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On Decomposing Complex Test Cases for Efficient Post-silicon Validation

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Motivation

Scenario 1 (industry-inspired)**:**

- A chip manufacturing company gives an extensively tested chip to an OEM for early evaluation and integration
- A system prototype of OEM which incorporates the chip into it crashes after running for (say) 10 minutes
- The application that triggered the crash cannot be shared with the chip manufacturers due to IP restrictions
- The chip validation team struggles to reproduce the error because their in-house verification and validation techniques and strategies failed to uncover the bug earlier
- Significant time is lost to reproducing the error

Motivation

Scenario 2 (industry-inspired)**:**

- Initial silicon samples are exercised on validation boards in-house
- A server powered with these initial silicon sample crashes after 5 days of operation
- Validation team struggles to reproduce the error because
  - the entire software stack needs to be analyzed
  - bug reproduction takes very long time

Wish-list

- Bug Reproduction

Wish-list

- Bug Reproduction
  - Deterministic

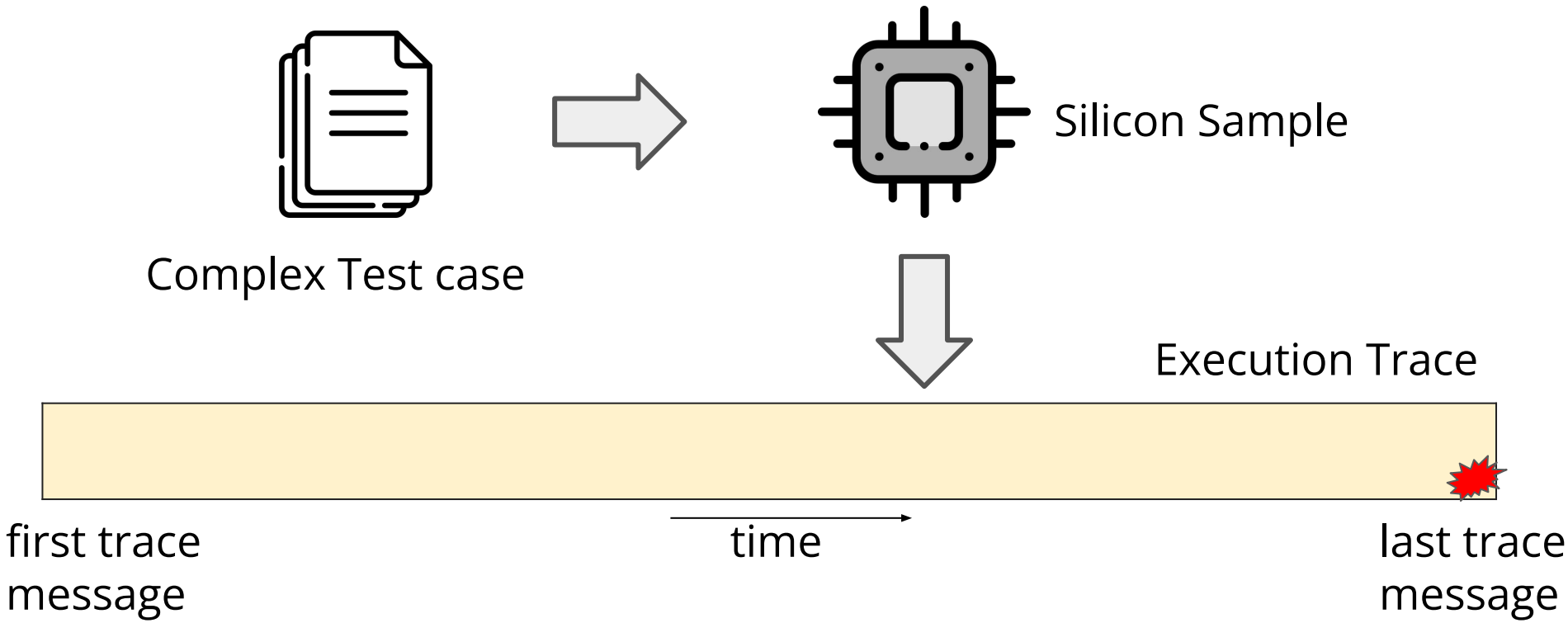
Wish-list

- Bug Reproduction
  - Deterministic
  - Privacy-aware

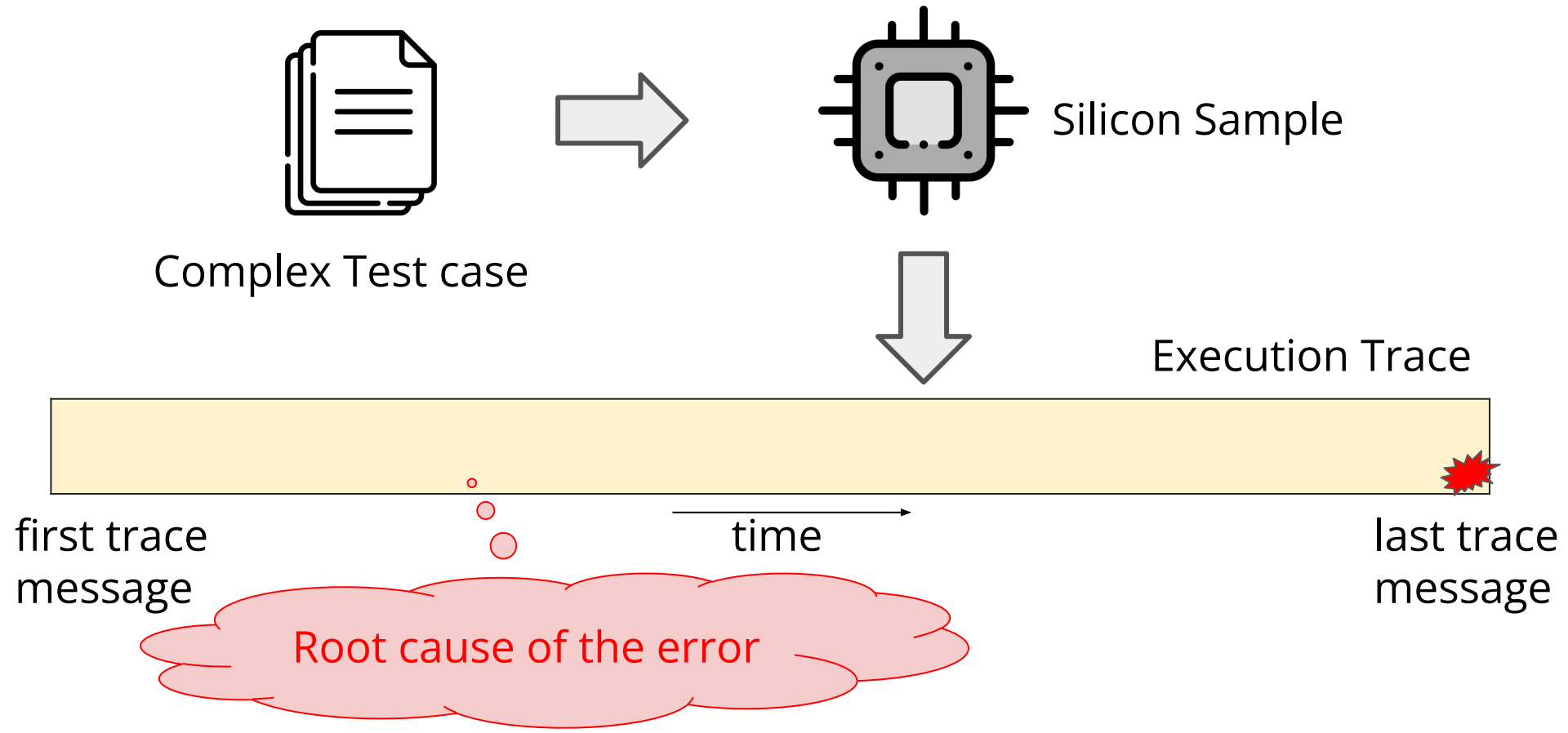
Wish-list

- Bug Reproduction
  - Deterministic
  - Privacy-aware
  - Fast

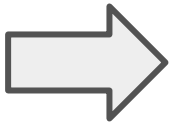
Solution Outline

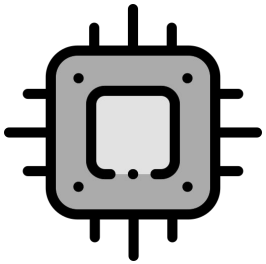


Solution Outline



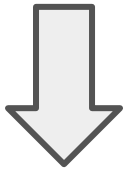
Solution Outline





Silicon Sample

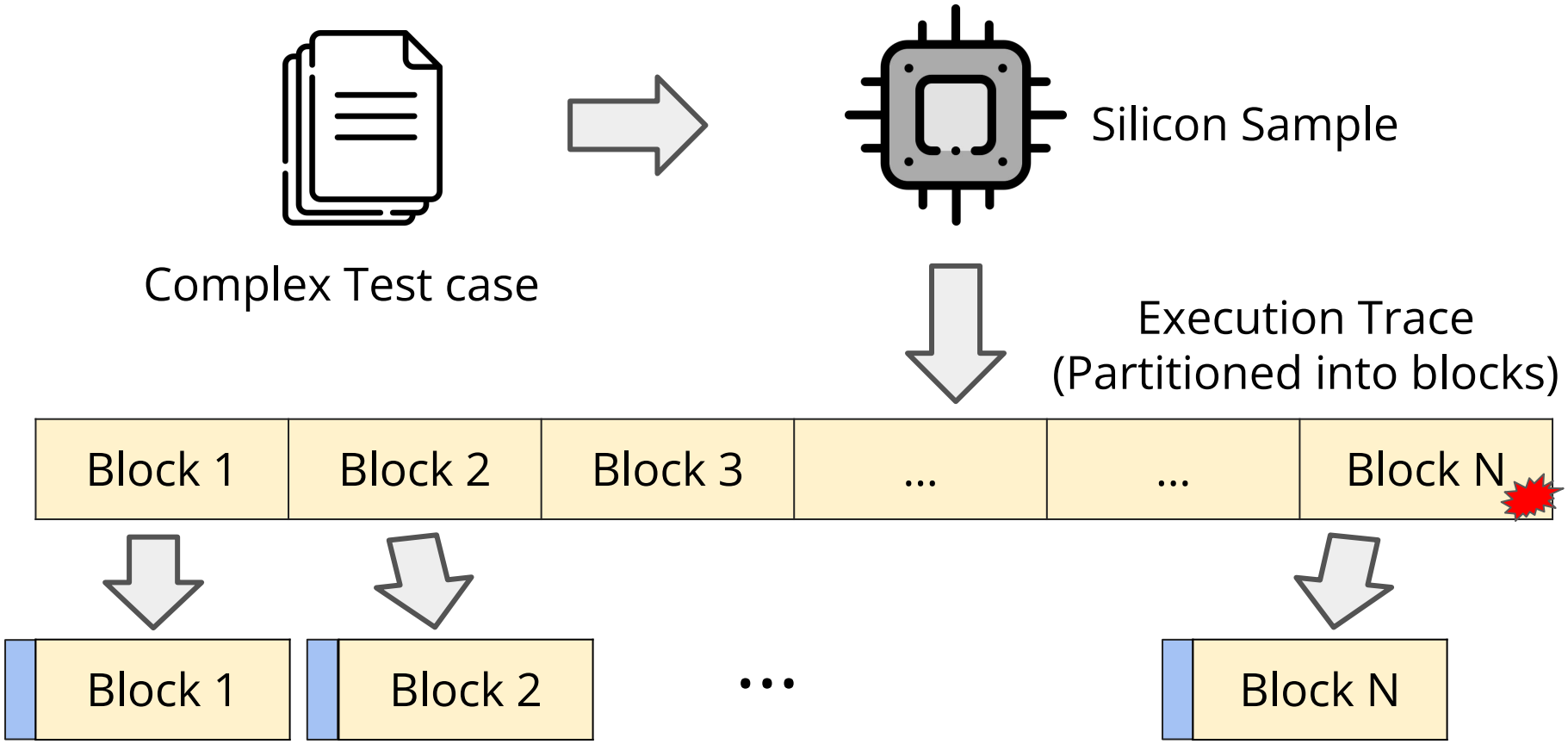
Complex Test case



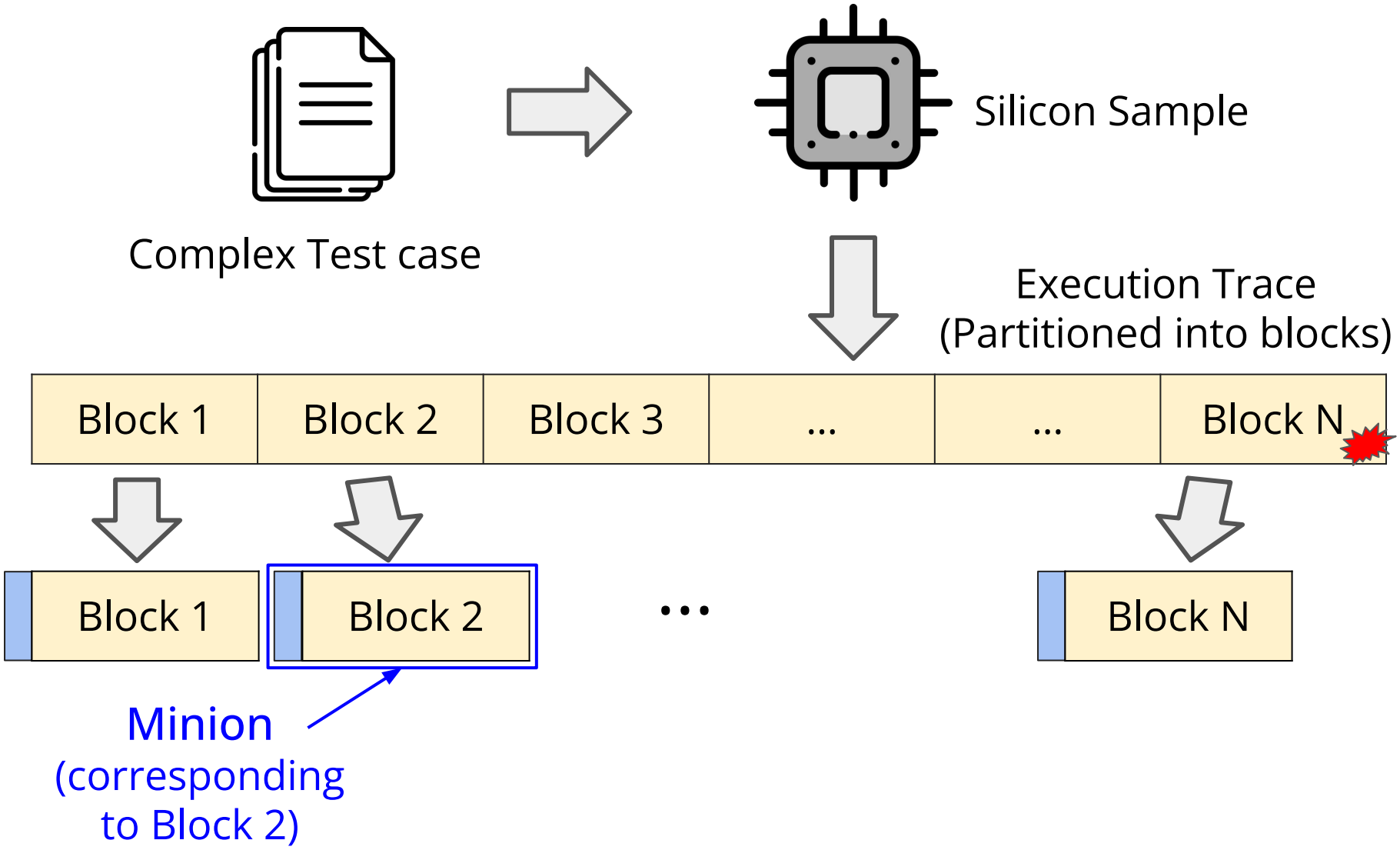
Execution Trace
(Partitioned into blocks
Block size is parameterized)

