Verifying Concurrent Programs using Contracts

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Outline

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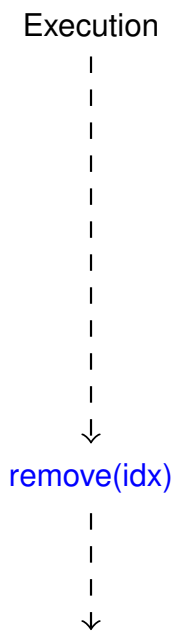

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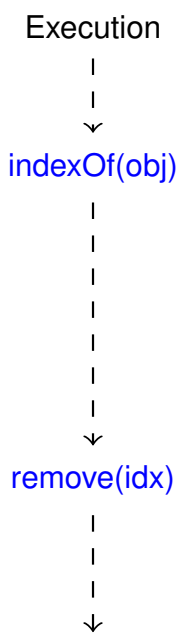

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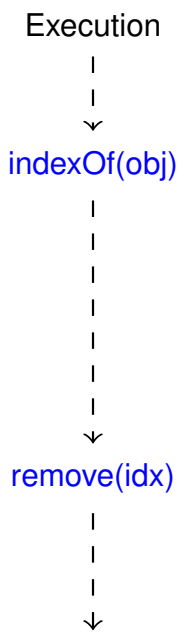

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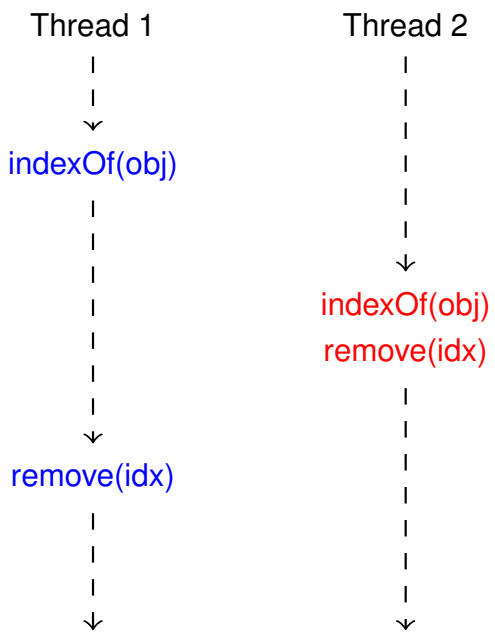

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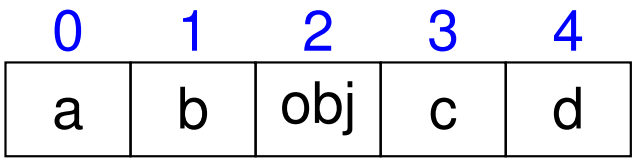

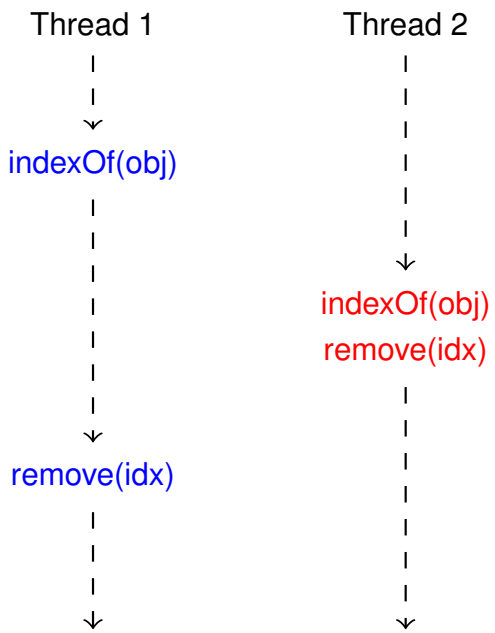

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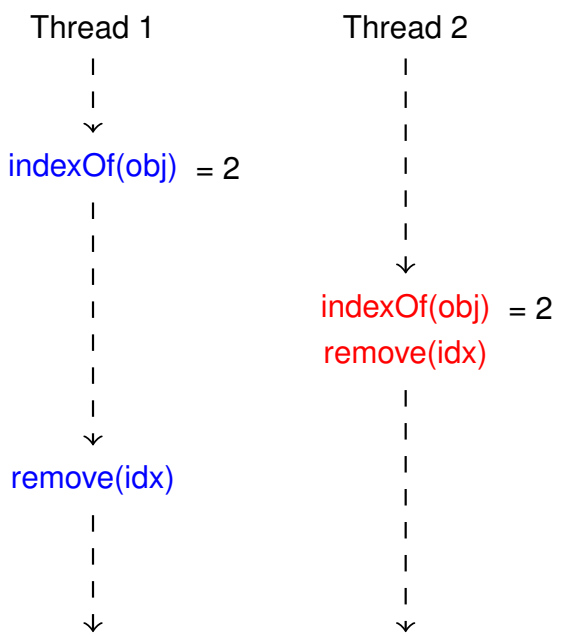
0	1	2	3	4
a	b	obj	c	d



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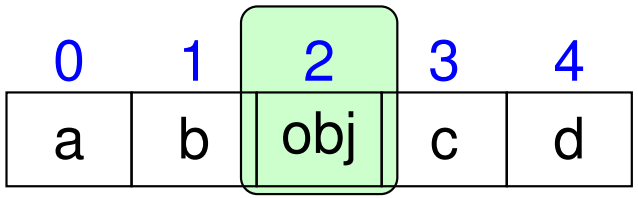

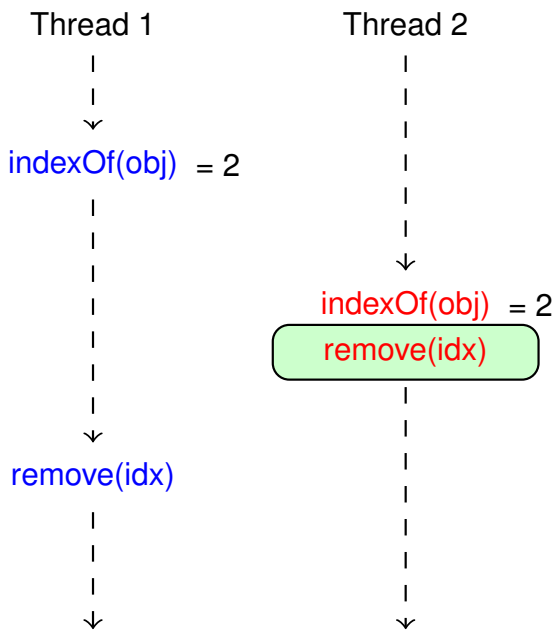

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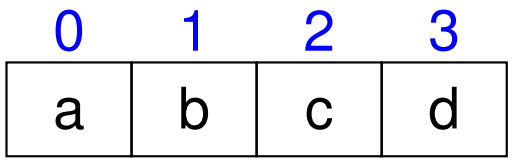

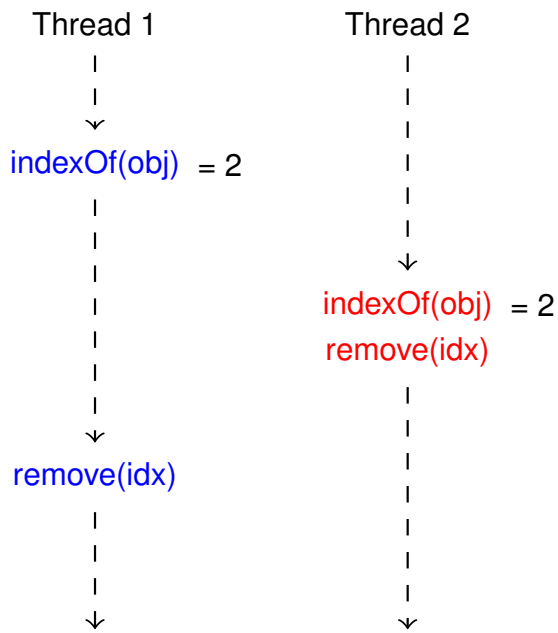

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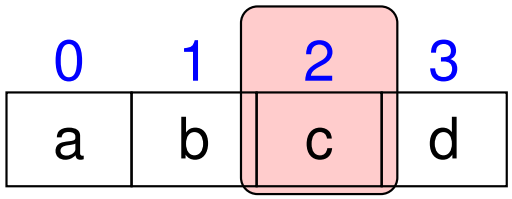

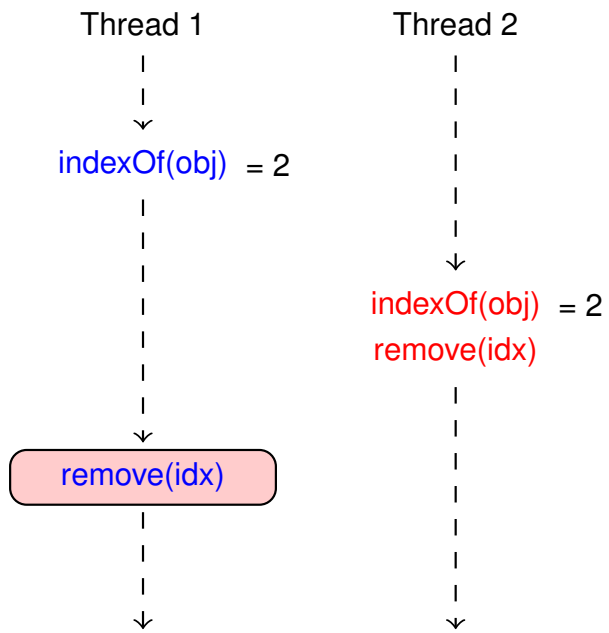

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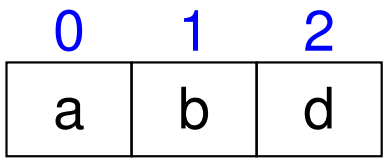

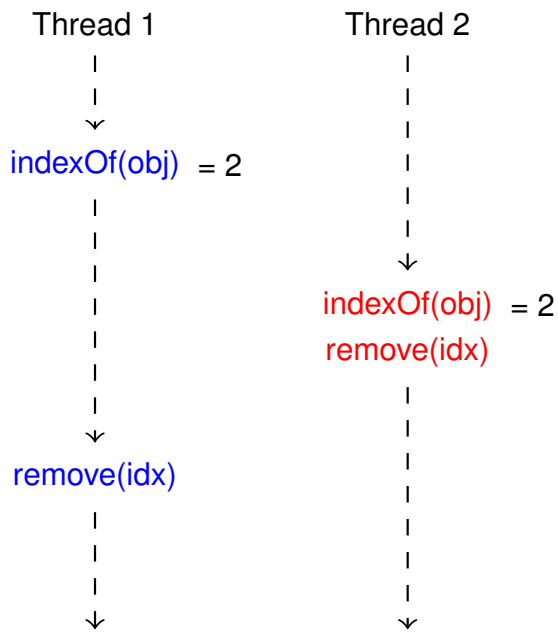

Contracts for Concurrency

Contract (in concurrent setting)

A sequence of method calls which must be executed atomically.

Definition

Let $\Sigma_{\mathbb{M}}$ be a set of all public method names (the API) of a software module (or library). A *contract* is a set $\mathbb{R}$ of *clauses* where each clause $\varrho \in \mathbb{R}$ is a regular expression over $\Sigma_{\mathbb{M}}$. A contract violation occurs if any of the sequences represented by the contract clauses is interleaved with an execution of methods from $\Sigma_{\mathbb{M}}$.

Contract for the `java.util.ArrayList` class

(ϱ_1) `contains indexOf`
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Extending Contracts with Parameters

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```
void replace(Object a, Object b) {
  if (array.contains(a)) {
    int idx=array.indexOf(a);
    array.set(idx,b);
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void erase(Object c) {
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void f() {
  Object x,y,z;
  ...
  replace(x,y);
  ...
  erase(z);
}
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Contract contains indexOf violated!

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Extending Contracts with Parameters

- Allows one to express how the flow of data influences the dependencies between methods
- Contract specification extended by considering
  - Method call parameters
  - Return values
- Expressed as meta-variables

Contract for the `java.util.ArrayList` class

(ϱ'_1) `contains(X)` `indexOf(X)`
(ϱ'_2) `X = indexOf(_)` (`remove(X)` | `set(X,_)` | `get(X)`)
(ϱ'_3) `X = size()` (`remove(X)` | `set(X,_)` | `get(X)`)
(ϱ'_4) `add(X)` (`get(X)` | `indexOf(X)`)

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(ϱ'_1) `contains(X)` `indexOf(X)`
(ϱ'_2) `X` $=$ `indexOf(_)` (`remove(X)` | `set(X,_)` | `get(X)`)
(ϱ'_3) `X` $=$ `size()` (`remove(X)` | `set(X,_)` | `get(X)`)
(ϱ'_4) `add(X)` (`get(X)` | `indexOf(X)`)

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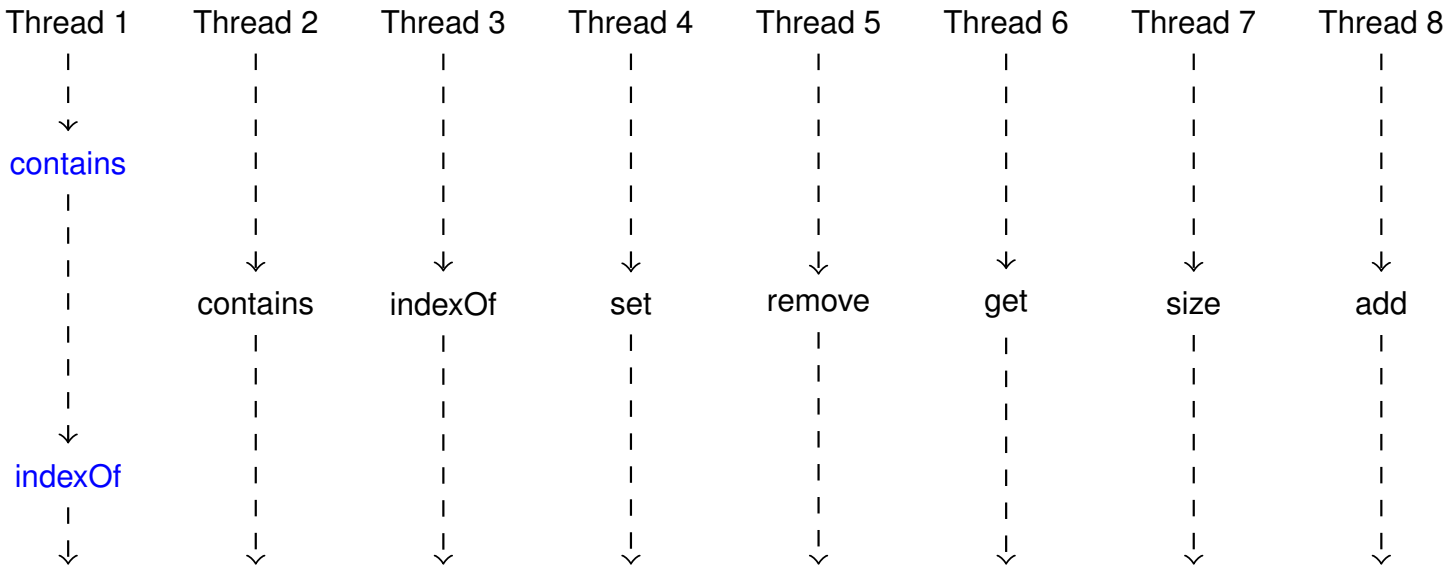

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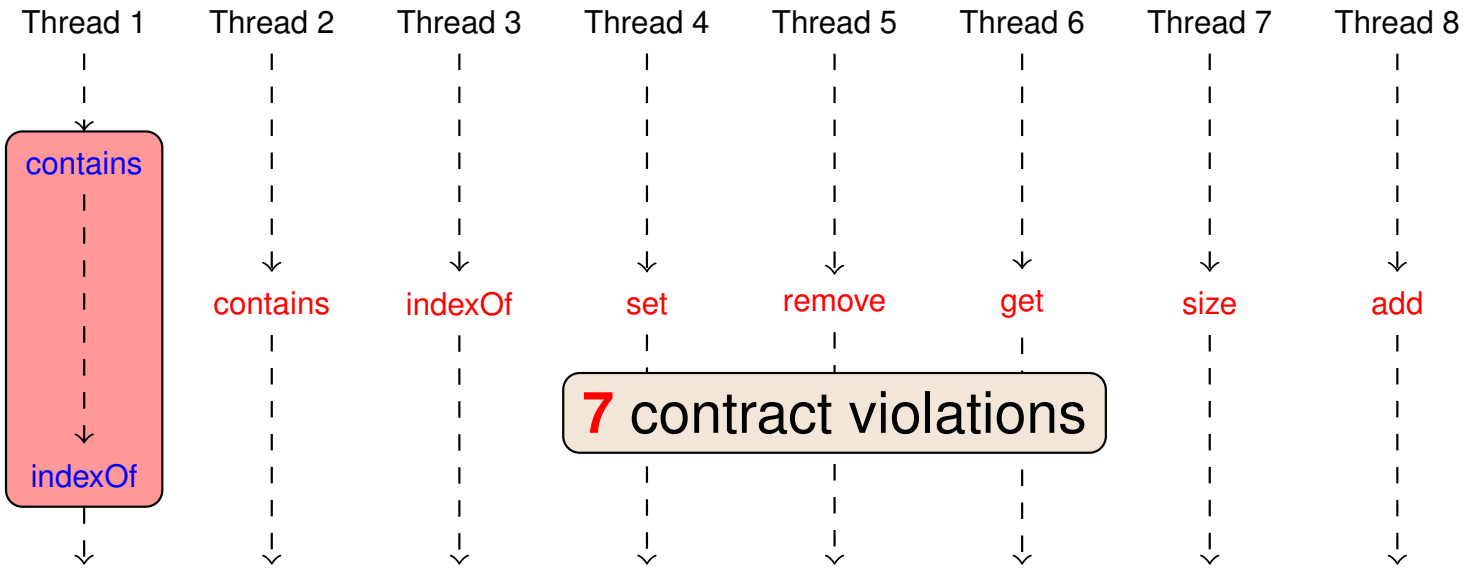

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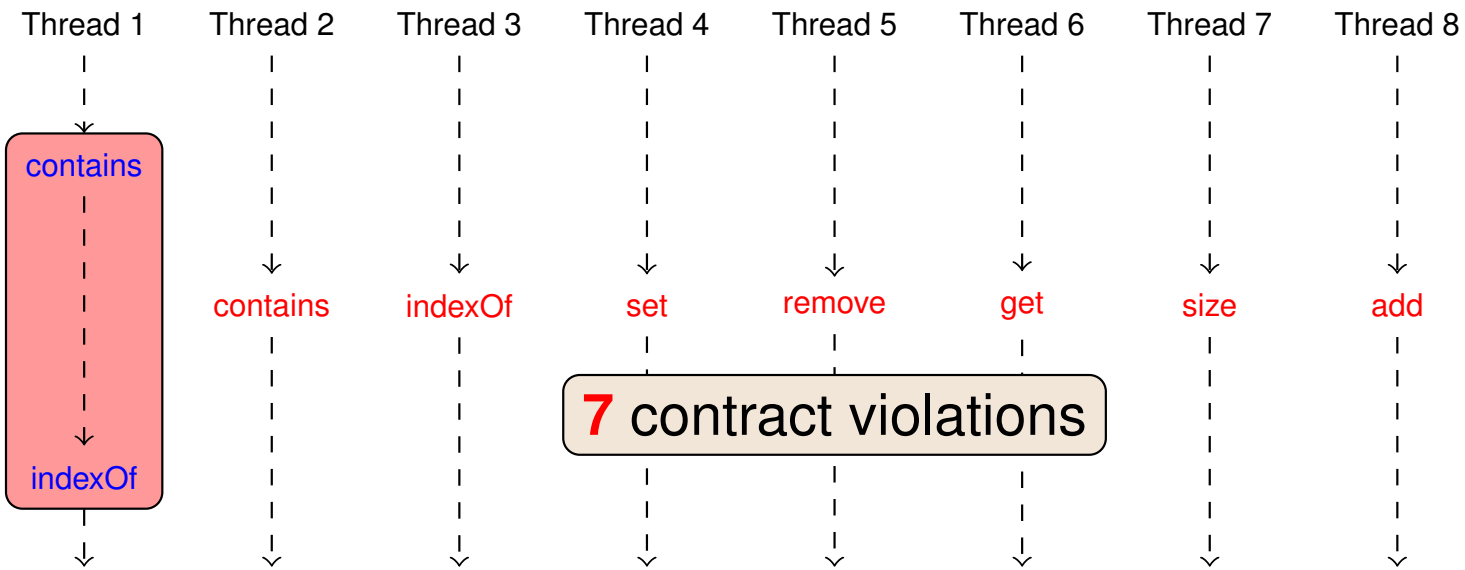
$\Sigma_{\mathbb{M}}$ (methods)

`contains`
`indexOf`
`set`
`remove`
`get`
`size`
`add`



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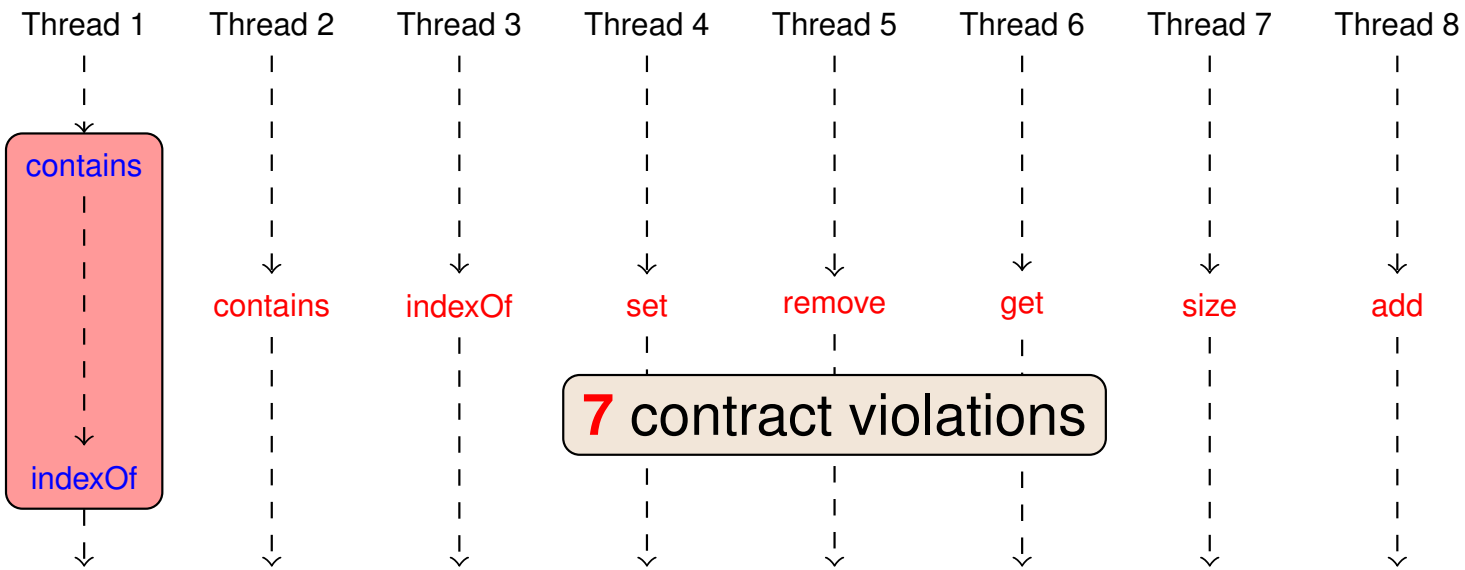

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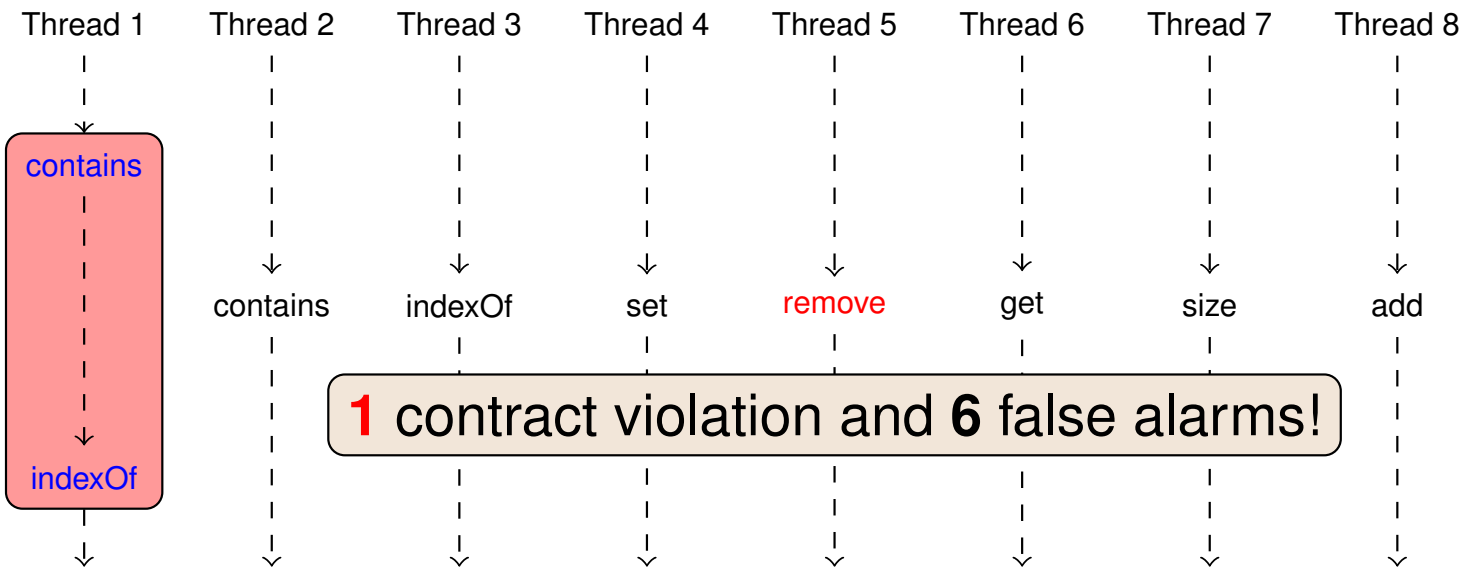

Extending Contracts with Spoilers

- Allows one to express in which context the contract clauses shall be enforced

Definition

Let $\mathbb{R}$ be the set of *target* clauses where each target $\varrho \in \mathbb{R}$ is a regular expression over $\Sigma_{\mathbb{M}}$. Let $\mathbb{S}$ be the set of *spoilers* where each spoiler $\sigma \in \mathbb{S}$ is a regular expression over $\Sigma_{\mathbb{M}}$. A *contract* is then a relation $\mathbb{C} \subseteq \mathbb{R} \times \mathbb{S}$ which defines for each target the spoilers that may cause atomicity violations.

