Bounding Data Races in *Space* and *Time*

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Darwin College, Cambridge

1851 Royal Commission

Multicore OCaml

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- OCaml is an industrial-strength, functional programming language
  - ★ Projects: MirageOS unikernel, Coq proof assistant, F* programming language
  - ★ Companies: Facebook (Hack, Flow, Infer, Reason), Microsoft (Everest, F*), JaneStreet (all trading & support systems), Docker (Docker for Mac & Windows), Citrix (XenStore)

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- Multicore OCaml
  - ★ Native support for *concurrency* and *parallelism* in OCaml
  - ★ Lead from OCaml Labs + (JaneStreet, Microsoft Research, INRIA).

Modelling Memory

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r1 = a * 2
r2 = b + 1
r3 = a * 2
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CSE ⟶

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   &&
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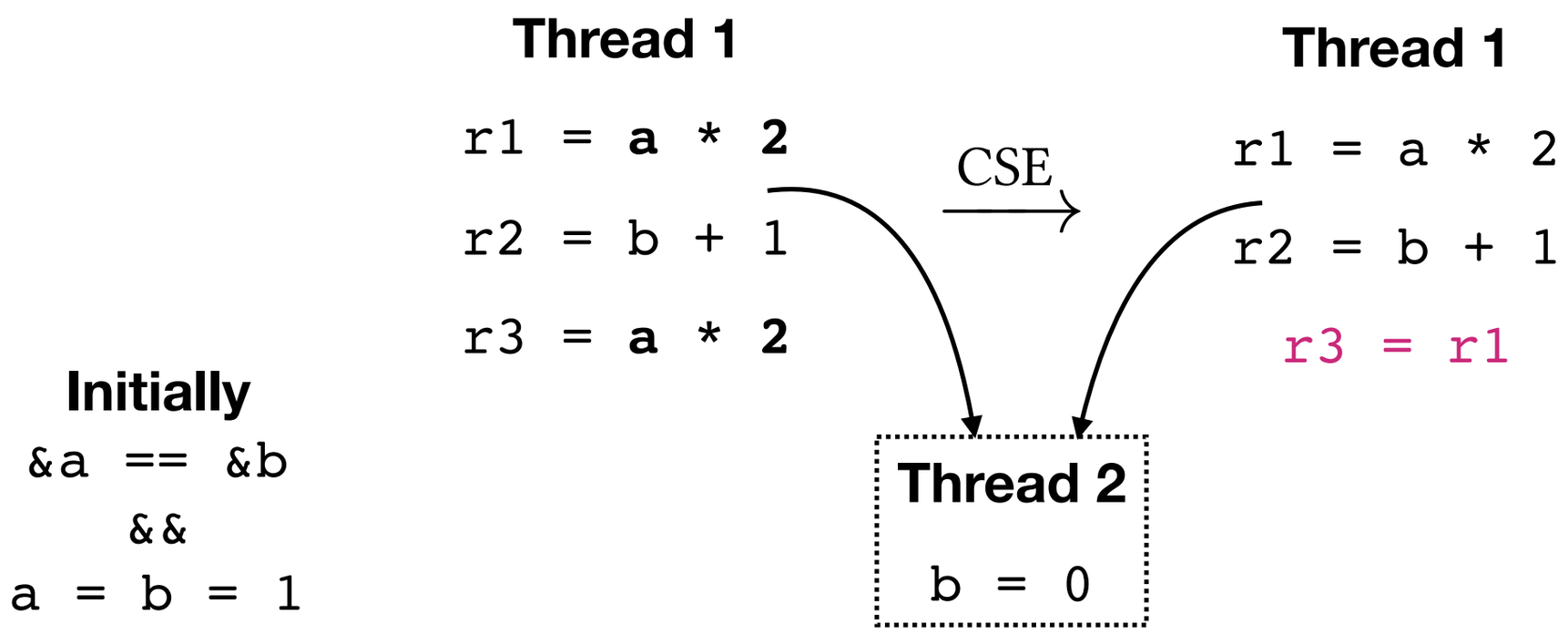

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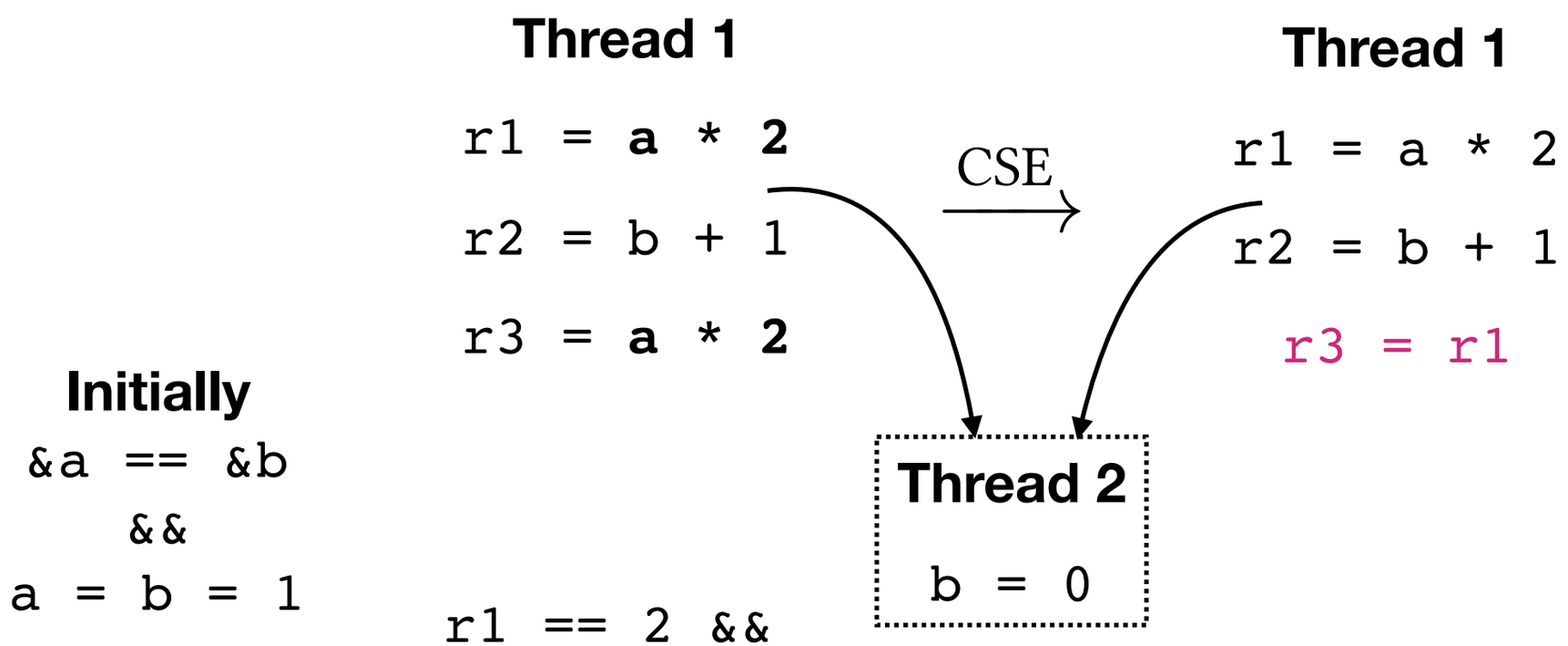

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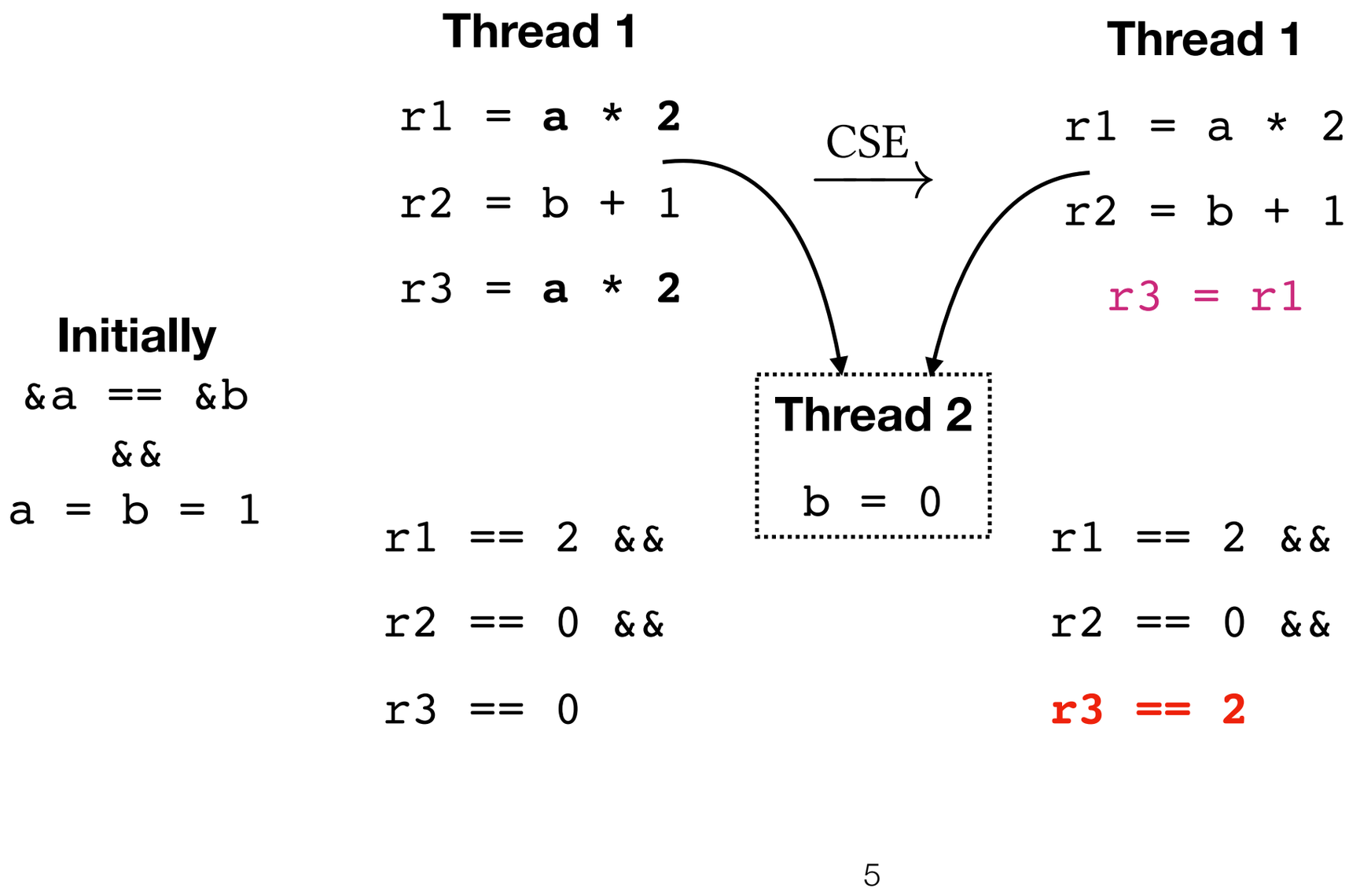

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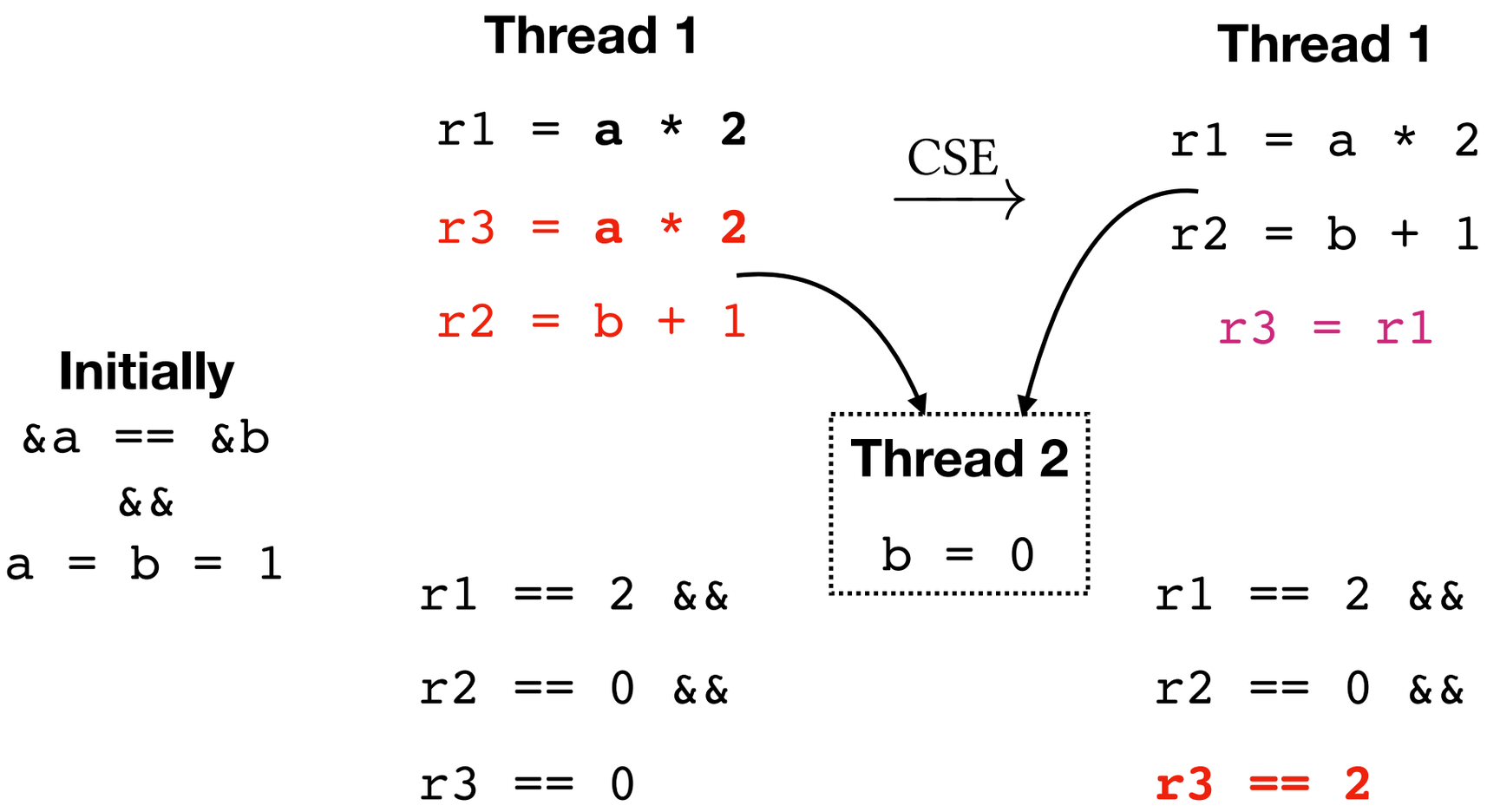

