Verifying Asynchronous programs with nested locks

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Joint work with

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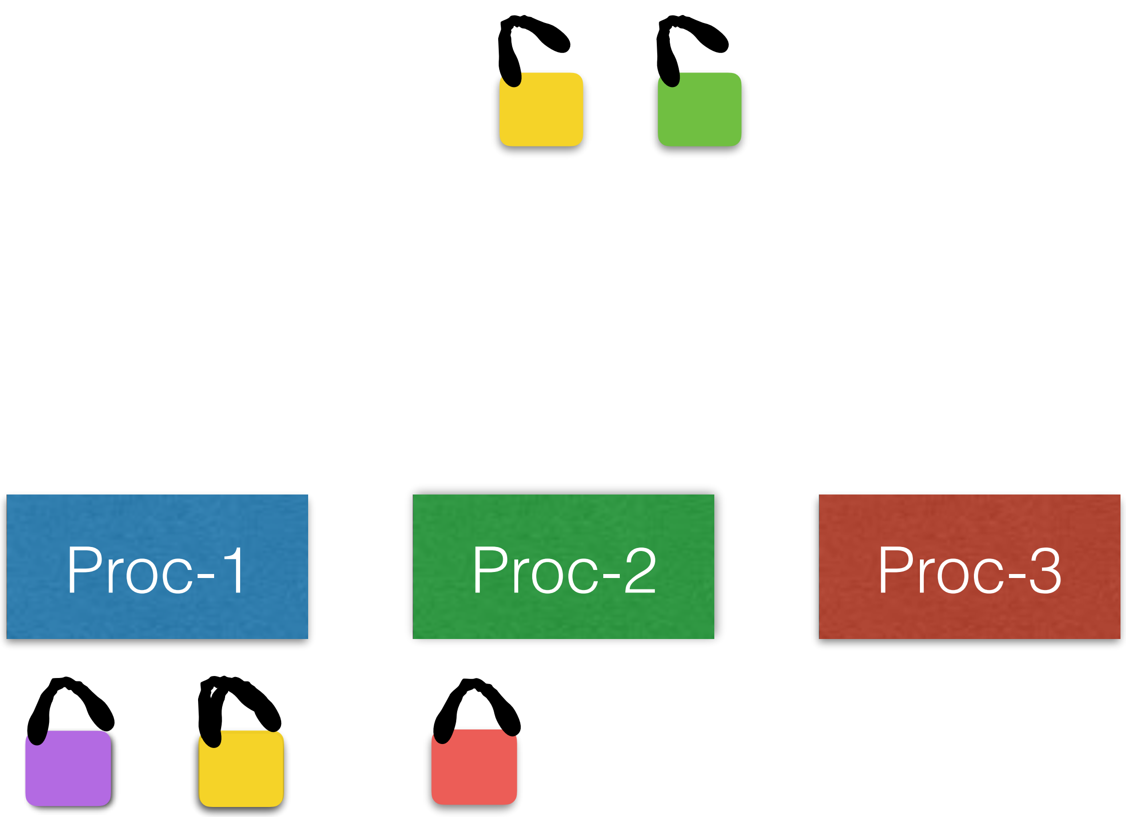
- M.F. Atig
- Prakash Saivasan

Programs with Locks:



- A collection of processes executing concurrently.
- A finite set of Locks

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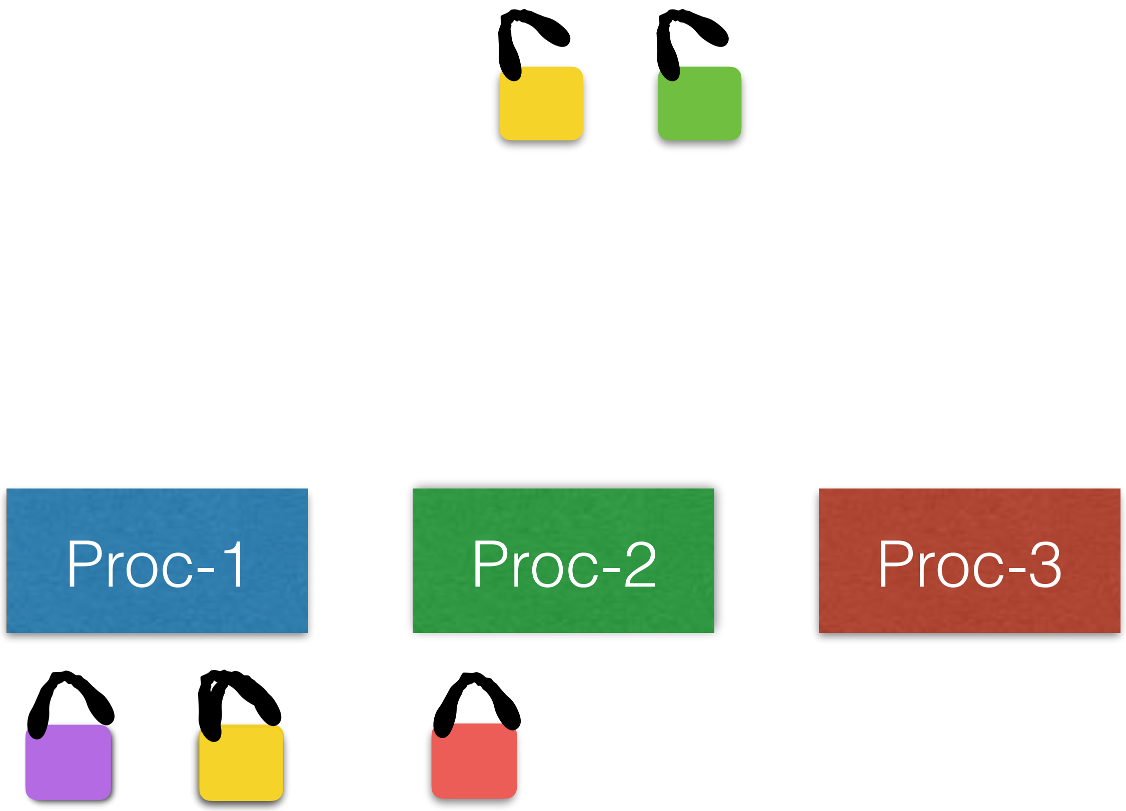
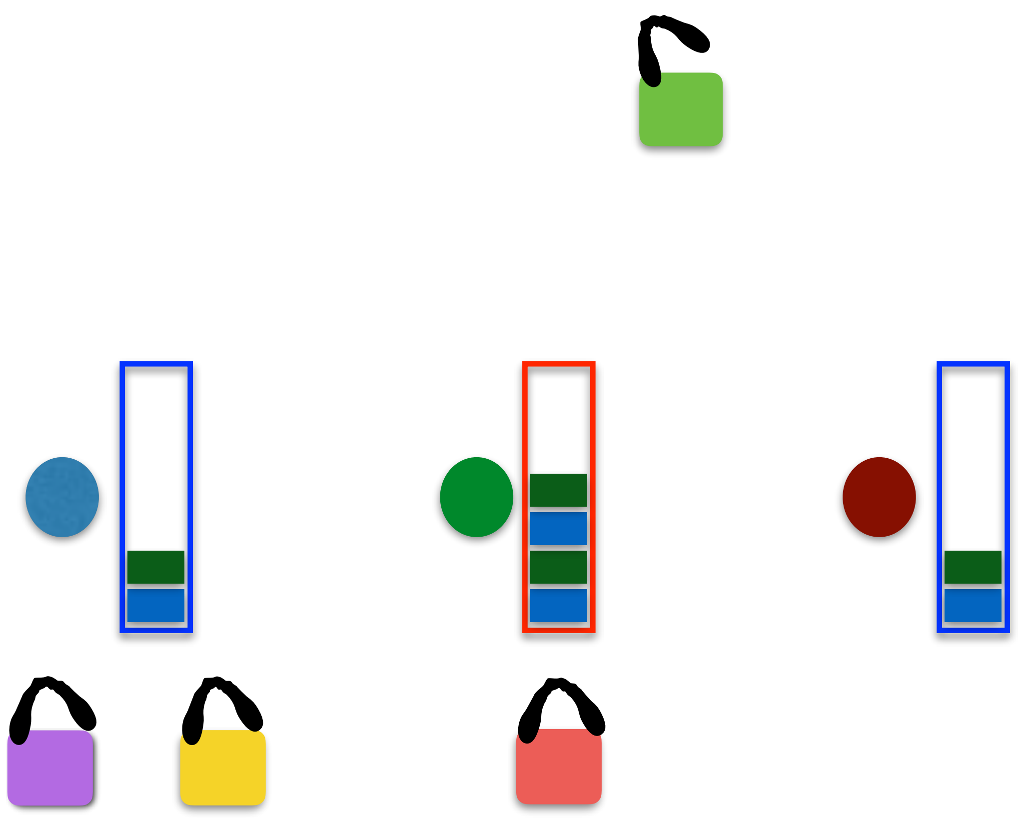


- A collection of processes executing concurrently.
- A finite set of Locks
- Processes may take locks that are available and release locks that they hold.
- Taking and releasing locks are atomic operations

Programs with Locks:



- Our processes will be recursive processes (over finite data domains)
- Modelled as Pushdown Systems

Why Locks

- Useful coordination mechanism.
- Can be built with protocols over shared memory. Usually supported by hardware.
- Available in many programming languages …

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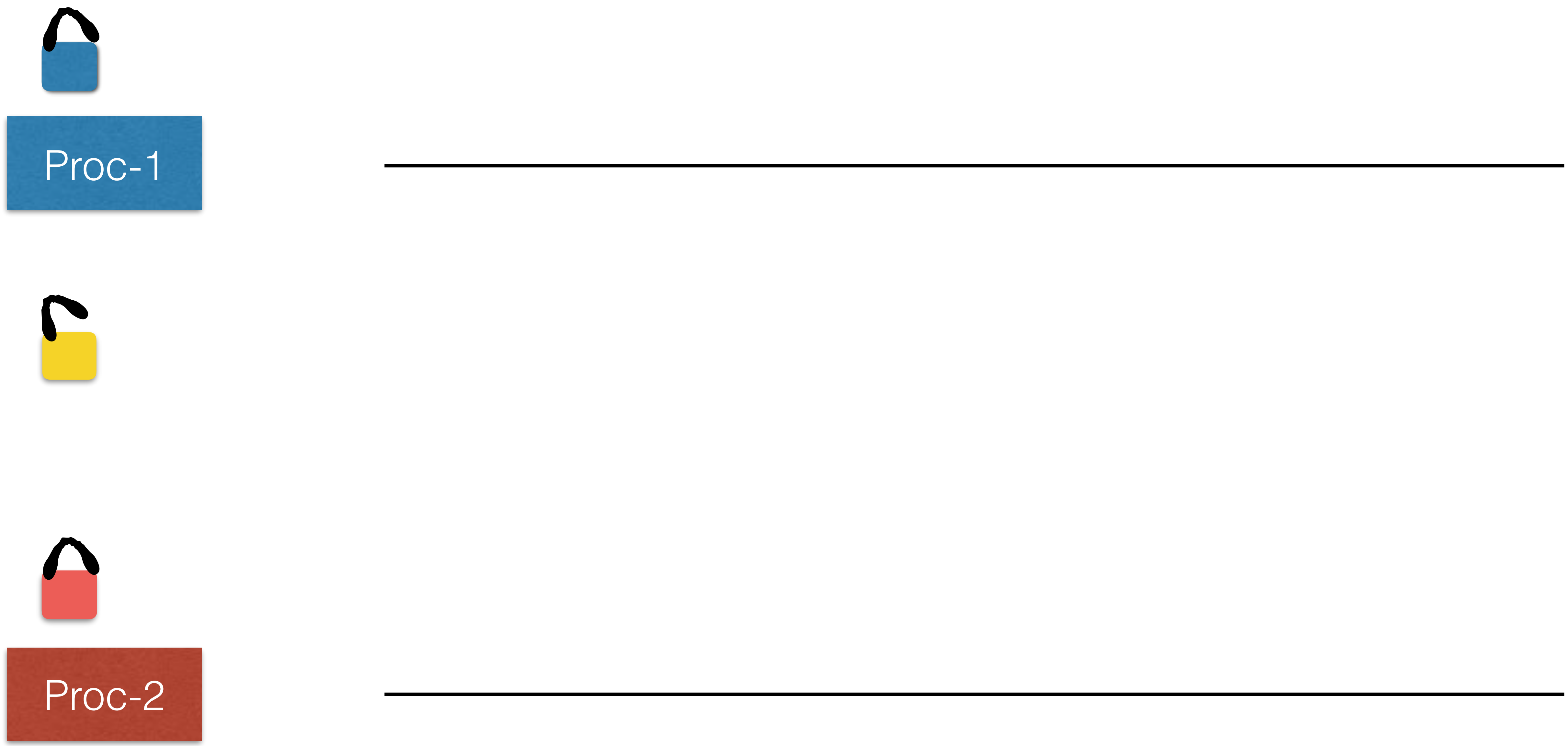
How good are they?
Can processes “synchronize” using just locks?

Synchronizing via Locks



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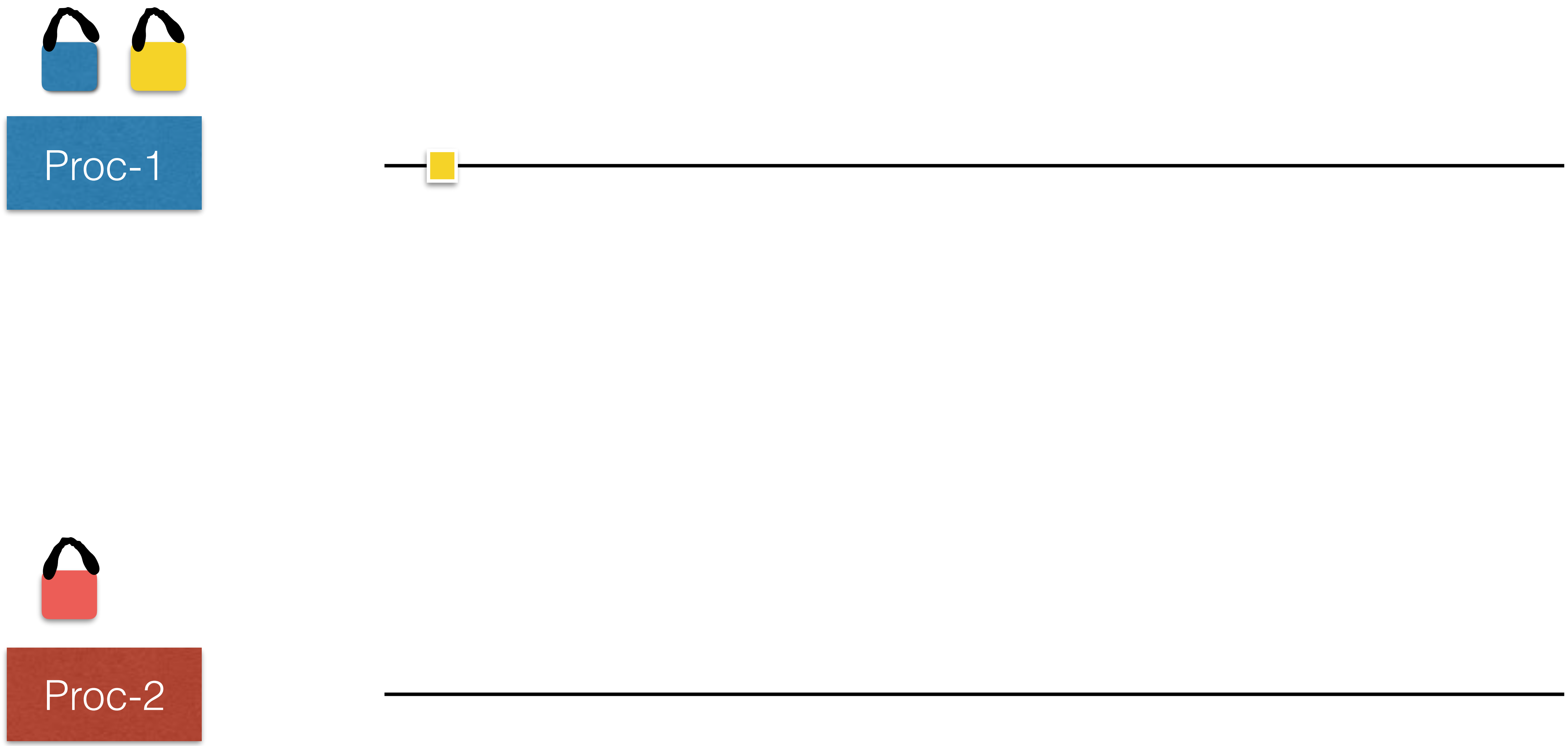

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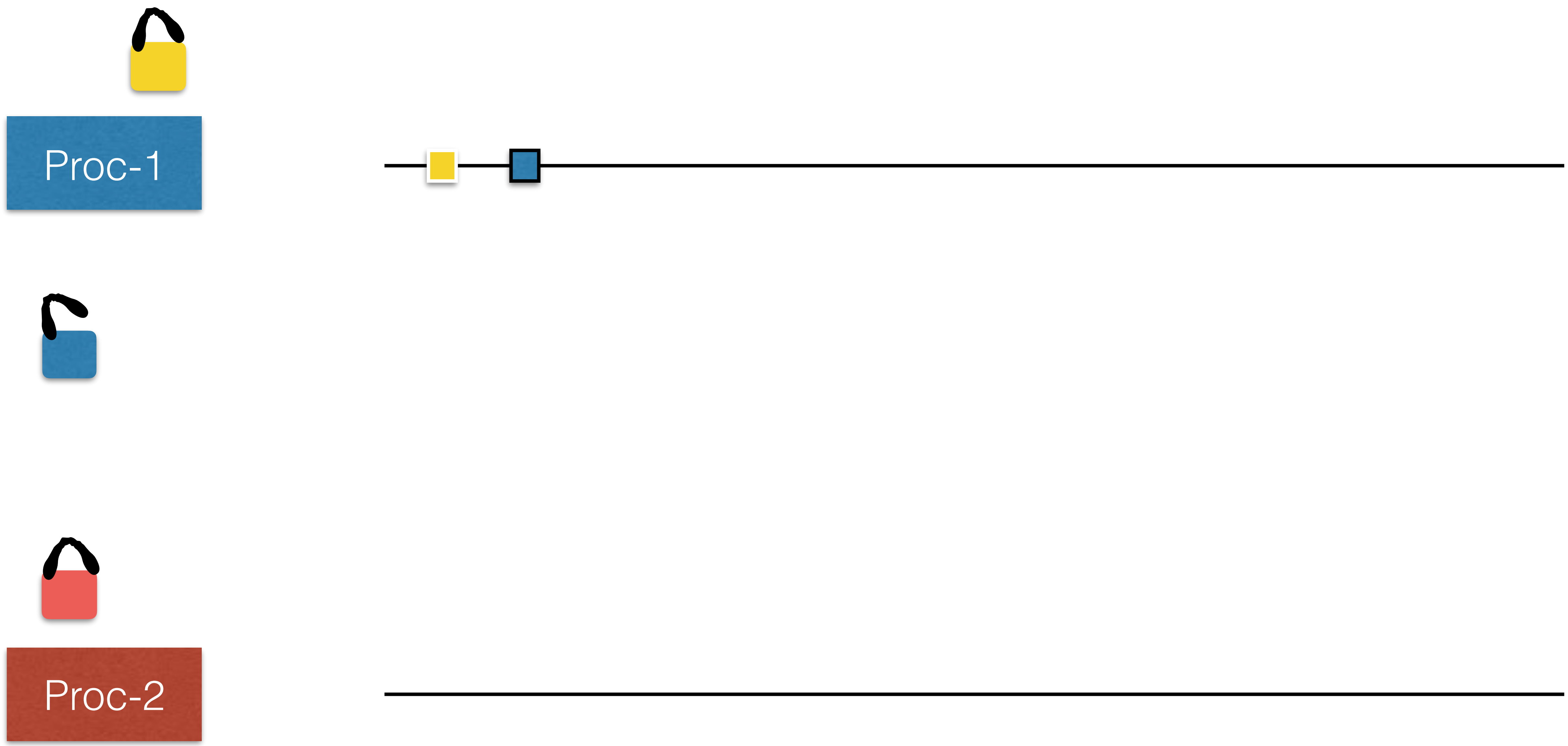

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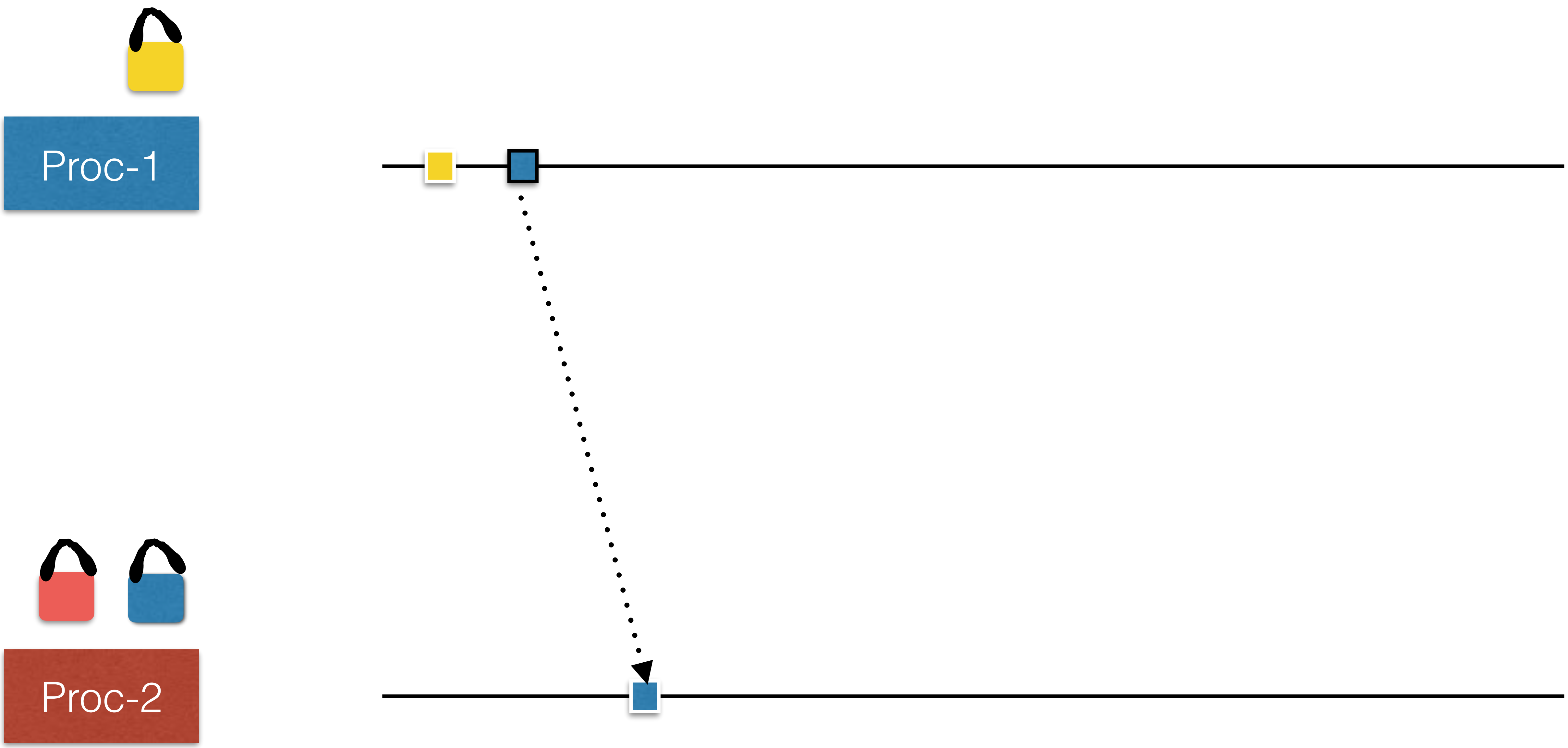

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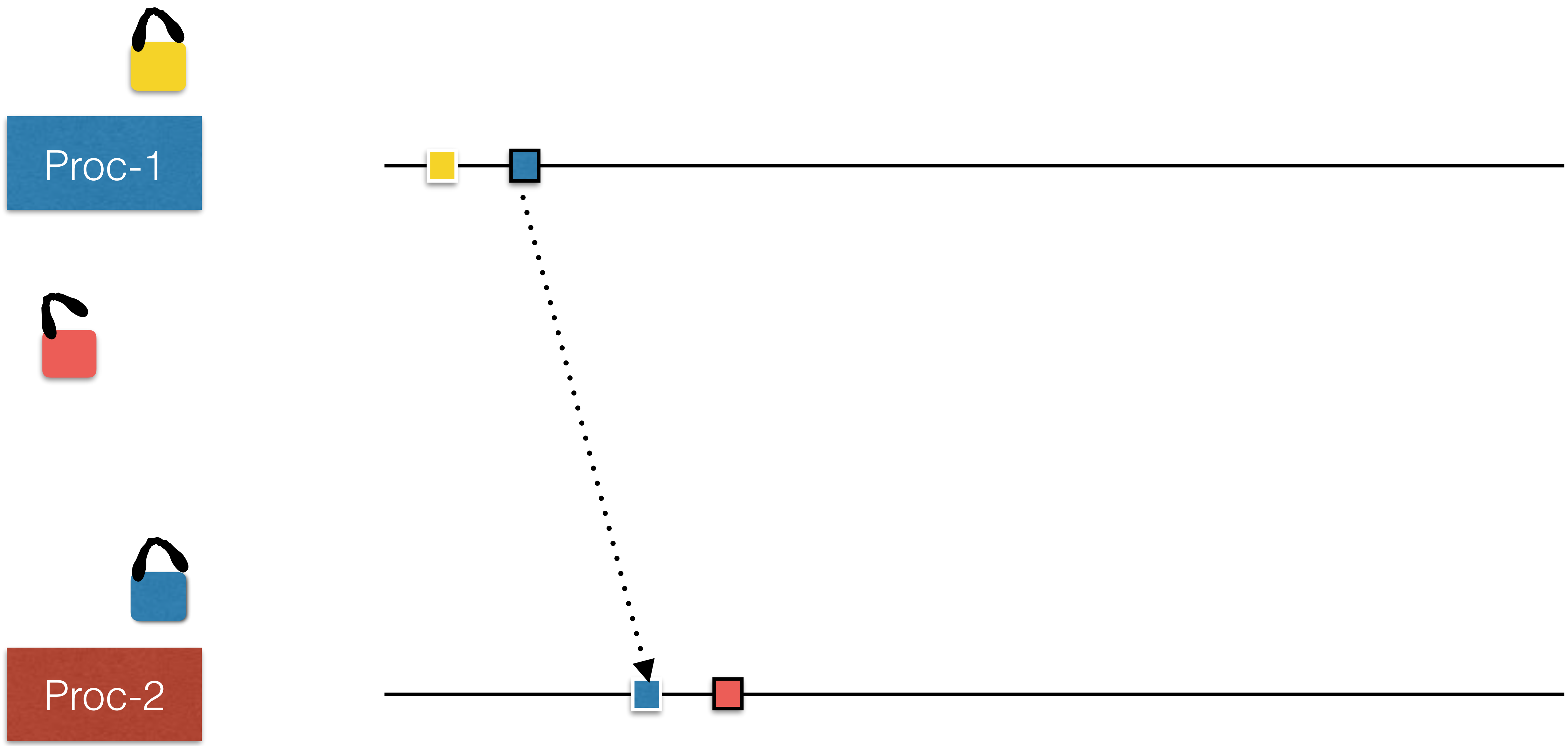

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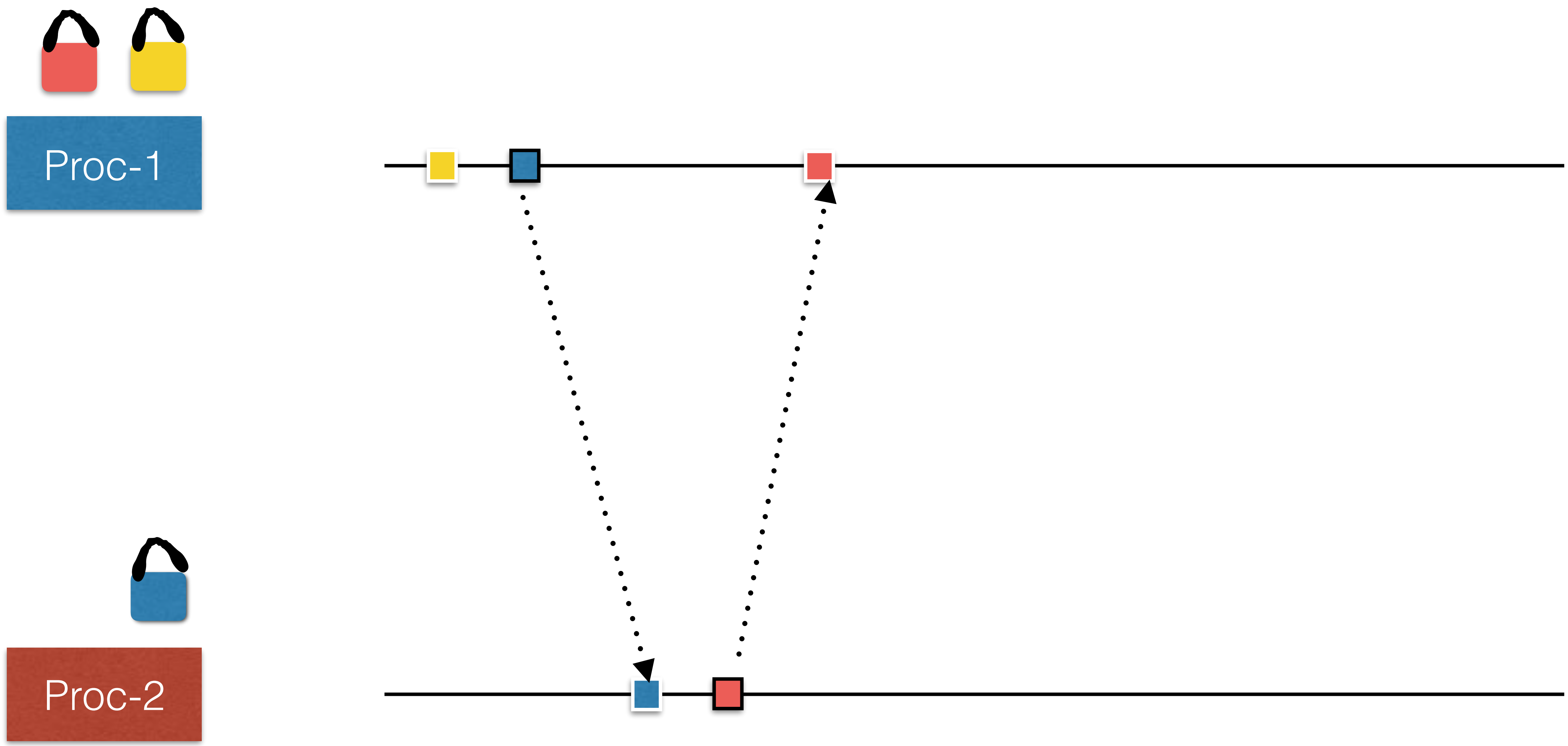

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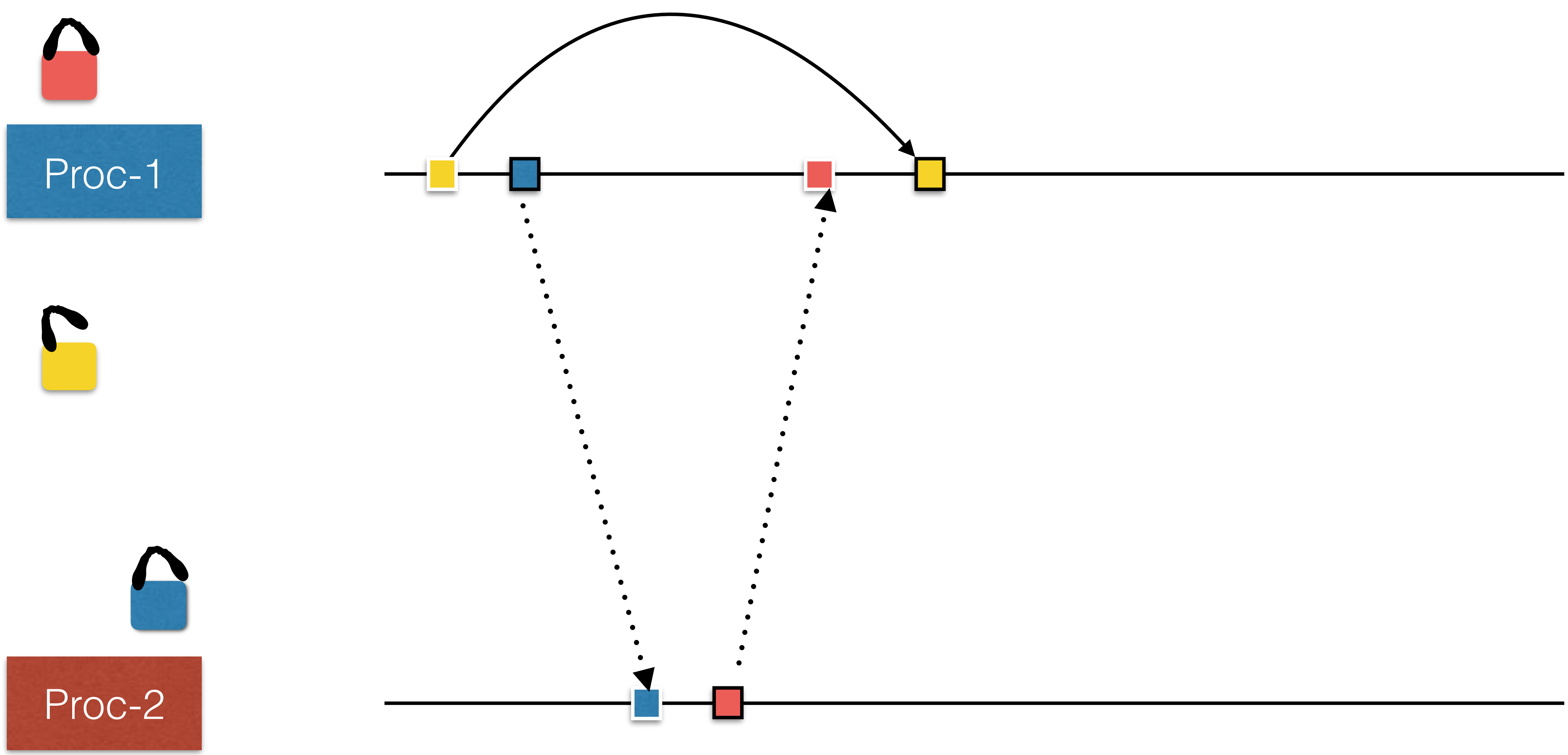

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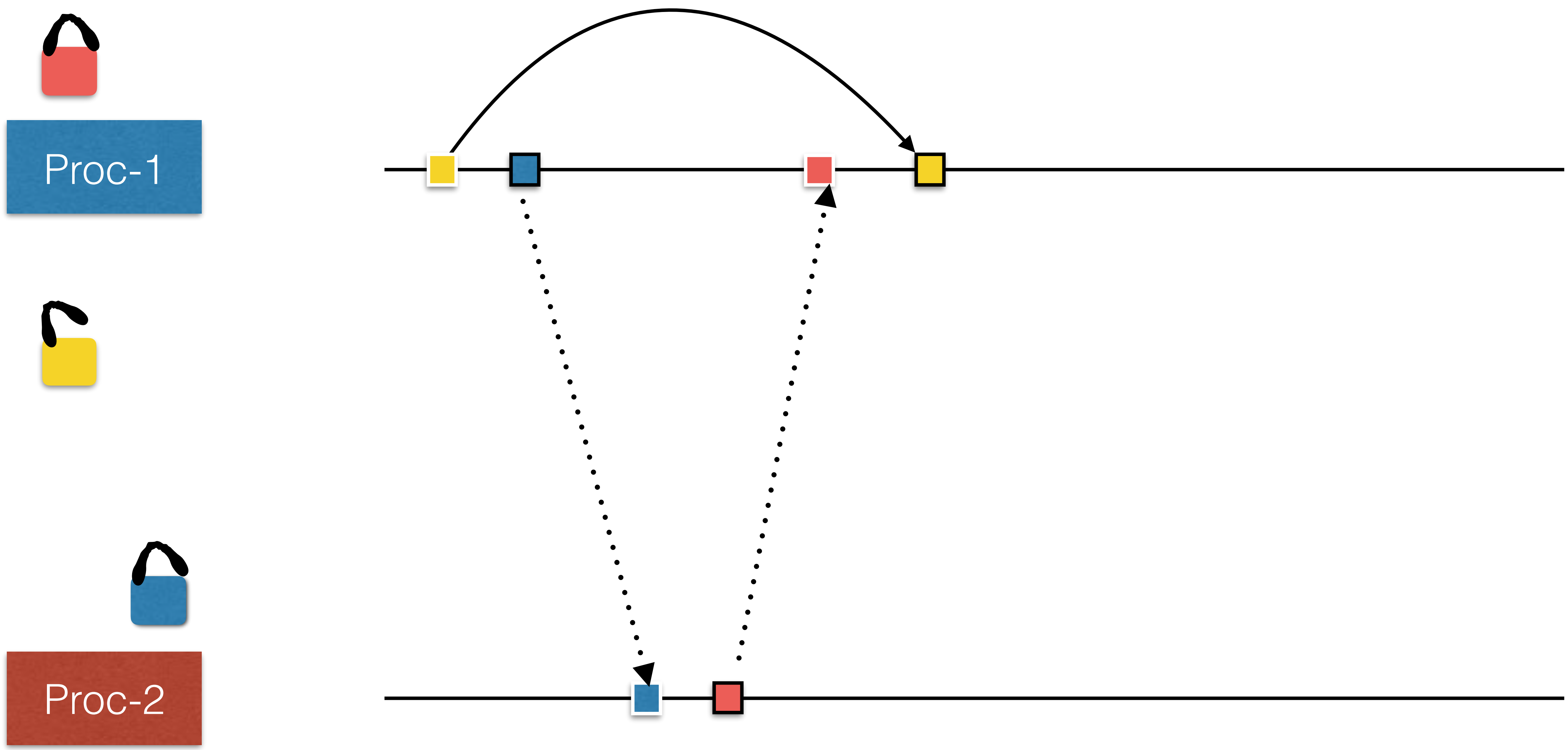
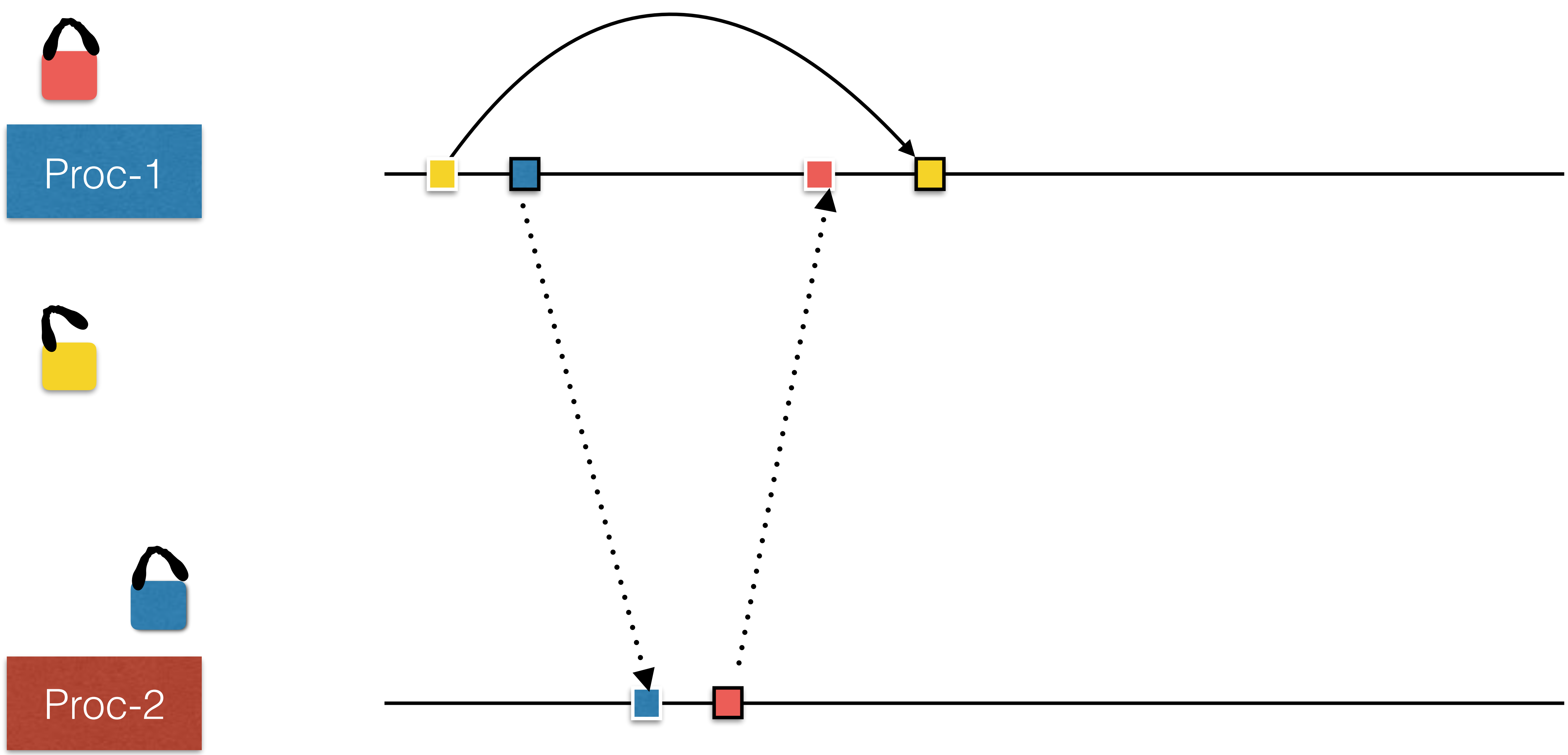


Locks Exchanged.

Synchronizing via Locks



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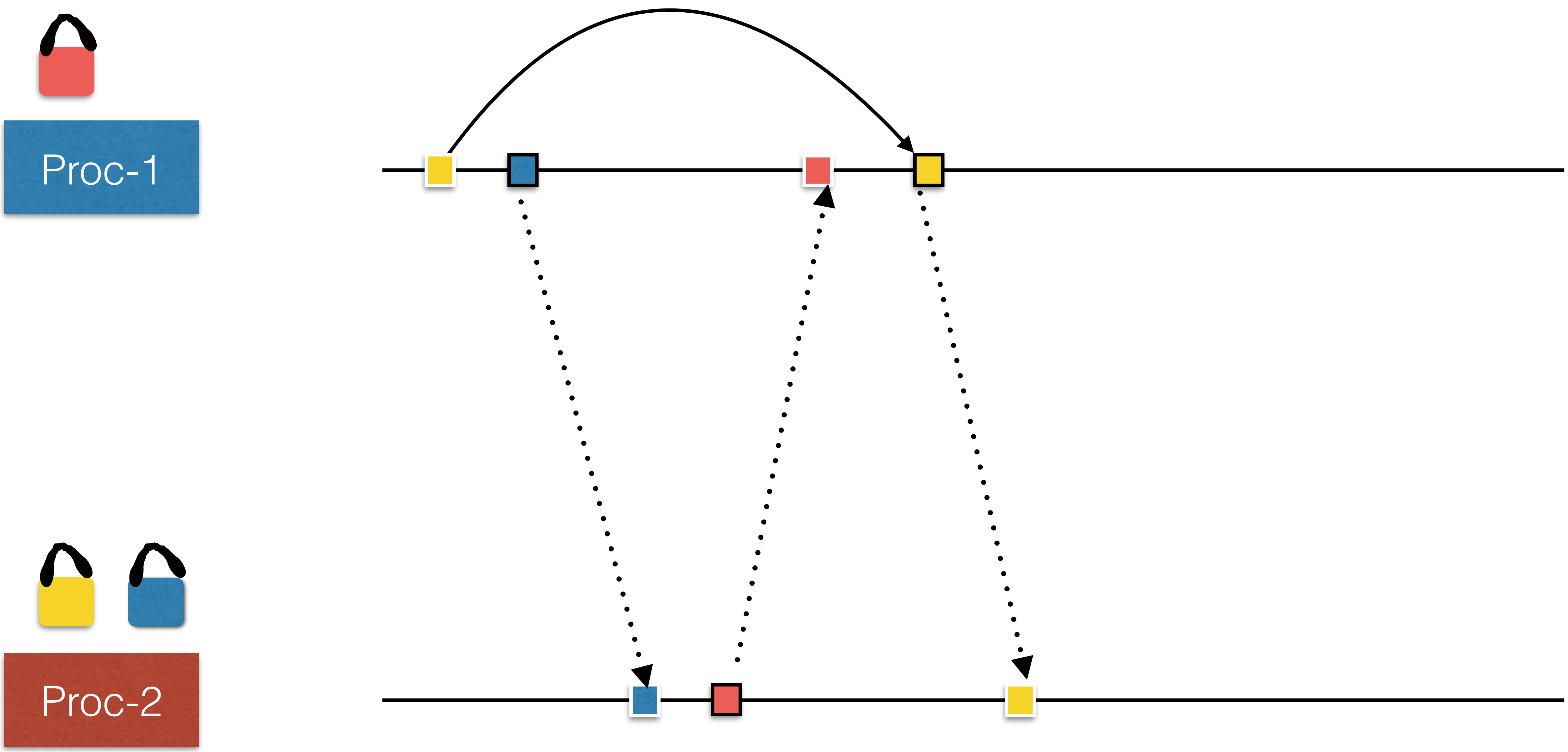

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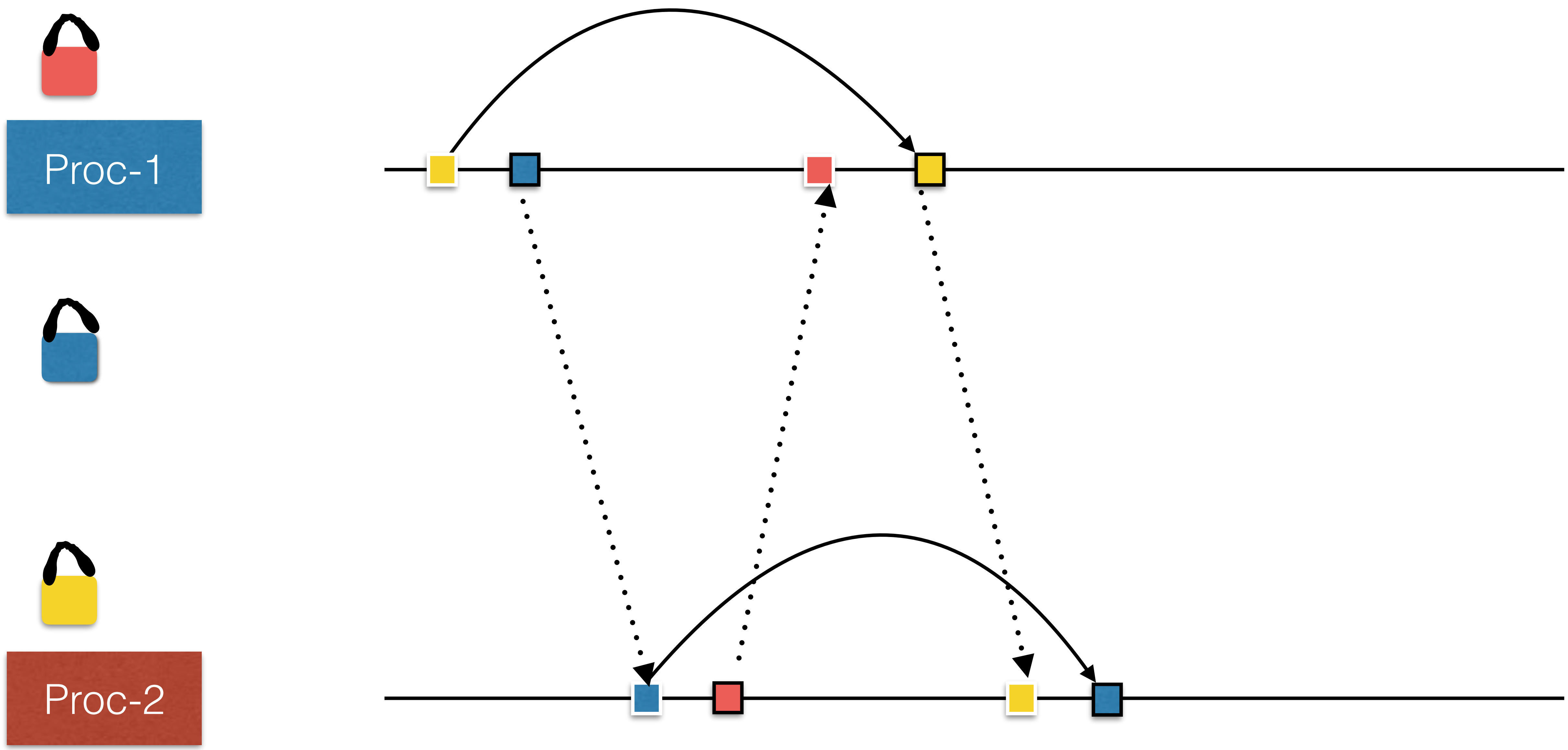