Contract for the `java.util.ArrayList` class

(ϱ''_1) `contains indexOf` $\nleftrightsquigarrow$ `remove`
(ϱ''_2) `indexOf (remove | set | get)` $\nleftrightsquigarrow$ `remove | add | set`
(ϱ''_3) `size (remove | set | get)` $\nleftrightsquigarrow$ `remove`
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(ϱ_4'') `add indexOf` $\nleftrightsquigarrow$ `remove|set`

Static Validation

- Based on grammars and parsing trees
- Supports contracts with parameters only
- Analyses all executions of a program
  - May report false positives
- Uses points-to information to handle multiple instances of a module
- Class Scope Mode
  - Allows the analysis to handle large programs
  - Checks each class individually
  - Calls to other classes are ignored

Static Validation Algorithm

```
1  Require:  P: client's program, ℝ: module contract;
2  for t ∈ threads(P) do
3      G_t ← build_grammar(t);
4      G'_t ← subword_grammar(G_t);
5      for ϱ ∈ ℝ do
6          T ← parse(G'_t, ϱ);
7          for τ ∈ T do
8              N ← lowest_common_ancestor(τ, ϱ);
9              if ¬run_atomically(N) then return ERROR;
10 return OK;
```

Illustration of the Static Validation Approach

```
void run() {
  if (cond)
    f();
  else {
    m.indexOf();
    g();
  }
}
void atomic f() {
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}
void atomic g() {
  m.remove();
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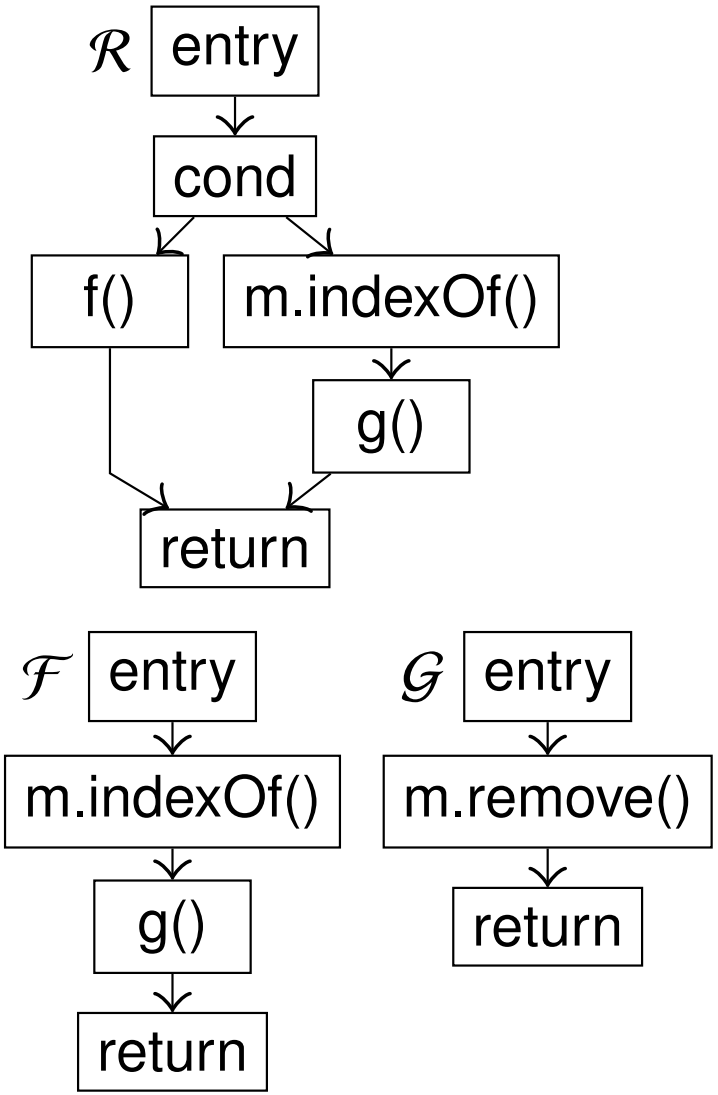

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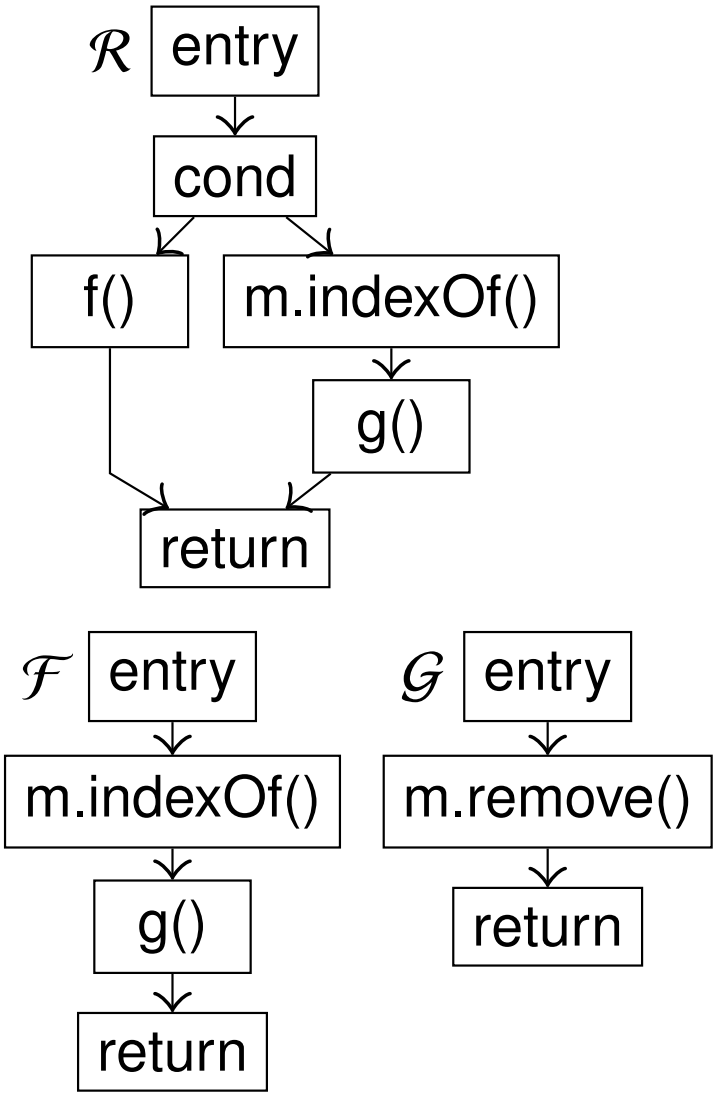

$\mathcal{R} \to \mathbf{a}\,\mathcal{G}$ $\quad$ $\mathcal{F} \to \mathbf{a}\,\mathcal{G}$

$\mathcal{R} \to \mathcal{F}$ $\quad$ $\mathcal{G} \to \mathbf{b}$

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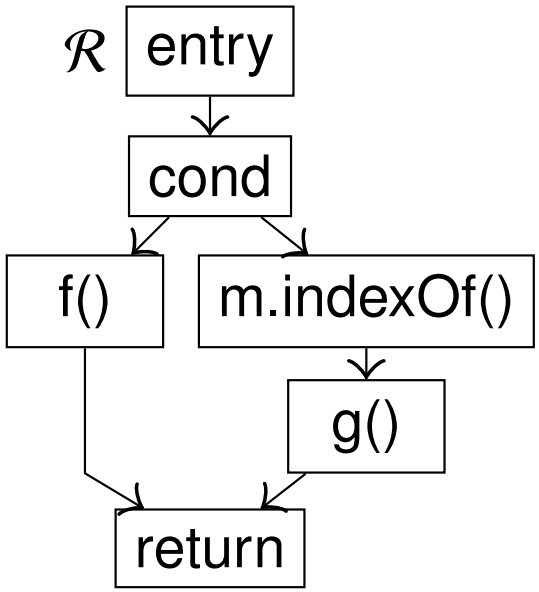

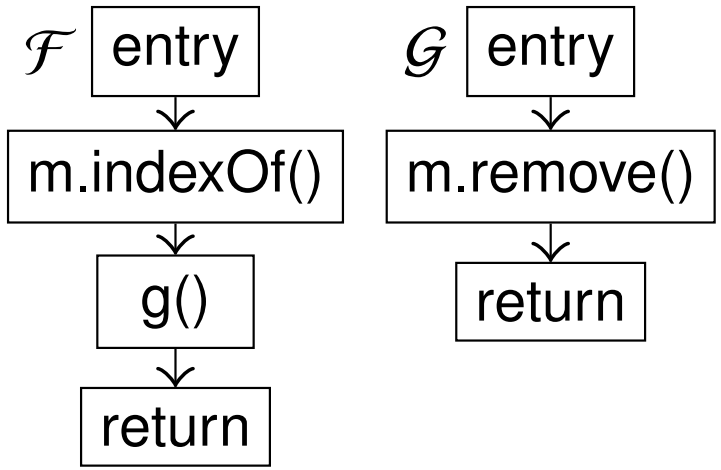

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$a \to \mathbf{a}$ $\quad$ $b \to \mathbf{b}$