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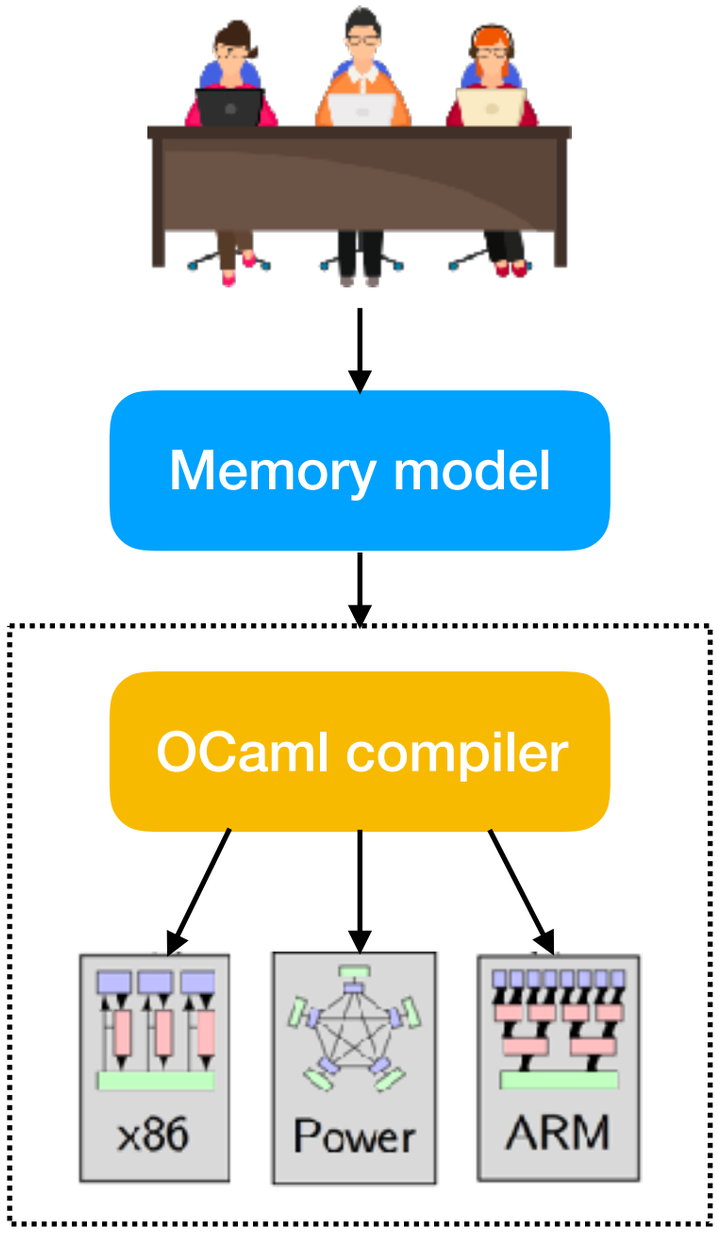

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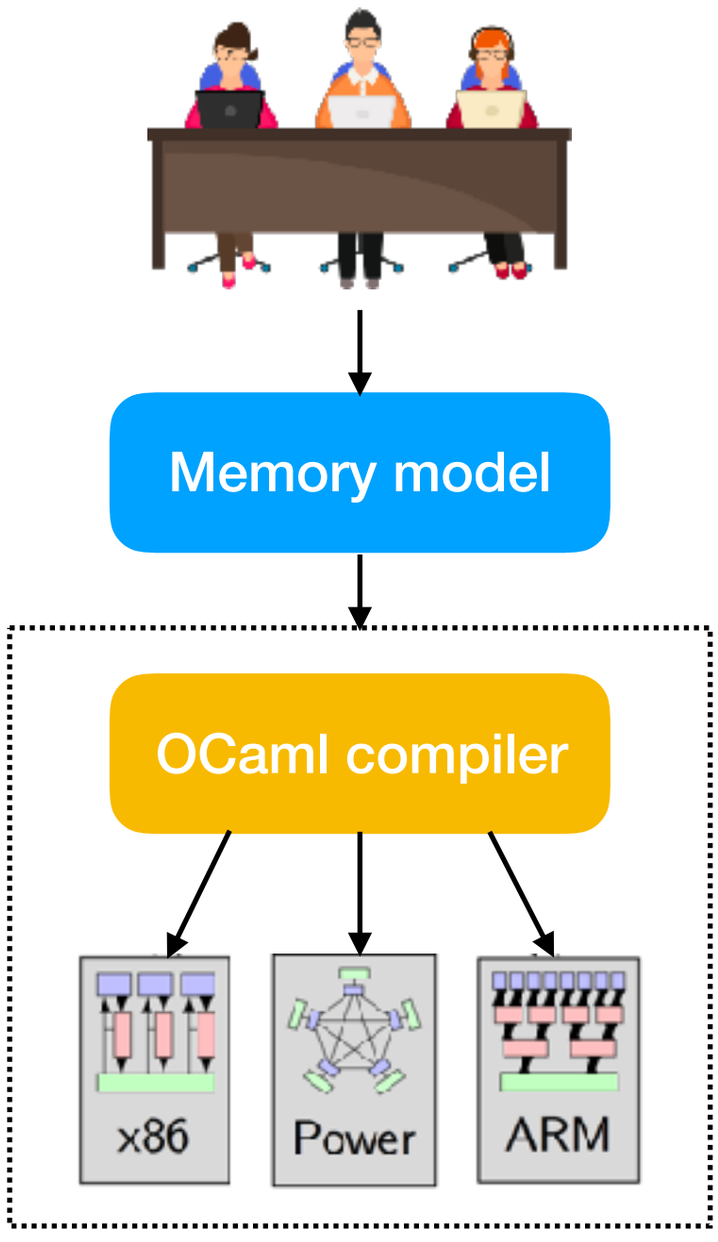

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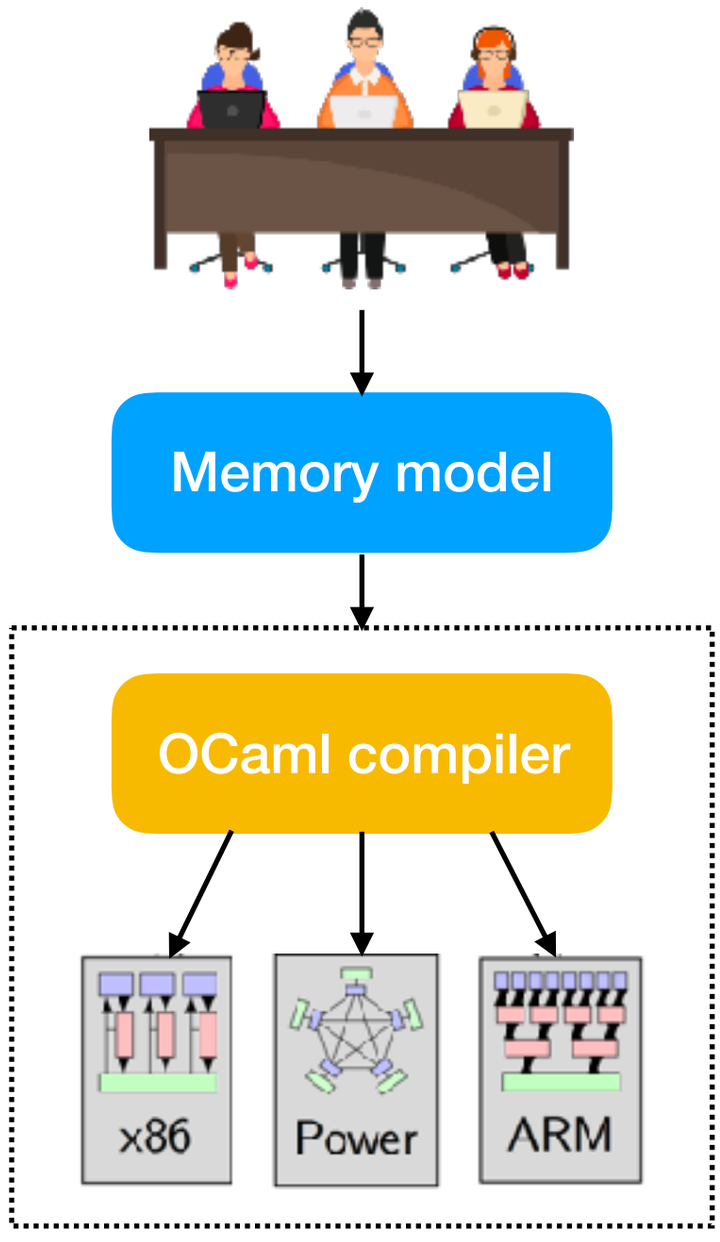

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- Difficult to get right
  - ★ C/C++11 memory model is flawed
  - ★ Java memory model is flawed
  - ★ Several papers every year in top PL conferences proposing / fixing models

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- **DRF-SC**: primary tool in concurrent programmers arsenal
  - ★ *If a program has no races (under SC semantics), then the program has SC semantics*
  - ★ Well-synchronised programs do not have surprising behaviours
- *Our observation: DRF-SC is too weak for programmers*

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- Races on unrelated locations can affect behaviour
  - ★ We would like a memory model where data races are ***bounded in space***

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int a;
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Thread 1

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a = 1;
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a = 2;
if (flag) {
  // no race here
  r1 = a;
  r2 = a;
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Can assert (r1 == 42) fail?

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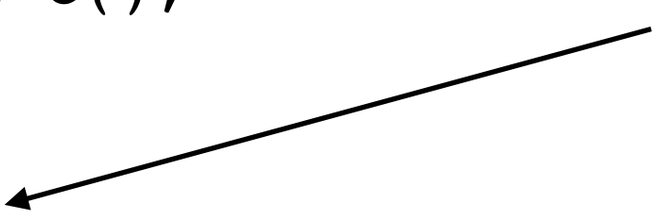

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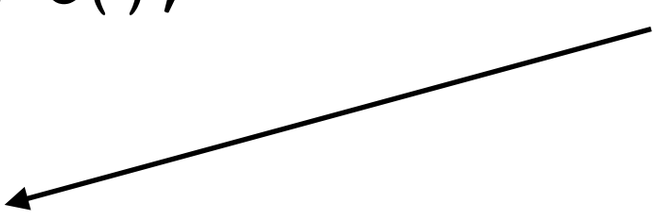

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- We would like a memory model that bounds data races in ***time***

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If I read a variable twice and there are no concurrent writes, then both reads return the same value

OCaml MM: Contributions

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- OCaml Memory model
  - ★ *Local version of DRF-SC — key discovery*
  - ★ Free on x86, 0.6% overhead on ARM, 2.6% overhead on POWER
  - ★ Allows most common compiler optimisations
  - ★ Simple operational and axiomatic semantics + proved soundness (optimization + to-hardware)

