# Fast Graph Simplification for Path-Sensitive Typestate Analysis through Tempo-Spatial Multi-Point Slicing

FSE 2024

**Xiao Cheng**, Jiawei Ren, Yulei Sui

xiao.cheng@unsw.edu.au

Computer Science and Engineering
UNSW Sydney

July 23, 2024

# Contributions

- A fast graph simplification approach for path-sensitive typestate analysis (PSTA) utilizing tempo-spatial multi-point slicing.

# Contributions

- A fast graph simplification approach for path-sensitive typestate analysis (PSTA) utilizing tempo-spatial multi-point slicing.
- A formulation of the multi-point markers extraction as a graph reachability problem based on the IFDS framework.

# Contributions

- A fast graph simplification approach for path-sensitive typestate analysis (PSTA) utilizing tempo-spatial multi-point slicing.
- A formulation of the multi-point markers extraction as a graph reachability problem based on the IFDS framework.
- A new multi-point slicing technique that efficiently captures the temporal and spatial correlations necessary for a path-sensitive typestate analysis.

# Contributions

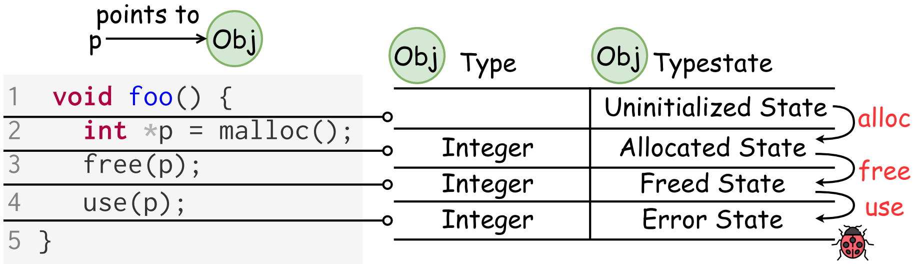
- A fast graph simplification approach for path-sensitive typestate analysis (PSTA) utilizing tempo-spatial multi-point slicing.
- A formulation of the multi-point markers extraction as a graph reachability problem based on the IFDS framework.
- A new multi-point slicing technique that efficiently captures the temporal and spatial correlations necessary for a path-sensitive typestate analysis.
- An implementation and an evaluation to demonstrate the effectiveness and efficiency of graph simplification for PSTA.

# Typestate

- Typestate (state of type) represents different **states of a given object type**, which expands the scope of standard **immutable types** to accommodate potential **object typestate changes**.

# Typestate

- Typestate (state of type) represents different **states of a given object type**, which expands the scope of standard **immutable types** to accommodate potential **object typestate changes**.




A Use-After-Free (UAF) Bug

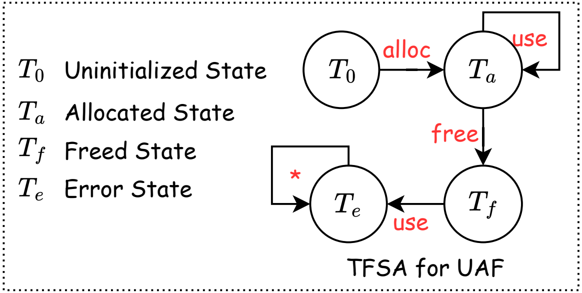
Type vs. Typestate

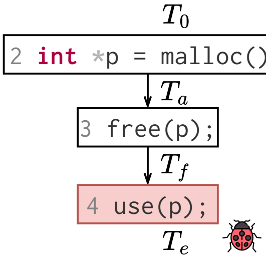
# Typestate Analysis

- Typestate analysis determines whether **a sequence of program operations**, e.g., an API calling chain, performed upon an instance of a given type violates safety specifications established by a **finite state automaton (TFSA)**.

# Typestate Analysis

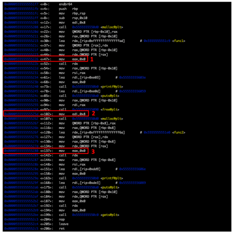
- Typestate analysis determines whether **a sequence of program operations**, e.g., an API calling chain, performed upon an instance of a given type violates safety specifications established by a **finite state automaton (TFSA)**.



# Typestate Analysis

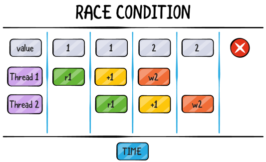
Incorrect file library usage



Use-after-frees

Memory leaks

Access control



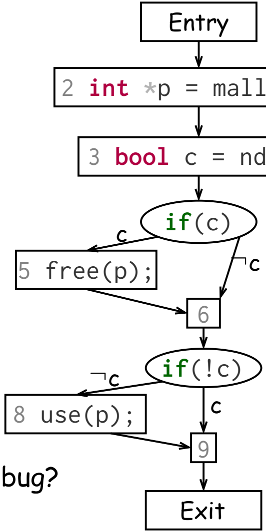

Concurrency bug

API misuse

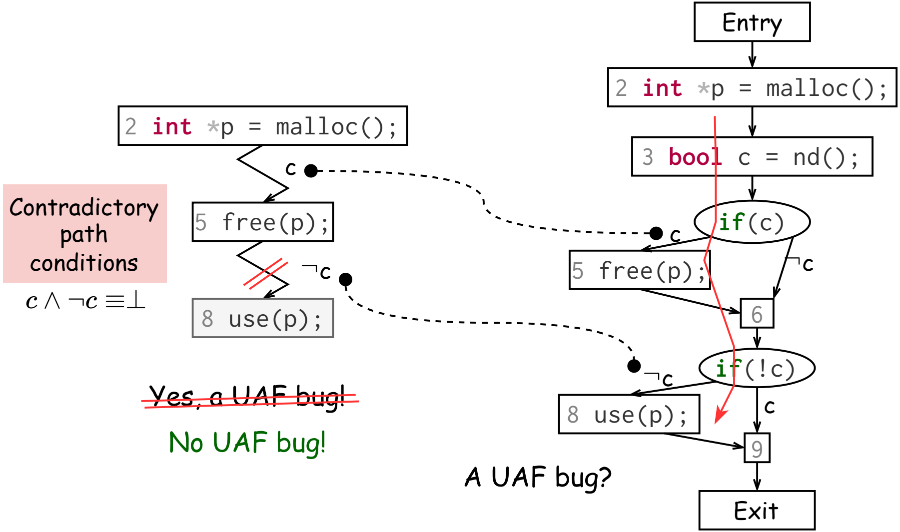
- Path-sensitive typestate analysis (PSTA) enhances the precision of its path-insensitive counterpart by **capturing correlations between different branches** and eliminating false alerts stemming from infeasible paths.