Block 1	Block 2	Block 3	...	...	Block N

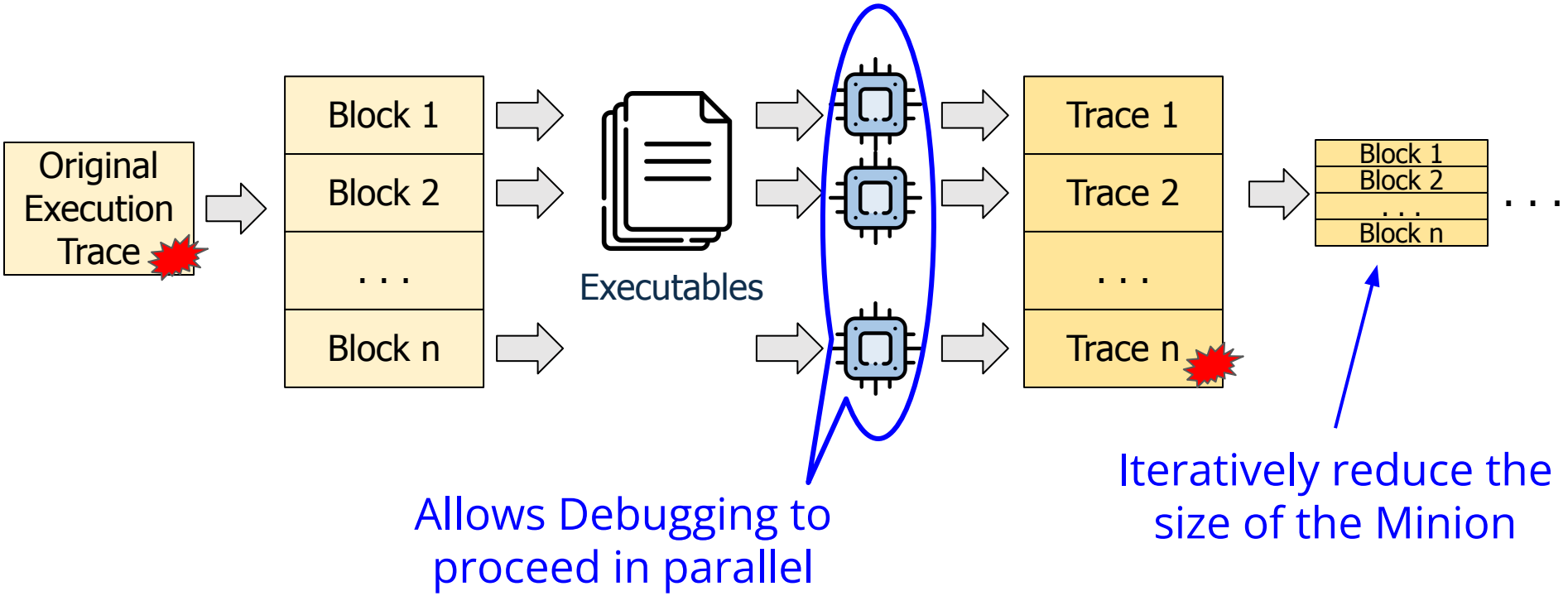
Solution Outline



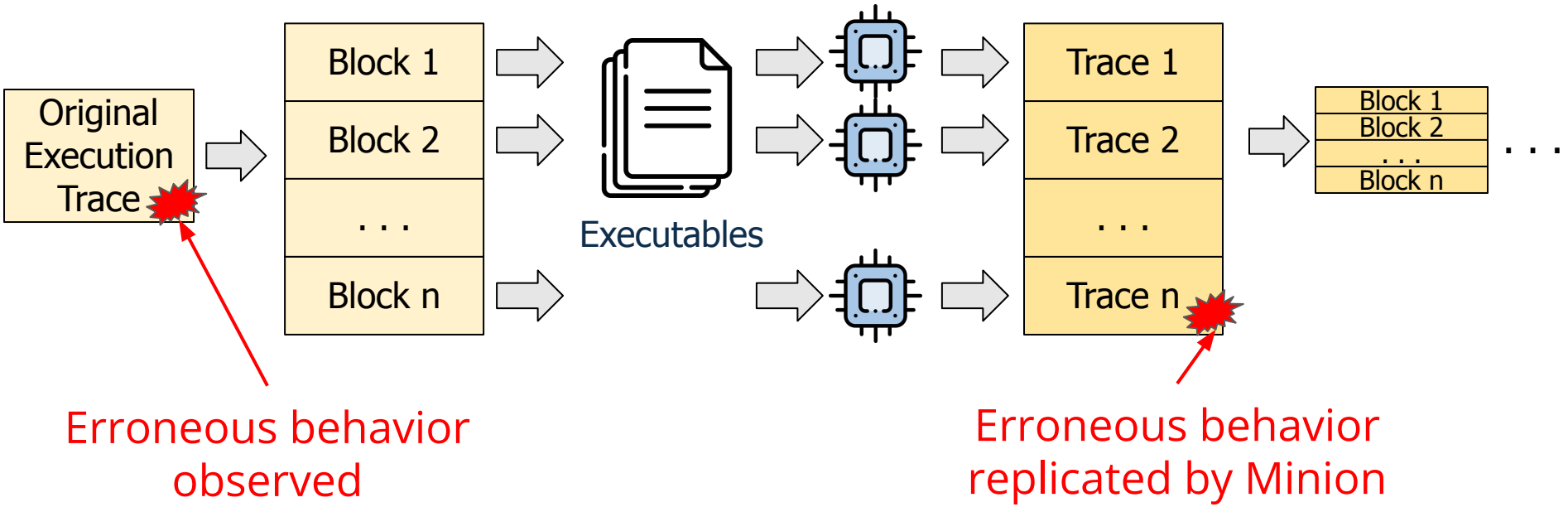
Solution Outline



Benefits of Gru

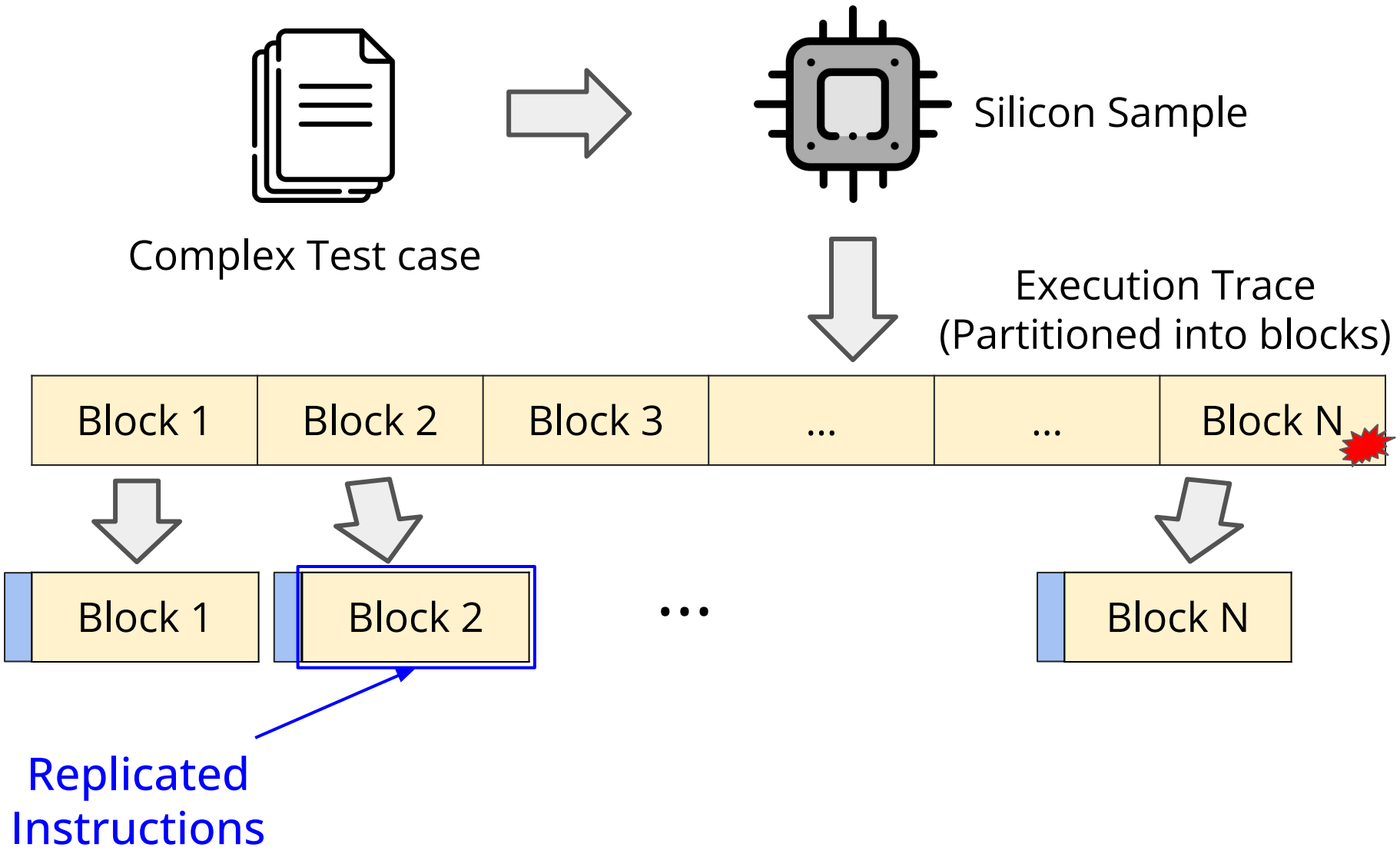


Benefits of Gru

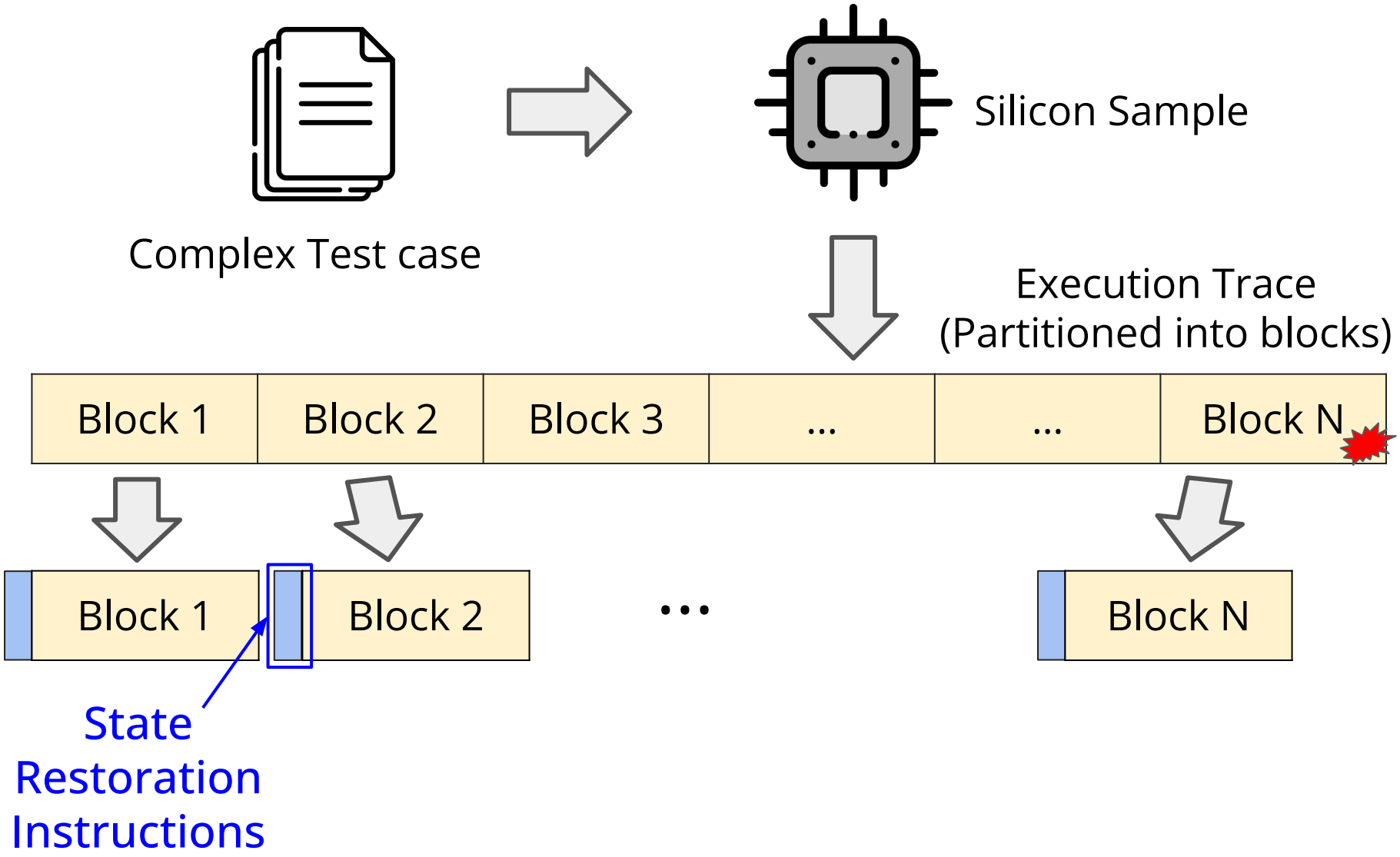


Privacy-aware Debugging

Solution Outline



Solution Outline



Minion Generation - Example

```
0x40010098: ld [%g2+0x000c], %o5 [0x00000300]
0x4001009c: st %o5,[%g1+0x000c]
0x400100a0: add %g2, 0x0010, %g2 [0xfffff020]
0x400100a4: bgu 0x40010078
0x400100a8: add %g1, 0x0010, %g1 [0x400ffe24]
0x400100ac: ld [%g2+0x000c], %o5 [0x00000010]
0x400100b0: srl %i2, 0x0004, %o5 [0x00000001]
0x400100b4: sll %o5, 0x0004, %g1 [0x00000010]
0x400100b8: add %o5, 0x0001, %o5 [0x00000002]
0x400100bc: sub %i2, %g1, %i2 [0x00000000]
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Minion Generation - Example

```
0x40010098: ld [%g2+0x000c], %o5 [0x00000300]
0x4001009c: st %o5,[%g1+0x000c]
```

PC:	Instruction	Output Value
0x400100a8:	add %g1, 0x0010, %g1	[0x400ffe24]

```
0x400100ac: ld [%g2+0x000c], %o5 [0x00000010]
0x400100b0: srl %i2, 0x0004, %o5 [0x00000001]
0x400100b4: sll %o5, 0x0004, %g1 [0x00000010]
0x400100b8: add %o5, 0x0001, %o5 [0x00000002]
0x400100bc: sub %i2, %g1, %i2 [0x00000000]
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Minion Generation - Example

```
0x40010098: ld [%g2+0x000c], %o5 [0x00000300]
0x4001009c: st %o5,[%g1+0x000c]
0x400100a0: add %g2, 0x0010, %g2 [0xfffff020]
0x400100a4: bgu 0x40010078
0x400100a8: add %g1, 0x0010, %g1 [0x400ffe24]
0x400100ac: ld [%g2+0x000c], %o5 [0x00000010]
0x400100b0: srl %i2, 0x0004, %o5 [0x00000001]
0x400100b4: sll %o5, 0x0004, %g1 [0x00000010]
0x400100b8: add %o5, 0x0001, %o5 [0x00000002]
0x400100bc: sub %i2, %g1, %i2 [0x00000000]
```

Block 1

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

Minion Generation - Example

```
sll %o5, 0x0004, %o5
subcc %i2, 0x0003, %g0
ld [%i2+0x000c], %g4
mov %i2, %g3
bgu 0x40010048
add %o5, %o5, %o5
subcc %o5, 0x0040, %g0
be 0x400100f0
mov 0x0000, %g1
ret
```

Minion corresponding to Block 2

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

Minion Generation - Example

```
sll %o5, 0x0004, %o5
subcc %i2, 0x0003, %g0
ld [%i2+0x000c], %g4
mov %i2, %g3
bgu 0x40010048
add %o5, %o5, %o5