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Flag is atomic

Thread 1

```
msg = 1;
b = 0;
Flag = 1;
```

Thread 2

```
b = 1;
if (Flag) {
  r = msg;
}
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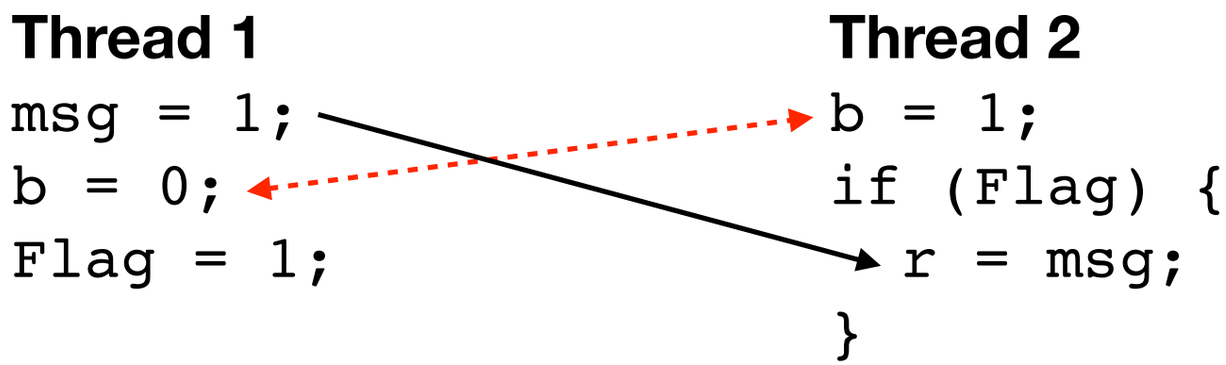

Due to local DRF, despite the race on **b**, message-passing idiom still works!

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(SILENT) $$\frac{e \overset{\epsilon}{\rightsquigarrow} e'}{\langle S, P[i \mapsto (F, e)]\rangle \rightarrow \langle S, P[i \mapsto (F, e')]\rangle}$$

(MEMORY) $$\frac{e \overset{\ell:\phi}{\rightsquigarrow} e' \qquad S(\ell); F \overset{\ell:\phi}{\longrightarrow\!\!\!\!\!\rightarrow} C'; F'}{\langle S, P[i \mapsto (F, e)]\rangle \rightarrow \langle S[\ell \mapsto C'], P[i \mapsto (F', e')]\rangle}$$

(b) Machine steps