$a \to \epsilon$ $\quad$ $b \to \epsilon$

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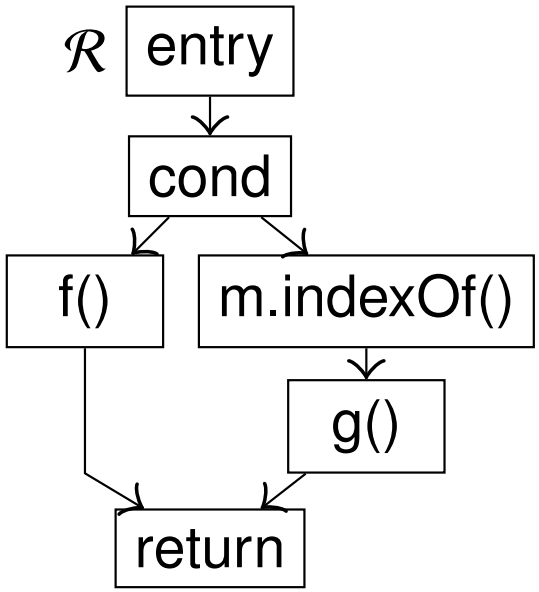

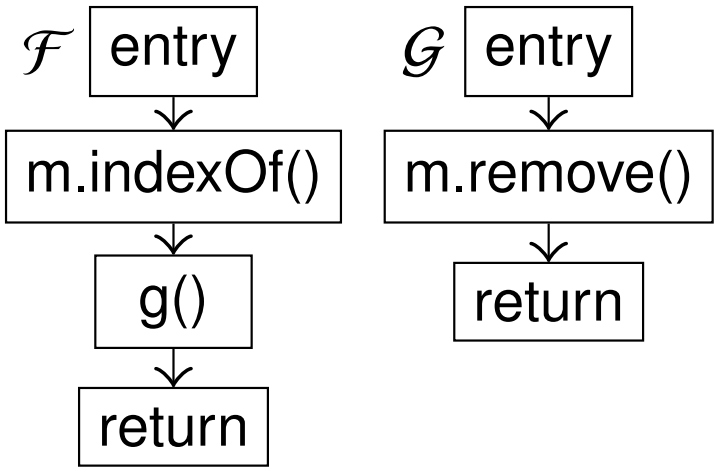

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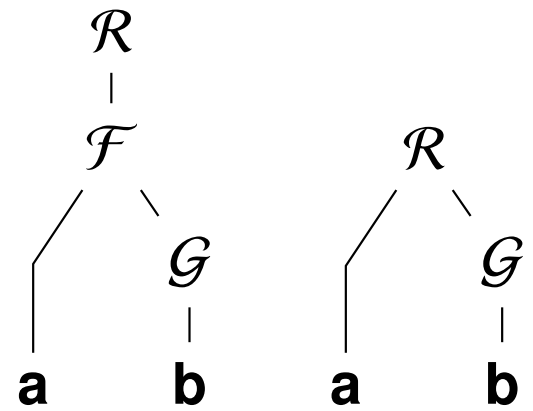

Experimental Results

Benchmark	Clauses	Contract Violations	False Positives	Potential AV	Real AV	SLOC	Time (s)
Allocate Vector	1	1	0	0	1	183	0.120
Coord03	4	1	0	0	1	151	0.093
Coord04	2	1	0	0	1	35	0.039
Jigsaw	1	1	0	0	1	100	0.044
Local	2	1	0	0	1	24	0.033
Knight	1	1	0	0	1	135	0.219
NASA	1	1	0	0	1	89	0.035
Store	1	1	0	0	1	621	0.090
StringBuffer	1	1	0	0	1	27	0.032
UnderReporting	1	1	0	0	1	20	0.029
VectorFail	2	1	0	0	1	70	0.048
Account	4	2	0	0	2	42	0.041
Arithmetic DB	2	2	0	0	2	243	0.272
Connection	2	2	0	0	2	74	0.058
Elevator	2	2	0	0	2	268	0.333
OpenJMS 0.7	6	54	10	28	4	163K	148
Tomcat 6.0	9	157	16	47	3	239K	3070
Cassandra 2.0	1	60	24	15	2	192K	246
Derby 10.10	1	19	5	7	1	793K	522
Lucene 4.6	3	136	21	76	0	478K	151

Dynamic Validation

- Based on happens-before relation and vector clocks
- Supports both contracts with spoilers and parameters
- Analyses a concrete execution of a program
  - If a contract is violated in the execution, it will be detected
  - Extrapolation based on the happens-before relation
  - Noise injection to force rare interleavings (executions)
- On-the-fly validation
  - Uses a partial trace (trace window)
  - Does not require a trace to be available
  - Each thread needs to remember
    1. Last instance of each spoiler
    2. Last instance of each target
    3. Up to $|\mathbb{T}|$ additional instances of each target

Dynamic Validation Algorithm

Data: trace window υ, event $e \in \mathbb{E}$ generated by thread $t \in \mathbb{T}$

1 **if** $\exists \varrho \in \mathbb{R}, r \in [\varrho]^{\upsilon}_{t} : e = end(r)$ **then**
2 **for** $\sigma \in \mathbb{C}(\varrho), u \in \mathbb{T} : u \neq t$ **do**
