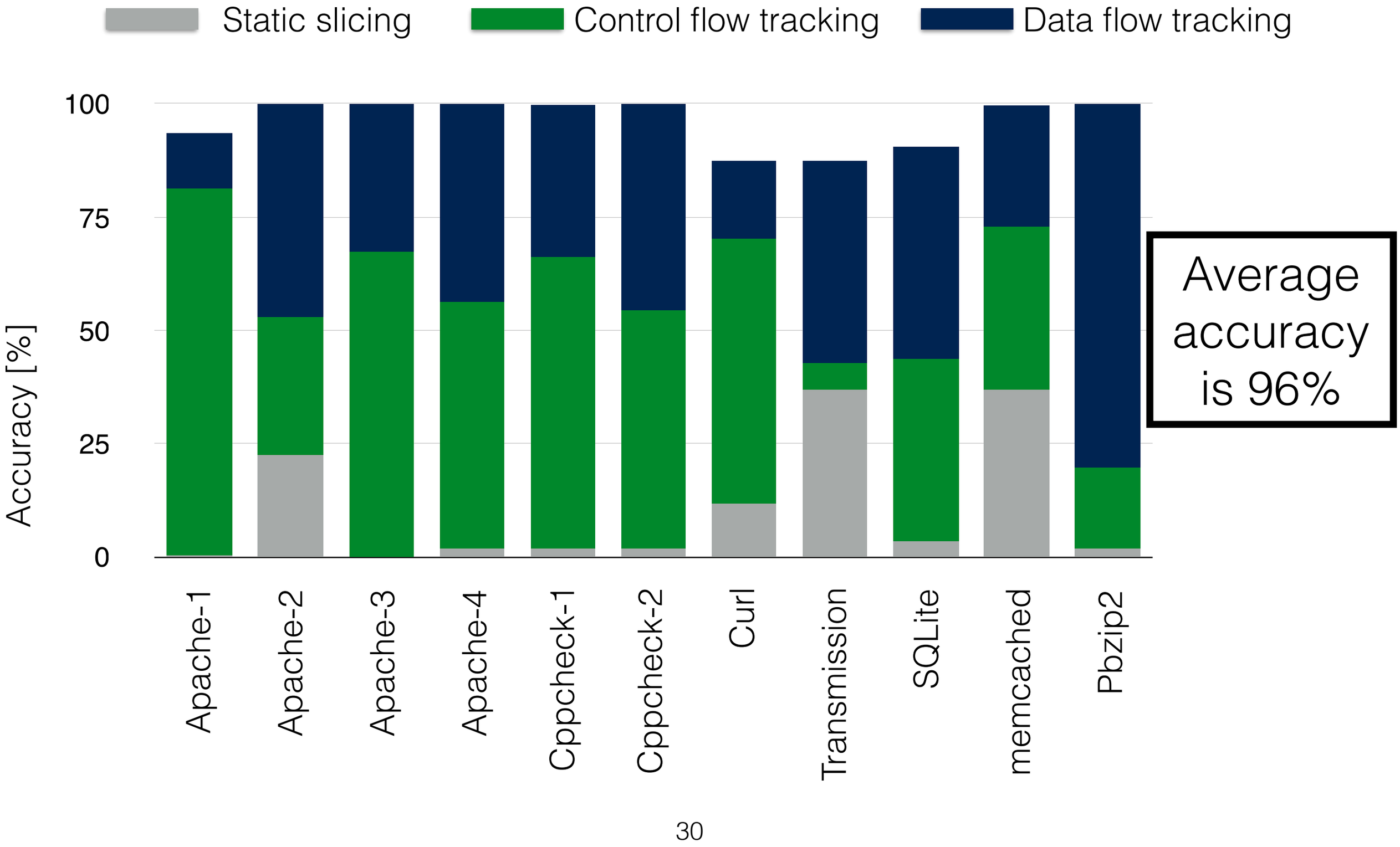
Accuracy


Static slicing
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Data flow tracking
Accuracy [%]
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50
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0