(READ-NA) $H; F \xrightarrow{\text{a: read } H(t)} H; F$ if $F(\mathsf{a}) \leq t, t \in \mathrm{dom}(H)$

(WRITE-NA) $H; F \xrightarrow{\text{a: write } x} H[t \mapsto x]; F[\mathsf{a} \mapsto t]$ if $F(\mathsf{a}) < t, t \notin \mathrm{dom}(H)$

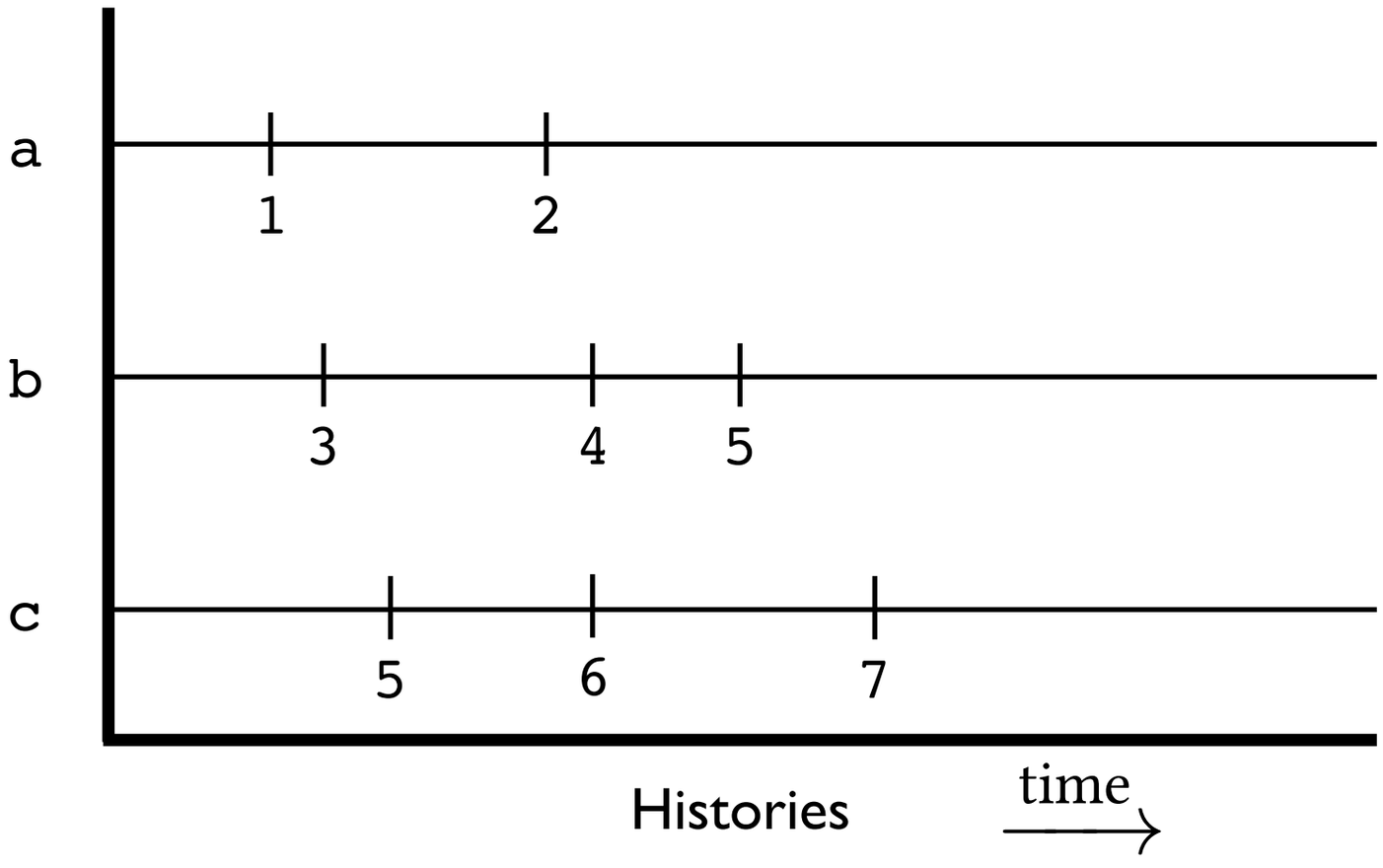
(READ-AT) $(F_{\mathsf{A}}, x); F \xrightarrow{\text{A: read } x} (F_{\mathsf{A}}, x); F_{\mathsf{A}} \sqcup F$

(WRITE-AT) $(F_{\mathsf{A}}, y); F \xrightarrow{\text{A: write } x} (F_{\mathsf{A}} \sqcup F, x); F_{\mathsf{A}} \sqcup F$

(c) Memory operations

Visualising operational semantics

Non atomic



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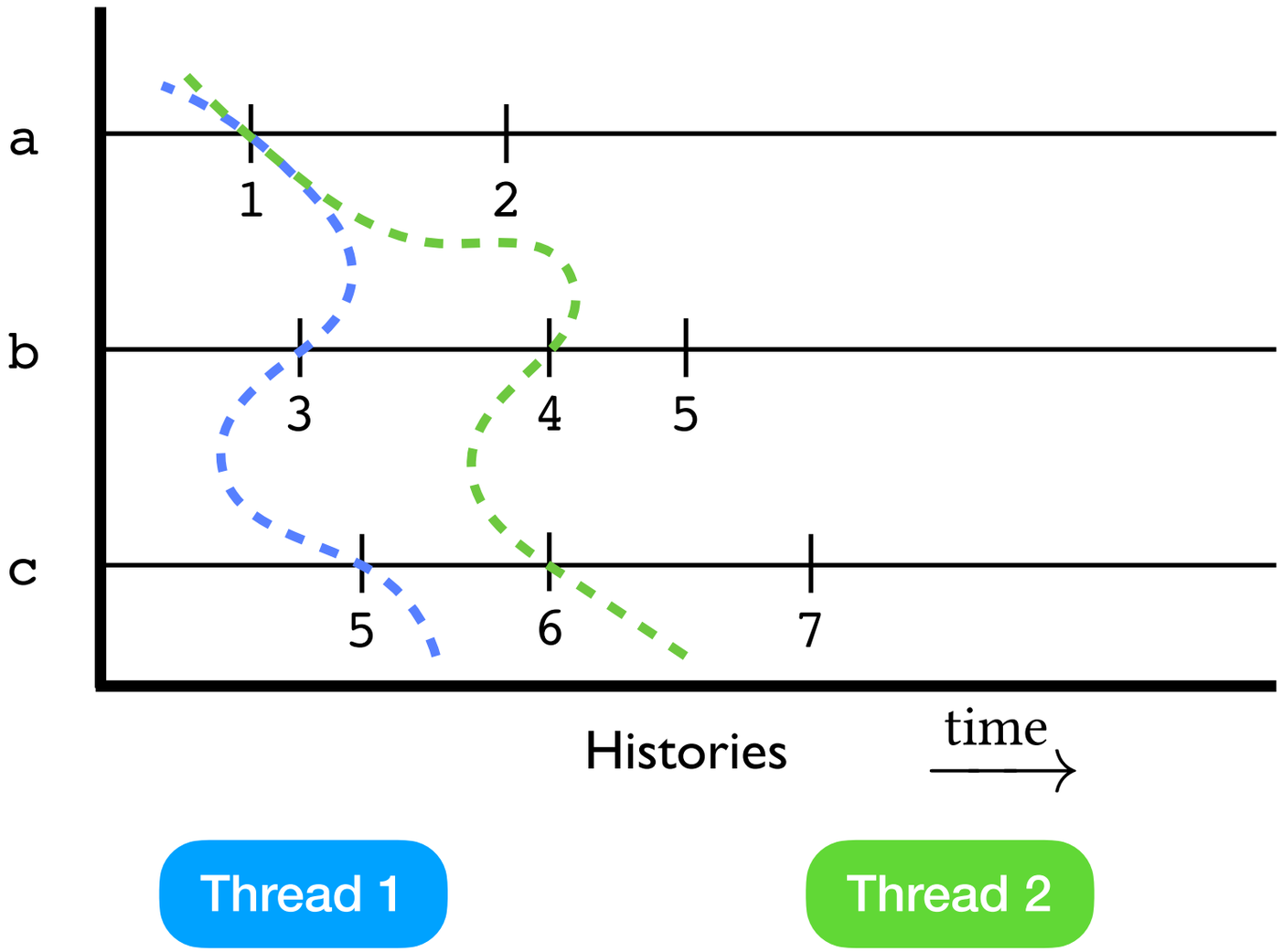

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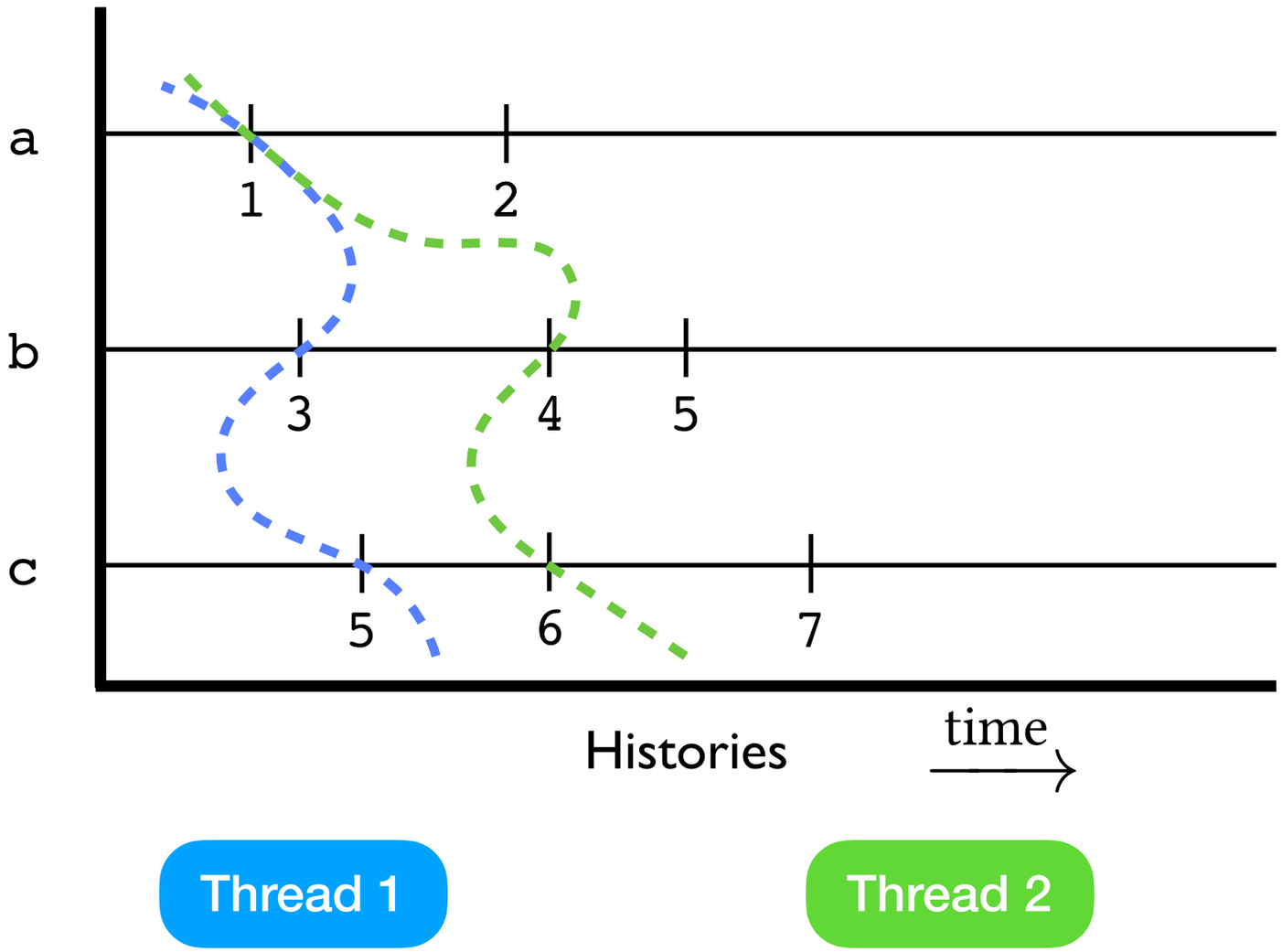


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read(b)