3 **if** $\exists s \in [\sigma]^{\upsilon}_{u} : start(s) \not\prec_{hb} start(r) \wedge end(r) \not\prec_{hb} end(s)$ **then** r is violated by s ;
4 **if** $\exists s \in [\sigma]^{\tau}_{u} : start(s) \in \upsilon \wedge end(s) \notin \upsilon$ **then**
5 **if** $start(s) \prec_{hb} start(r)$ **then**
6 **if** $\exists r' \in [\varrho]^{\upsilon}_{t} : r' \neq r \wedge start(s) \not\prec_{hb} start(r')$ **then** $PV^{\varrho,\sigma}_{t}(u) = VC_{end(r')}(t)$;
7 **if** $\exists r' \in [\varrho]^{\upsilon}_{t} : r' \neq r$ **then** $\upsilon \rightarrow r'$;
8 **if** $\sigma \in \mathbb{S}, s \in [\sigma]^{\upsilon}_{t} : end(s) = e$ **then**
9 **if** $\exists s' \in [\sigma]^{\upsilon}_{t} : s' \neq s$ **then** $\upsilon \rightarrow s'$;
10 **for** $\varrho \in \mathbb{C}(\sigma), u \in \mathbb{T} : u \neq t$ **do**
11 **if** $\exists r \in [\varrho]^{\upsilon}_{u} : start(s) \not\prec_{hb} start(r) \wedge end(r) \not\prec_{hb} end(s)$ **then** r is violated by s ;
12 **if** $PV^{\varrho,\sigma}_{u}(t) \neq 0 \wedge PV^{\varrho,\sigma}_{u}(t) \leq VC_{end(s)}(u)$ **then**
13 an instance of ϱ is violated by s;

Illustration of the Dynamic Validation Approach

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void worker(void* data) {
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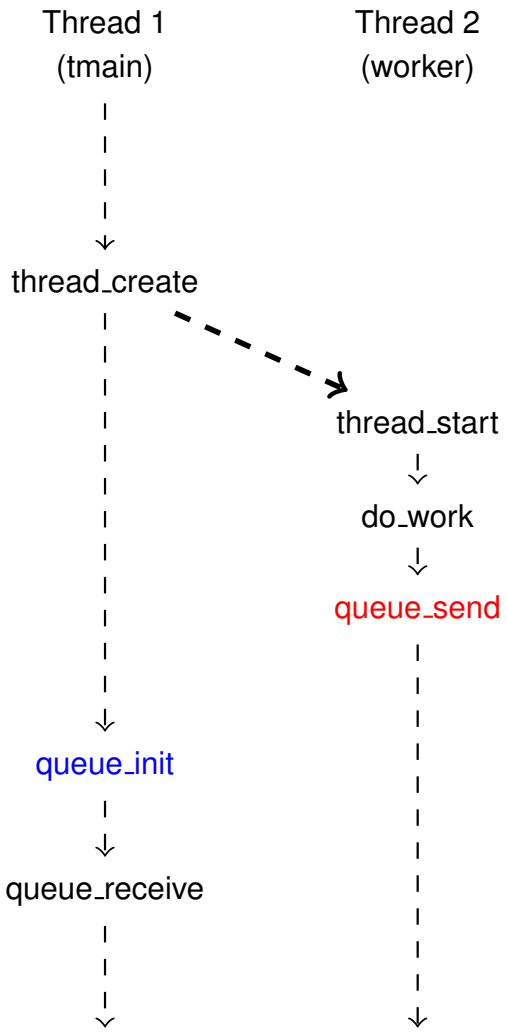

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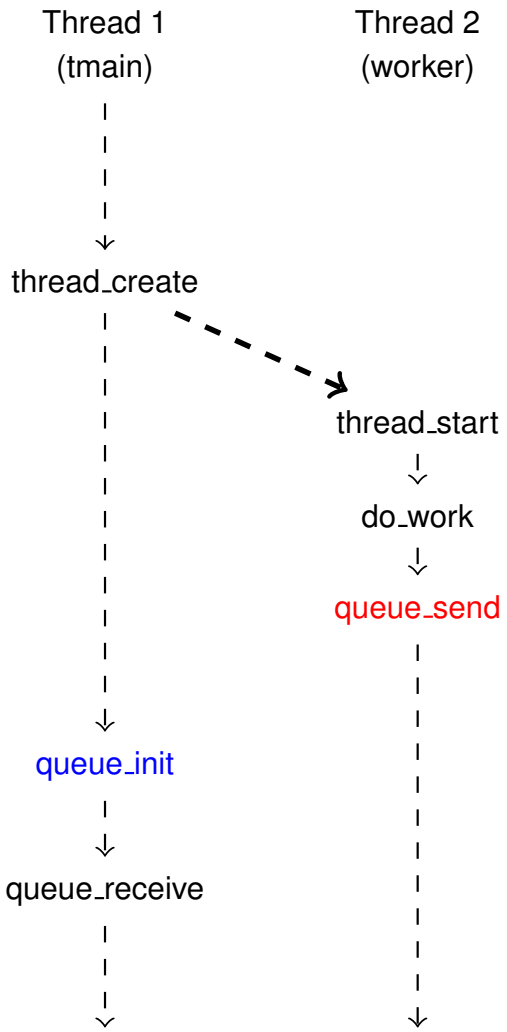

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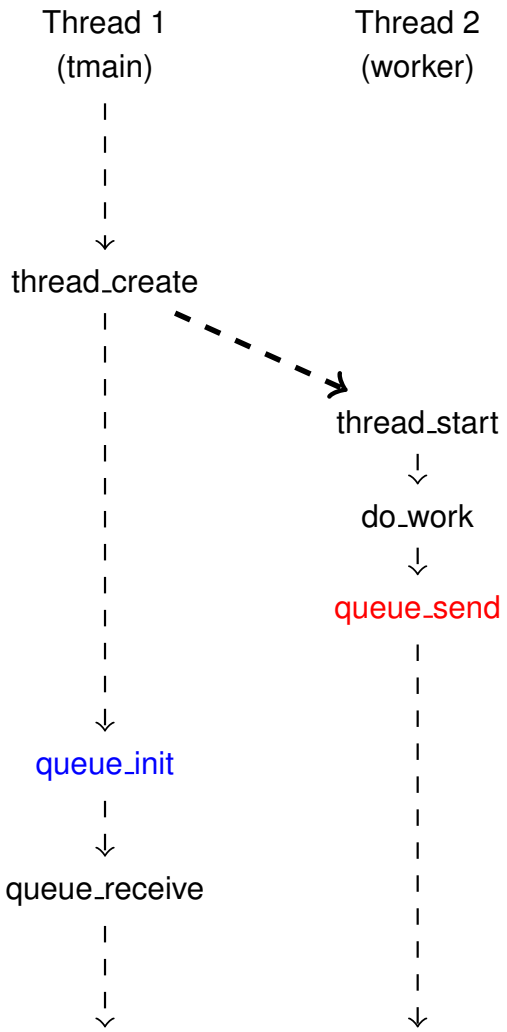

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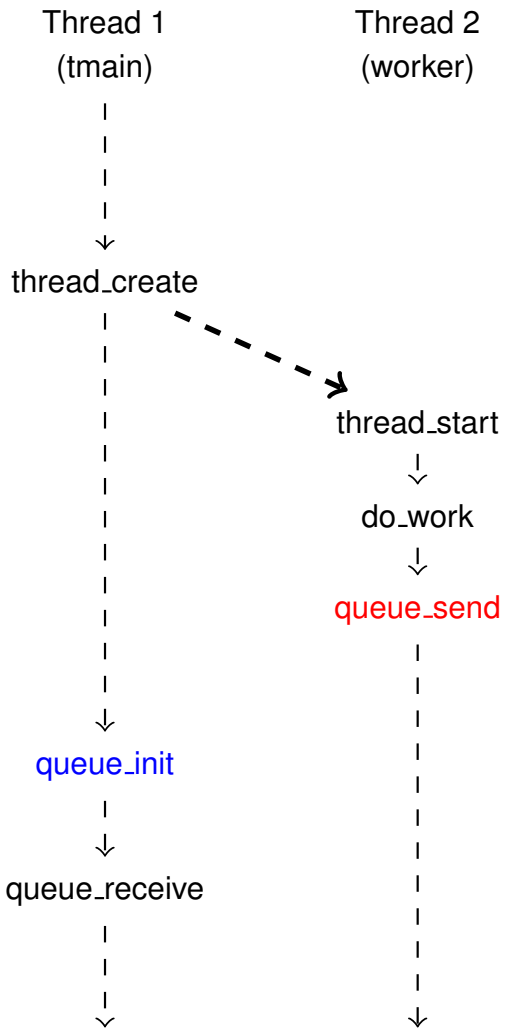
Data Race?



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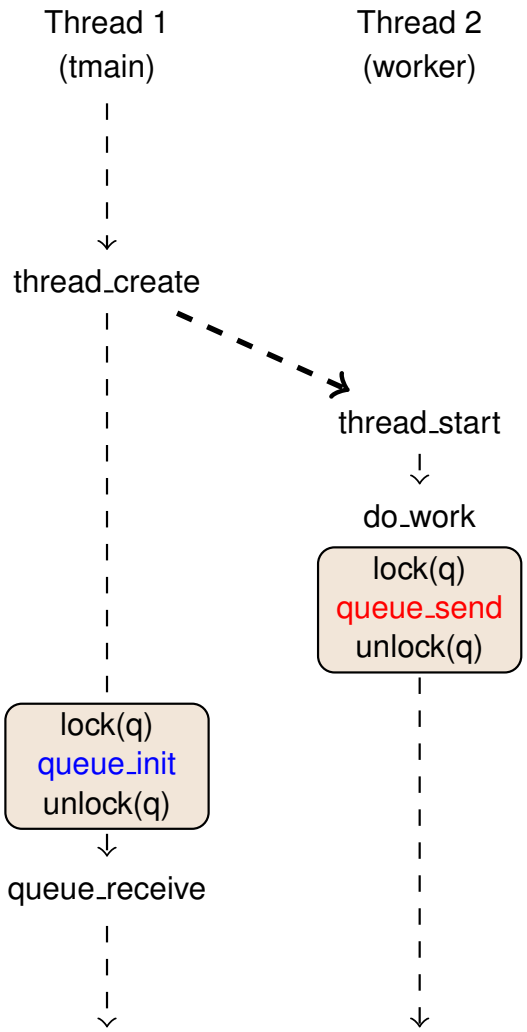

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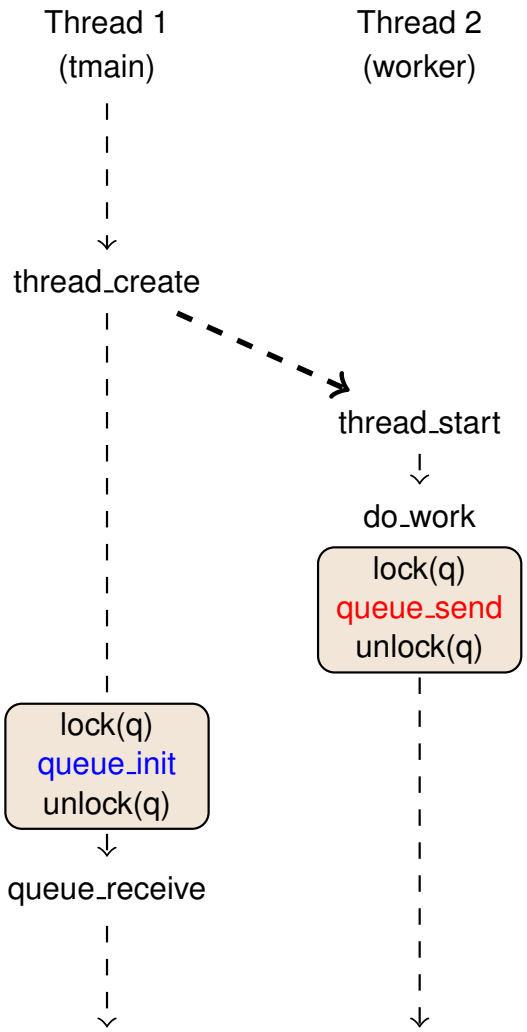

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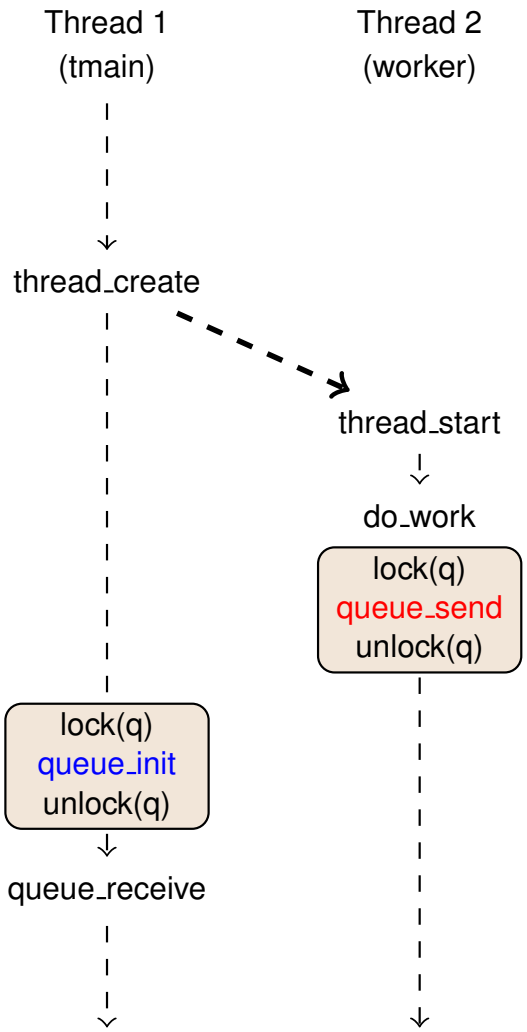