subcc %o5, 0x0040, %g0
be 0x400100f0
mov 0x0000, %g1
ret
```

Incorrect

Mi[illegible]
corr[illegible]onding
to Block 2

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

Minion Generation - Example

Incorrect

```
sll %o5, 0x0004, %o5
subcc %i2, 0x0003, %g0
ld [%i2+0x000c], %g4
mov %i2, %g3
bgu 0x40010048
add %o5, %o5, %o5
subcc %o5, 0x0040, %g0
be 0x400100f0
mov 0x0000, %g1
ret
```

The value in %o5 in the minion should match the value that prevailed at the end of Block 1 ([0x00000002]) so that it produces the same value as in the original trace

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

Minion Generation - Example

The Minion should restore the values in the register %o5, %i2 and the memory location [0x0000000c] to the value that prevailed at the end of Block 1 to replicate the behavior observed in the original trace

State: %o5:??, %i2:??, [0x0000000c]:??

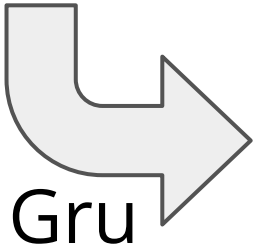
```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

Minion corresponding to Block 2



restore.s

```
 1: .global rstr
 2: .extern test
 3: .text
 4: rstr:
 5:   sethi %hi(0x00000300), %o1
 6:   or %o1, %lo(0x00000300), %o1
 7:   sethi %hi(0x0000000c), %o2
 8:   or %o2, %lo(0x0000000c), %o2
 9:   st %o1, [%o2]
10:   sethi %hi(0x00000002), %o5
11:   or %o5, %lo(0x00000002), %o5
12:   sethi %hi(0x00000000), %i2
13:   or %i2, %lo(0x00000000), %i2
14:   wrpsr 0xff400120
15:   ba test
16:   nop
```

replica.s

```
 1: .global test
 2: .text
 3: test:
 4:   sll %o5, 0x0004, %o5
 5:   subcc %i2, 0x0003, %g0
 6:   ld [%i2+0x000c], %g4
 7:   mov %i2, %g3
 8:   bgu 0x40010048
 9:   add %o5, %o5, %o5
10:   subcc %o5, 0x0040, %g0
11:   be 0x400100f0
12:   mov 0x0000, %g1
13:   nop
14:   nop
15:   nop
16:   ret
```

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

Block 2

Minion corresponding to Block 2

Gru

restore.s

```
 1: .global rstr
 2: .extern test
 3: .text
 4: rstr:
 5:   sethi %hi(0x00000300), %o1
 6:   or %o1, %lo(0x00000300), %o1
 7:   sethi %hi(0x0000000c), %o2
 8:   or %o2, %lo(0x0000000c), %o2
 9:   st %o1, [%o2]
10:   sethi %hi(0x00000002), %o5
11:   or %o5, %lo(0x00000002), %o5
12:   sethi %hi(0x00000000), %i2
13:   or %i2, %lo(0x00000000), %i2
14:   wrpsr 0xff400120
15:   ba test
16:   nop
```

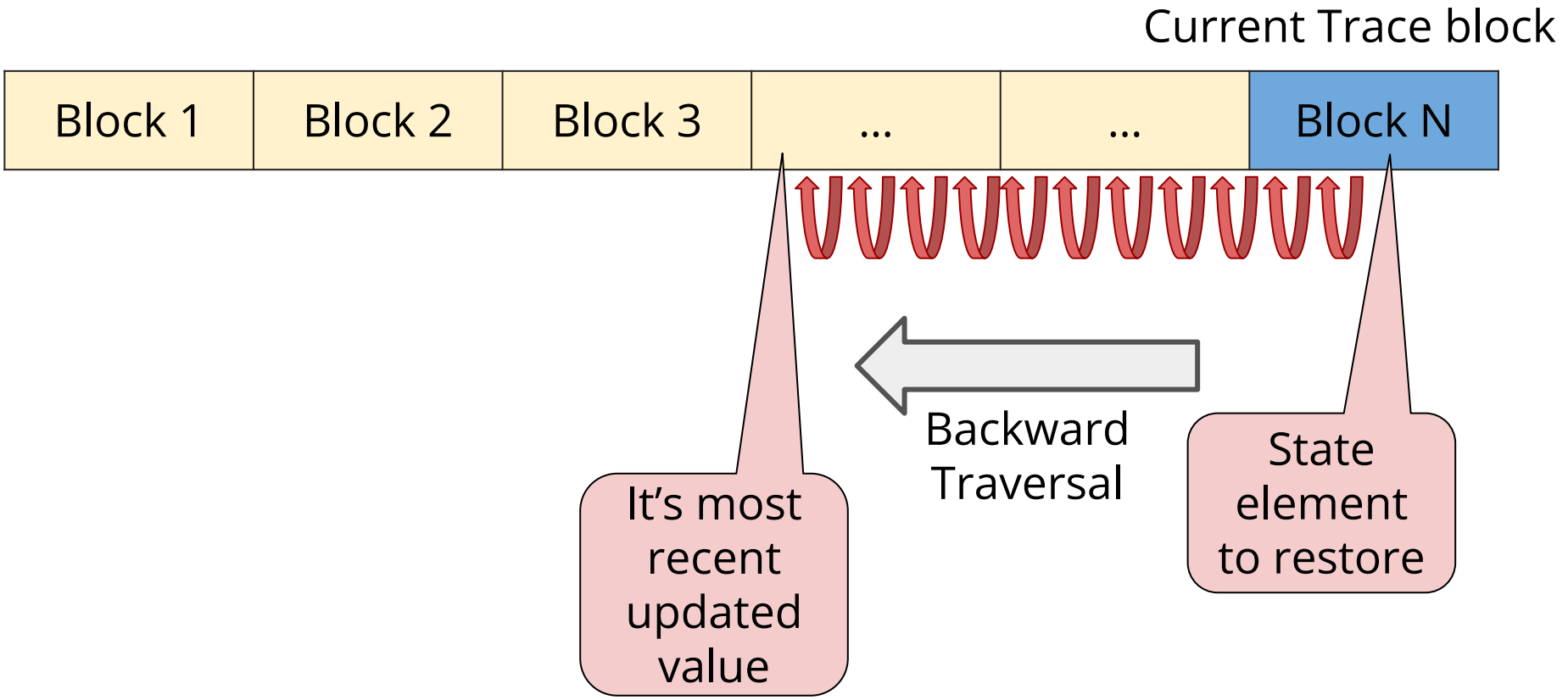
replica.s