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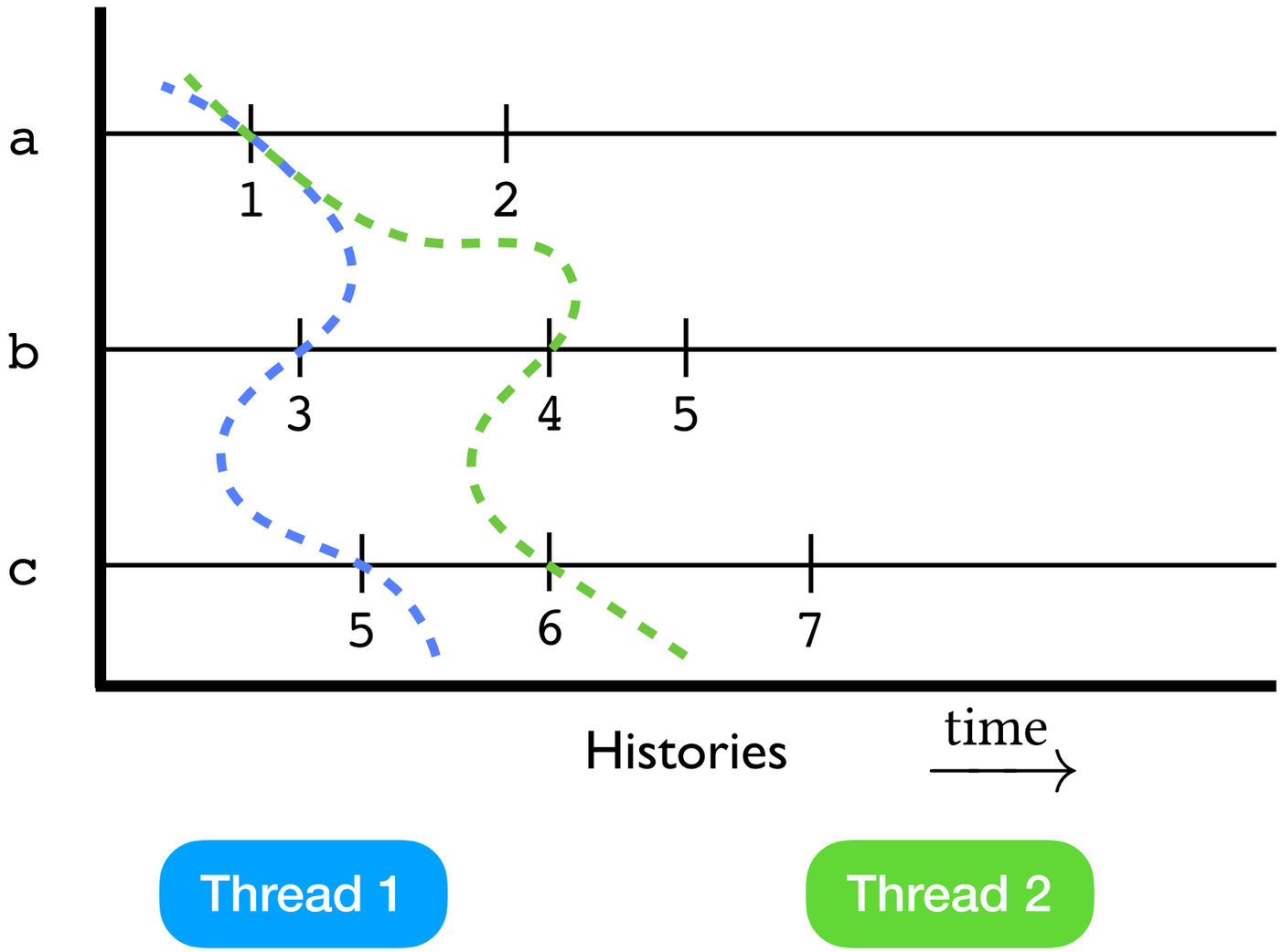


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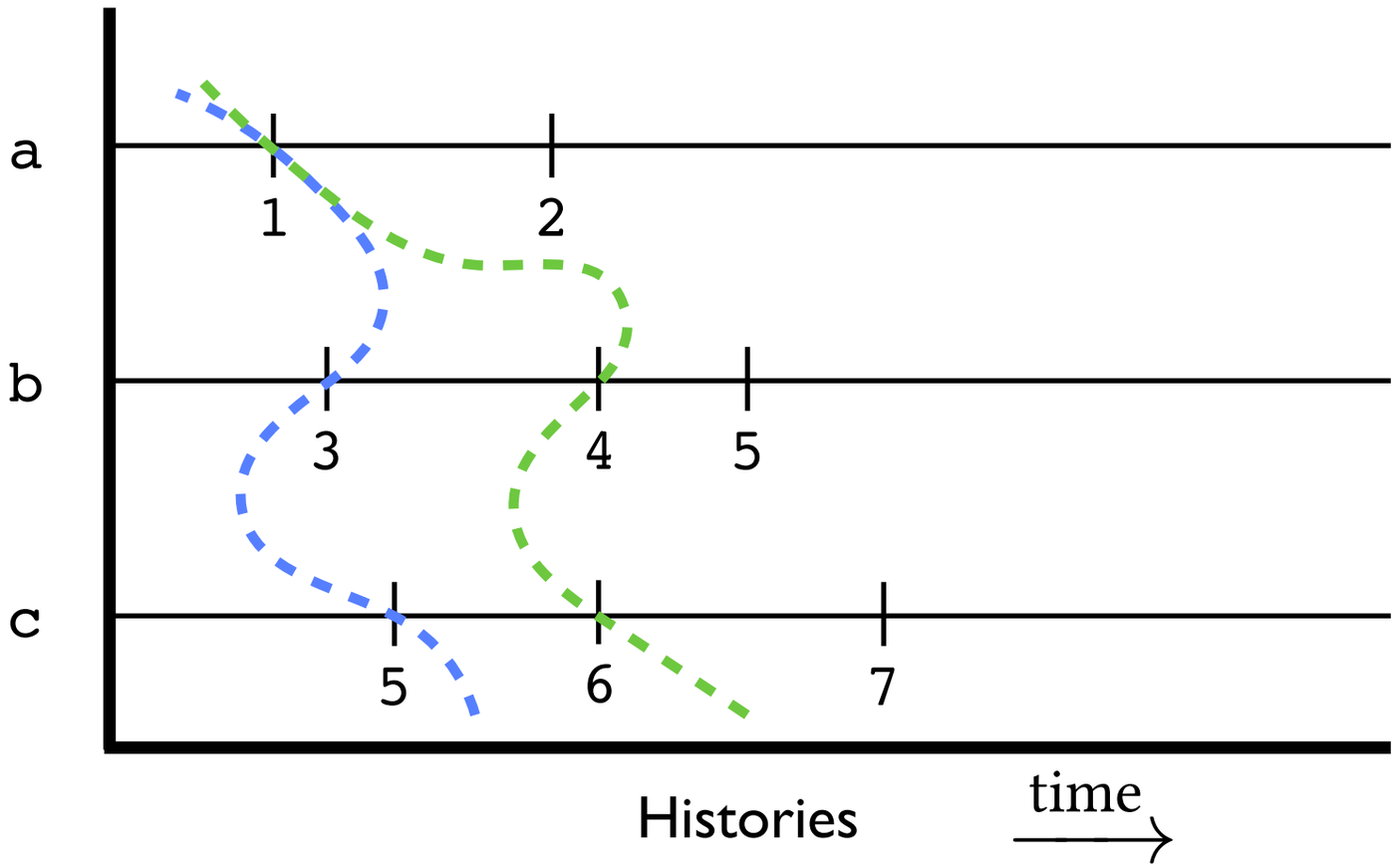

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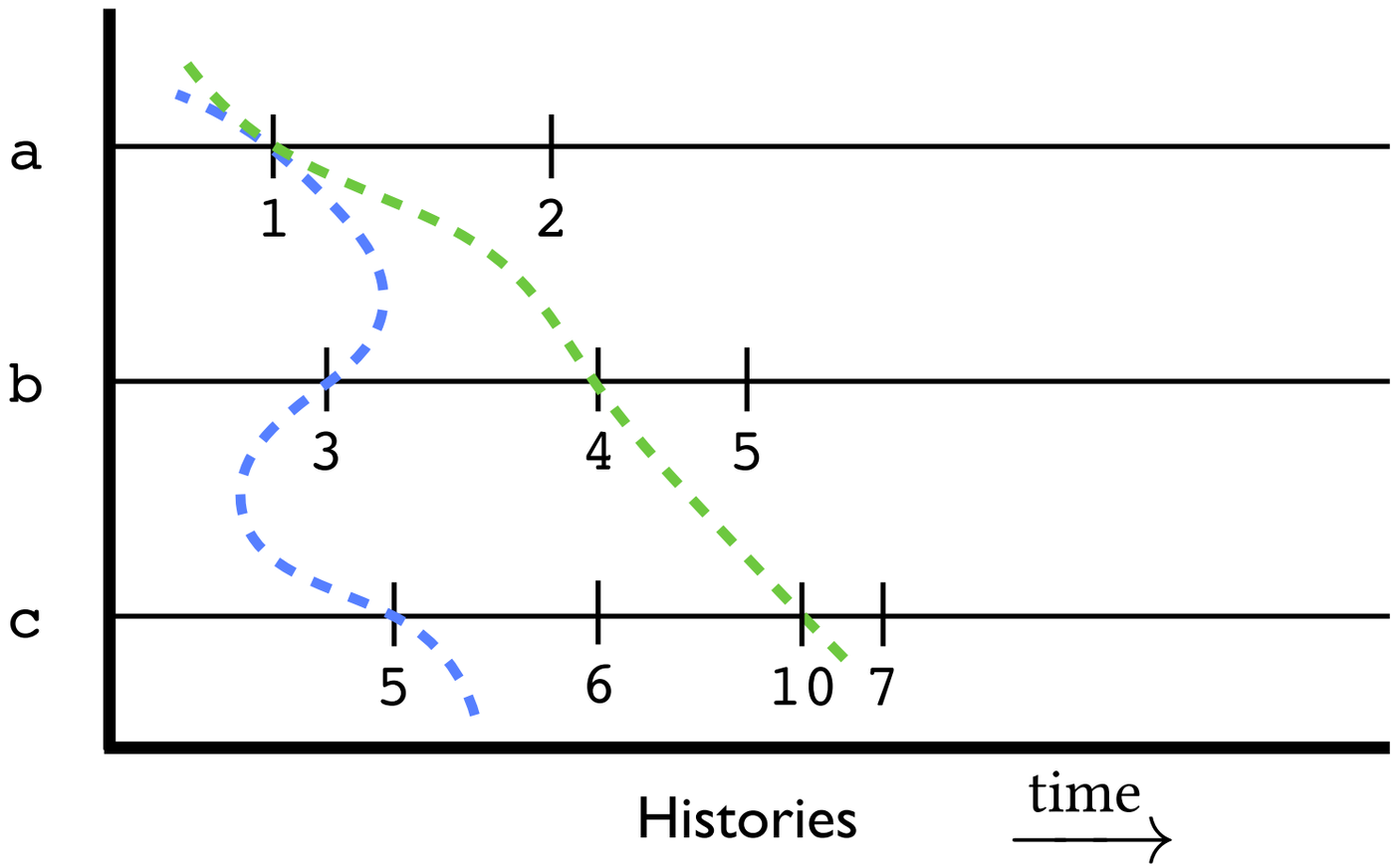

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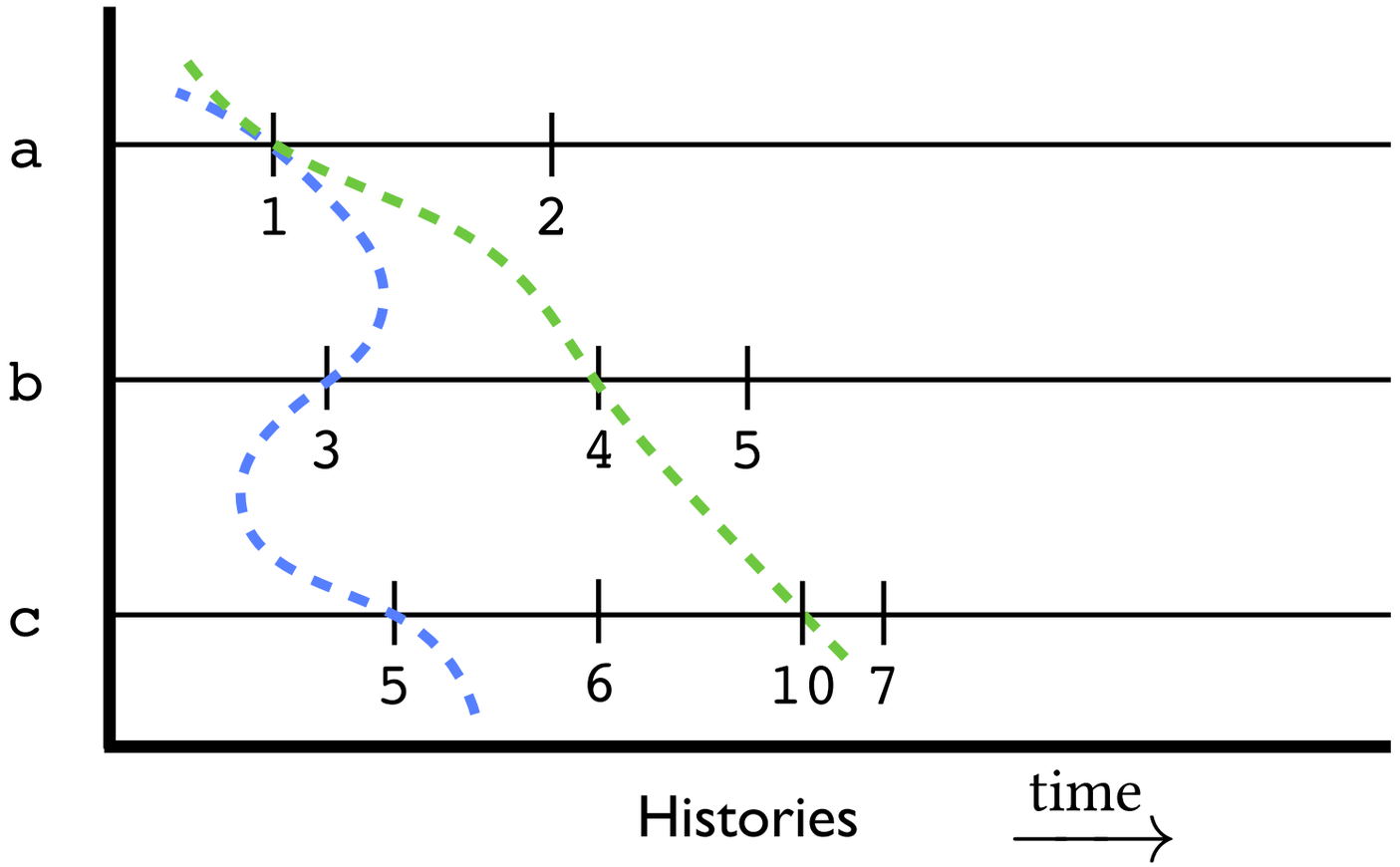

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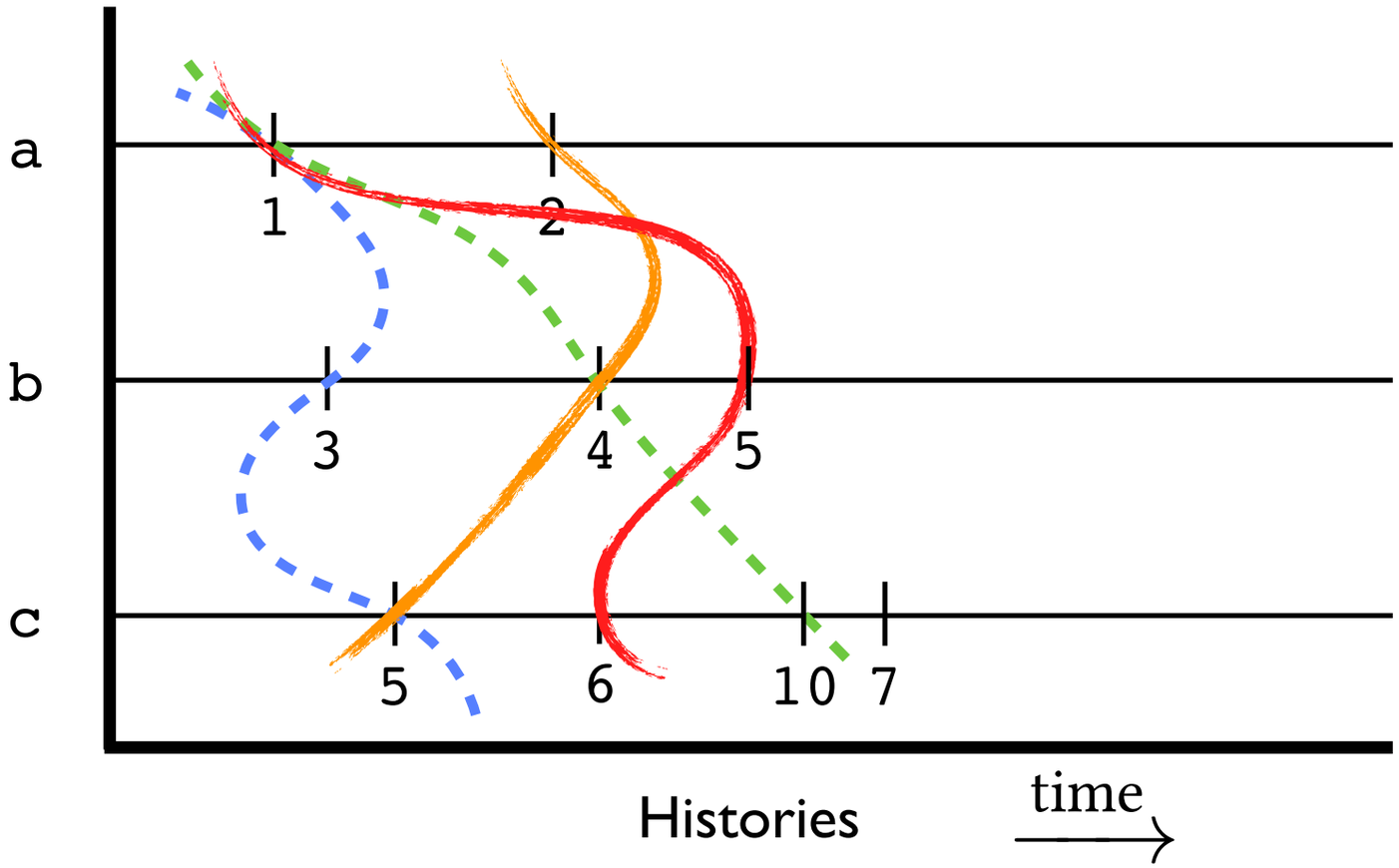

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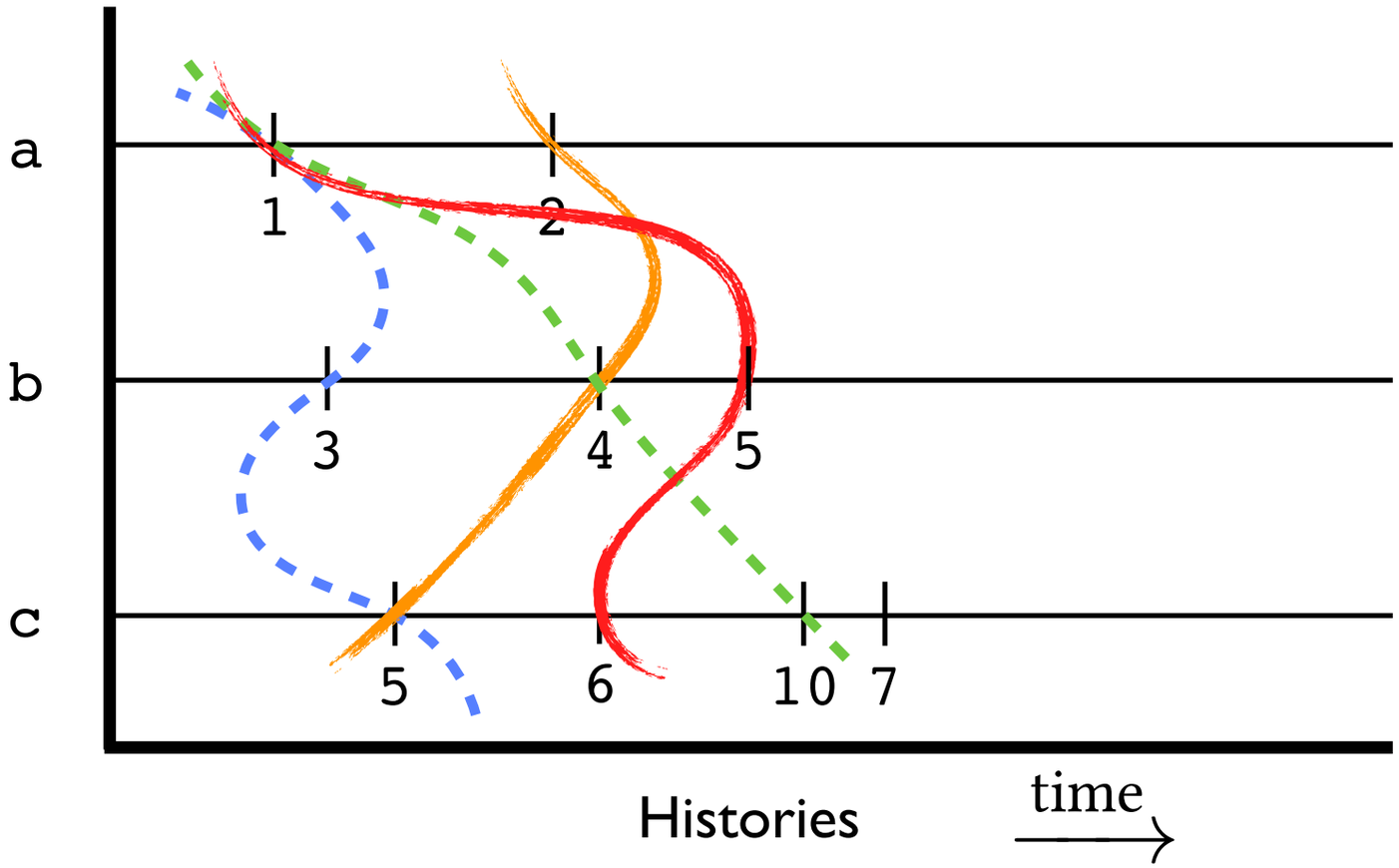

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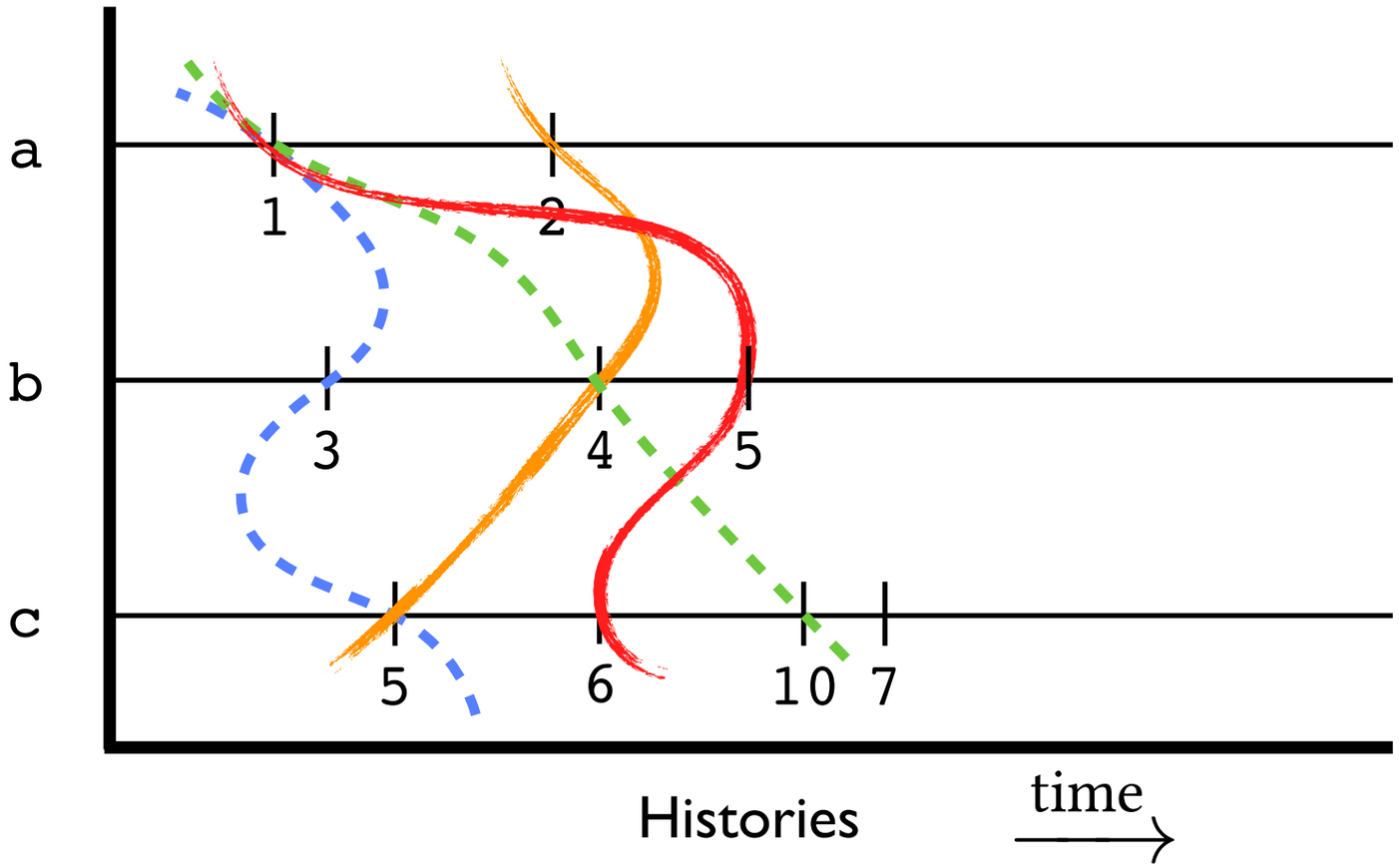

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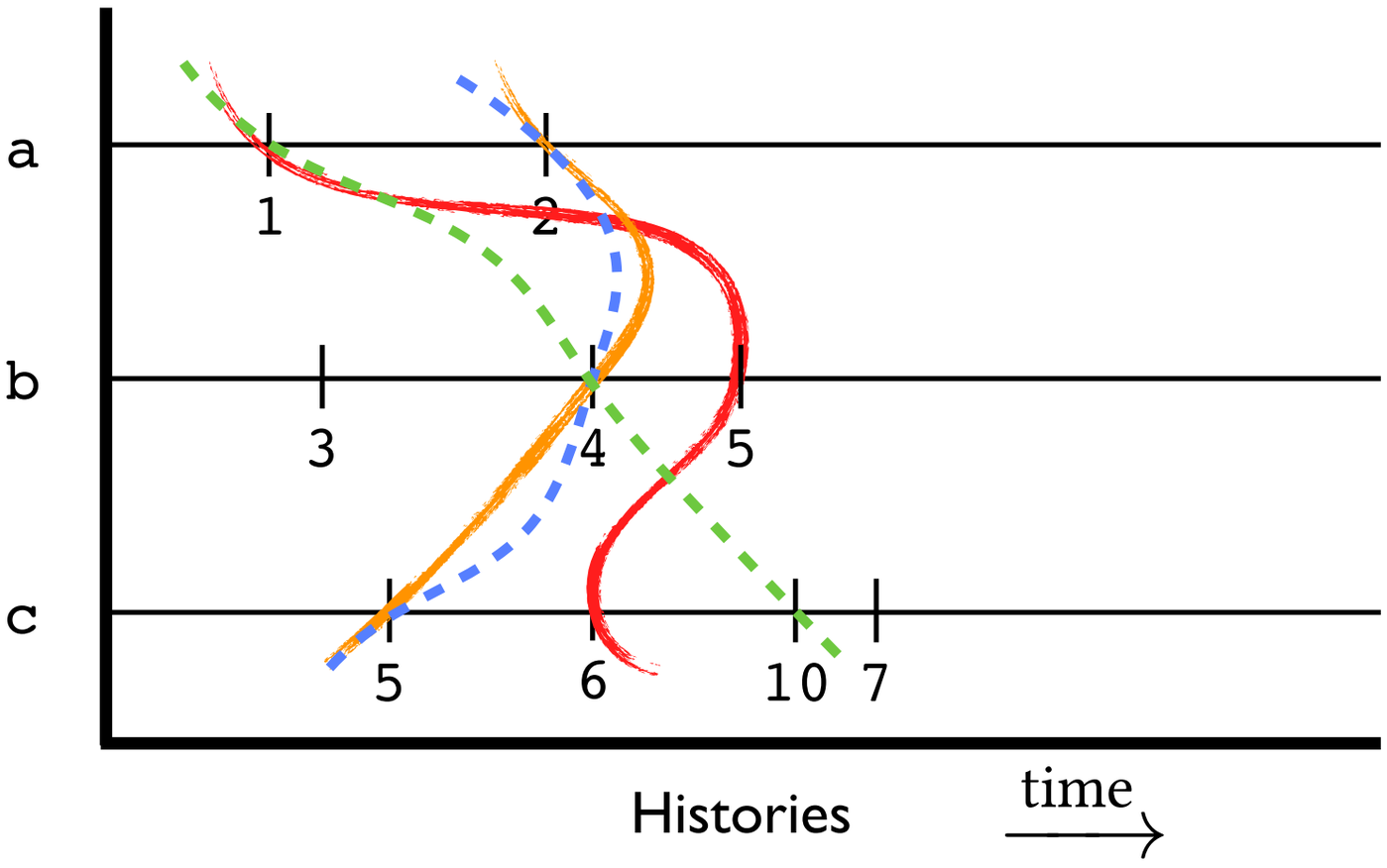
Visualising operational semantics

Non atomic



Thread 1

Thread 2