Order Violation!



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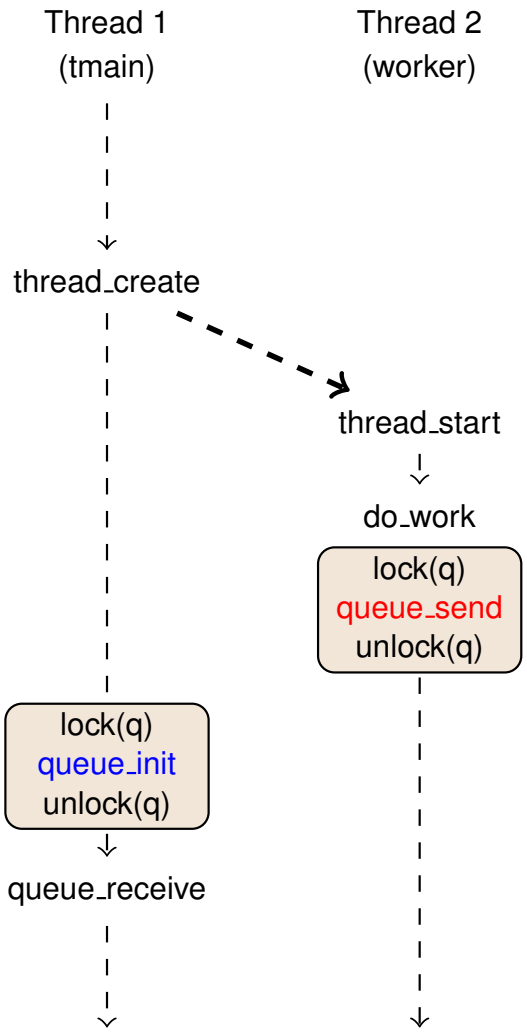

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Order Violation!

Can we detect it using contracts?

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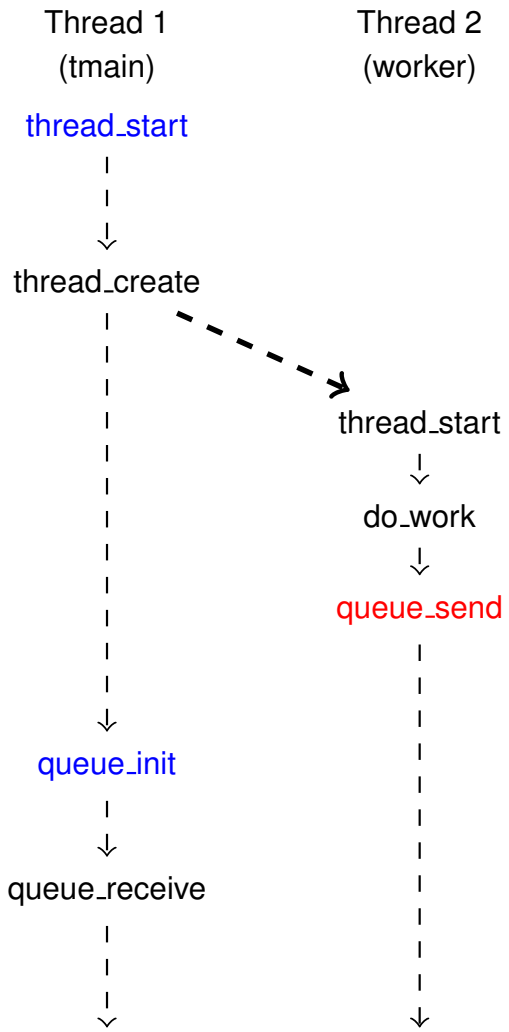

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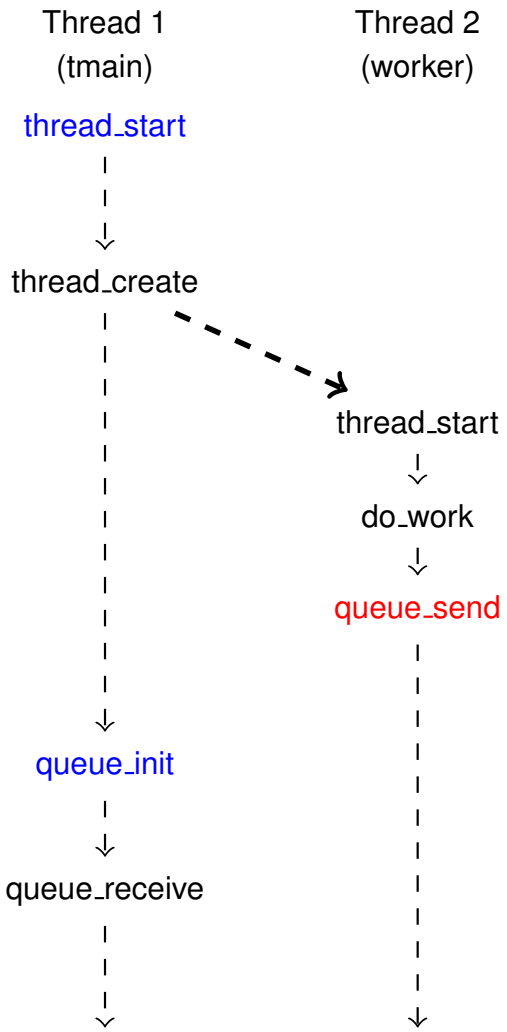
Contract: thread_start queue_init
← {queue_send, queue_receive}



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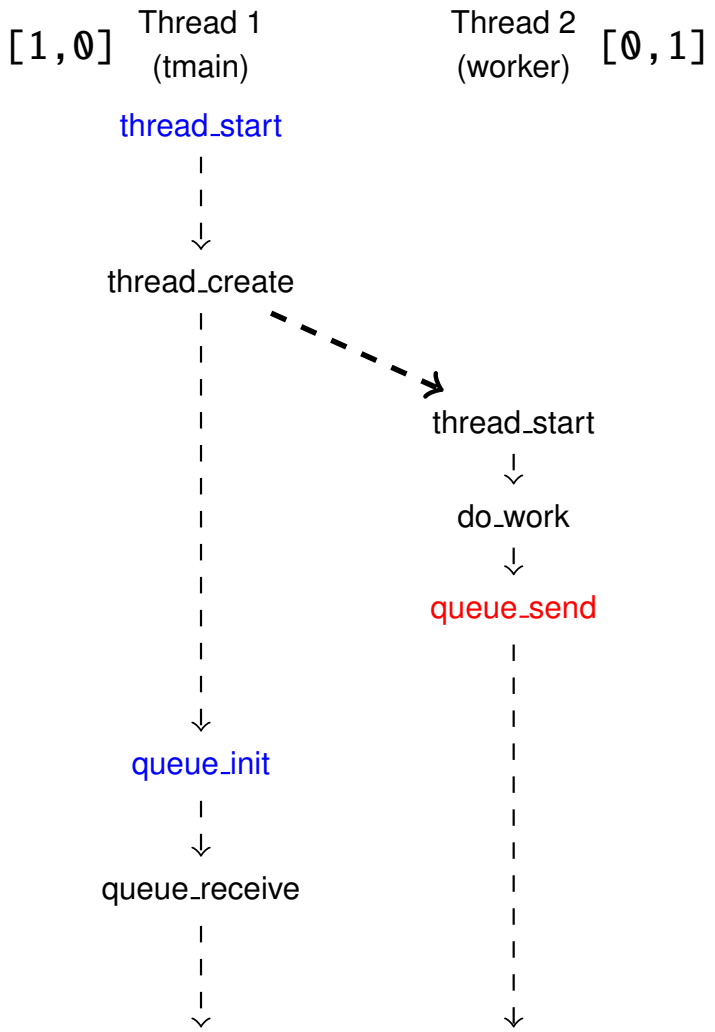

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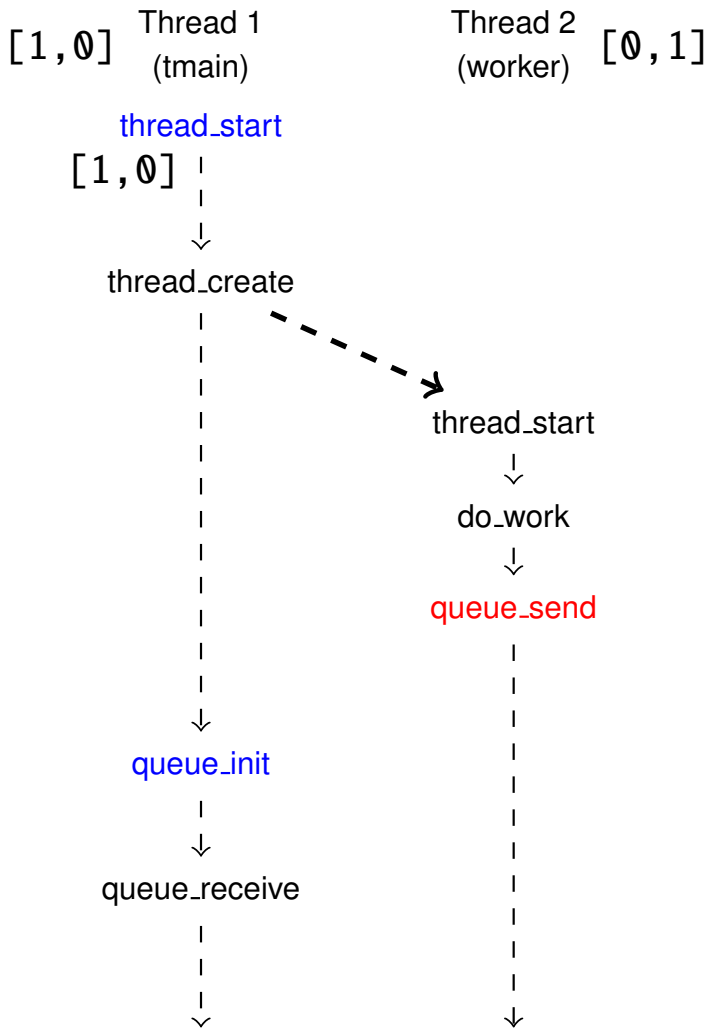

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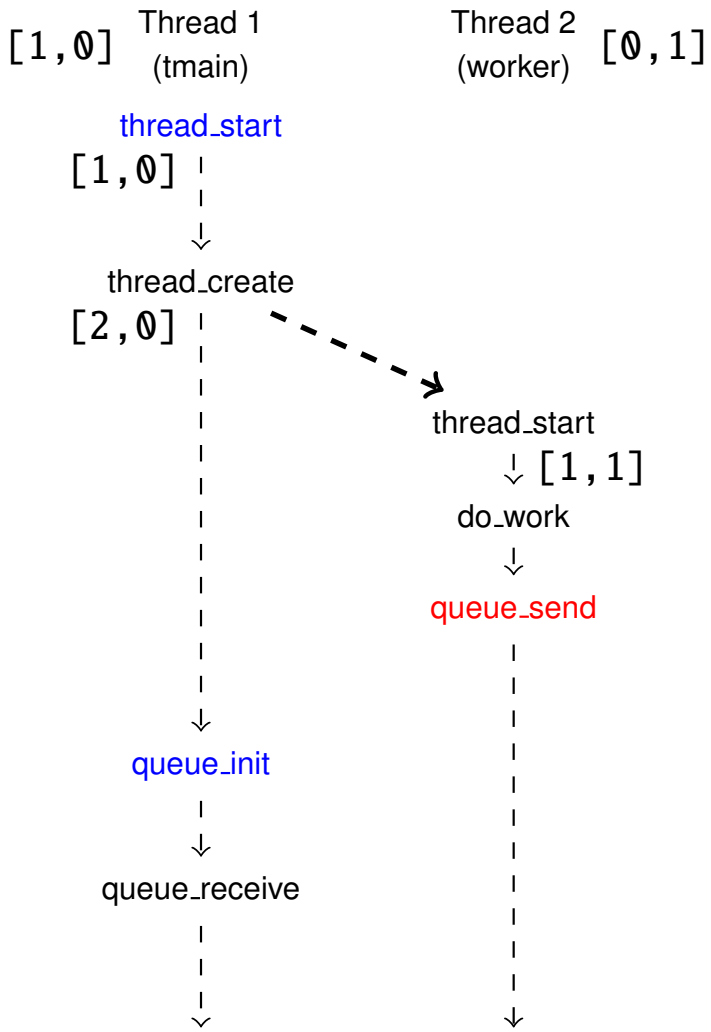

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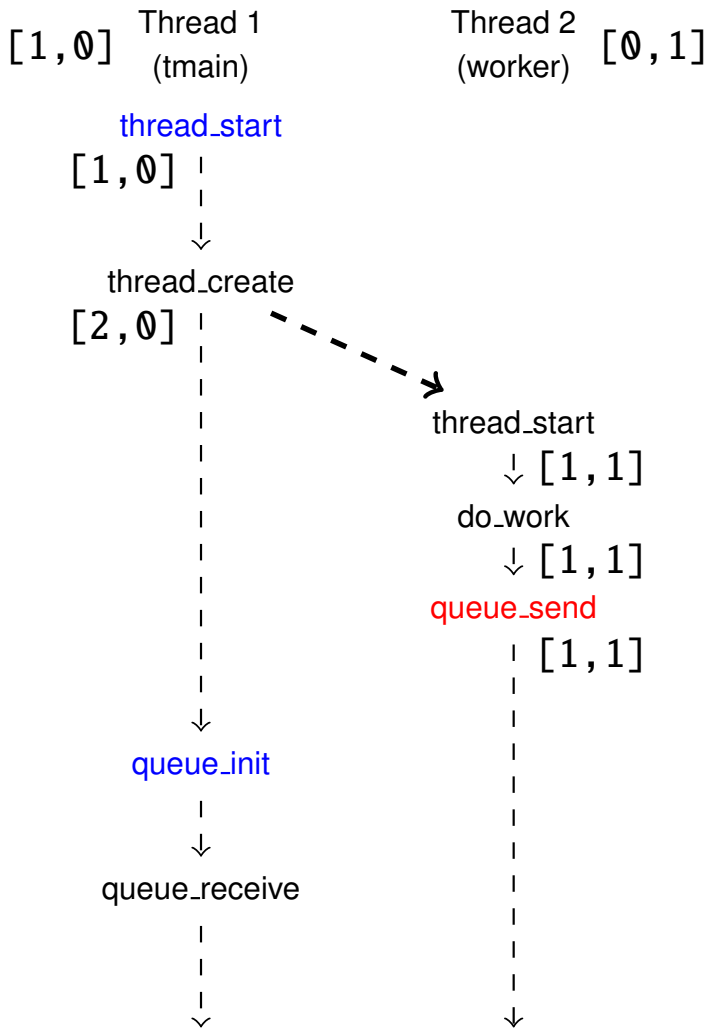

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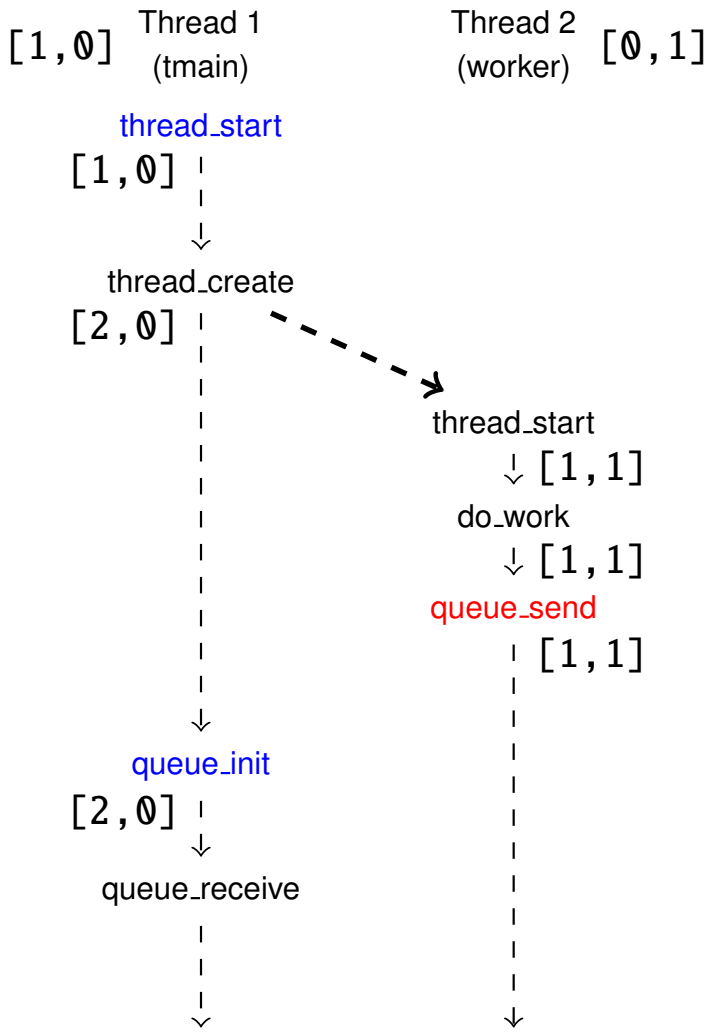

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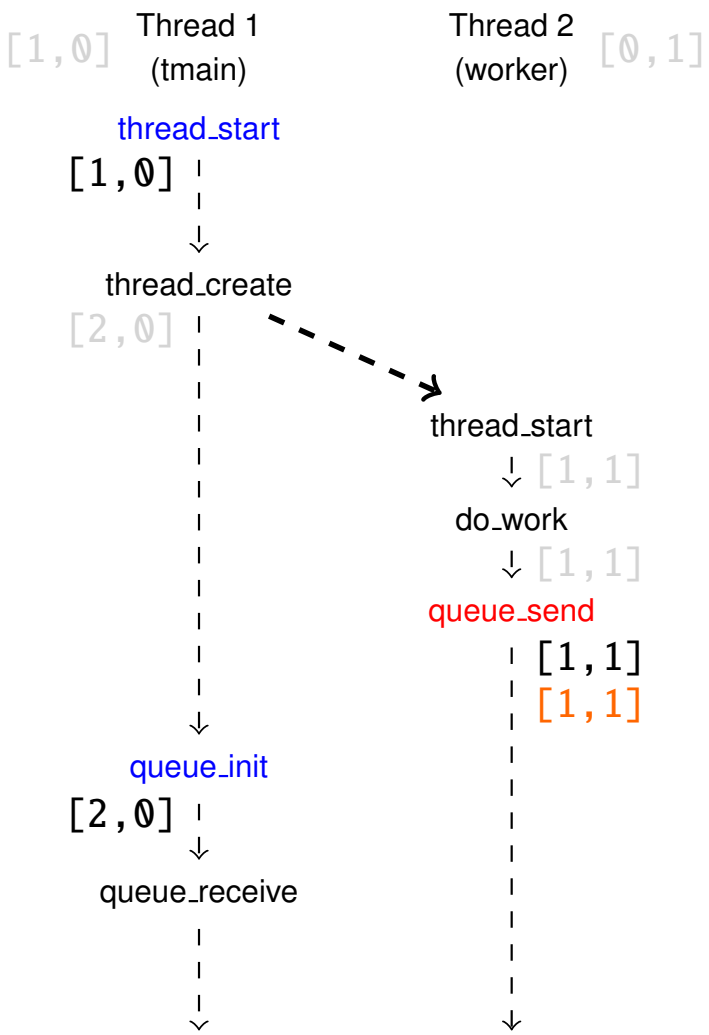

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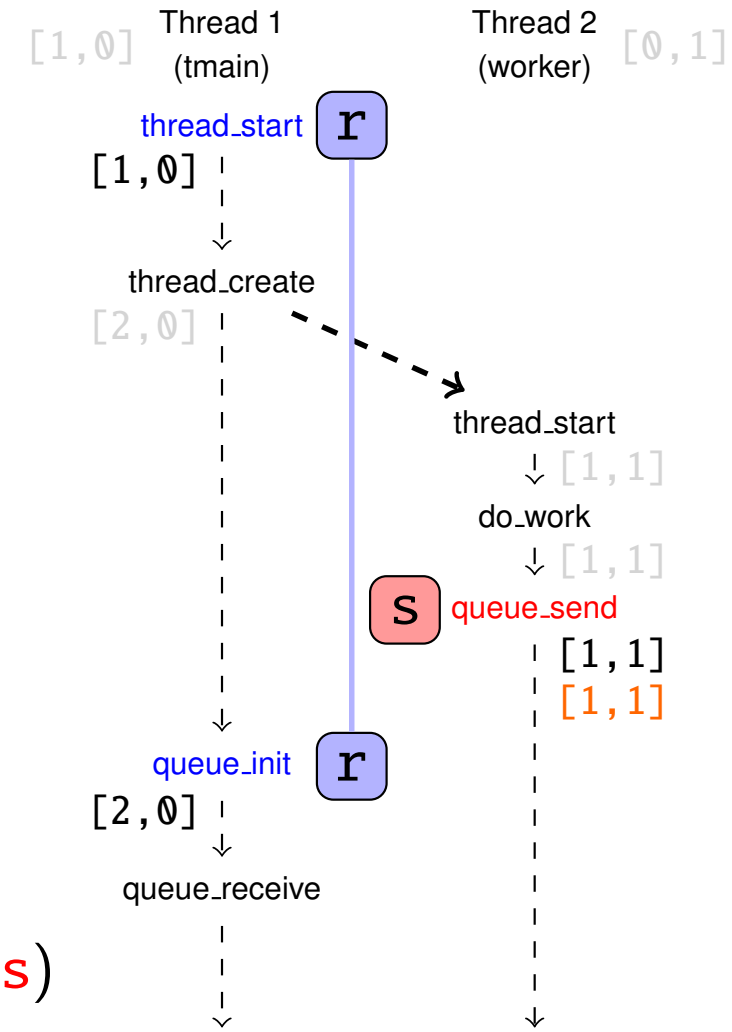
$start(s) \not\leq_{hb} start(r) \wedge end(r) \not\leq_{hb} end(s)$



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$$e_t \prec_{hb} e_u \sim VC_{e_t}(t) \leq VC_{e_u}(t)$$

Contract: thread_start queue_init

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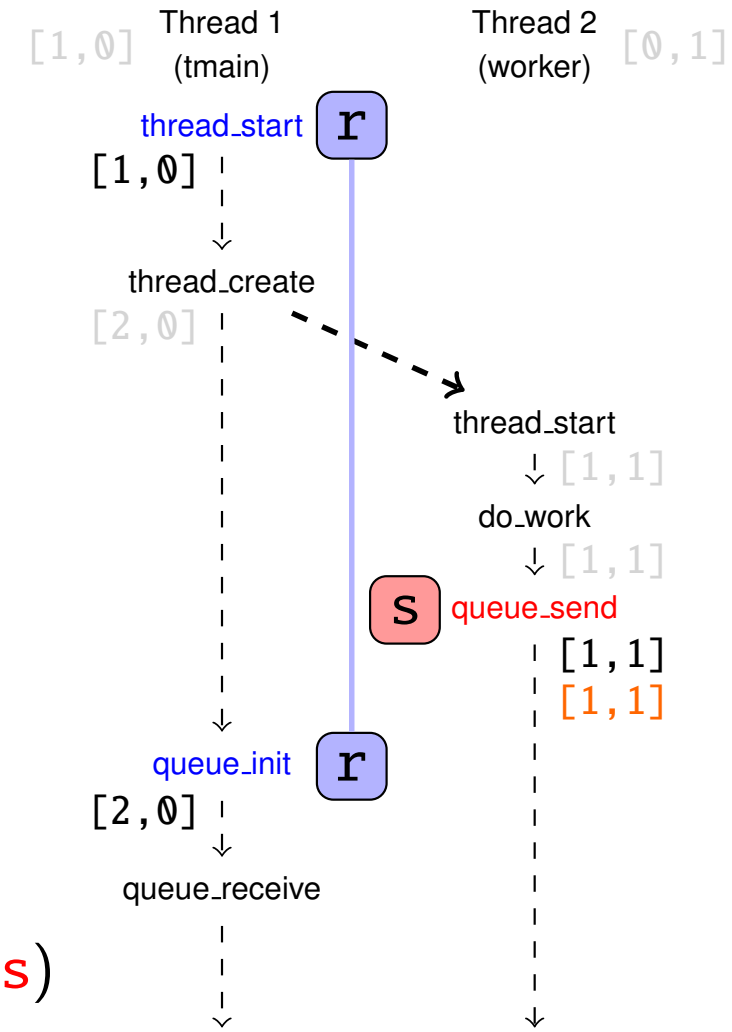

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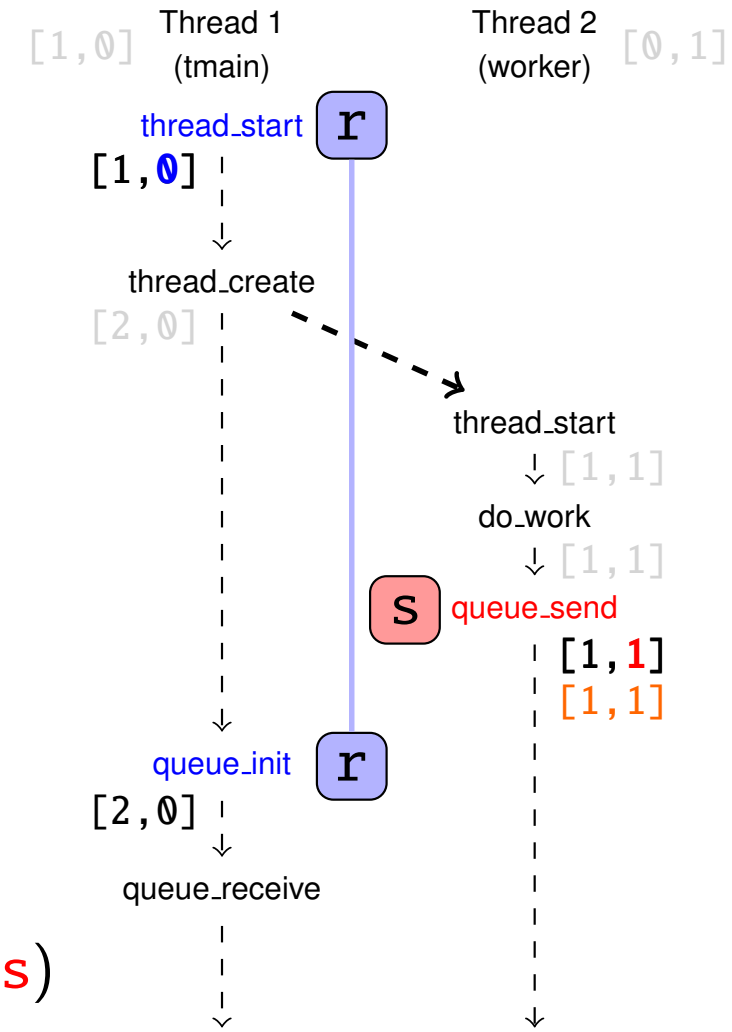
$\neg(1 \leq 0)$



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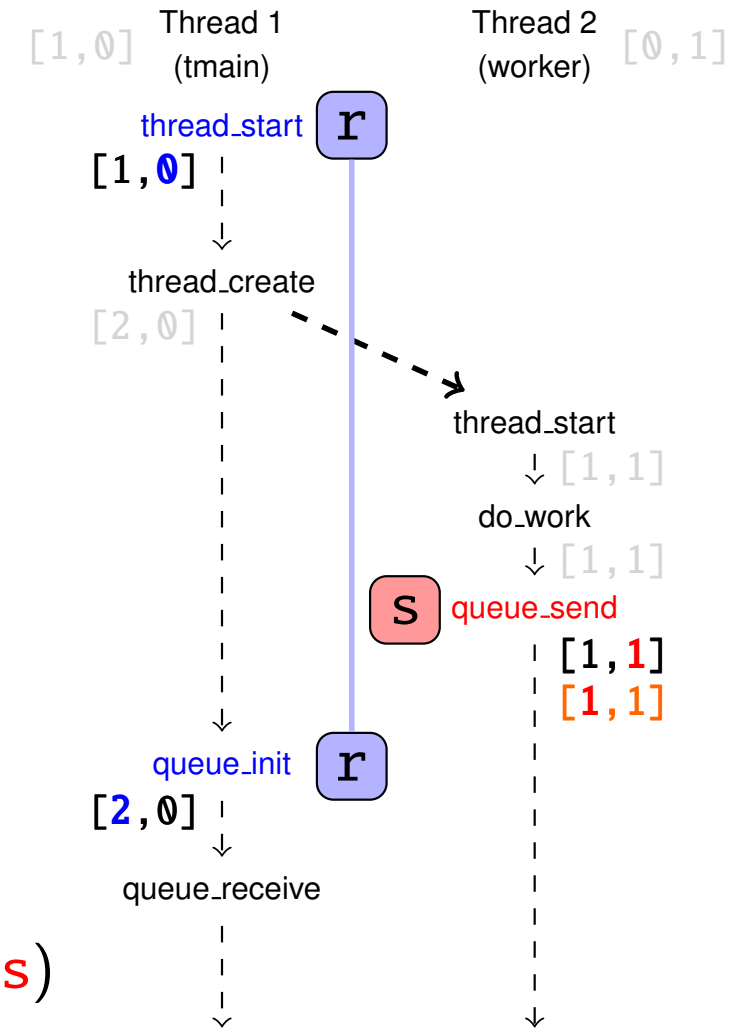
$\neg(1 \leq 0) \quad \wedge \quad \neg(2 \leq 1)$



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$\neg(1 \leq 0) \quad \wedge \quad \neg(2 \leq 1)$

Contract violated!

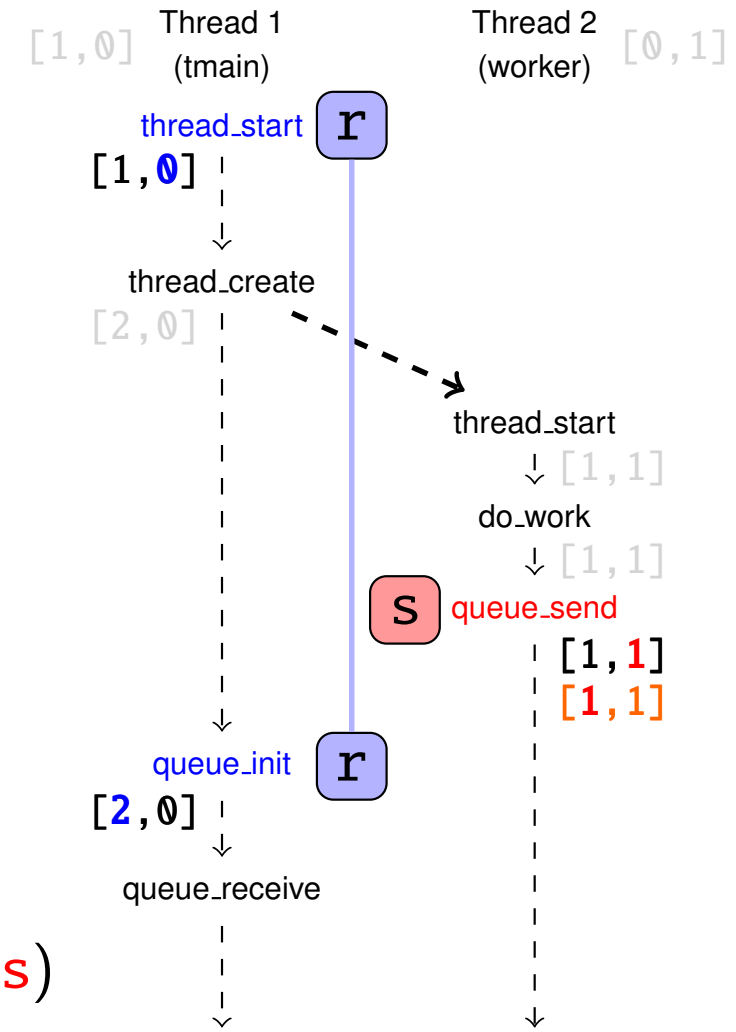

Illustration of the Dynamic Validation Approach