```
 1: .global test
 2: .text
 3: test:
 4:   sll %o5, 0x0004, %o5
 5:   subcc %i2, 0x0003, %g0
 6:   ld [%i2+0x000c], %g4
 7:   mov %i2, %g3
 8:   bgu 0x40010048
 9:   add %o5, %o5, %o5
10:   subcc %o5, 0x0040, %g0
11:   be 0x400100f0
12:   mov 0x0000, %g1
13:   nop
14:   nop
15:   nop
16:   ret
```

Minion Generation - Procedure

- **Step 1**: Identify registers that are read before being written to in the current trace block
- **Step 2**: Infer the values of these registers using State-inference techniques
- **Step 3**: Identify memory locations that are read before being written to in the current trace block (using reg values identified above, if required)
- **Step 4**: Infer the values of these memory locations using State-inference techniques
- **Step 5**: Emit State Restoration Instructions (SRIs) into the Minion (`restore.s`) for the memory locations and registers identified in Steps 3 and 1 respectively.
- **Step 6**: Copy instructions in the current trace block into the Minion (`replica.s`).
- **Step 7:** Compile and link `restore.s` and `replica.s`

State Inference Technique - Brute Force



State Inference Technique - Brute Force

```
0x40010098: ld [%g2+0x000c], %o5 [0x00000300]
0x4001009c: st %o5,[%g1+0x000c]
0x400100a0: add %g2, 0x0010, %g2 [0xffffff020]
0x400100a4: bgu 0x40010078
0x400100a8: add %g1, 0x0010, %g1 [0x400ffe24]
0x400100ac: ld [%g2+0x000c], %o5 [0x00000010]
0x400100b0: srl %i2, 0x0004, %o5 [0x00000001]
0x400100b4: sll %o5, 0x0004, %g1 [0x00000010]
0x400100b8: add %o5, 0x0001, %o5 [0x00000002]
0x400100bc: sub %i2, %g1, %i2 [0x00000000]
```

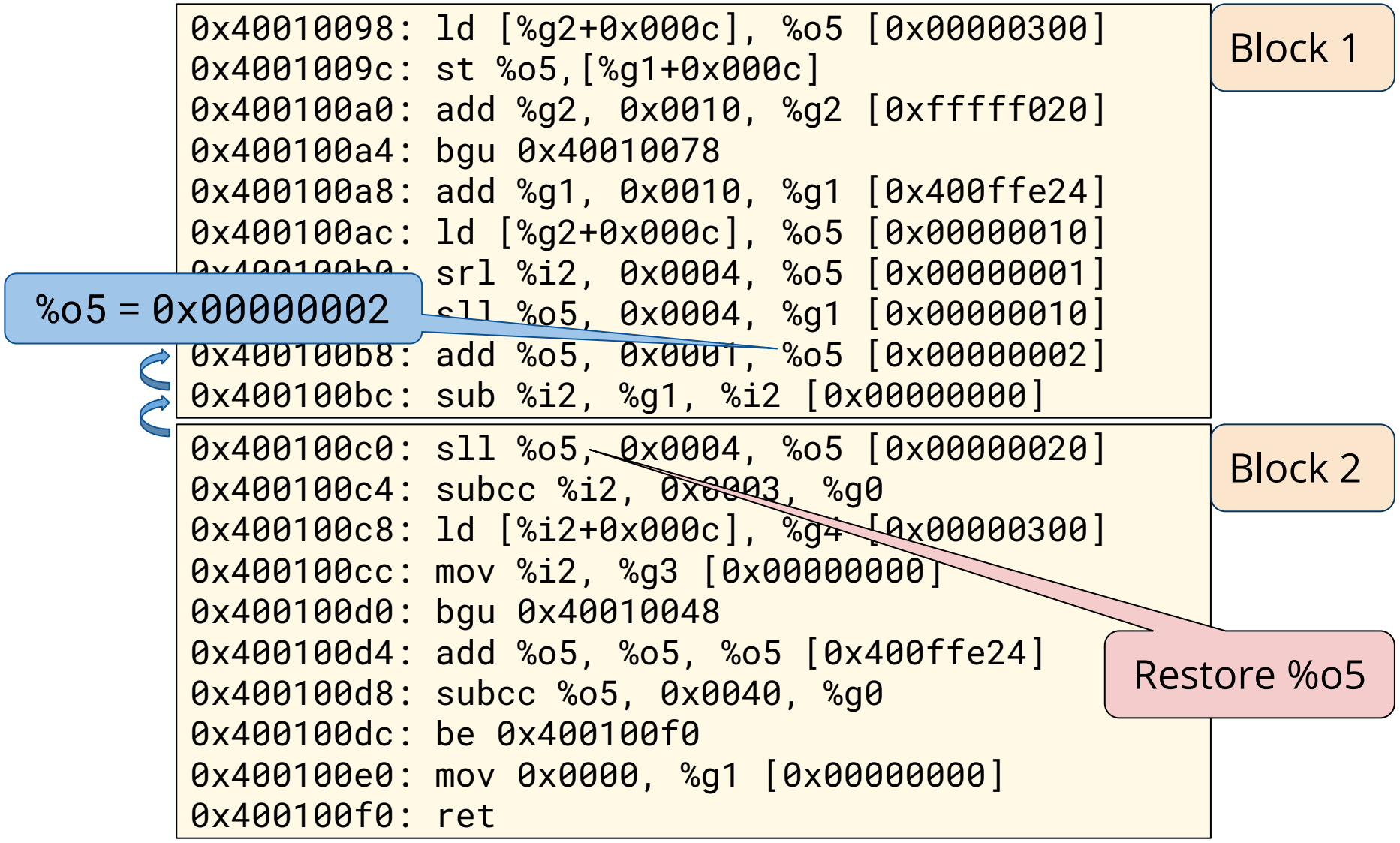
Block 1