- Path-sensitive typestate analysis (PSTA) enhances the precision of its path-insensitive counterpart by **capturing correlations between different branches** and eliminating false alerts stemming from infeasible paths.
- In PSTA, the maintenance of an **(abstract) execution state** that captures **program variable values and path constraints** is crucial, and it evaluates the feasibility of paths when encountering branching points.

```
void foo() {
  int *p = malloc();
  bool c = nd();
  if(c) {
     free(p);
  }
  if(!c) {
     use(p);
  }
}
```



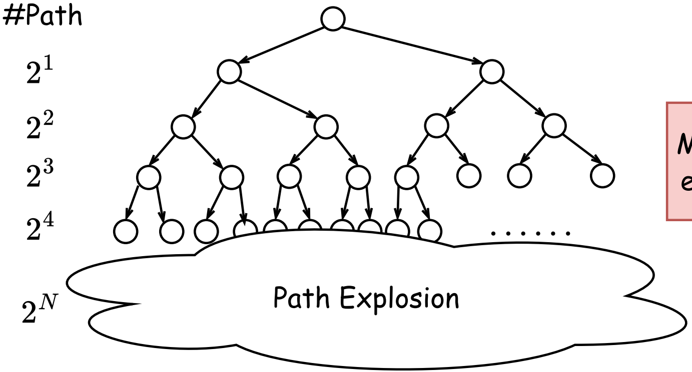

A UAF bug?



2 int *p = malloc();
c
5 free(p);
¬c
8 use(p);
Contradictory path conditions
$c \wedge \neg c \equiv \perp$
~~Yes, a UAF bug!~~
No UAF bug!
Entry
2 int *p = malloc();
3 bool c = nd();
if(c)
c
5 free(p);
¬c
6
if(!c)
¬c
8 use(p);
c
9
Exit
A UAF bug?

- Path sensitivity: analyzing each path individually?

- Path sensitivity: analyzing each path individually?
- With each if branch, the possible paths the program can take might **double**. This means the complexity of the program grows **exponentially** as it gets longer.




MOP is too expensive!

- ESP is a representative PSTA working in polynomial time. At a control-flow joint point, ESP merges execution states with identical typestates, yielding a single symbolic state and thus achieving a **maximal-fixed-point (MFP)** solution with **program paths sensitive to typestate preserved**.

[1] Manuvir Das, Sorin Lerner, and Mark Seigle. 2002. ESP: path-sensitive program verification in polynomial time. SIGPLAN Not. 37, 5 (May 2002), 57–68. https://doi.org/10.1145/543552.512538

Symbolic State:

$\langle$ Typestate, Execution state $\rangle$

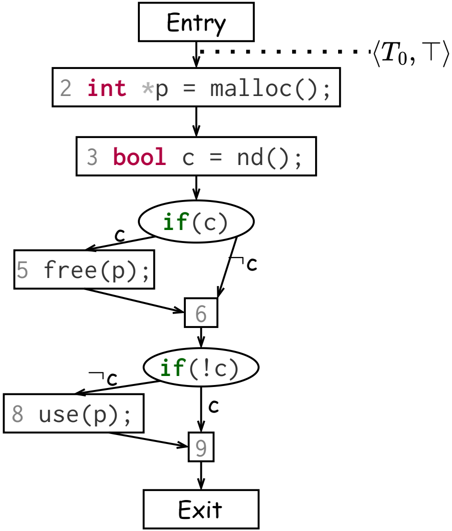
Execution State:

$\top$ :All behaviors

$\perp$ :No behaviors (infeasible)

$c$ :feasible when c is satisfied

......



Symbolic State:

⟨ Typestate, Execution state ⟩

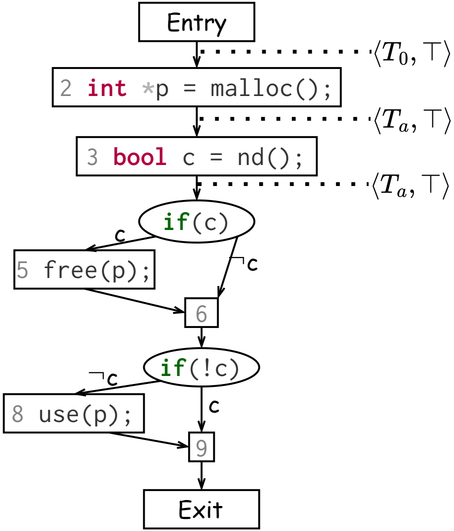
Execution State:

$\top$ :All behaviors

$\bot$ :No behaviors (infeasible)

$c$ :feasible when c is satisfied

......



Symbolic State:

⟨ Typestate, Execution state ⟩

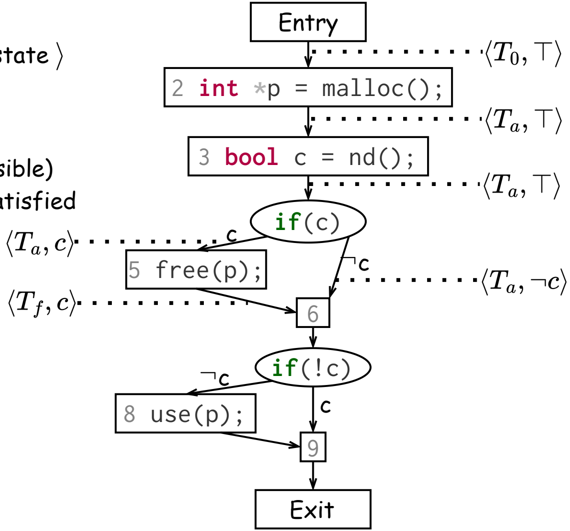
Execution State:

$\top$ :All behaviors

$\bot$ :No behaviors (infeasible)

$c$ :feasible when c is satisfied

......



Symbolic State:

⟨ Typestate, Execution state ⟩

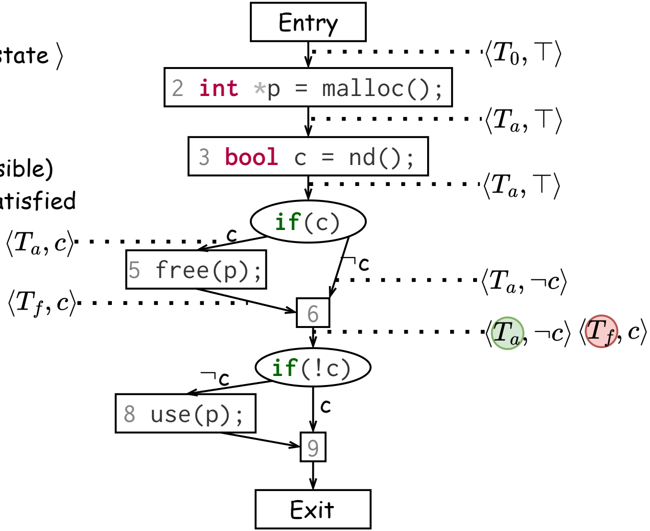
Execution State:

$\top$ :All behaviors

$\perp$ :No behaviors (infeasible)

$c$ :feasible when c is satisfied

……



Symbolic State:

⟨ Typestate, Execution state ⟩

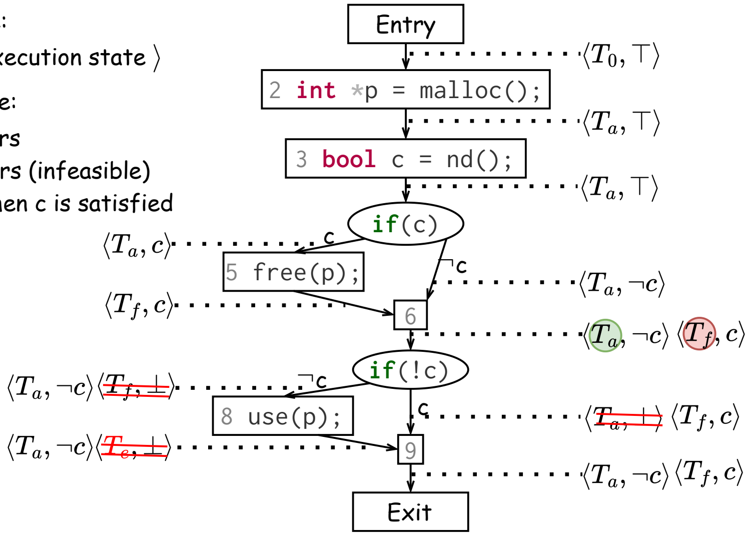
Execution State:

$\top$ :All behaviors

$\bot$ :No behaviors (infeasible)

$c$ :feasible when c is satisfied

......



- To the best of our knowledge, all previous endeavors in PSTA primarily focused on enhancing the precision of typestate transitions through **alias analysis** [1-5] or exploring new opportunities for integrating **dynamic analysis** techniques [6-8].
- We focus on a new and orthogonal perspective, **improving the efficiency of the path-sensitive algorithm**.

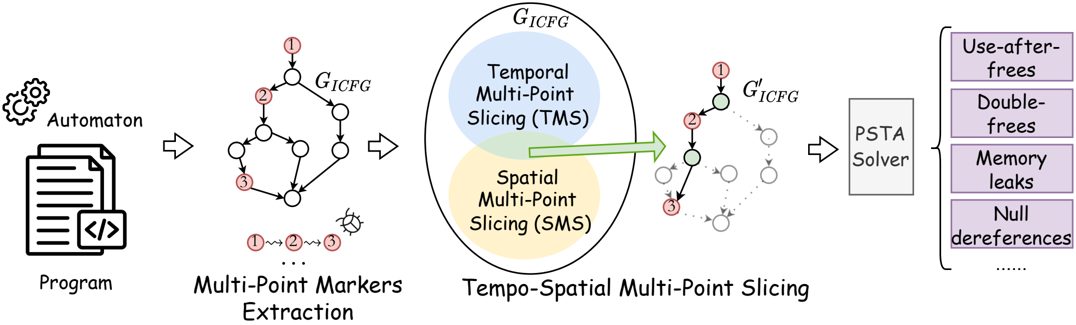
[1] Stephen J. Fink et al. Effective typestate verification in the presence of aliasing. ISSTA 2006.
[2] Mathias Jakobsen et al. Papaya: Global Typestate Analysis of Aliased Objects. PPDP 2021.
[3] Tuo Li et al. Path-Sensitive and Alias-Aware Typestate Analysis for Detecting OS Bugs. ASPLOS 2022.
[4] Zhiqiang Zuo et al. Grapple: A Graph System for Static Finite-State Property Checking of Large-Scale Systems Code. Eurosys 2019.
[5] Eric Bodden. Efficient hybrid typestate analysis by determining continuation-equivalent states. ICSE 2010.
[6] Eric Bodden et al. Partially Evaluating Finite-State Runtime Monitors Ahead of Time. TOPLAS.
[7] Matthew B. Dwyer et al. Residual Dynamic Typestate Analysis Exploiting Static Analysis: Results to Reformulate and Reduce the Cost of Dynamic Analysis. ASE 2007.
[8] Haijun Wang et al. Typestate-Guided Fuzzer for Discovering Use-after-Free Vulnerabilities. ICSE2020.

- We aim to tackle the overhead by using sparse idea that skips unnecessary control flows using def-use information.

- We aim to tackle the overhead by using sparse idea that skips unnecessary control flows using def-use information.
- Sparse analysis cannot capture **multi-point temporal use-to-use information**.

- We aim to tackle the overhead by using sparse idea that skips unnecessary control flows using def-use information.
- Sparse analysis cannot capture **multi-point temporal use-to-use information**.
- We focus on a more practical perspective–reducing the size of the control flow graph (**graph simplification**), rendering it a sparser structure with unnecessary control flows eliminated, while preserving the multi-point temporal information.

# Framework Overview



# Motivating Example

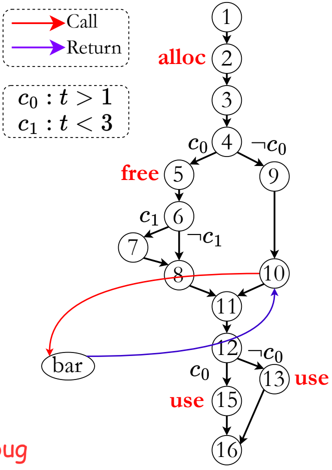
## Source Code and ICFG

```
void foo(T t) {
    int *p = malloc(10);
    int *q = malloc(10);
    ...
    if (t > 1) {
      free(p);
      if (t < 3)
        free(q);
    } else {
      free(q);
      p = bar(p);
    }
    ...
    if (t <= 1)
      printf("%d\n", *p);
    else
      log_error(*p);
}
```