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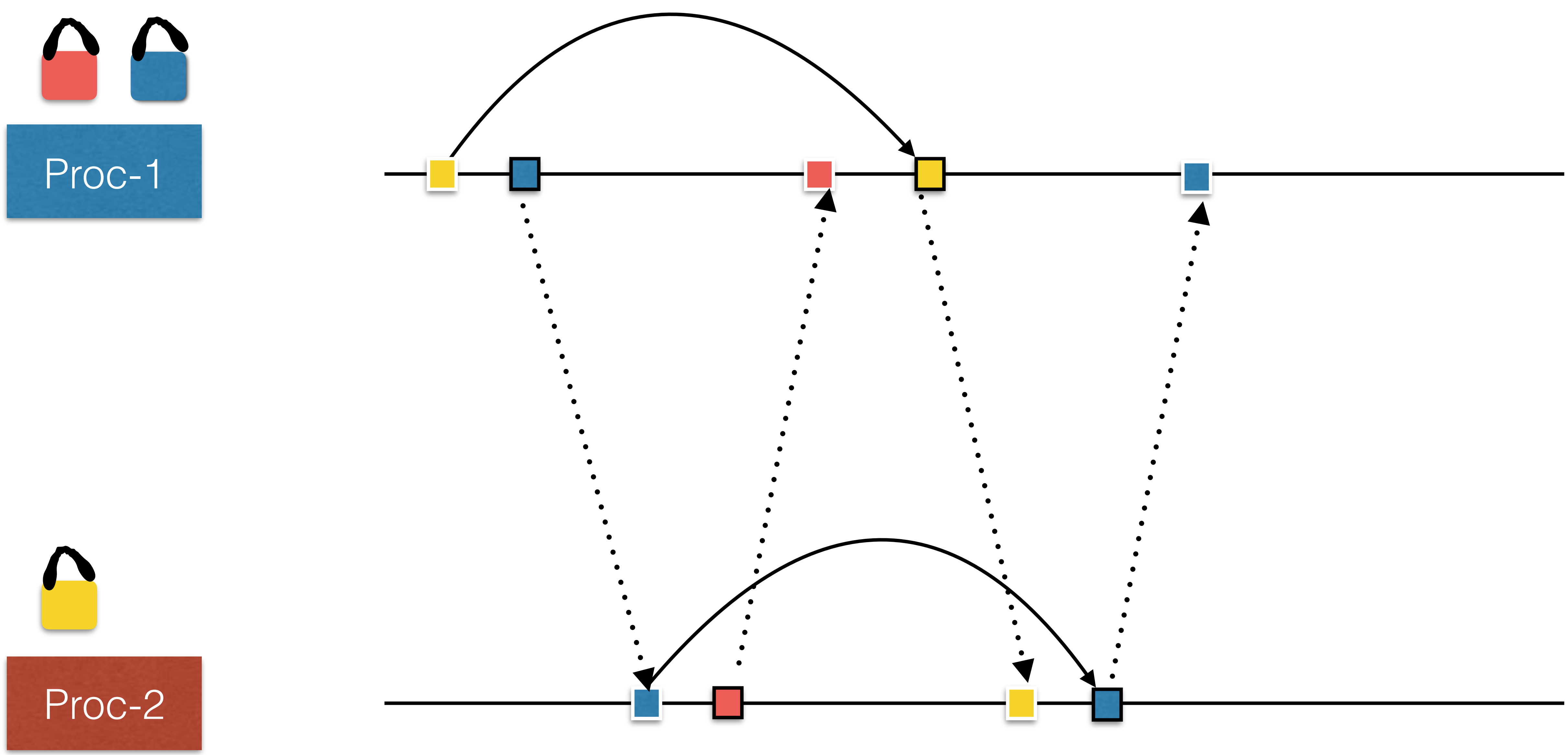

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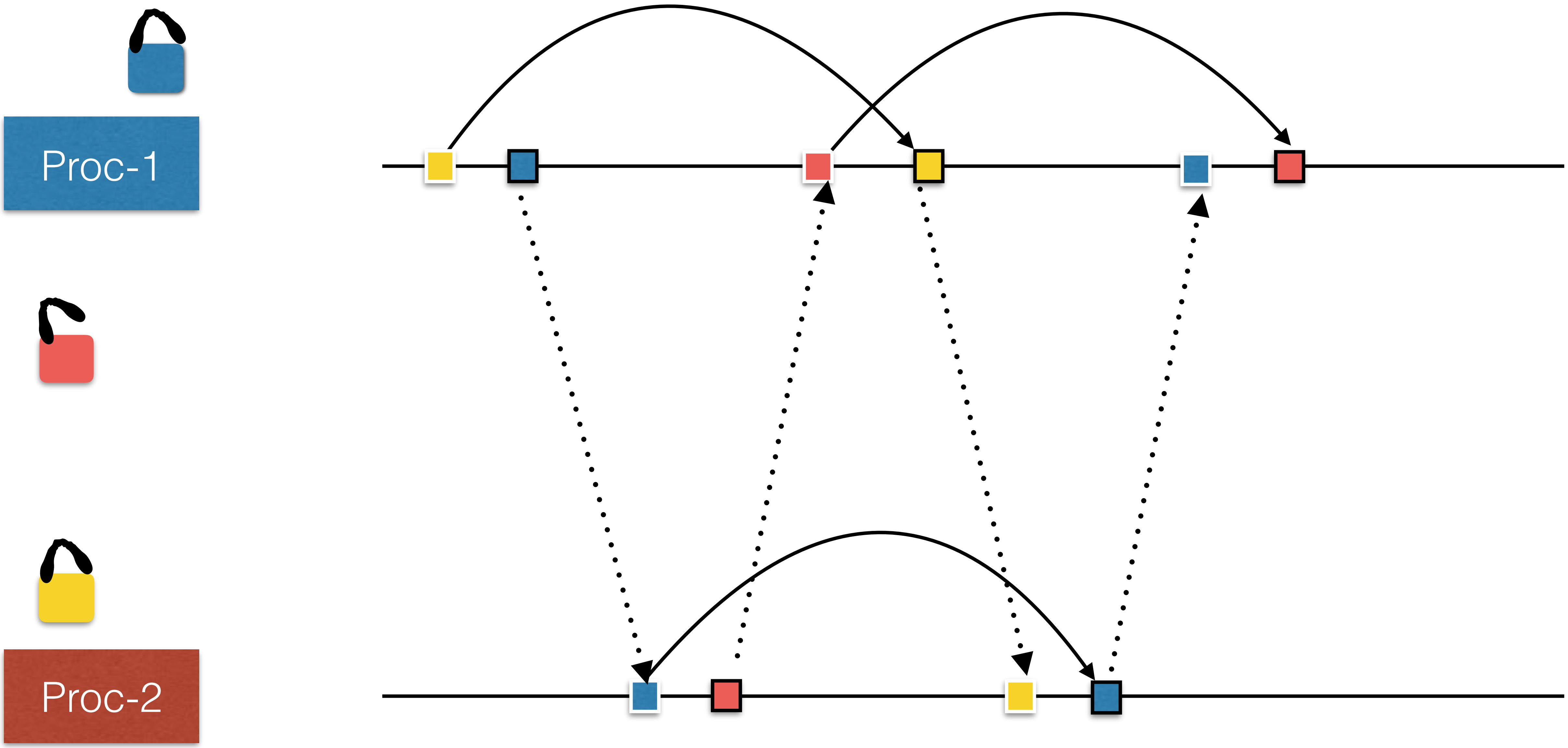

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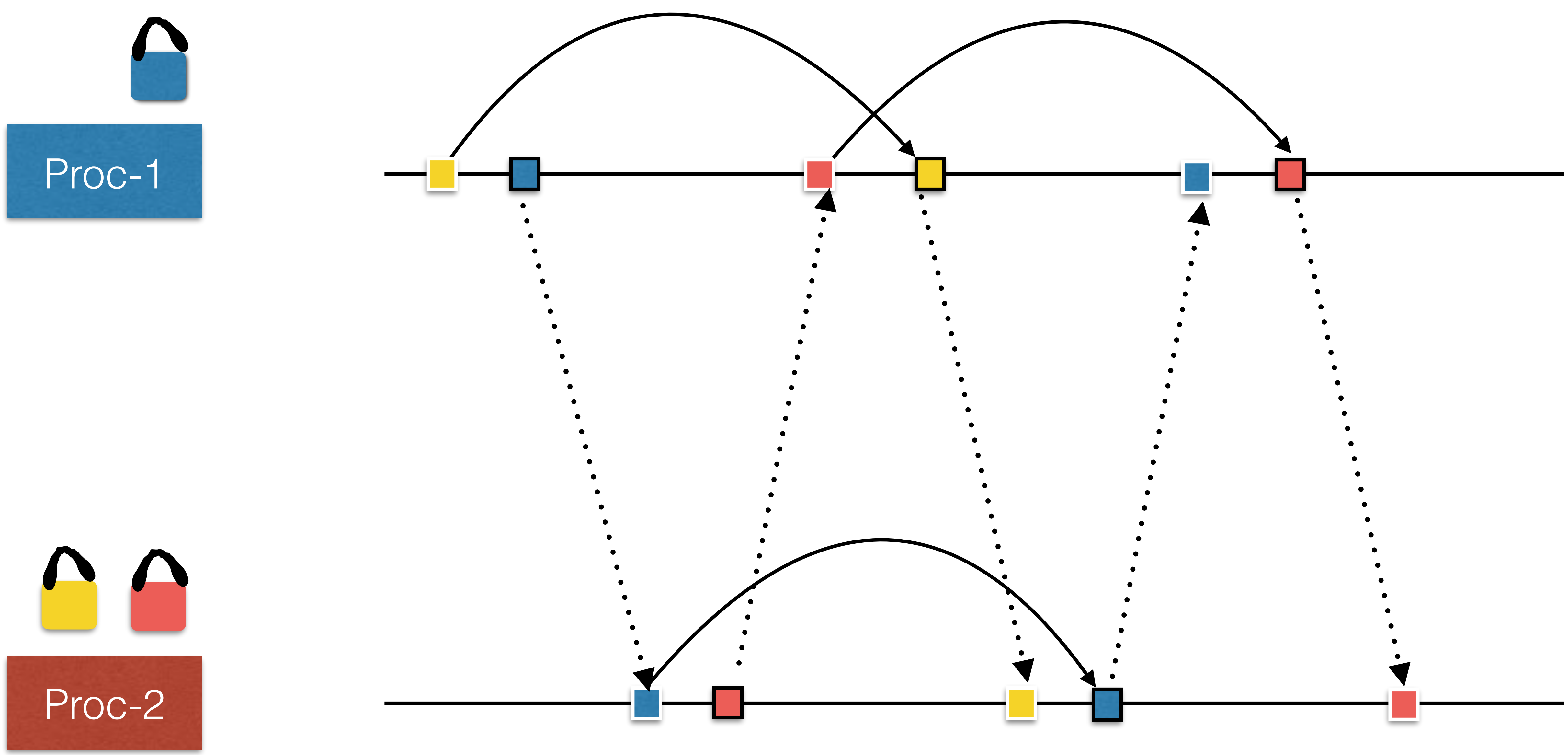

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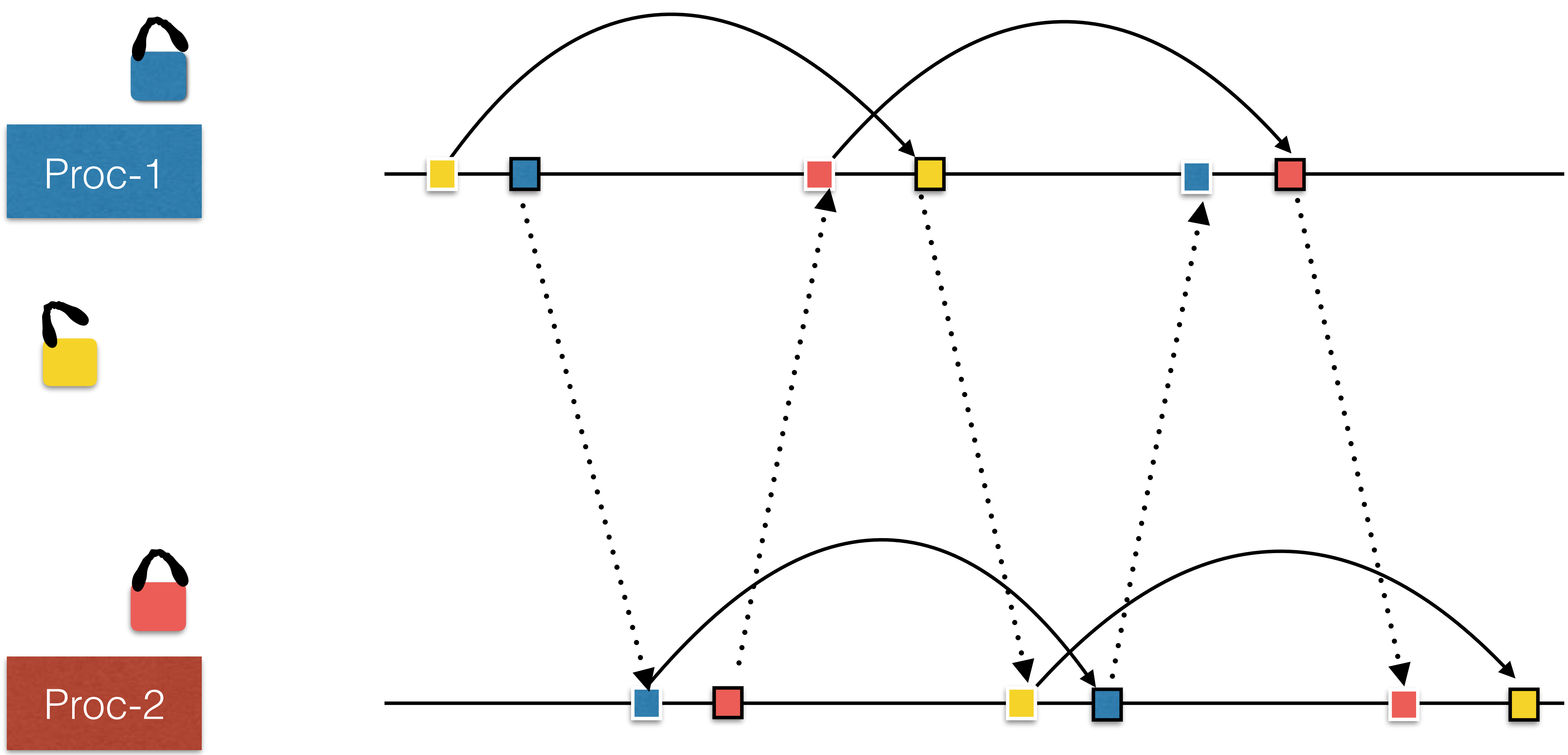

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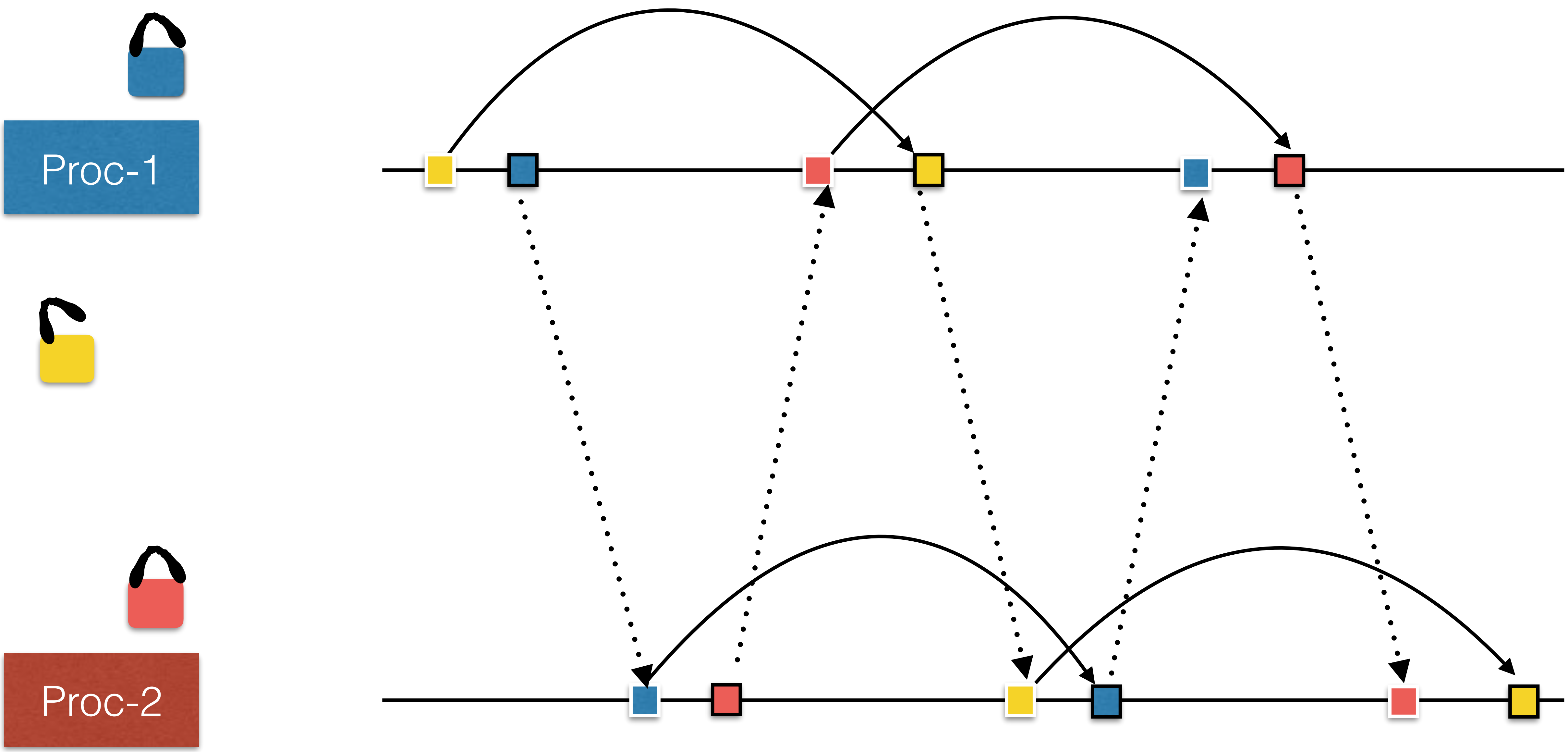
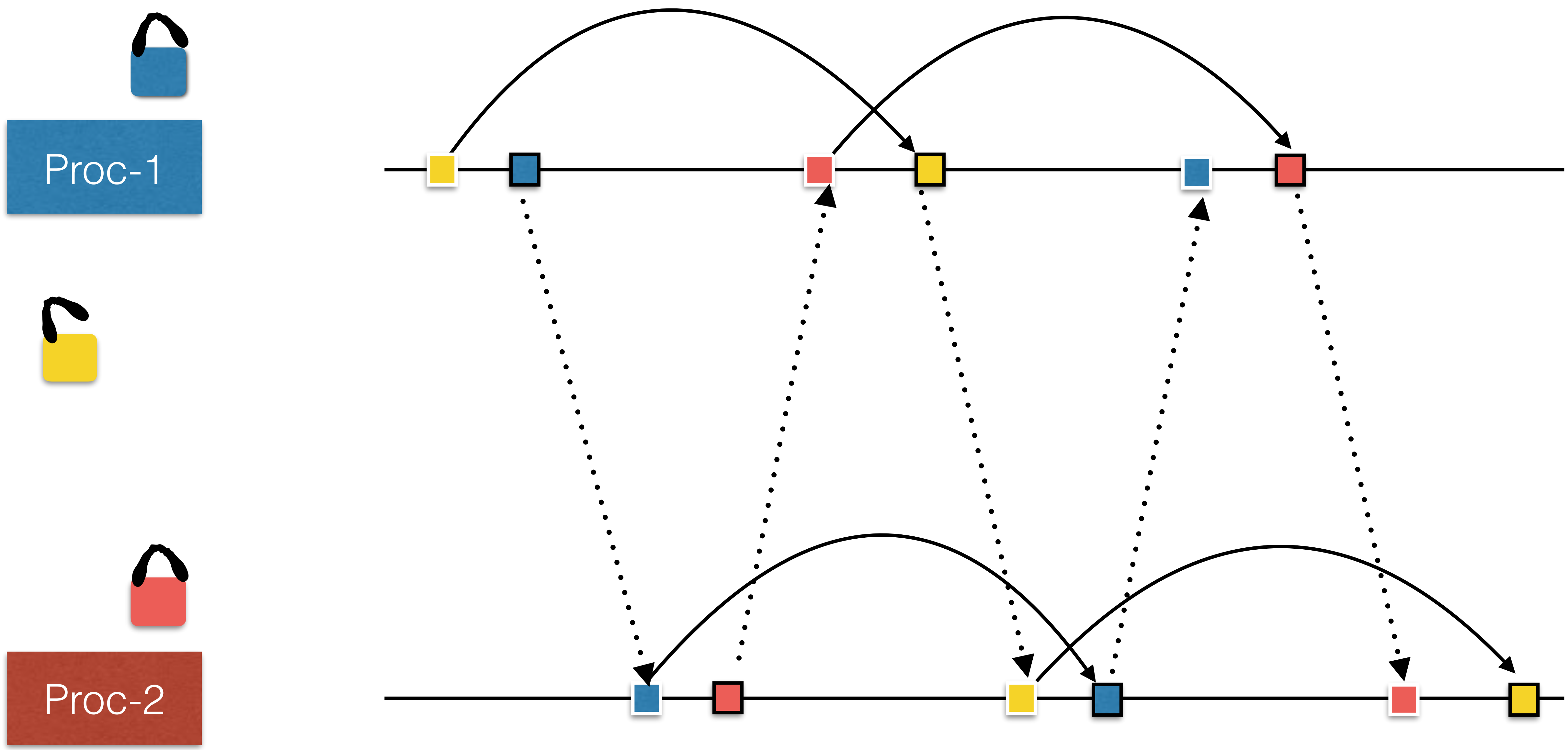


Locking not well-nested

Synchronizing via Locks



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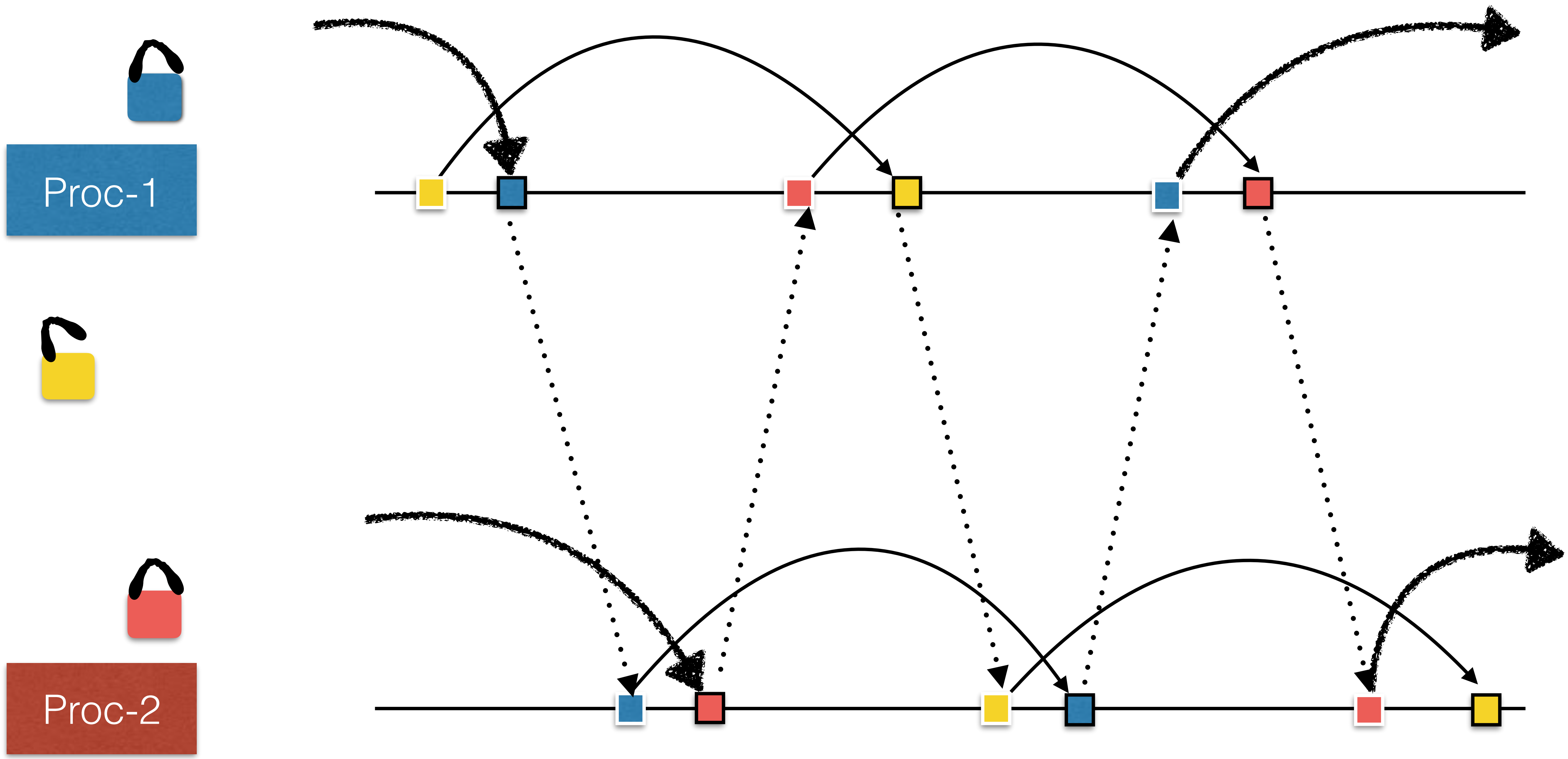

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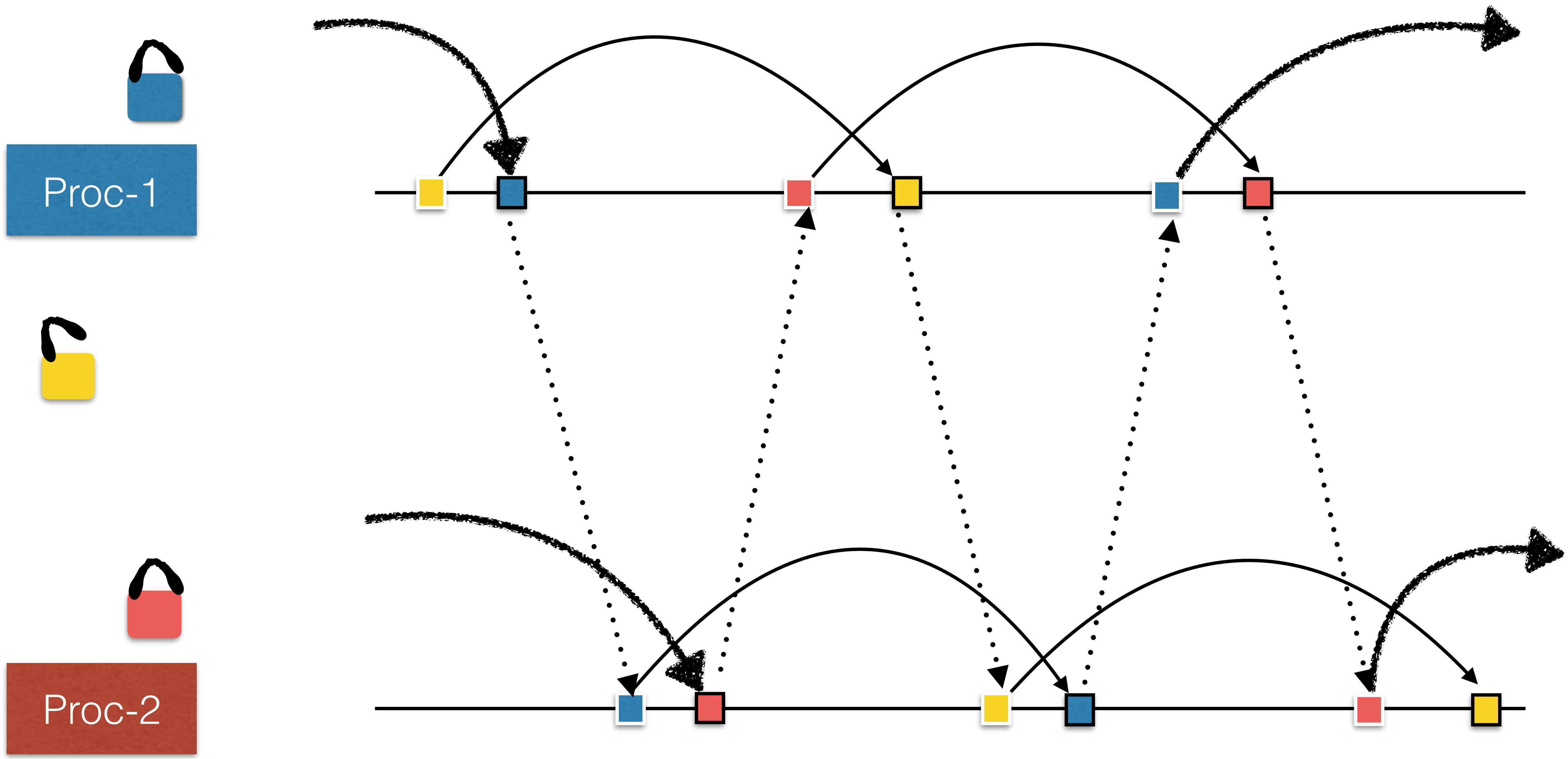


Chaining of locks. Unboundedly long chains.

Reachability:

The control state reachability problem asks if a given global state can be reached from the initial configuration

Reachability problem for a (even two) recursive programs (PDS) with locks is undecidable.

Ramalingam TOPLAS 2000,
Kahlon,Ivancic,Gupta CAV05

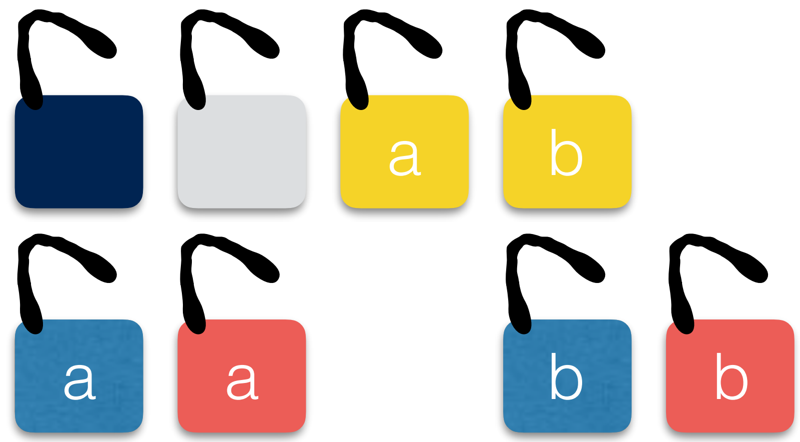
Initial Condition on Locks:

What if we need all locks to be free at the beginning?

A somewhat more elaborate protocol with additional locks works.

Kahlon,Ivancic,Gupta CAV05

Initializing the Locks:



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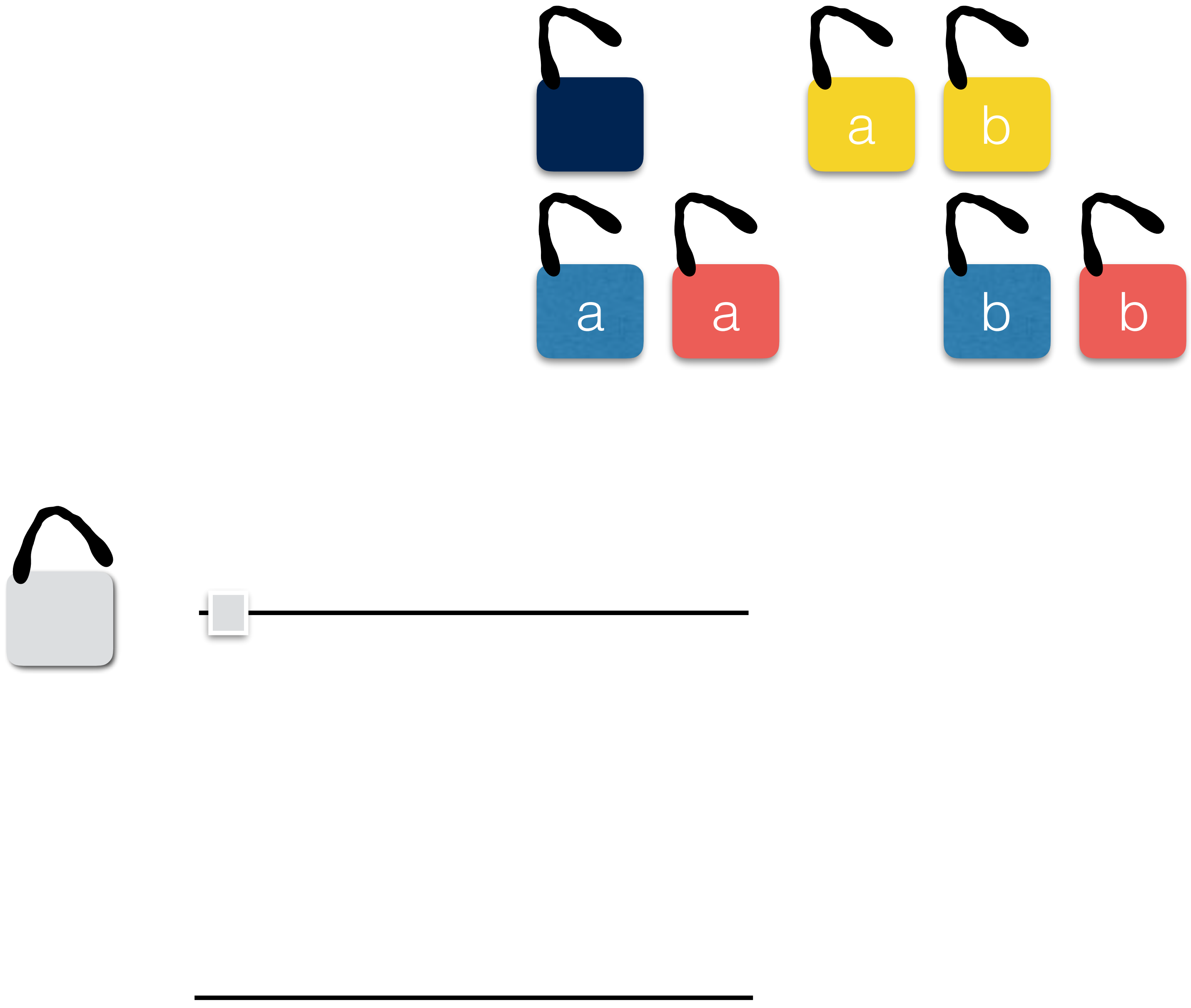

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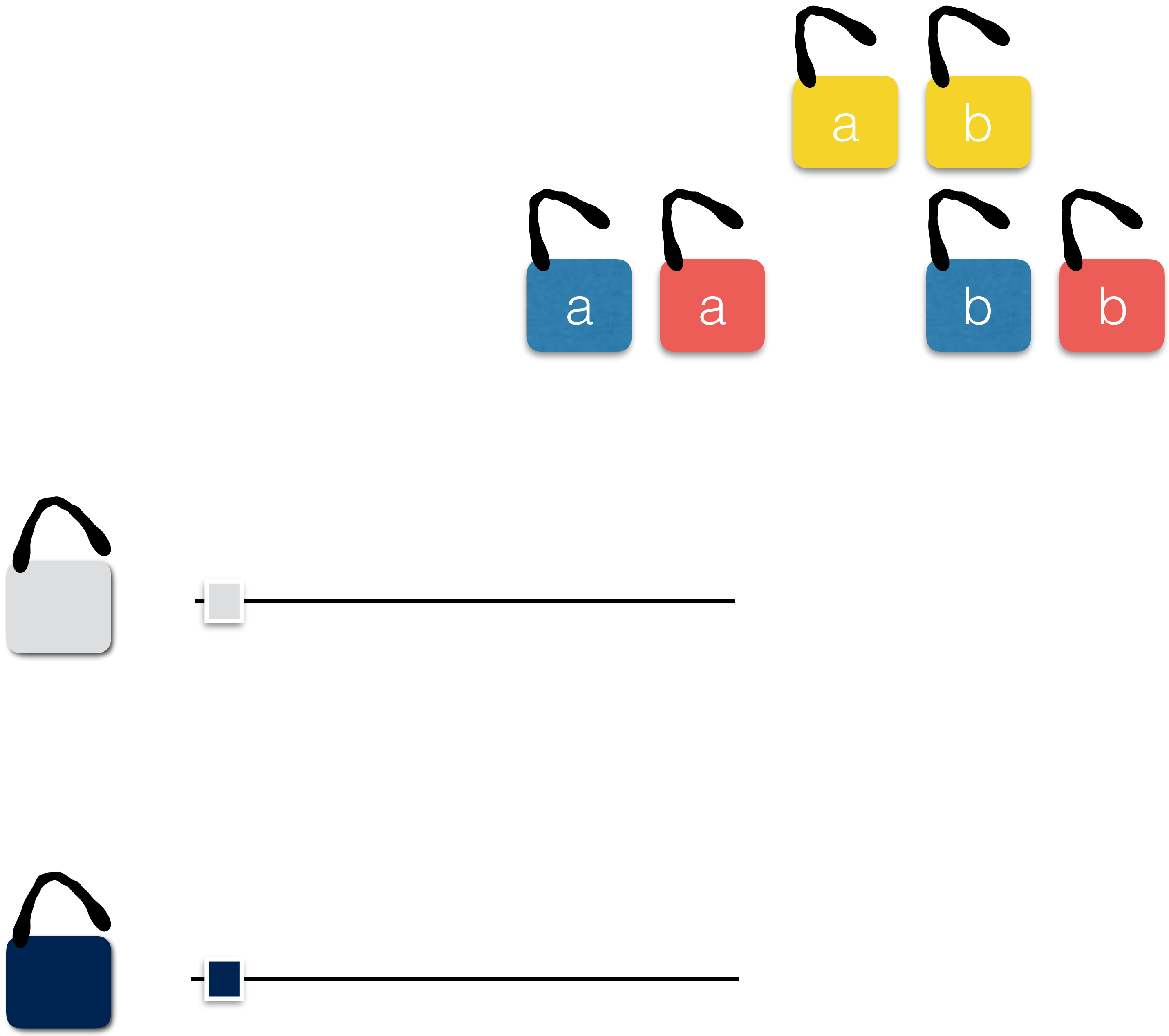

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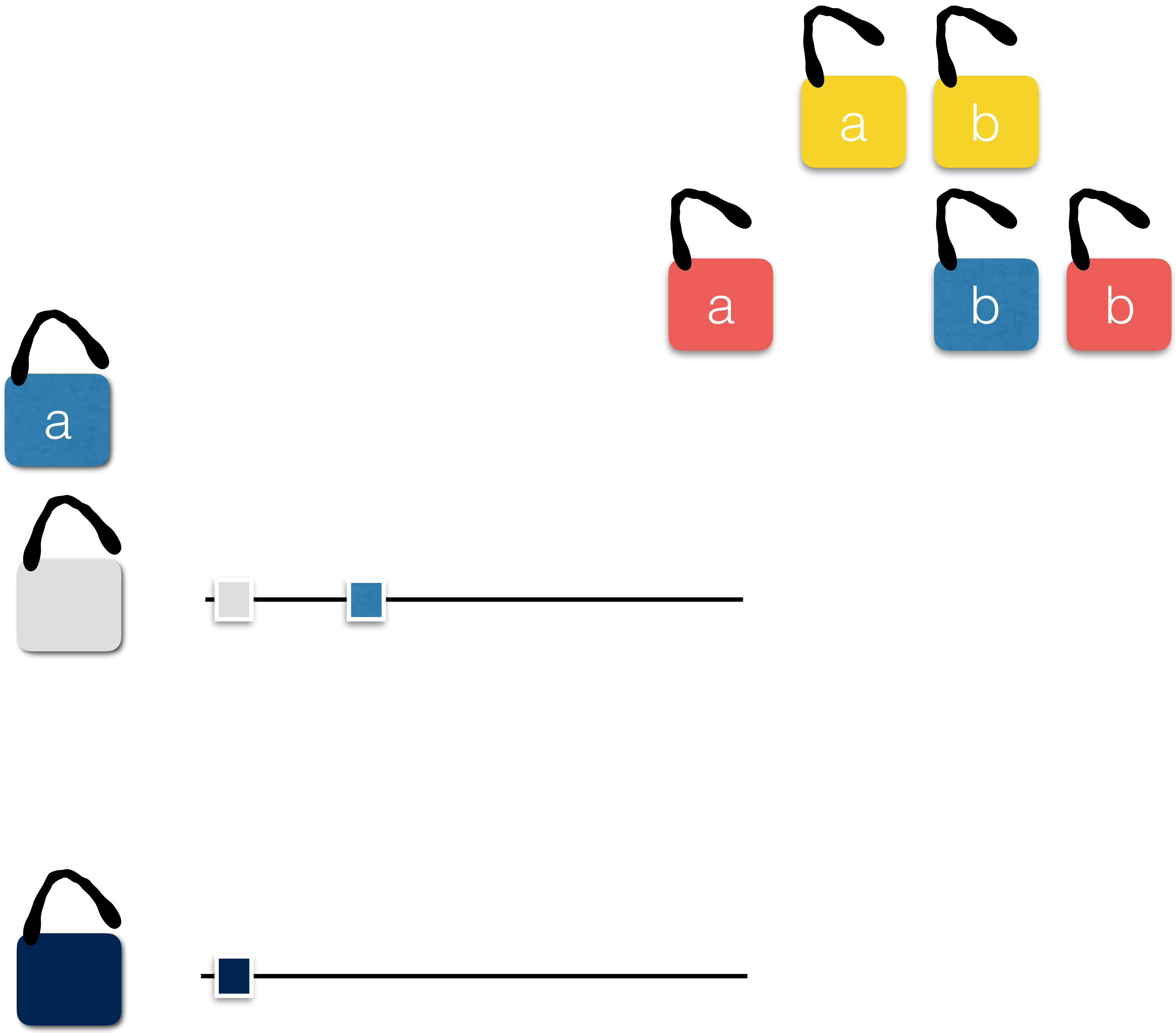

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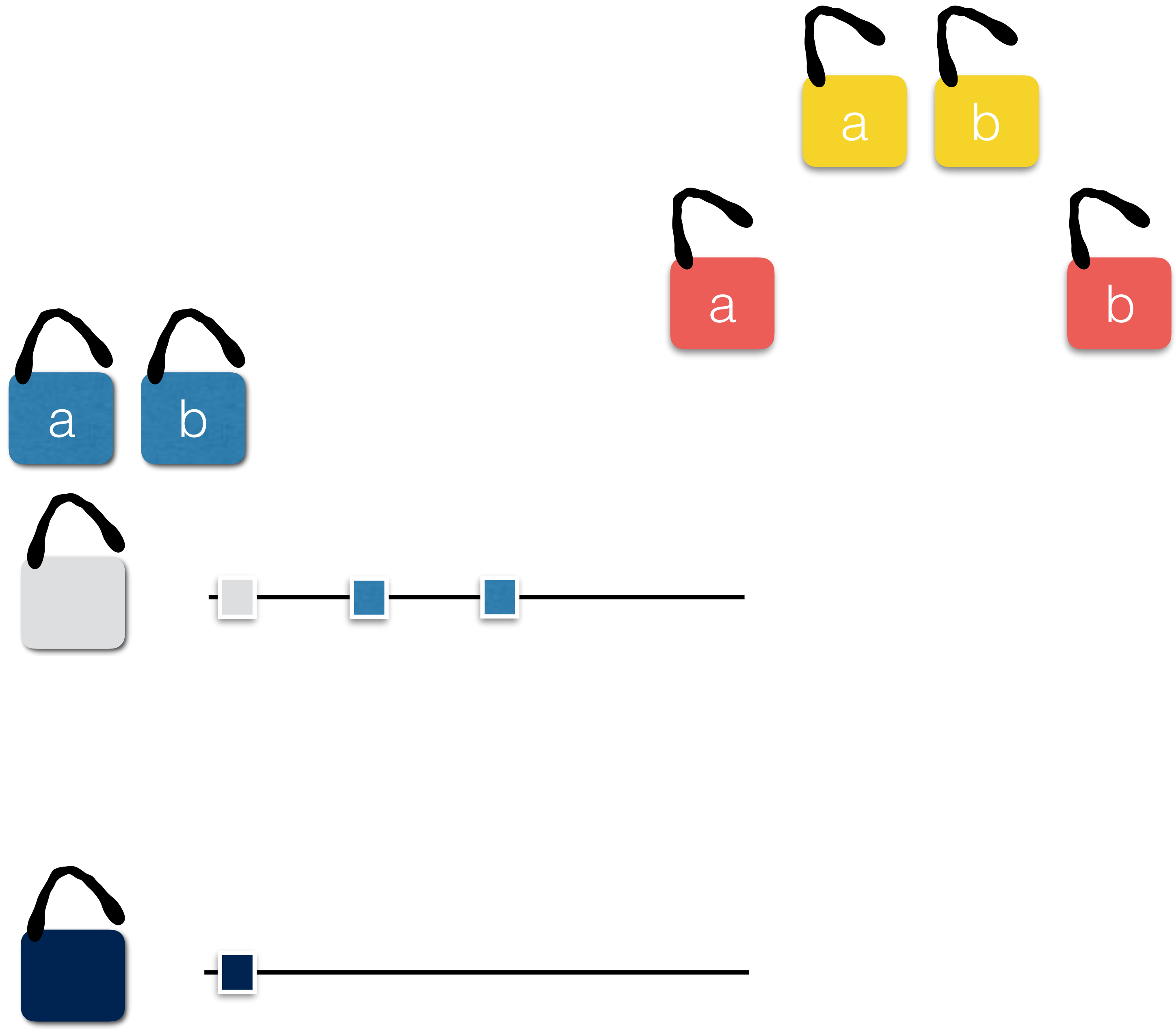

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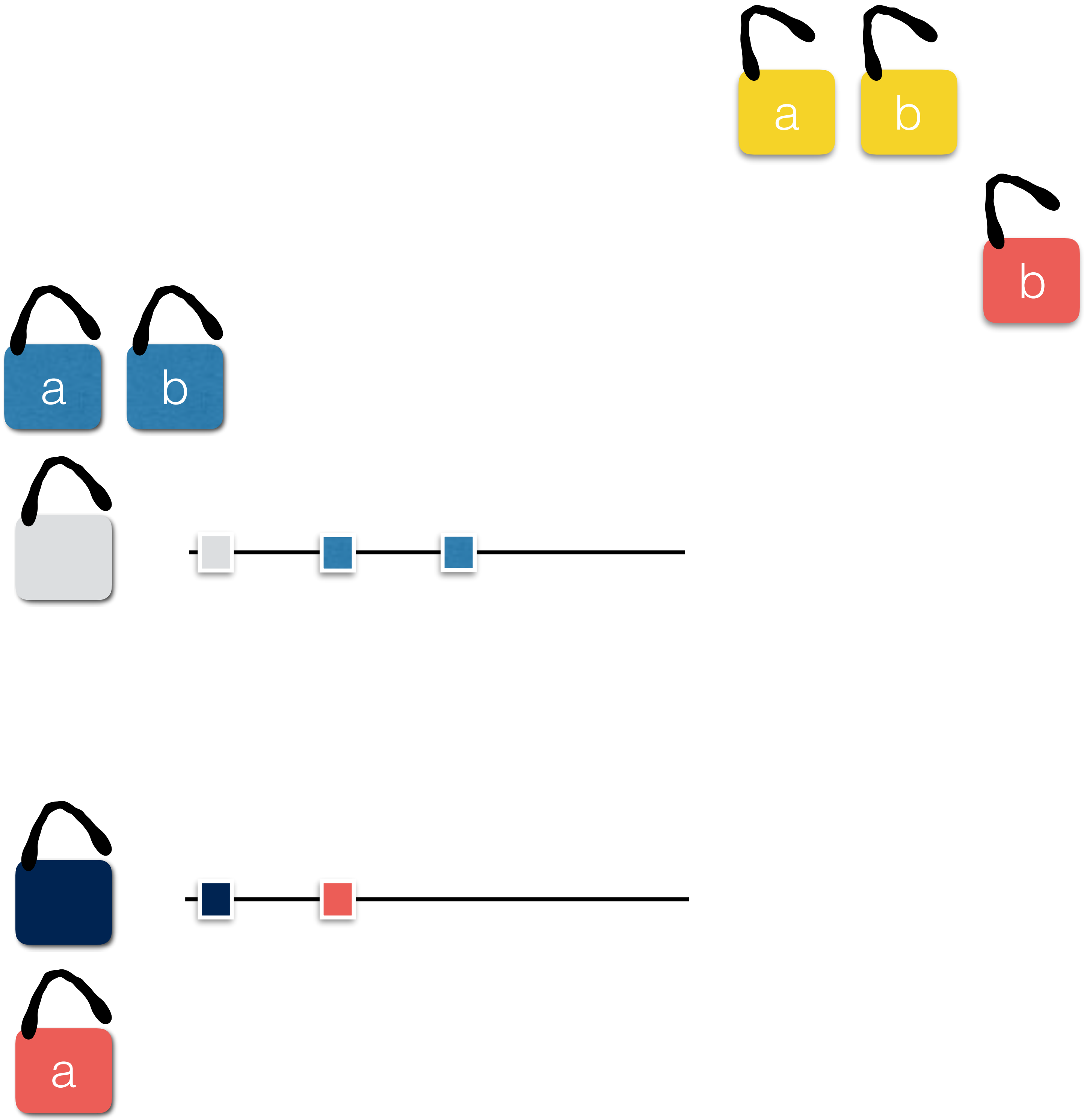

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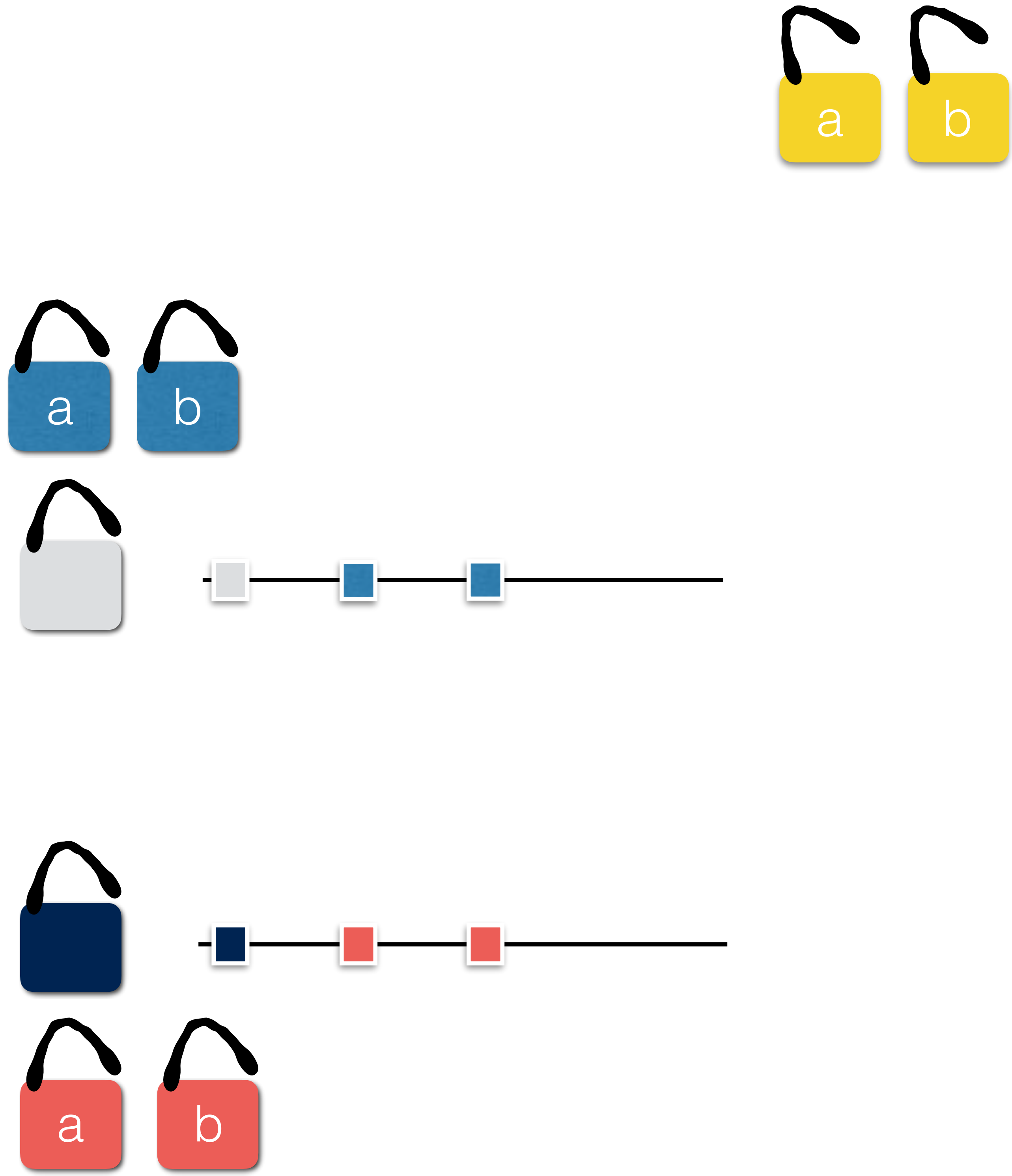