```
read(B) -> 5
```

Atomic

A 10

B 5

Visualising operational semantics

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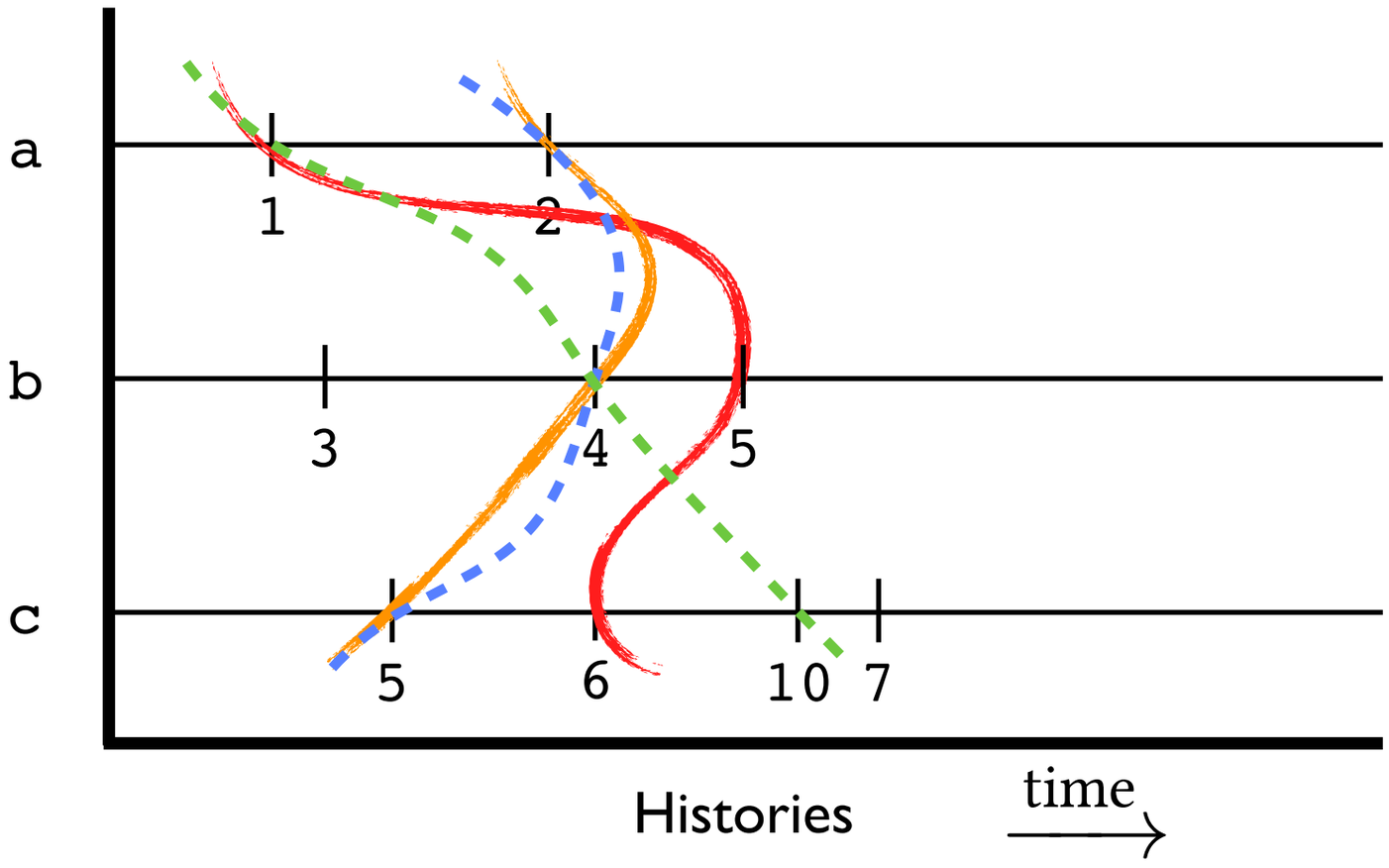


Atomic

A 10

B 5

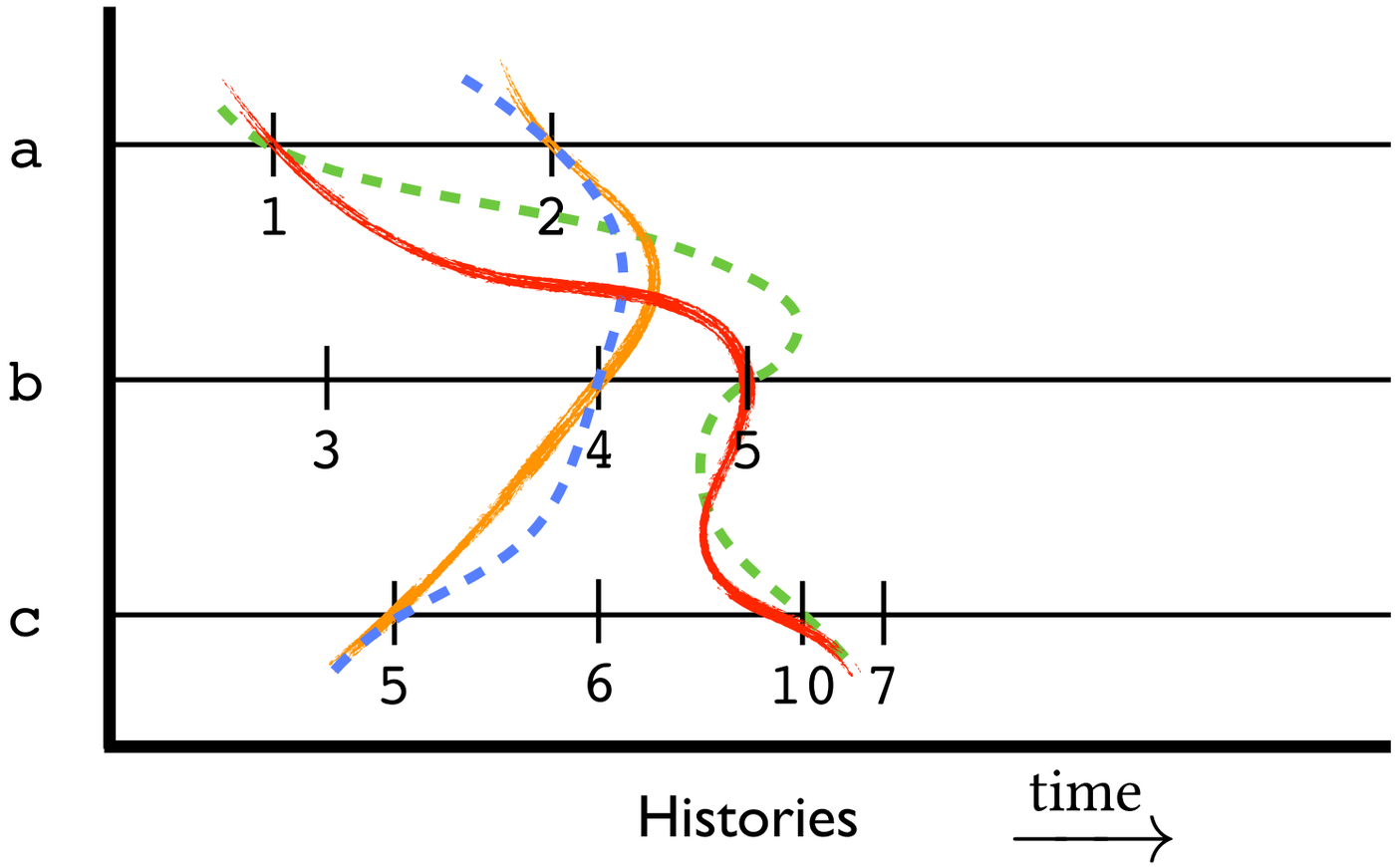
Thread 1

Thread 2