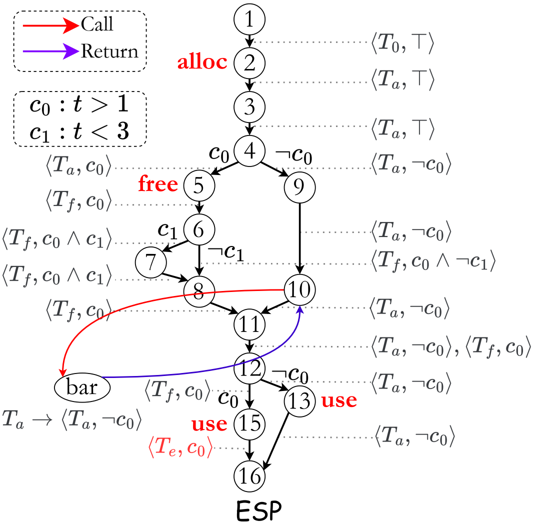
Not a UAF bug

A UAF bug

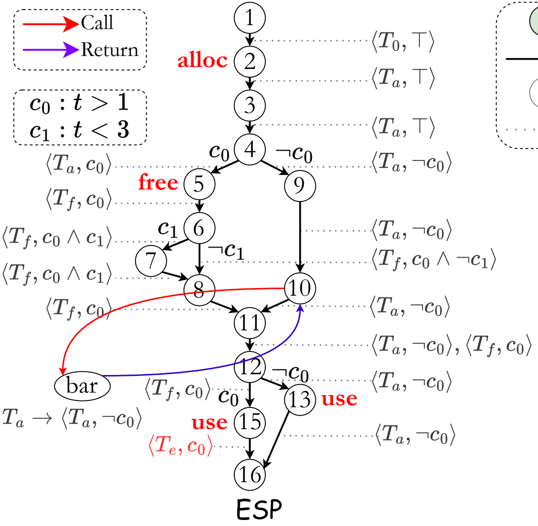
Source Code



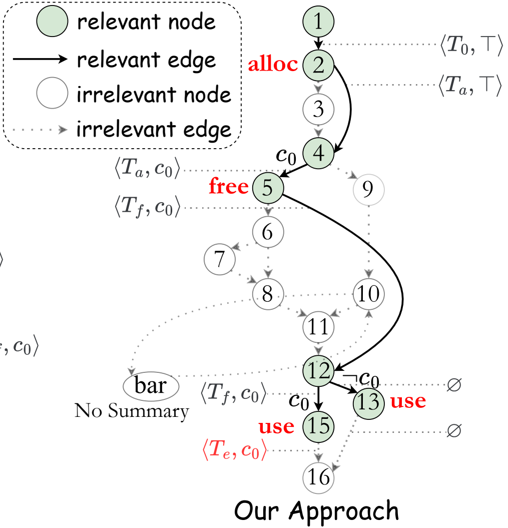

ICFG



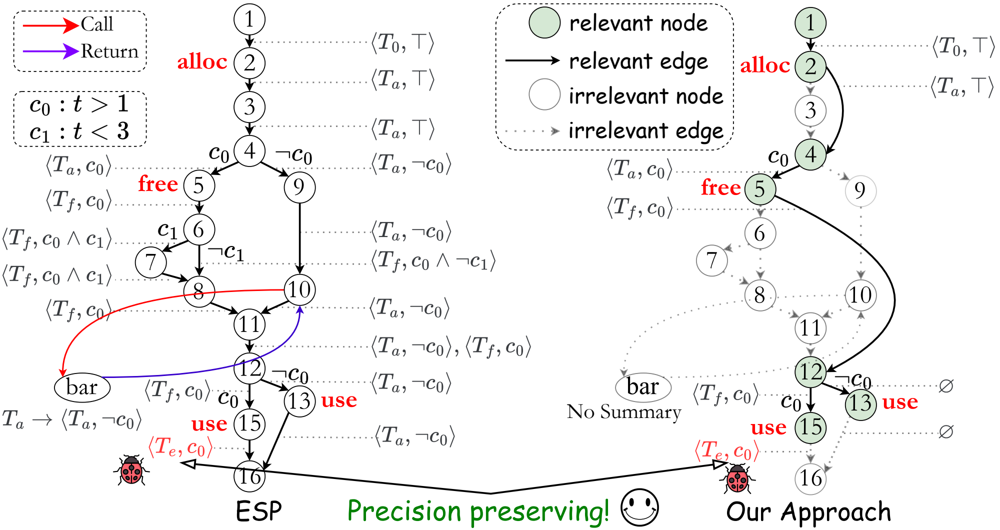
Call
Return
$c_0 : t > 1$
$c_1 : t < 3$
alloc
free
use
use
bar
$T_a \to \langle T_a, \neg c_0 \rangle$
$\langle T_0, \top \rangle$
$\langle T_a, \top \rangle$
$\langle T_a, c_0 \rangle$
$\langle T_a, \neg c_0 \rangle$
$\langle T_f, c_0 \rangle$
$\langle T_f, c_0 \wedge c_1 \rangle$
$\langle T_f, c_0 \wedge \neg c_1 \rangle$
$\langle T_a, \neg c_0 \rangle, \langle T_f, c_0 \rangle$
$\langle T_e, c_0 \rangle$
ESP



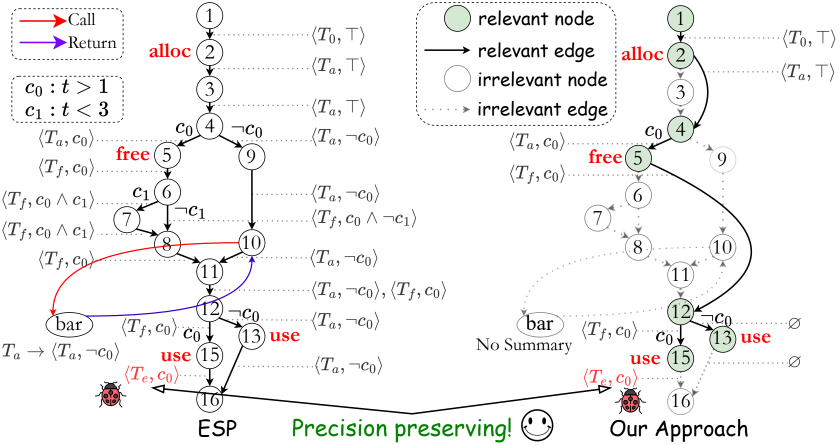
Call
Return
c0 : t > 1
c1 : t < 3
alloc
free
use
use
bar
Ta → ⟨Ta, ¬c0⟩
ESP

relevant node
relevant edge
irrelevant node
irrelevant edge
alloc
free
use
use
bar
No Summary
Our Approach



Call
Return
$c_0 : t > 1$
$c_1 : t < 3$
relevant node
relevant edge
irrelevant node
irrelevant edge
alloc
free
use
bar
$T_a \to \langle T_a, \neg c_0 \rangle$
No Summary
$\langle T_0, \top \rangle$
$\langle T_a, \top \rangle$
$\langle T_a, c_0 \rangle$
$\langle T_a, \neg c_0 \rangle$
$\langle T_f, c_0 \rangle$
$\langle T_f, c_0 \wedge c_1 \rangle$
$\langle T_f, c_0 \wedge \neg c_1 \rangle$
$\langle T_a, \neg c_0 \rangle, \langle T_f, c_0 \rangle$
$\langle T_e, c_0 \rangle$
$\emptyset$
ESP
Precision preserving!
Our Approach