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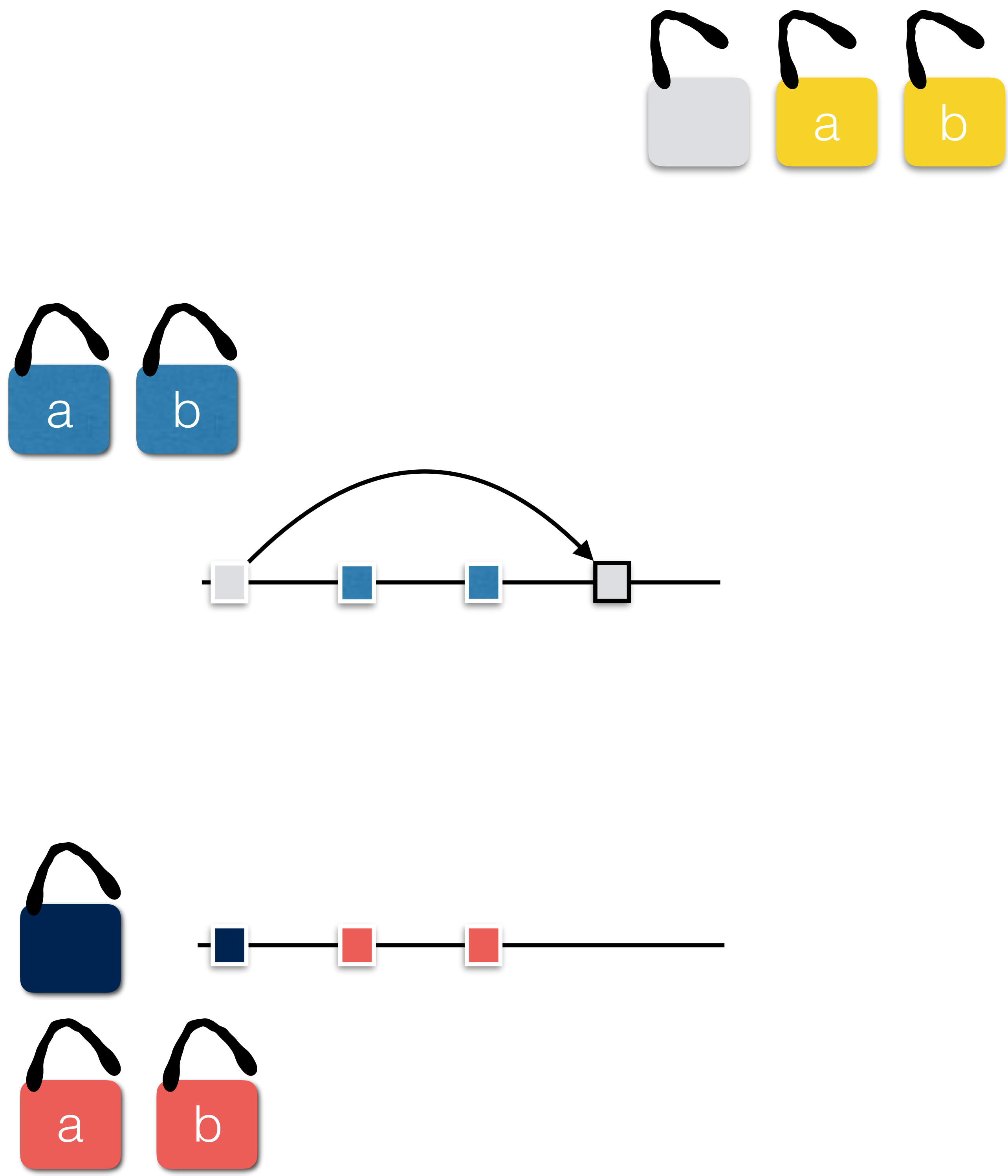

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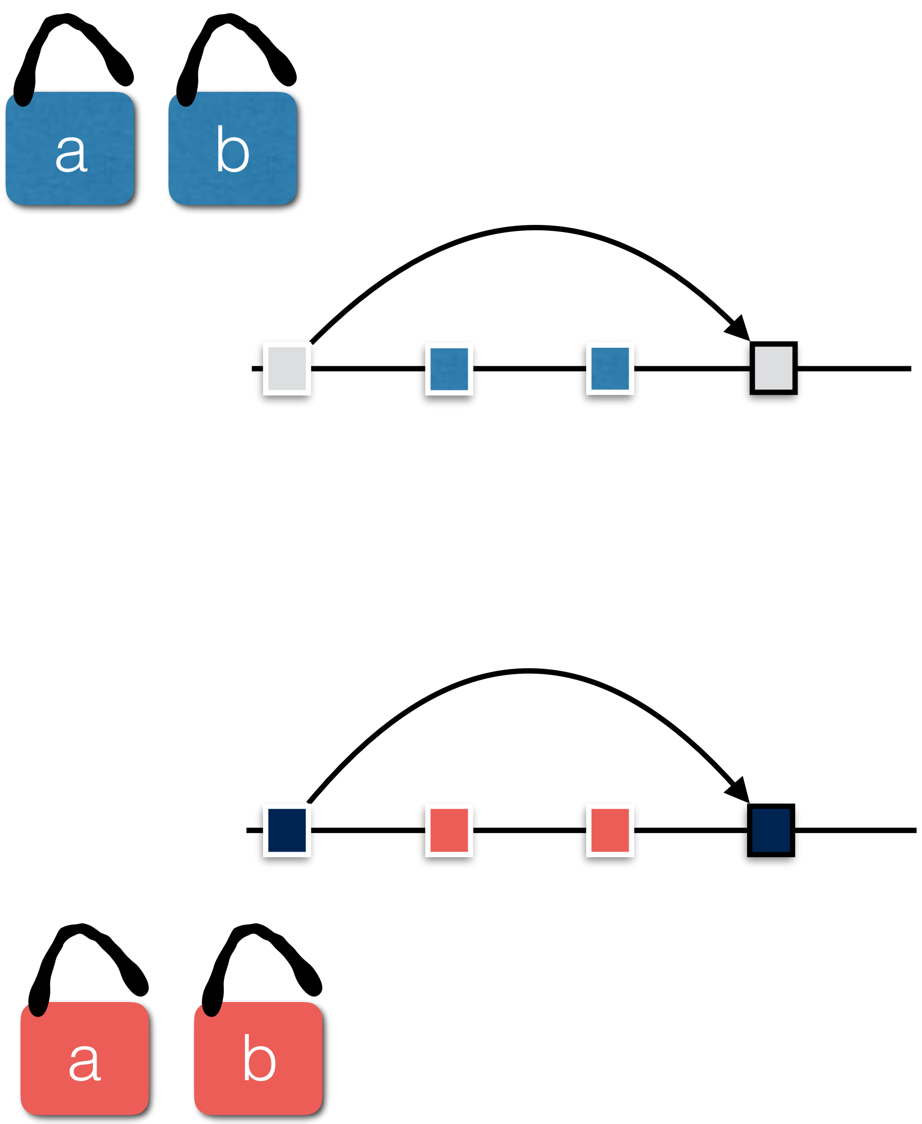

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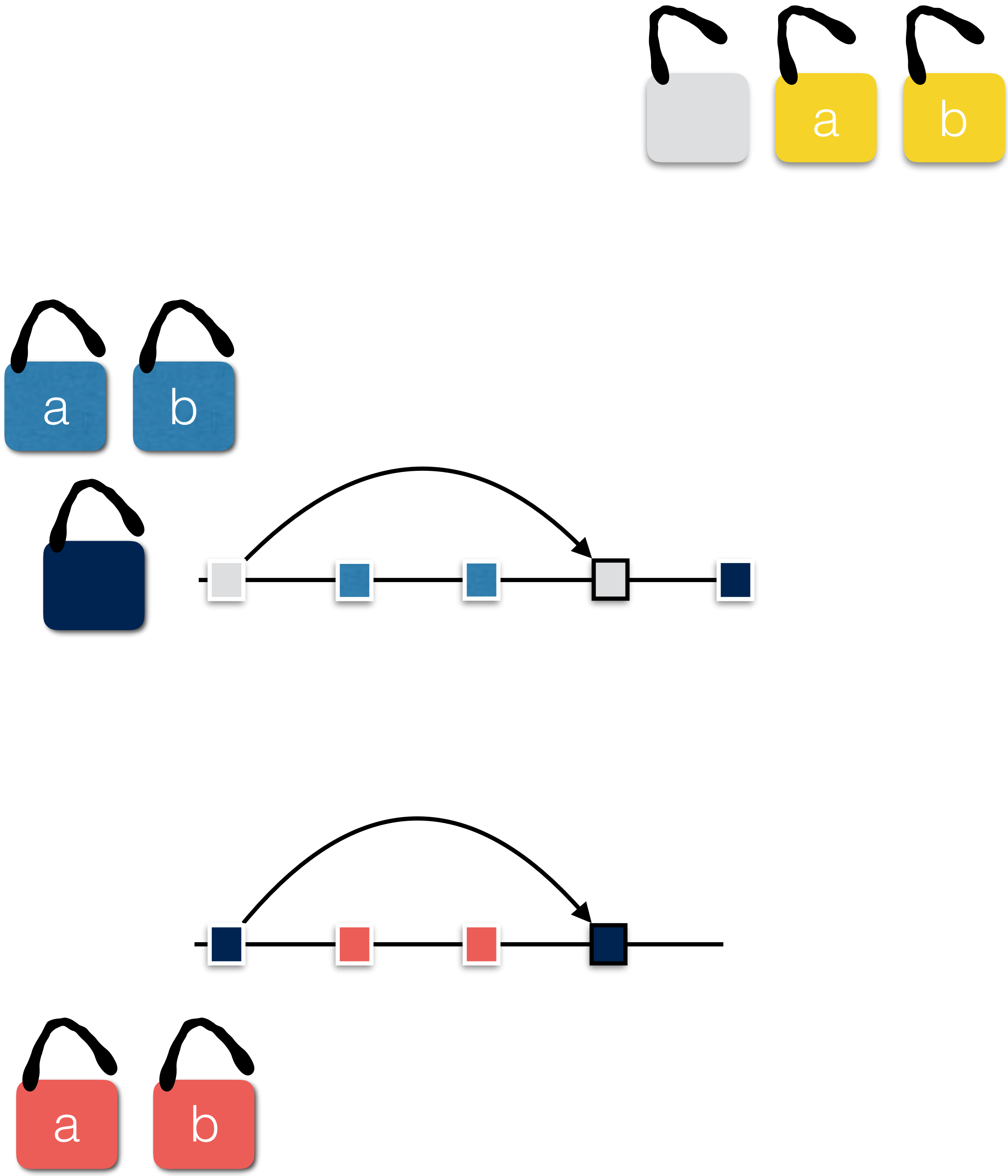

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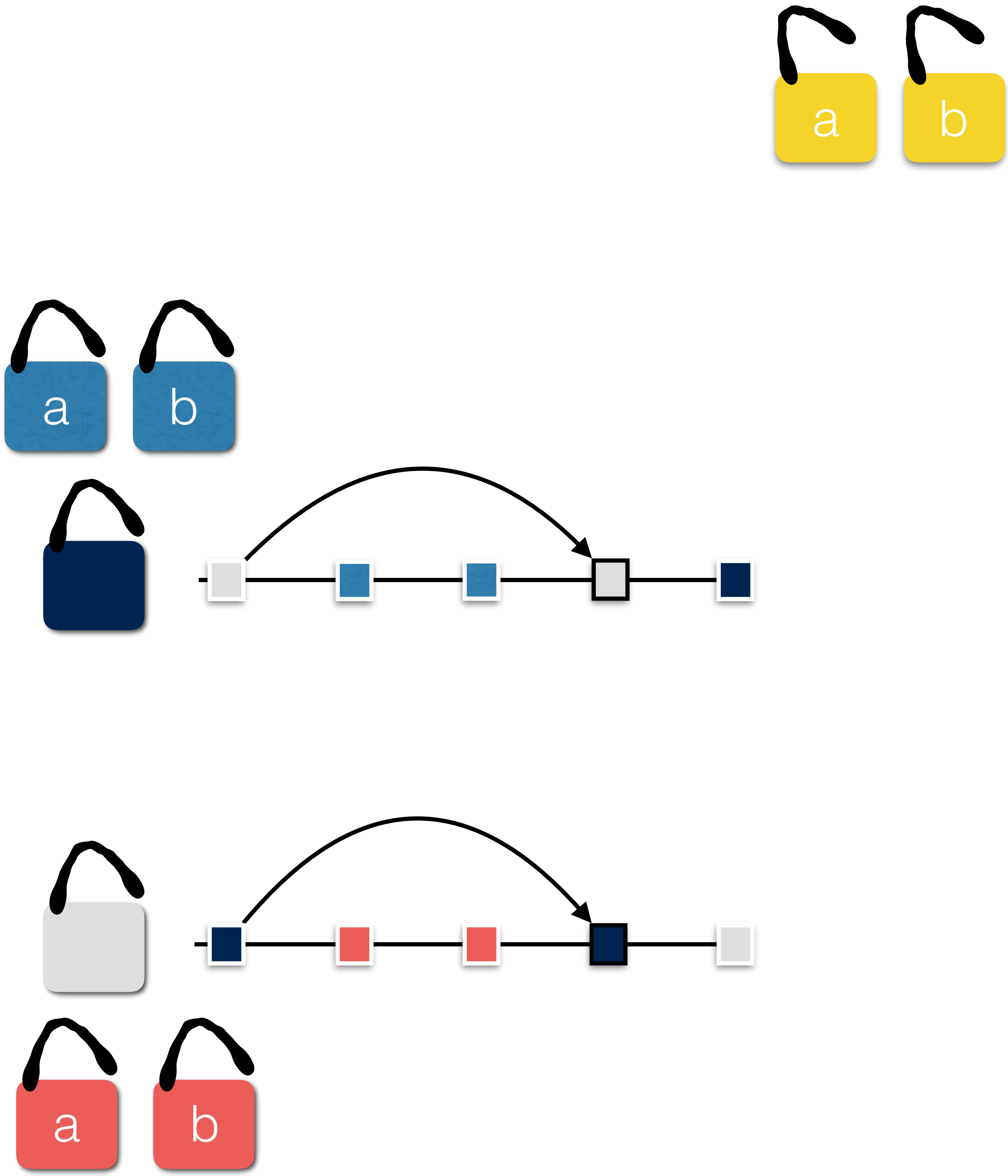

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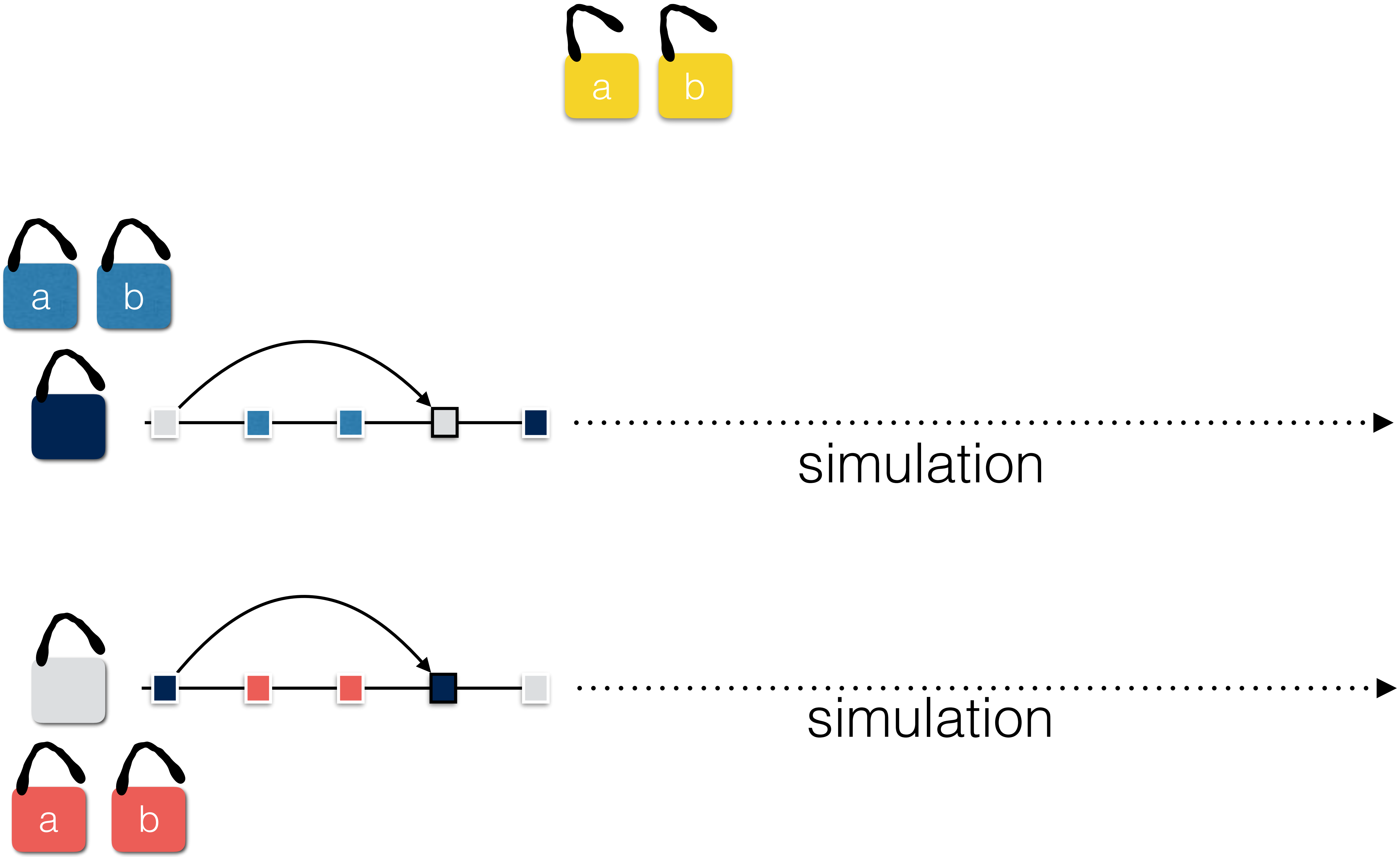

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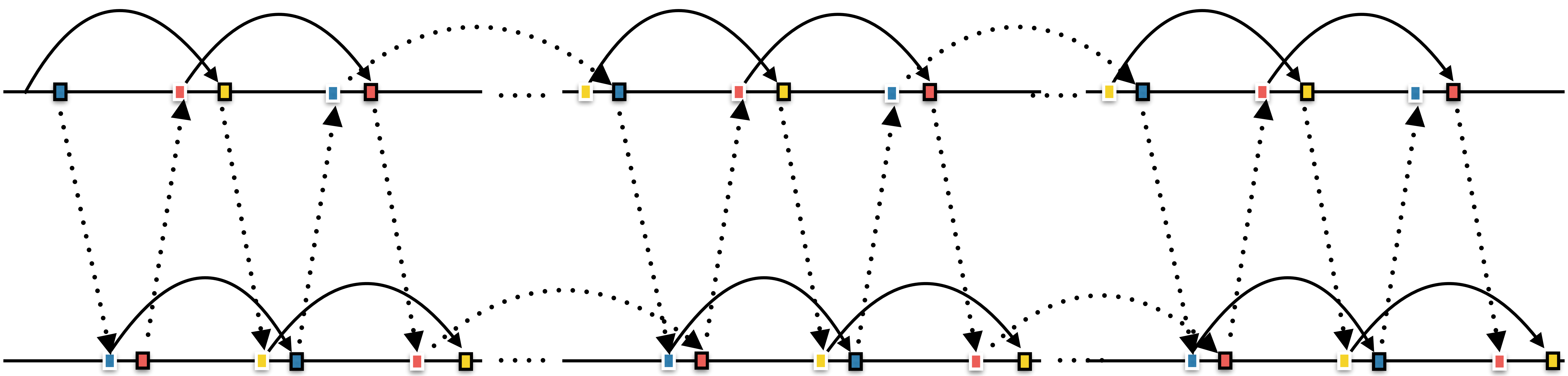
Recursive Programs with Locks



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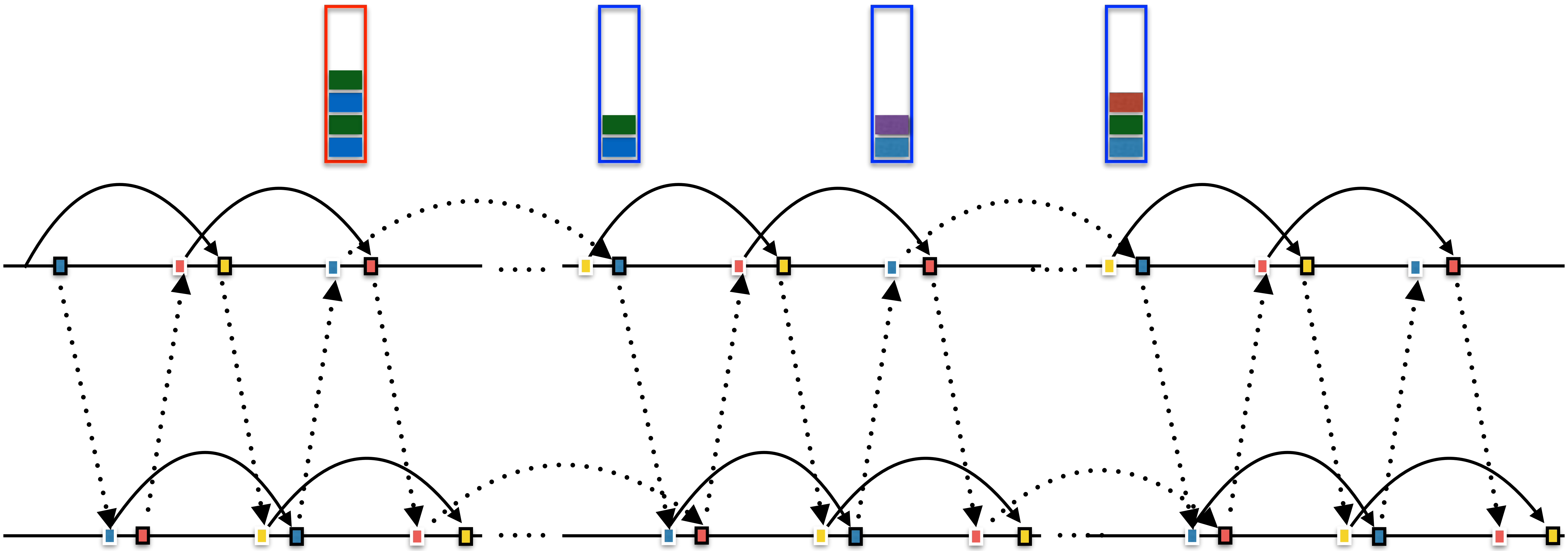

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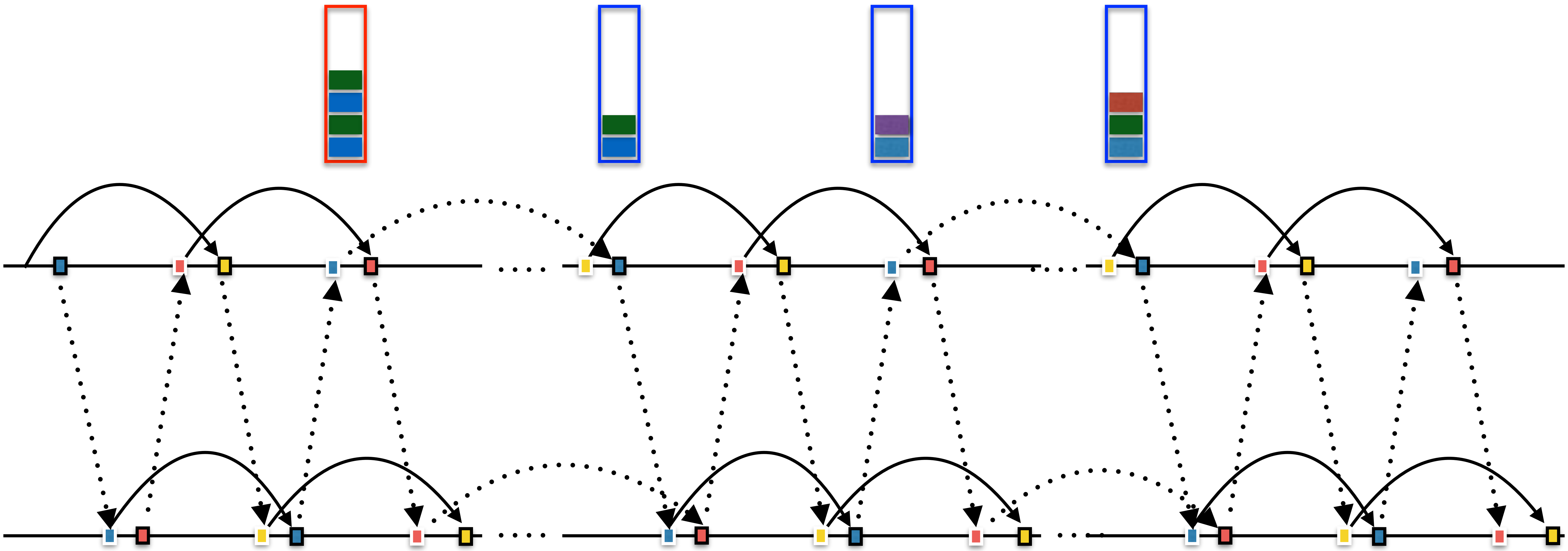
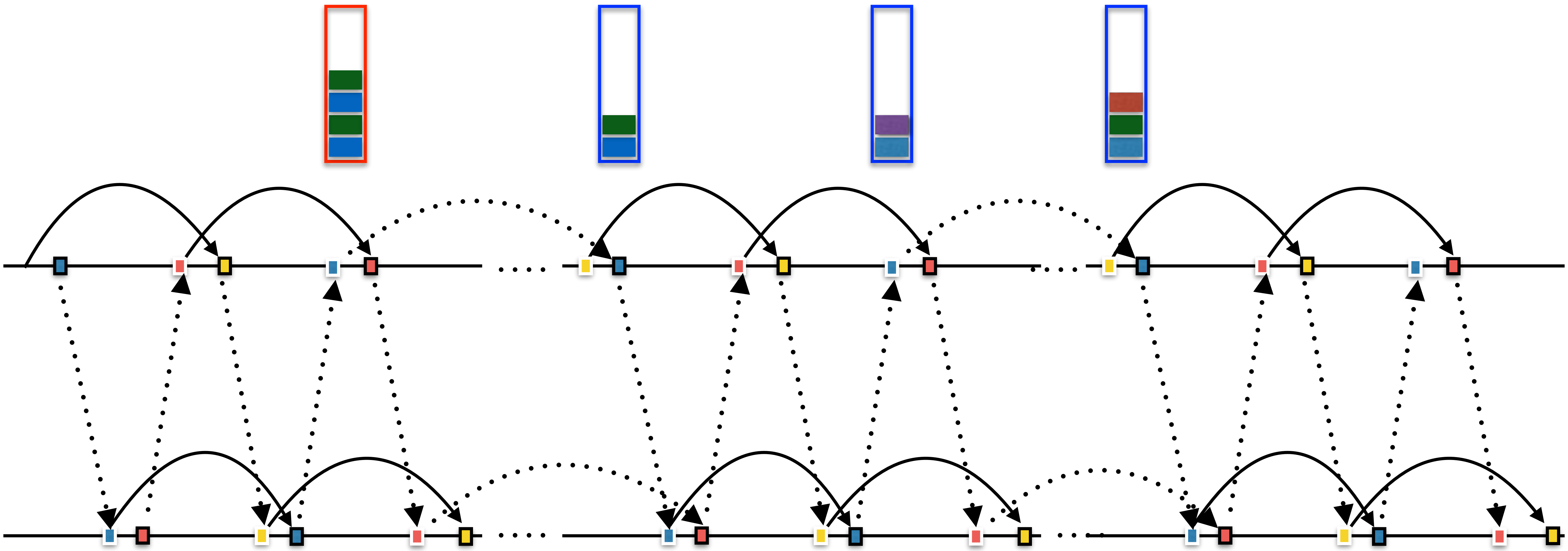


Locks taken in procedure may be released after the procedure terminates

Recursive Programs with Locks



Procedures may return locks they did not take

Decidable Underapproximations:

Nested Locking

Locks are taken and released by each process in well-nested (last in first out/stack-like) manner

Kahlon,Ivancic,Gupta CAV05

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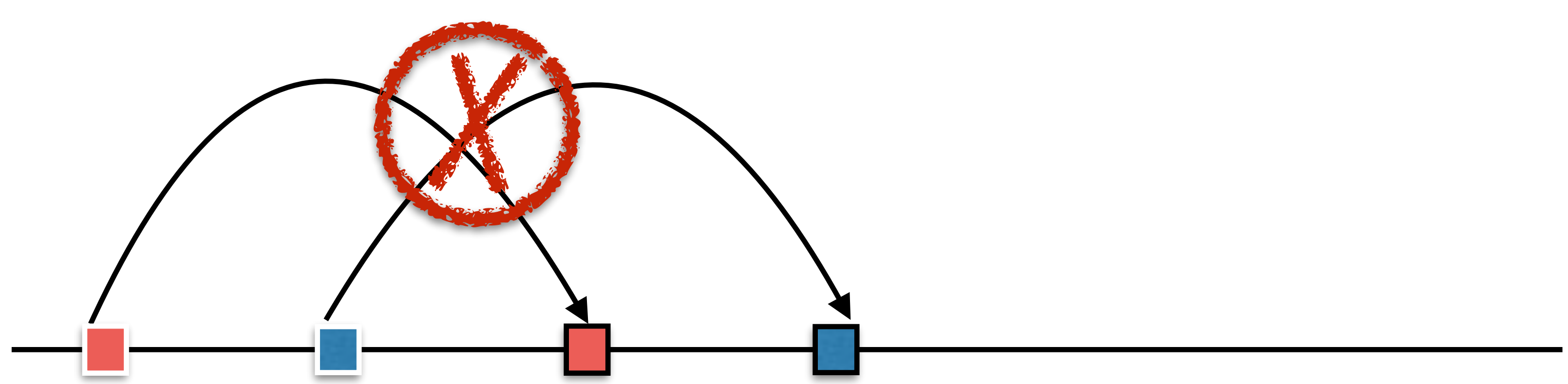

The well-nested assumption is per process (not global).

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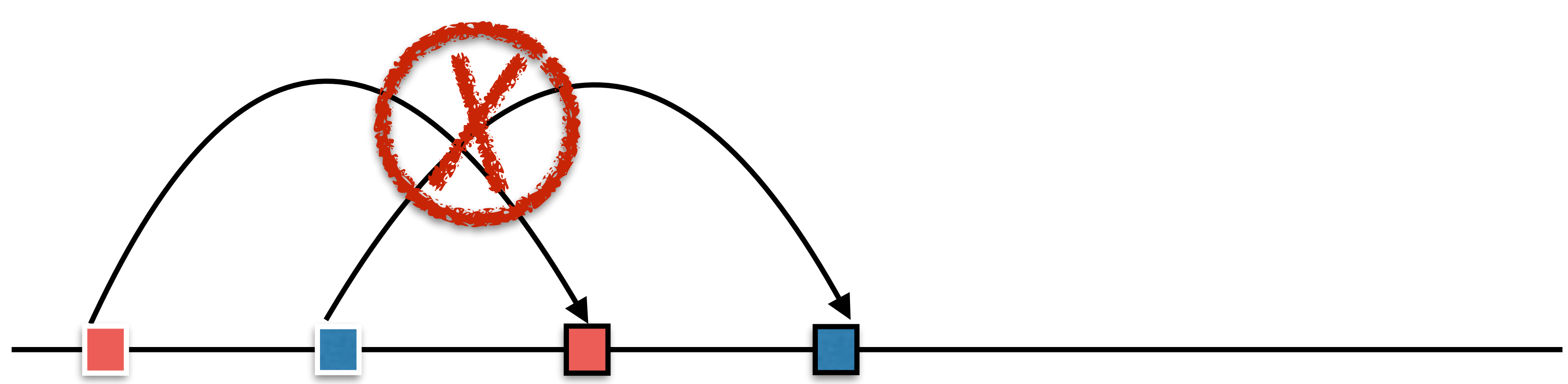


The well-nested assumption is per process (not global).

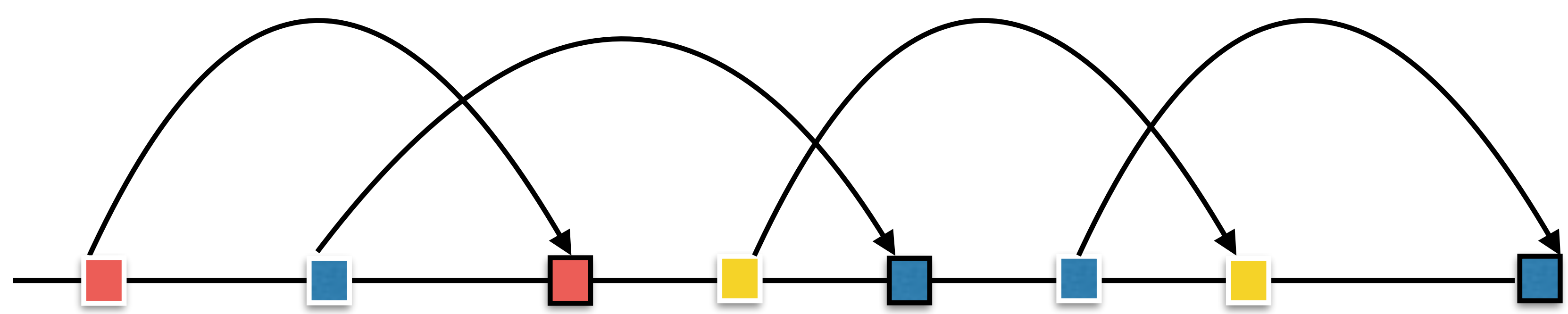
More on nested locking later …

Decidable Underapproximations:

Bounded Lock Chains

Lock chaining is permitted but there is a priori bound on length of such chains.

Kahlon LICS09



A length 4 lock-chained run

Contextual Locking

Contextual Locking

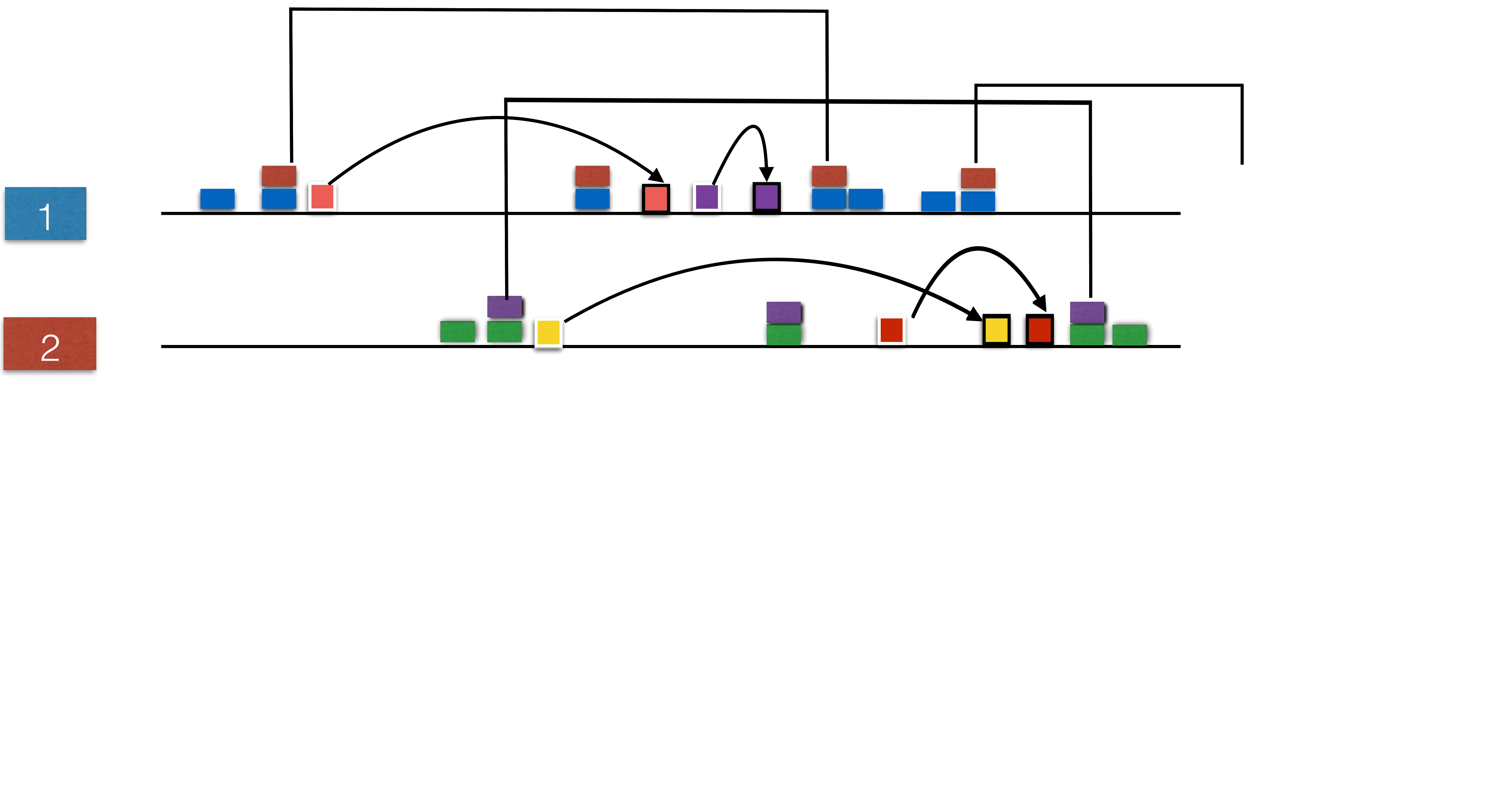
Locks taken by a procedure call are returned during the execution of that very procedure call.

Chadha,Madhusudan,Vishwanathan
TACAS12

Reachability is decidable for 2 processes under contextual locking

Chadha, Madhusudan, Vishwanathan
TACAS12
Bonnet, Chadha, Madhusudan, Viswanathan
LMCS 2013

Sequentializing the runs:



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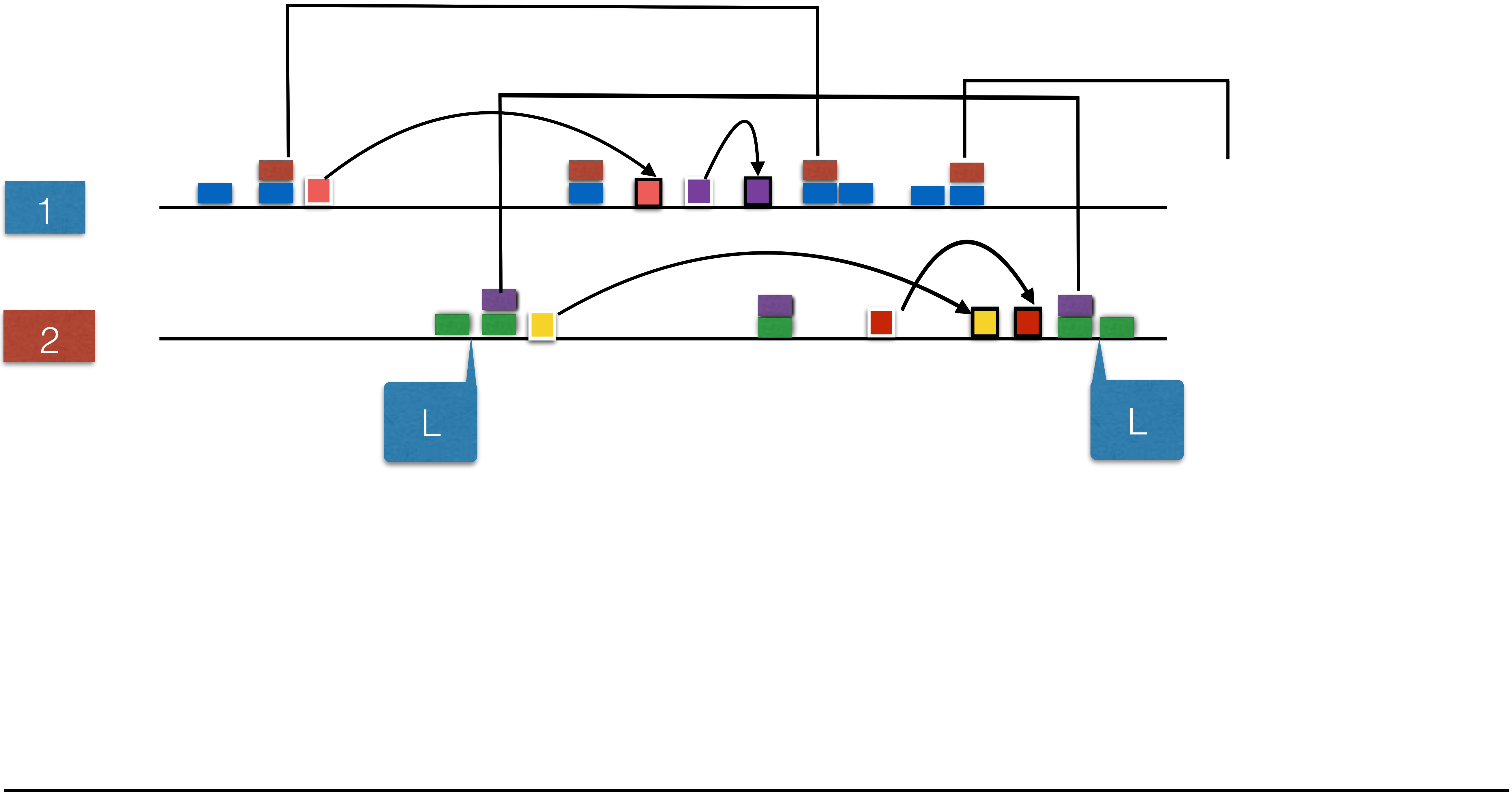

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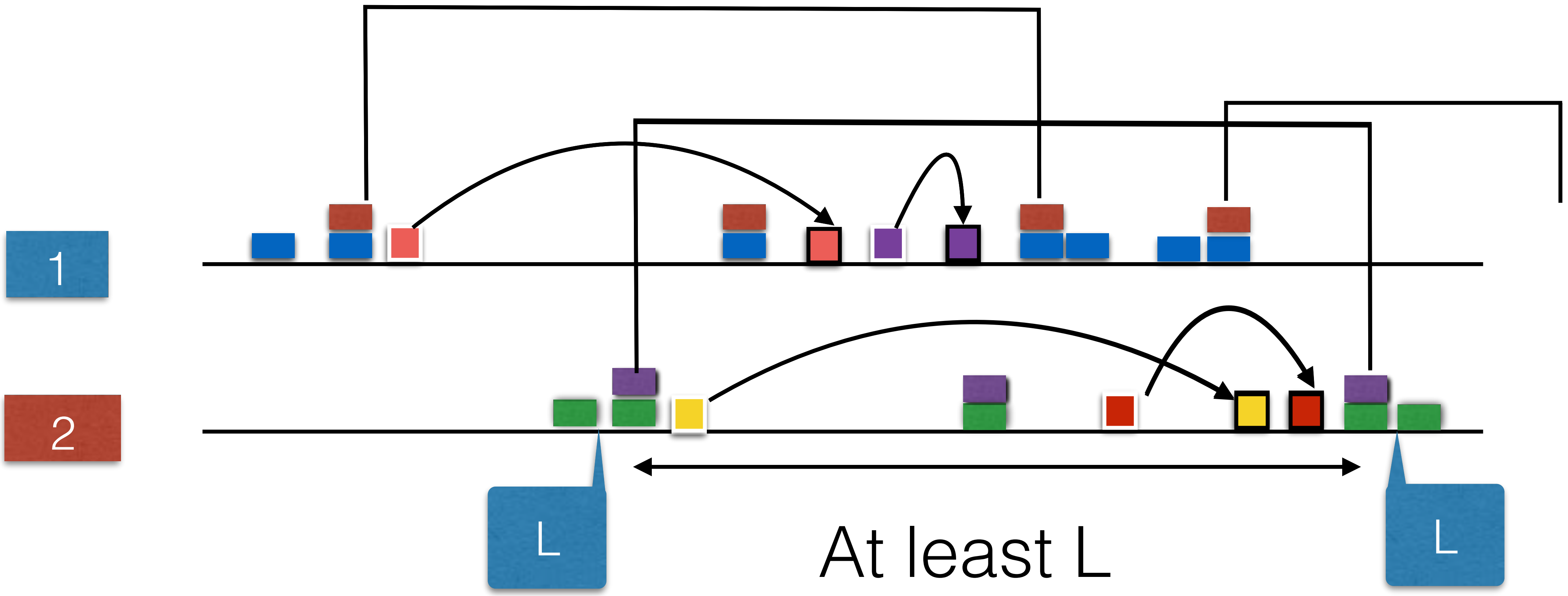

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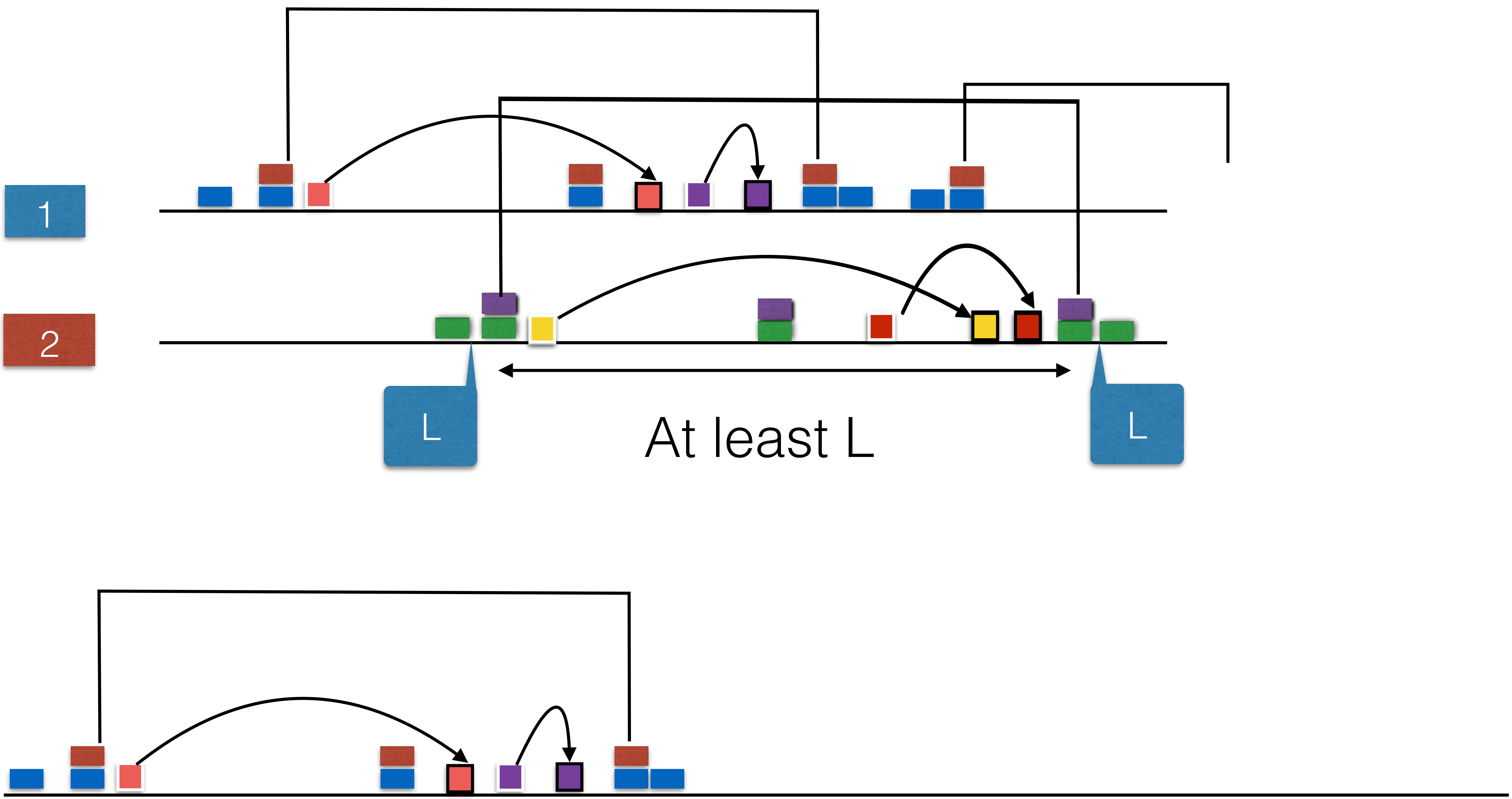