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$$e_t \prec_{hb} e_u \sim VC_{e_t}(t) \leq VC_{e_u}(t)$$

Contract: thread_start queue_init

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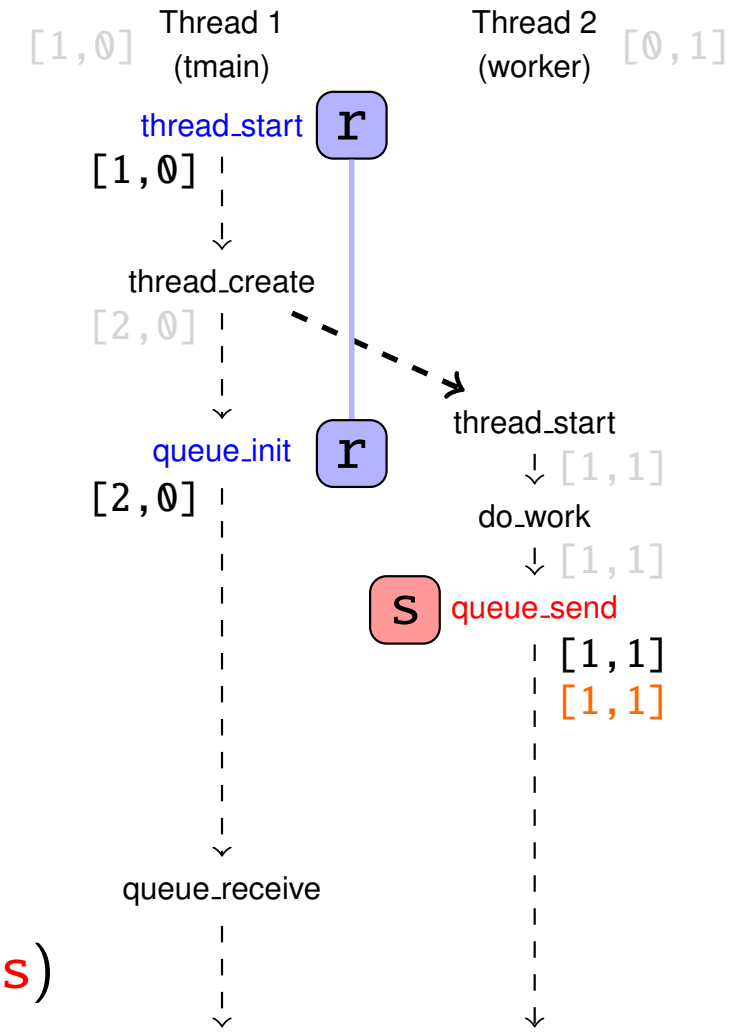

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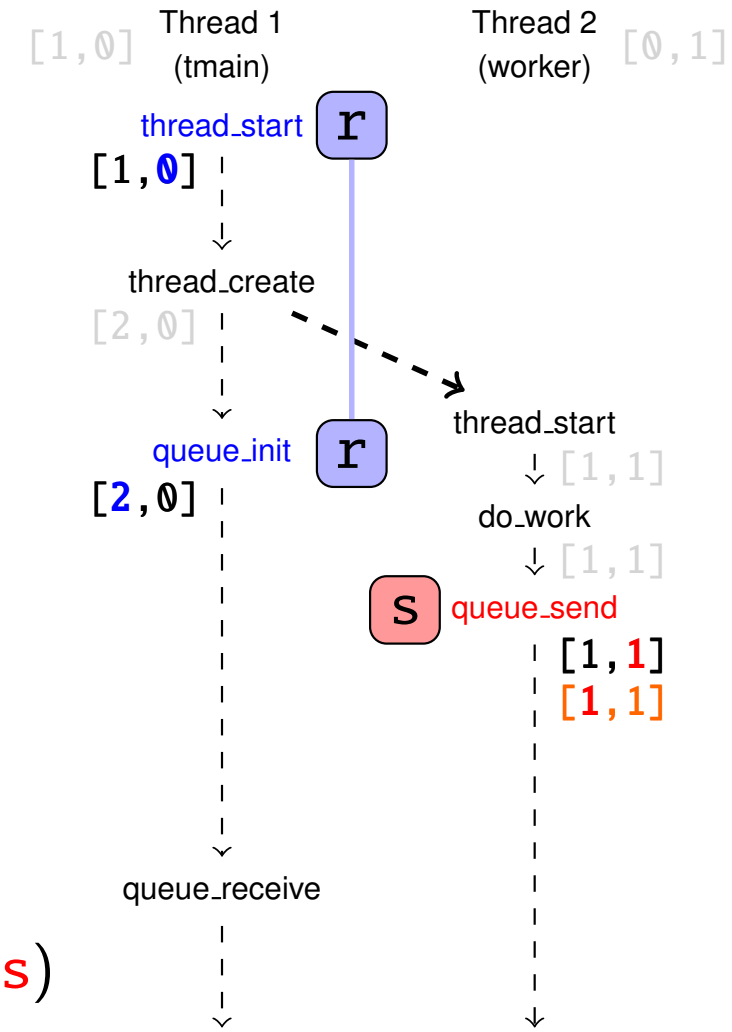

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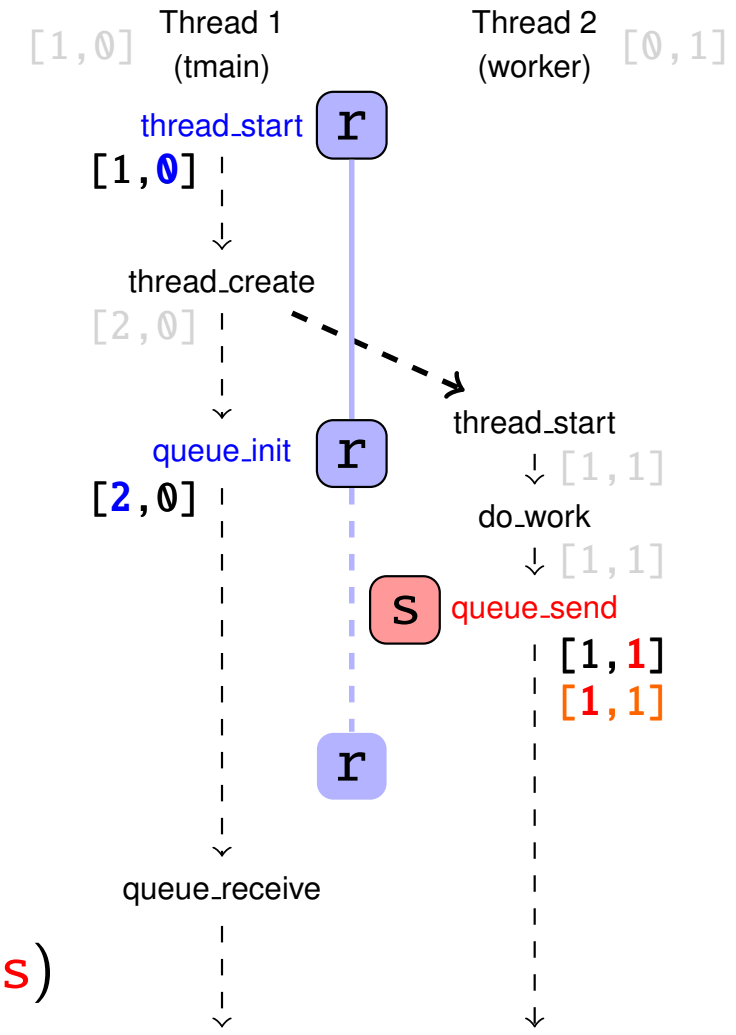

Extrapolation!

Illustration of the Dynamic Validation Approach

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Contract: thread_start queue_init $\leftarrow$ {queue_send, queue_receive}

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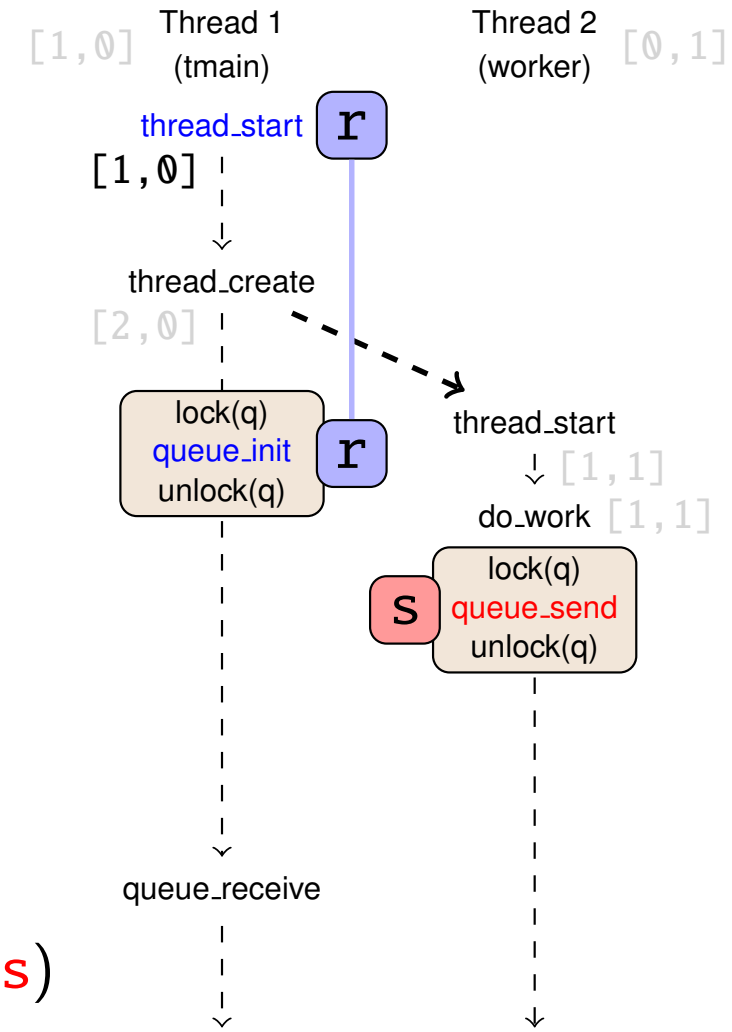

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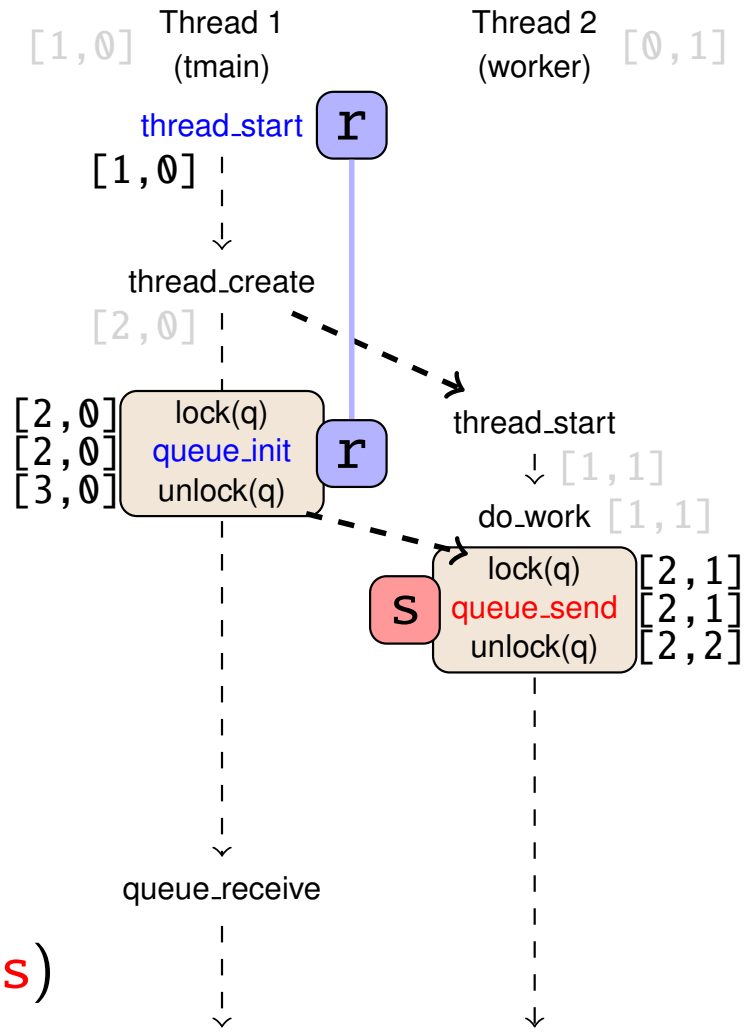

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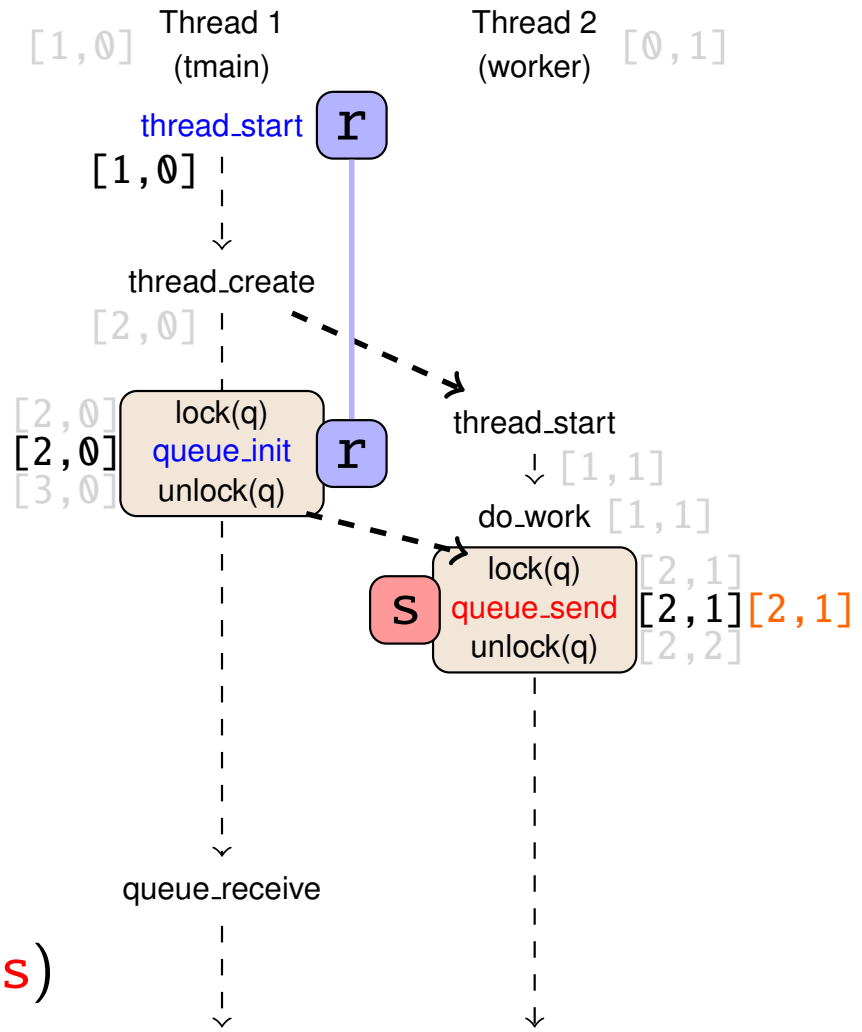

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Contract: thread_start queue_init

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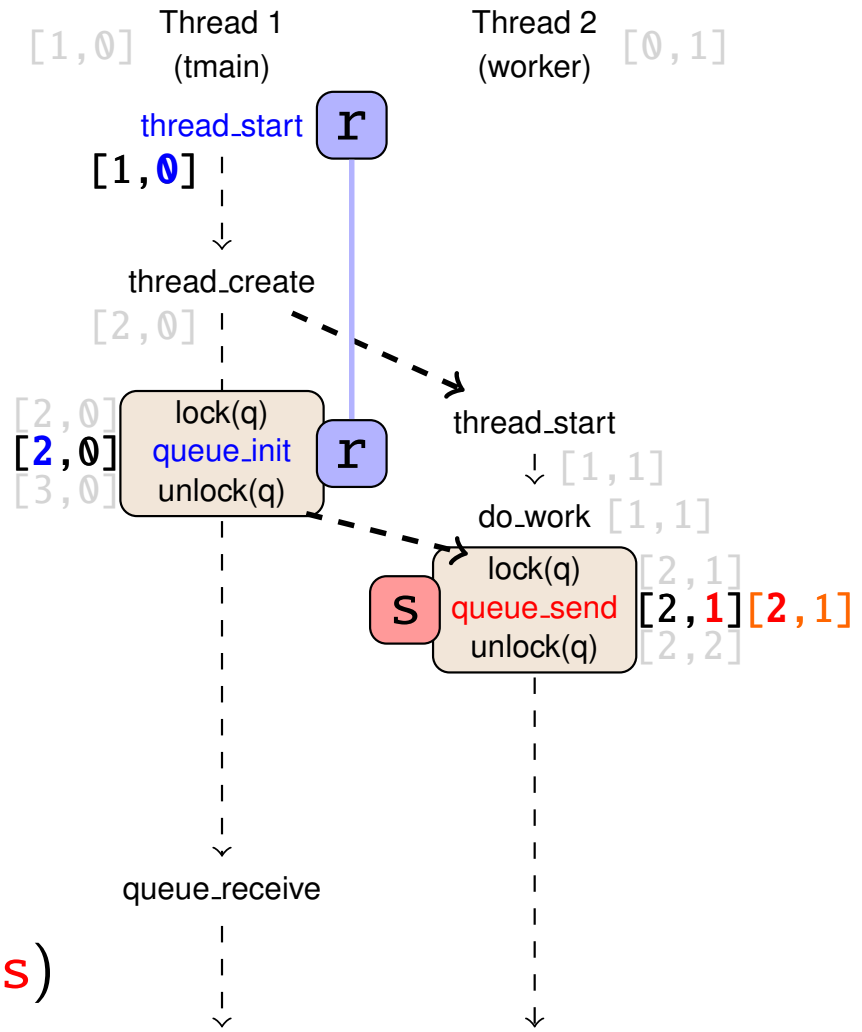
$start(s) \not\prec_{hb} start(r) \wedge end(r) \not\prec_{hb} end(s)$

$\neg(1 \leq 0) \quad \wedge \quad \neg(2 \leq 2)$

No violation



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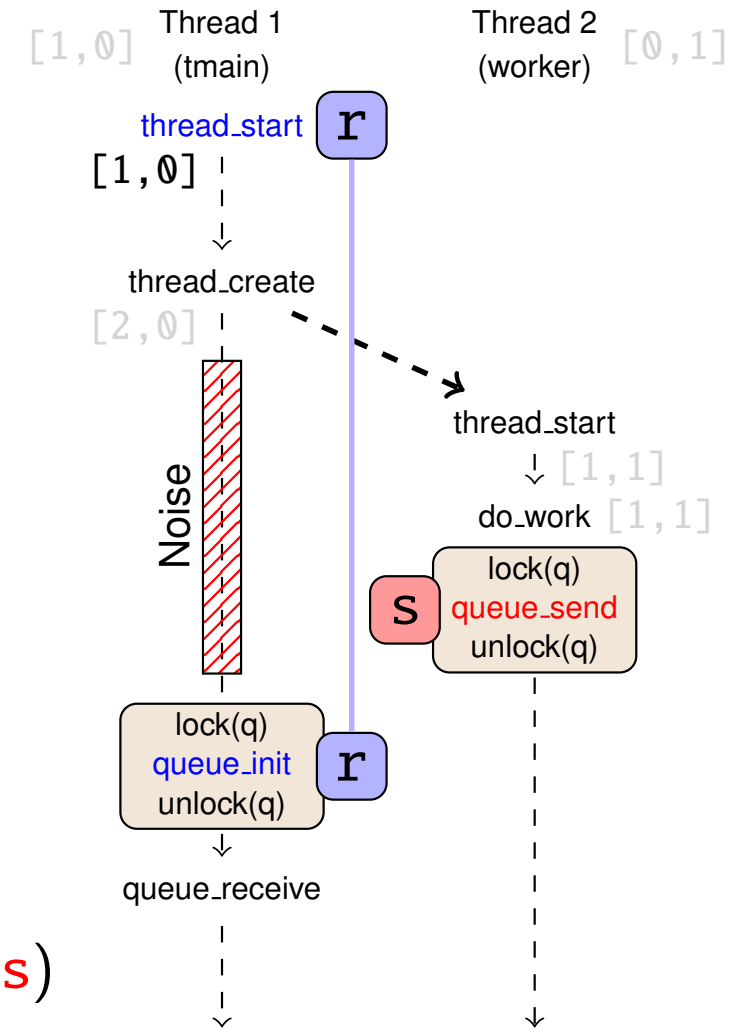

Noise injection!

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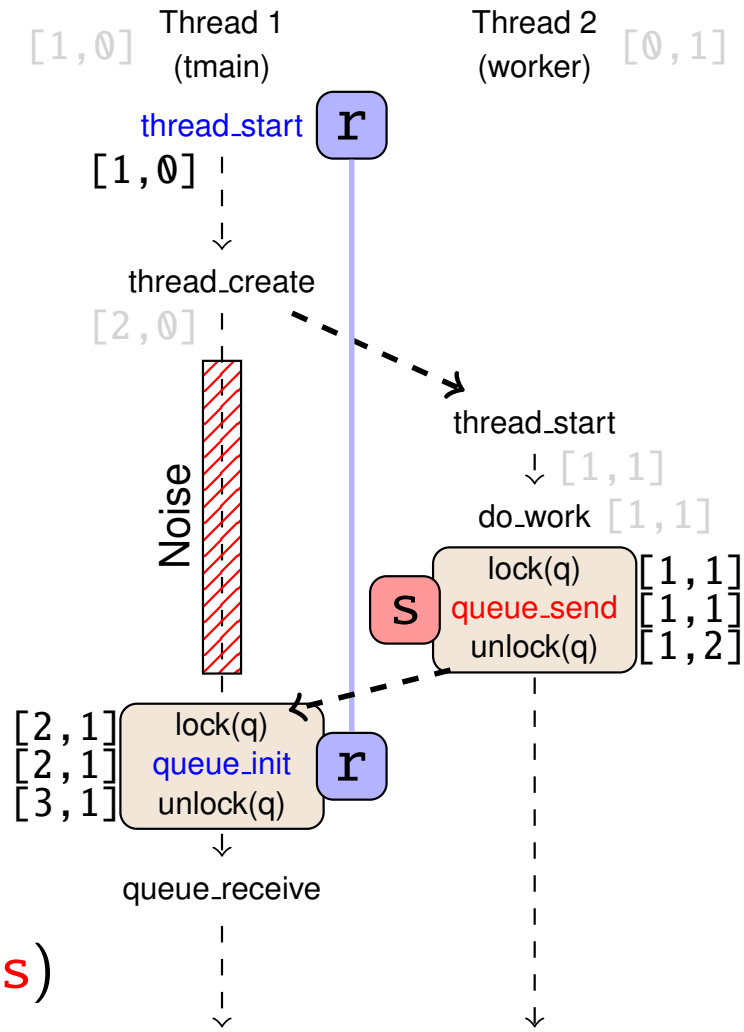

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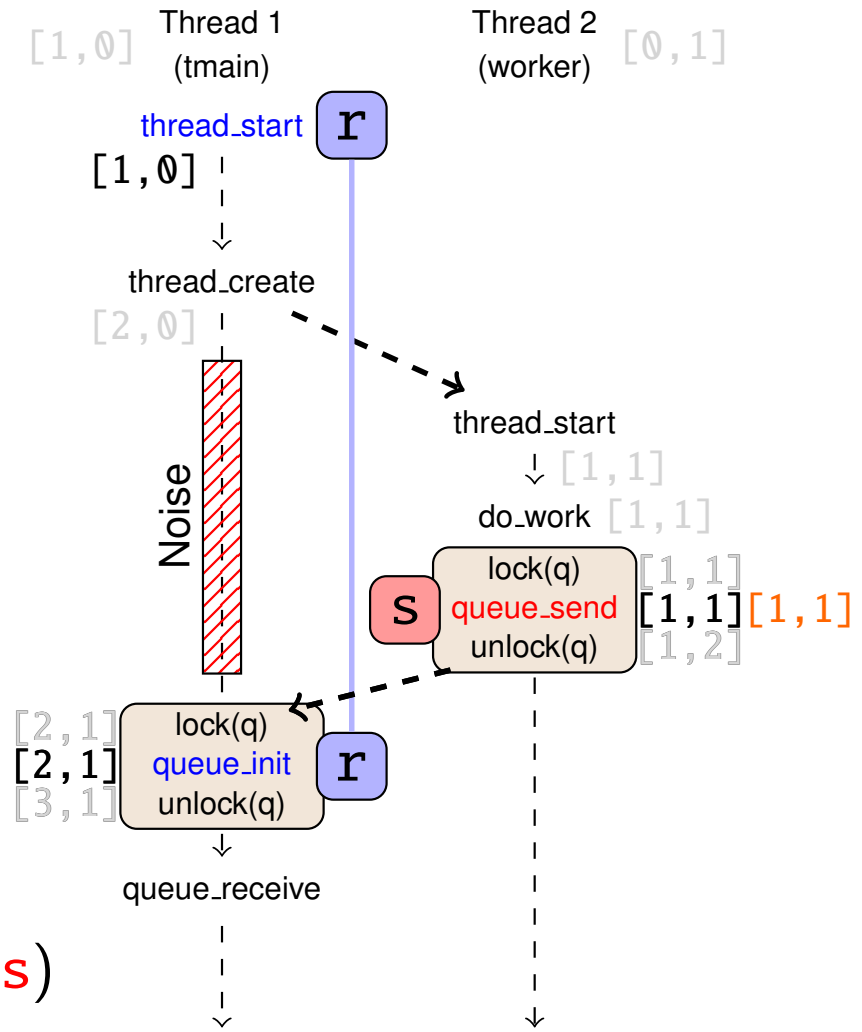

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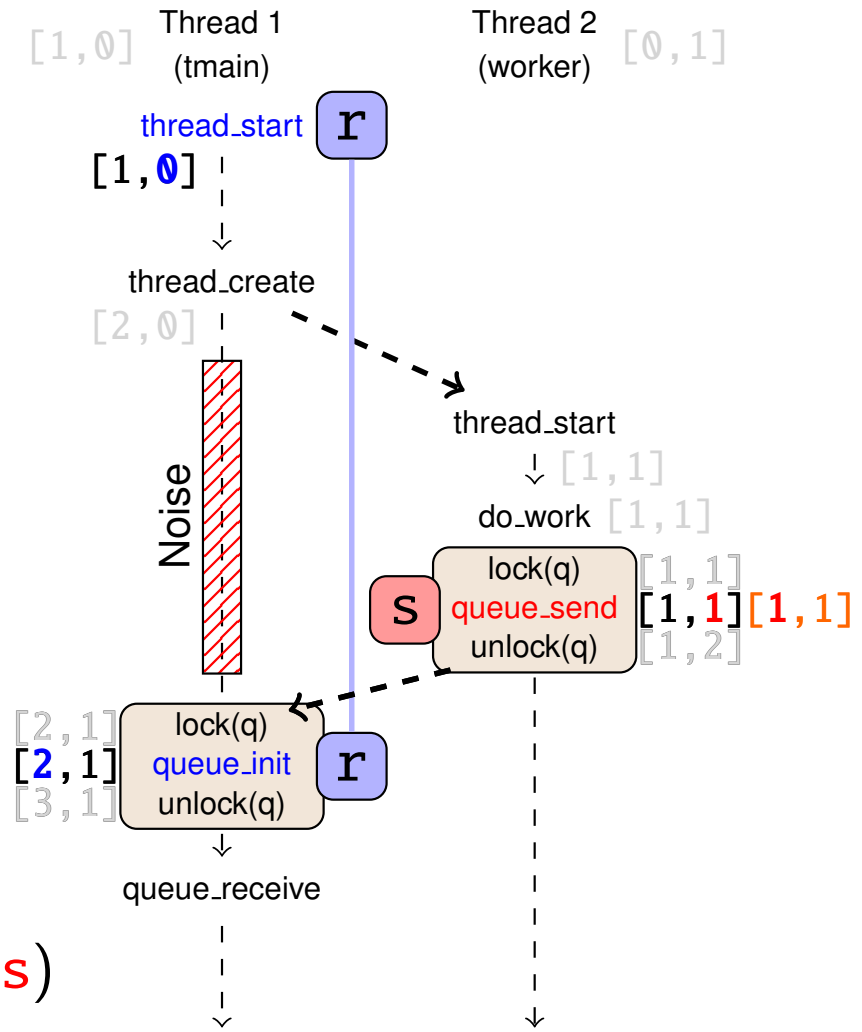

Noise injection!

Discarding Spoilers

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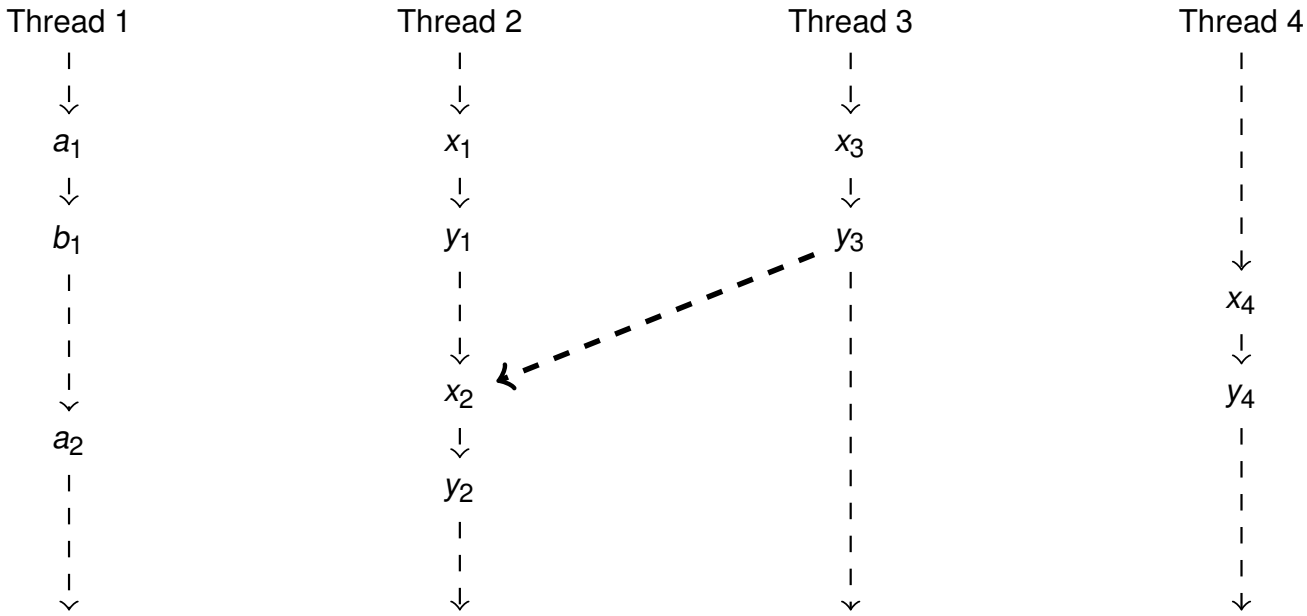

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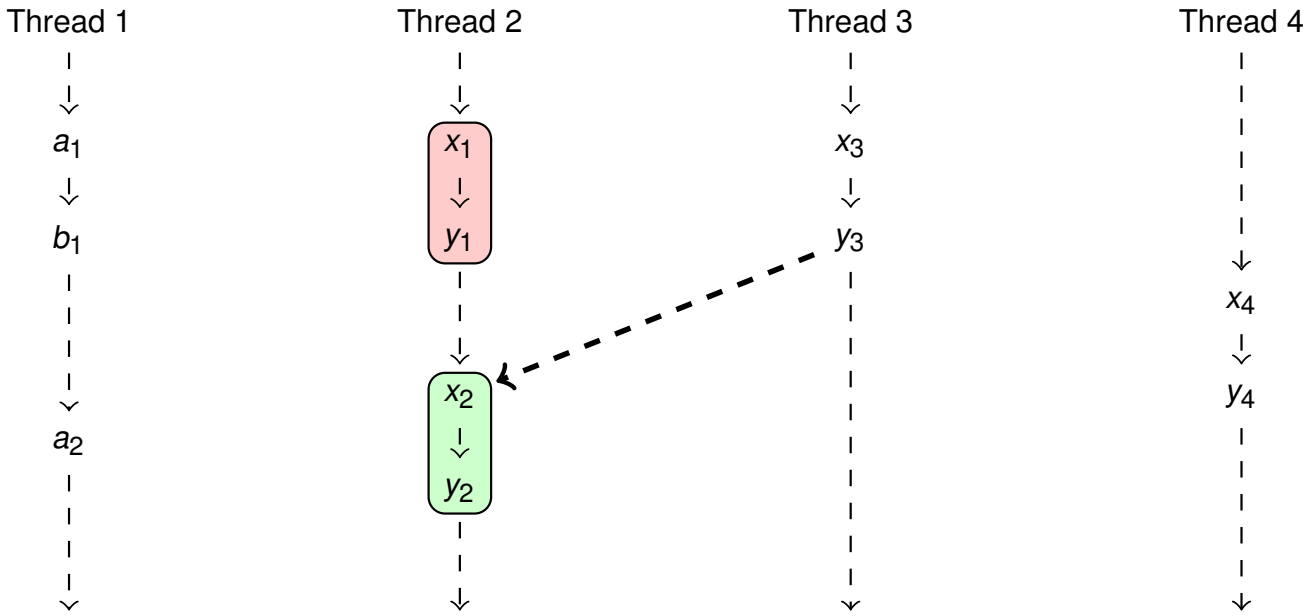

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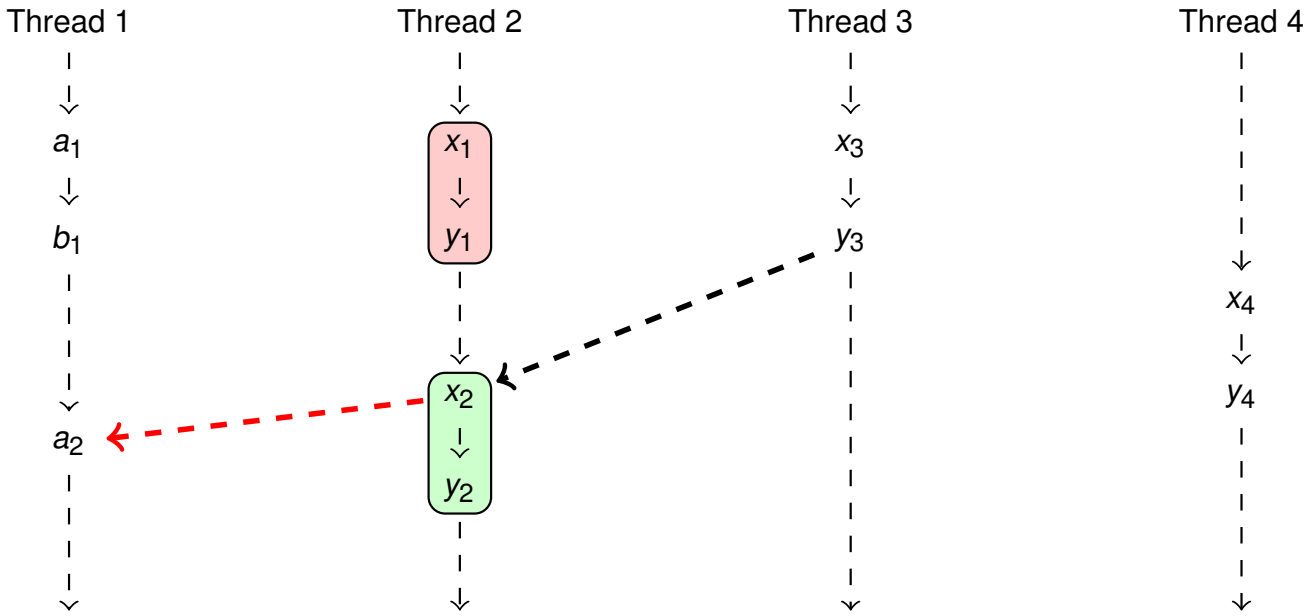