```
0x400100c0: sll %o5, 0x0004, %o5 [0x00000020]
0x400100c4: subcc %i2, 0x0003, %g0
0x400100c8: ld [%i2+0x000c], %g4 [0x00000300]
0x400100cc: mov %i2, %g3 [0x00000000]
0x400100d0: bgu 0x40010048
0x400100d4: add %o5, %o5, %o5 [0x400ffe24]
0x400100d8: subcc %o5, 0x0040, %g0
0x400100dc: be 0x400100f0
0x400100e0: mov 0x0000, %g1 [0x00000000]
0x400100f0: ret
```

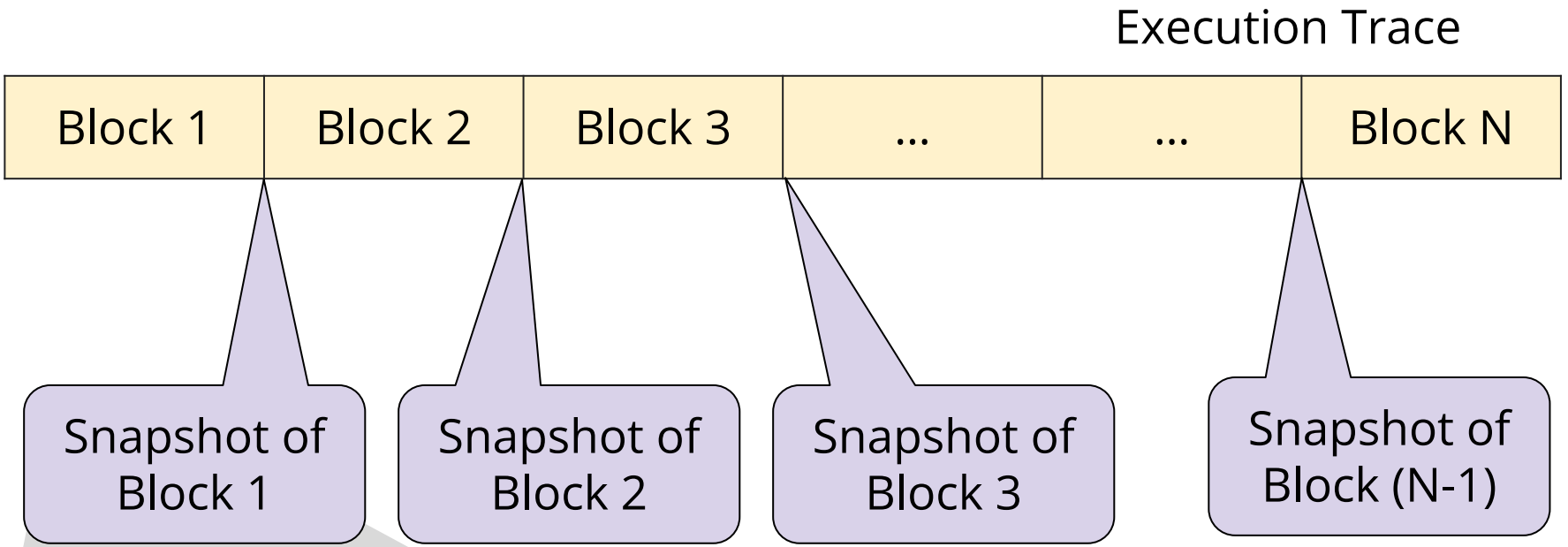
Block 2

Restore %o5

State Inference Technique - Brute Force



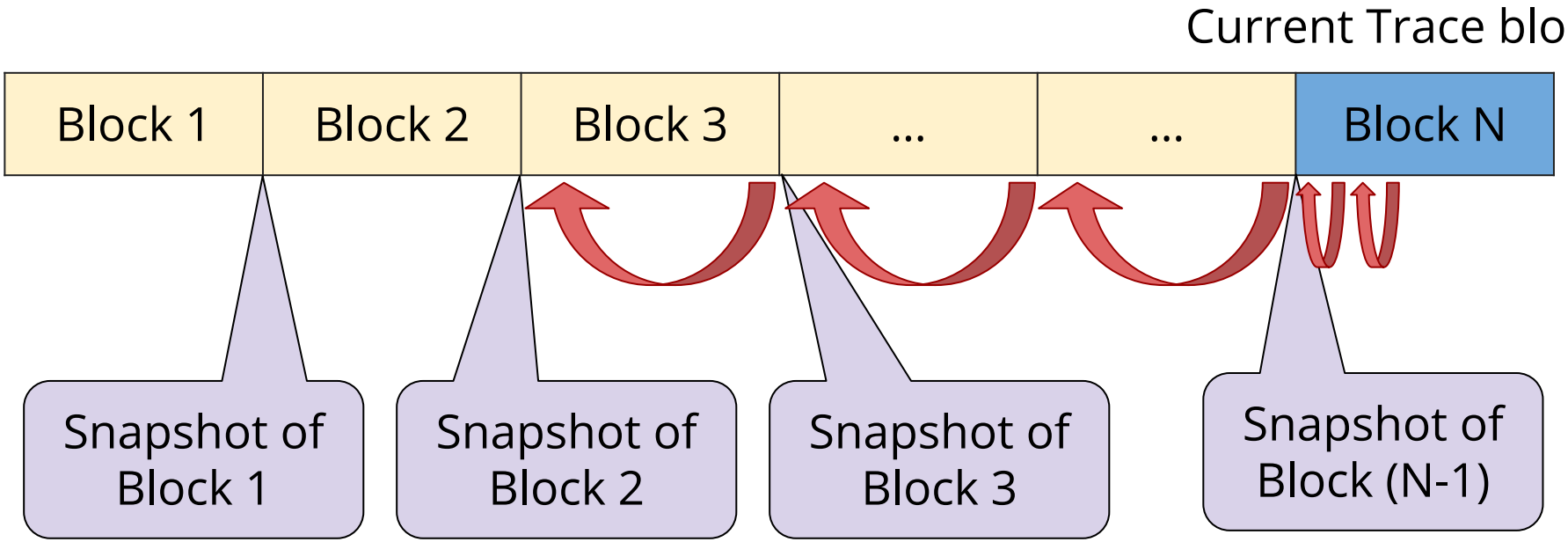
State Inference Technique - Snapshots-saving



State Element	Updated Value
%o5	0x00000002
%g1	0x00000010
%g2	0xfffff020

- Snapshots capture state-updates in each trace block
- Snapshots created as trace is decoded

State Inference Technique - Snapshots-saving



- Backward traversal jumps from one snapshot to an earlier snapshot till the most recently updated value is found

State Inference Technique - Inverted Map

Block 1	Block 2	Block 3	...	...	Block N

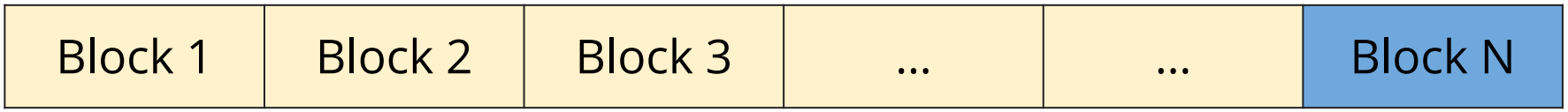
Inverted Map

State Element	Current Value