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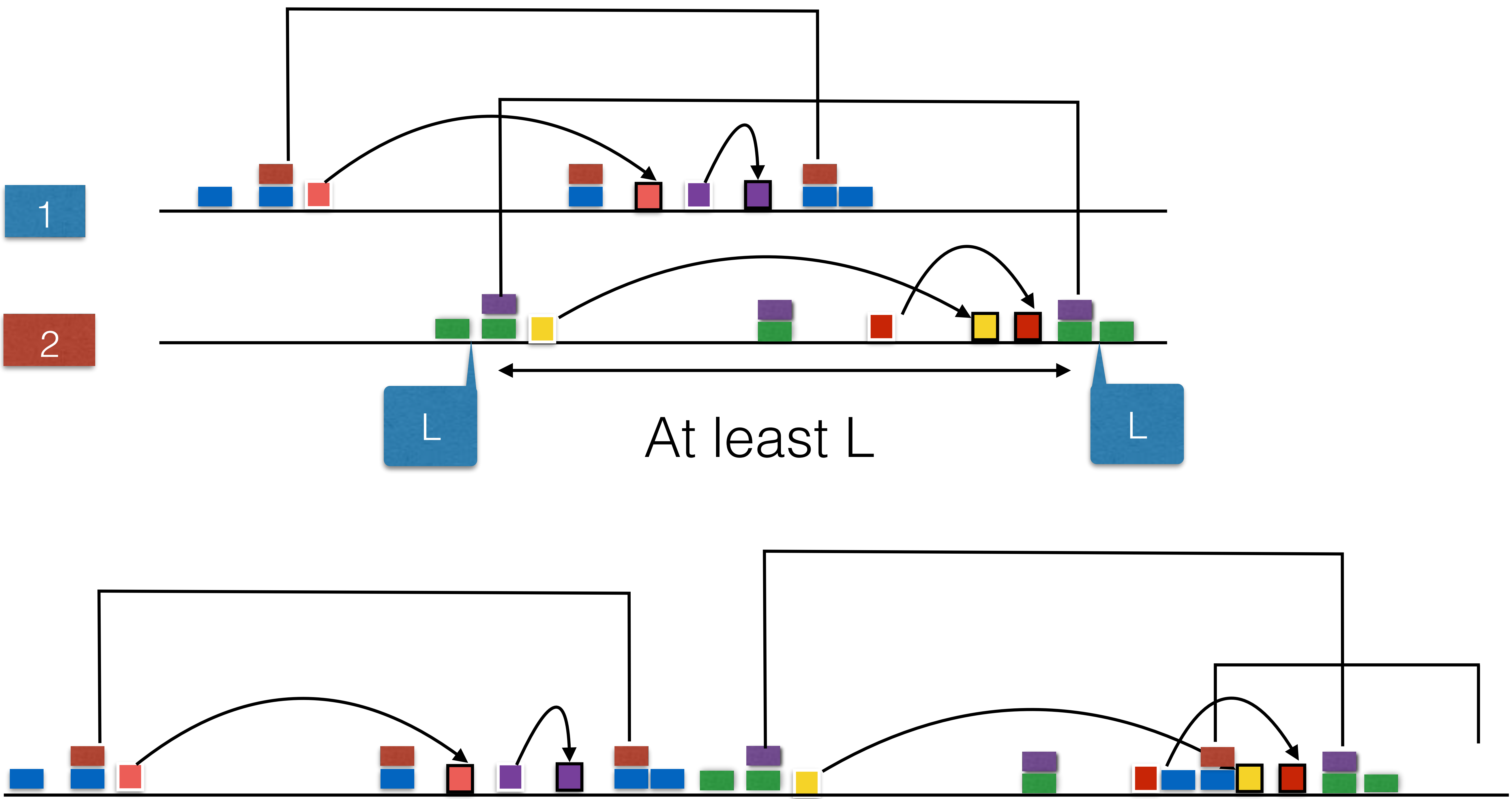

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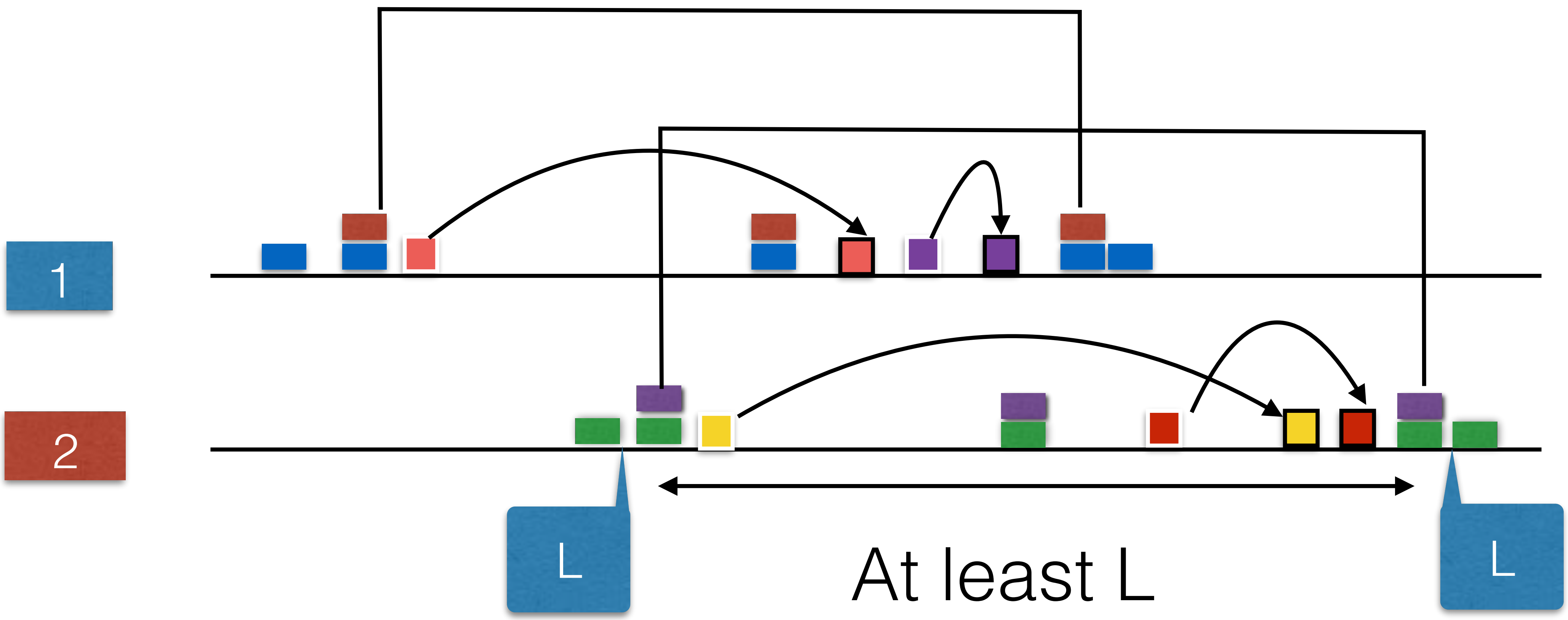

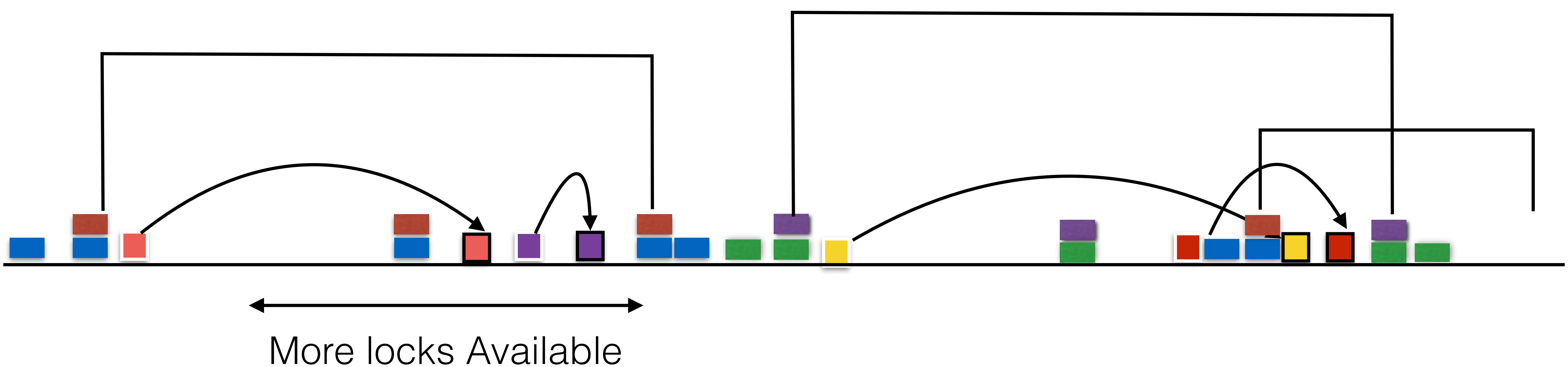

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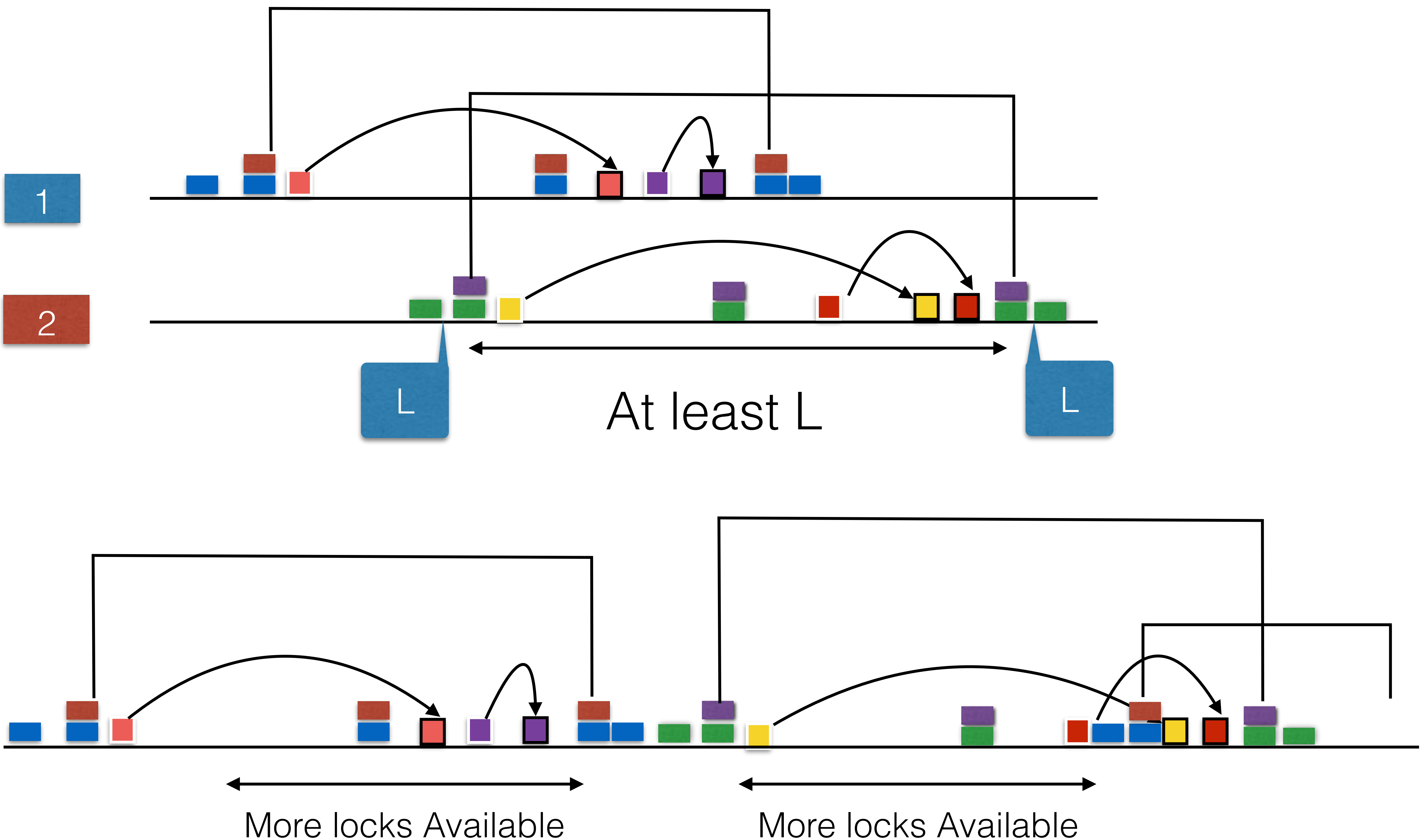

Contextual Locking: 2 processes

Contextual Locking with 2 processes

It suffices to consider runs where the procedure calls of the two processes are also well-nested. Can be simulated by a single PDS.

Chadha,Madhusudan,Vishwanathan
TACAS12

This does not work if there are 3 processes or more.

Contextual Locking: >2 processes

The reachability problem for any number of pushdown systems synchronising via contextual locks is decidable.

Lammich, Muller-Olm, Seidl, Werner SAS13

Stack height bounding argument.

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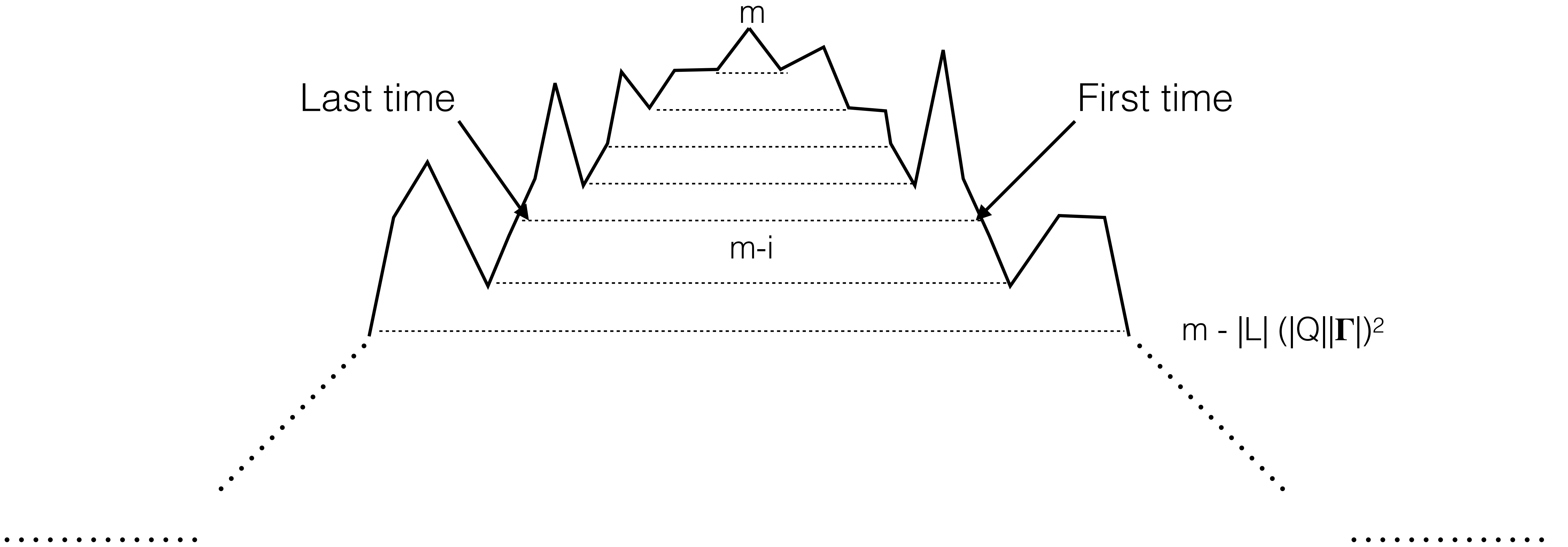

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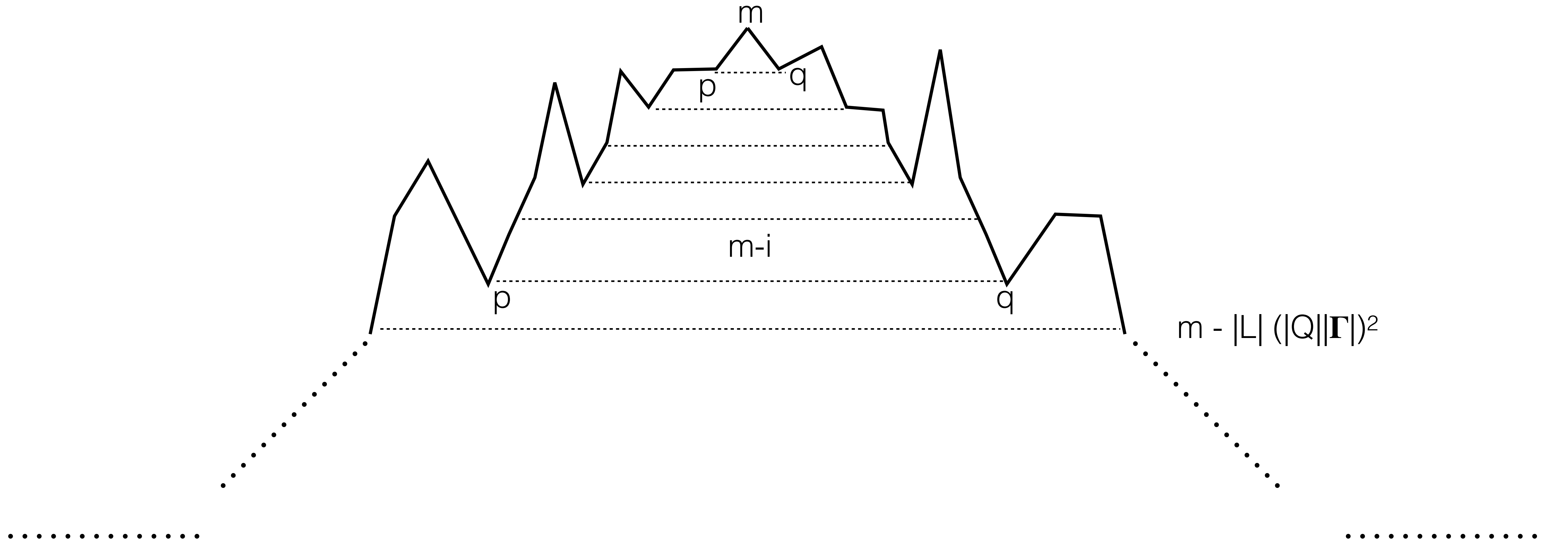

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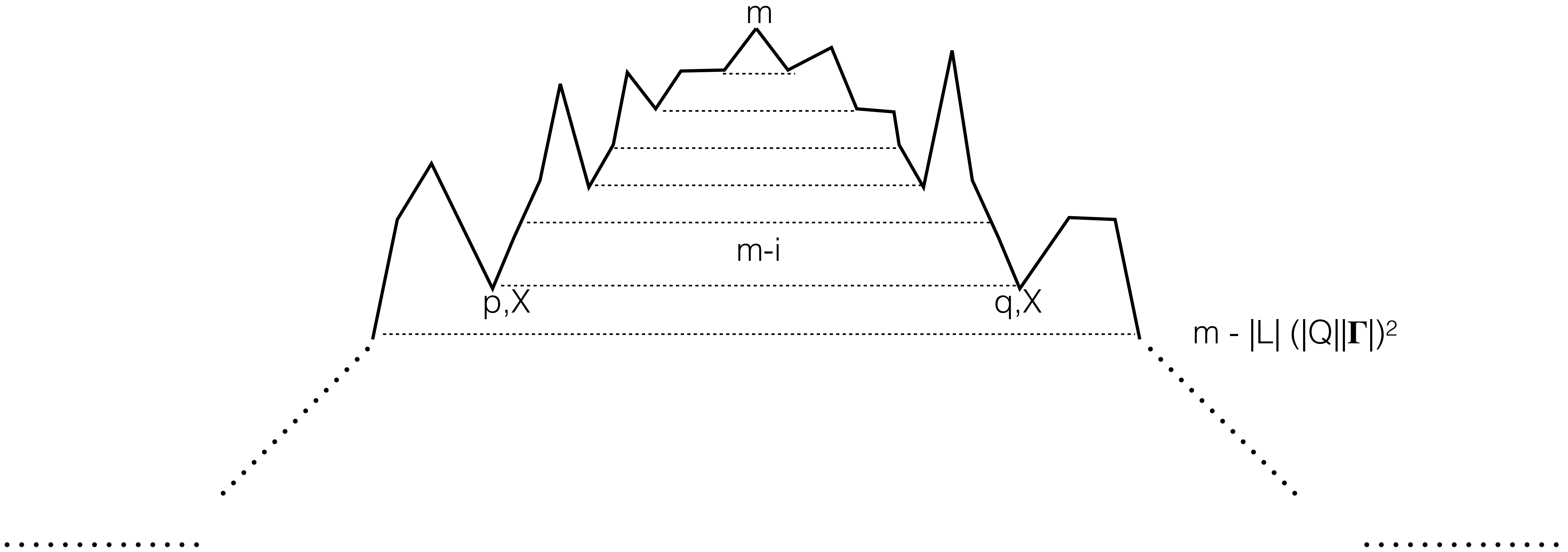

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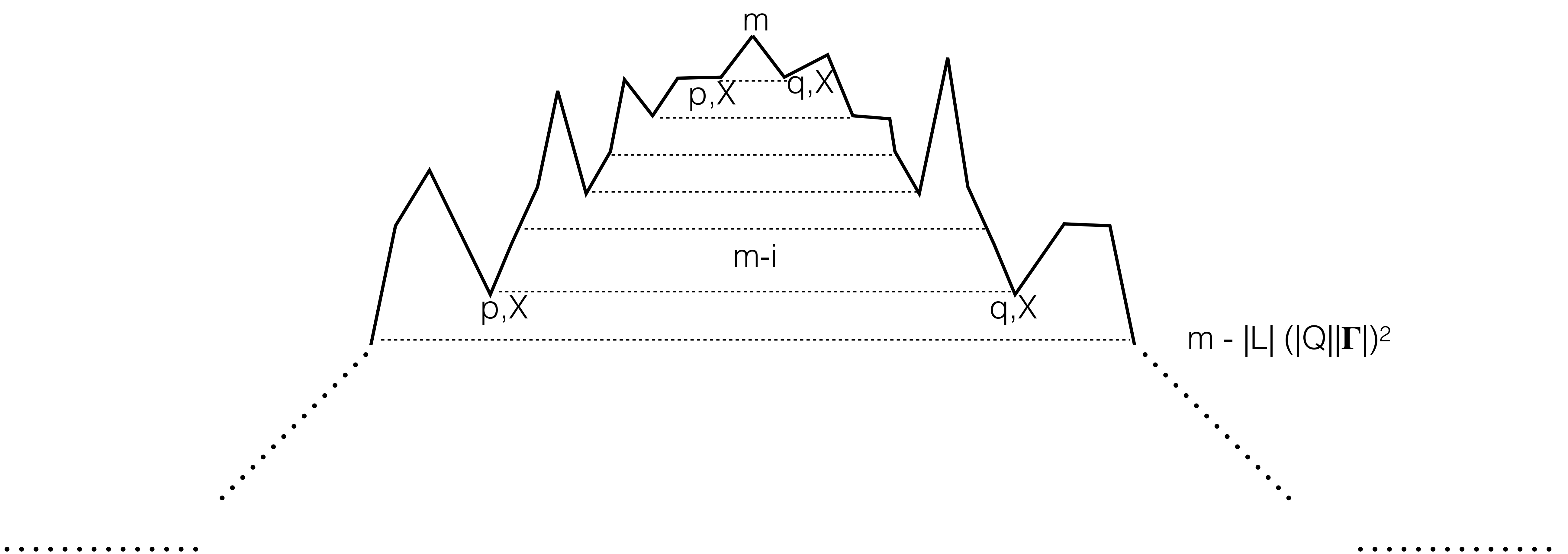

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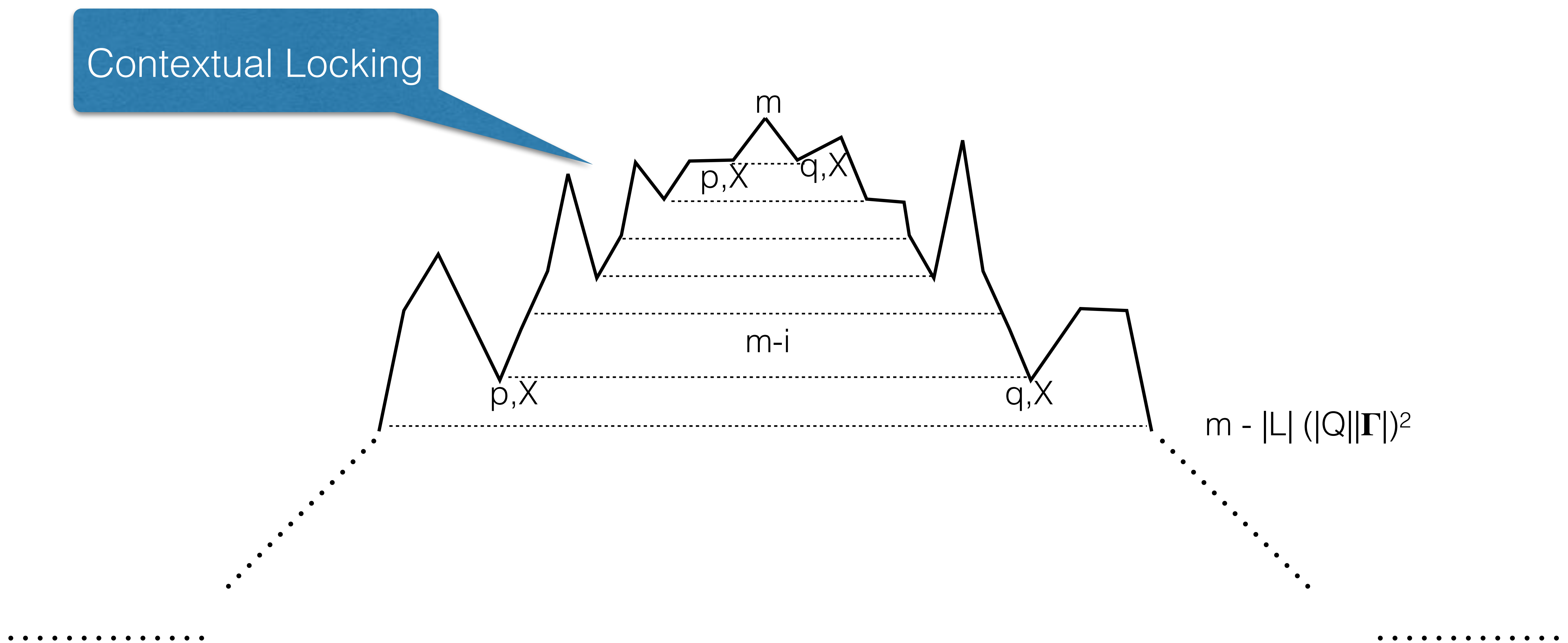

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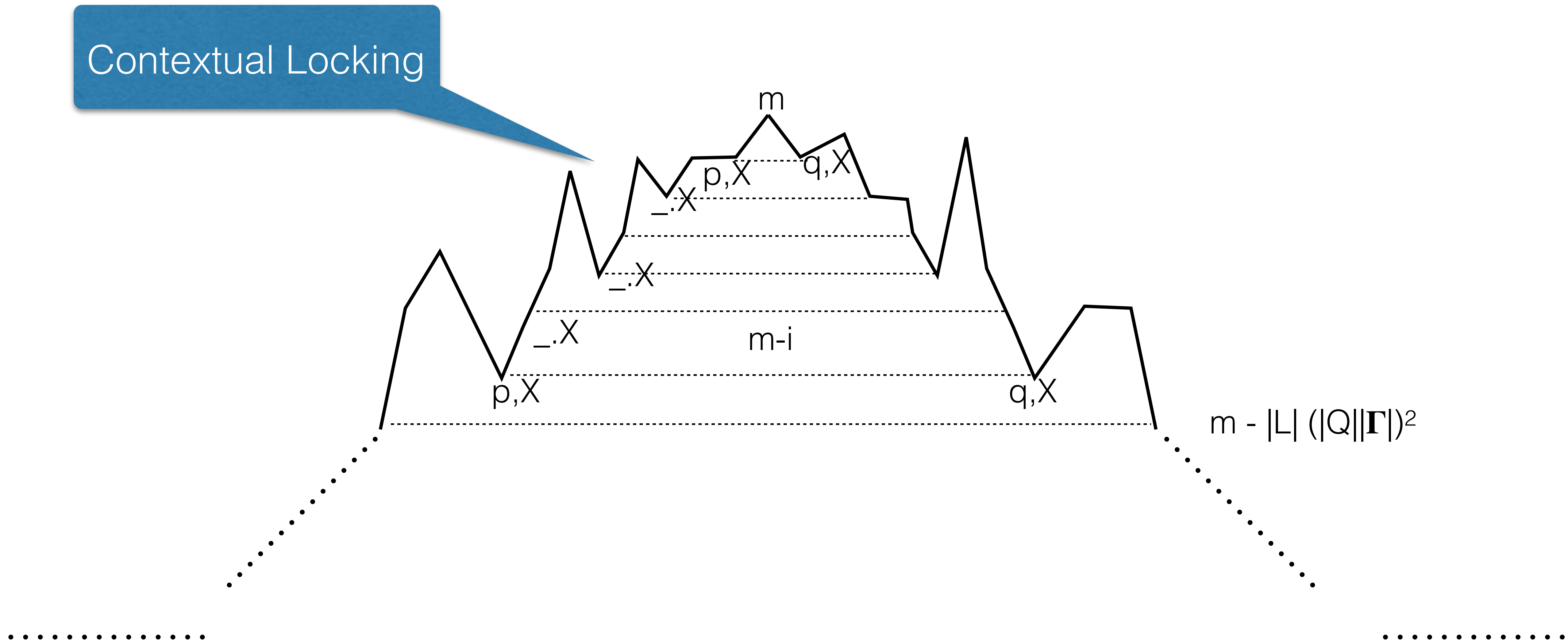

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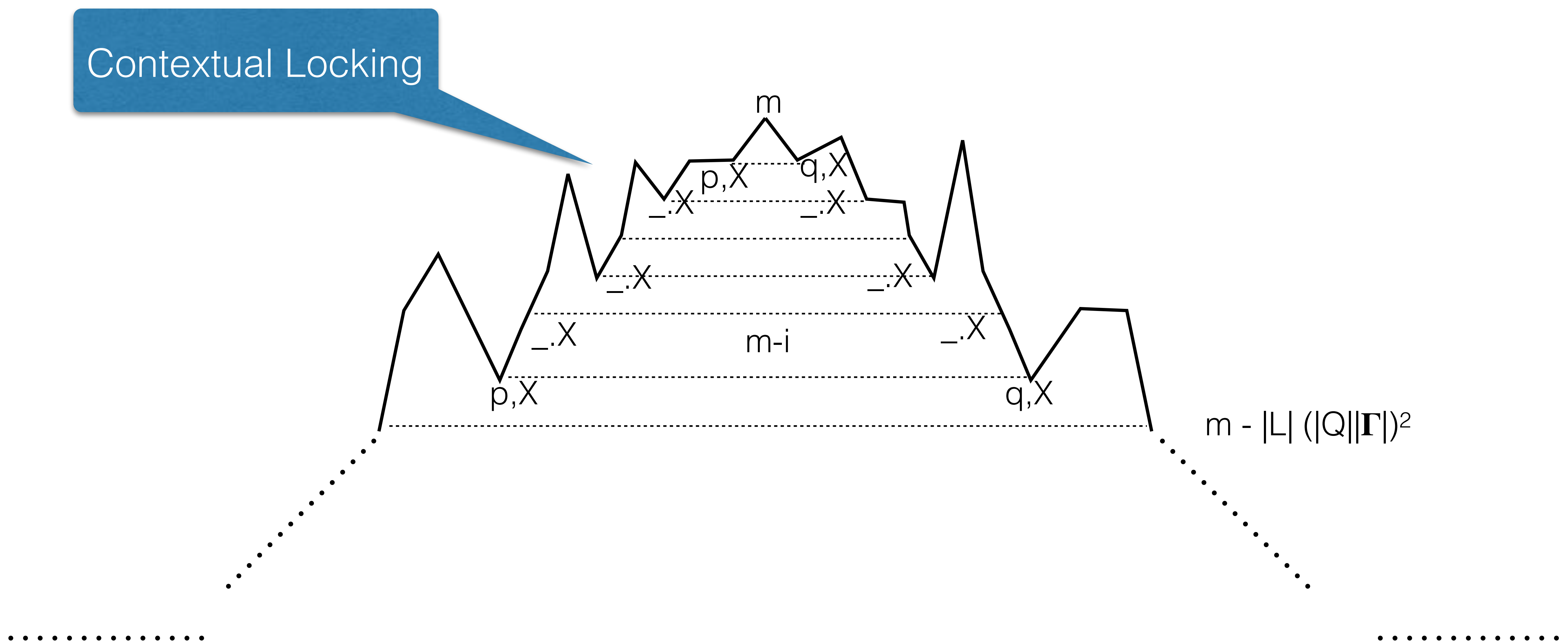

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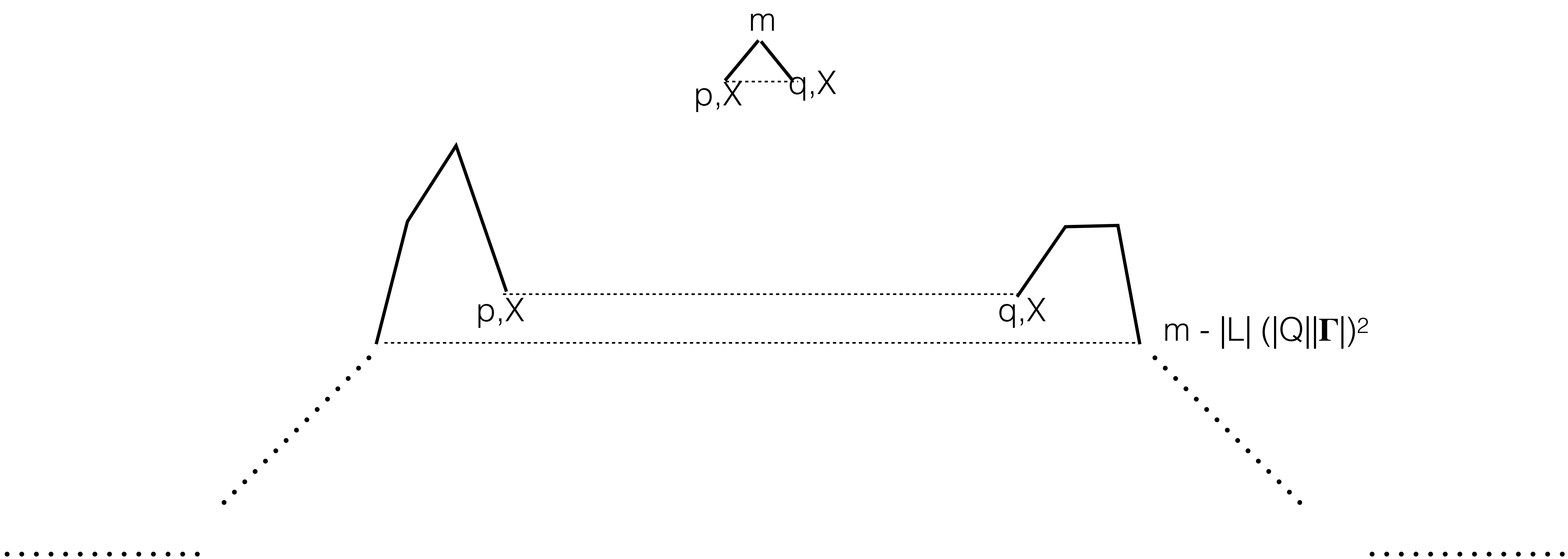

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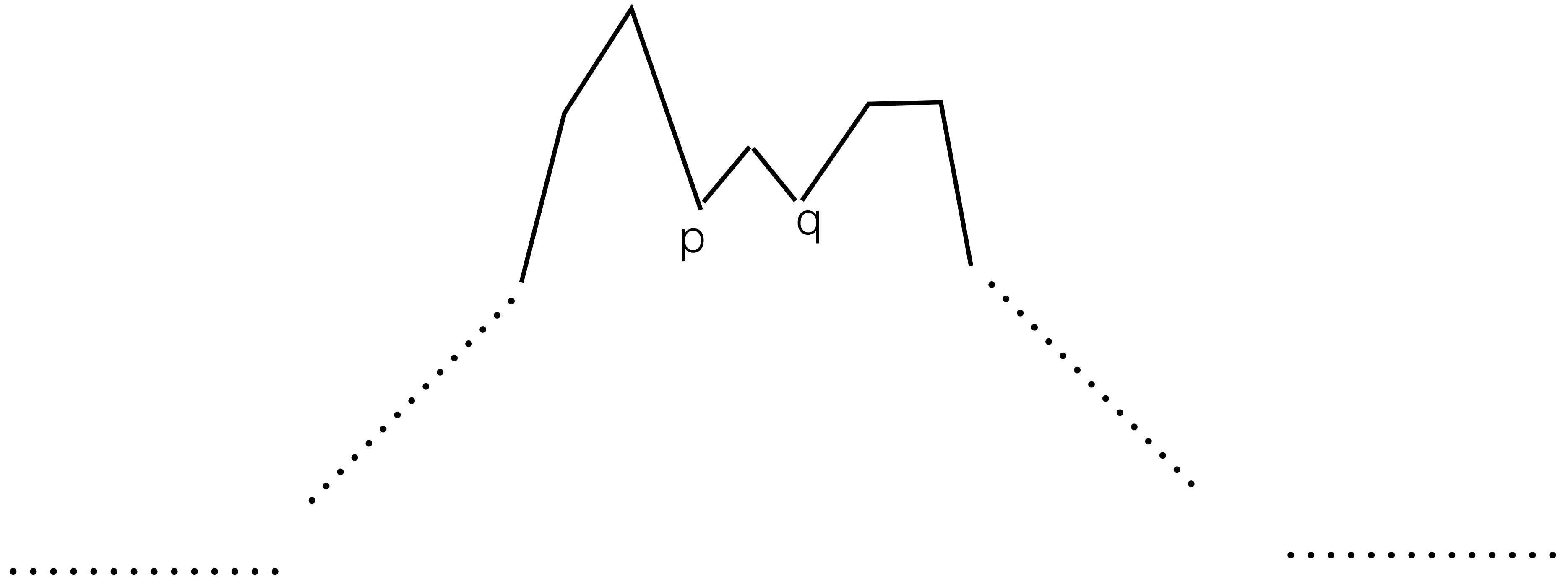

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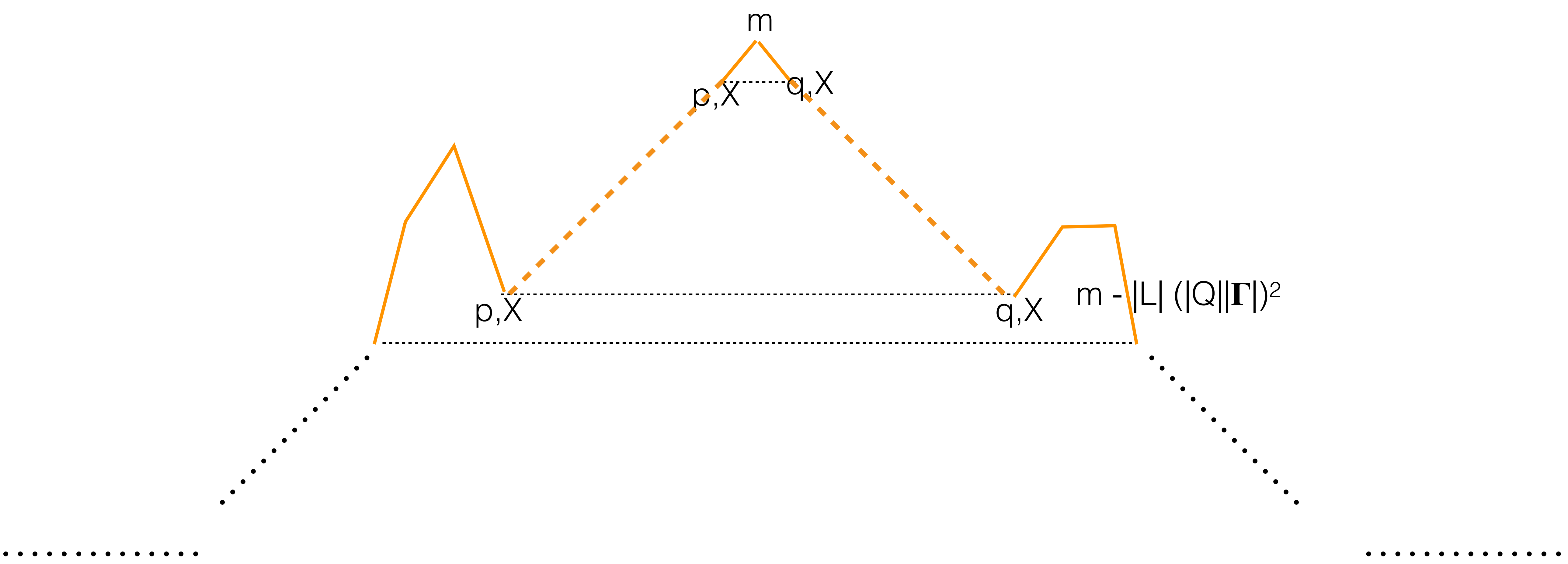

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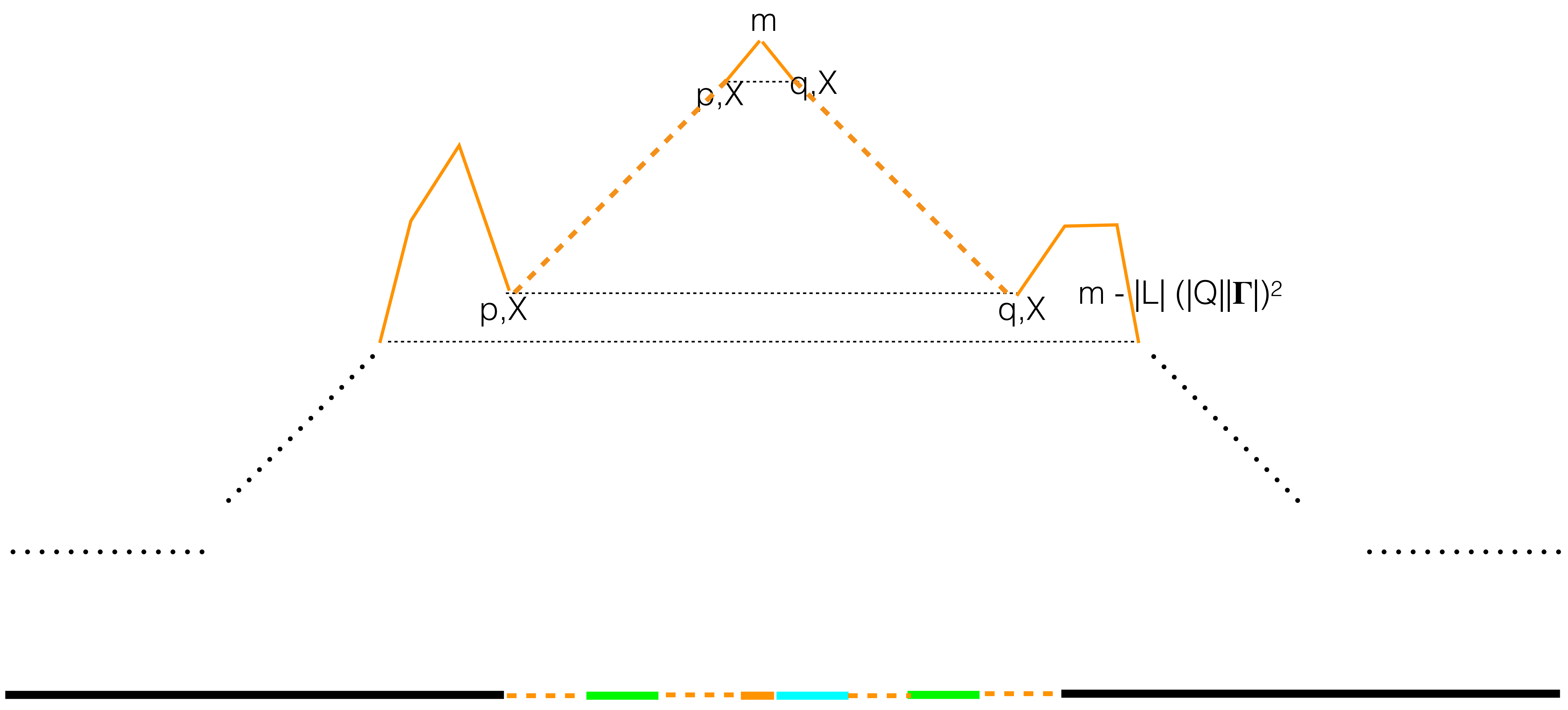

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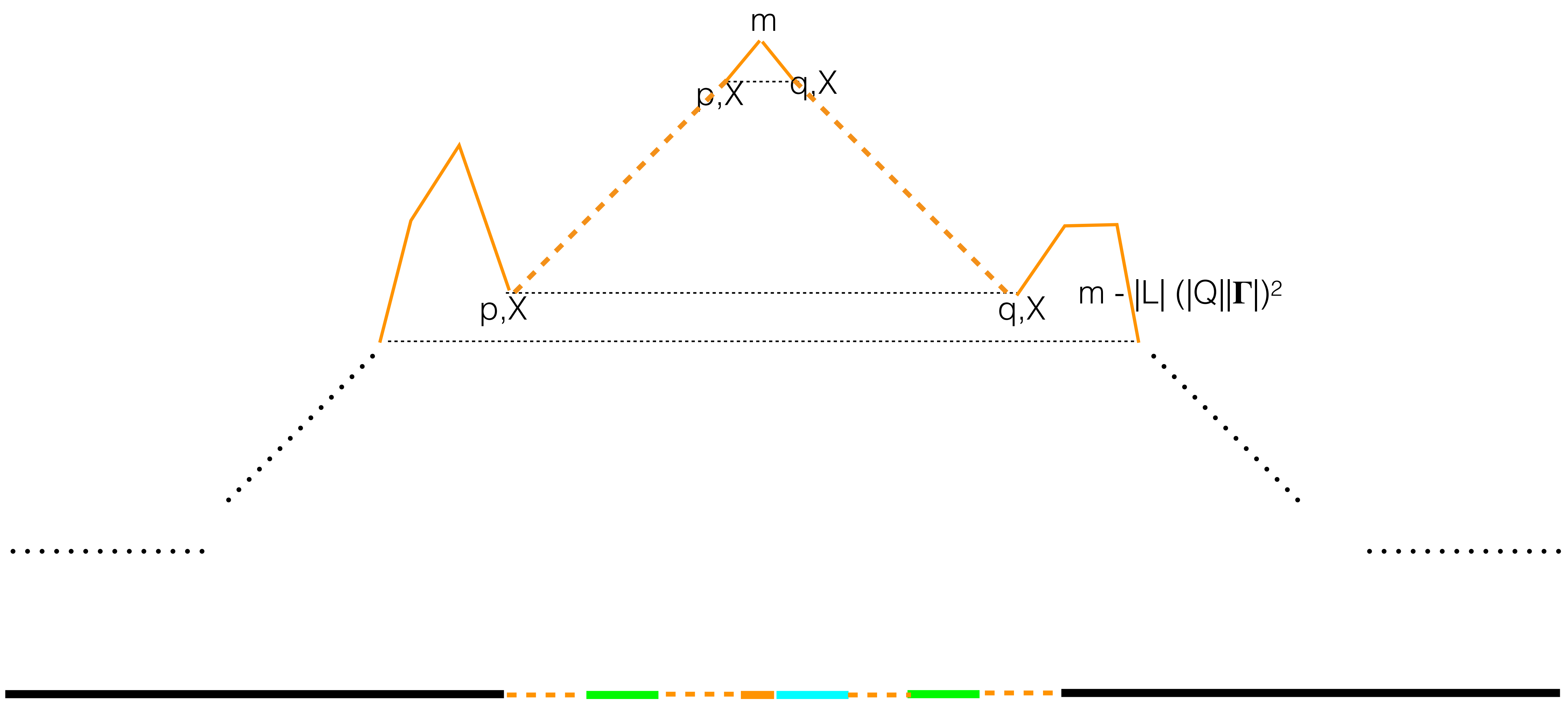

More locks available for other processes below

Contextual Locking: >2 processes

The reachability problem for any number of pushdown systems synchronising via contextual locks is decidable.

Exponential (in states, stack alphabet, locks) length paths suffice.
In PSPACE.

Extends to systems with Dynamic thread creation.

Lammich, Muller-Olm, Seidl, Werner SAS13

Asynchronous programs:

Sen and Vishwanathan CAV06, Ganty and Majumdar TOPLAS12 …,

```
Proc one()
{
        < …. >
         call function();
         async-call function();

}
```

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```

- Recursive programs with option to invoke asynchronous calls.
- The asynchronous calls are stored as tasks that can be retrieved later and executed
- The stored tasks have no specific order.
- The tasks are executed atomically when there are no other pending calls.

Asynchronous programs:

Sen and Vishwanathan CAV06, Ganty and Majumdar TOPLAS12 …,

```
Proc one()
{
        < …. >
         call function();
         async-call function();

}
```

- Recursive programs with option to invoke asynchronous calls.
- The asynchronous calls are stored as tasks that can be retrieved later and executed
- The stored tasks have no specific order.
- The tasks are executed atomically when there are no other pending calls.