Apache-1
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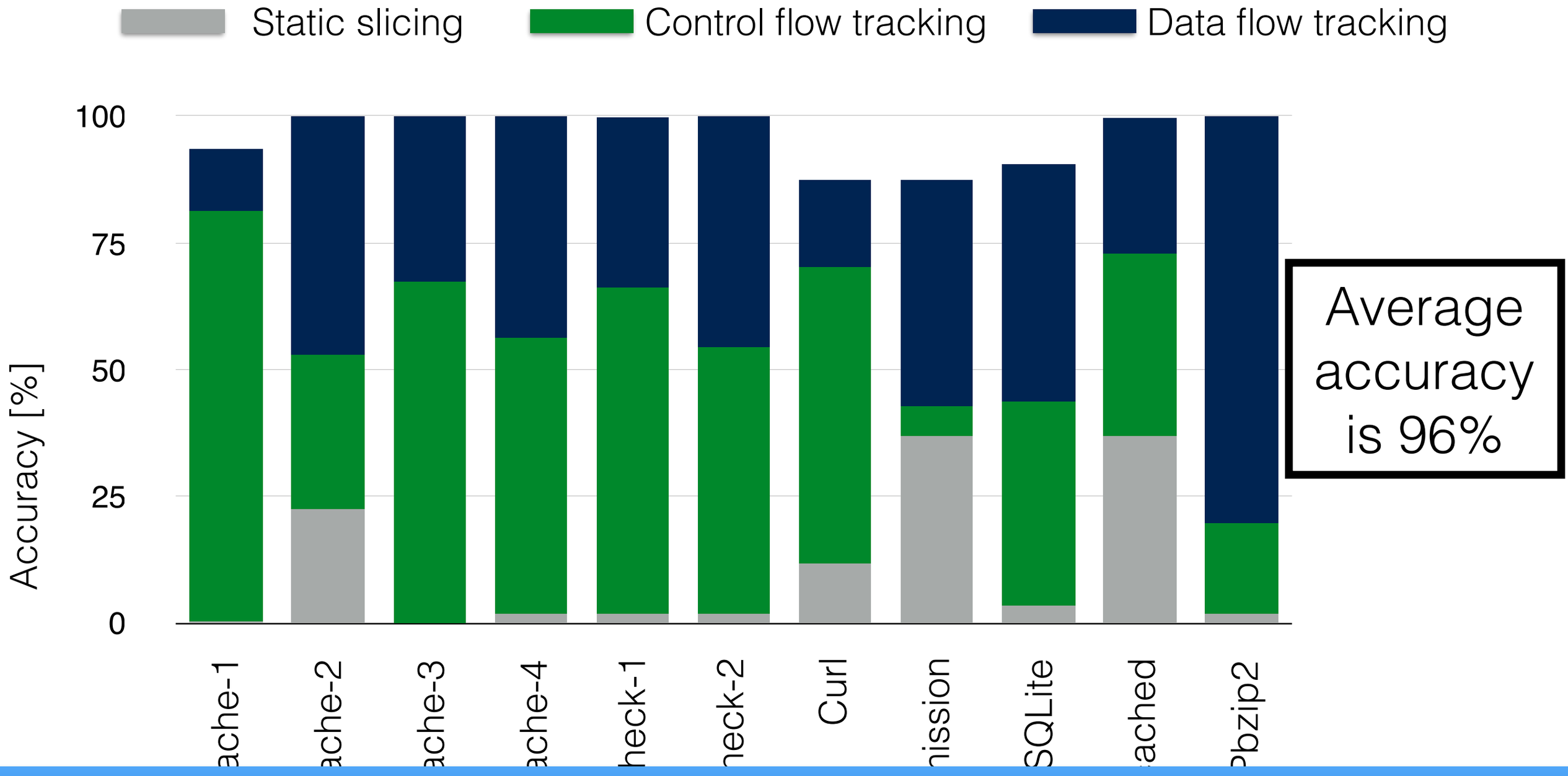
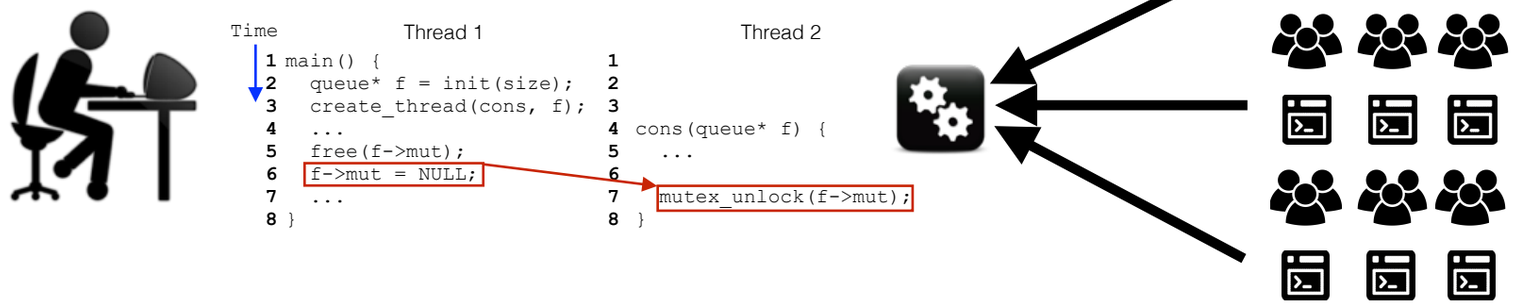
Apache-4
Cppcheck-1
Cppcheck-2
Curl
Transmission
SQLite
memcached
Pbzip2
Average accuracy is 96%