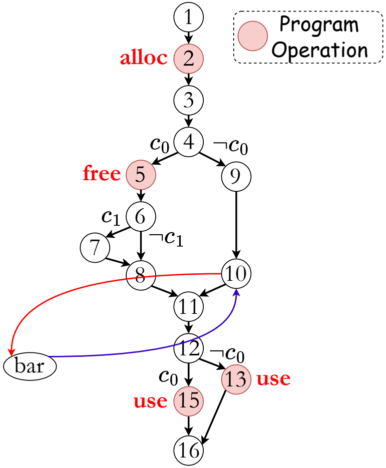



### Benefits

| |
|---|
| #Symbolic States: reduces from 18 to 6 |
| #ICFG Nodes: reduces from 16 to 7 |

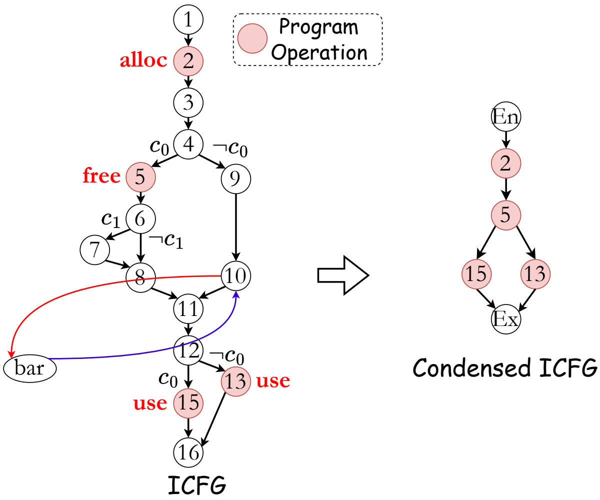
| |
|---|
| #SMT Solving: reduces from 6 to 3 |
| #Merge Points: reduces from 2 to 0 |
| #Function Summary: reduces from 1 to 0 |

# Multi-Point Markers Extraction

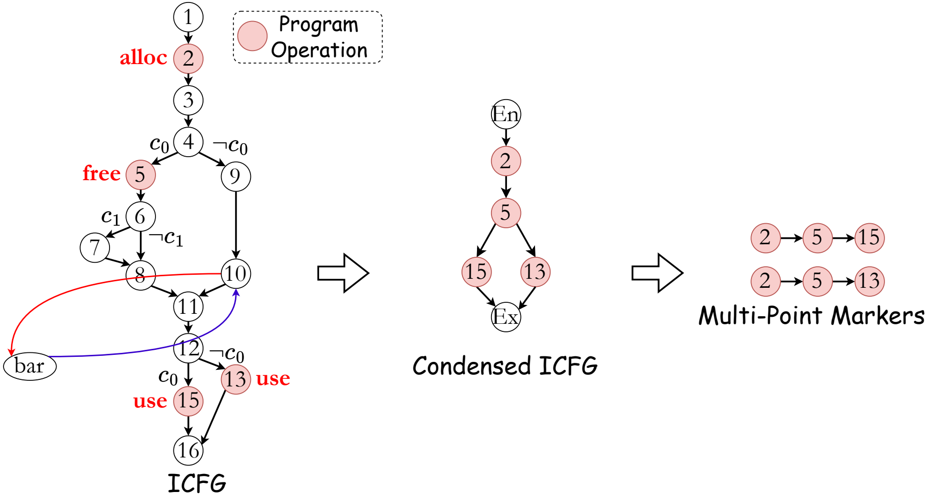



ICFG

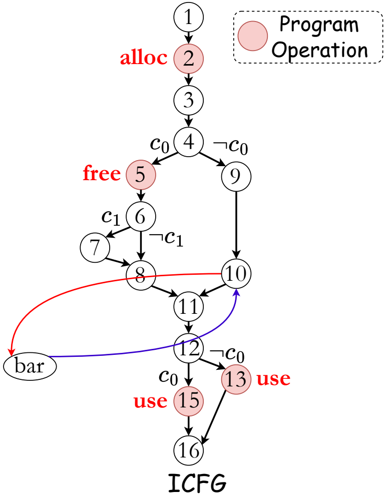
# Multi-Point Markers Extraction

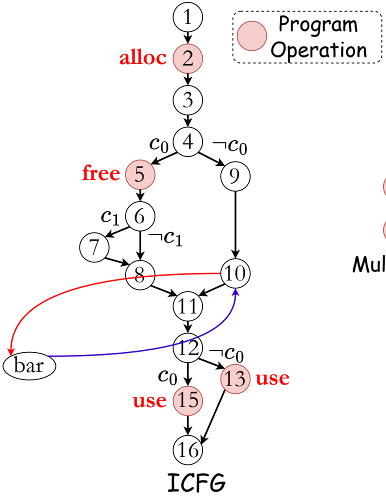


# Multi-Point Markers Extraction

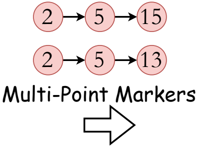


# Temporal Multi-Point Slicing (TMS)



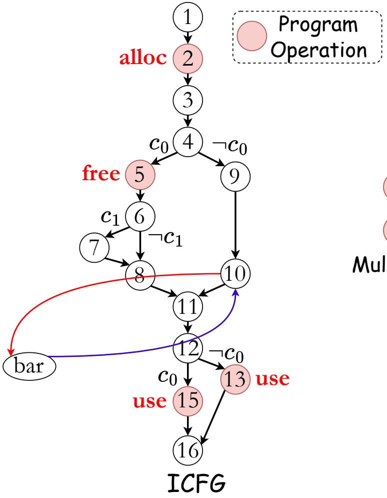


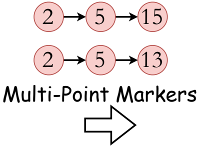
Program Operation
alloc
free
use
use
bar
$c_0$
$\neg c_0$
$c_1$
$\neg c_1$
ICFG

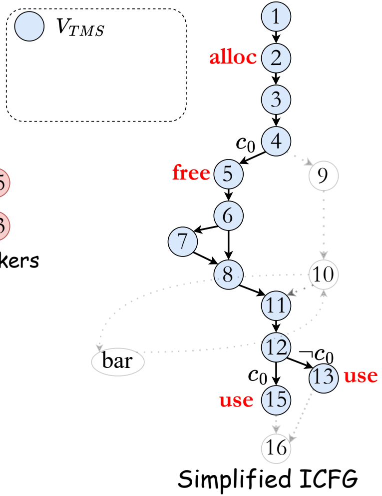



2 → 5 → 15
2 → 5 → 13
Multi-Point Markers

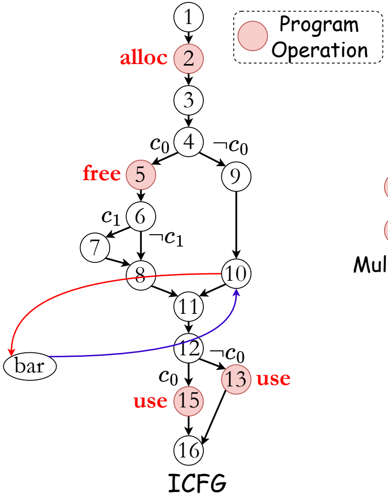
# Temporal Multi-Point Slicing (TMS)