Modeled as a PDS augmented with a multi-set. (MPDS)

Decidability:

Control state reachability for pushdown systems equipped with a multi-set is EXPSPACE-Complete

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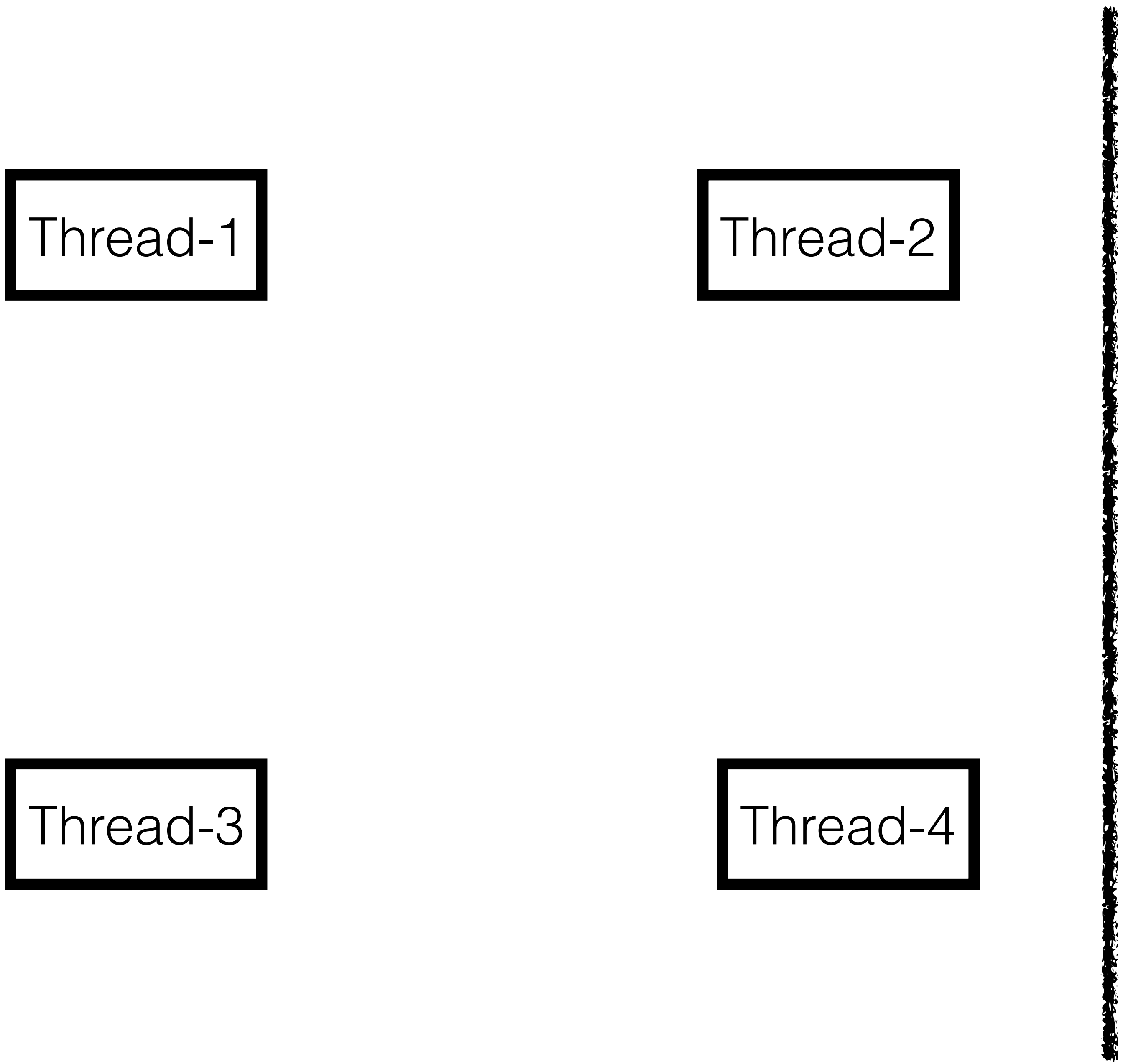
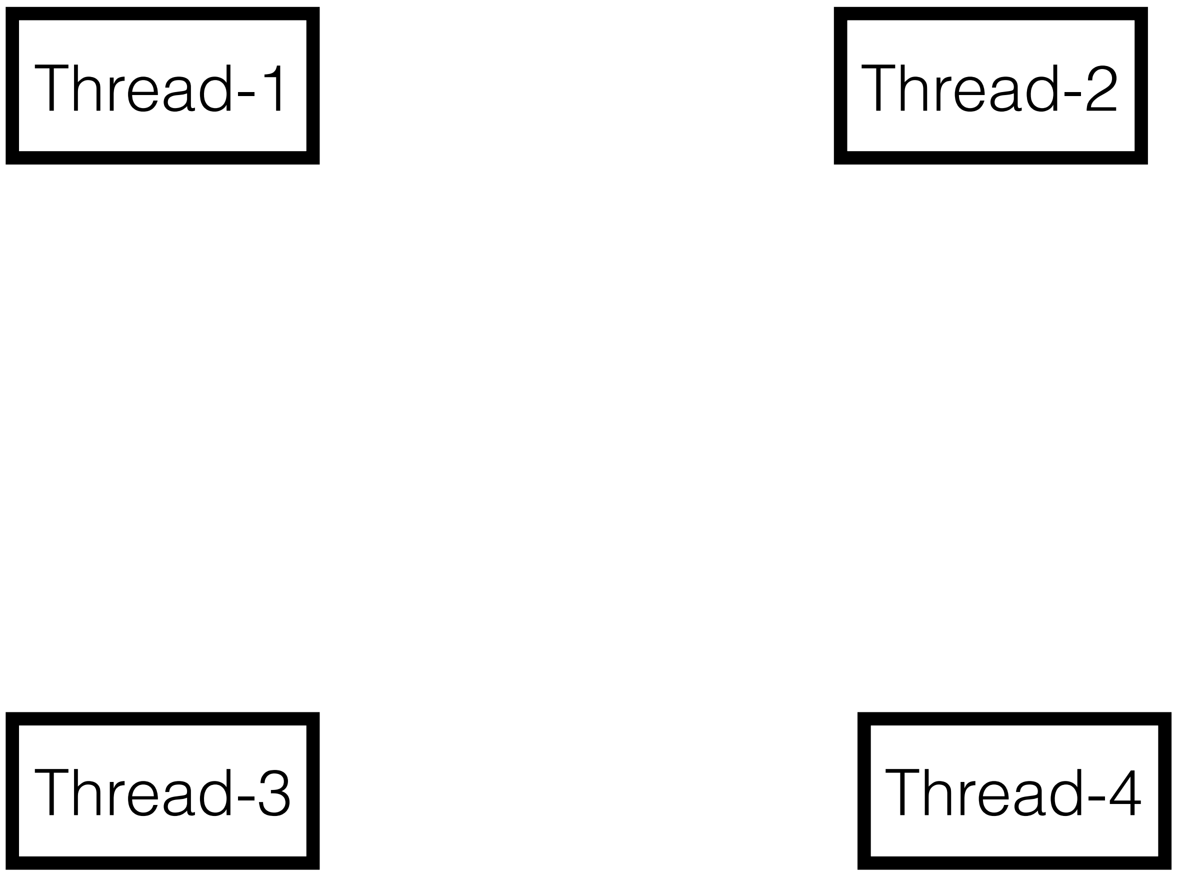
Sen and Vishwanathan CAV06
Atig, Bouajjani, Touili FSTTCS08
Ganty and Majumdar TOPLAS12

Multi-threaded version:

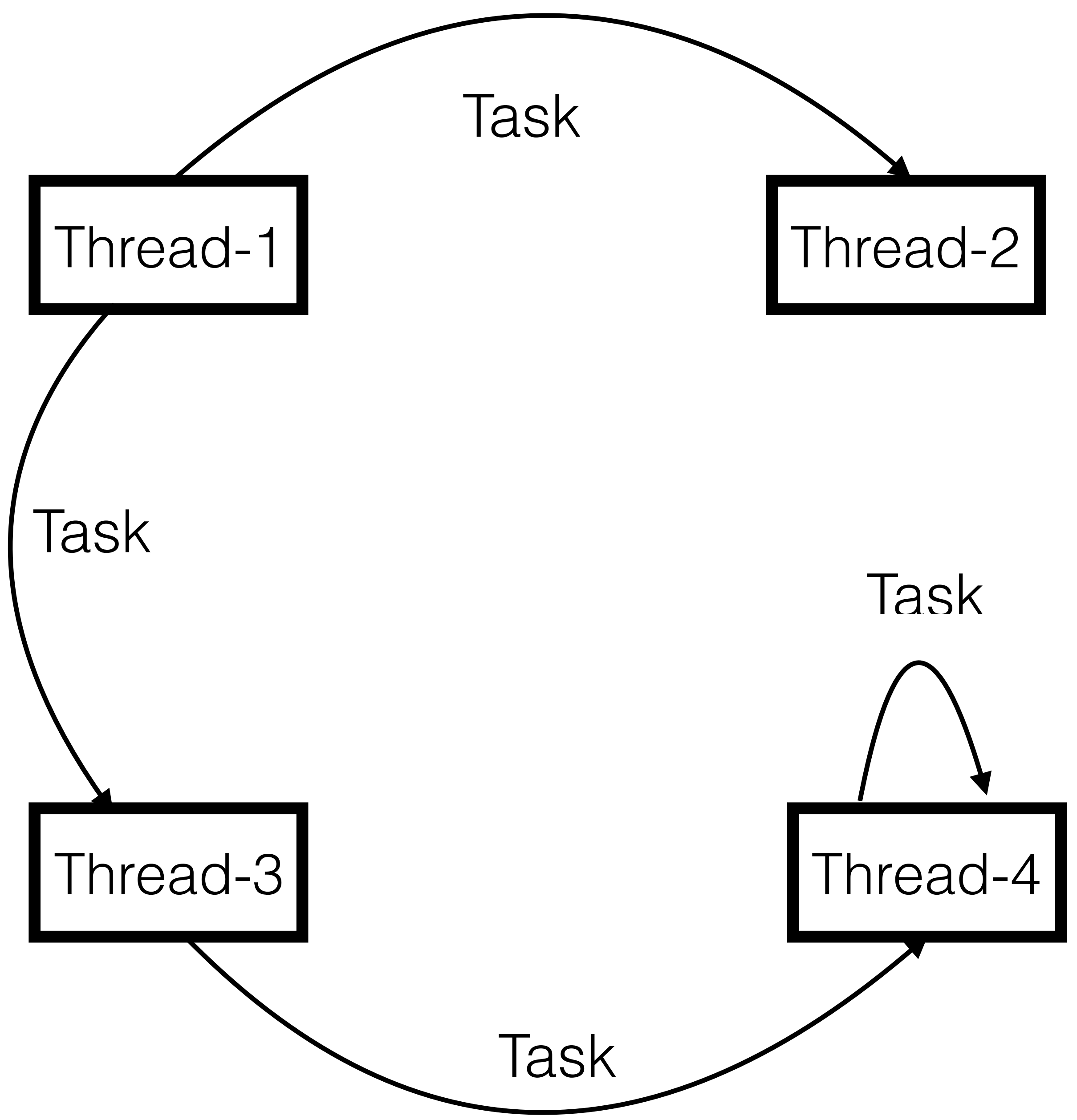


Multi-threaded version:



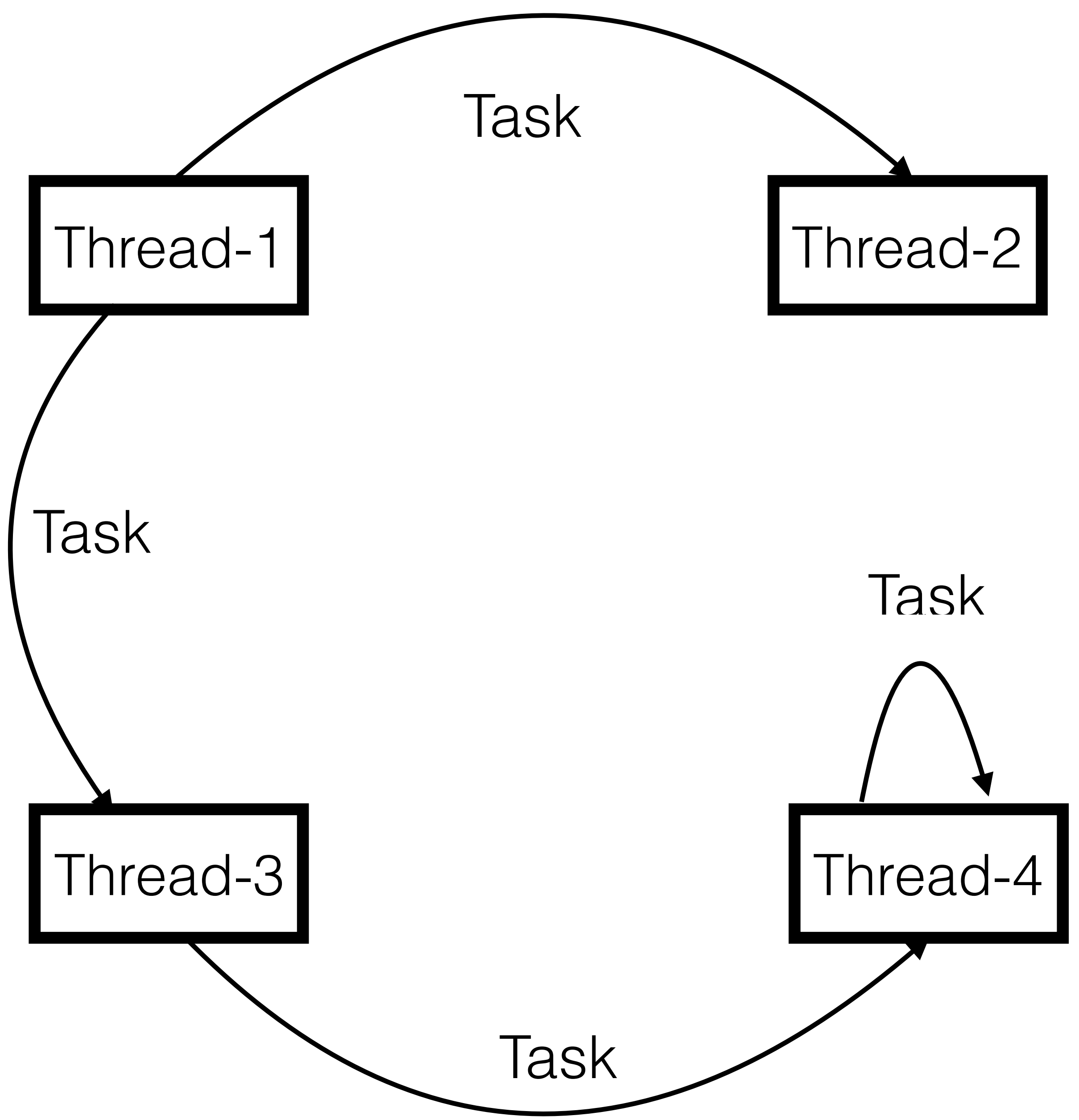
- Programs with multiple threads running in parallel

Multi-threaded version:



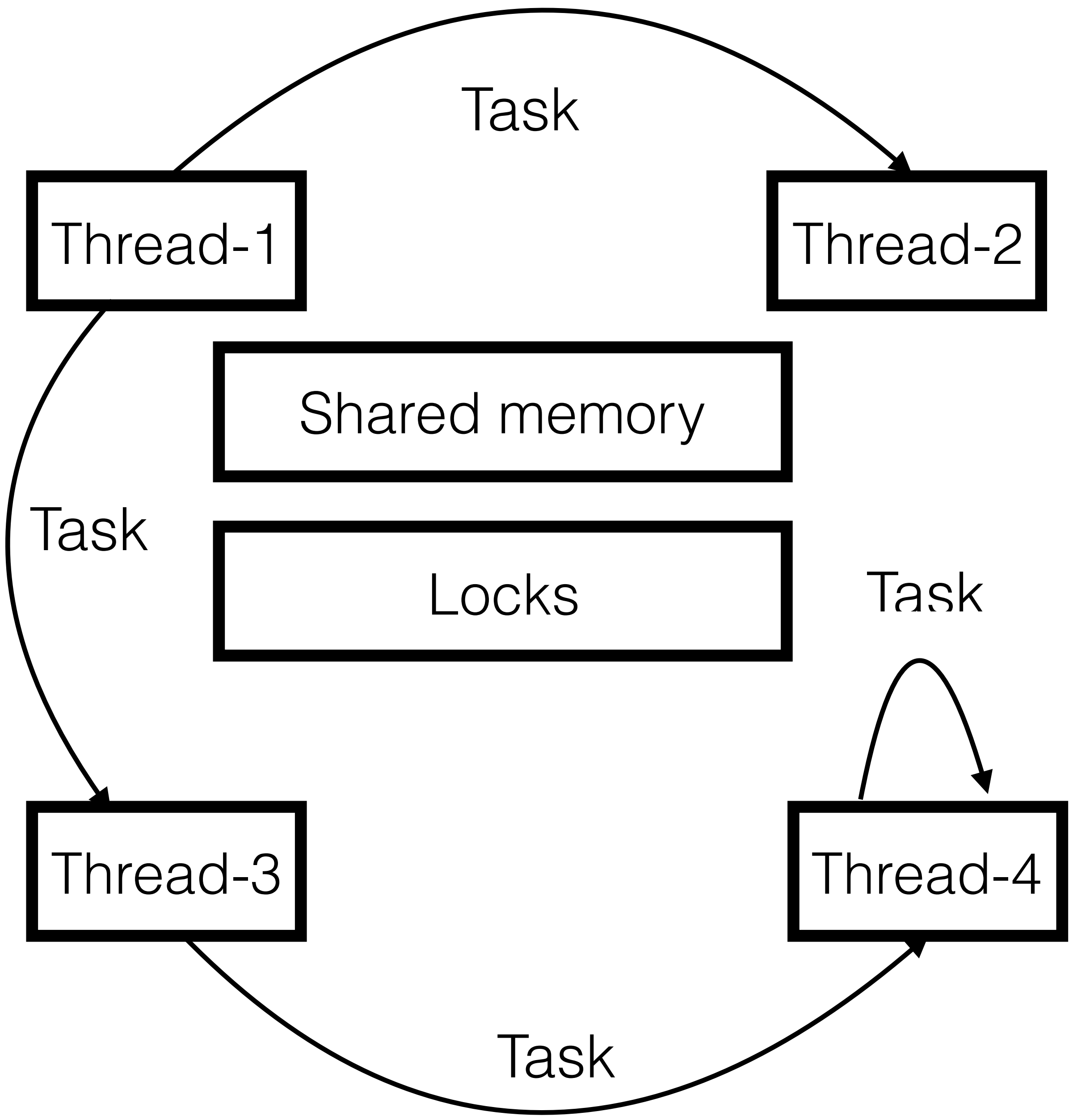
- Programs with multiple threads running in parallel
- Threads can either make a synchronous call or an asynchronous call by delegating it to a thread

Multi-threaded version:



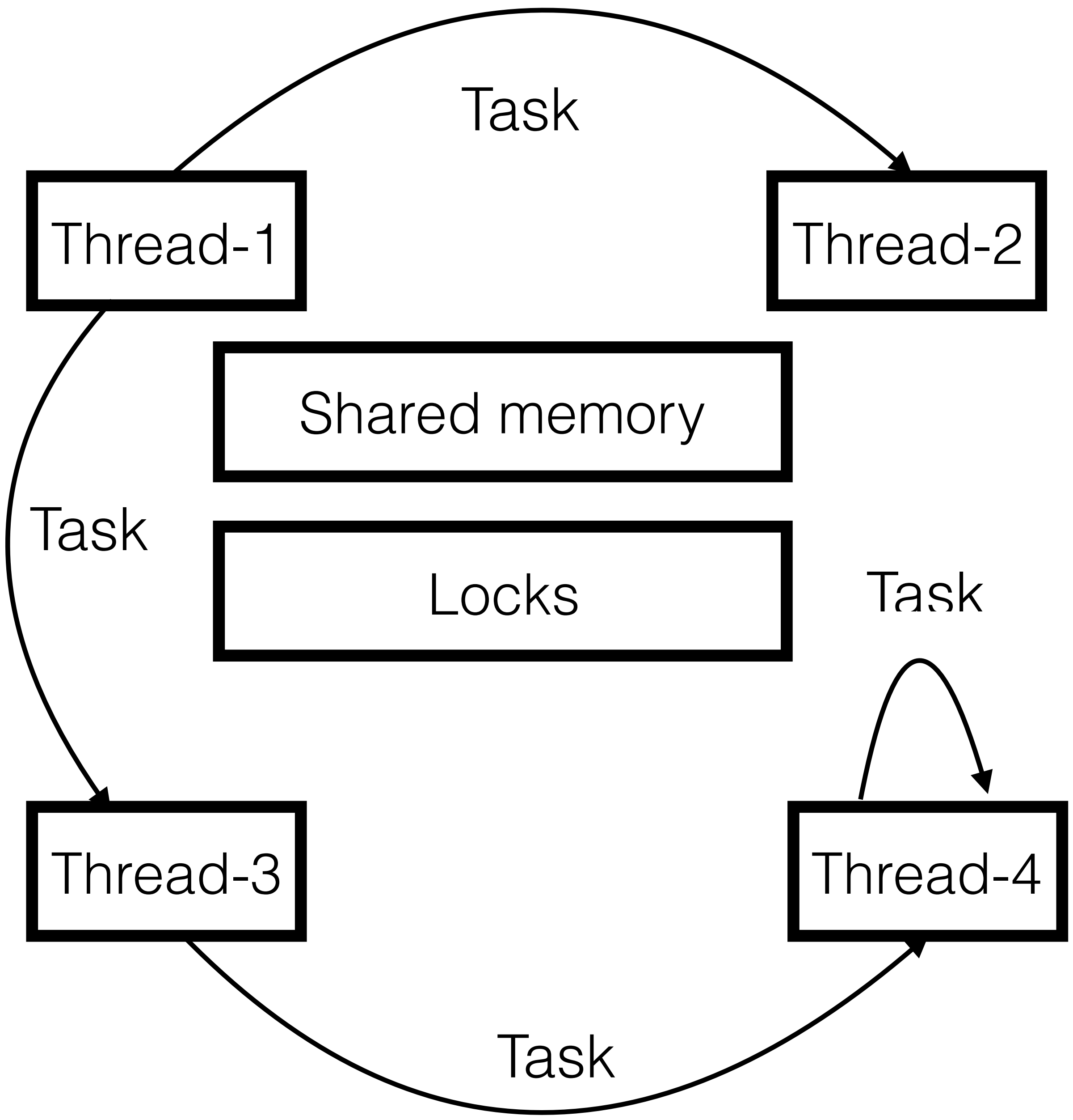
- Programs with multiple threads running in parallel
- Threads can either make a synchronous call or an asynchronous call by delegating it to a thread
- Threads have unbounded unordered buffers to store the tasks

Communication:



- Communication via shared memory and locks.

Communication:



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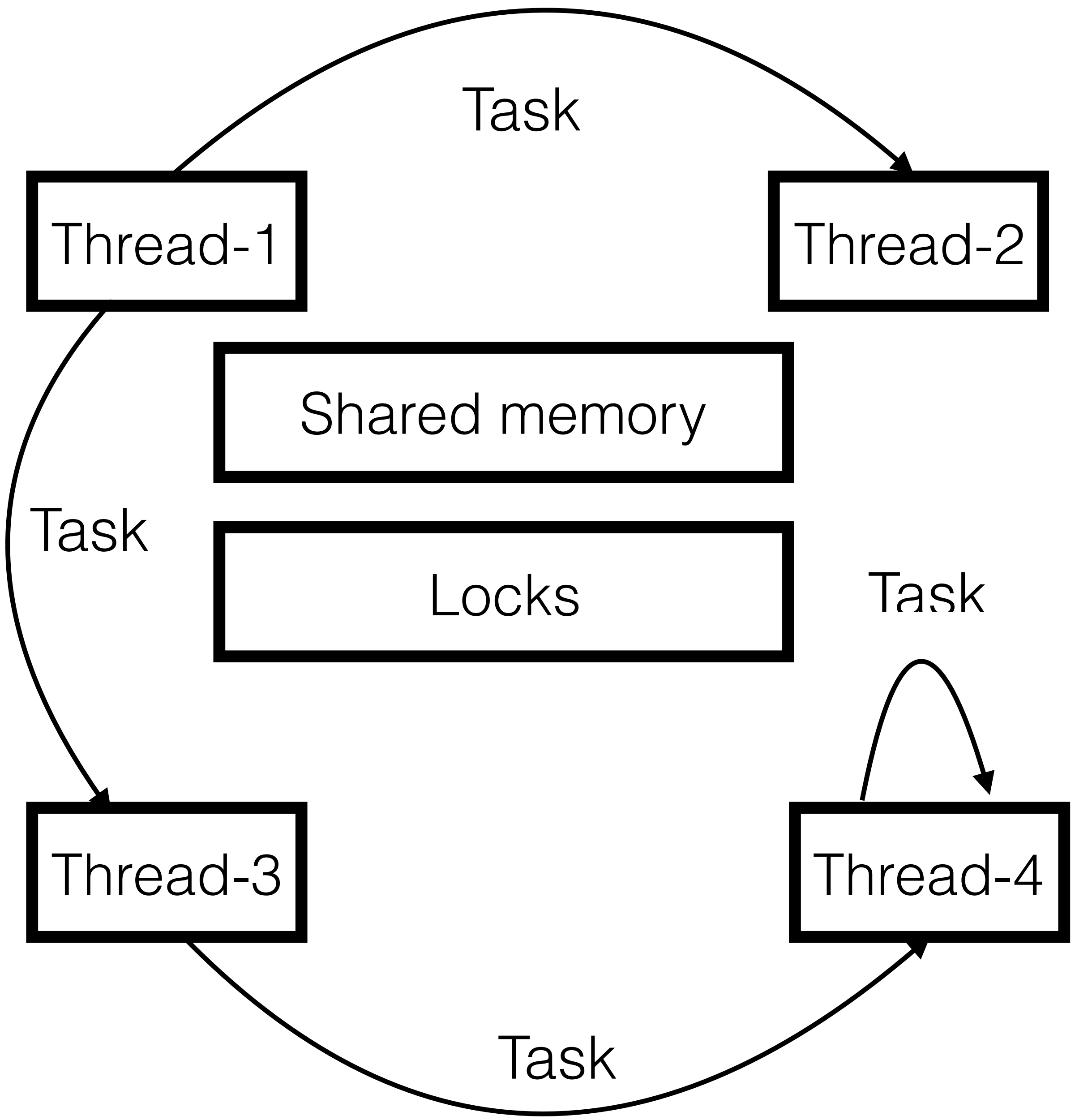
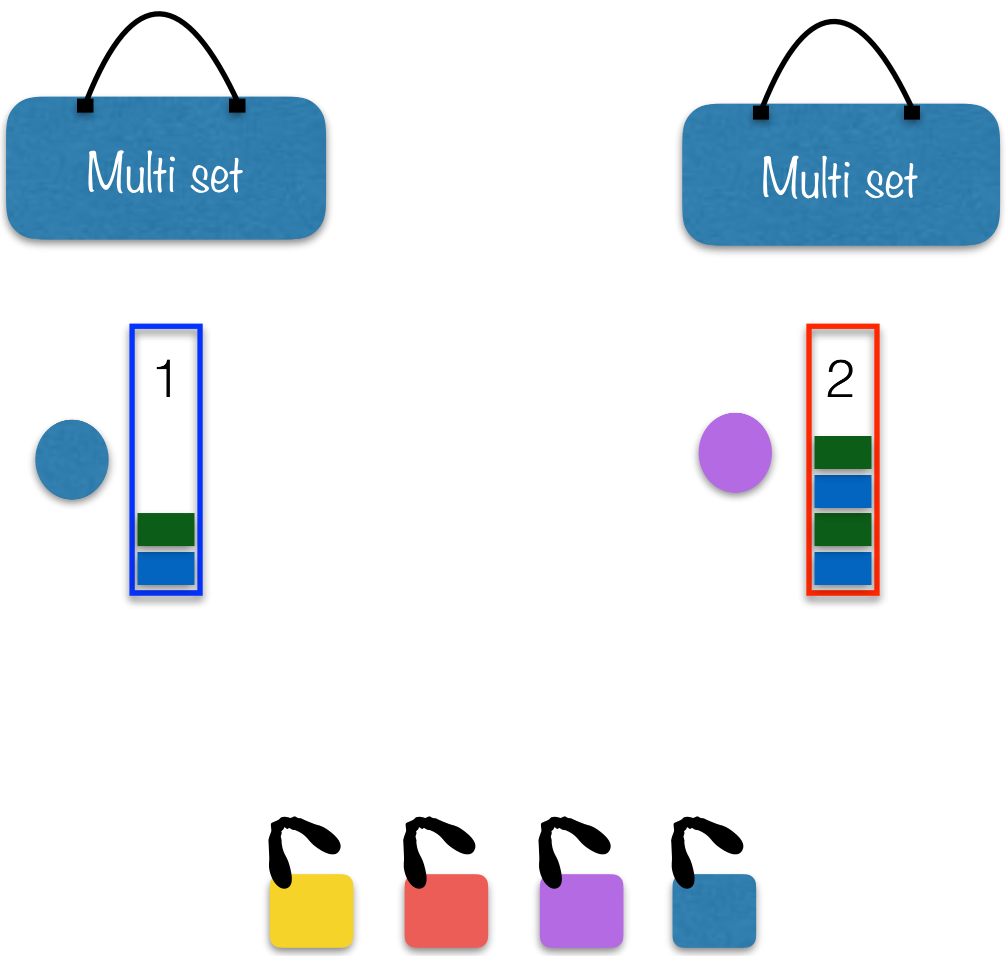


- Communication via shared memory and locks.
- Shared memory is difficult to handle.

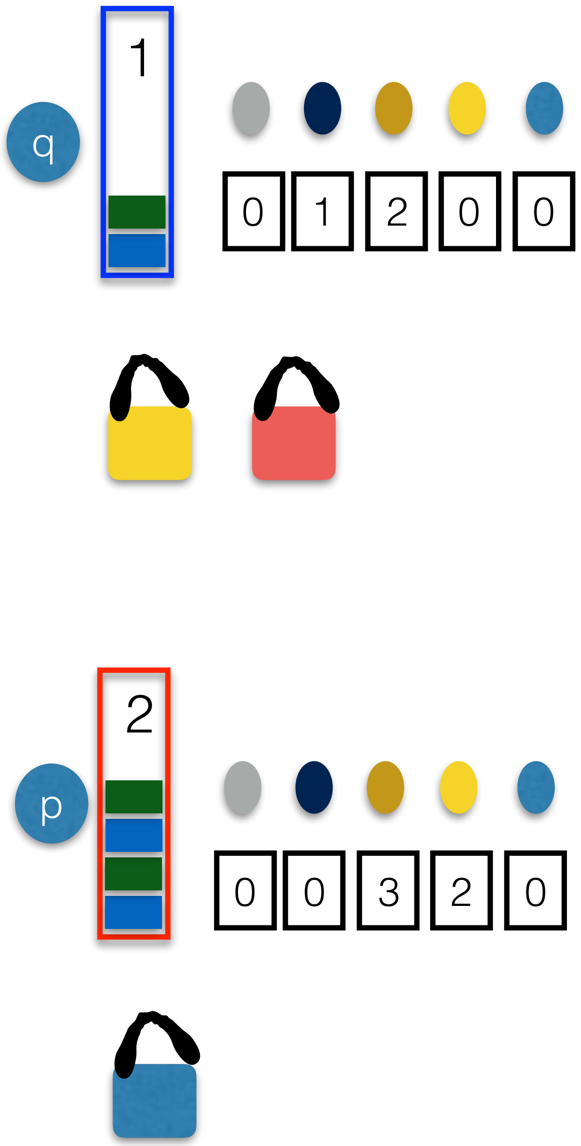
We consider in asynchronous programs synchronising only through locks

Asynchronous programs + Locks:



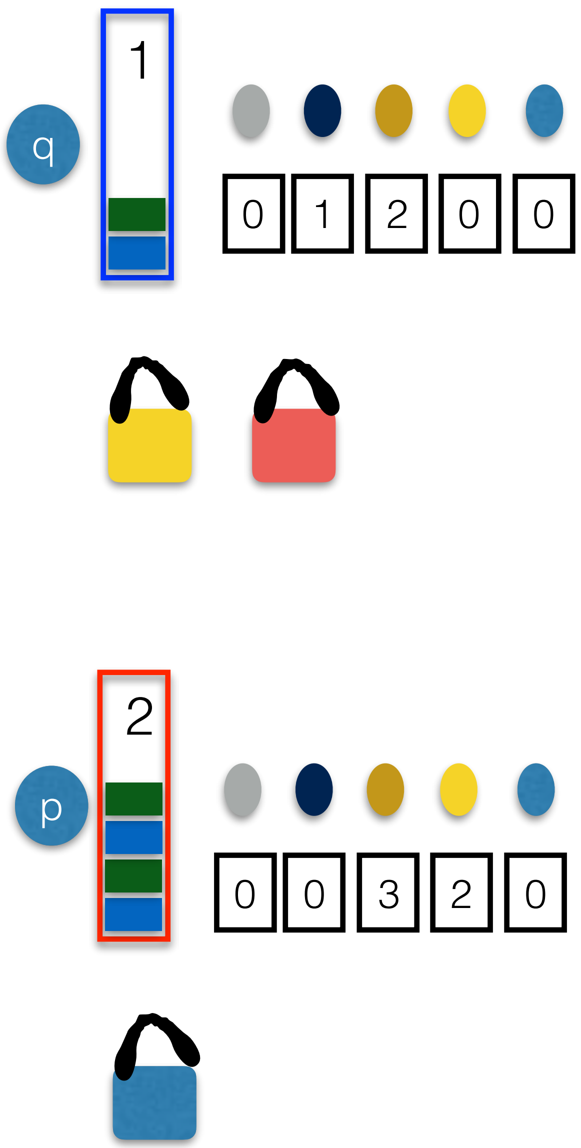
- Pushdown systems with
  - Multi-sets to hold tasks
- A finite set of global locks

Configuration:



- State
- Content of the stack
- Content of the multi-set
- Set of locks held

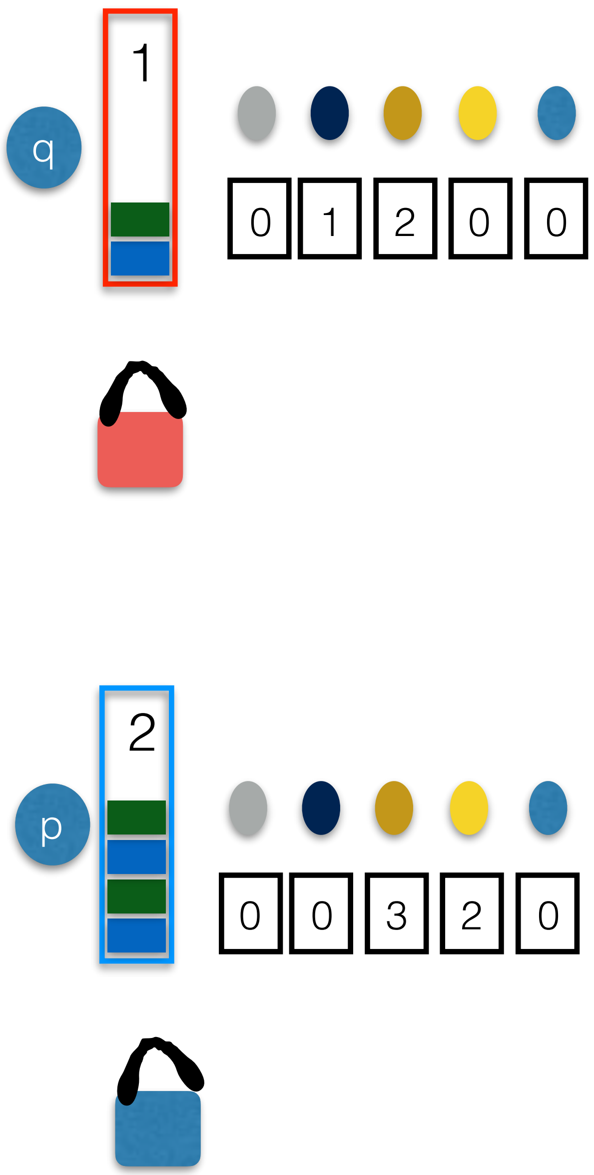
Configuration:



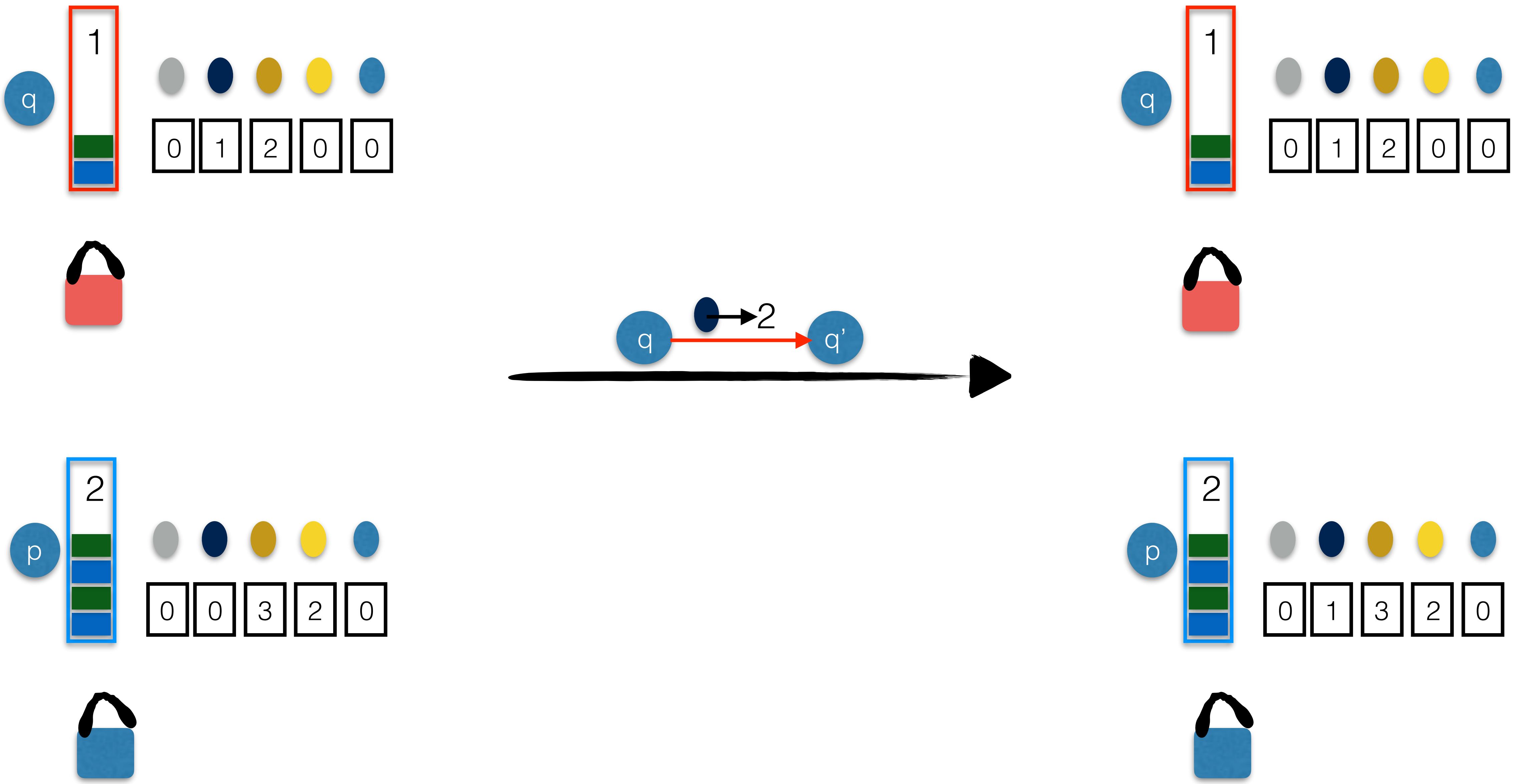
per thread

- State
- Content of the stack
- Content of the multi-set
- Set of locks held

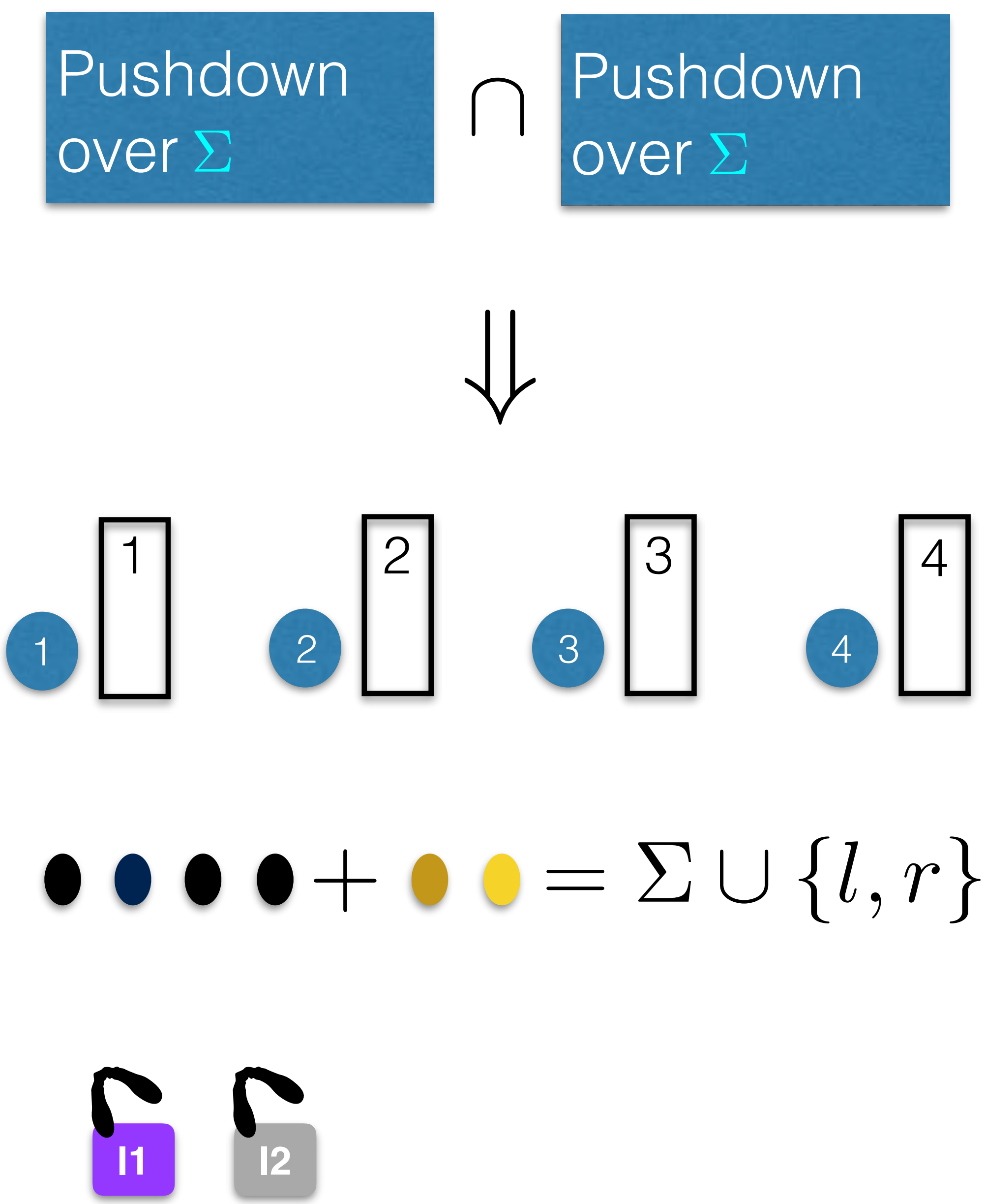
Move:



Move:

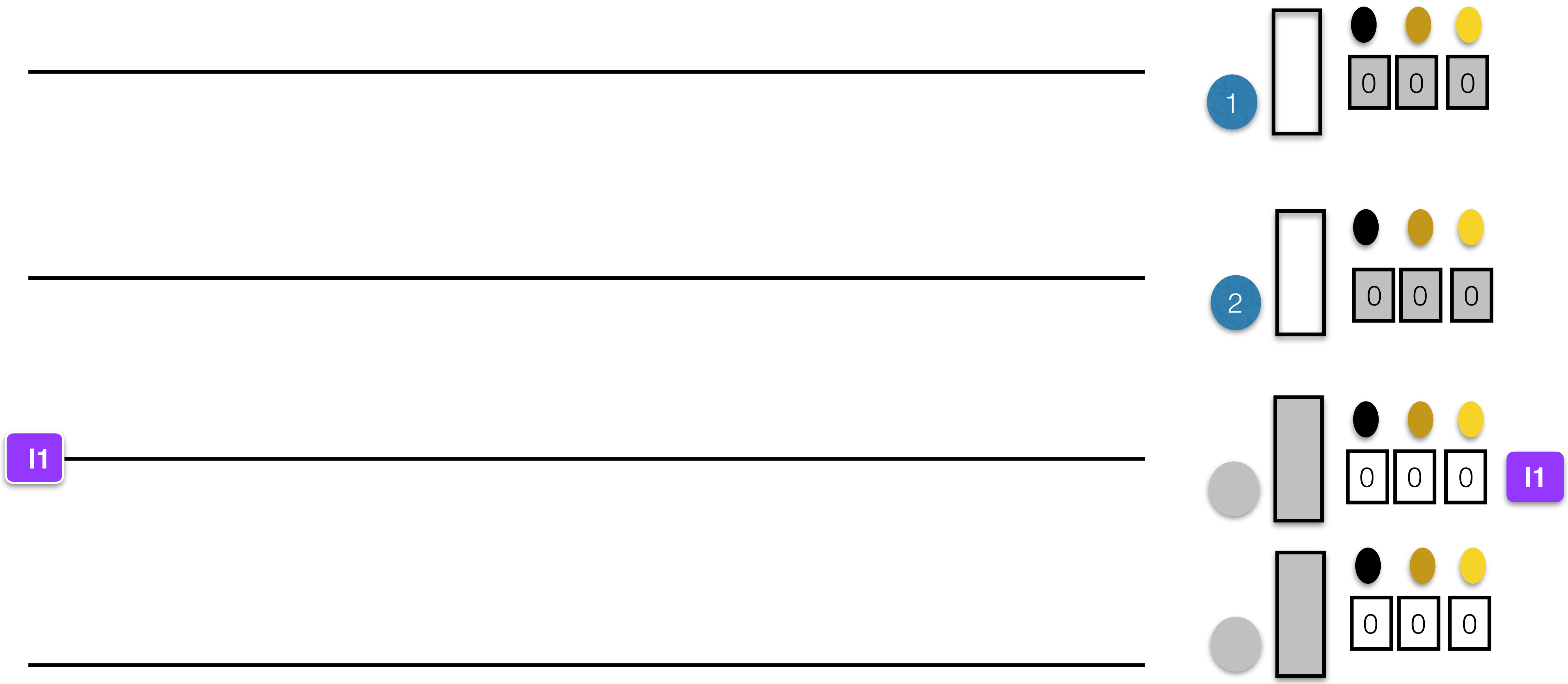


Undecidability under nested locking



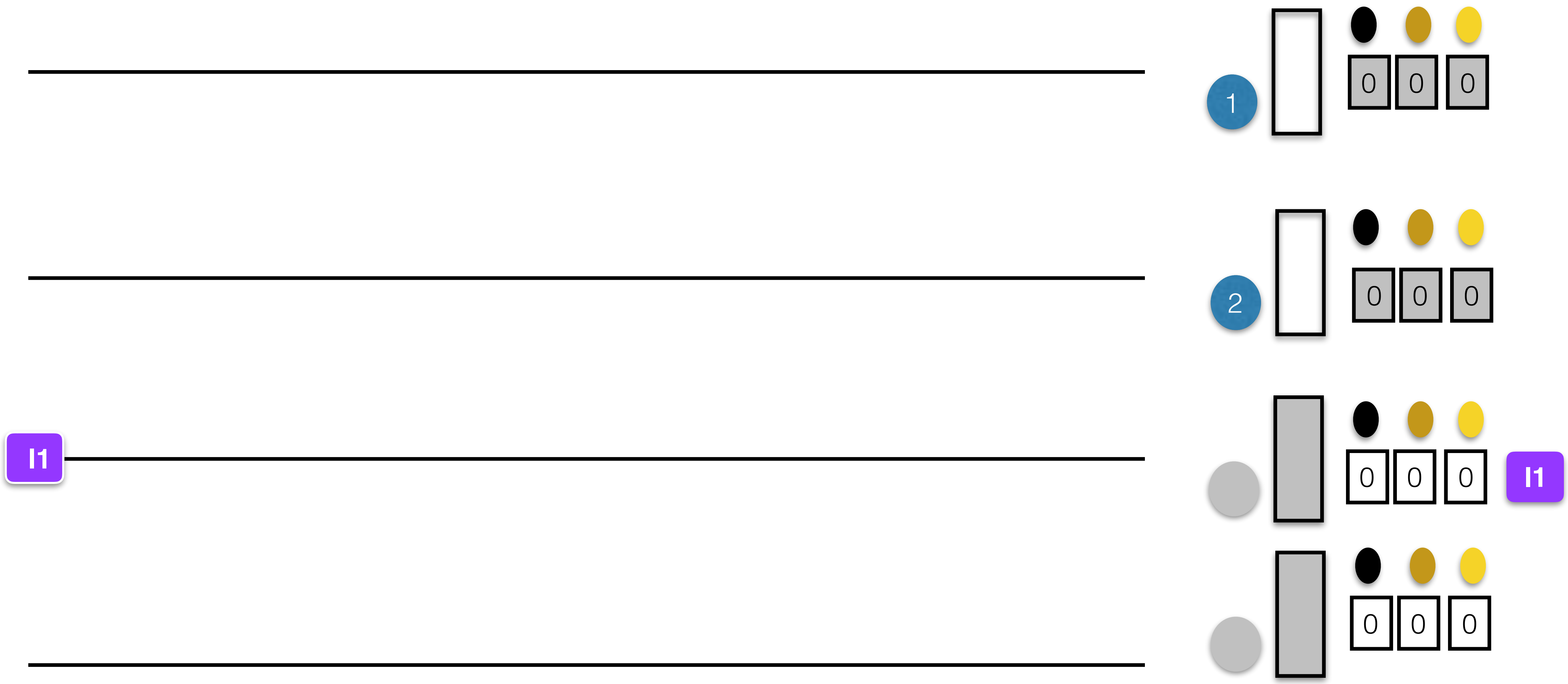
- Reduce intersection of two pushdown systems
- 4 threads along with two locks and set of tasks
- The set of tasks is the alphabet of pushdown systems along with two additional tasks

Simulation of a move:



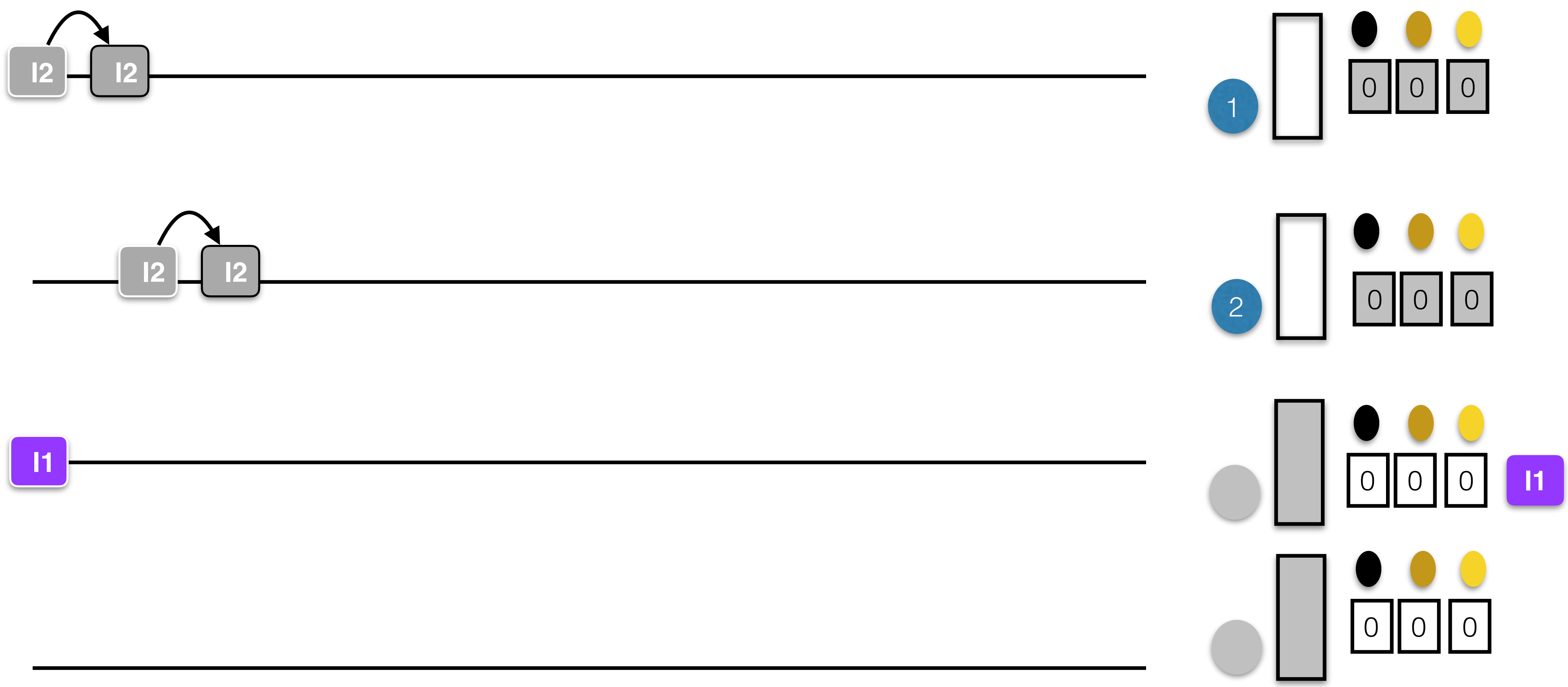
We will show how to simulate a single move of each of the pushdown systems

Simulation of a move:



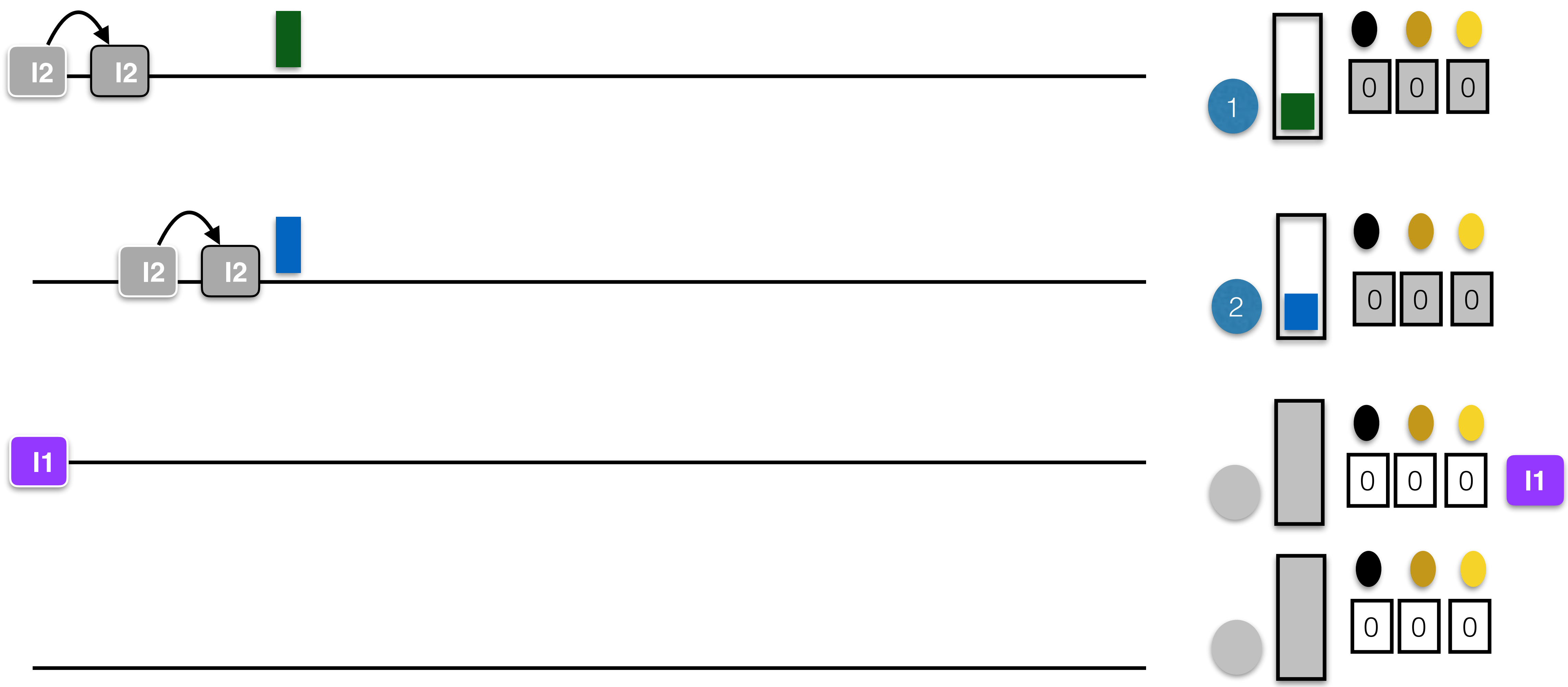
The Simulation starts with process 3 holding I1

Simulation of a move:



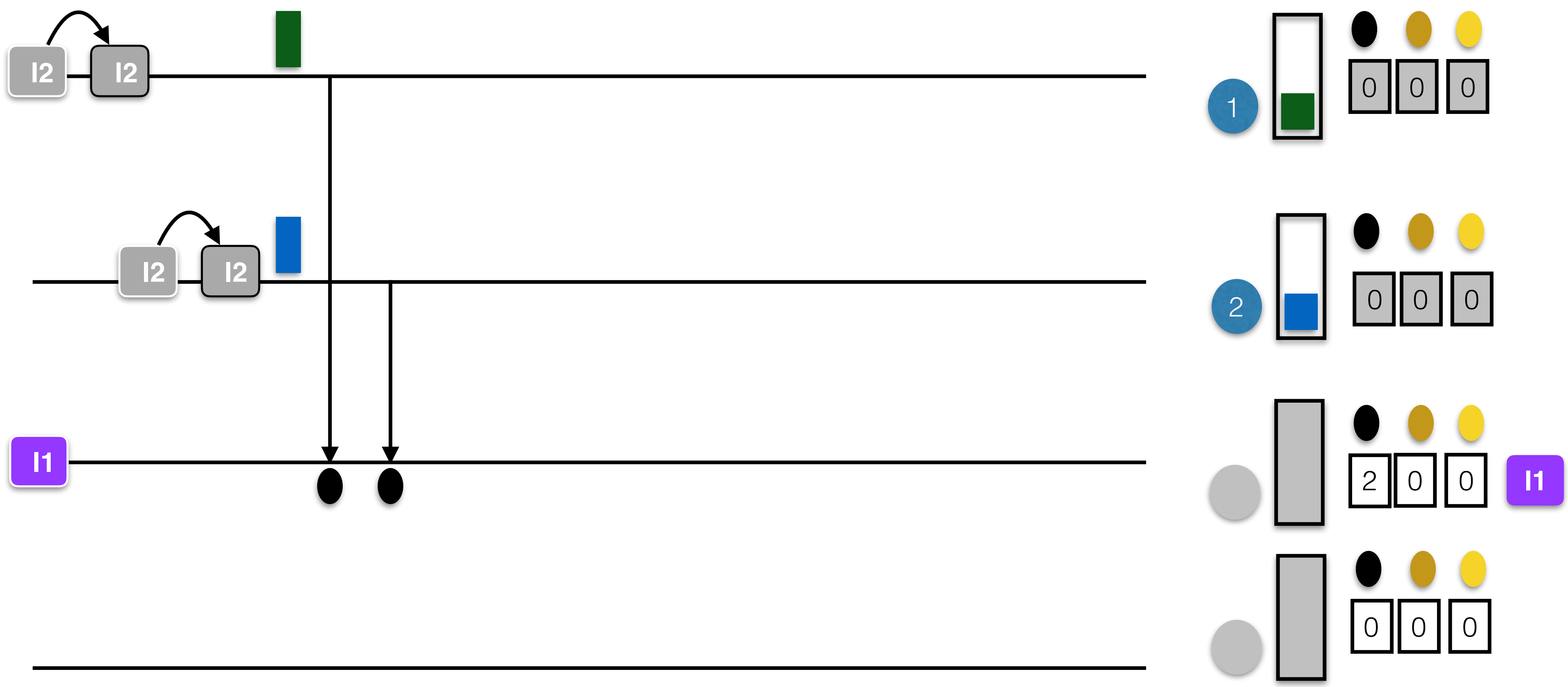
Process 1 and 2 test lock l2

Simulation of a move:



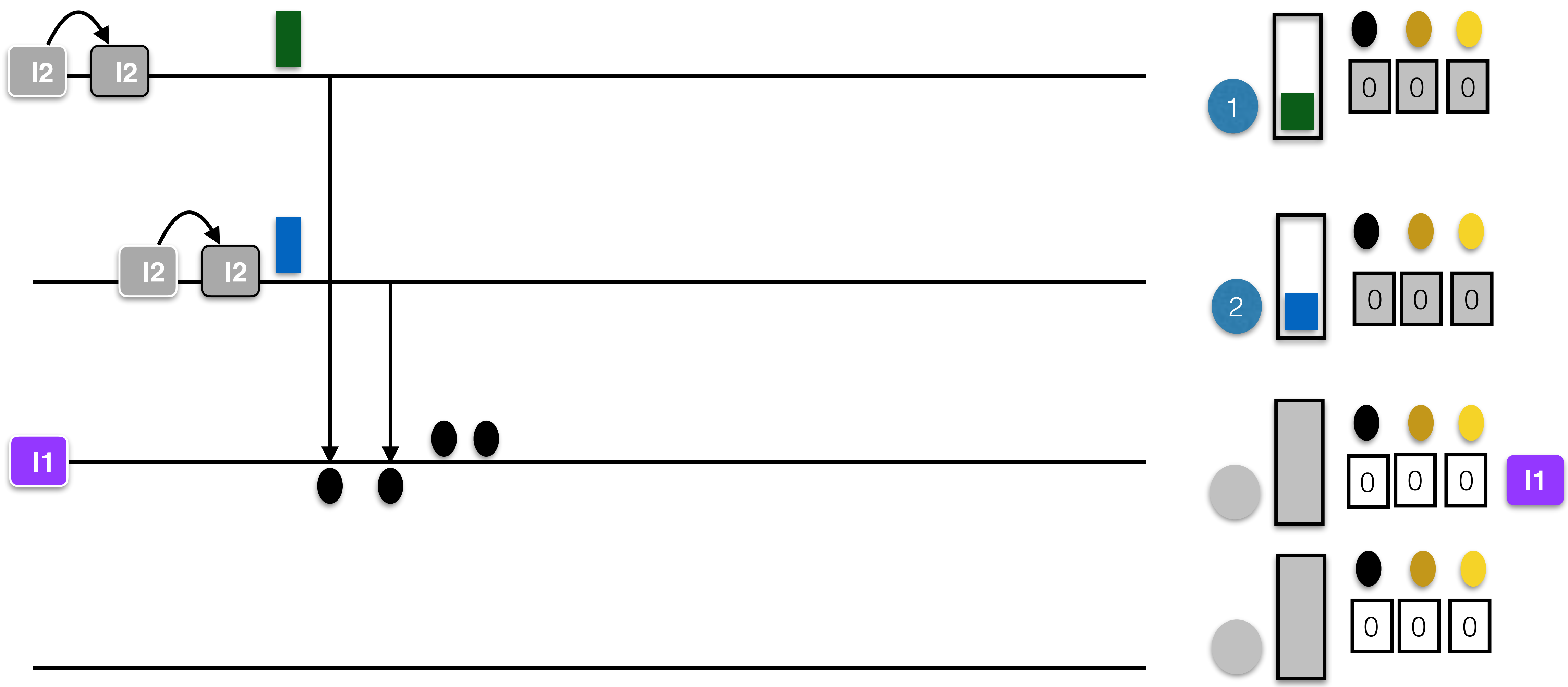
Process 1 and 2 guess an letter and simulate the move

Simulation of a move:



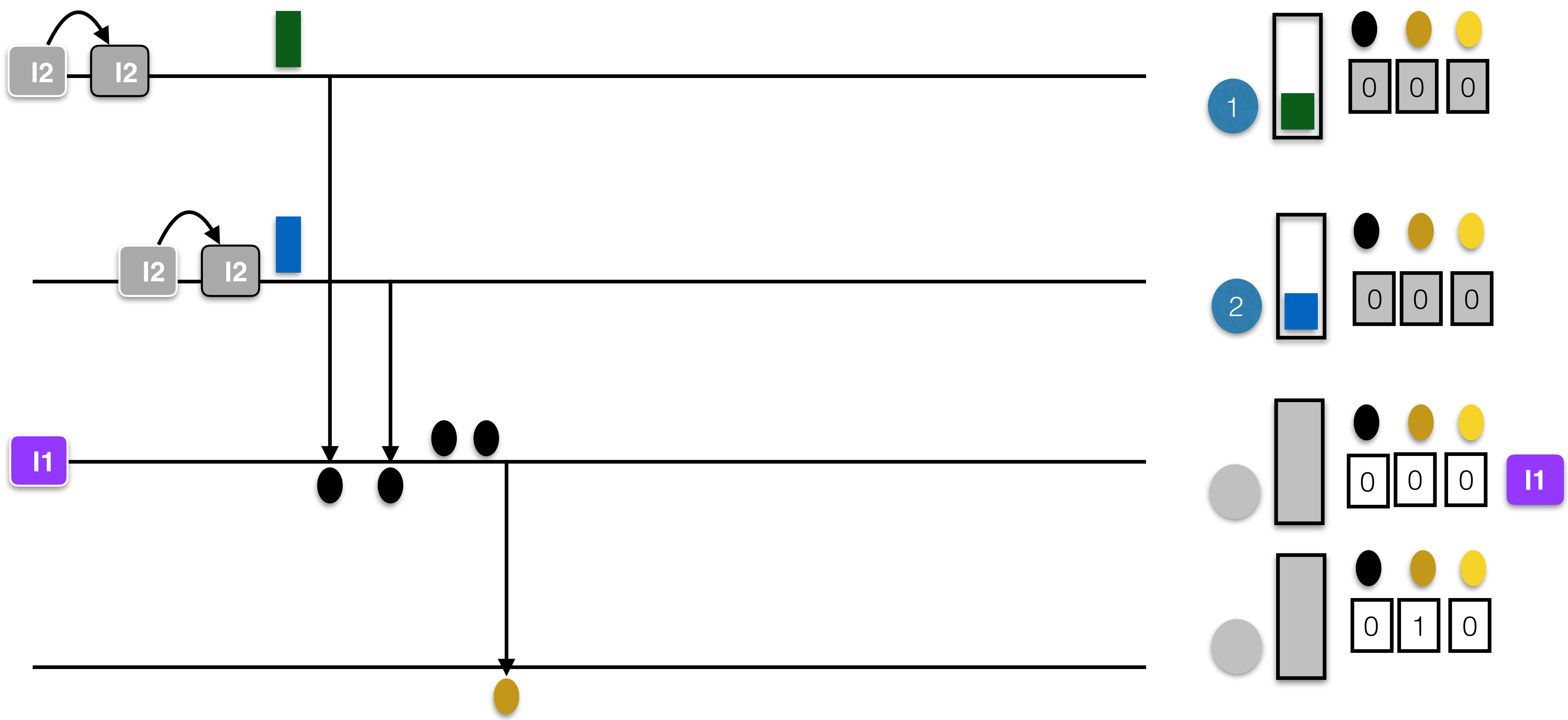
Process 1 and 2 sends the guessed letter to 3

Simulation of a move:



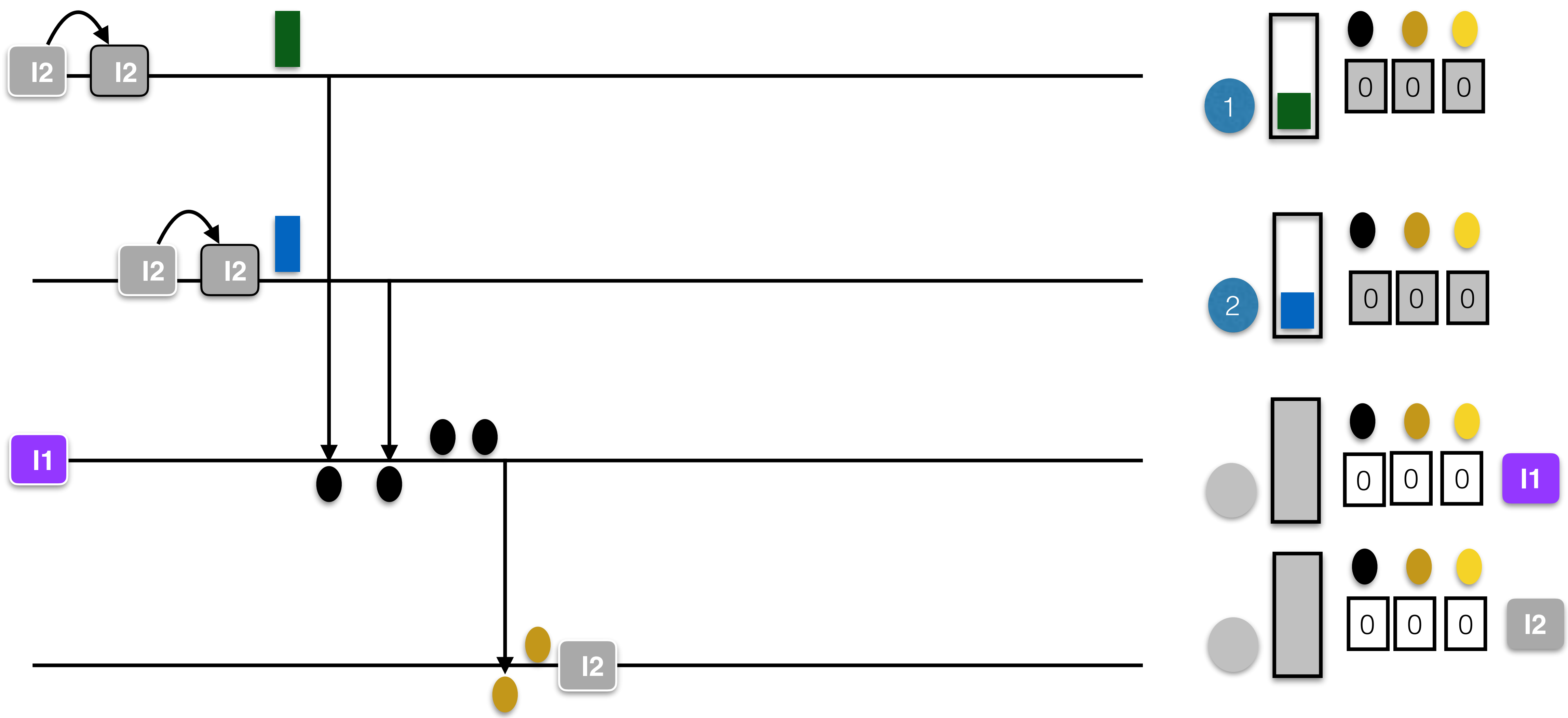
Process 3 reads and verifies that the letters match

Simulation of a move:



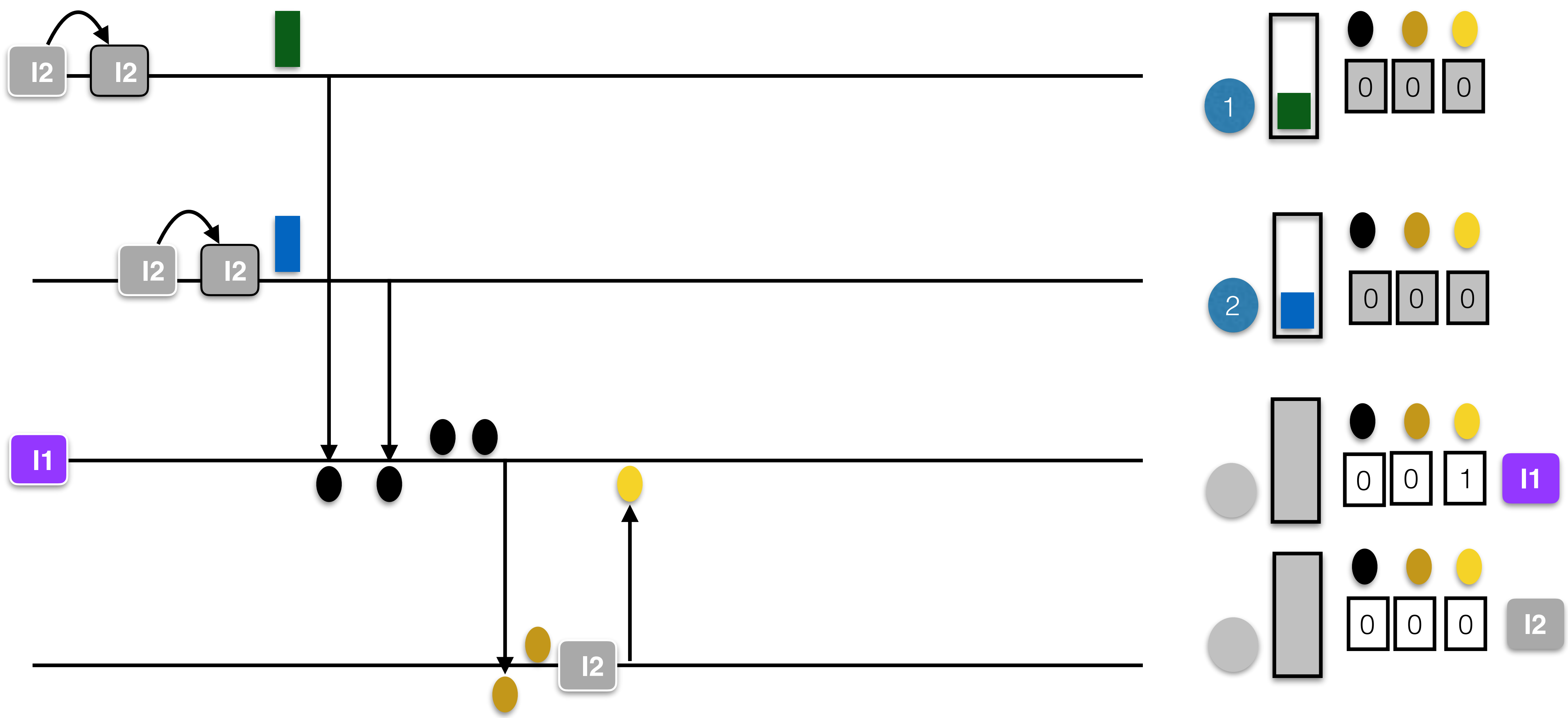
Process 3 requests 4 to hold lock l2

Simulation of a move:



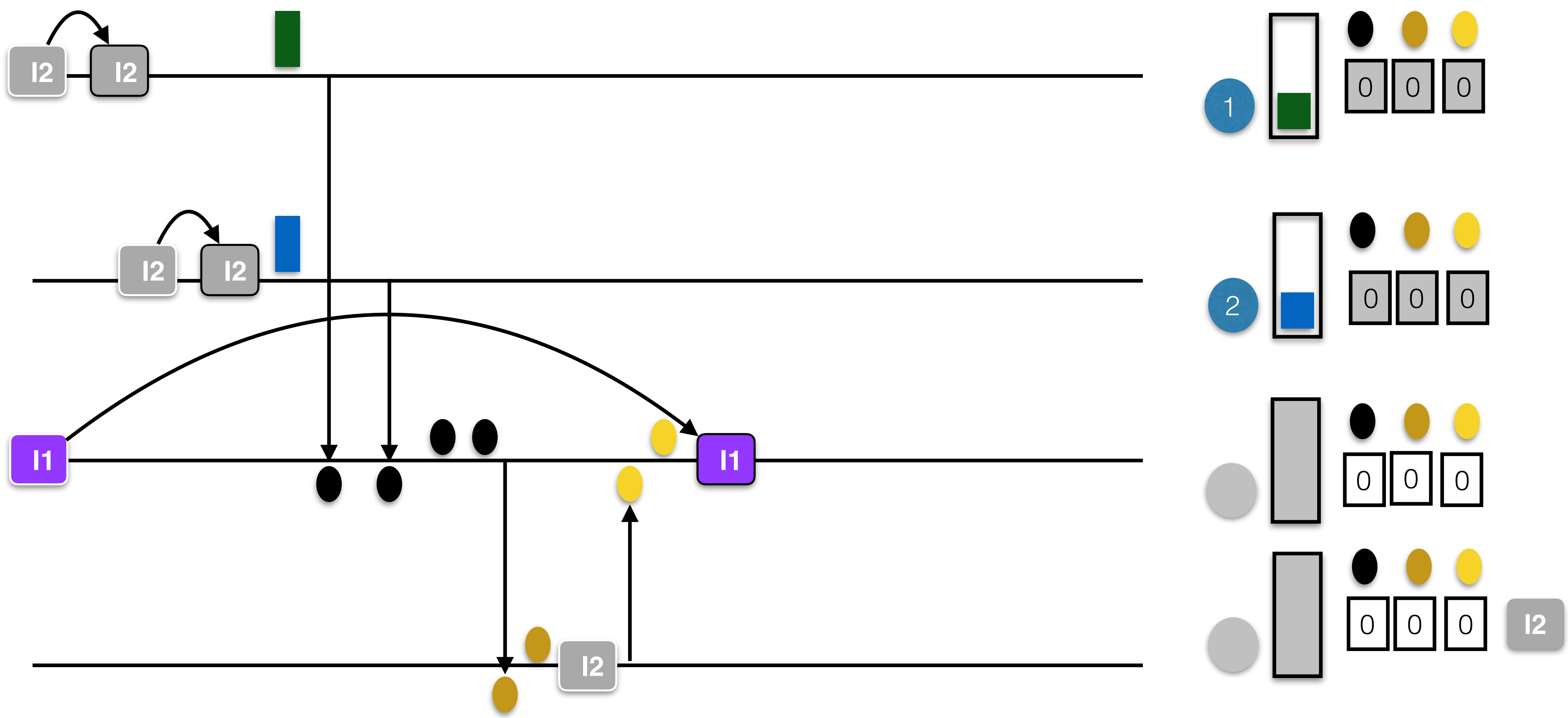
Process 4 reads the request and holds lock l2

Simulation of a move:



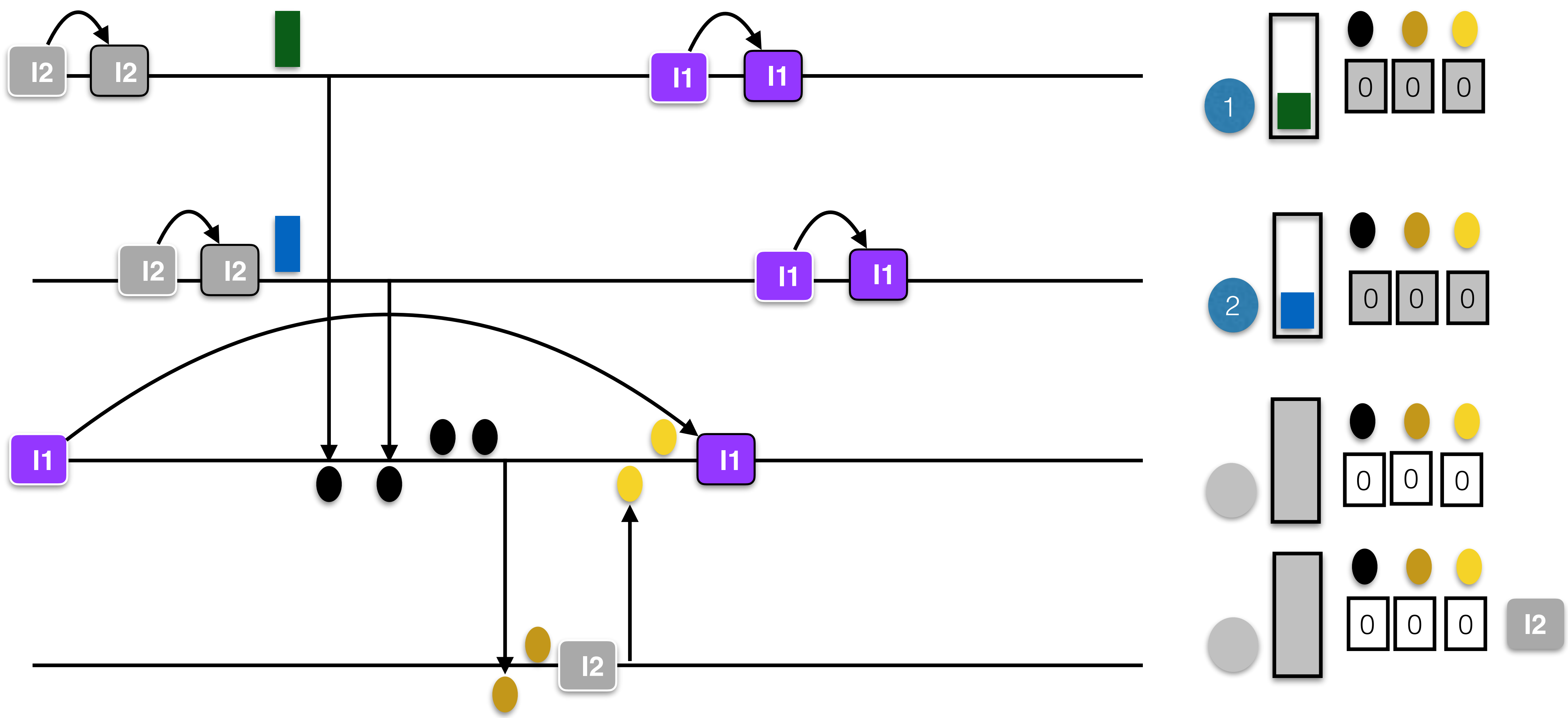
Process 4 reads the request and holds lock l2

Simulation of a move:



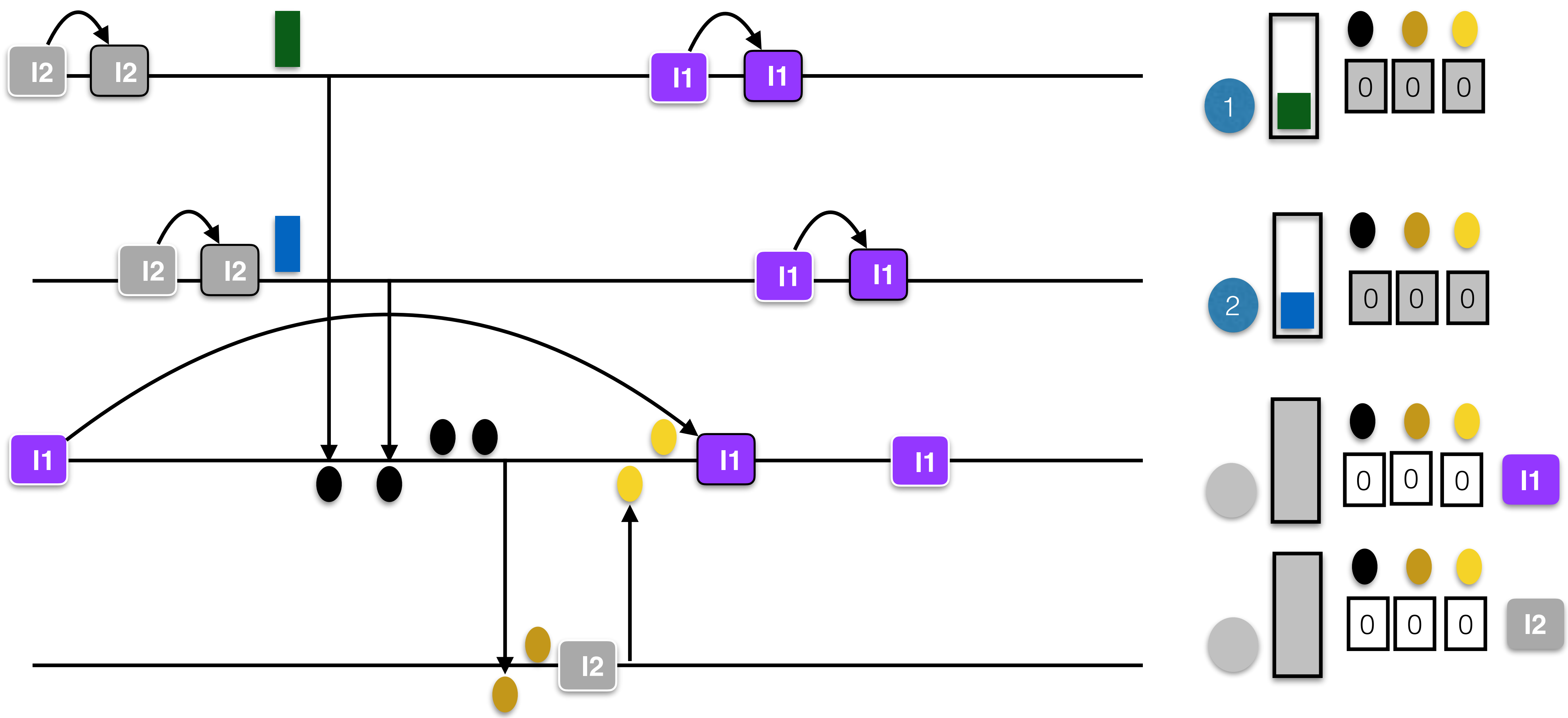
Process process 3 releases I1 on learning I2 is taken

Simulation of a move:



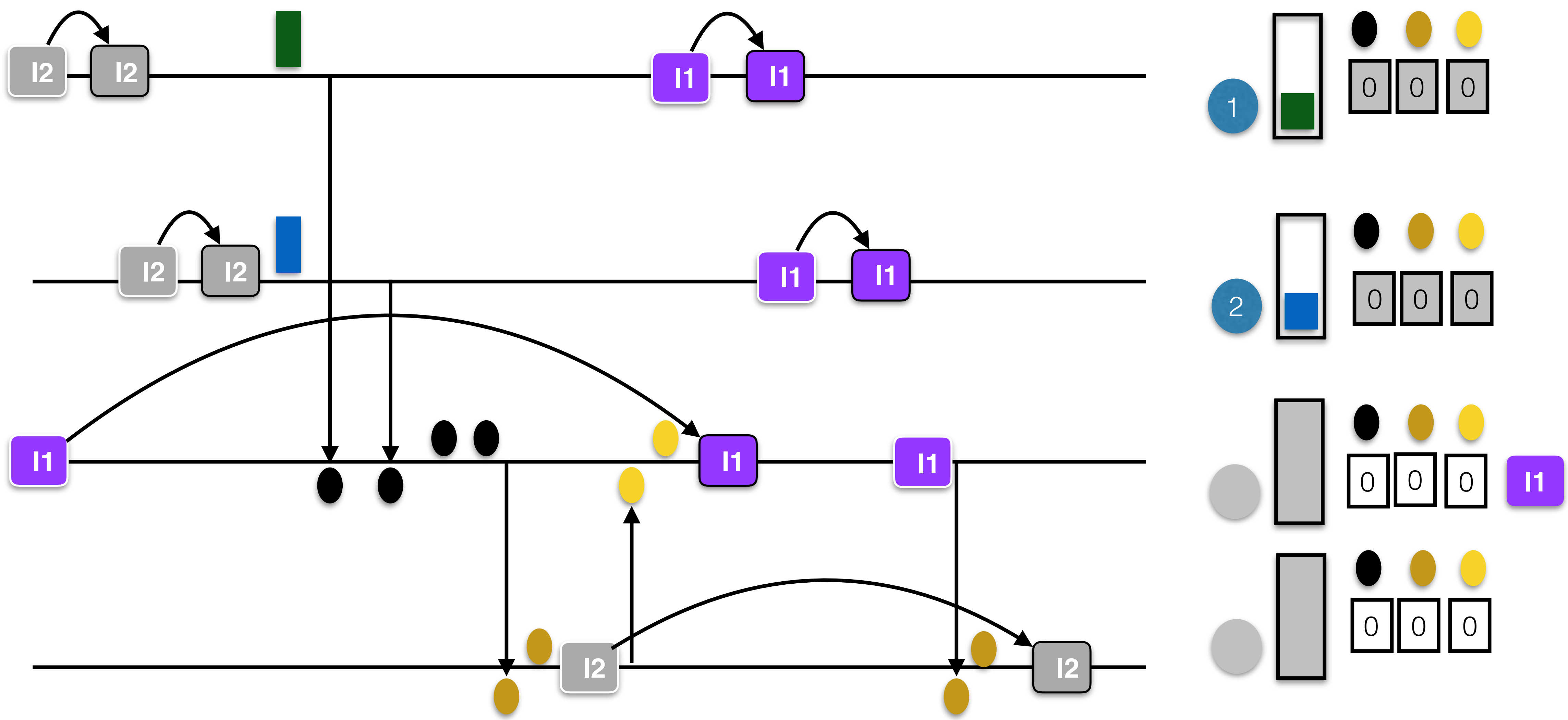
Process 1 and 2 tests lock I1

Simulation of a move:



Process 3 retakes lock l1 and asks 4 to release l2

Simulation of a move:

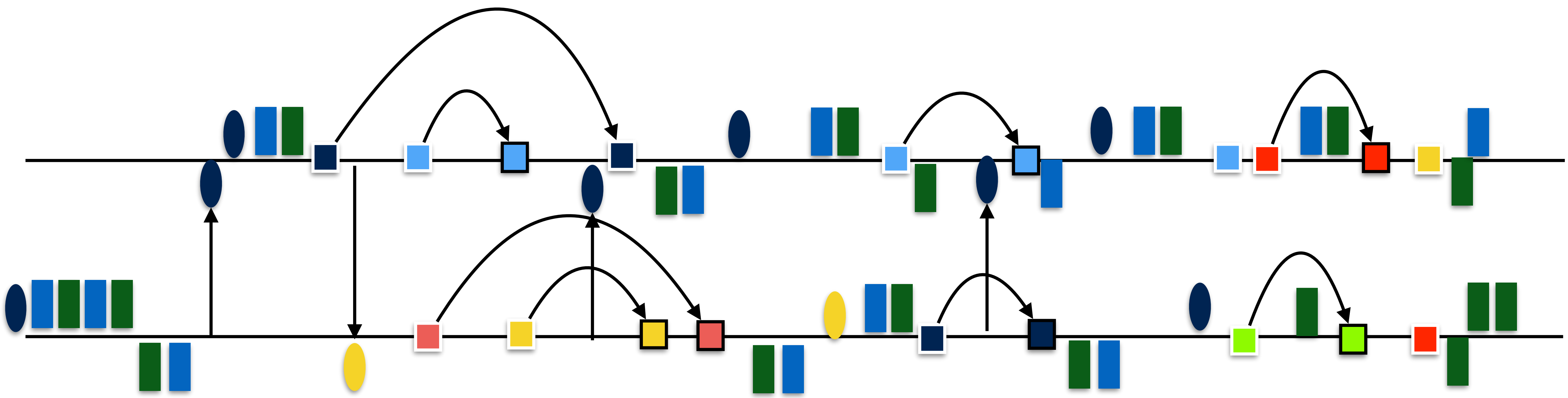


Process 3 retakes lock l1 and asks 4 to release l2

Task locking restriction:

Locks can be held only by task. That is, locks are held only when the stack is not empty

Phases of a thread:



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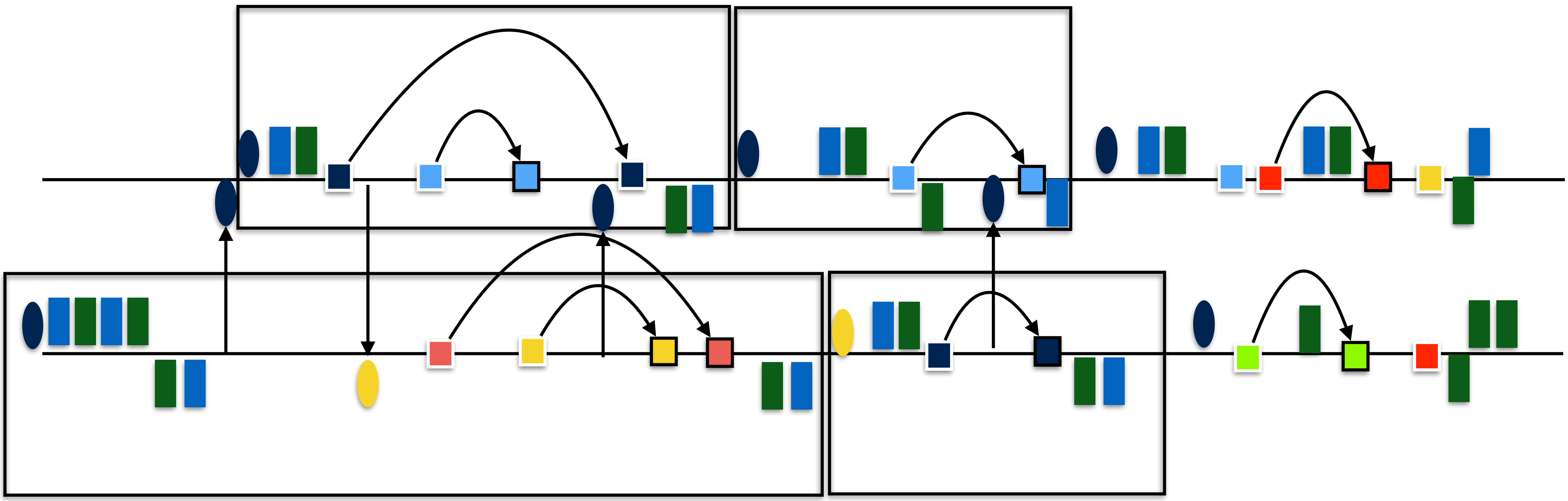

- Task Phases: Complete execution of one task

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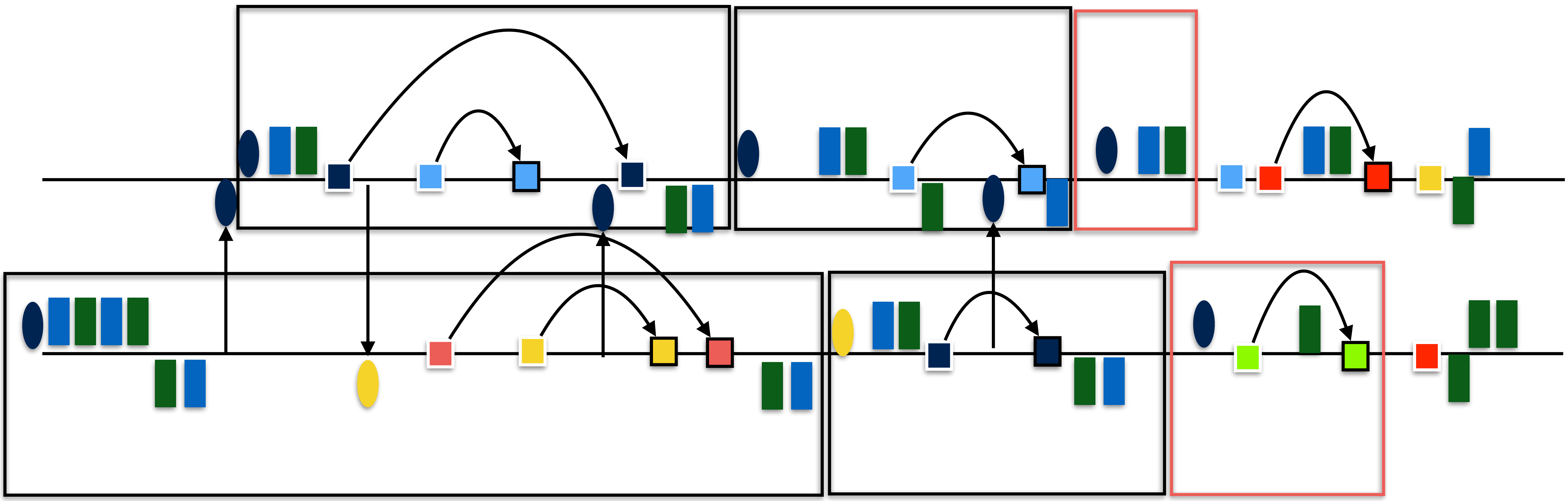

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- Boundary Phase: Initial part of a nonterminating task where all locks are returned

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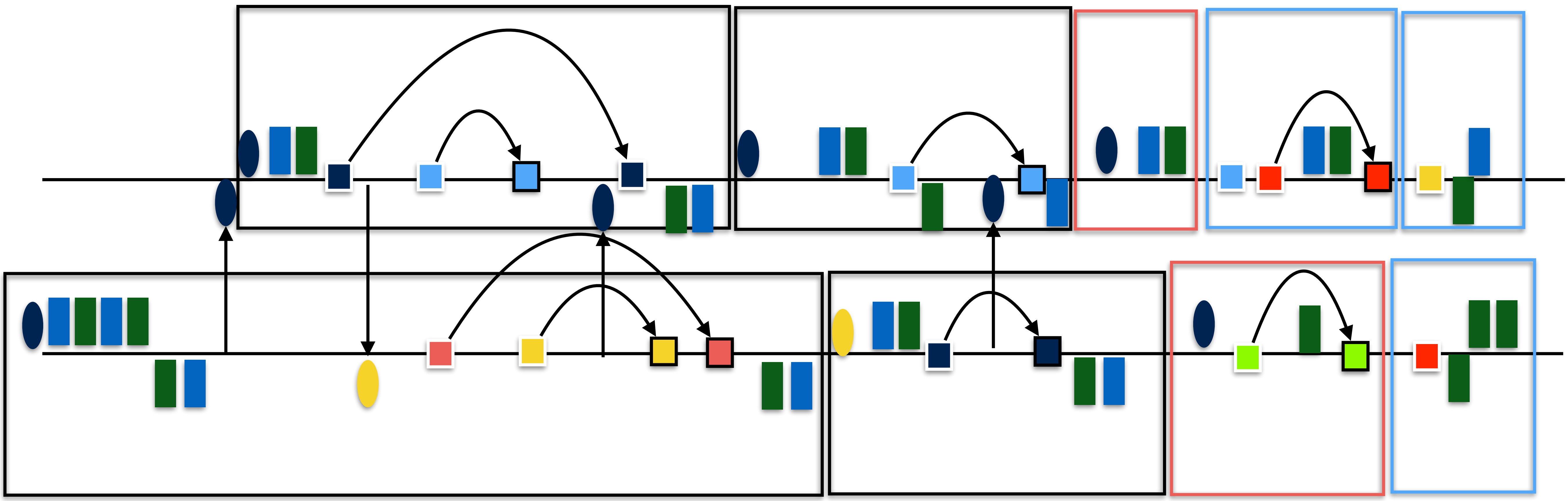
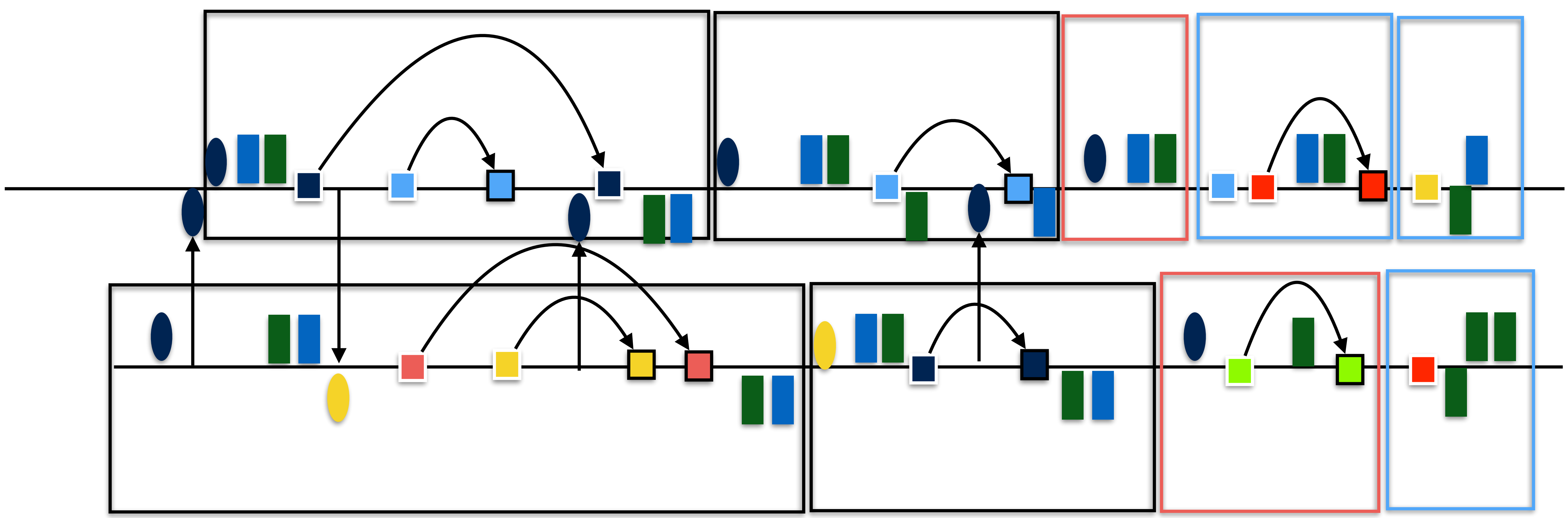


- Task Phases: Complete execution of one task
- Boundary Phase: Initial part of a nonterminating task where all locks are returned
- Lock phases: Part of a nonterminating task that begins with a lock that is never returned, until the next such action.

Sequentialisation Lemma:

Every reachable configuration can be reached via a run that is a sequence of phases (of the different threads). That is, phases can be executed atomically.