Accuracy



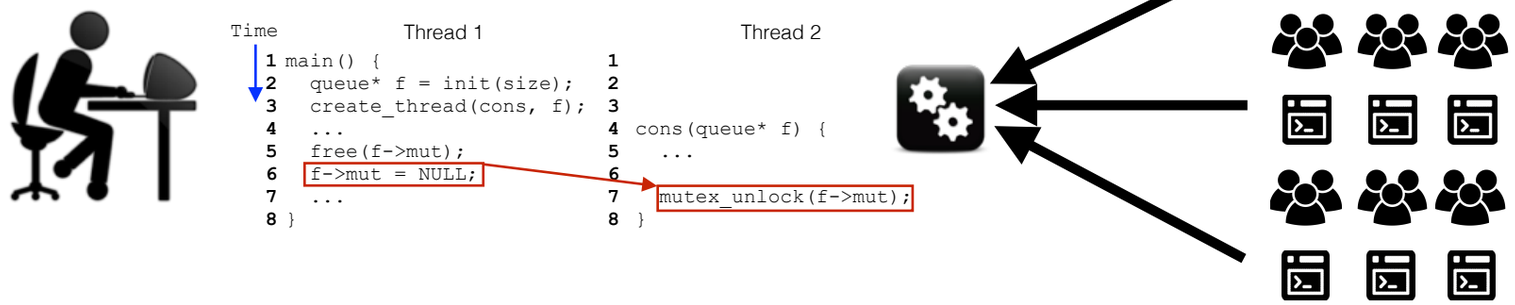
Each technique is needed for accuracy

Conclusion



- Failure sketching
  - *Combination of static and dynamic program analysis*
  - *Failure sketches are summaries explaining failure root causes*
  - *Accurate, efficient, improves developer productivity*

Conclusion



- Failure sketching
  - *Combination of static and dynamic program analysis*
  - *Failure sketches are summaries explaining failure root causes*
  - *Accurate, efficient, improves developer productivity*

http://dslab.epfl.ch/proj/gist

Baris Ben Cristiano Gilles George