%o5	0x00000002
%g1	0x00000010
%g2	0xfffff020
%i2	0x00000000
%g4	0xfffff020

- Inverted Map is constructed as the execution trace is decoded

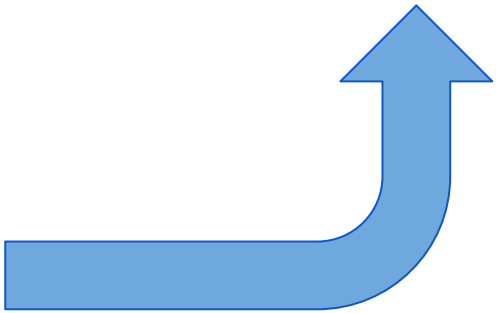
State Inference Technique - Inverted Map

Current Trace block



Inverted Map

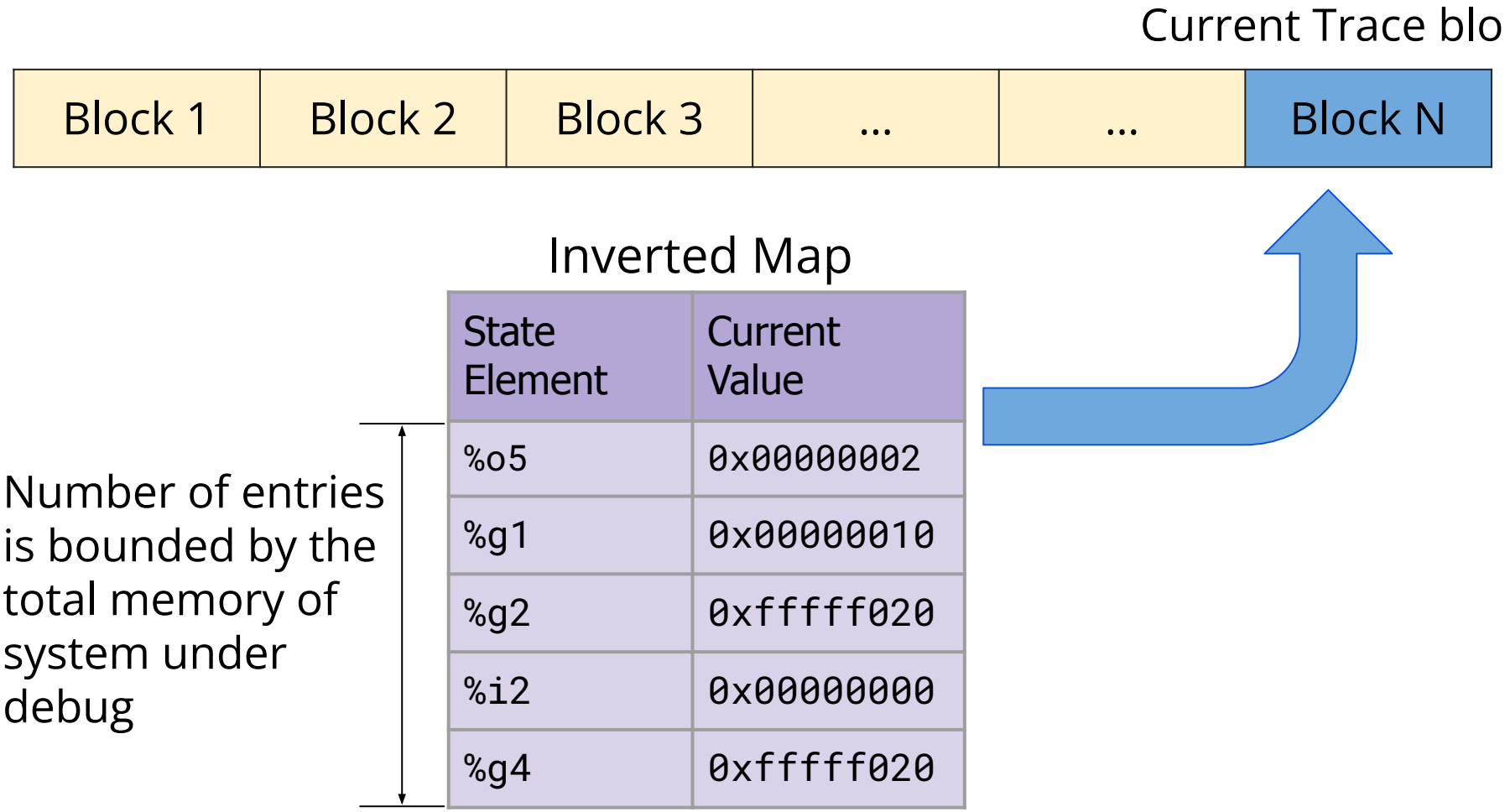
State Element	Current Value
%o5	0x00000002
%g1	0x00000010
%g2	0xfffff020
%i2	0x00000000
%g4	0xfffff020



Inverted Map is looked up to determine the most recent value of a state element

Avoids backward passes over the trace

State Inference Technique - Inverted Map

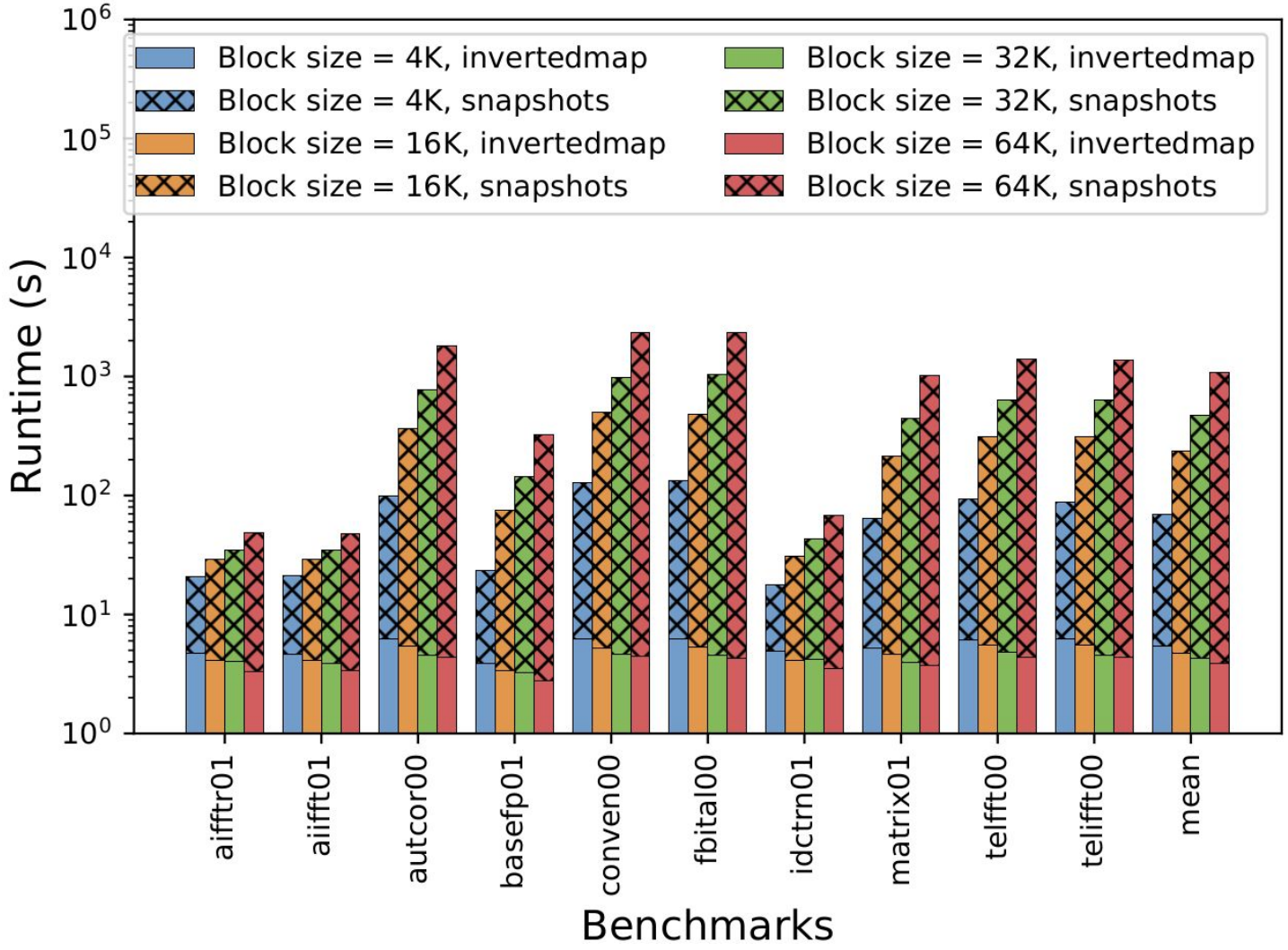


Experimental Setup

- LEON3 SoC with one SPARCv8 core, AHB, DDR and a Debug Support Unit (DSU)
  - 4KB Instruction Trace Buffer and 4KB AHB Trace Buffer
- Executed 10 (out of 17) benchmarks from the EEMBC AutoBench and TeleBench suites
  - Compiled using Bare-C Cross Compiler (BCC) - Bare-metal runs
- Execution time of 10ms
  - Captured traces had 369K messages (on average)
  - Approx. size of 5.6 MB