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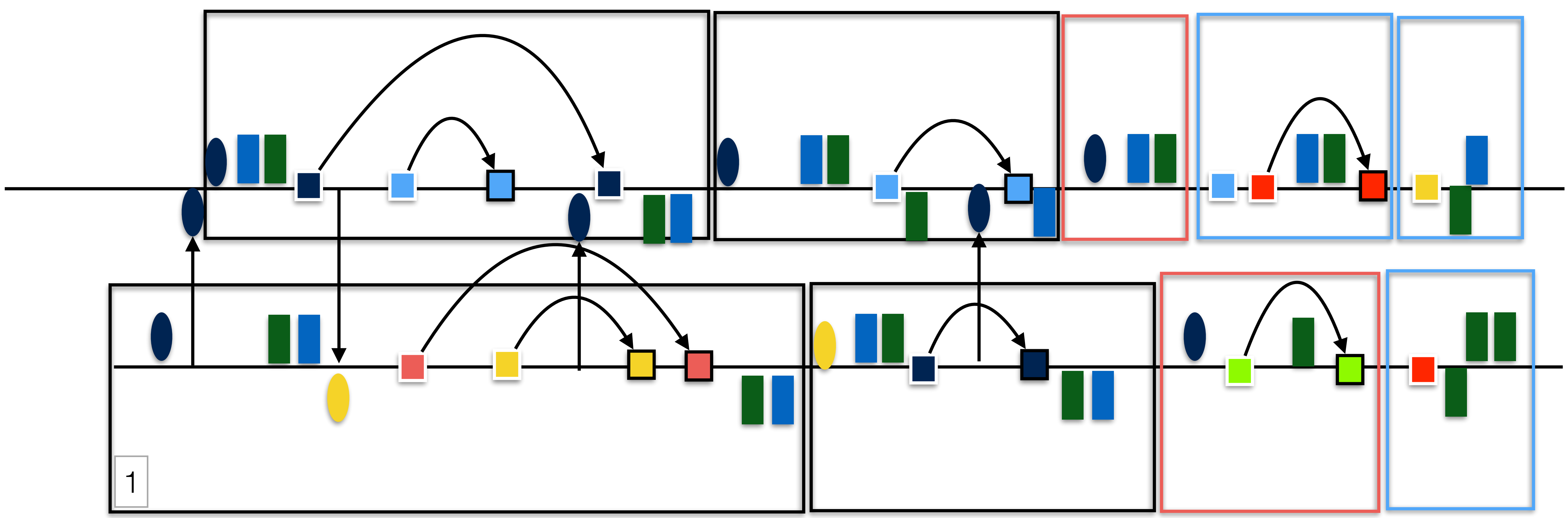

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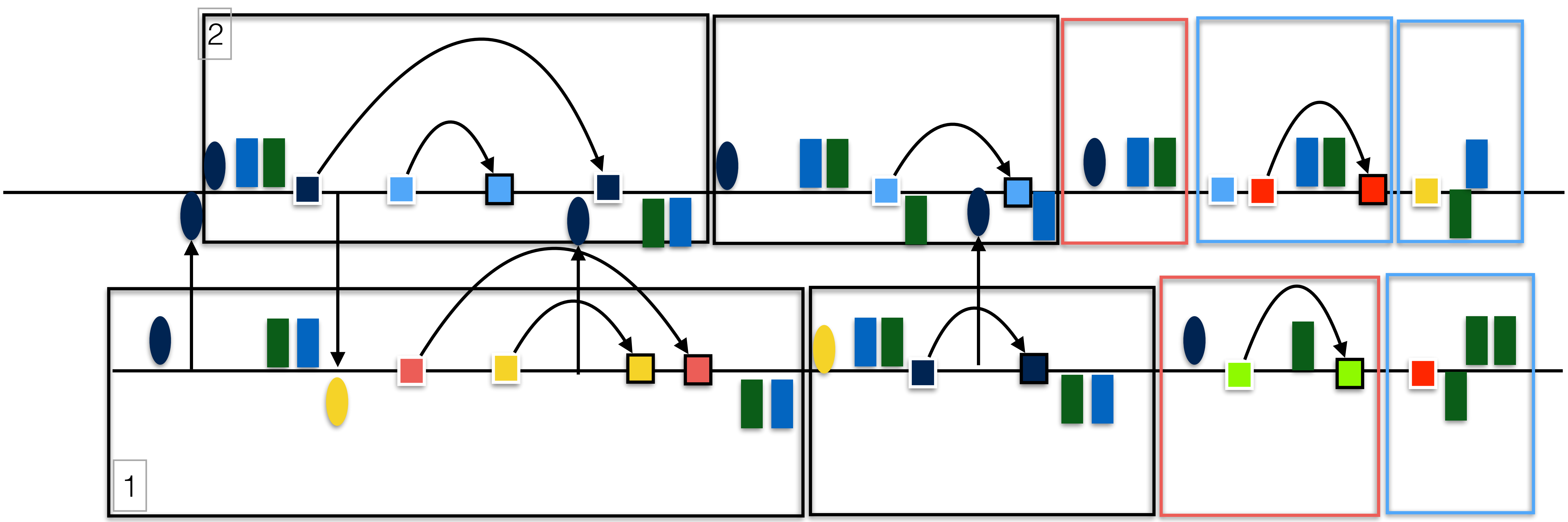

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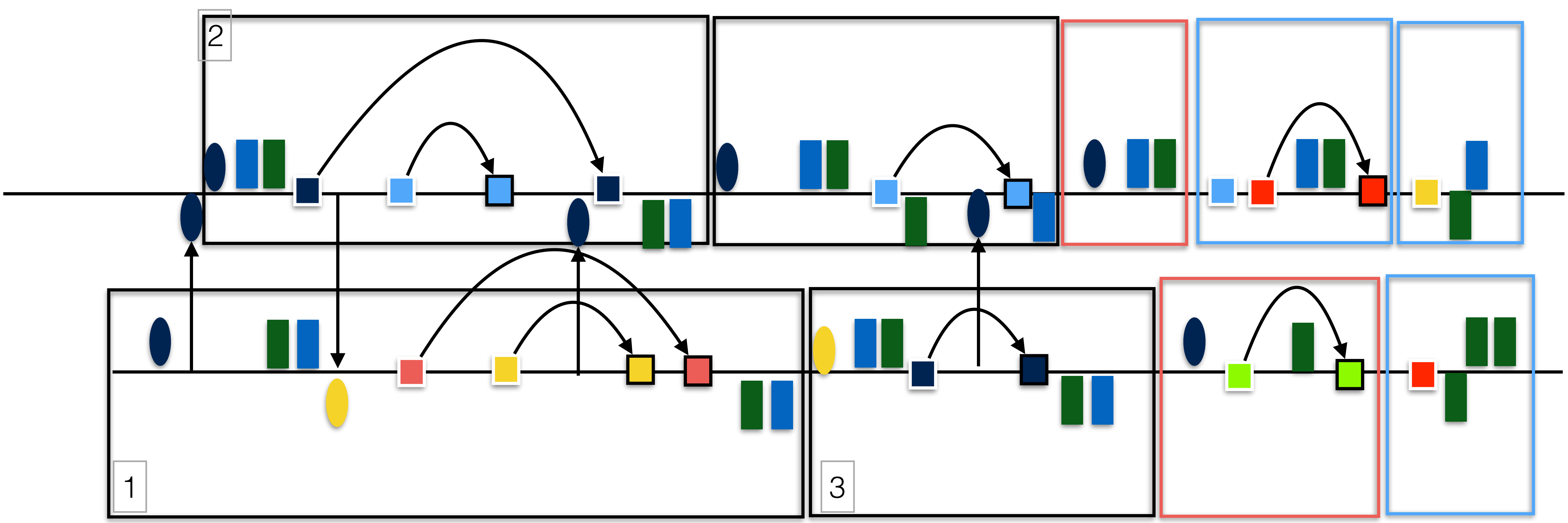

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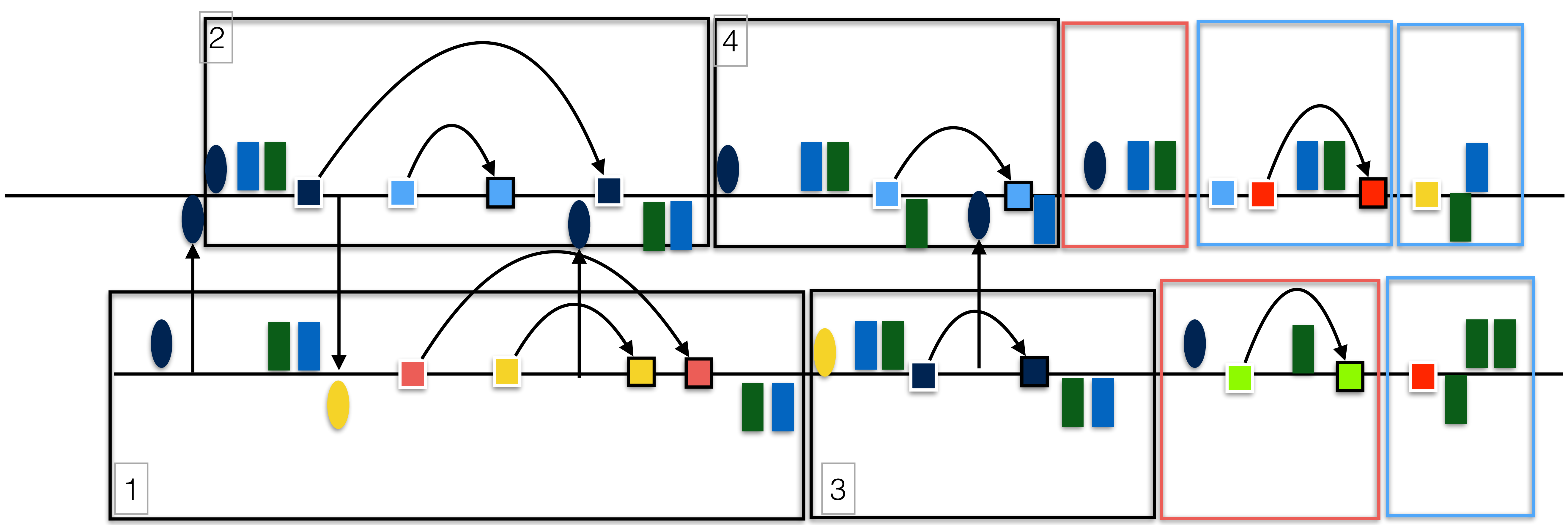

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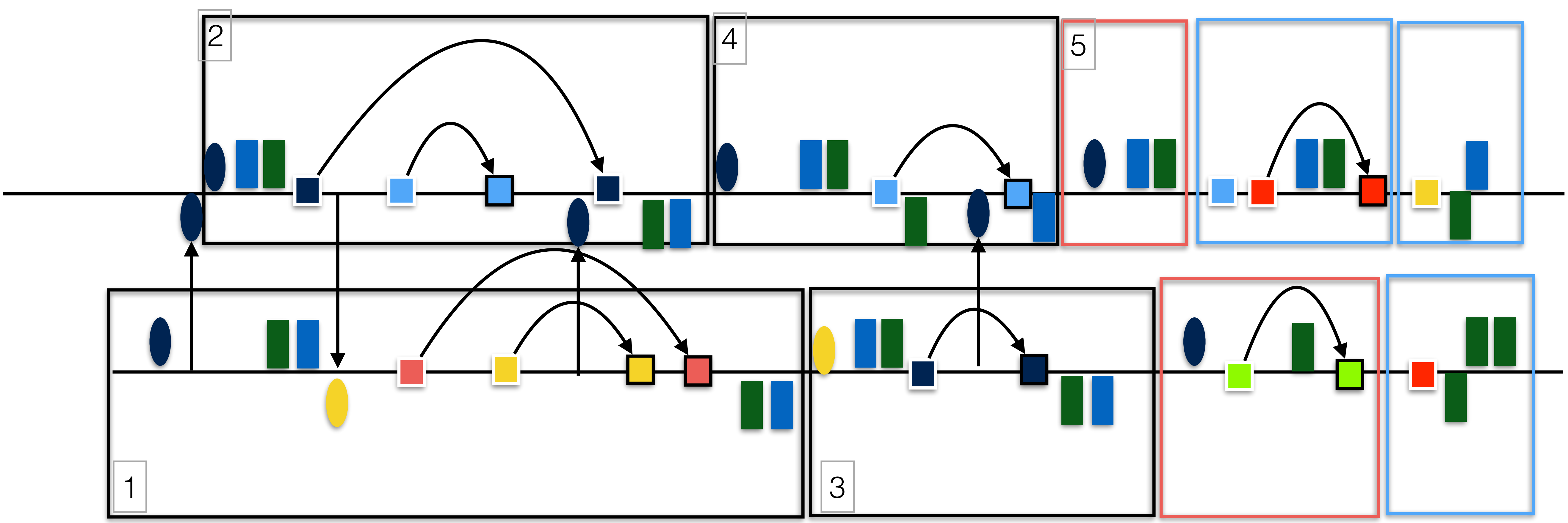

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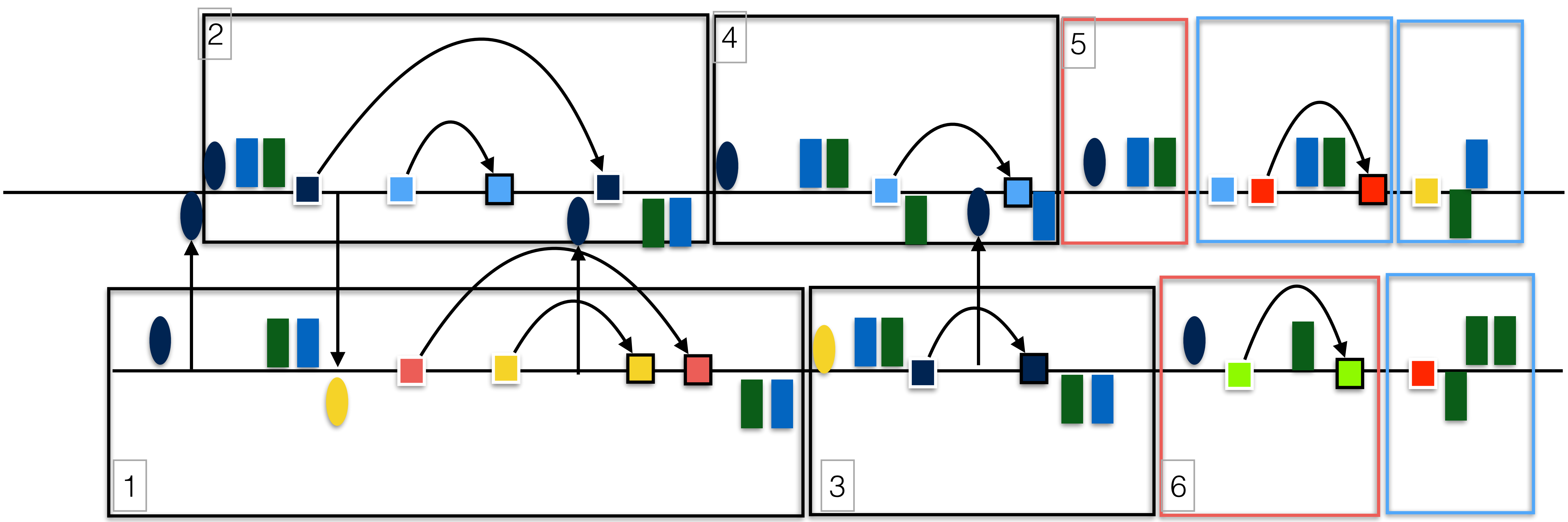

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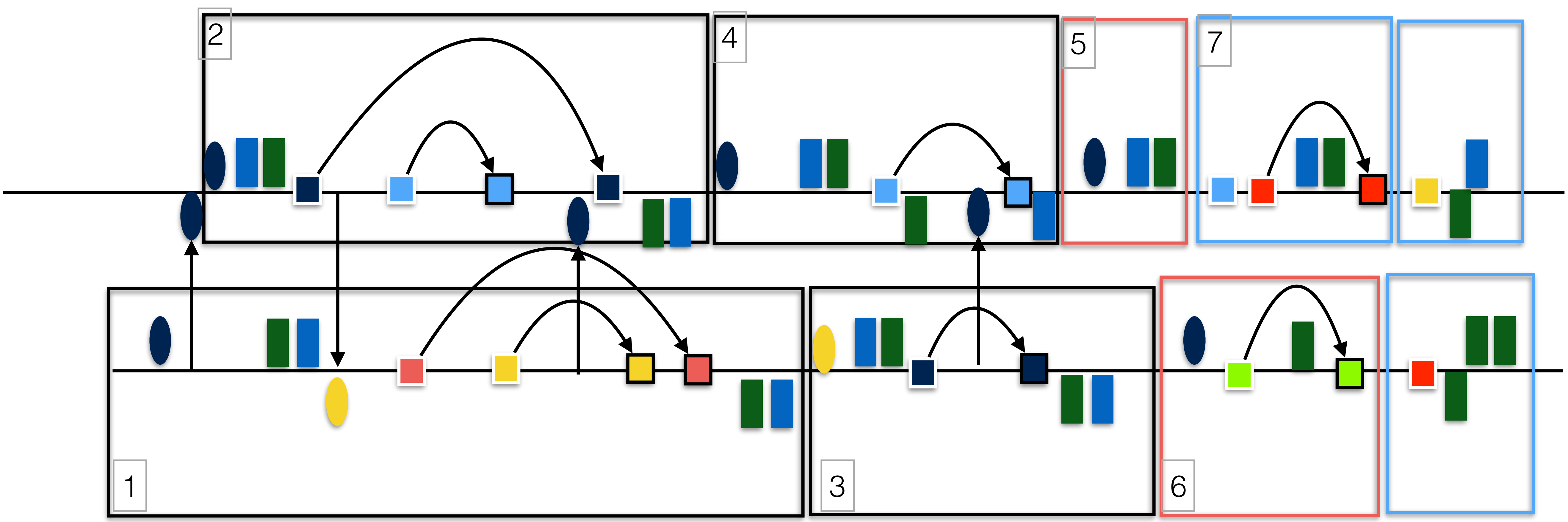

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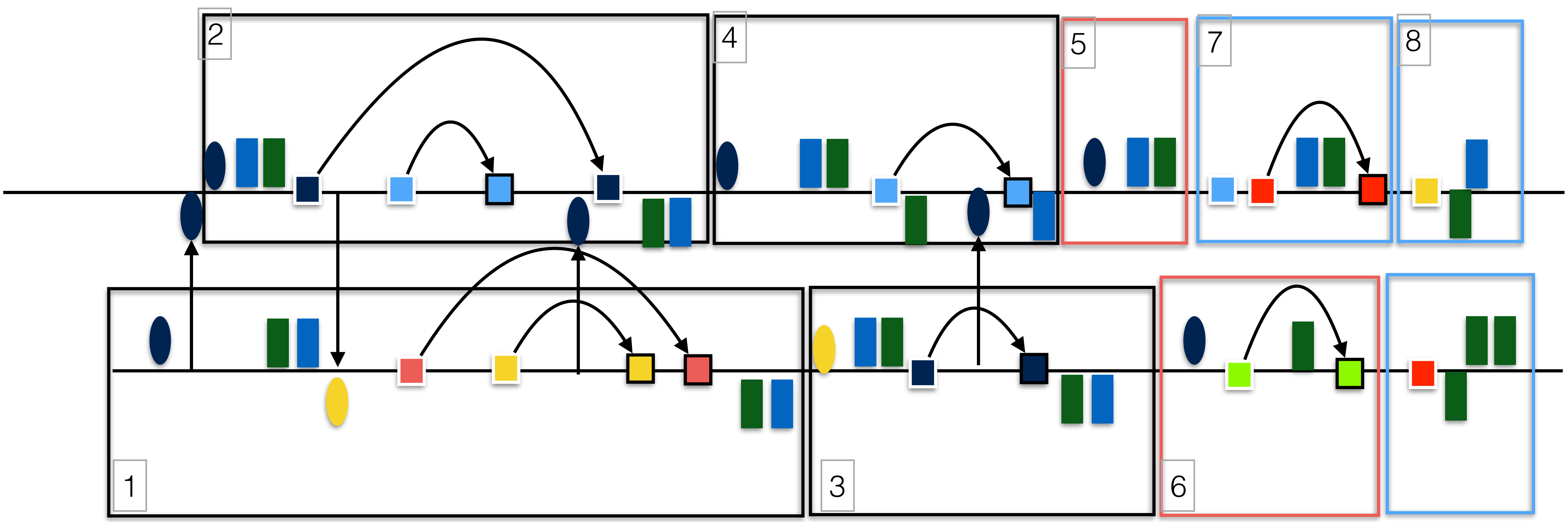

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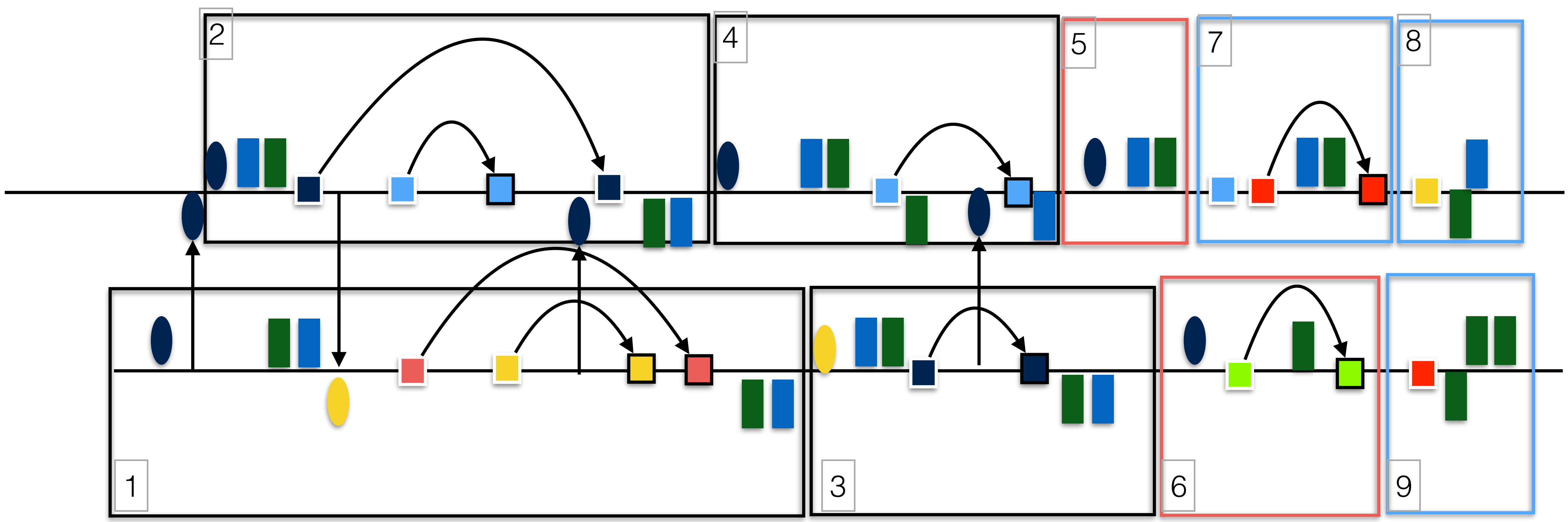

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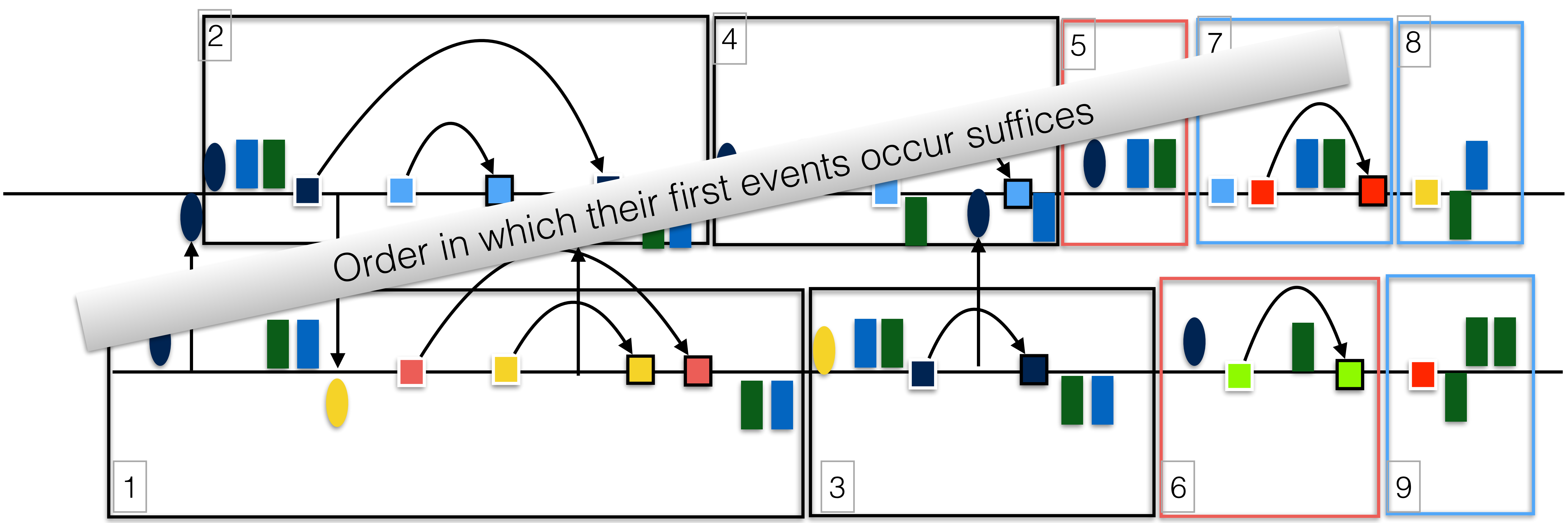
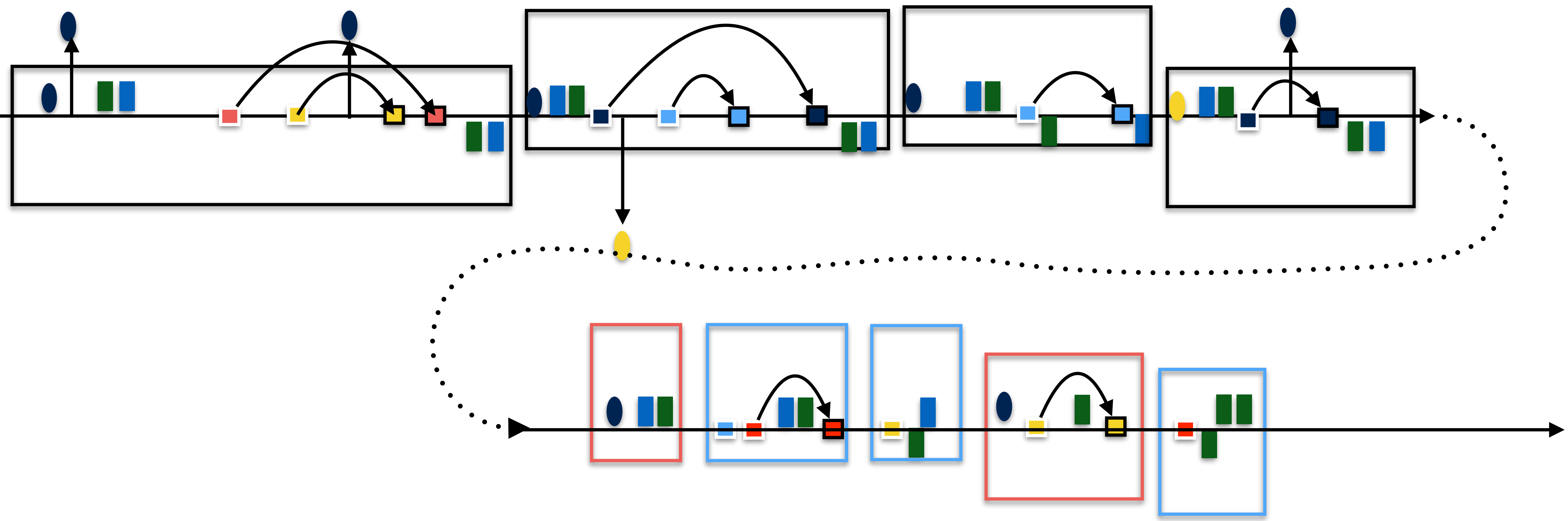


N-threads to 1-thread:

(Guess and) Simulate the phases of all the threads using a single thread.



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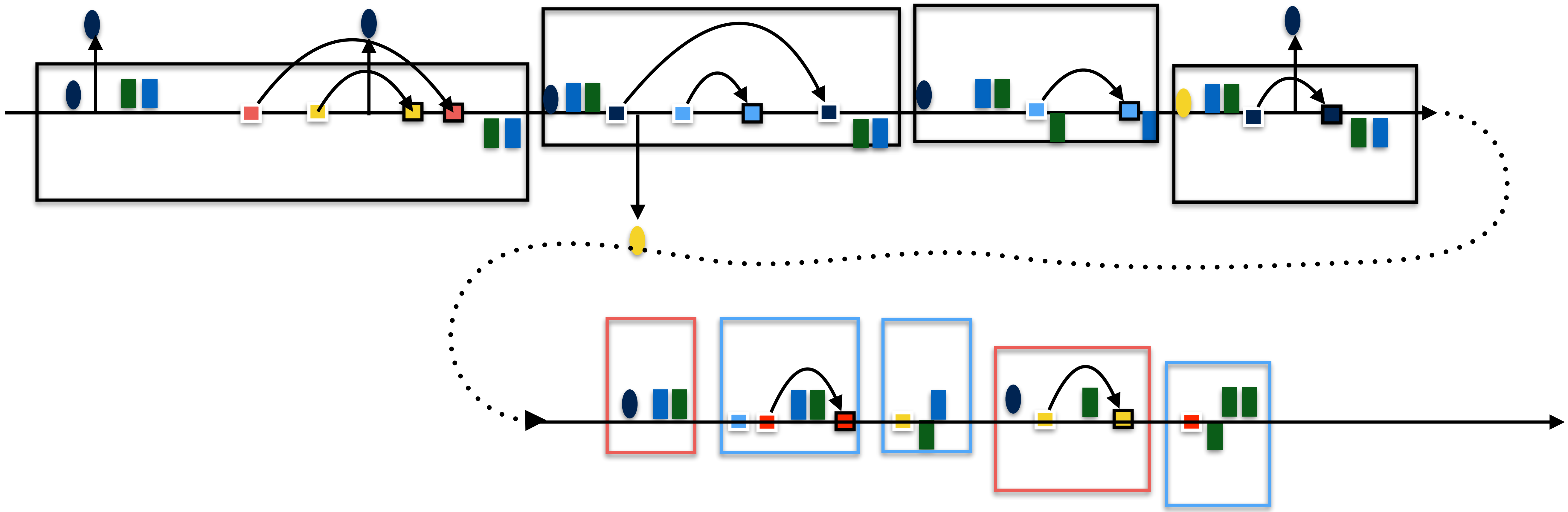
- Locks should be handled correctly (taken only when available …)
- Handle multiple pushdown stores

N-threads to 1-thread: locks



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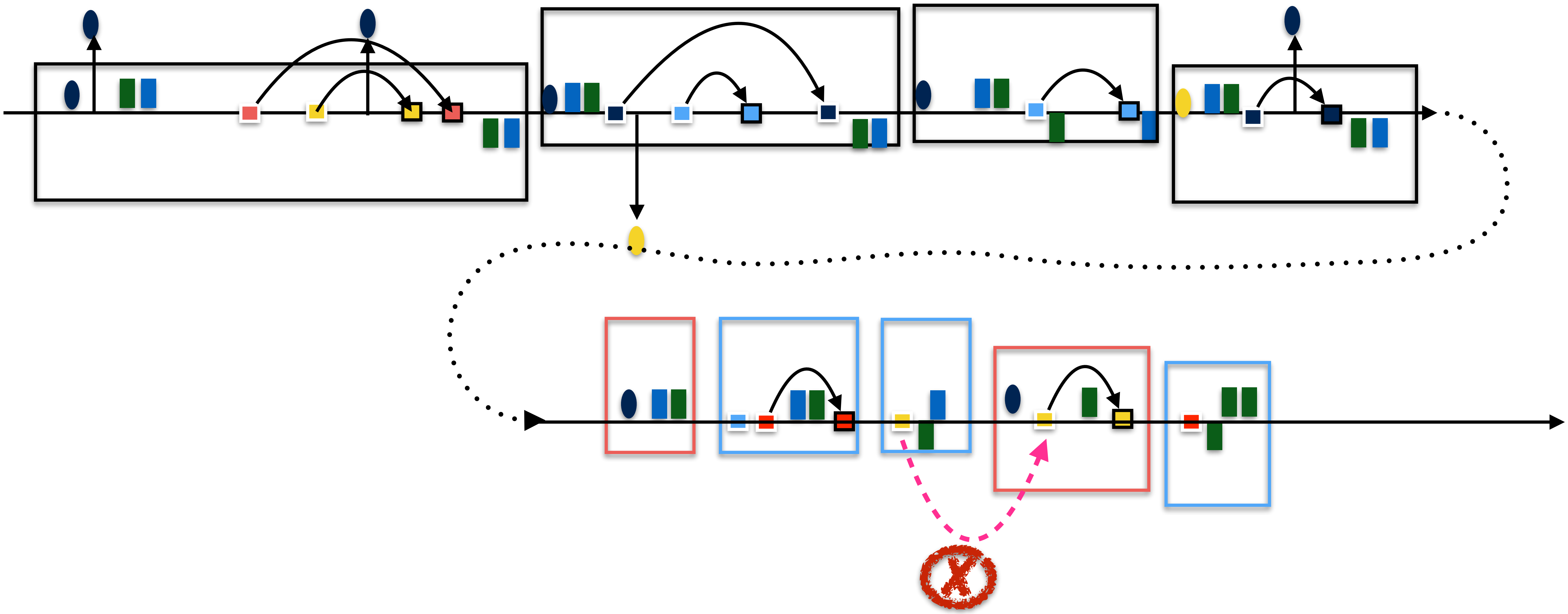
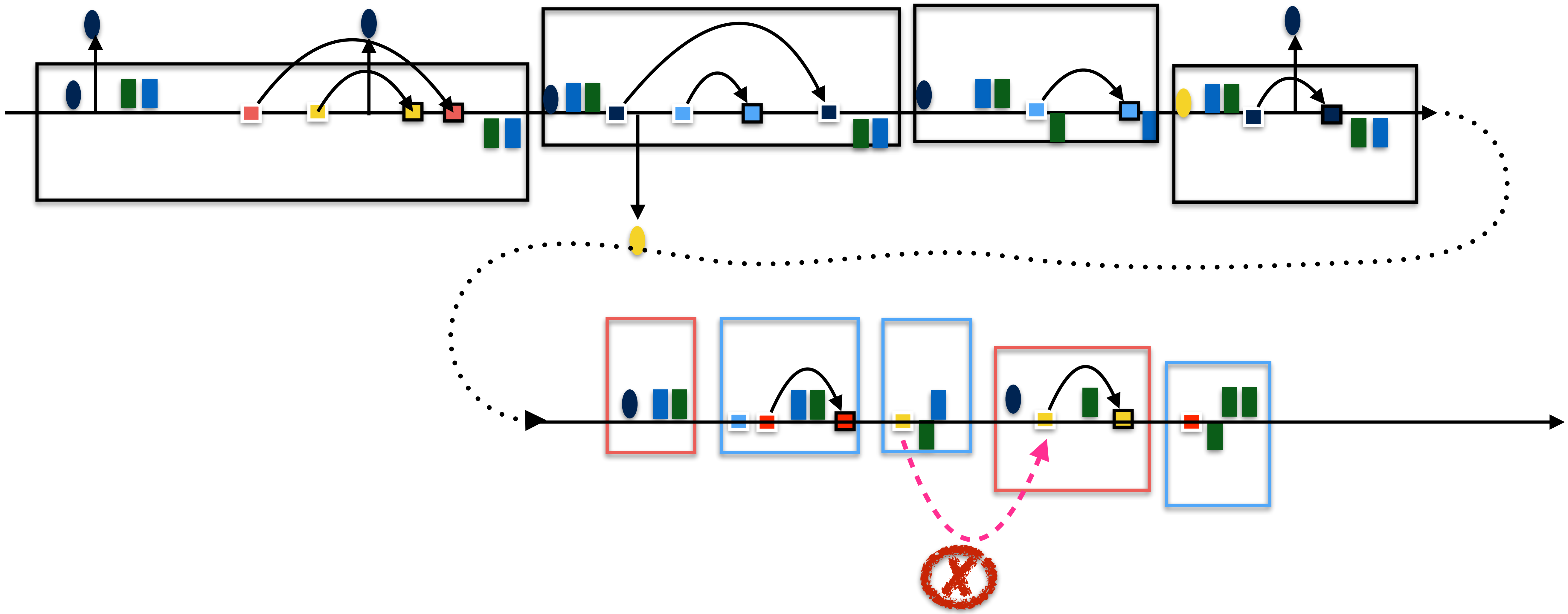


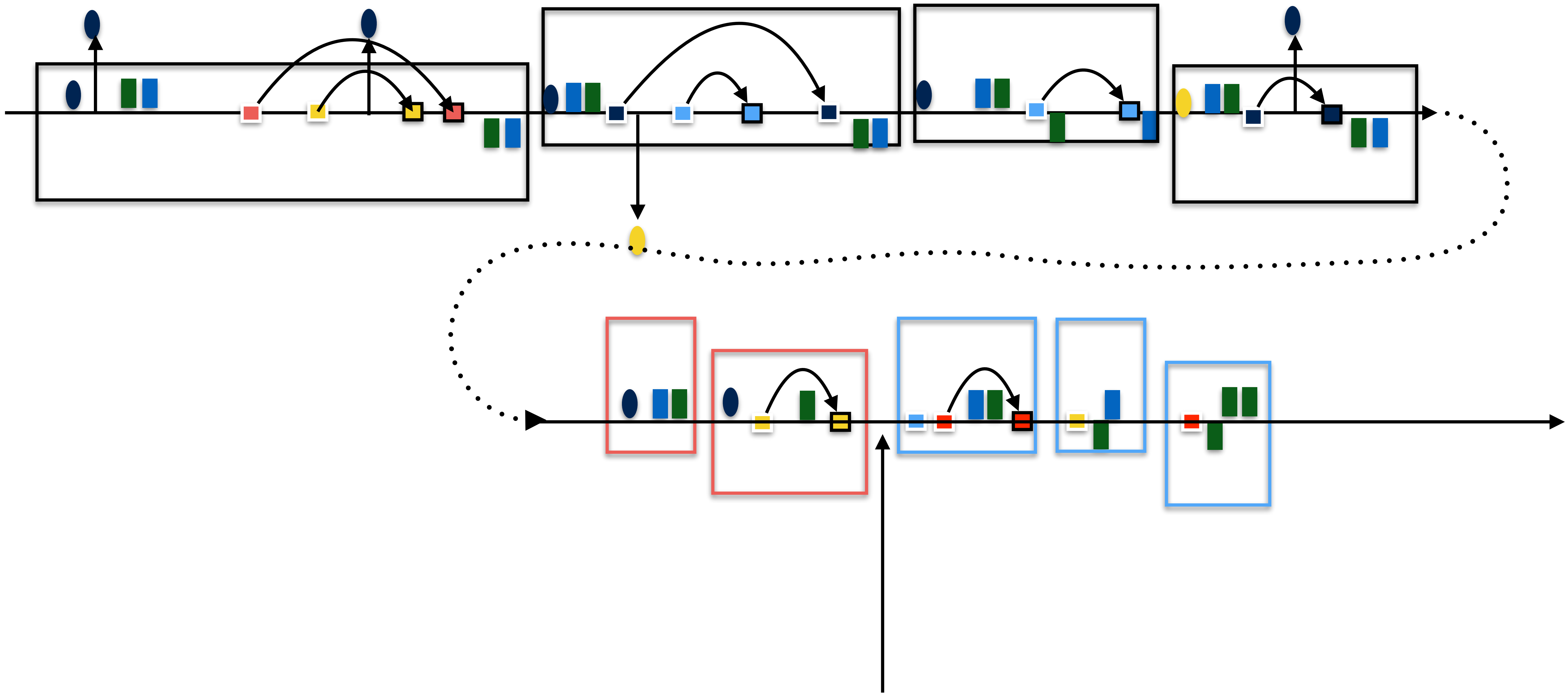
- Lock phases impose restrictions on availability of locks to future phases.

N-threads to 1-thread: locks



- Lock phases impose restrictions on availability of locks to future phases.
    - Maintain information on availability of locks

N-threads to 1-thread: stacks



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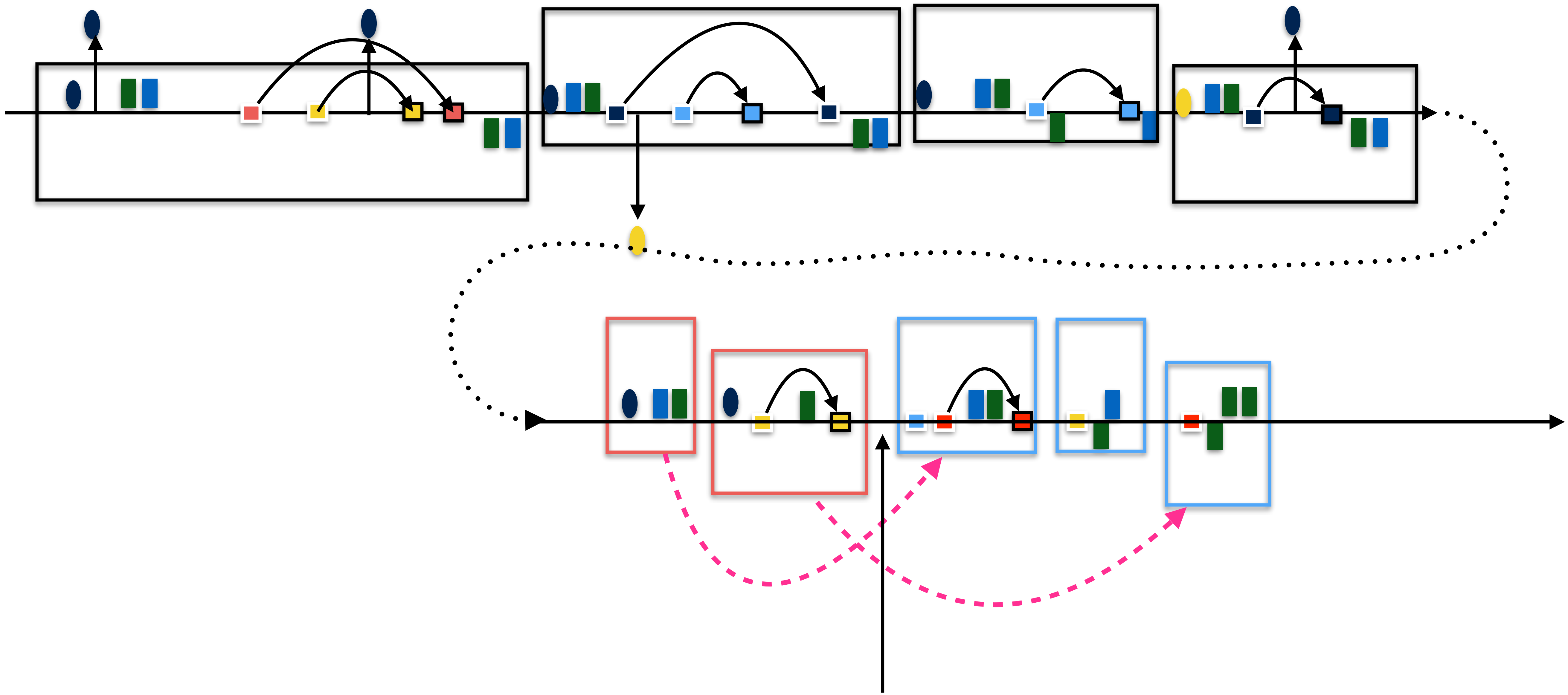

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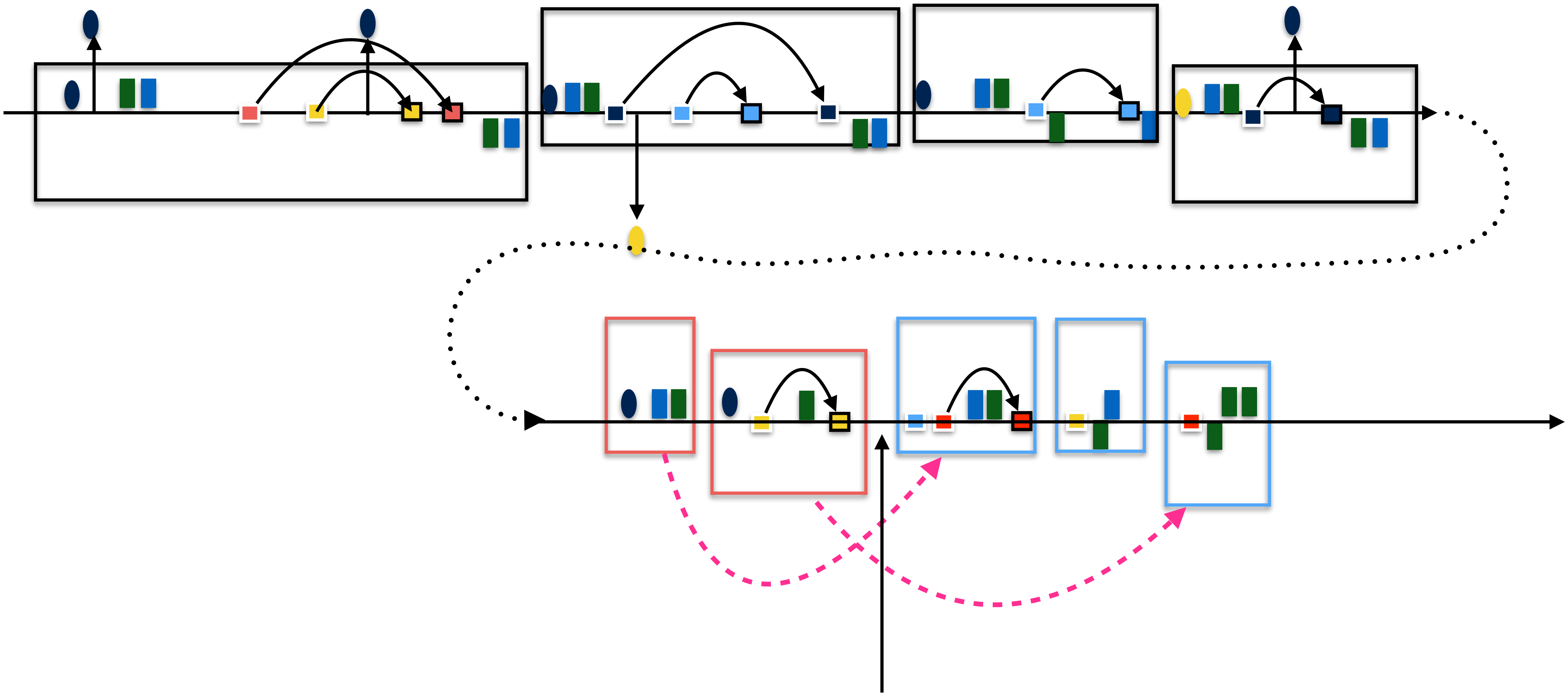


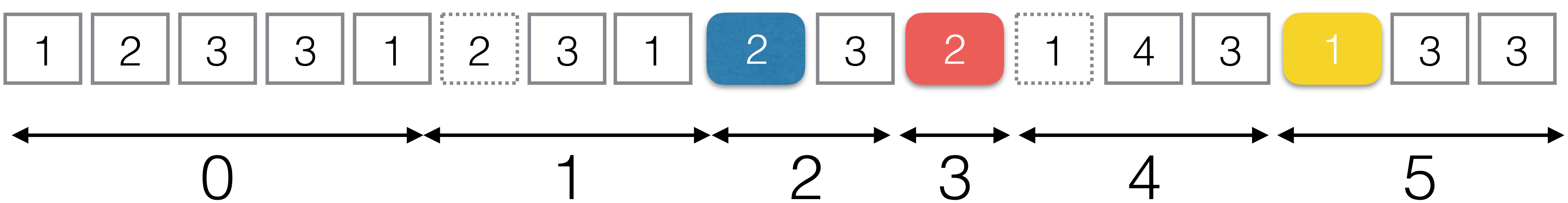
- Multiple stacks have to be maintained simultaneously.

Segments of phases:

i — A task phase of thread i

i — Boundary phase of thread i

i — A lock phase of thread i with lock



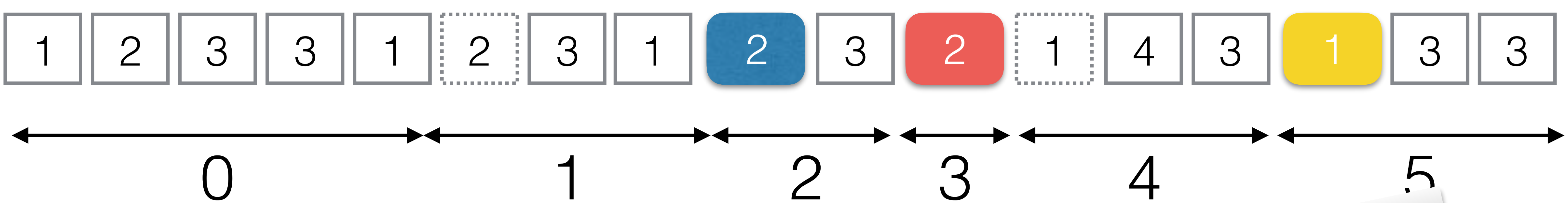
- Segment 0 — only task phases
- Segment i+1 — begins with boundary or lock phase, rest are task phases.

Segments of phases:

i — A task phase of thread i

i — Boundary phase of thread i

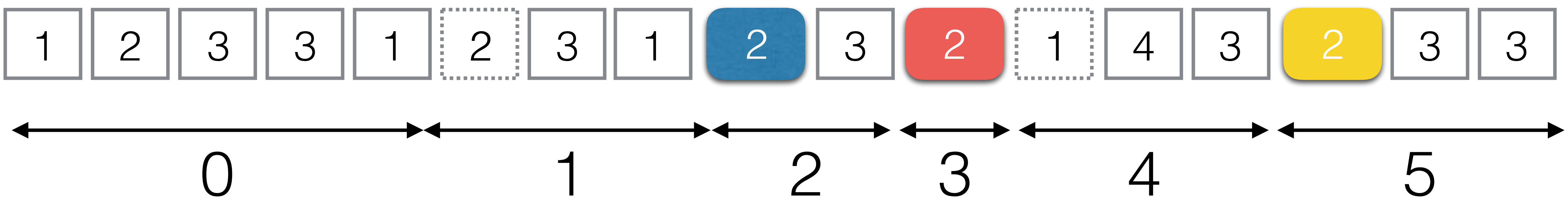
i — A lock phase of thread i with lock



- Segment 0 — only task phas…
- Segmen… …gins with boundary or lock phase, rest are task …ases.