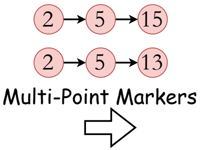


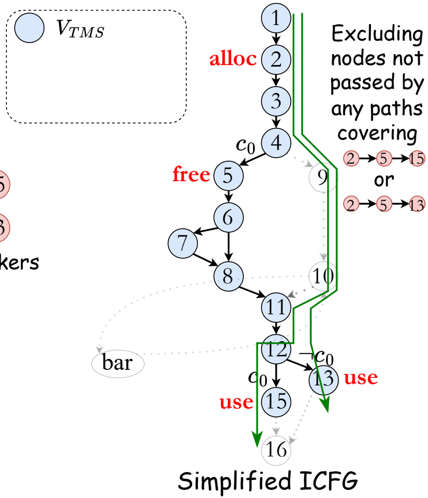



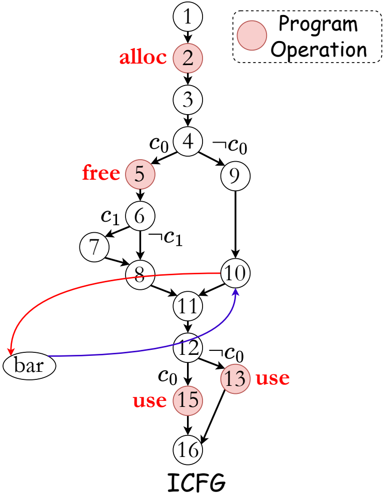
# Temporal Multi-Point Slicing (TMS)



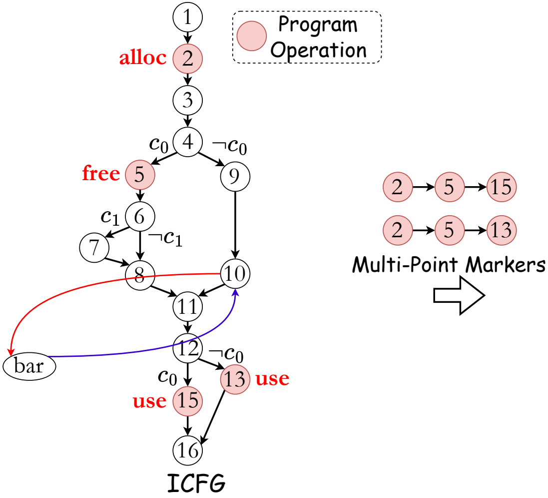



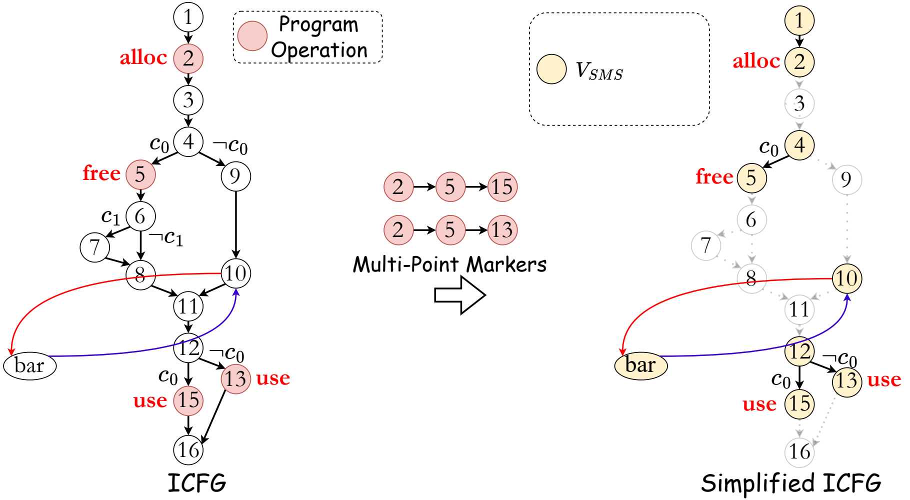
# Spatial Multi-Point Slicing (SMS)



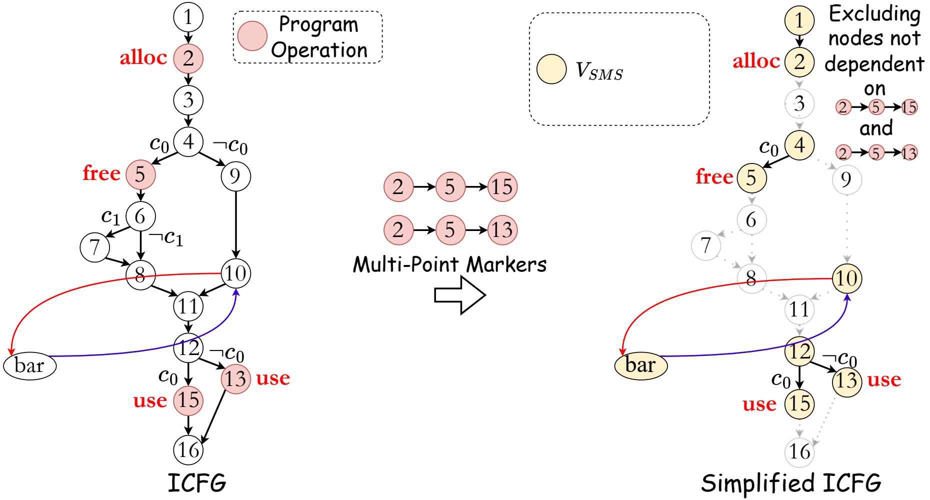
# Spatial Multi-Point Slicing (SMS)