- Gru implemented in Python v3.10 and executed on an Intel Xeon Gold 5218R processor (2.1 GHz base frequency) with 32 GB RAM
  - Varied block size from 4KB to 64KB

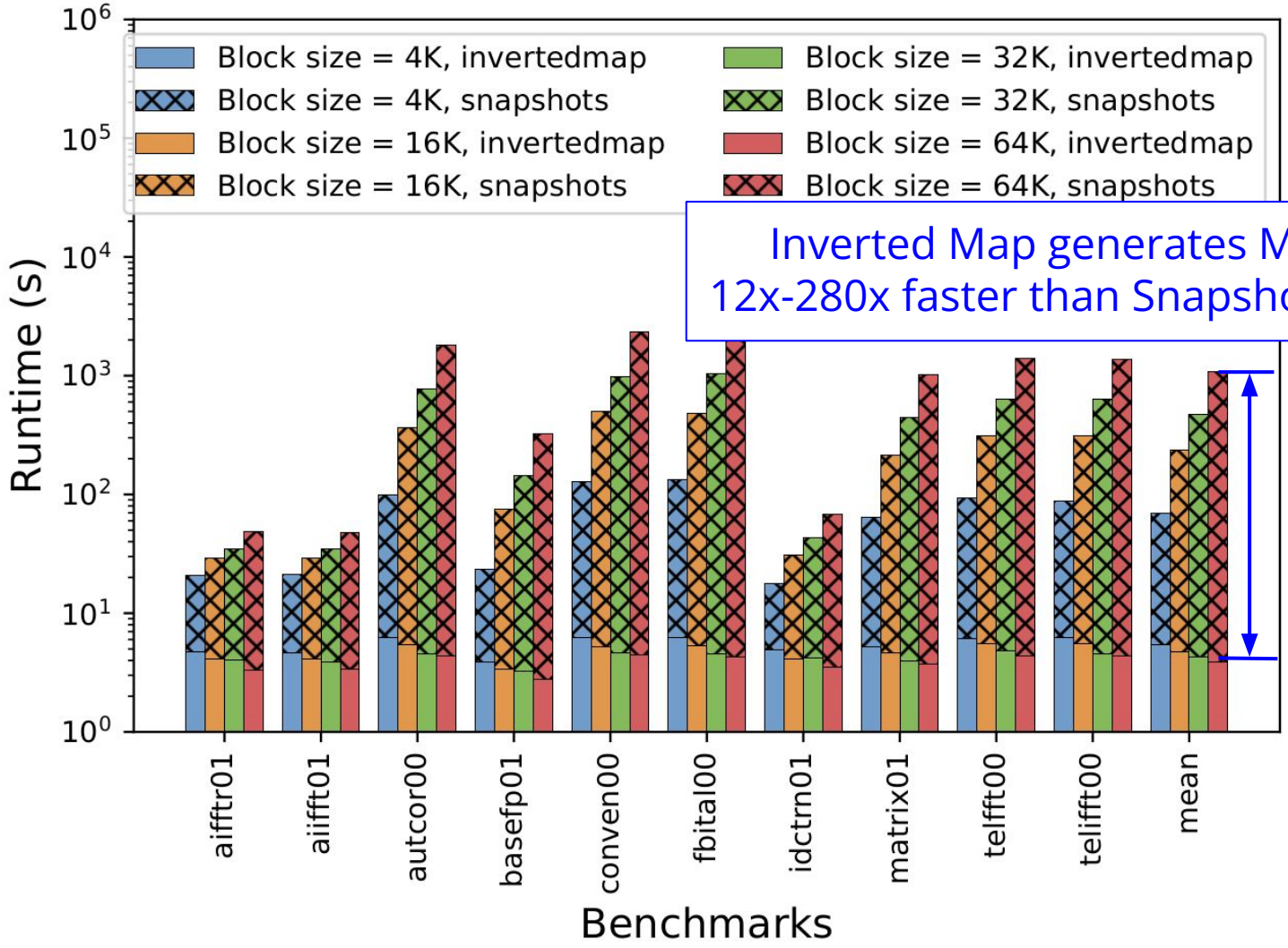
Results

Minion Generation Times



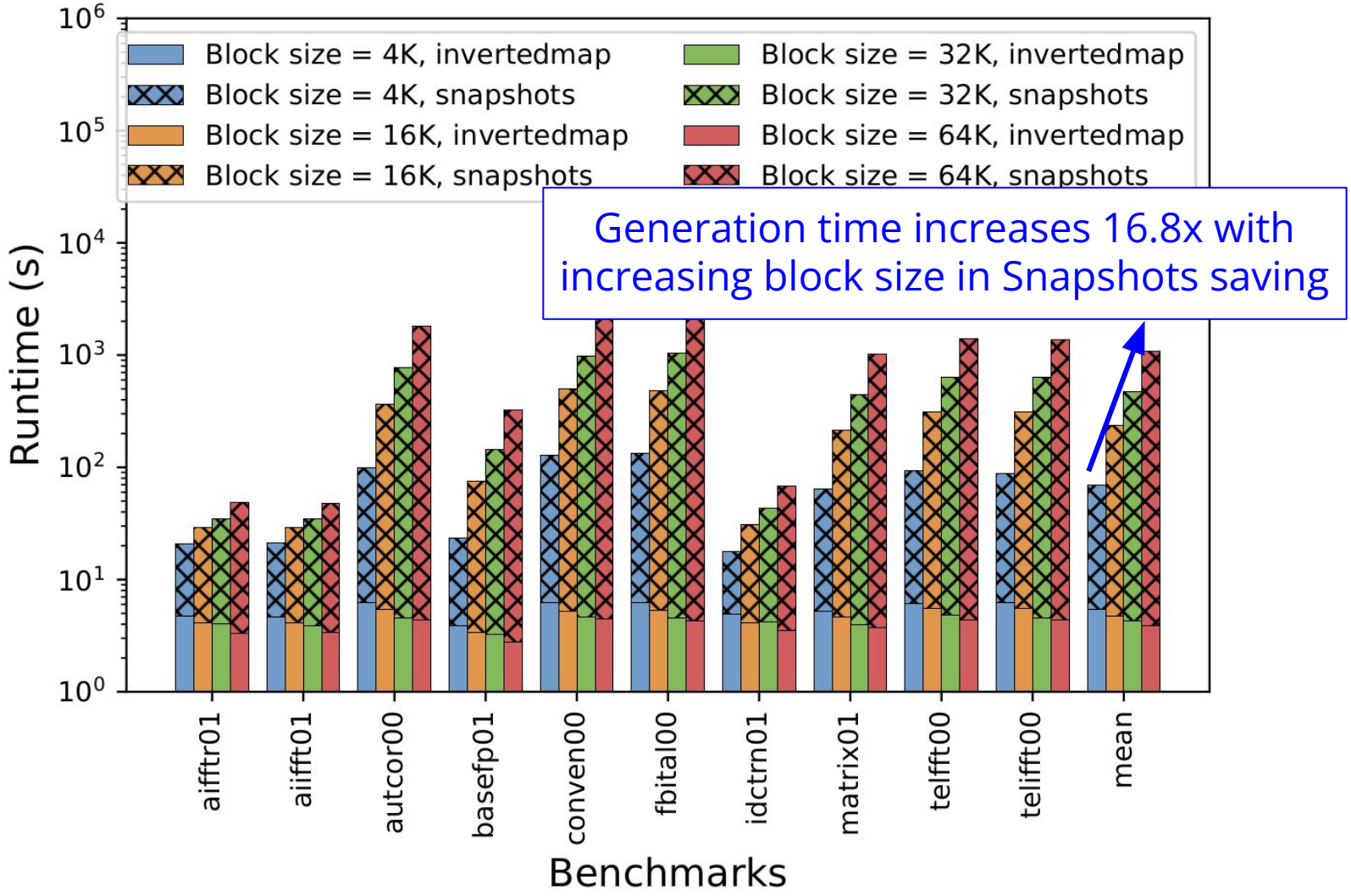
Results

Minion Generation Times



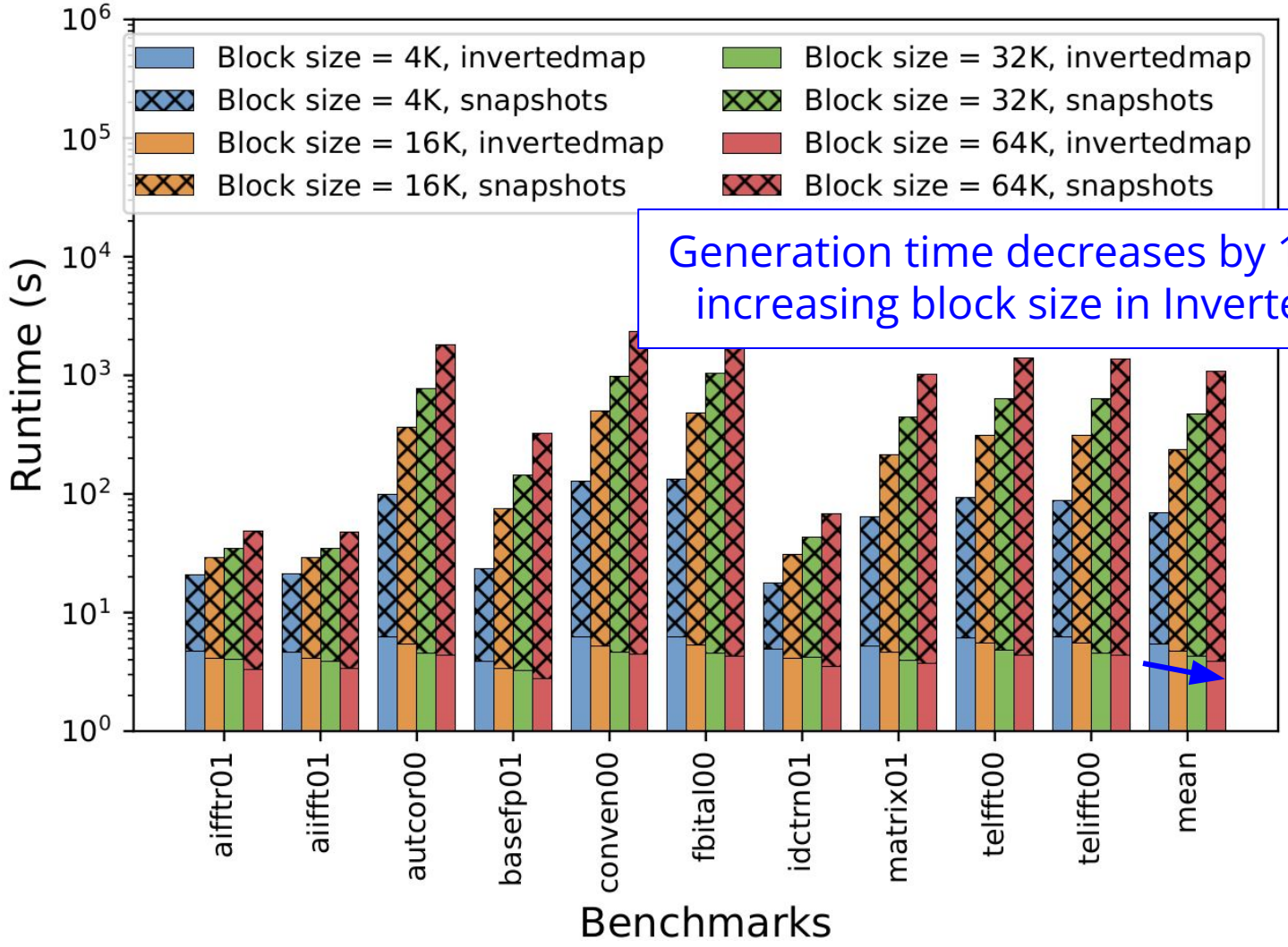
Results

Minion Generation Times



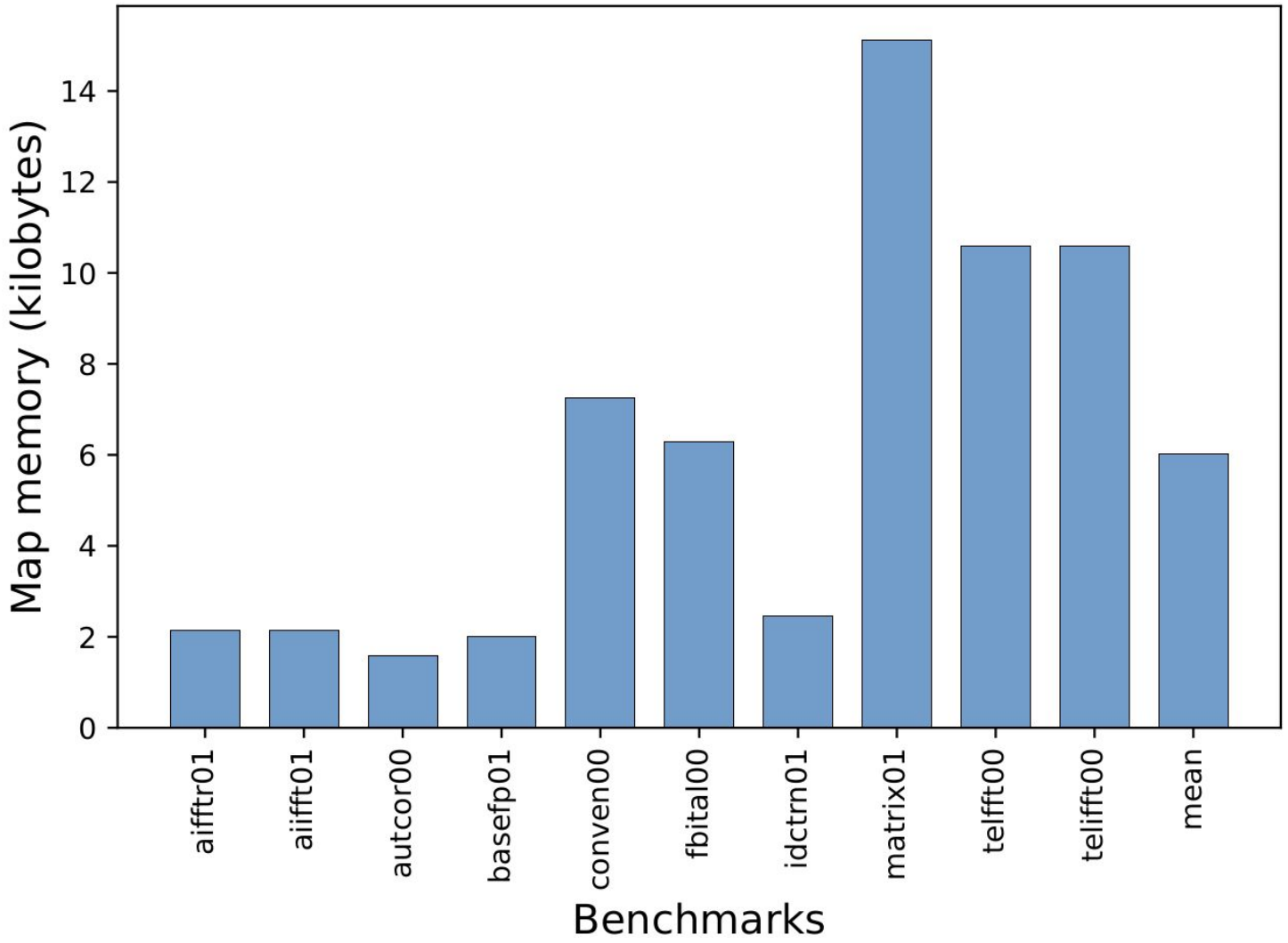
Results

Minion Generation Times



Results

Space Consumed by Inverted Map



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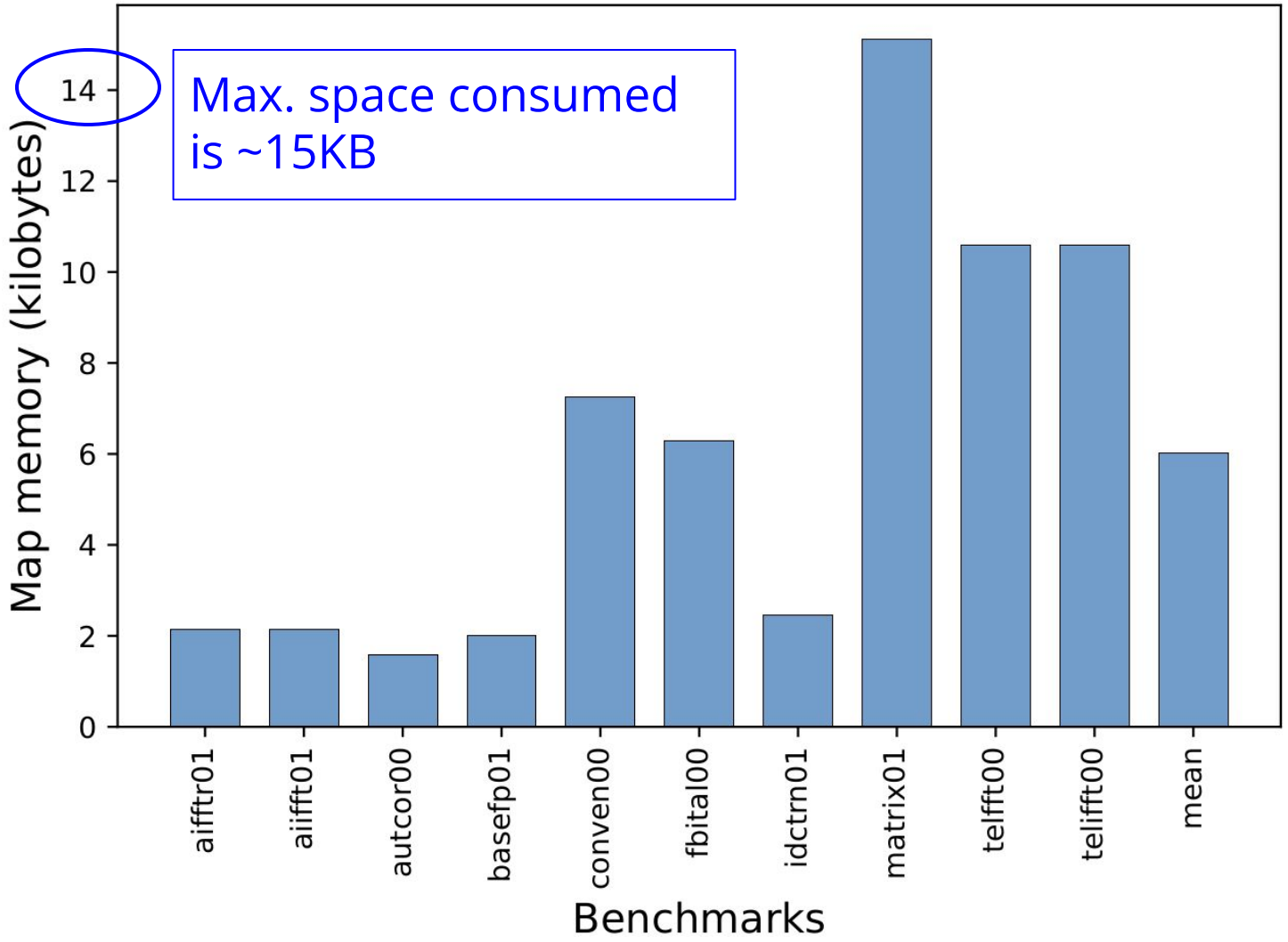
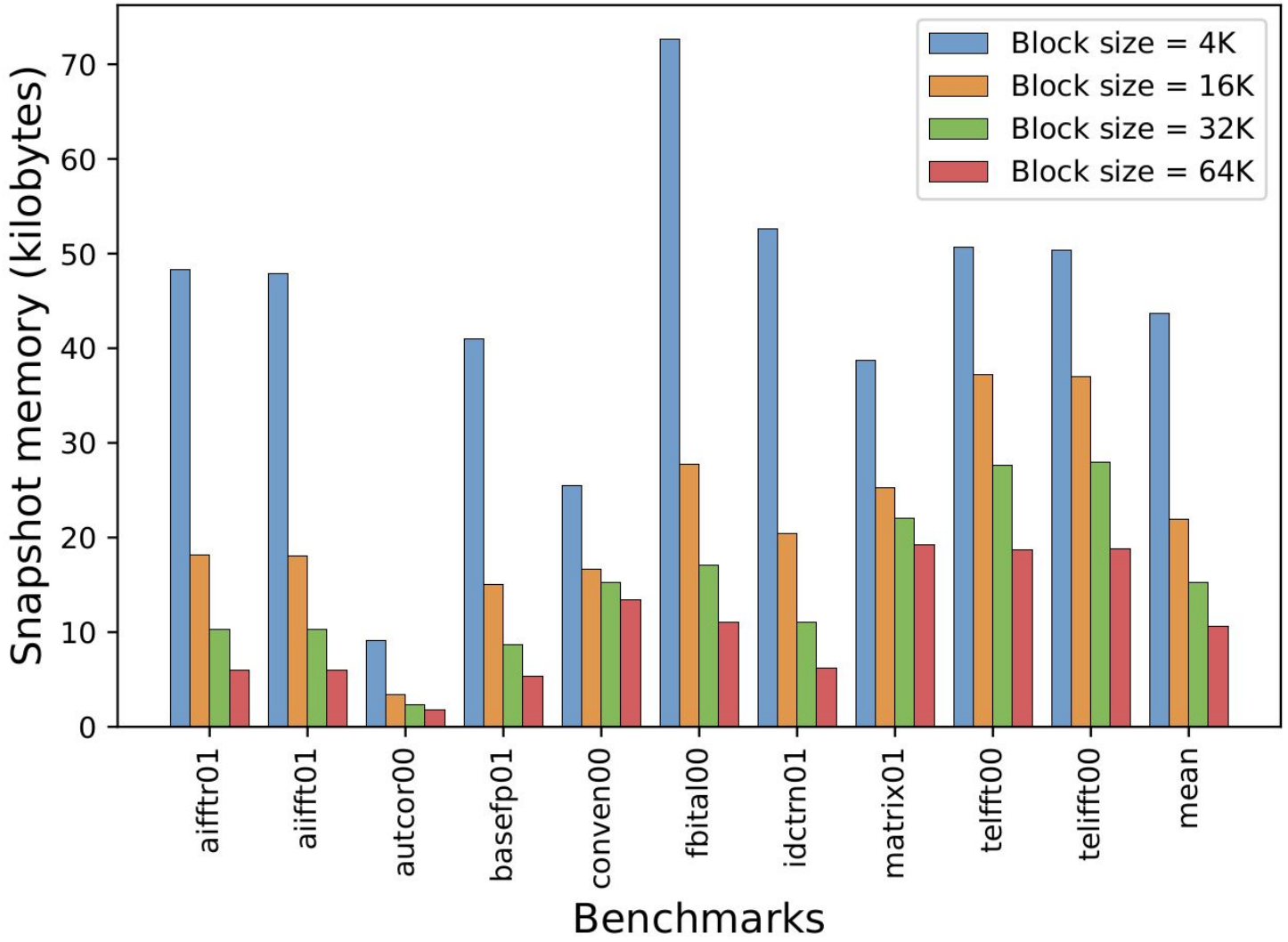
Space Consumed by Inverted Map



Results

Space Consumed by Snapshots (cumulative)



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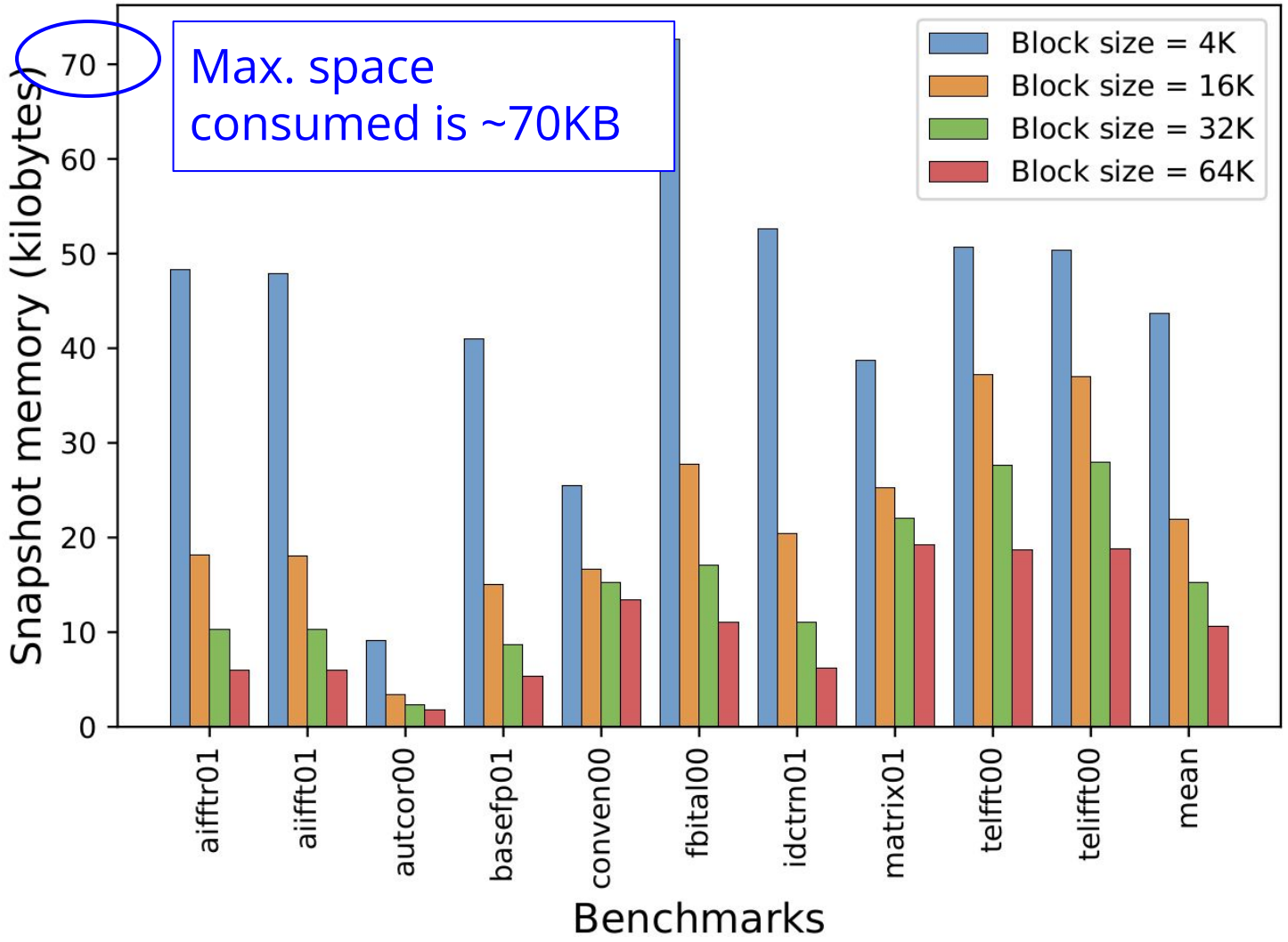

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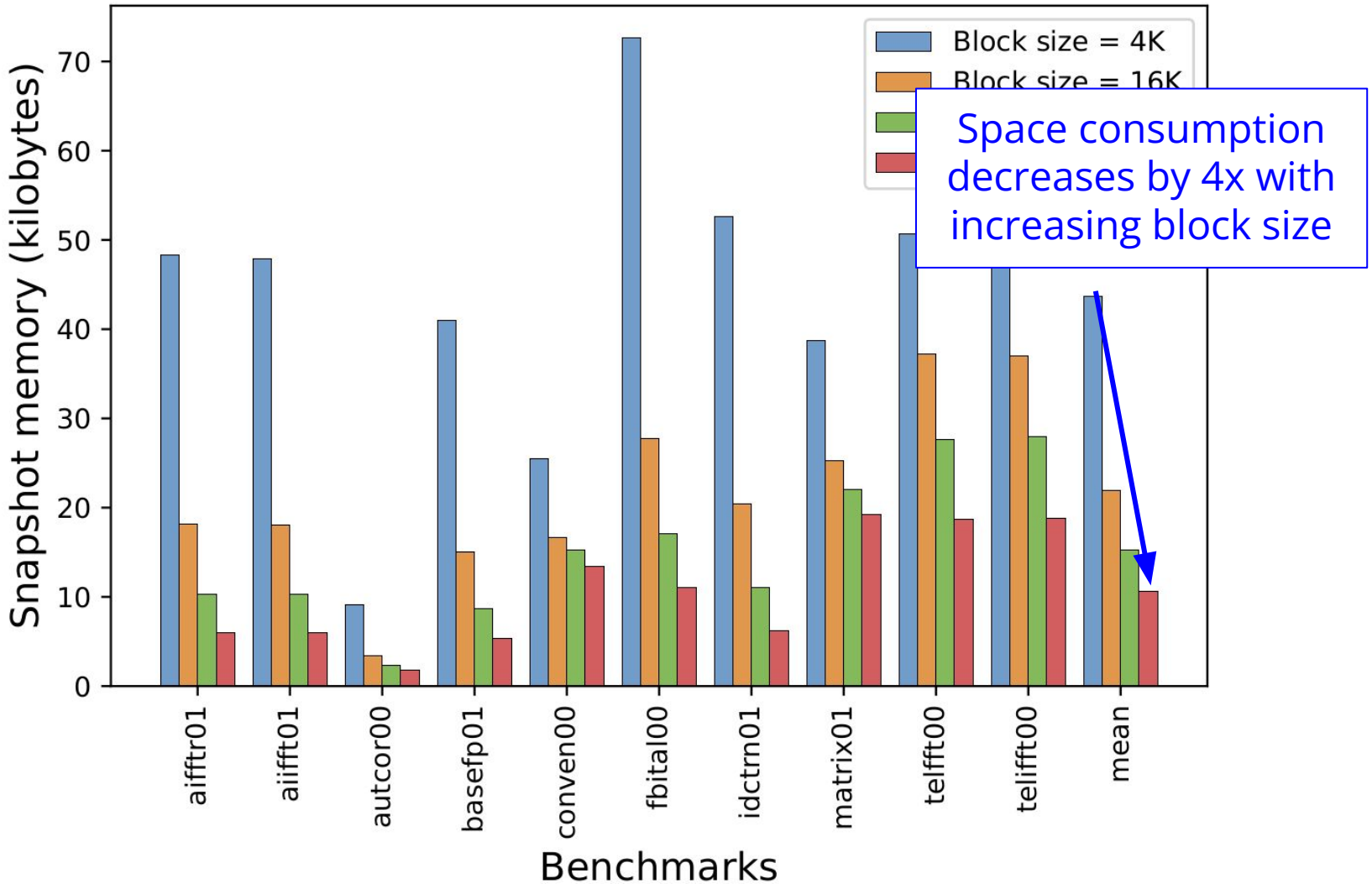
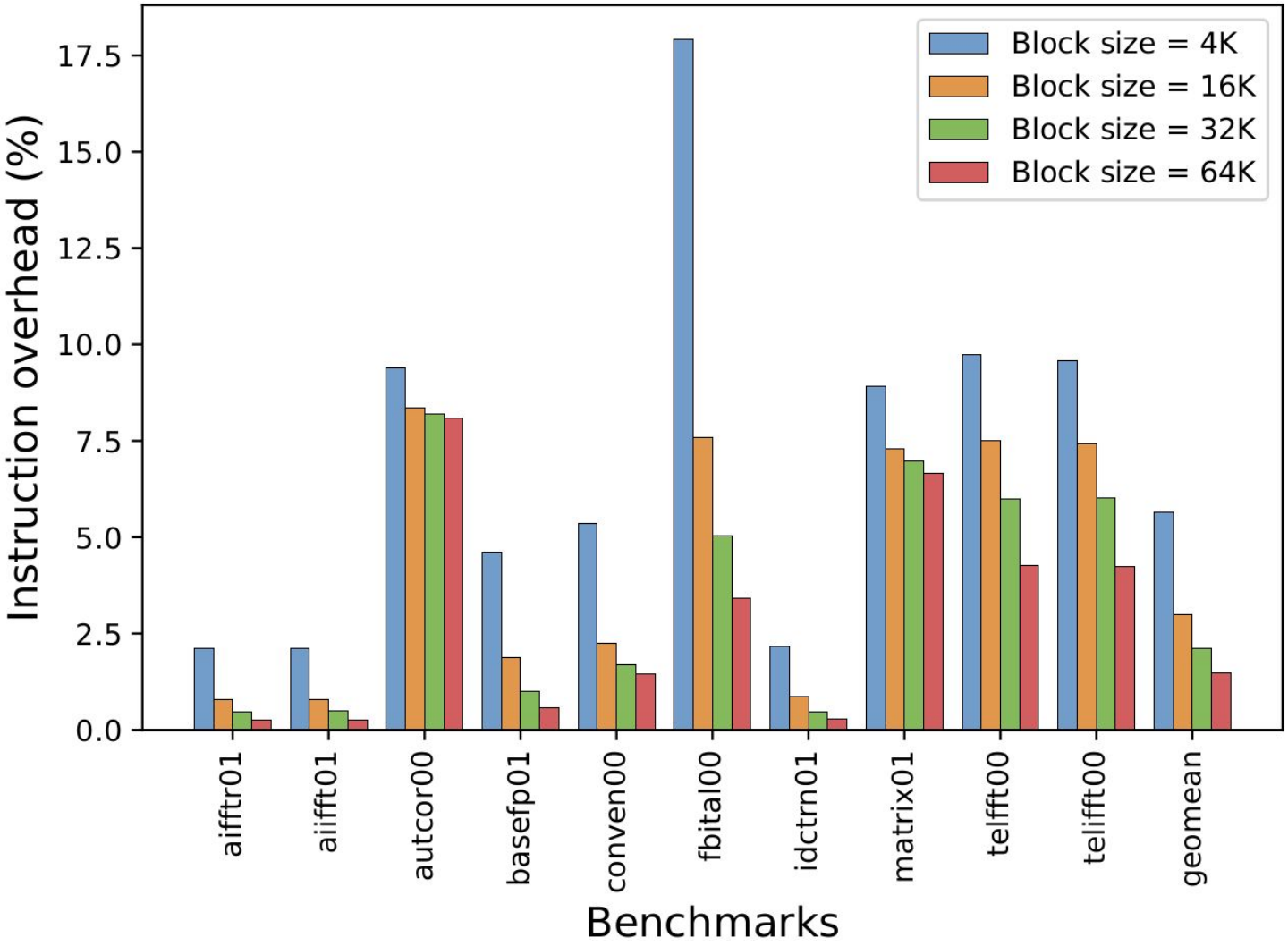


Results

Overhead of State Restoration Instructions



Results