Number of segments is bounded by locks + threads

Guiding Sequences:



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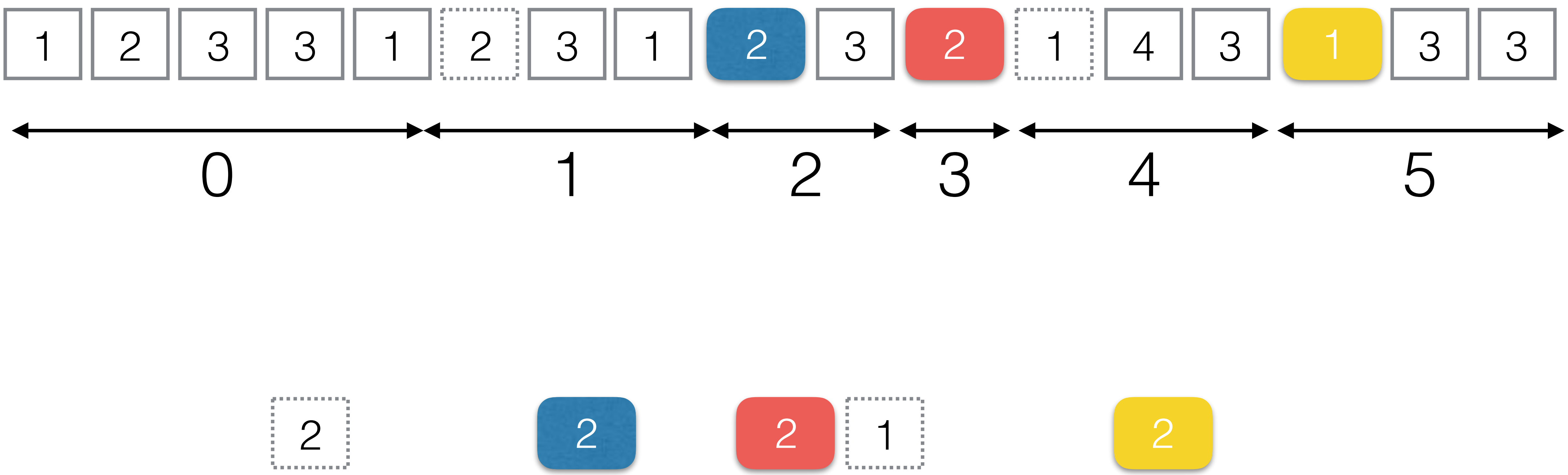
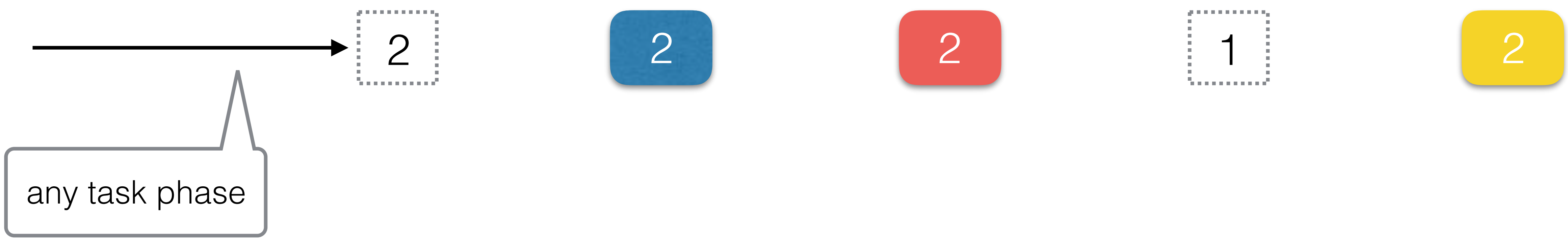


A sequence identifying the first element of each segment

Simulation with a single stack:

Seg No = 0

Simulation with a single stack:



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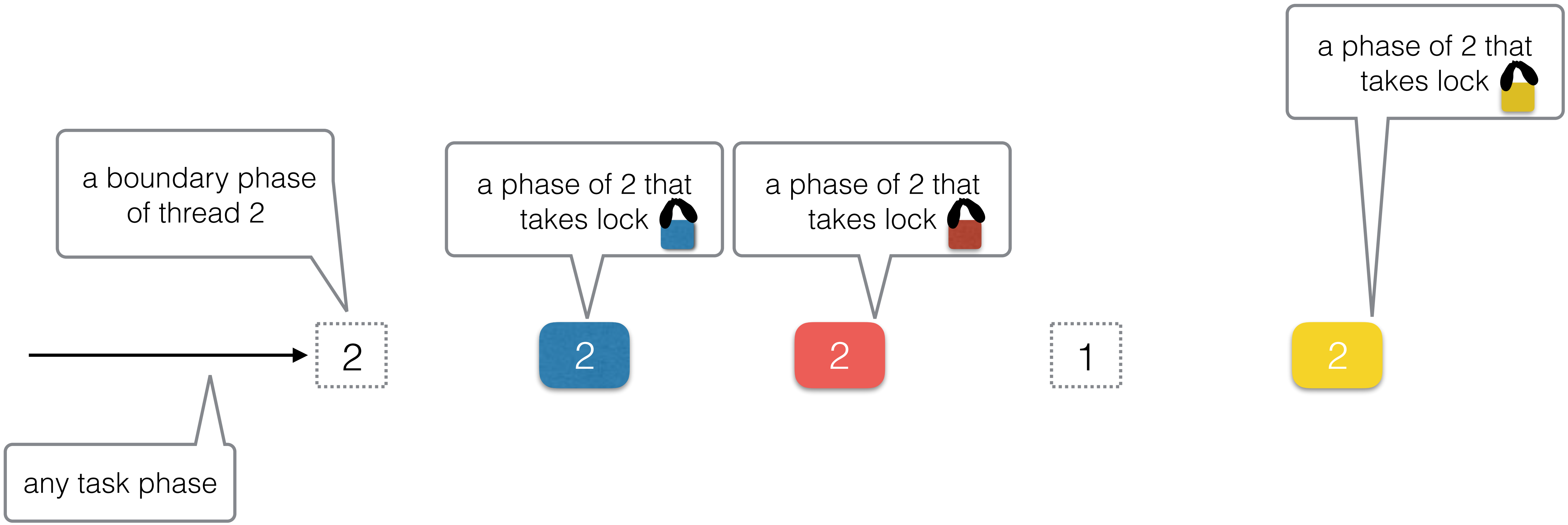
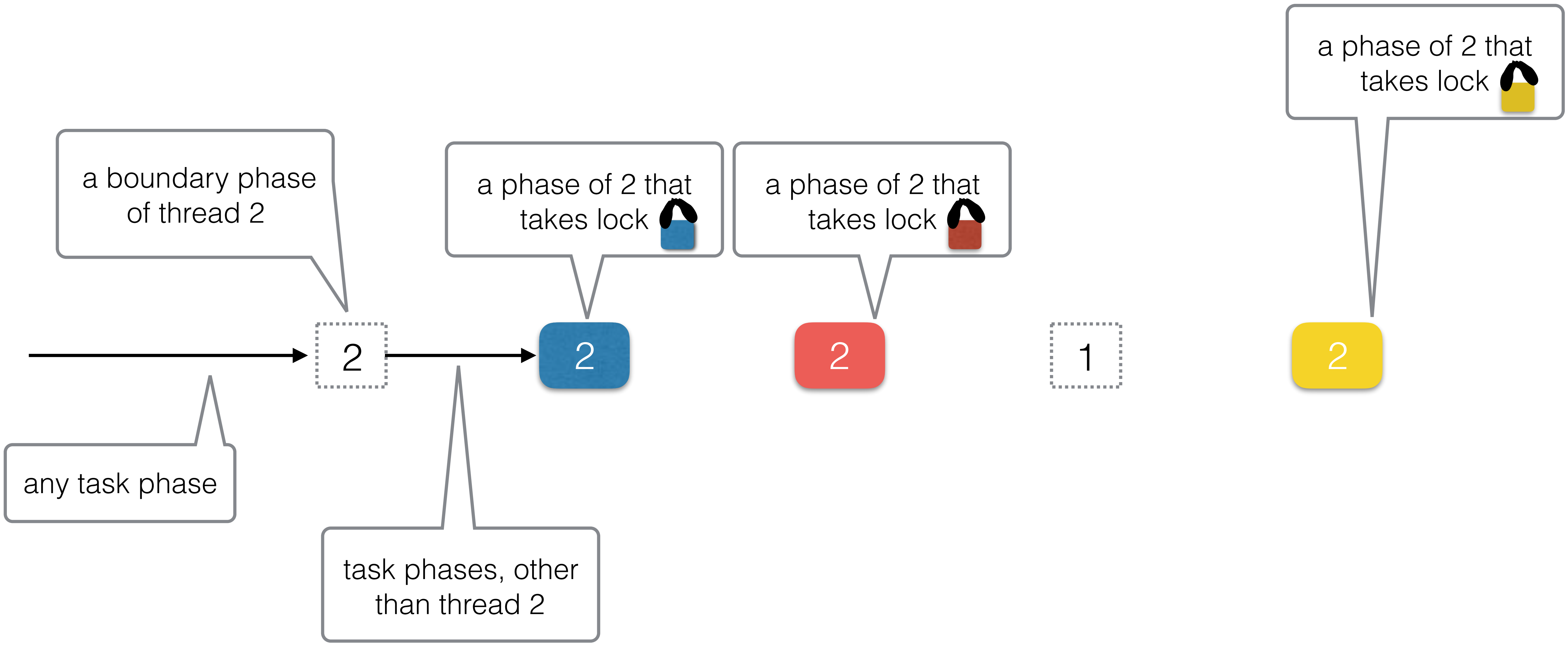


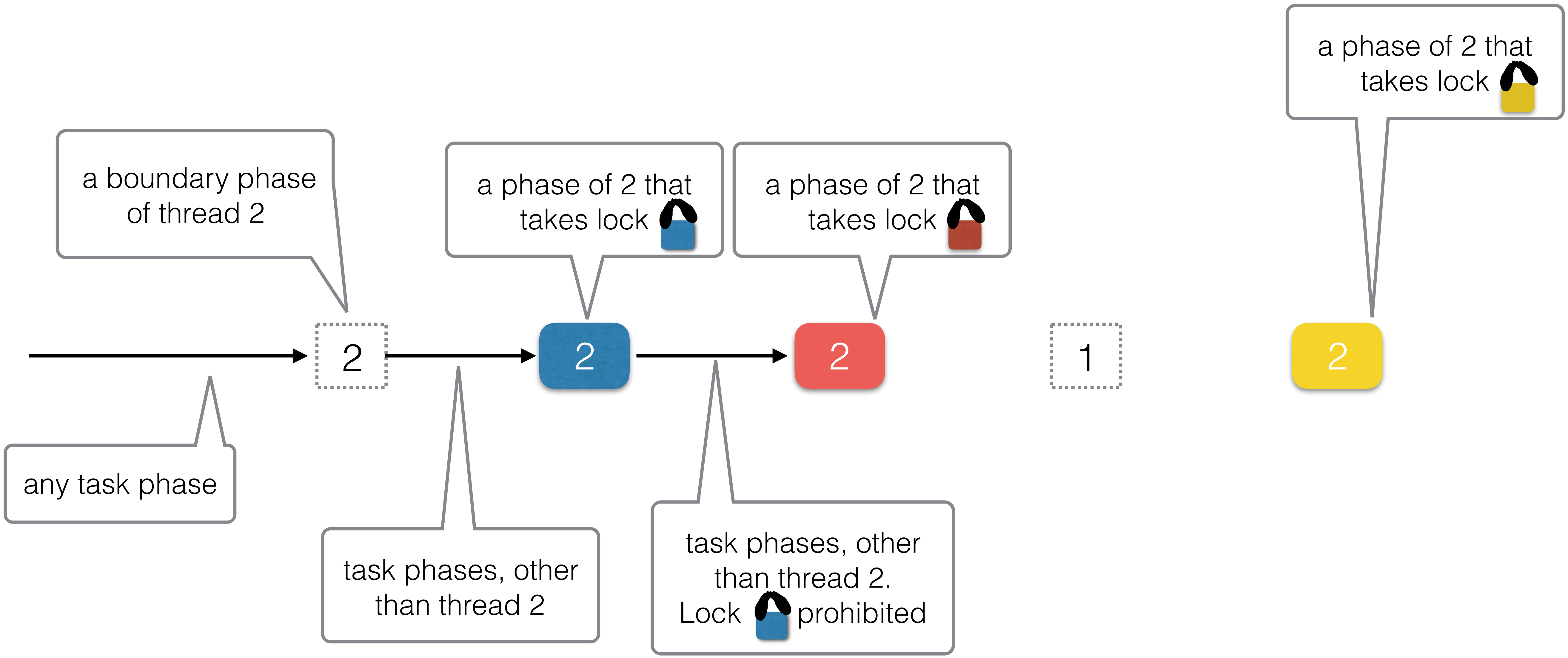
Seg No = 1

Simulation with a single stack:



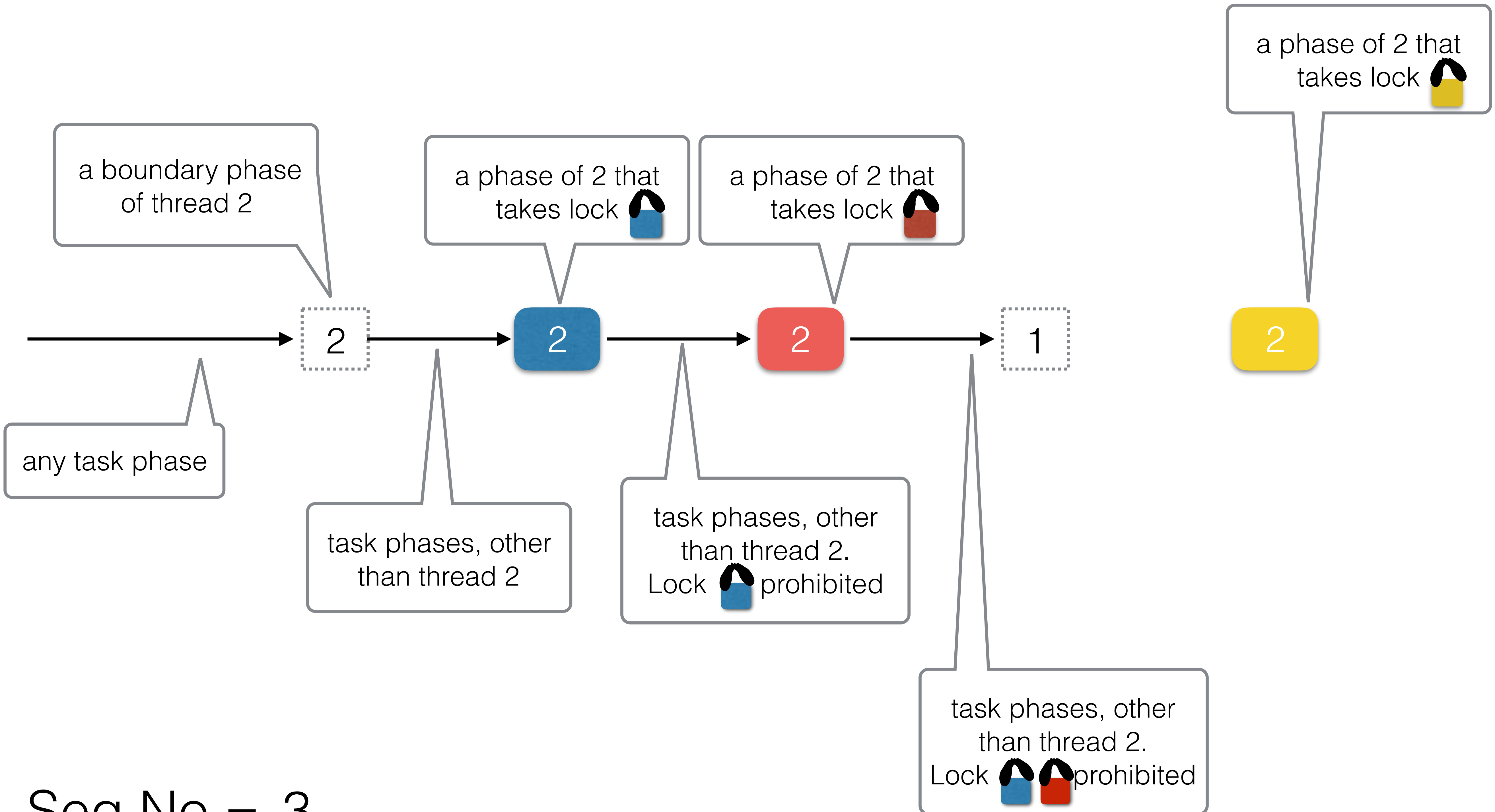
Seg No = 1

Simulation with a single stack:



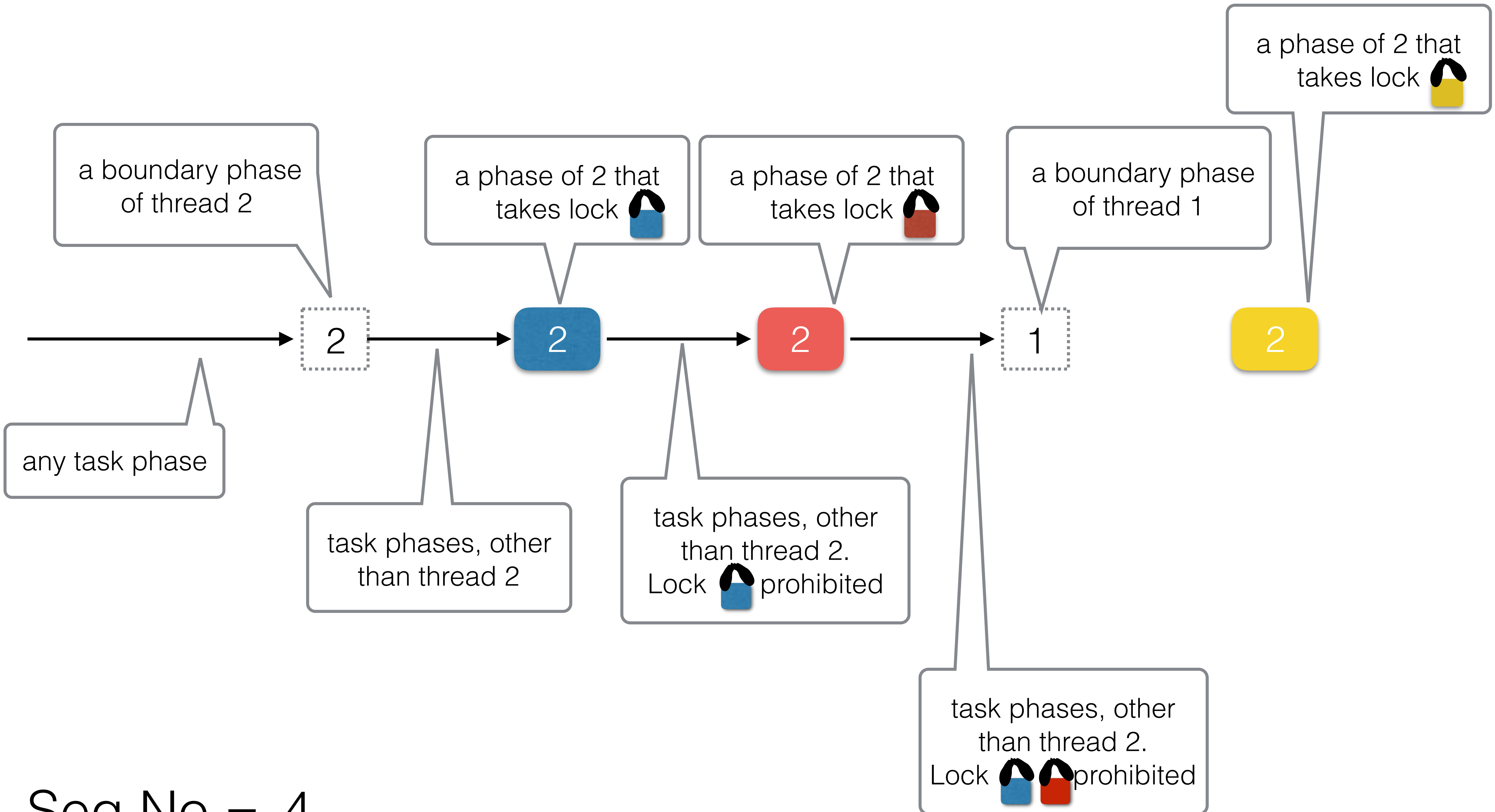
Seg No = 2

Simulation with a single stack:



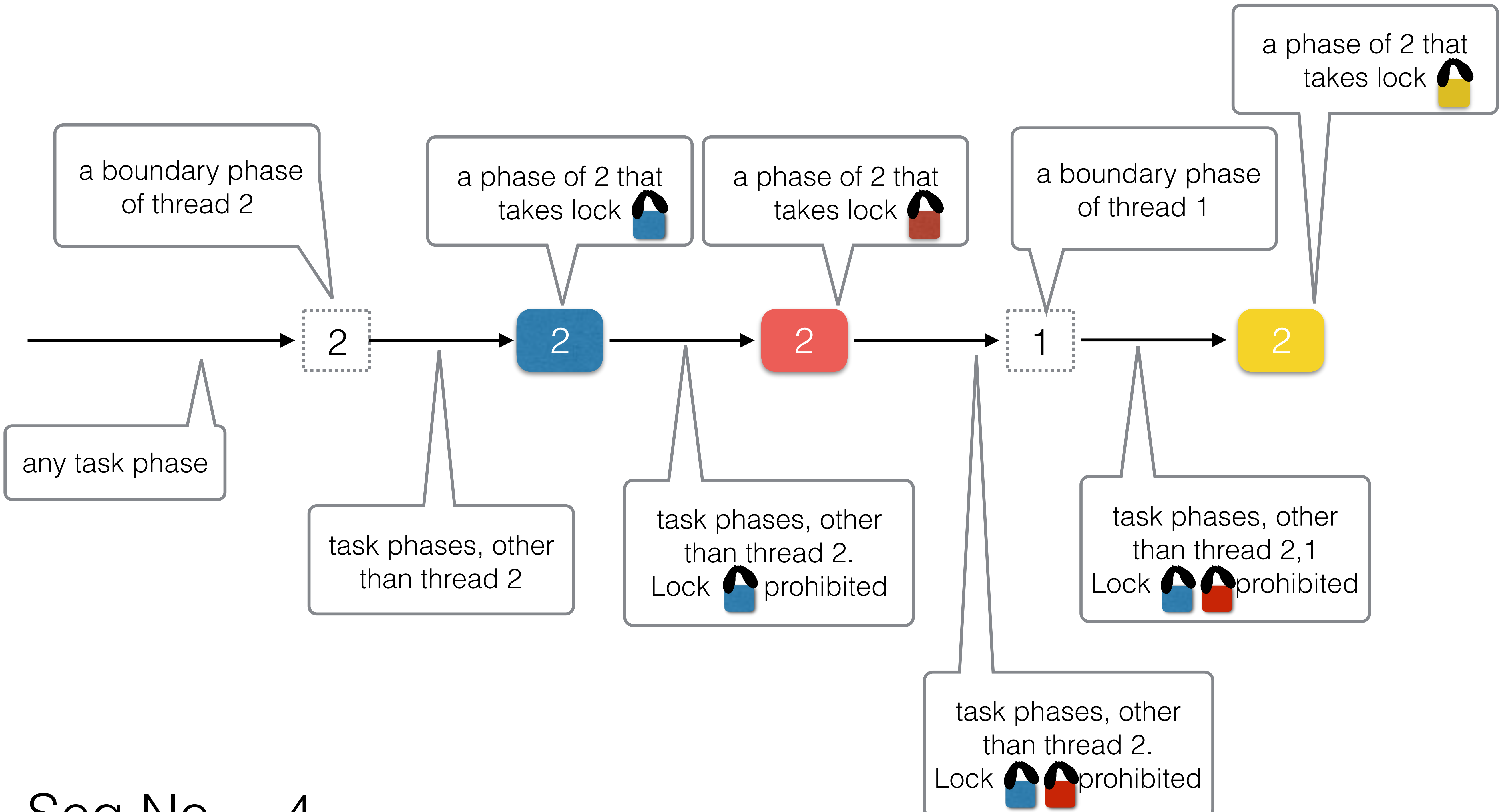
Seg No = 3

Simulation with a single stack:



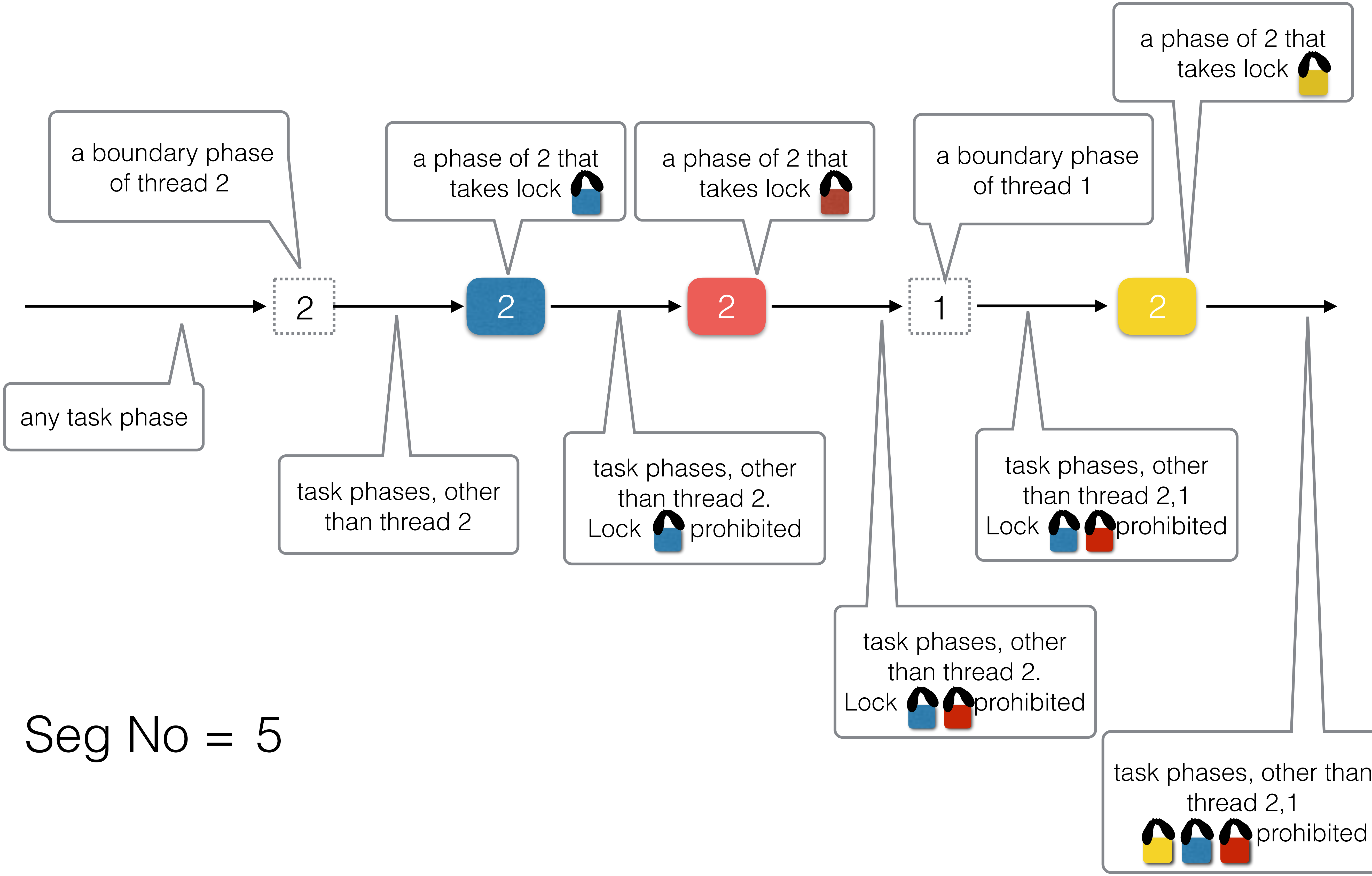
Seg No = 4

Simulation with a single stack:



Seg No = 4

Simulation with a single stack:



Seg No = 5

Complexity:

- For a given guiding sequence
  - Exponential blow up due to product of state spaces

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Reachability via runs consistent with a given guiding sequence reduces to a polynomially larger 1-Thread system.

Complexity …

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- There are only exponentially many guiding sequences

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Reachability via runs consistent with a given guiding sequence is in EXPSPACE.

- There are only exponentially many guiding sequences

Theorem: Reachability for Asynchronous programs with locks under well-nested, task locking is EXPSPACE-Complete

Complexity: underapproximation

- What if we also want to verify that the system uses nested locking?
  - Exponential blow up due to set of locks to be maintained.
  - Locks are accessed when the stack is not empty, so can't be simply moved to the multi-set.
  - Using Parikh's theorem transform this into FA with multi-sets with 2-EXP number of states, but same multi-set alphabet as in the input.
  - Treat as a VASS with 2-EXP number of states and polynomial number of places.
  - Yen-Rosier show that coverability for VASS can be solved space logarithmic in the number of states and exponential in the number of places.

Stateless task scheduling:

Each thread may schedule a new task only from a fixed local state.

- Tasks cannot “communicate” via local state of threads
- A thread is just schedules and runs tasks.

Stateless task scheduling:

Theorem: Reachability for Asynchronous programs with locks under state-less scheduling, well-nested locks and task locking is NP-Complete

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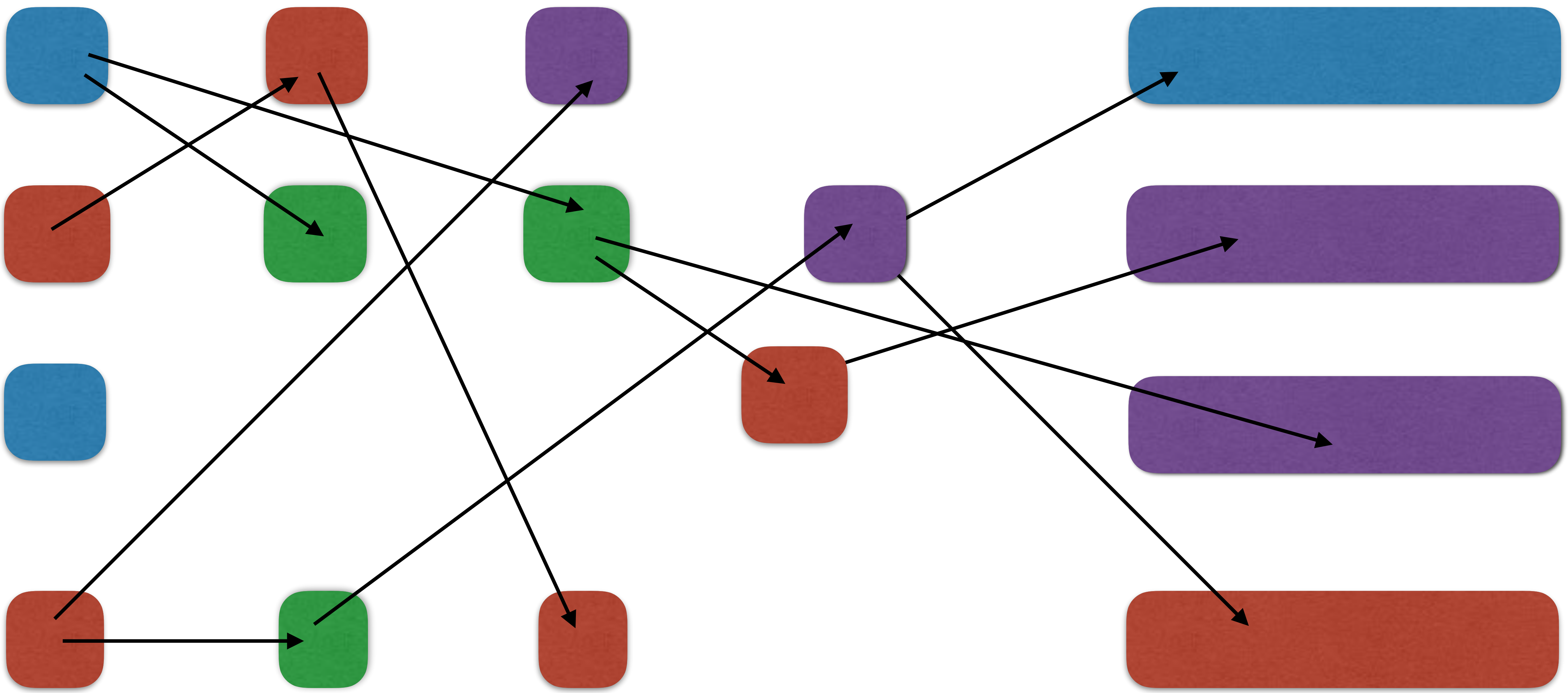
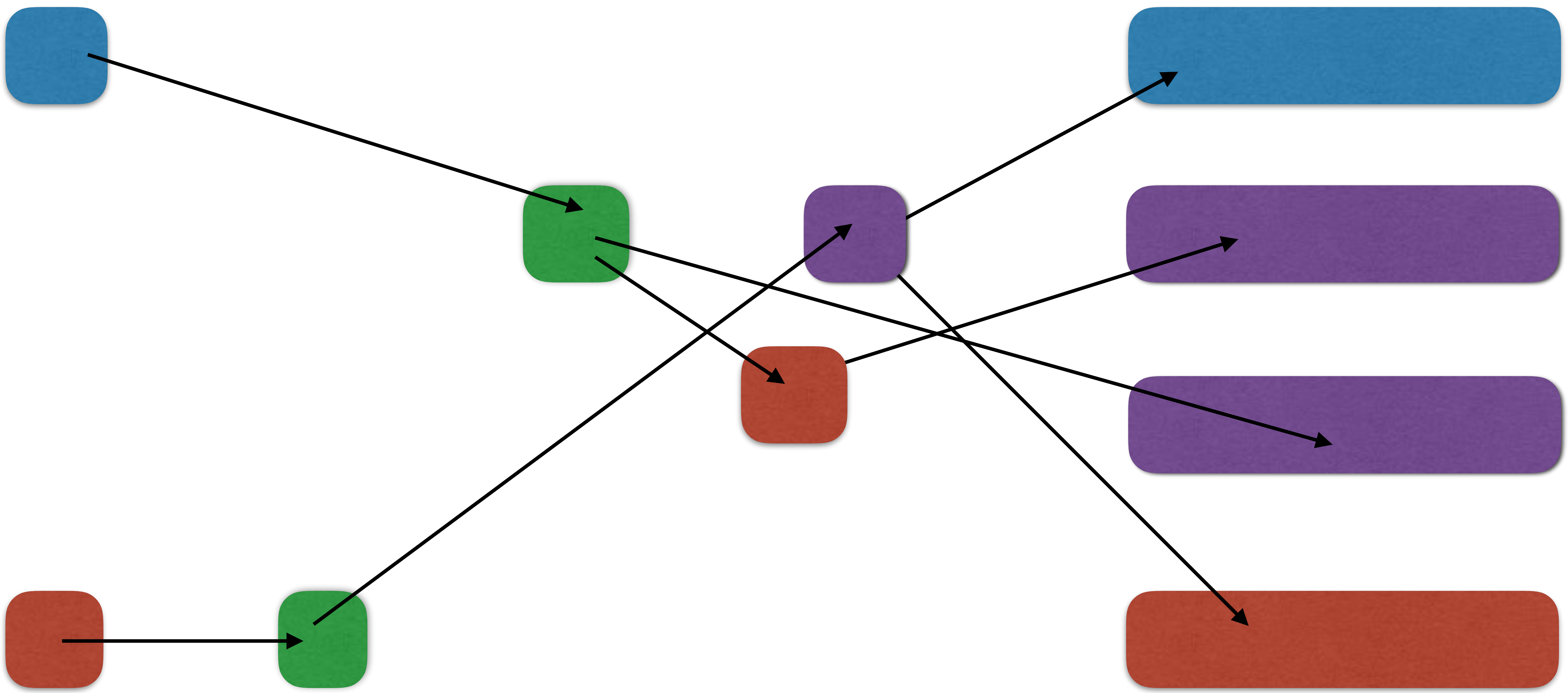
- A polynomial bound on the number of tasks that need to be scheduled to reach any (reachable) state.

Bounding the number of tasks



Bounding the number of tasks



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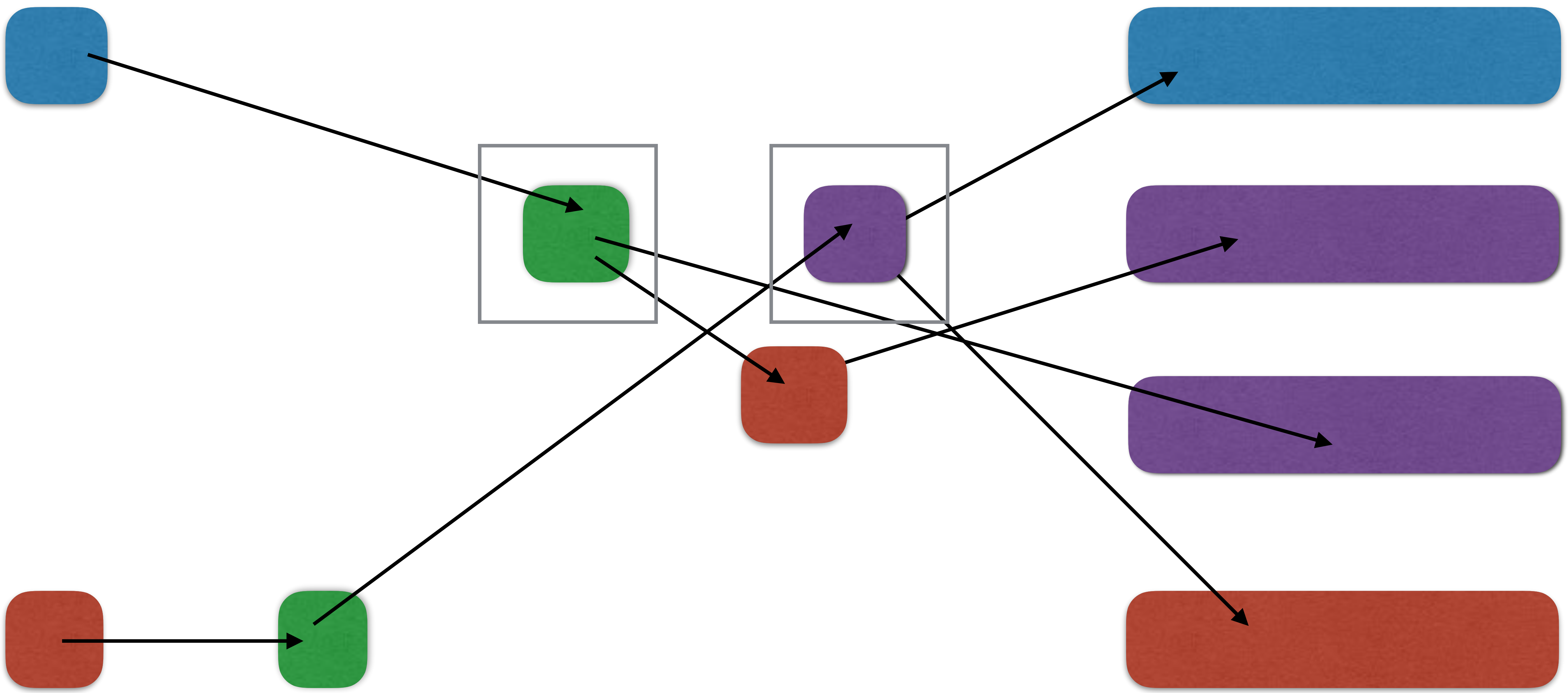

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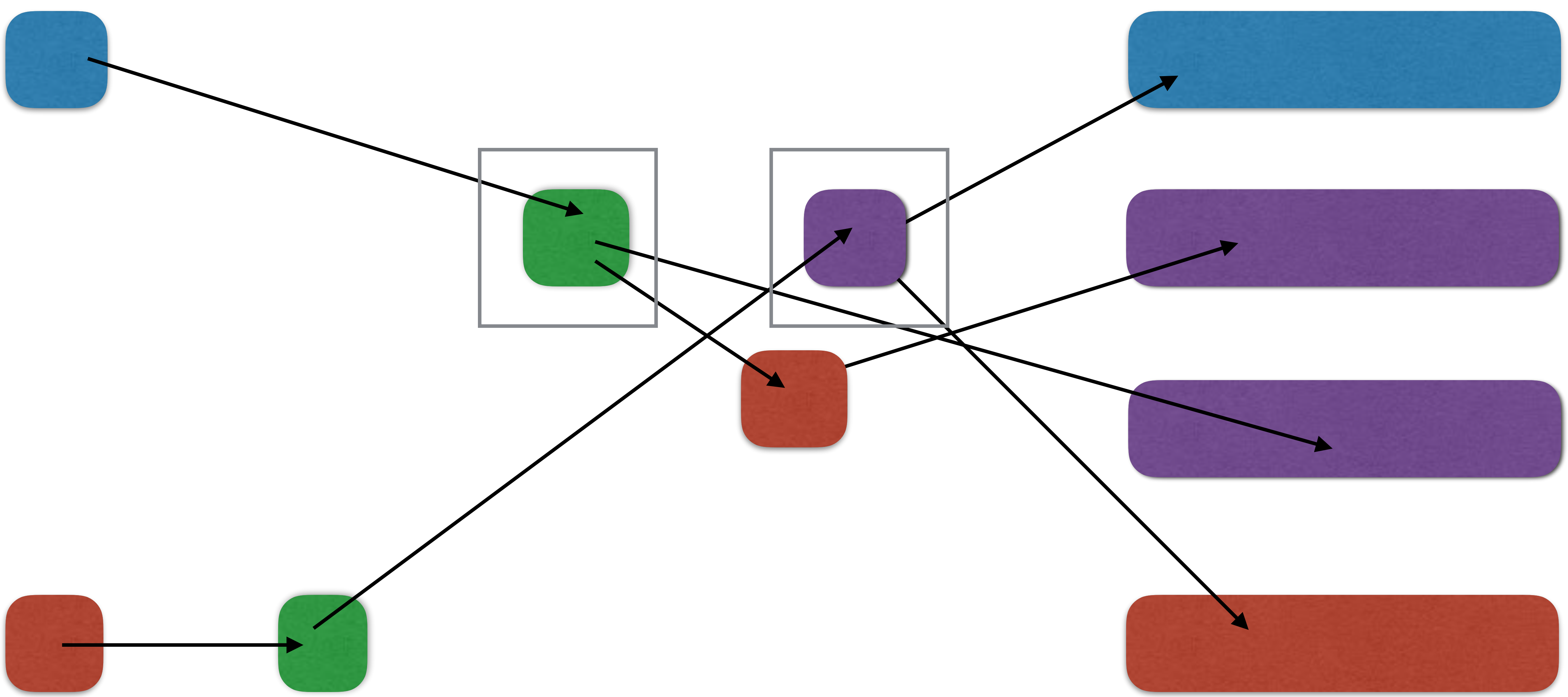
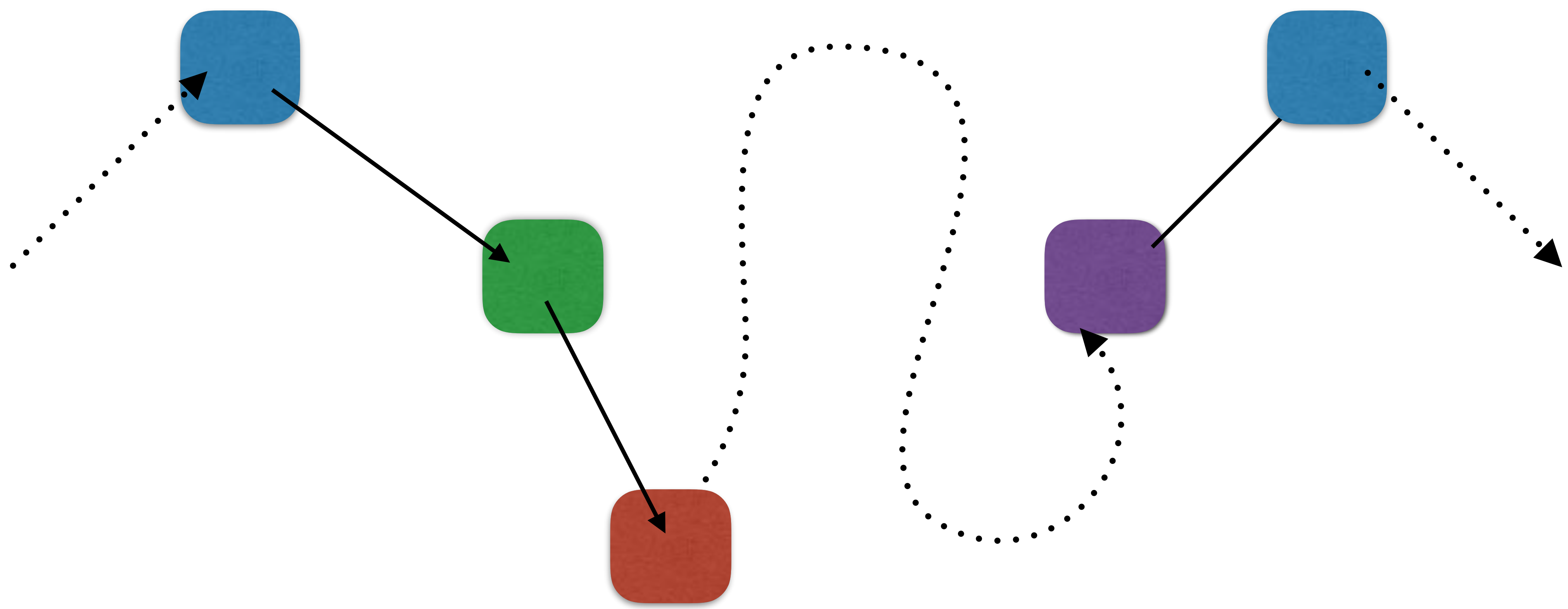


Number of branching points bounded by threads

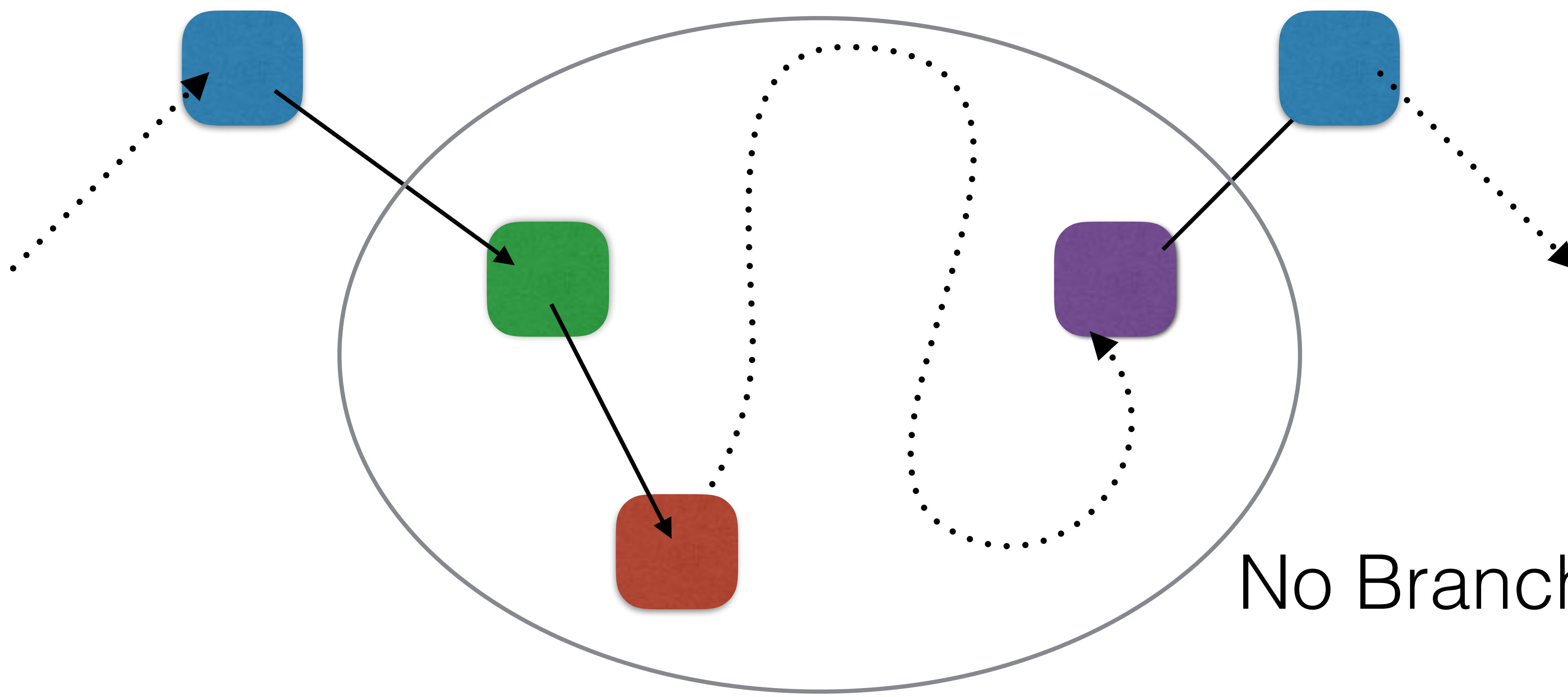
Bounding Path length



Path length bounded by Poly(threads, tasks)

Width also bounded by threads.

Bounding Path length



No Branching

Path length bounded by Poly(threads, tasks)

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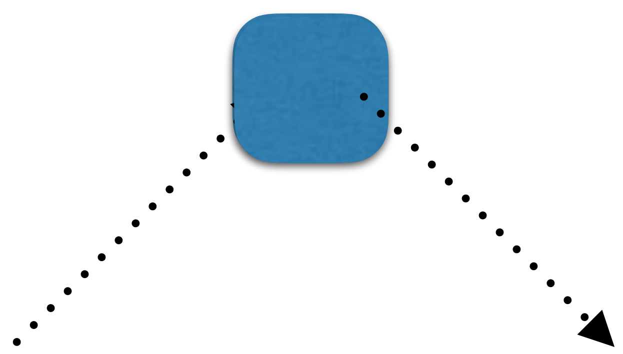
Bounding Path length



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Complexity of emptiness of Asynchronous Programs with at most polynomial number of operations on the multi-set.

- Guess and write down a consistent sequence of Multi-set operations (consistent: add >= remove at each point for each task)
- Simulate the Asynchronous program as a pushdown on this input.

Stateless task scheduling:

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Theorem: Reachability for Asynchronous programs with locks under state-less scheduling, well-nested locks and task locking is NP-Complete

- Lower-bound —- reduction from SAT.
  - Take locks to decide on valuation (taking lock x if x = False)
  - Cycle through clauses and check that at least one literal is true.

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Thank you