```
read(B) -> 5          write (A,20)
```

Visualising operational semantics

Non atomic



Atomic

A 20

B 5

Thread 1

```
read(B) -> 5
```

Thread 2

```
write (A,20)
```

Formalizing Local DRF

Trace $\Sigma = M_0 \xrightarrow{T_1} M_1 \xrightarrow{T_2} \ldots \xrightarrow{T_n} M_n$

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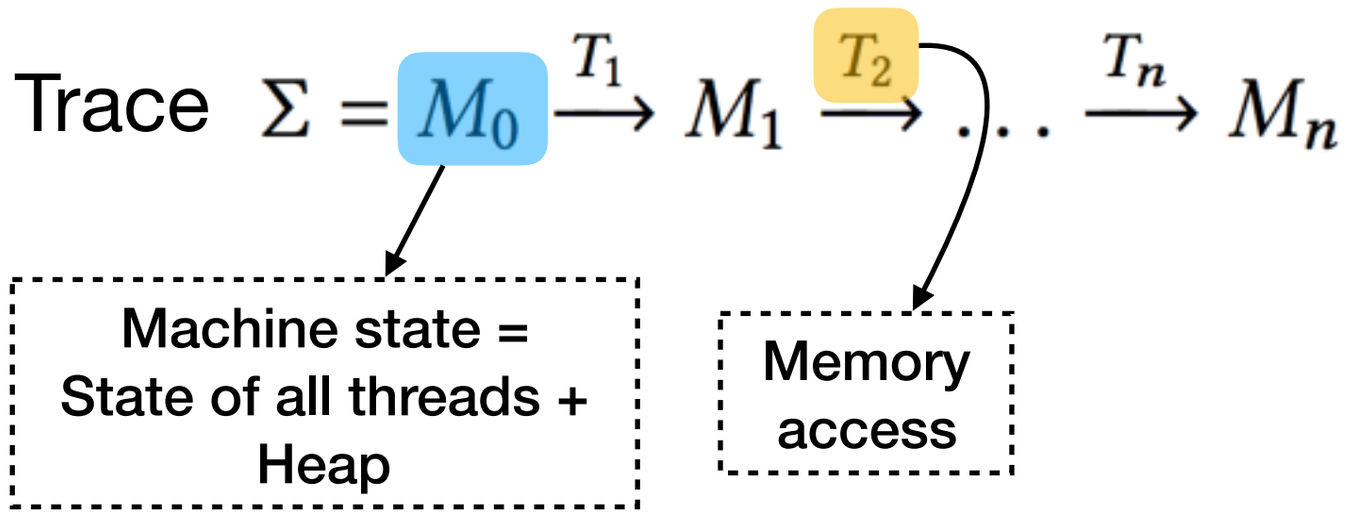
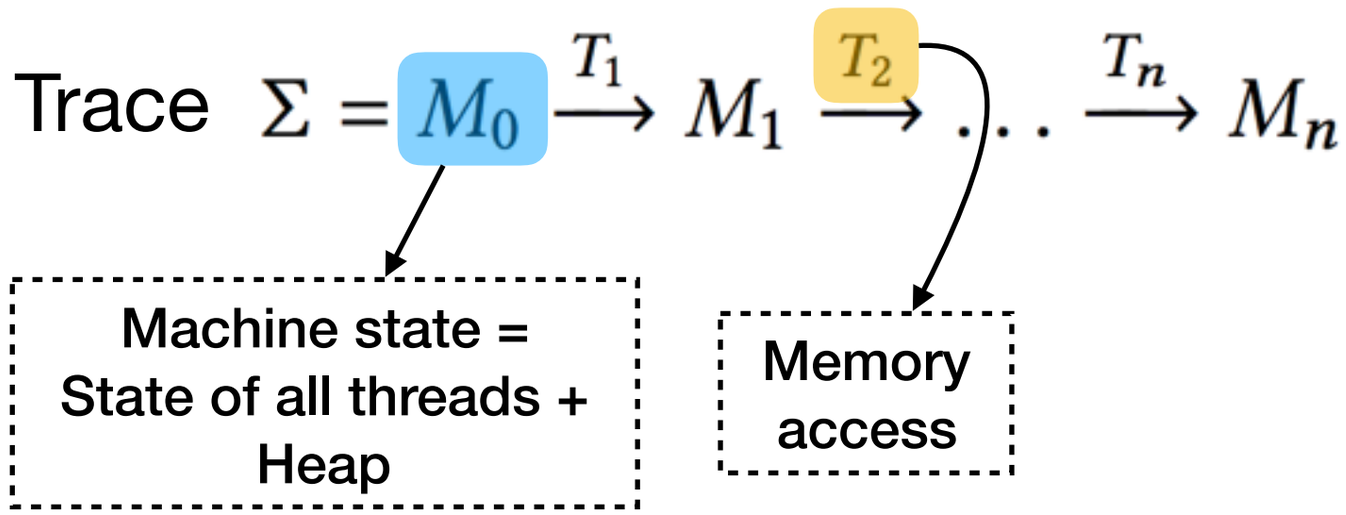
Machine state =
State of all threads +
Heap

Formalizing Local DRF

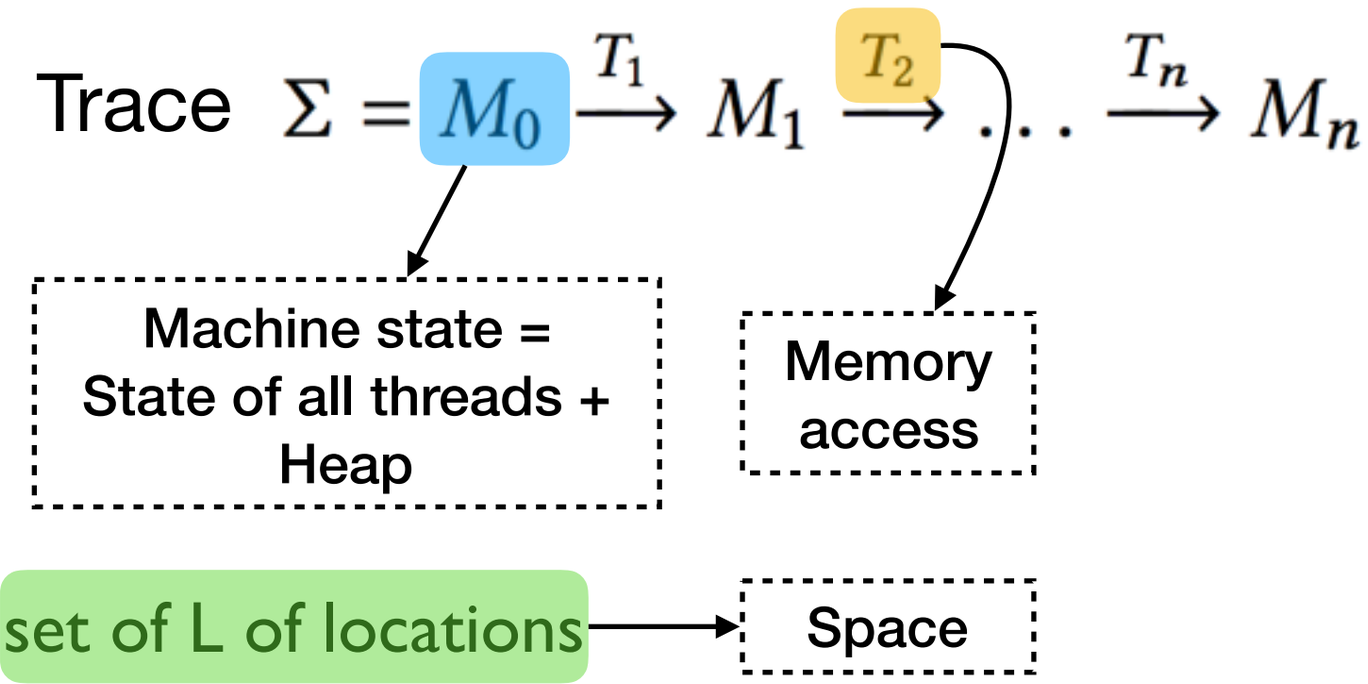


Formalizing Local DRF



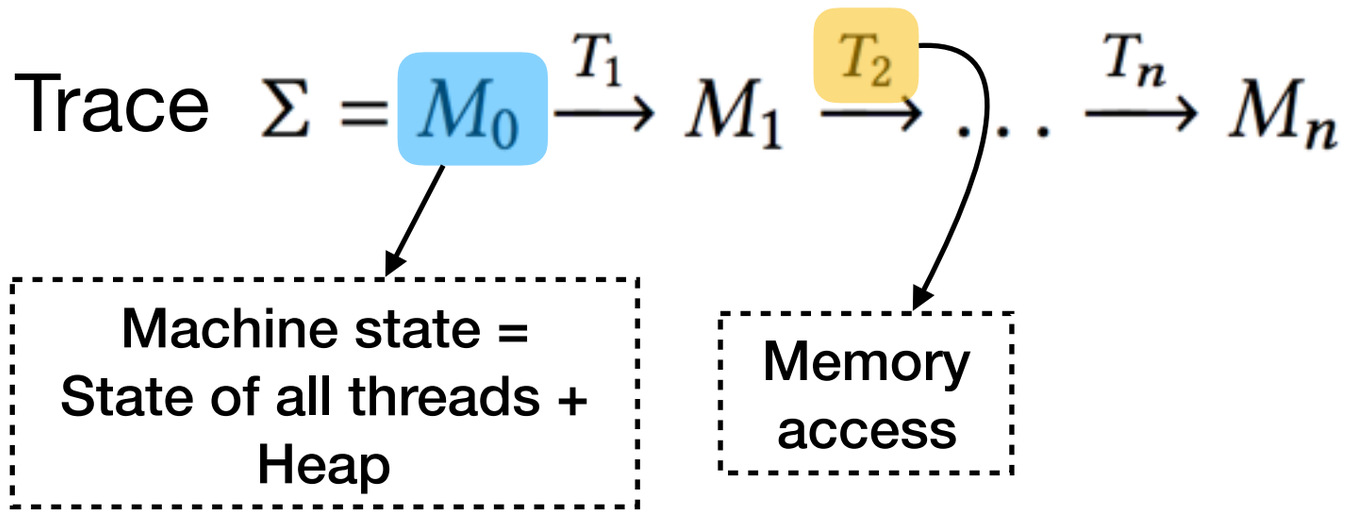
- Pick a set of L of locations

Formalizing Local DRF



- Pick a set of L of locations → Space

Formalizing Local DRF



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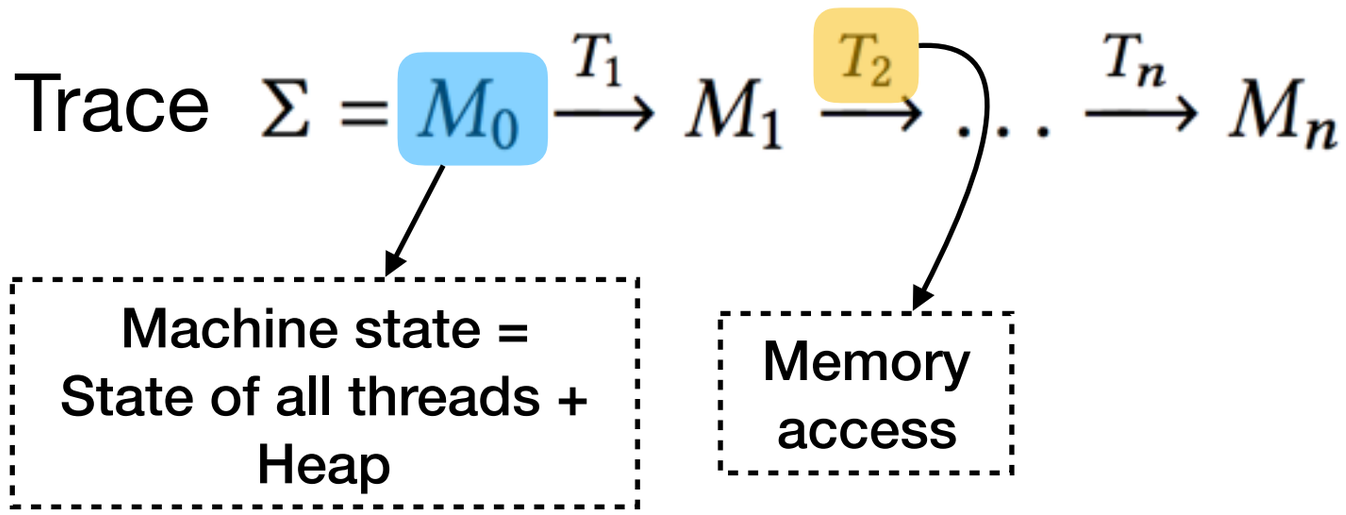
- Pick a machine state M where there are no ongoing races in L
  - ★ M is said to be L-stable

Formalizing Local DRF



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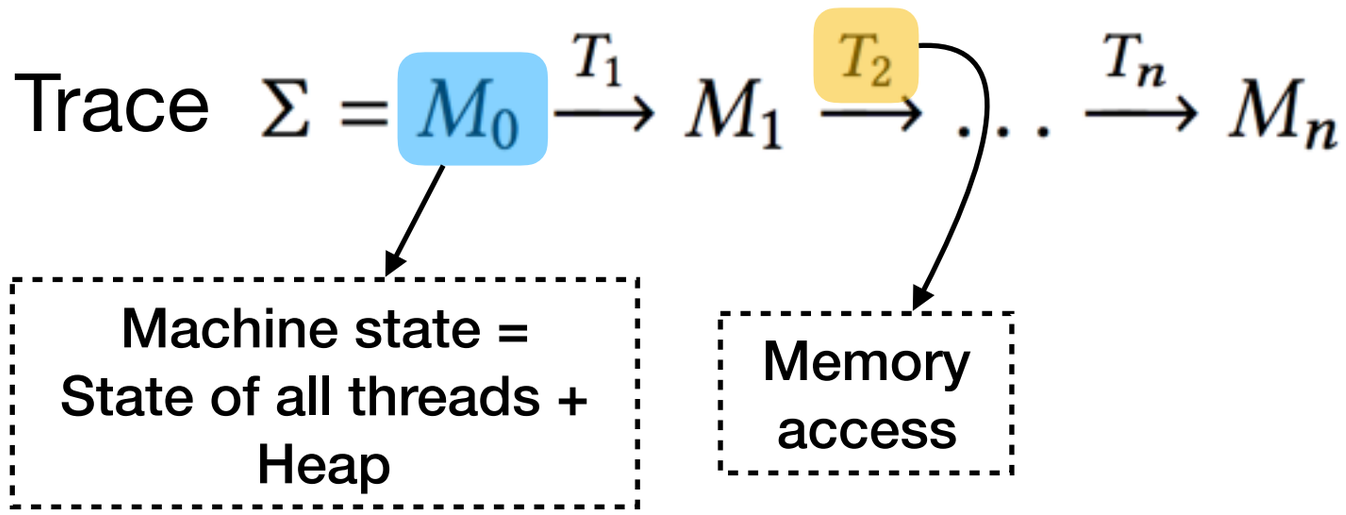

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Time

Performance Implication

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```
r1 = a;
b = c;      ——Redundant store elimination——→
a = r1;
```

```
r1 = a;
b = c;
;
```