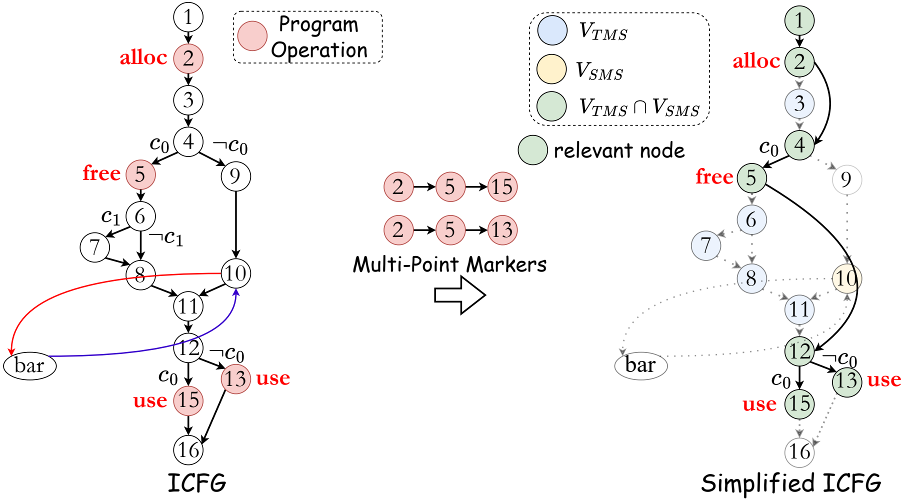
# Spatial Multi-Point Slicing (SMS)



# Spatial Multi-Point Slicing (SMS)



# Putting it All Together



# Datasets

- A micro-benchmark comprising 846 vulnerabilities from NIST, which includes memory leaks, double-frees, use-after-frees and null dereferences.
- Ten open-source C/C++ projects across a variety of different domains: `YAJL` (JSON parsing library), `gzip` (data compression program), `MP4v2` (MP4 file library), `bzip2` (data compressor), `darknet` (neural network framework), `nasm` (assembler), `tmux` (terminal multiplexer), `Teeworlds` (online multiplayer game), `NanoMQ` (MQTT broker for IoT edge platform) and `redis` (in-memory database).

Table 1: The statistics of the open-source projects. #*LOI* denotes the number of lines of LLVM instructions. #*Method* and #*Call* are the numbers of functions and method calls. #*Ptr* and #*Obj* represent the quantities of pointer variables and memory objects. $|V|$ and $|E|$ indicate the numbers of ICFG nodes and ICFG edges.

| Project | #*LOI* | #*Method* | #*Call* | #*Ptr* | #*Obj* | $\lvert V\rvert$ | $\lvert E\rvert$ |
|---:|---:|---:|---:|---:|---:|---:|---:|
| `YAJL` | 20,592 | 151 | 561 | 10,197 | 208 | 9,253 | 9,922 |
| `gzip` | 33,058 | 195 | 459 | 19,264 | 457 | 16,889 | 16,582 |
| `MP4v2` | 39,178 | 601 | 610 | 15,925 | 1,991 | 15,595 | 16,733 |
| `bzip2` | 48,181 | 116 | 250 | 28,710 | 263 | 26,220 | 25,912 |
| `darknet` | 159,205 | 985 | 9,776 | 136,510 | 2,550 | 136,094 | 147,852 |
| `nasm` | 186,935 | 652 | 7,435 | 121,836 | 3,736 | 79,330 | 81,638 |
| `tmux` | 446,626 | 1,967 | 22,369 | 187,315 | 3,879 | 162,879 | 178,924 |
| `Teeworlds` | 529,737 | 2,306 | 28,267 | 292,621 | 5,754 | 251,356 | 246,029 |
| `NanoMQ` | 788,967 | 3,235 | 47,646 | 379,798 | 30,838 | 358,312 | 443,670 |
| `redis` | 1,363,507 | 6,314 | 68,664 | 708,251 | 13,958 | 589,019 | 704,356 |
| *Total* | **3,615,986** | 165,22 | 186,037 | 1,900,427 | 63,634 | 1,644,947 | 1,871,618 |

# Research Questions

RQ1 **How do different components impact the overall performance of FGS?** We want to investigate how different slicing methods influence the effectiveness and efficiency of FGS.

RQ2 **Does FGS outperform popular static tools for bug detection?** We aim to explore whether FGS can detect more bugs with lower false alarm rates than the state-of-the-art on detecting existing bugs using the NIST benchmark with ground truths.

RQ3 **Can FGS find bugs with lower false positives efficiently in real-world projects?** We would like to examine the effectiveness (in terms of true and false positives) and efficiency (in terms of running time and memory usage) of FGS on real-world popular applications.

Table 2: Graph simplification result. $|V|$, $|V'|$, $|V_{\text{TMS}}|$ and $|V_{\text{SMS}}|$ represent the number of nodes in $G_{ICFG}$, $G'_{ICFG}$, temporal slice and spatial slice, respectively. $\#Call$ and $\#Call'$ represent the number of calling contexts of $G_{ICFG}$ and $G'_{ICFG}$. $|E|$ and $|E'|$ represent the number of edges in $G_{ICFG}$ and $G'_{ICFG}$.

| Project | $\|V\|$ | $\|V'\|$ | $\|V_{\text{TMS}}\|$ | $\|V_{\text{SMS}}\|$ | $\#Call$ | $\#Call'$ | $\|E\|$ | $\|E'\|$ |
|---|---|---|---|---|---|---|---|---|
| darknet | 136,094 | **1,791** | 5,523 | 1,928 | 9,776 | **93** | 147,852 | **1,802** |
| nasm | 79,330 | **24,946** | 38,081 | 26,604 | 7,435 | **2,317** | 81,638 | **26,034** |
| tmux | 162,879 | **2,671** | 4,273 | 3,693 | 22,369 | **205** | 178,924 | **2,810** |
| Teeworlds | 251,356 | **565** | 1,380 | 1,875 | 28,267 | **40** | 246,029 | **578** |
| NanoMQ | 358,312 | **62,543** | 102,118 | 118,663 | 47,646 | **5,801** | 443,670 | **61,696** |
| redis | 589,019 | **87,446** | 102,416 | 111,041 | 68,664 | **17,844** | 704,356 | **240,956** |

Table 3: Ablation analysis results. The "–" in the Time columns indicates a running time of more than 48 hours. FGS-TMS and FGS-SMS represent the versions of FGS using only temporal slicing and spatial slicing respectively. FGS-Base represent the version of FGS without slicing.

| Project | FGS | | FGS-TMS | | FGS-SMS | | FGS-Base | |
|---|---|---|---|---|---|---|---|---|
| | Time (secs) | Mem (MB) | Time (secs) | Mem (MB) | Time (secs) | Mem (MB) | Time (secs) | Mem (MB) |
| darknet | **750** | **2,104** | 2,542 | 2,785 | 817 | 2,784 | 81,422 | 34,244 |
| nasm | **894** | **2,482** | 1,681 | 4,132 | 940 | 3,413 | 111,750 | 31,781 |
| tmux | **1,932** | **5,251** | 5,782 | 9,064 | 3,102 | 7,223 | – | – |
| Teeworlds | **407** | **4,320** | 1,424 | 5,014 | 1,700 | 6,062 | – | – |
| NanoMQ | **8,722** | **10,176** | 25,890 | 13,600 | 29,100 | 18,424 | – | – |
| redis | **14,266** | **58,231** | 23,146 | 78,131 | 31,103 | 98,064 | – | – |

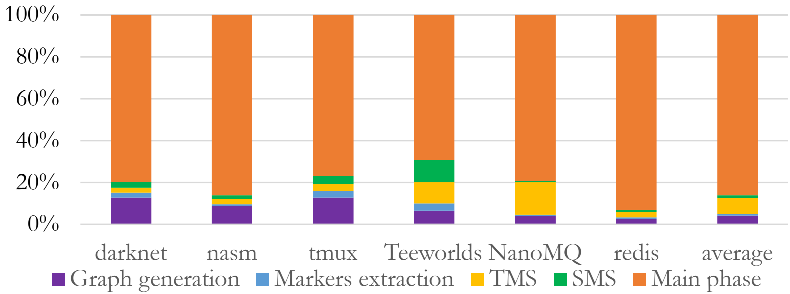



Figure 1: The proportions of different phases of FGS.