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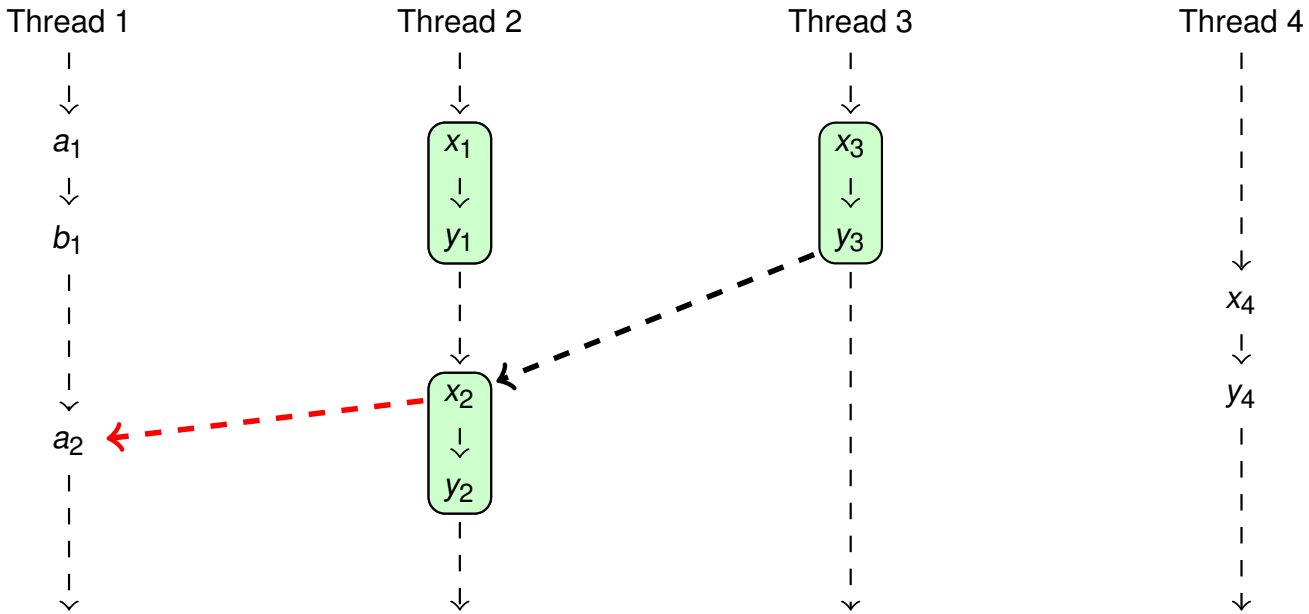

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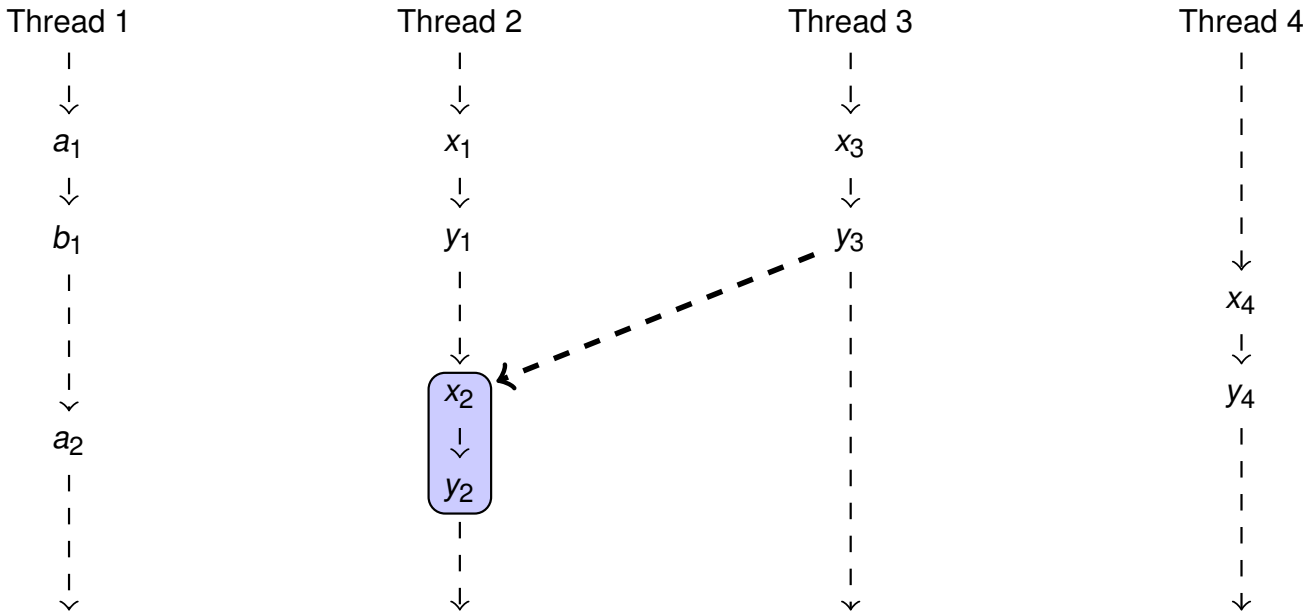

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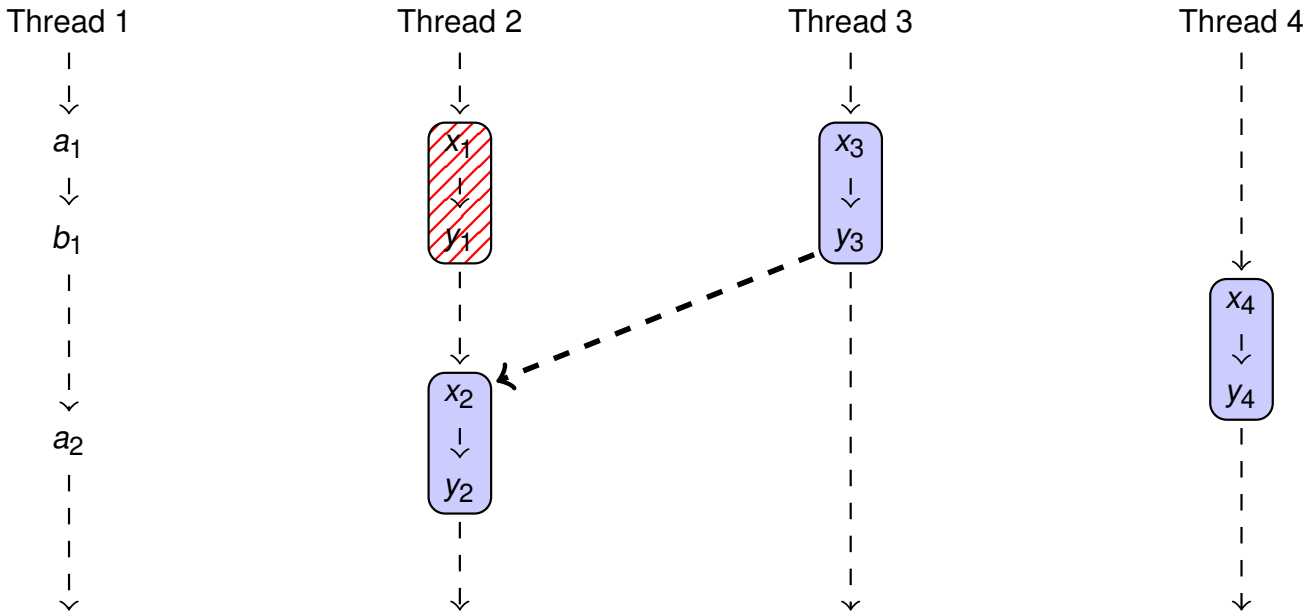

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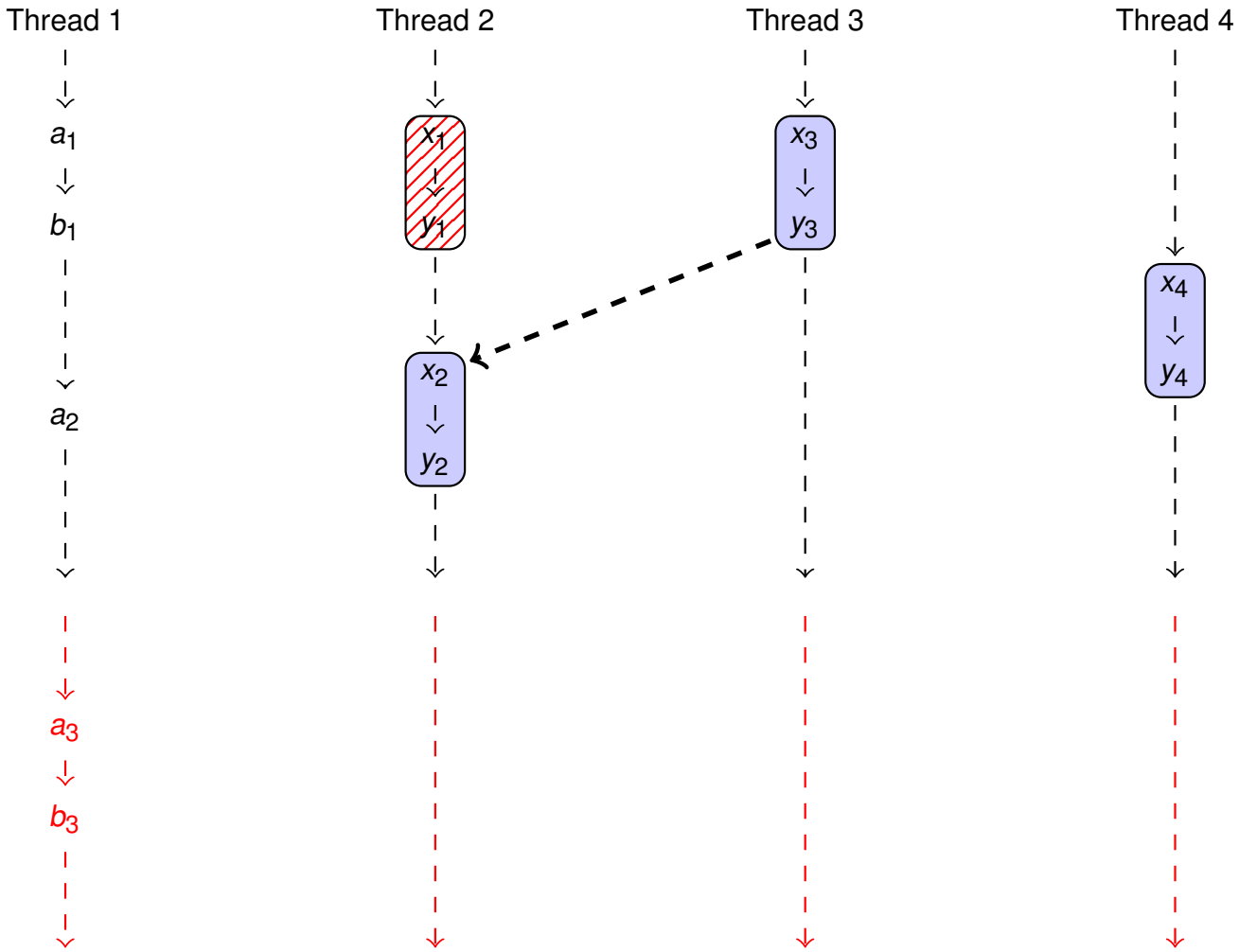

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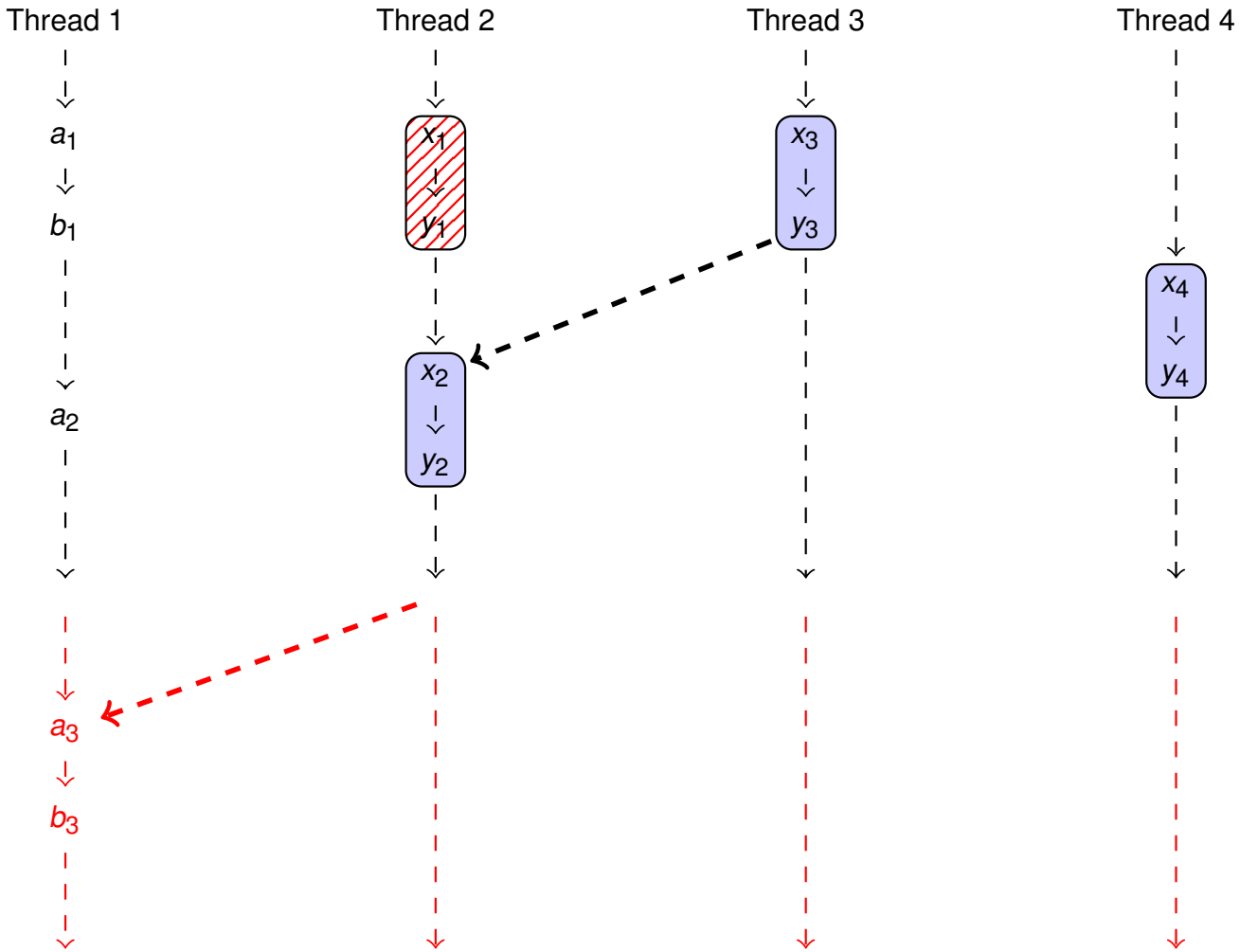

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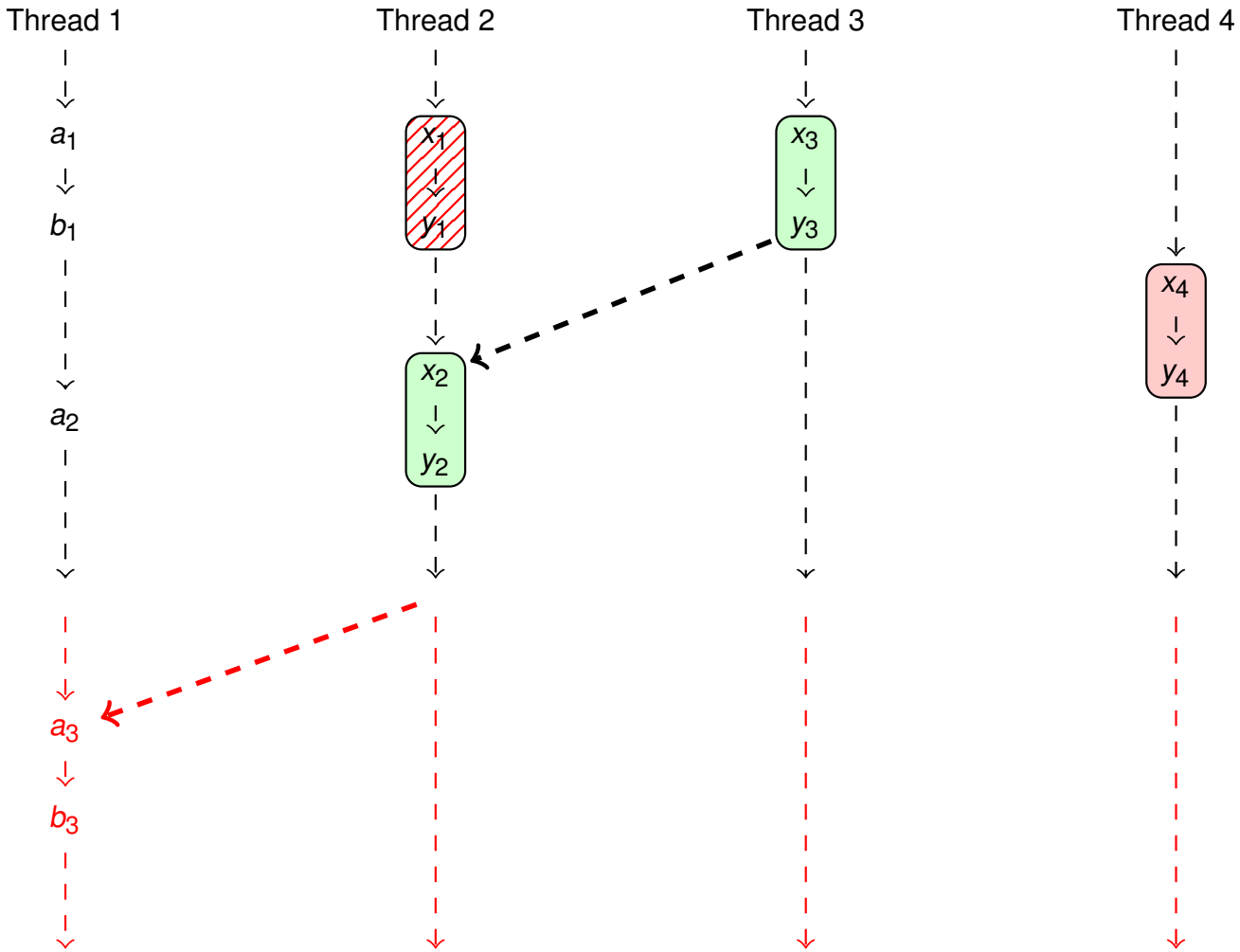

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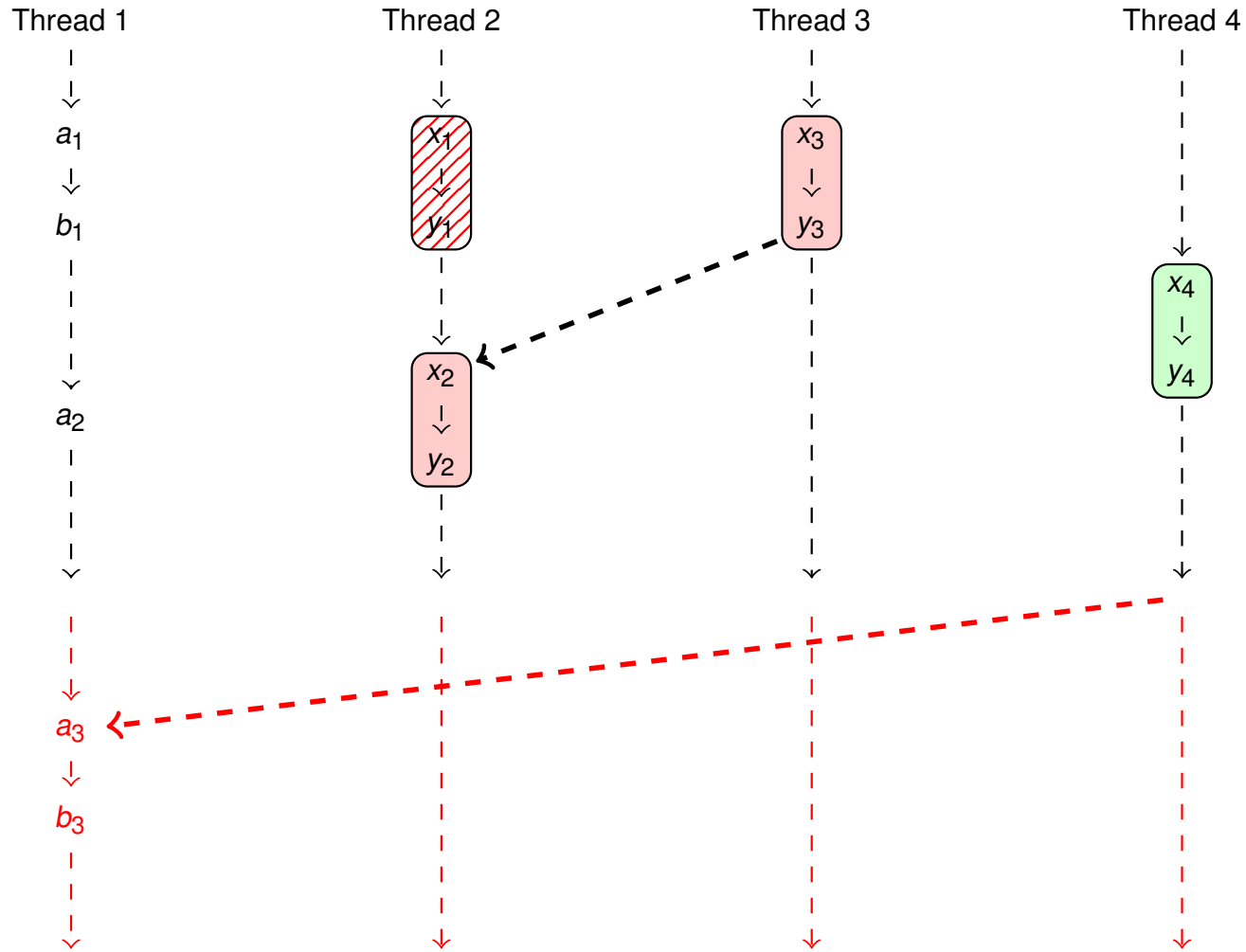

Discarding Targets

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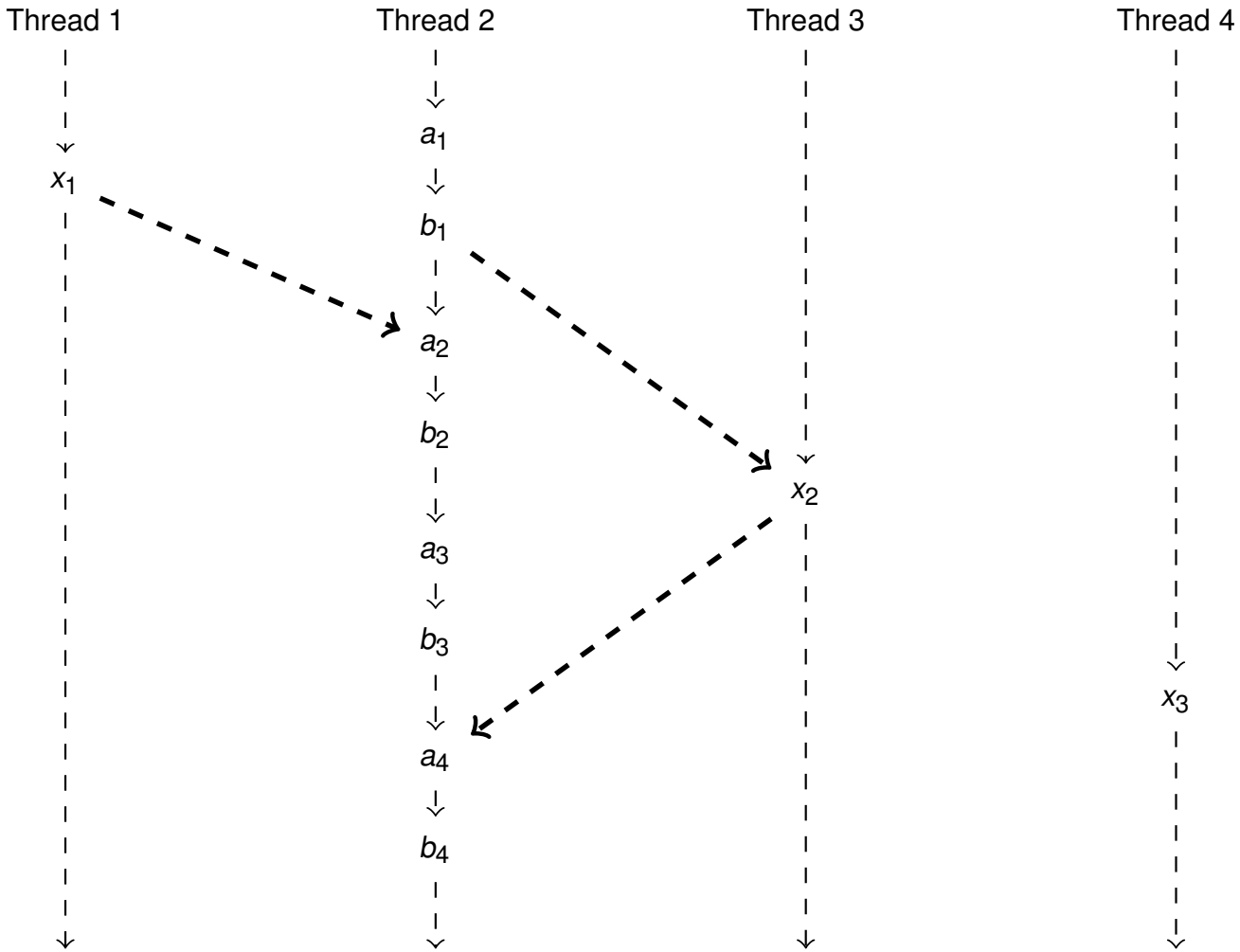

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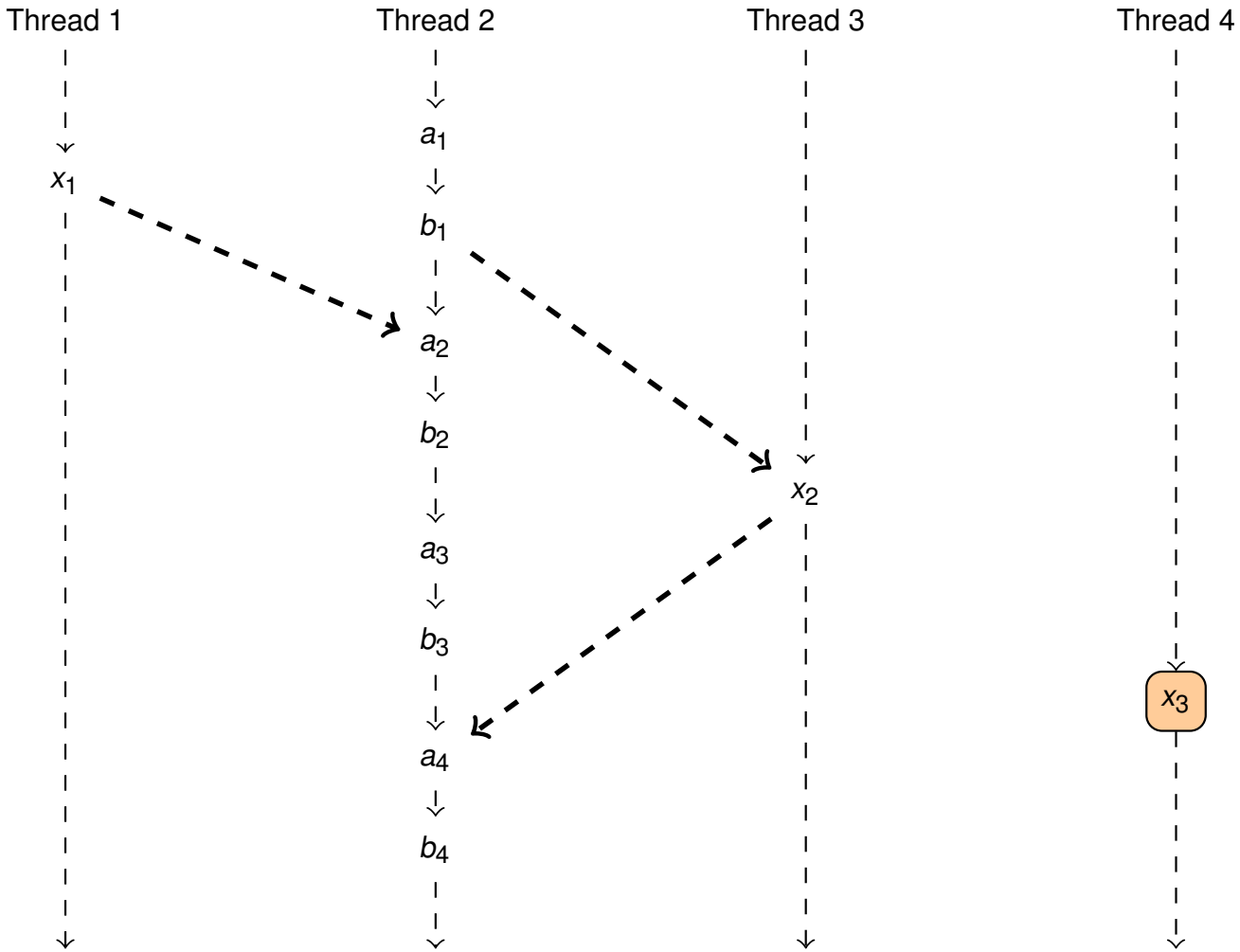

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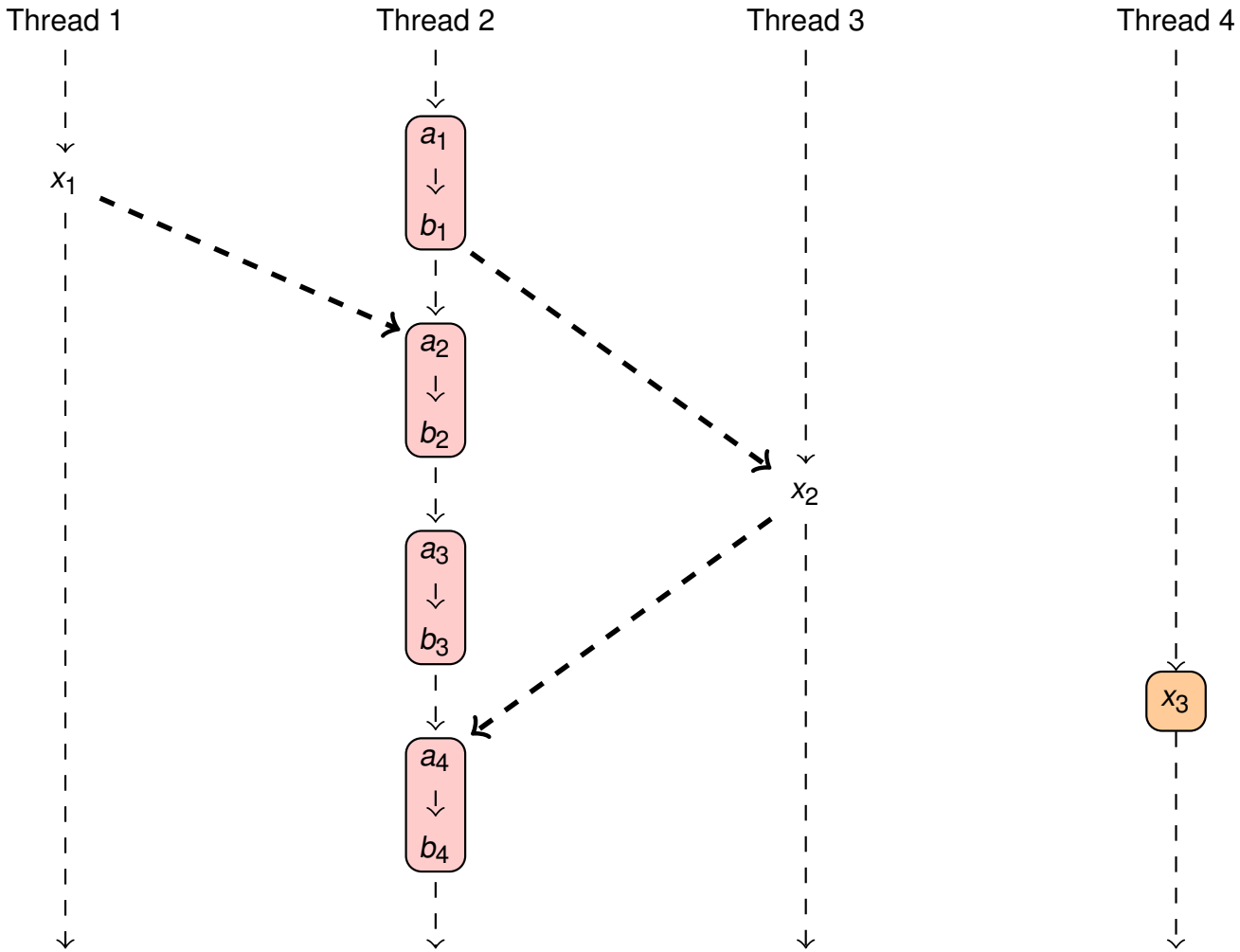

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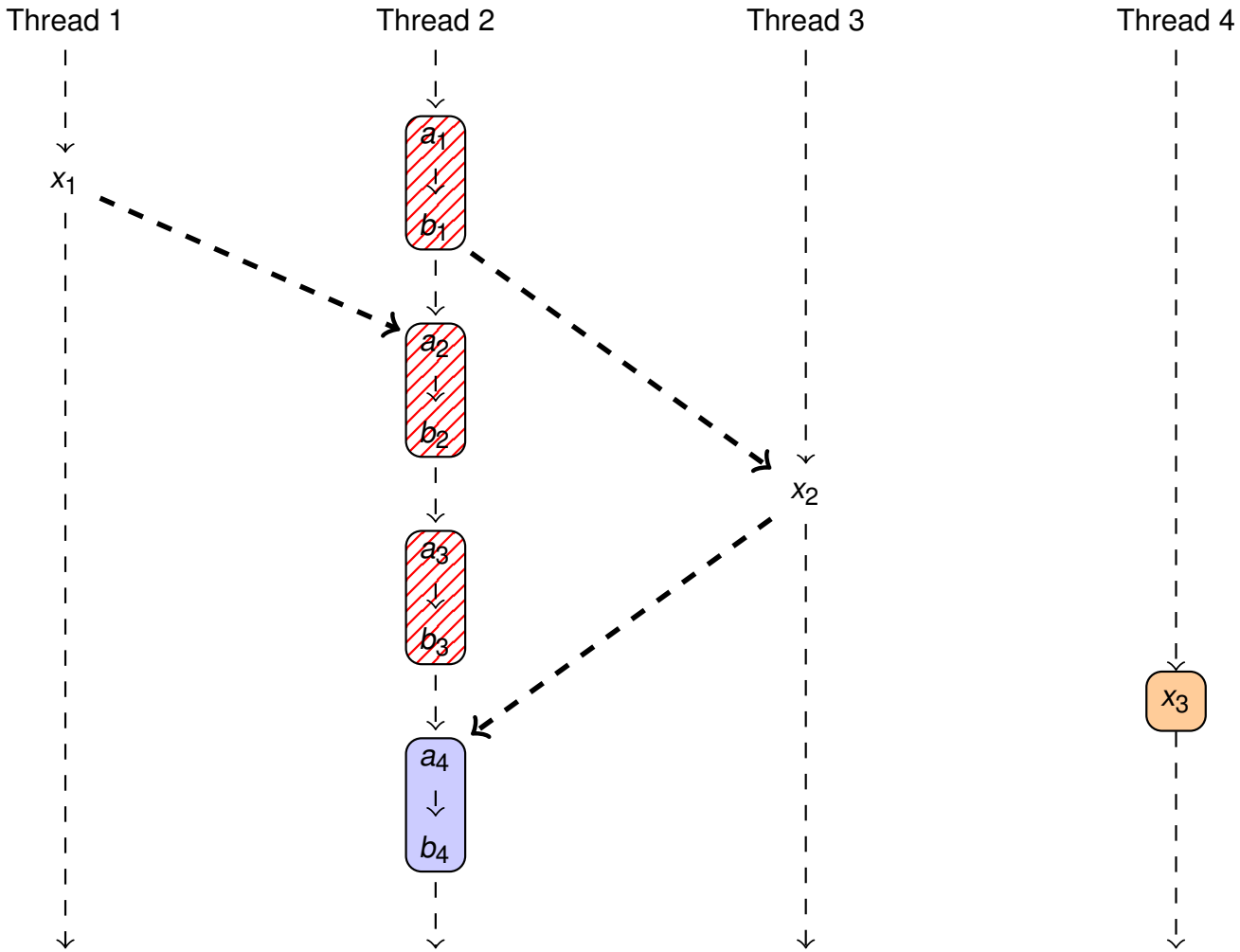

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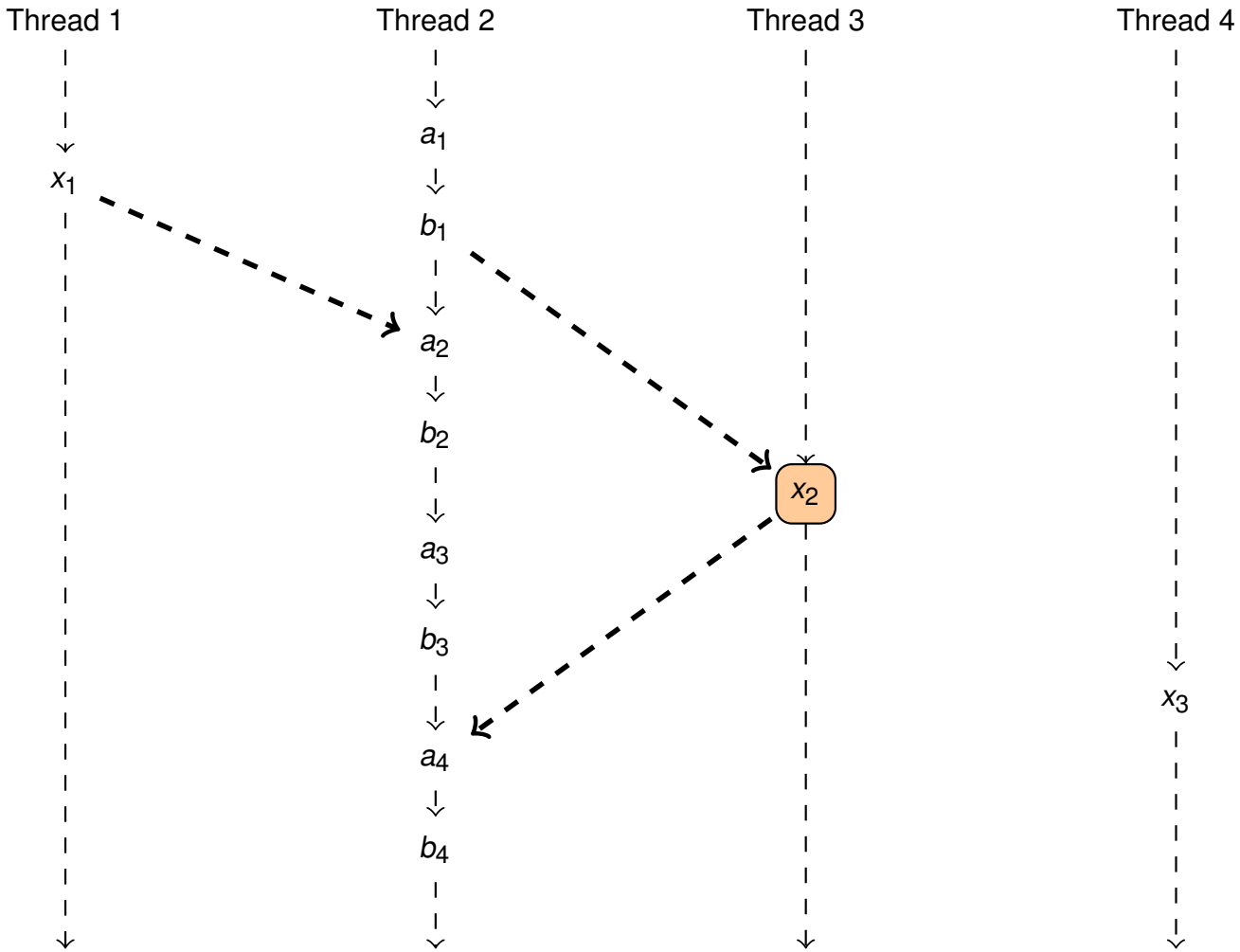

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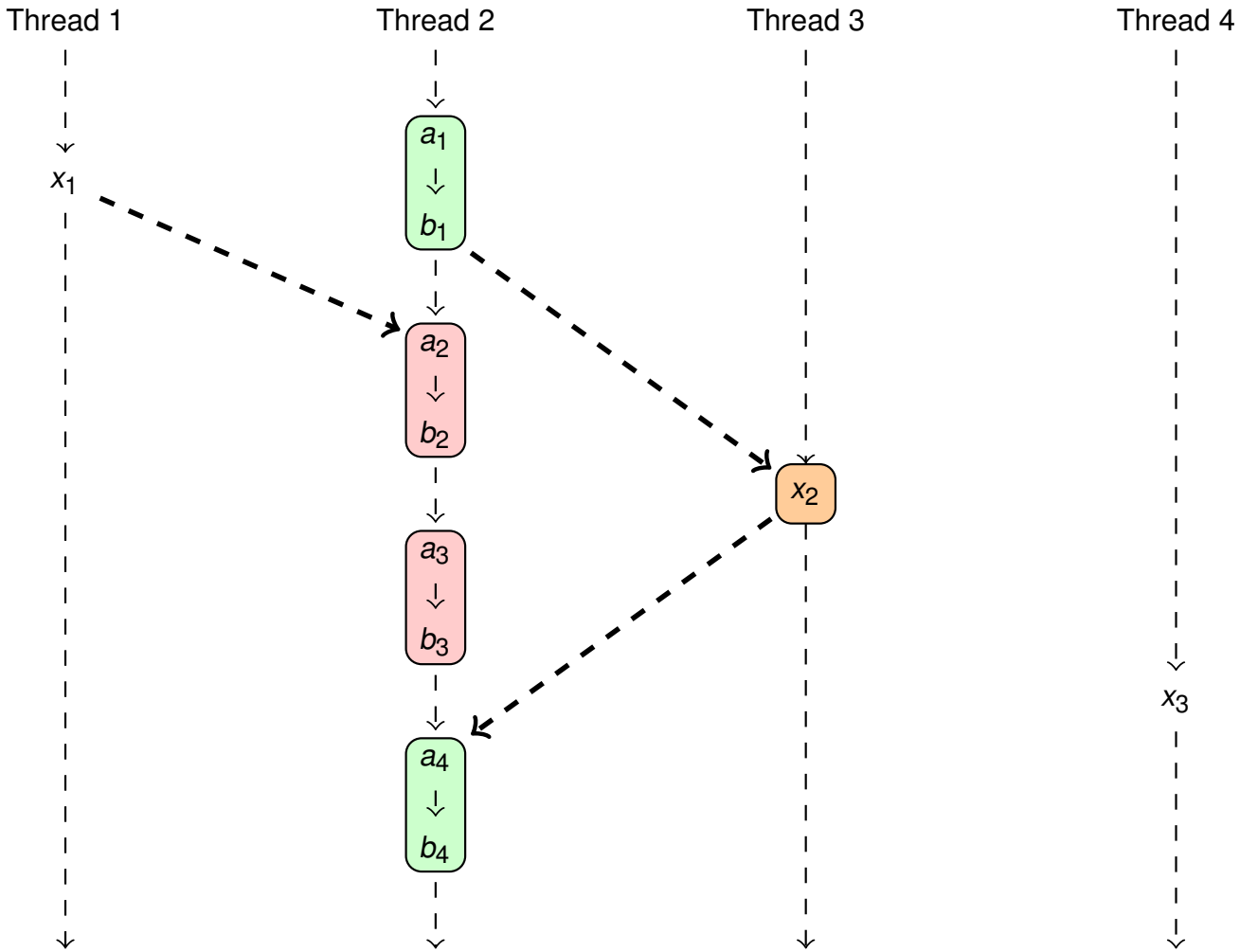

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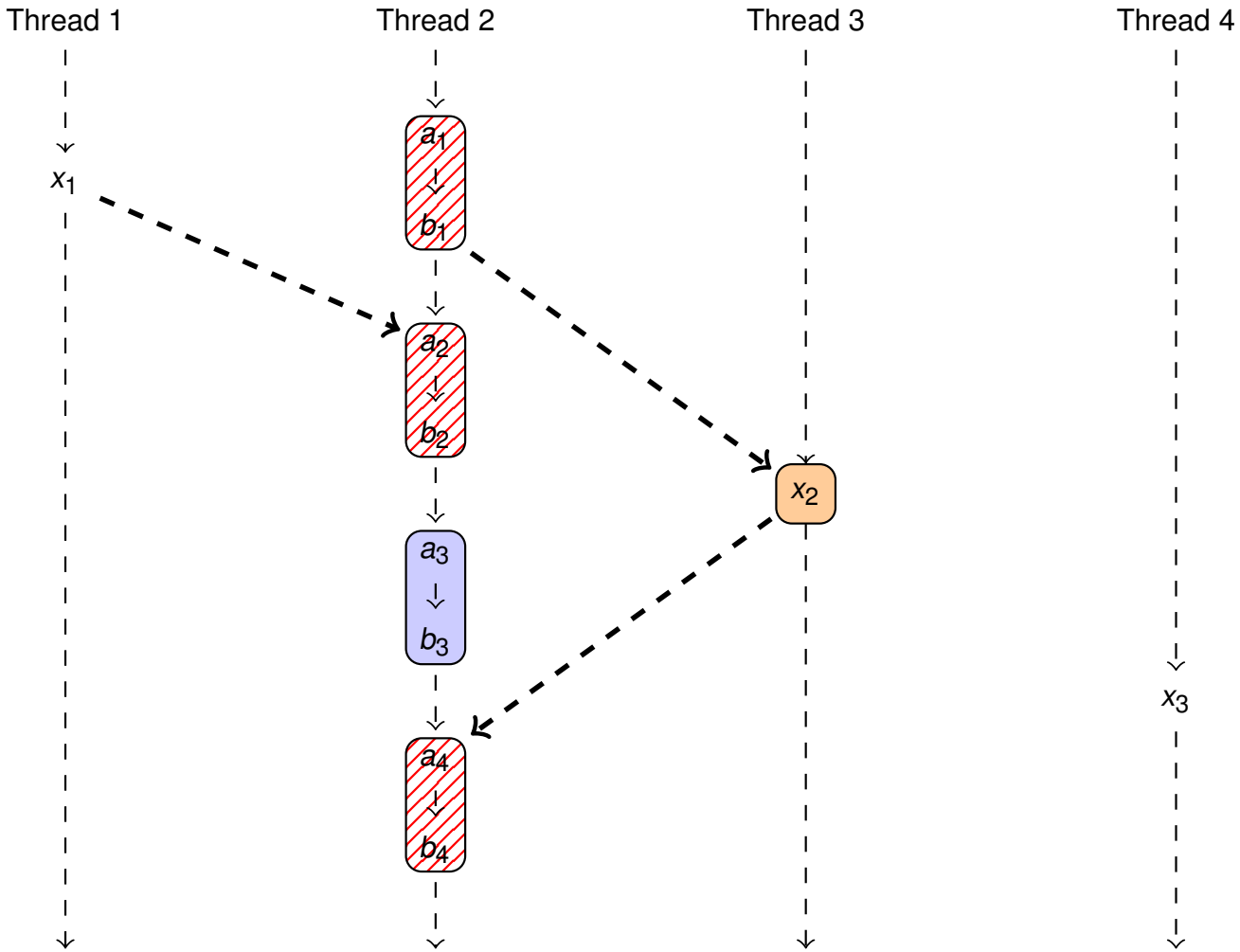

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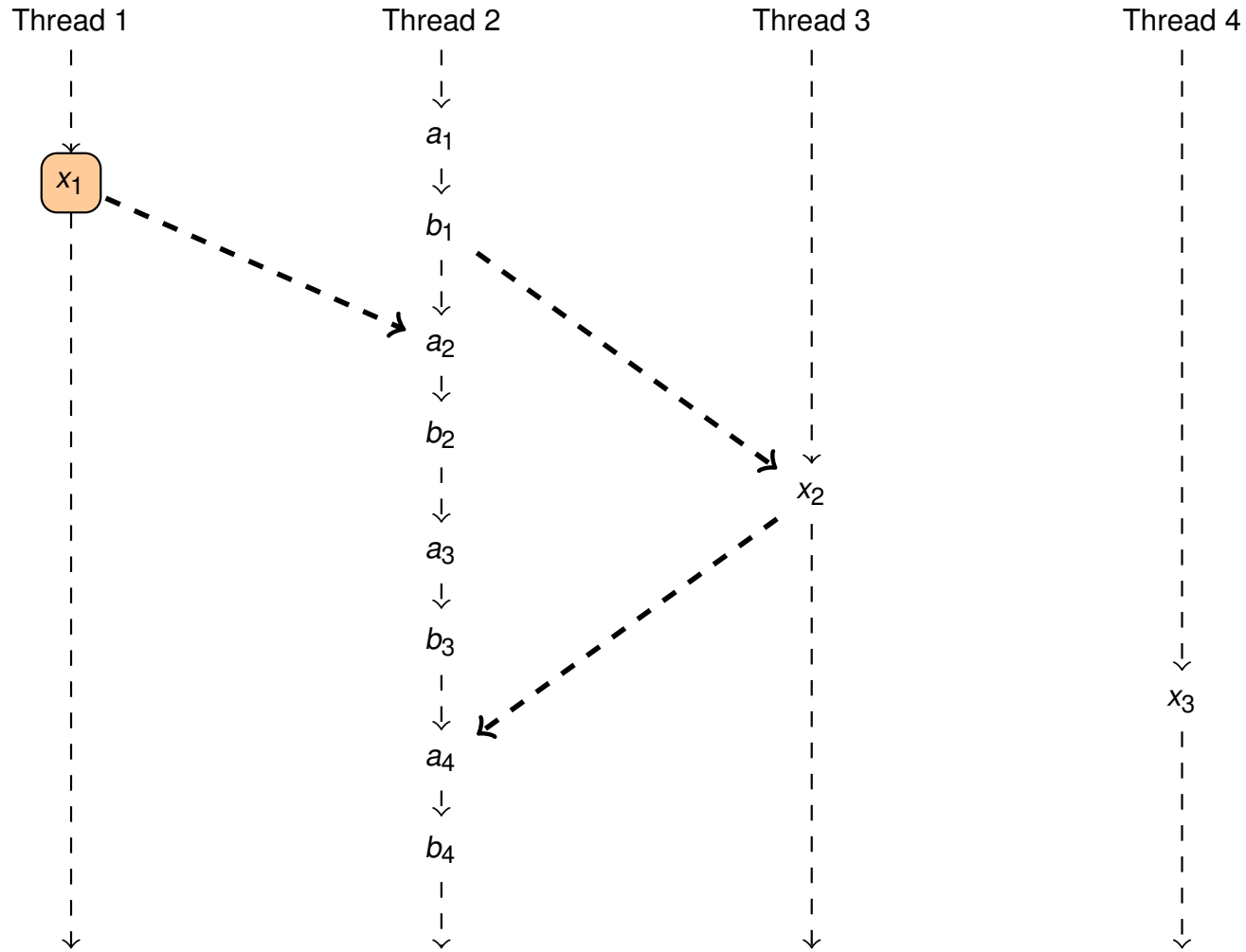

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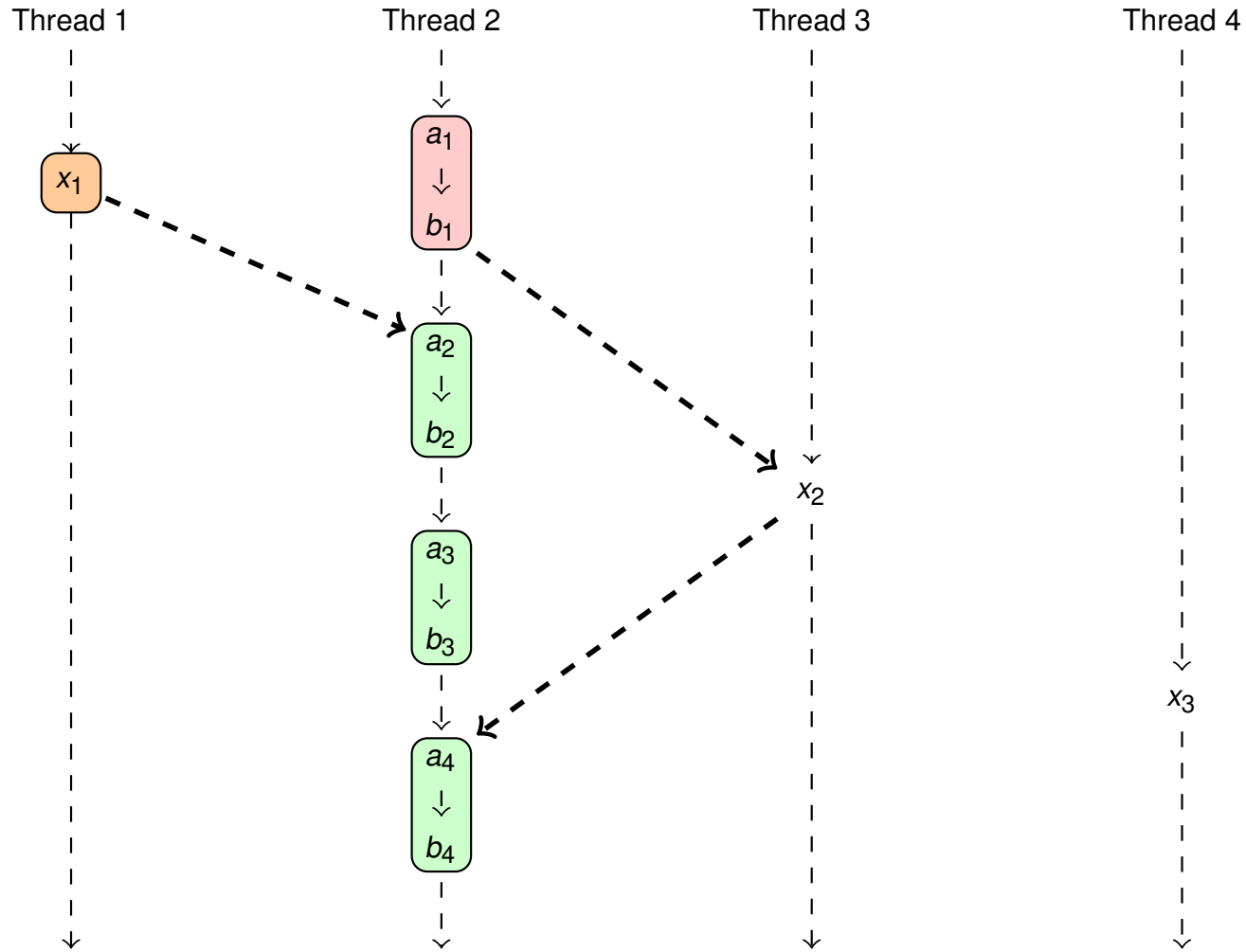

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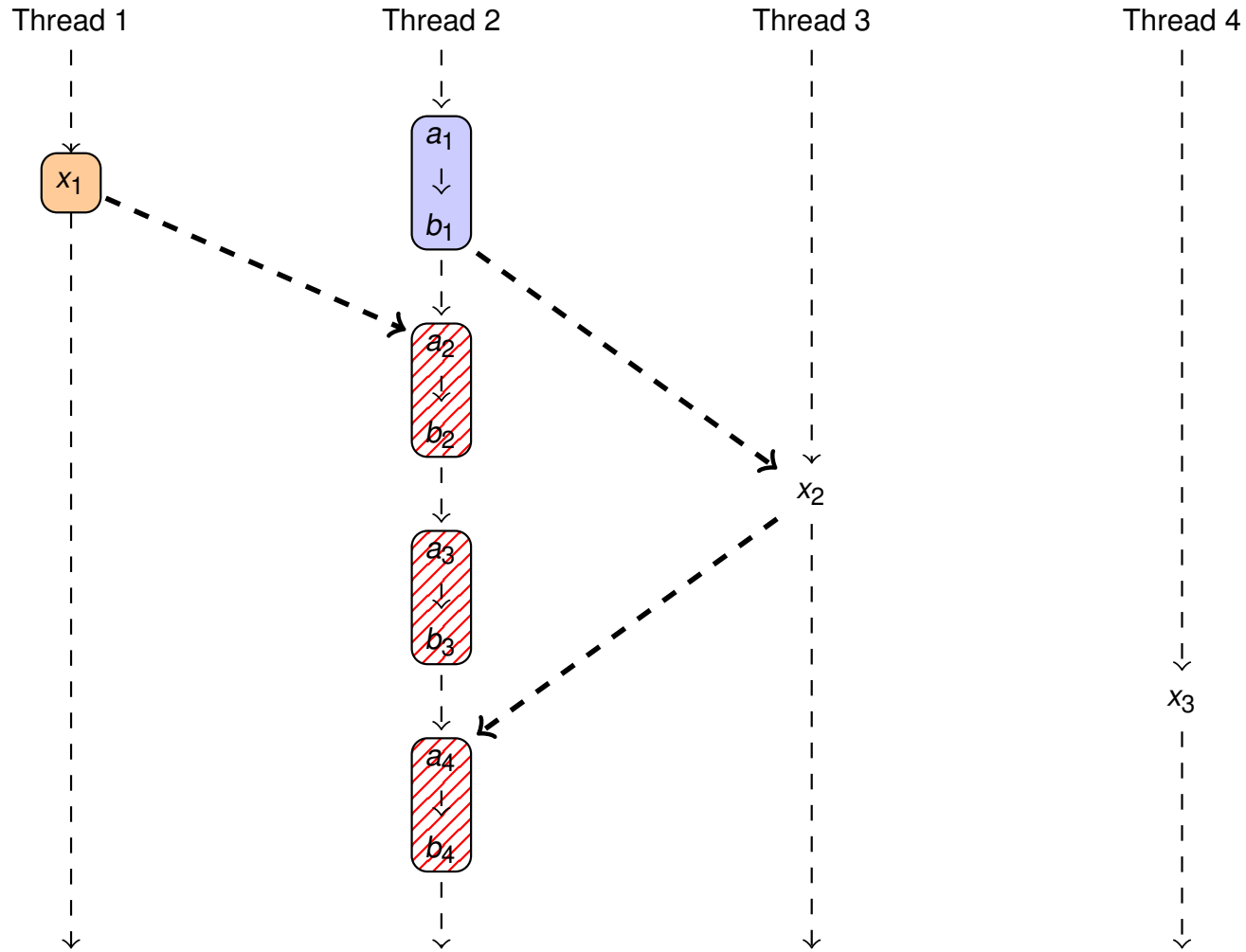

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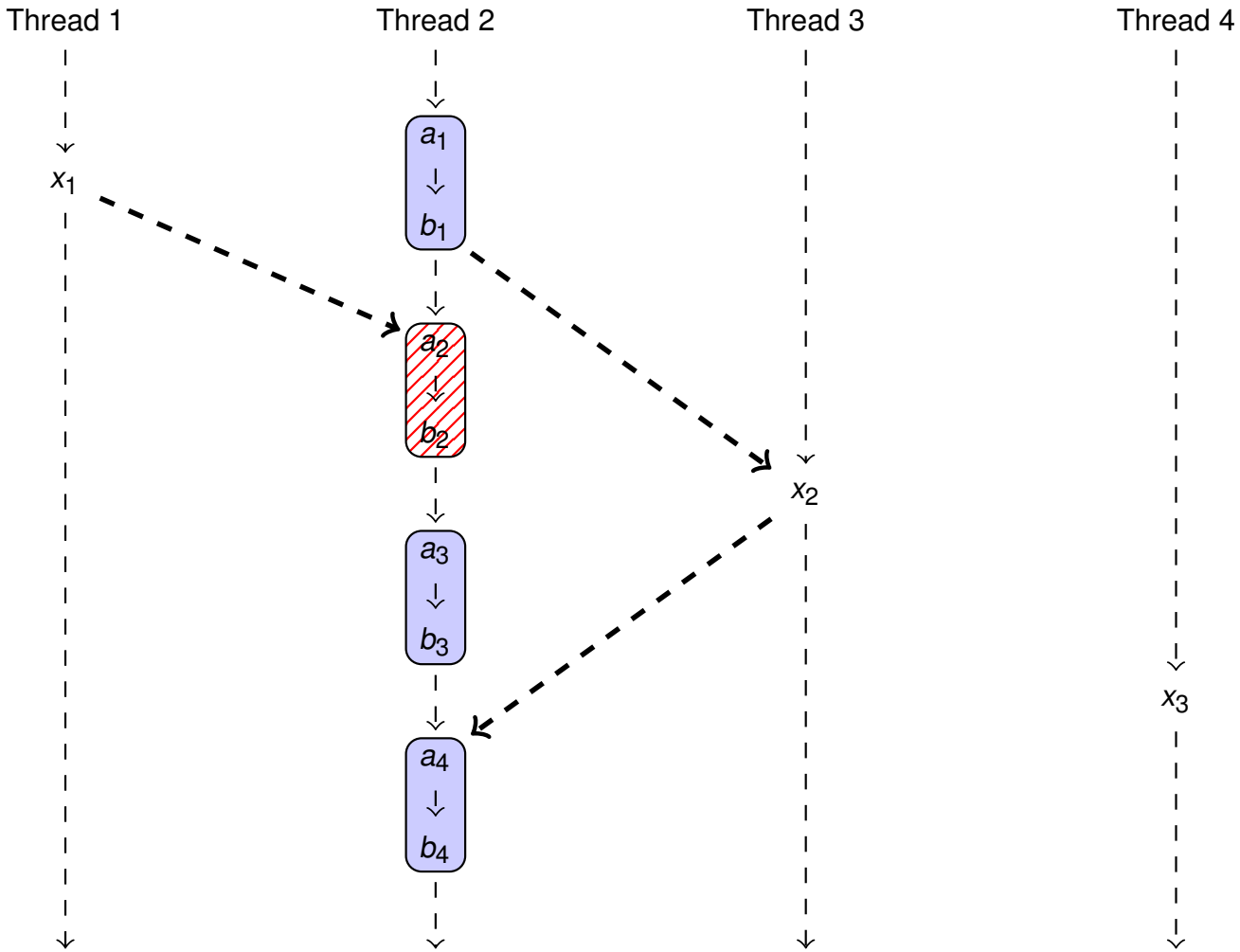

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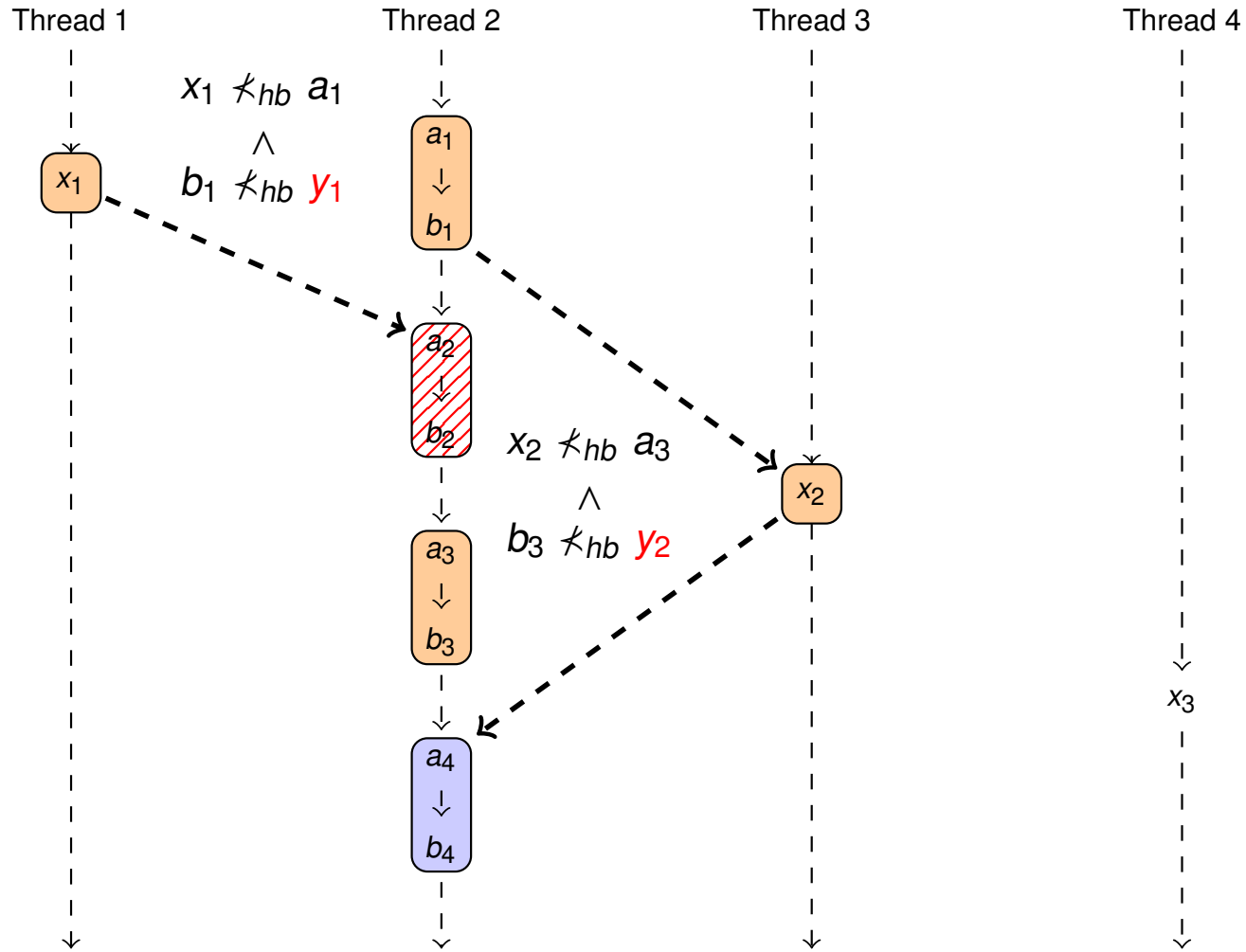

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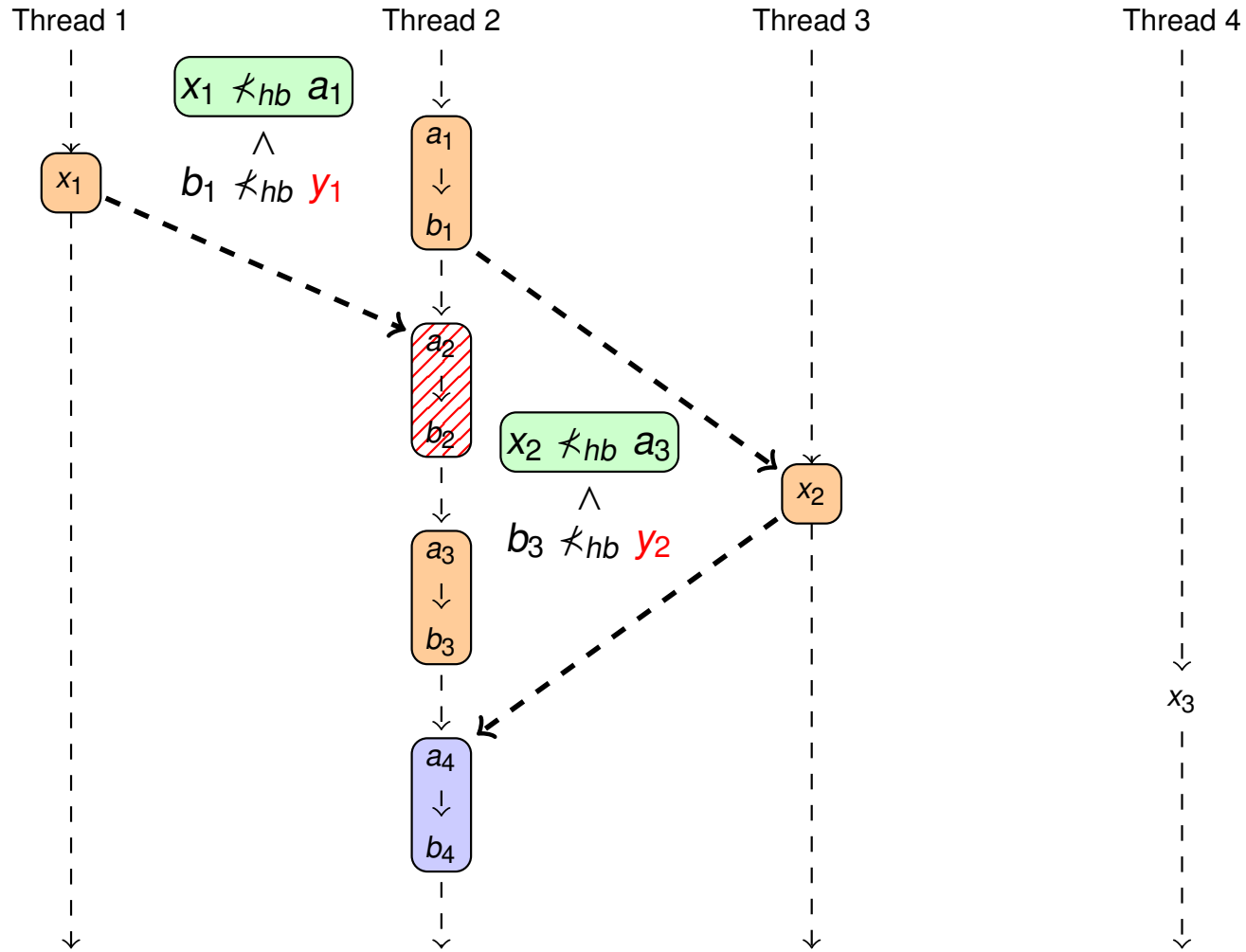