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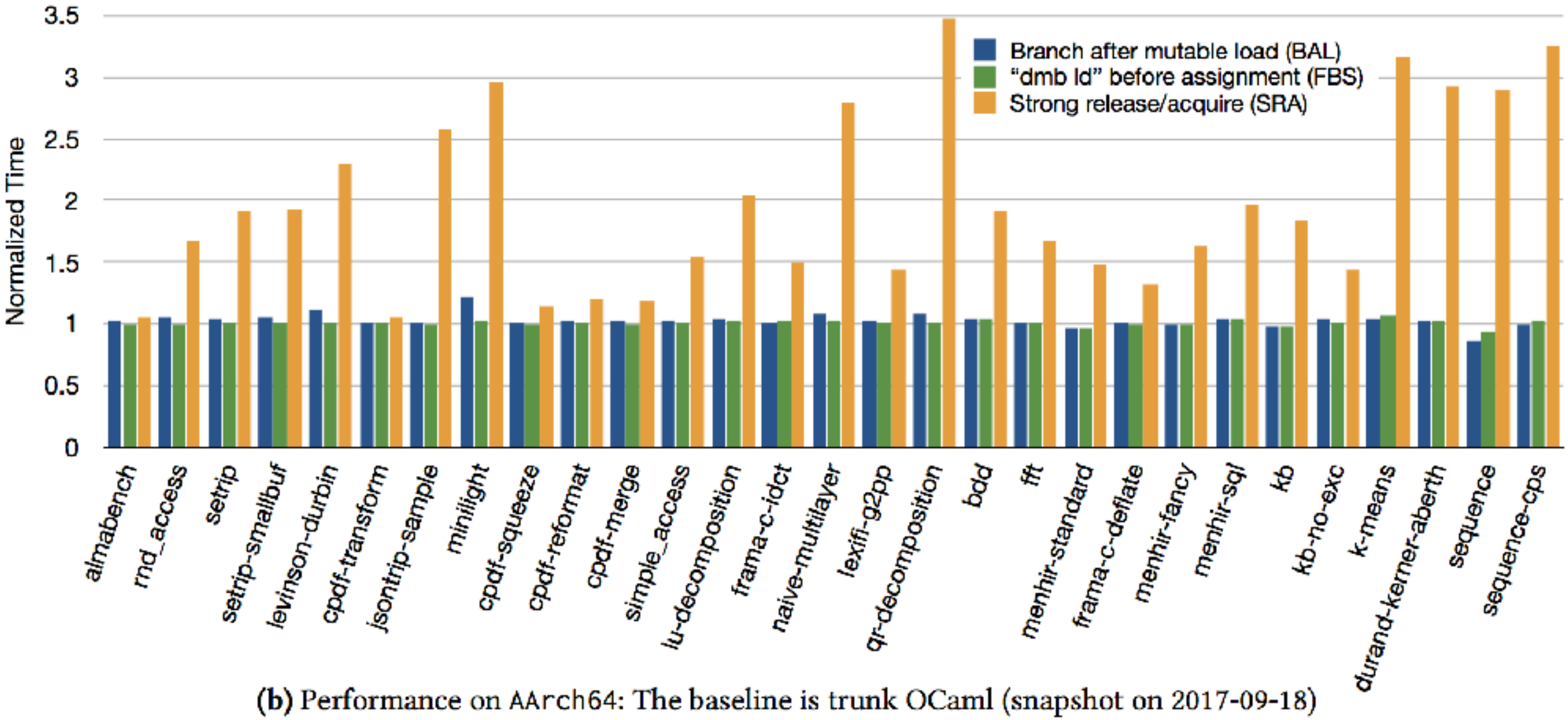
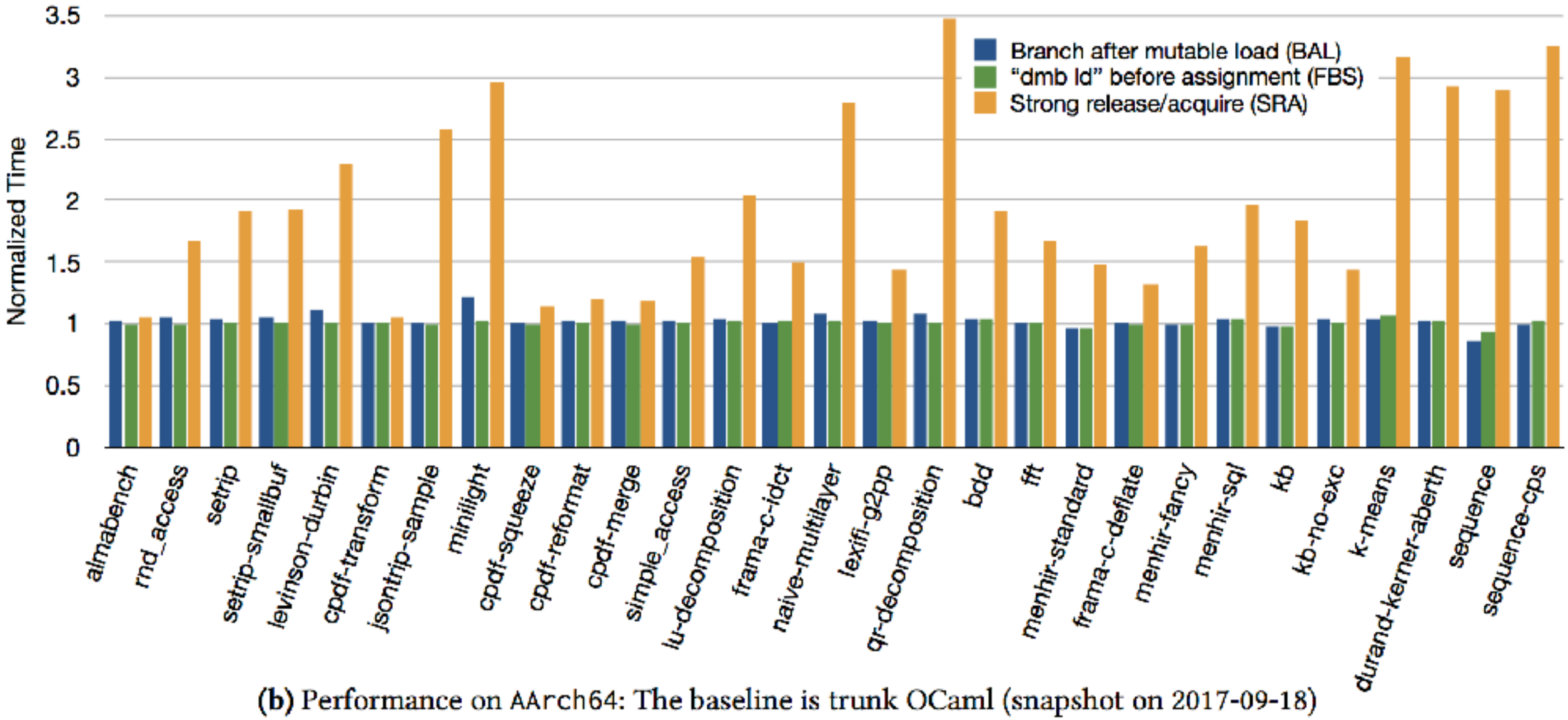
- ARM & POWER do not preserve load-to-store ordering
  - ★ Insert necessary synchronisation between every mutable load and store
  - ★ *What is the performance cost?*

Performance



(b) Performance on AArch64: The baseline is trunk OCaml (snapshot on 2017-09-18)

Performance



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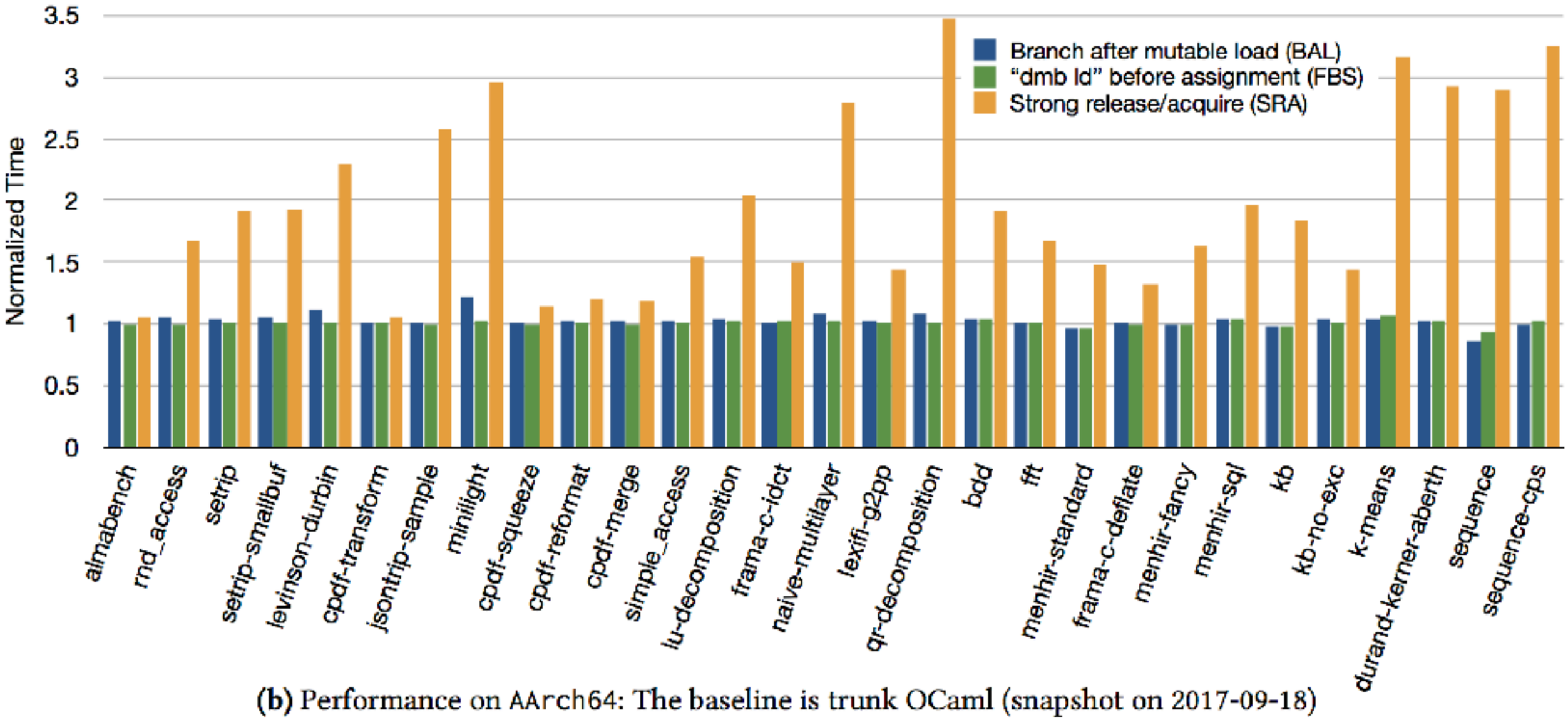
0.6% overhead on AArch64 (ARMv8)

Performance



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Summary

- OCaml memory model
  - ★ Balances *comprehensibility* (Local DRF theorem) and *Performance* (free on x86, 0.6% on ARMv8, 2.6% on POWER)
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  - ★ Compilation + Optimisations proved sound

Summary

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  - ★ Allows common compiler optimisations
  - ★ Compilation + Optimisations proved sound
- Proposed as the memory model for OCaml
  - ★ Also suitable for other safe languages (Swift, WebAssembly, JavaScript)