# Analysis Results using NIST Benchmark (RQ2)

Table 4: Comparing true positives (#*TP*) and false positives (#*FP*) with six tools using the NIST benchmark. The "–" means that the detection of specific vulnerabilities is not supported by the corresponding tools.

| Category | IKOS | | ClangSA | | Saber | | Cppcheck | | Infer | | Sparrow | | FGS | | Ground Truth |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | #*TP* | #*FP* | #*TP* | #*FP* | #*TP* | #*FP* | #*TP* | #*FP* | #*TP* | #*FP* | #*TP* | #*FP* | #*TP* | #*FP* | |
| Memory leak | – | – | 128 | 112 | 200 | 126 | 0 | 0 | 126 | 162 | – | – | **228** | **0** | 228 |
| Double-free | 228 | 18 | 156 | 20 | 204 | 20 | 84 | 144 | – | – | – | – | **228** | **0** | 228 |
| Use-after-free | – | – | 40 | 0 | – | – | 0 | 0 | 0 | 0 | – | – | **138** | **0** | 138 |
| Null dereference | 234 | 18 | 216 | 24 | 234 | 18 | 108 | 18 | 134 | 82 | 228 | 18 | **252** | **0** | 252 |
| *Total* | 462 | 36 | 540 | 156 | 638 | 164 | 192 | 162 | 260 | 244 | 228 | 18 | **846** | **0** | 846 |

# Bugs in Real-World Projects (RQ3)

Table 5: Comparing FGS with six open-source tools using ten popular applications. #*TP* and #*FP* are true positive and false positive, respectively. Time (secs), Mem (MB) are running time and memory costs. The "–" in the Time columns indicates a running time of more than 4h. The "–" in the Mem columns indicates a cost of more than 100 Gigabytes.

| Project | IKOS | | | | ClangSA | | | | Saber | | | | Cppcheck | | | | Infer | | | | Sparrow | | | | FGS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Report | | Time | Mem | Report | | Time | Mem | Report | | Time | Mem | Report | | Time | Mem | Report | | Time | Mem | Report | | Time | Mem | Report | | Time | Mem |
| | #*TP* | #*FP* | (secs) | (MB) | #*TP* | #*FP* | (secs) | (MB) | #*TP* | #*FP* | (secs) | (MB) | #*TP* | #*FP* | (secs) | (MB) | #*TP* | #*FP* | (secs) | (MB) | #*TP* | #*FP* | (secs) | (MB) | #*TP* | #*FP* | (secs) | (MB) |
| YAJL | 4 | 15 | 2895 | 4822 | 0 | 0 | 4 | 111 | 3 | 22 | 2 | 206 | 1 | 5 | 1 | 13 | 2 | 15 | 13 | 133 | 3 | 86 | 6 | 59 | 5 | 0 | 2 | 168 |
| gzip | 4 | 4 | 3114 | 4949 | 0 | 1 | 27 | 151 | 0 | 4 | 18 | 179 | 1 | 3 | 89 | 35 | 1 | 17 | 36 | 177 | 1 | 22 | 14 | 89 | 4 | 0 | 18 | 835 |
| MP4v2 | 2 | 1 | 3684 | 6215 | 0 | 0 | 11 | 145 | 3 | 24 | 3 | 380 | 0 | 6 | 56 | 38 | 4 | 28 | 496 | 426 | 1 | 20 | 214 | 231 | 5 | 0 | 2 | 344 |
| bzip2 | 0 | 0 | 3690 | 6809 | 0 | 6 | 16 | 181 | 0 | 2 | 18 | 179 | 0 | 0 | 3 | 17 | 0 | 37 | 53 | 271 | 0 | 0 | 77 | 148 | 1 | 0 | 9 | 280 |
| darknet | 19 | 75 | 5216 | 8622 | 11 | 39 | 75 | 301 | 20 | 300 | 245 | 1145 | 2 | 24 | 11 | 55 | 12 | 104 | 1185 | 612 | 25 | 10 | 951 | 954 | 30 | 7 | 750 | 2104 |
| nasm | 2 | 8 | 5007 | 9951 | 2 | 7 | 180 | 515 | 2 | 102 | 572 | 2258 | 0 | 1 | 1 | 76 | 1 | 16 | 621 | 919 | 2 | 9 | 942 | 1132 | 3 | 1 | 894 | 2482 |
| tmux | 4 | 29 | 11325 | 38366 | 6 | 12 | 409 | 799 | 4 | 160 | 597 | 3882 | 0 | 0 | 61 | 39 | 2 | 34 | 693 | 637 | 3 | 12 | 1036 | 1894 | 5 | 1 | 1932 | 5251 |
| Teeworlds | 8 | 8 | 13569 | 40368 | 0 | 0 | 83 | 654 | 10 | 50 | 88 | 1877 | 1 | 4 | 2 | 54 | 6 | 48 | 267 | 449 | 5 | 24 | 1593 | 2984 | 12 | 2 | 407 | 4320 |
| NanoMQ | 17 | 29 | 9344 | 63068 | 0 | 0 | 52 | 555 | 10 | 426 | 1421 | 7613 | 5 | 54 | 111 | 40 | 18 | 74 | 910 | 555 | 6 | 354 | 1642 | 3125 | 31 | 11 | 8722 | 10176 |
| redis | – | – | – | – | 0 | 23 | 502 | 1499 | 7 | 141 | 8775 | 16752 | 0 | 1 | 637 | 123 | 1 | 51 | 2699 | 1655 | 1 | 149 | 2654 | 9211 | 9 | 1 | 14266 | 58231 |
| Total | 60 | 169 | 57844 | 183170 | 19 | 88 | 1359 | 4911 | 59 | 1231 | 11739 | 34471 | 10 | 98 | 972 | 490 | 47 | 424 | 6973 | 5834 | 47 | 686 | 9129 | 19827 | **105** | **23** | 27002 | 84191 |

# Thank You!