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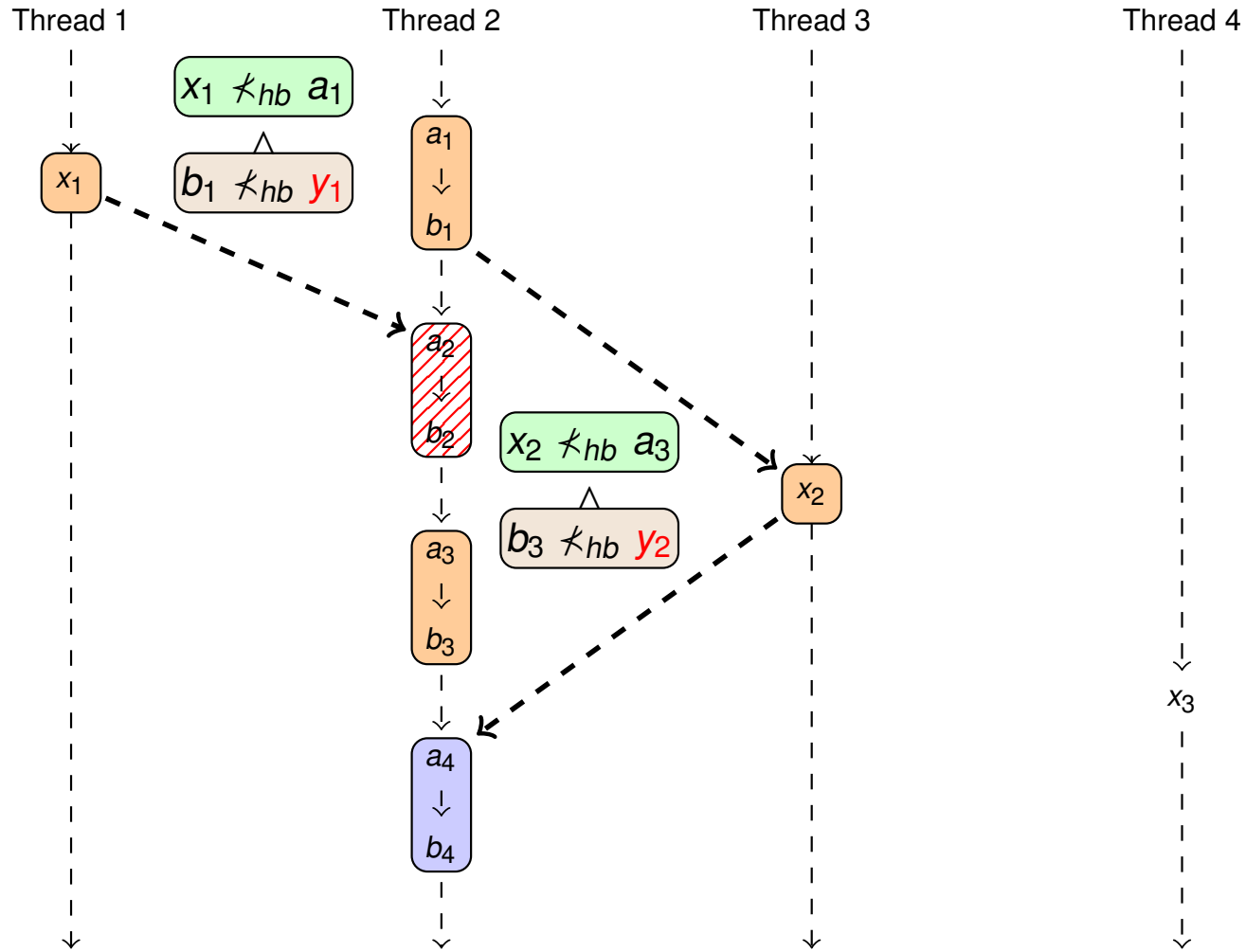

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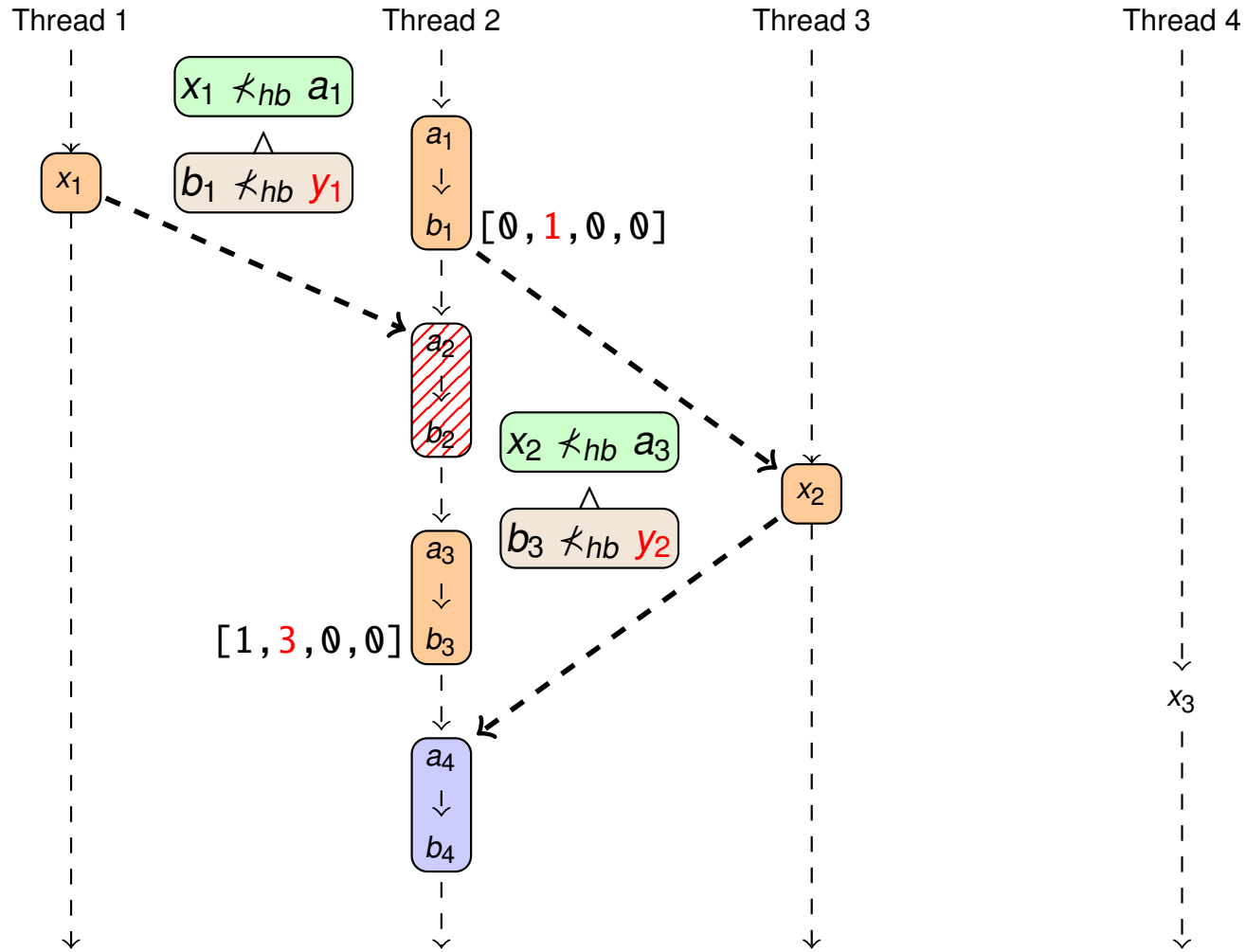

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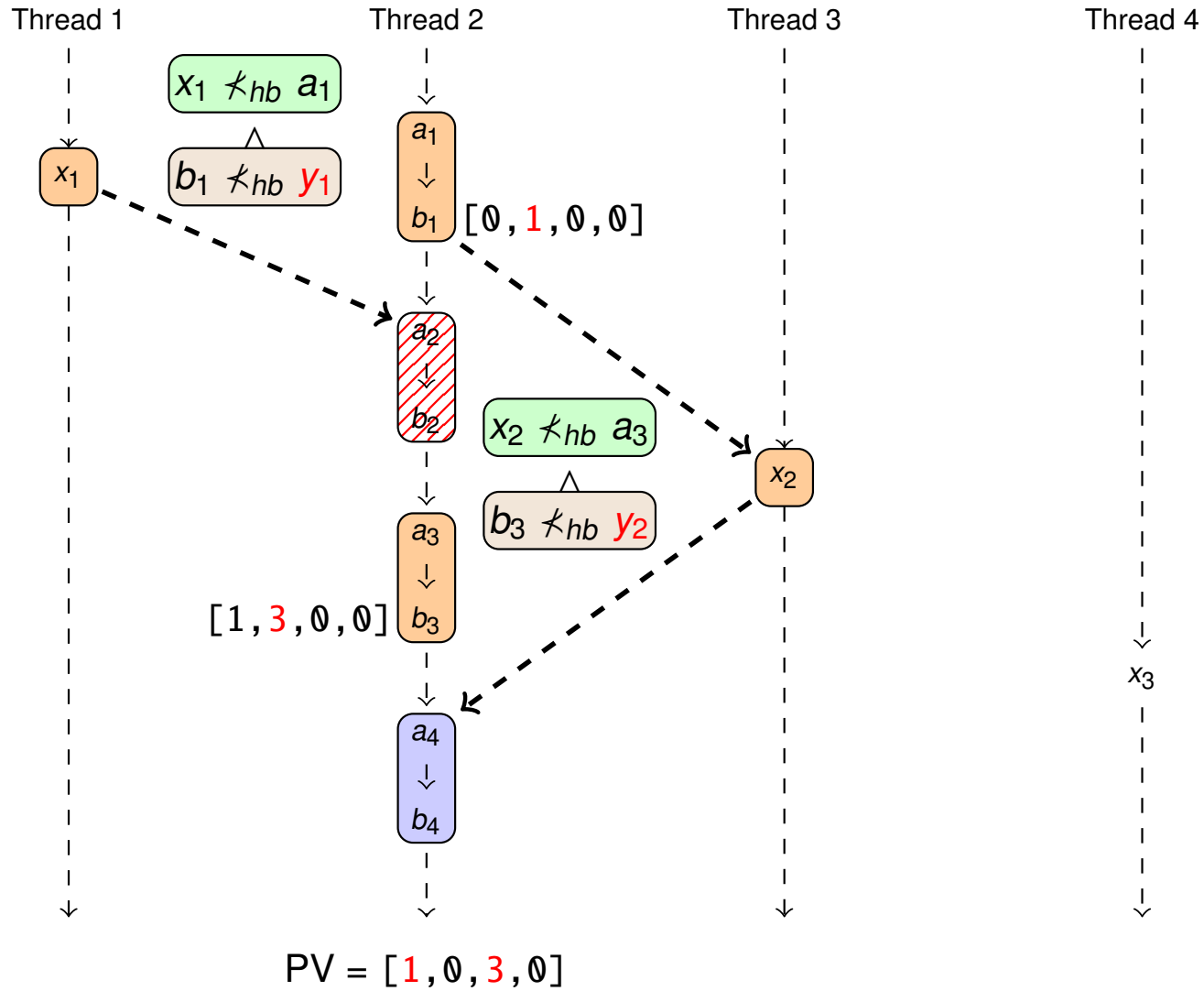

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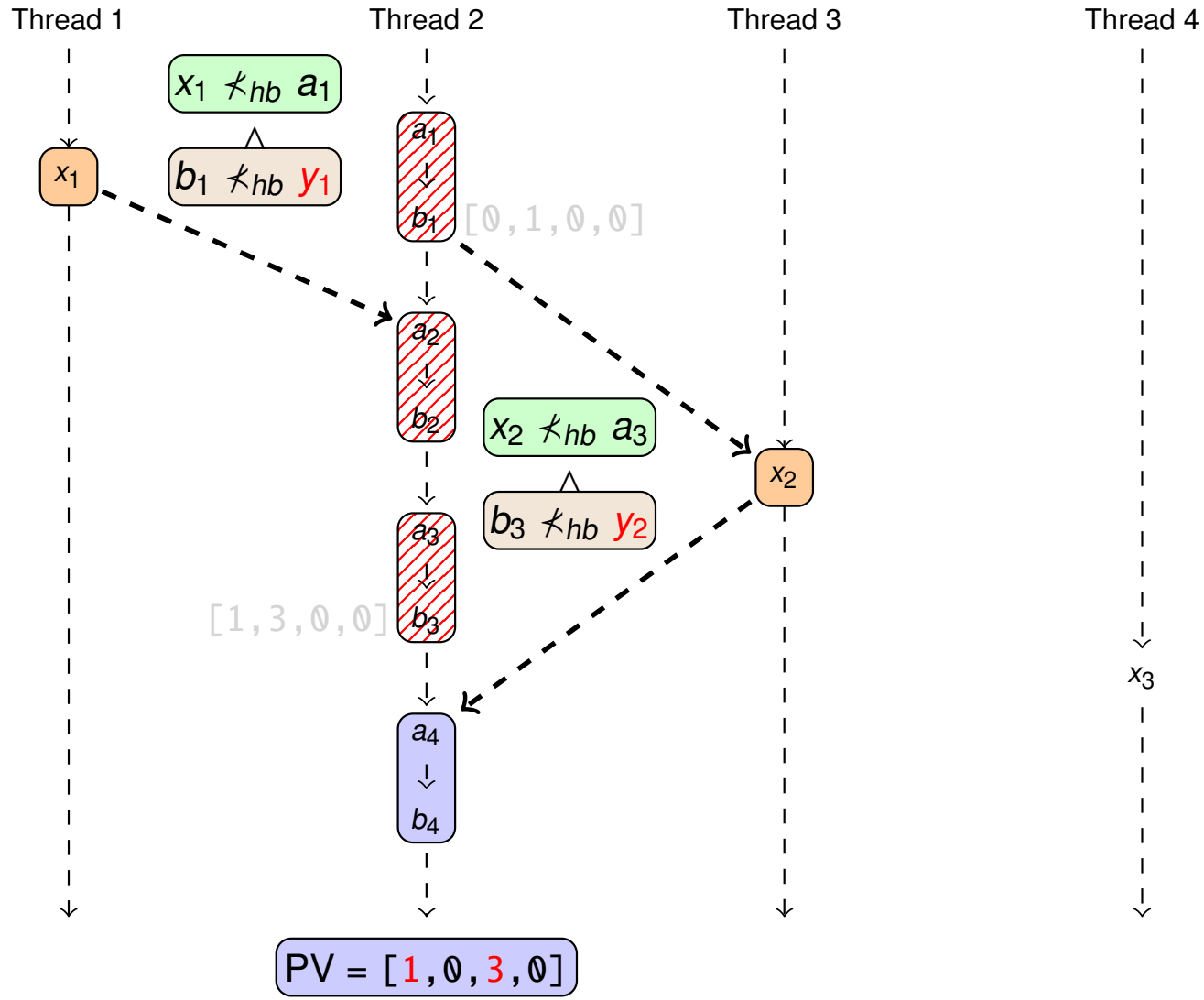

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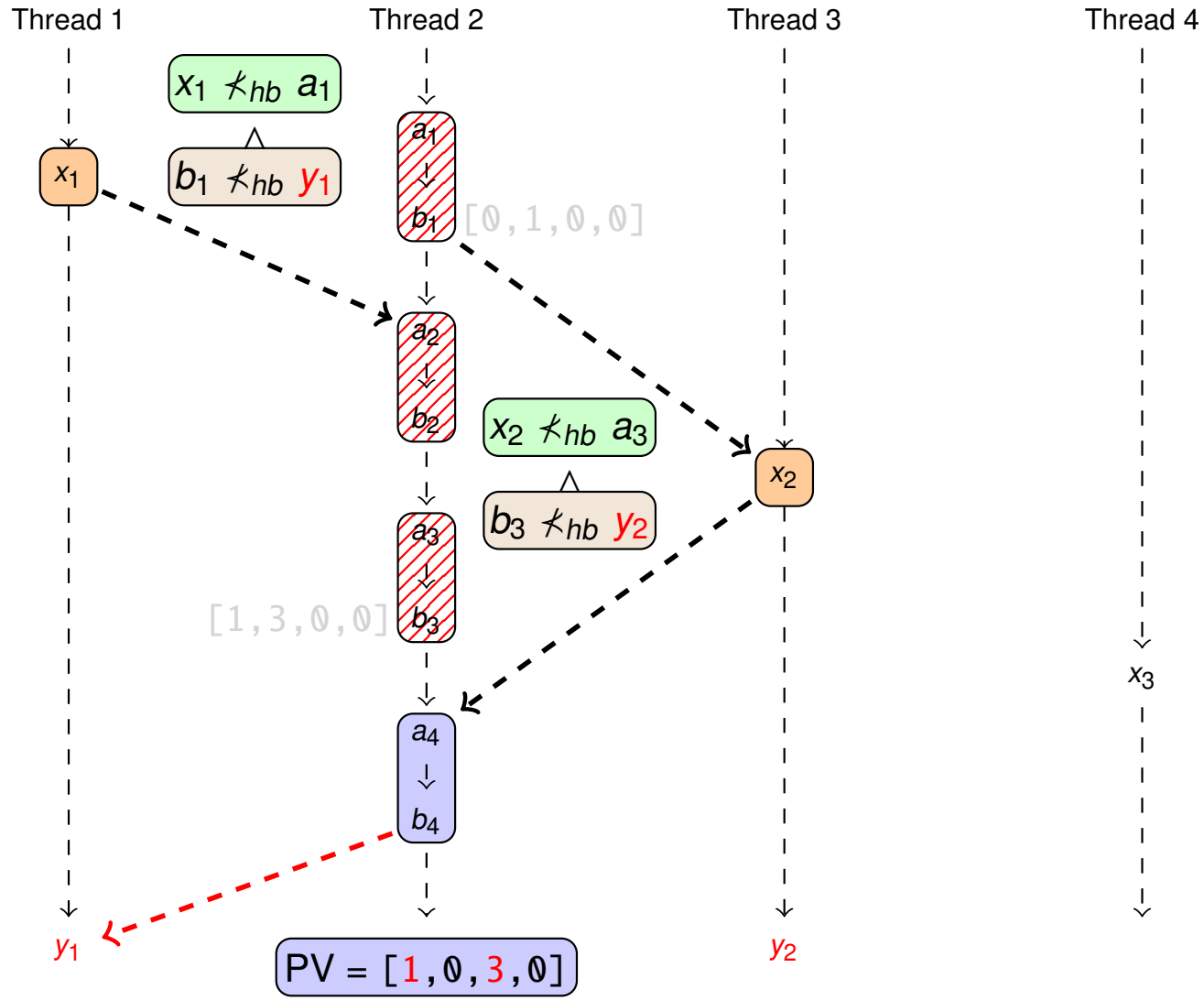

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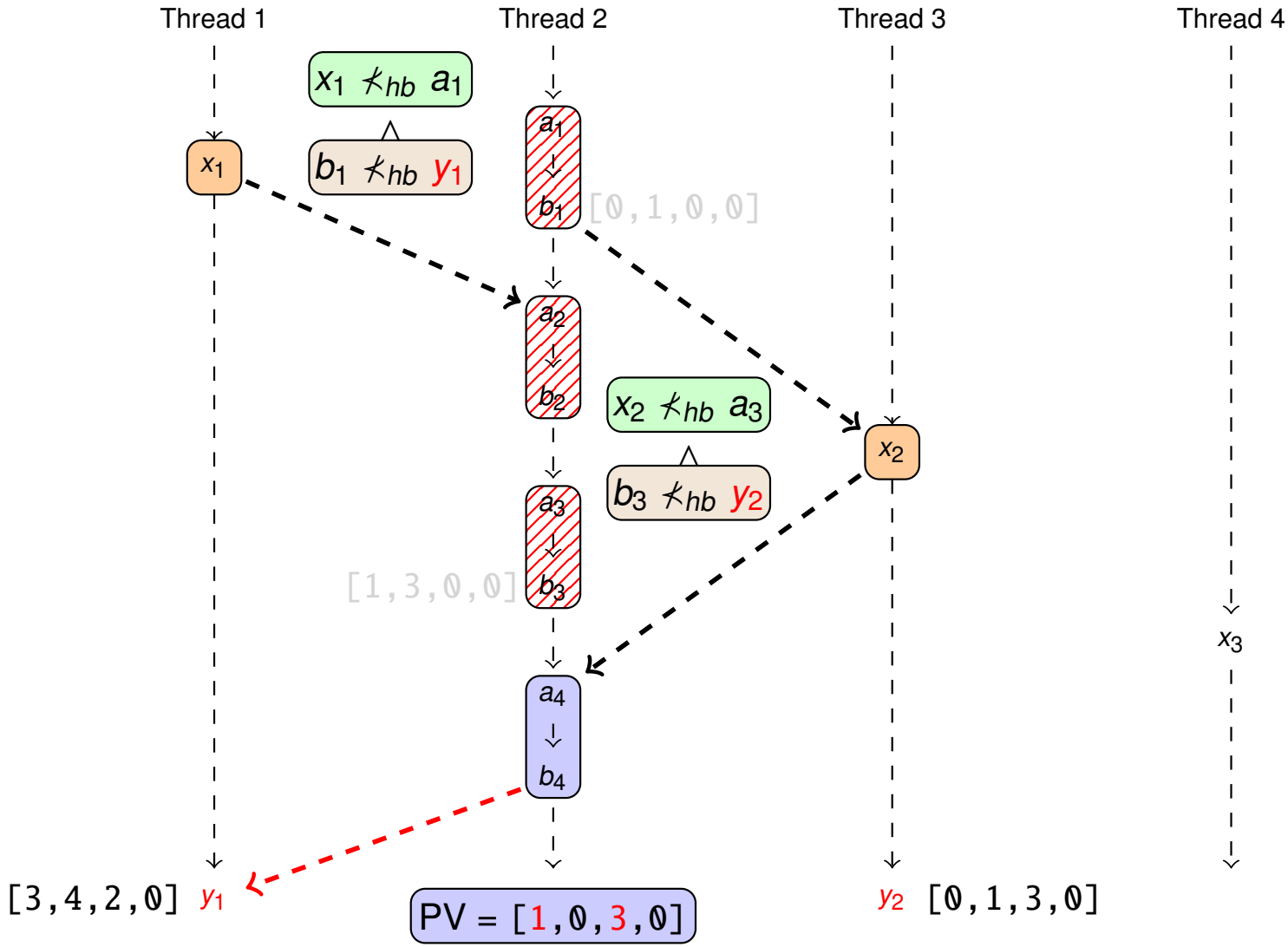

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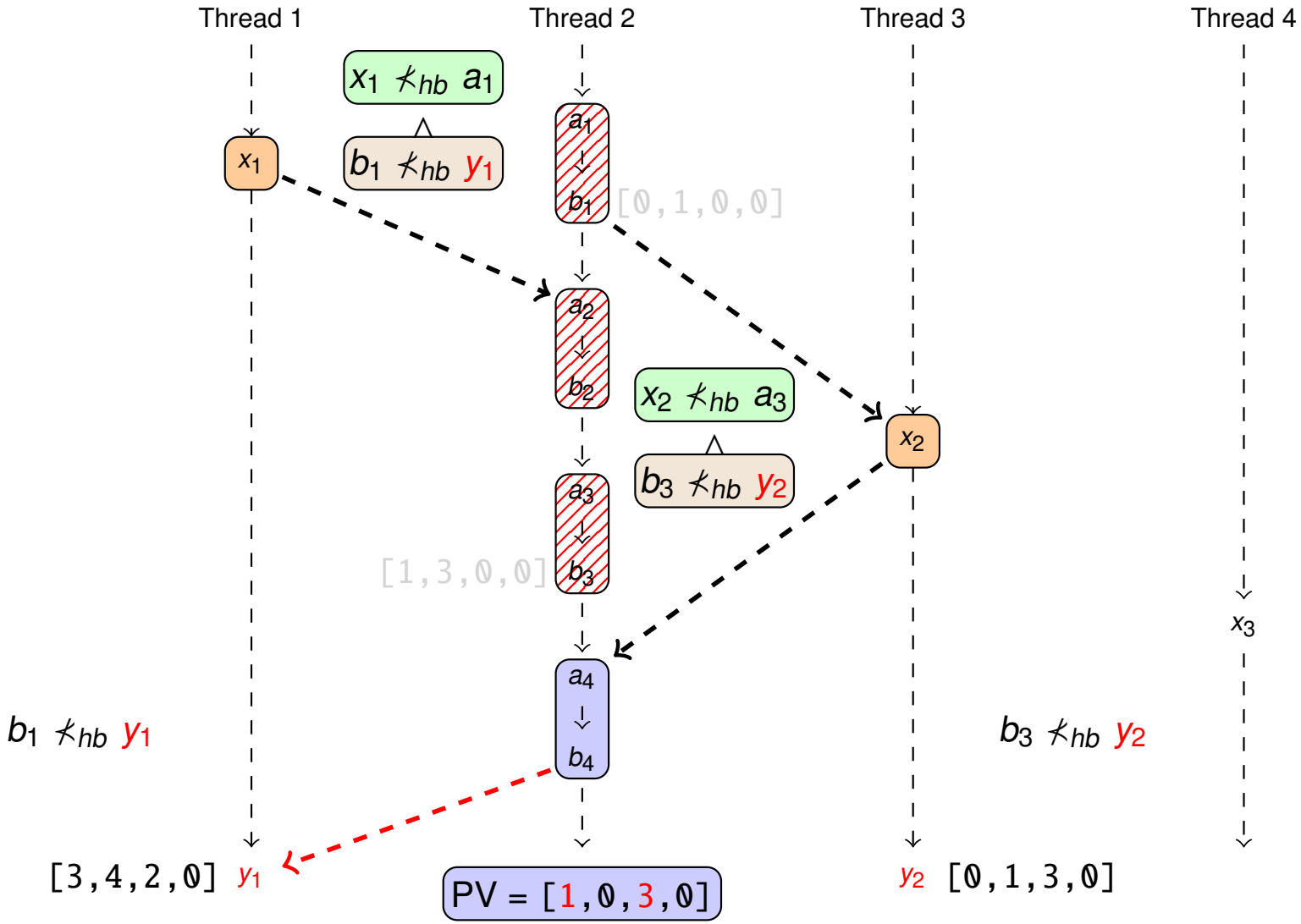

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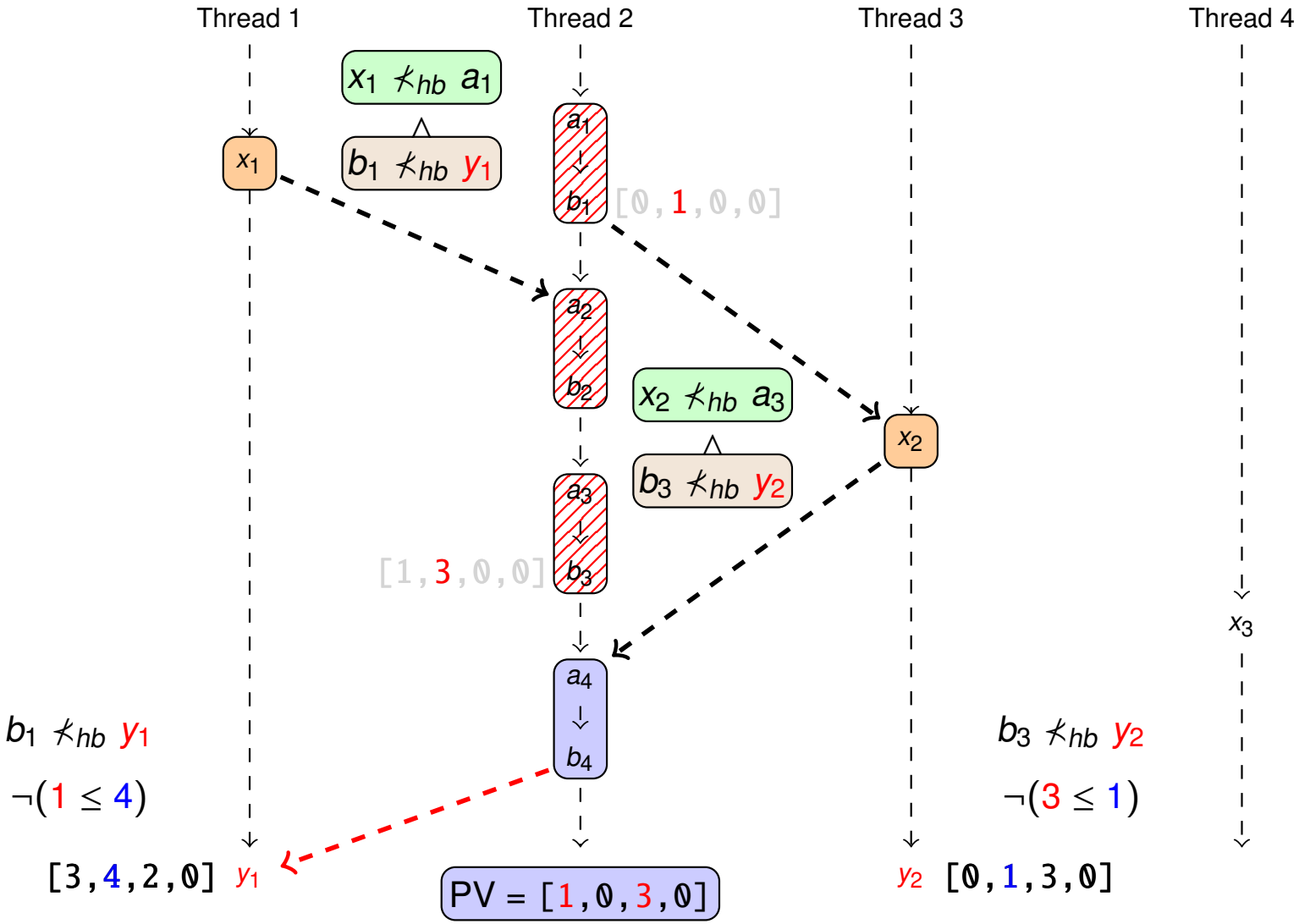

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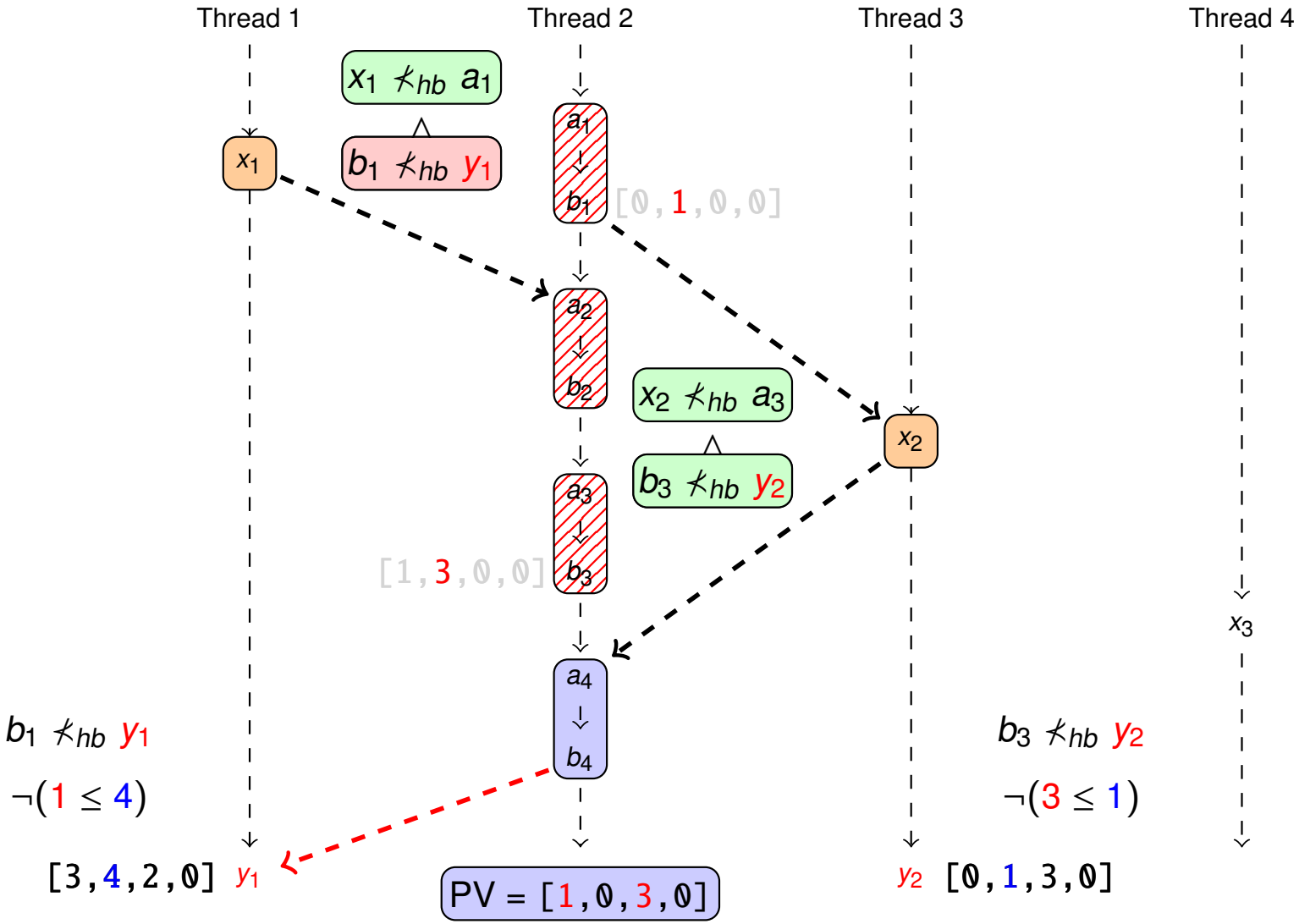

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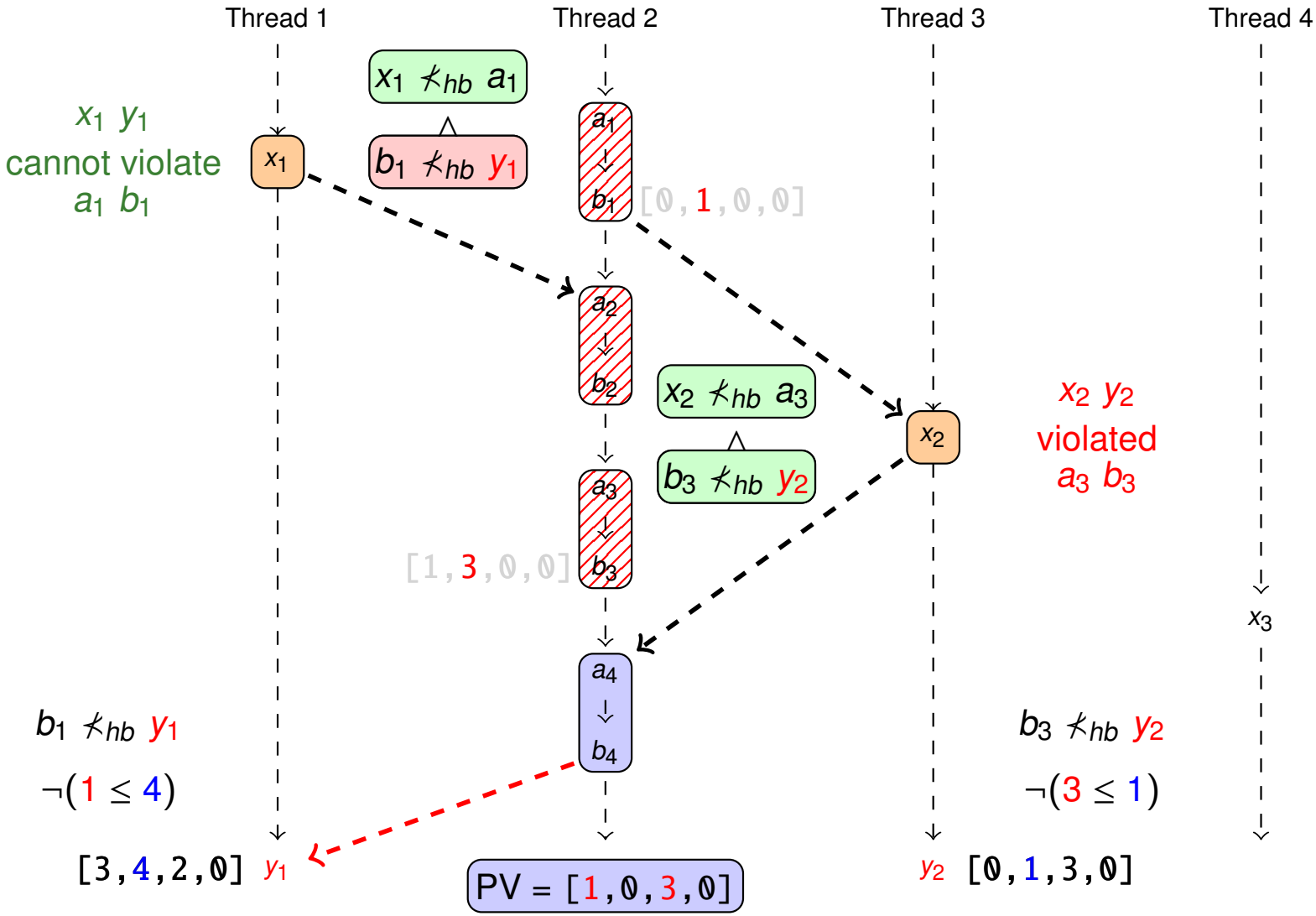

Experimental Results

Benchmark	T/S pairs	Contract Violations	False Positives	Potential AV	Real AV	SLOC	Time (s)
Coord03	8	380	0	0	380	116	1.01
Coord04	4	24	0	0	24	53	0.52
Local	4	2	0	0	2	27	0.52
NASA	1	100	0	0	100	96	0.60
Account	1	176	0	0	176	54	0.53
Link Manager	2	1	0	0	1	1.5K	1.14
Chromium-1	2	2	0	0	2	7.5M	49.12

Conclusion and Future Work

- We have extended contracts for concurrency with
  - Parameters (flow of data)
  - Spoilers (contextual information)
- We have proposed two methods to validate such contracts
  - Static method based on grammars and parsing trees
  - On-the-fly dynamic method based on happens-before relation and vector clocks
- We have evaluated both of these methods on both simple as well as real-world programs
- Future work
  - Support for more parameters in the dynamic approach
  - Support for spoilers in the static approach
  - Combine the static and dynamic approaches
  - Automatically derive contracts