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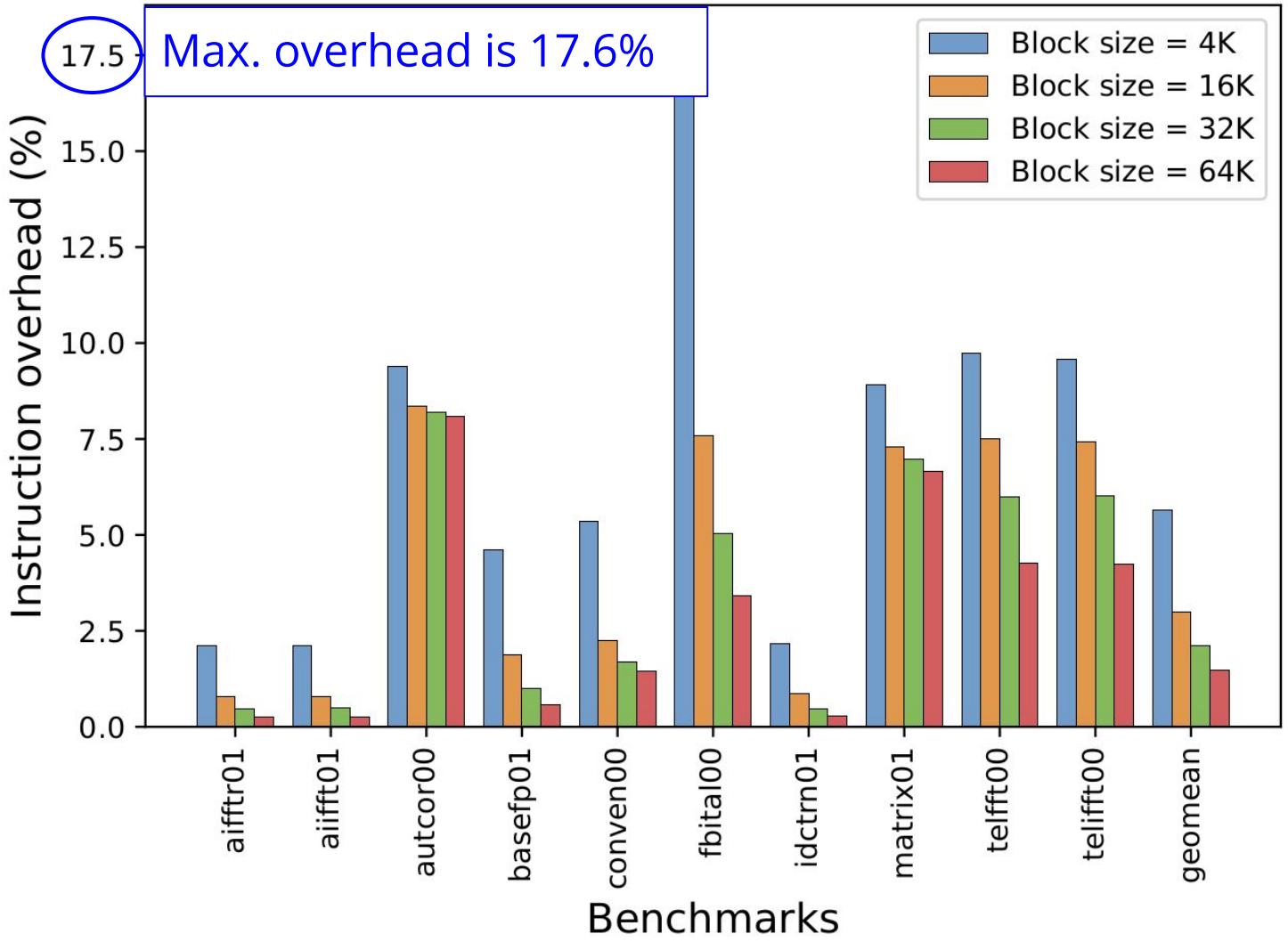

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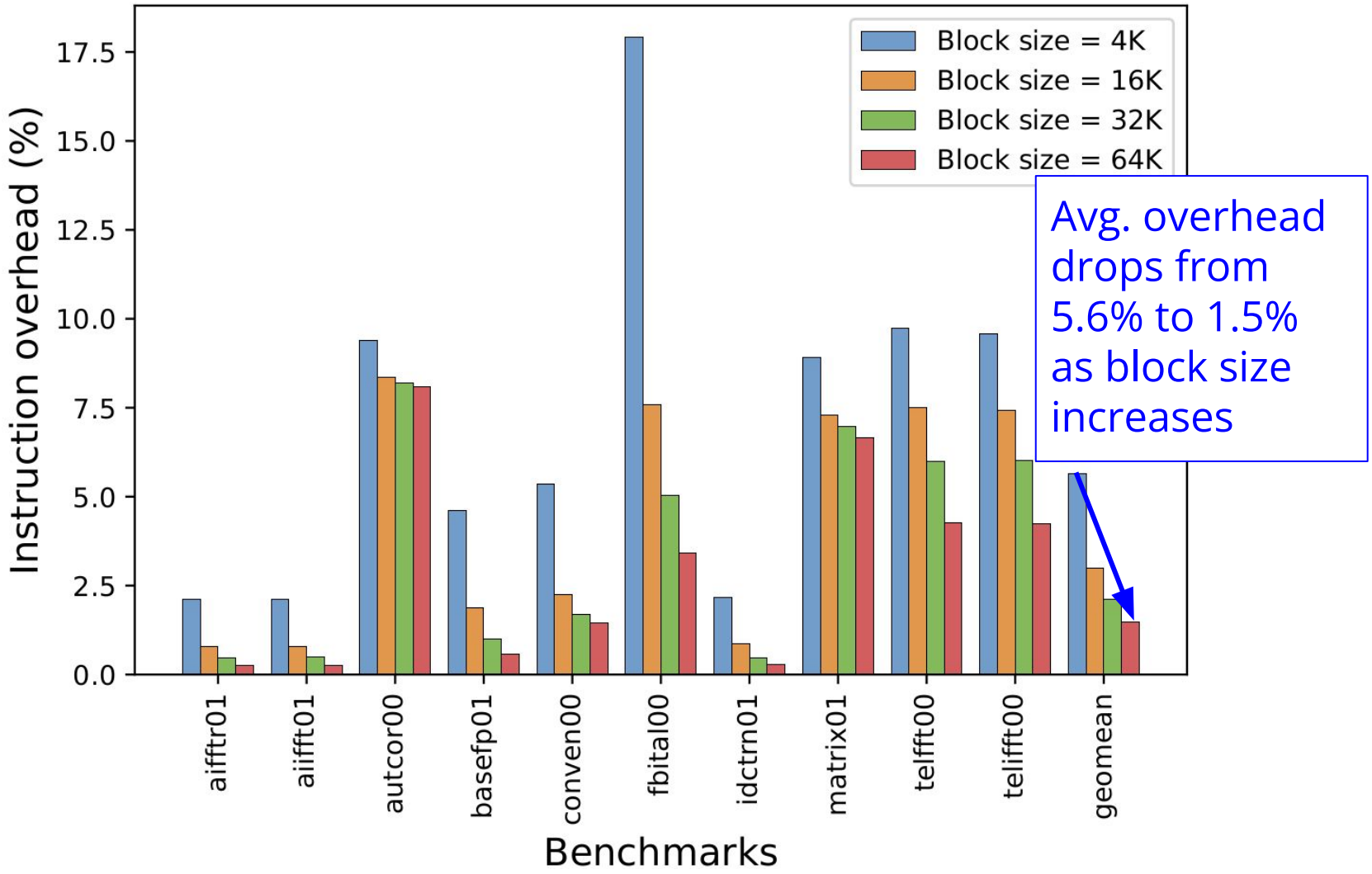

Conclusion

- We proposed a tool called, Gru, that
  - generates Minion executables (of parameterizable size) which reproduce behavior observed in the corresponding sections of an earlier run of the system
  - relies only on execution traces captured during the earlier execution
  - adds only 1.5% additional instructions

Conclusion

- Benefits:
  - Supports privacy-aware bug replication
  - Debugging activities parallelized
  - Bug replication using smaller executables makes it amenable to use other tools for bug localization and root-cause analysis

- Current Limitations and Future Directions
  - Micro-architectural State restoration
  - Replicating multi-core behavior

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  - Micro-architectural State restoration
  - Replicating multi-core behavior

Thank You!

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