wPerf: Generic Off-CPU Analysis to Identify Bottleneck Waiting Events

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Optimizing bottleneck is critical to throughput

- Bottleneck: factors that limit the throughput of application.

- Question: where is the bottleneck?

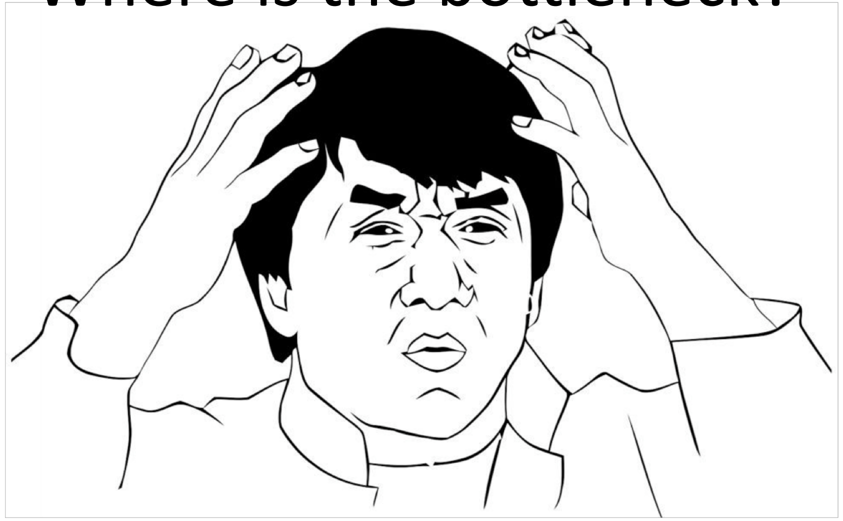
Where is the bottleneck?

- Both execution and waiting can create the bottlenecks.

PID	%CPU	%MEM	COMMAND
930	20.0%	0.0%	test
931	50.0%	0.0%	test

Device	tps	kB_read/s	kB_wrtn/s
sda	7.37	0	1778.27

Where is the bottleneck?



On-CPU & Off-CPU analysis

- On-CPU analysis
  - What execution events are creating the bottleneck?
  - Quite well studied: Recording execution time (perf, oprofile, etc.), Critical Path Analysis, Causal Profiler (Coz SOSP'15), etc.

- Off-CPU analysis
  - What waiting events are creating the bottleneck?
  - Common waiting events: lock contention, condition variable, I/O waiting, etc.
  - Lock-based (e.g., SyncPerf EuroSys'17, etc.) solutions are incomplete.
  - Length-based (e.g., Off-CPU flamegraph, etc.) solutions are inaccurate.

Key challenge of off-CPU analysis

Local impact vs global impact

- Local impact: impact on threads directly waiting for the event
- Global impact: impact on the whole application
- Large local impact does not mean large global impact

Overview of wPerf

- Goal: identify bottlenecks caused by all kinds of waiting events.
  - (Note: how to optimize bottlenecks requires the users’ efforts)
- To compute global impact
  - Generate a holistic view (wait-for graph) of the application
  - Theorem: knot in a wait-for graph must contain a bottleneck
- Results:
  - Up to 4.83x improvement in seven open source applications

Concrete example

Thread A

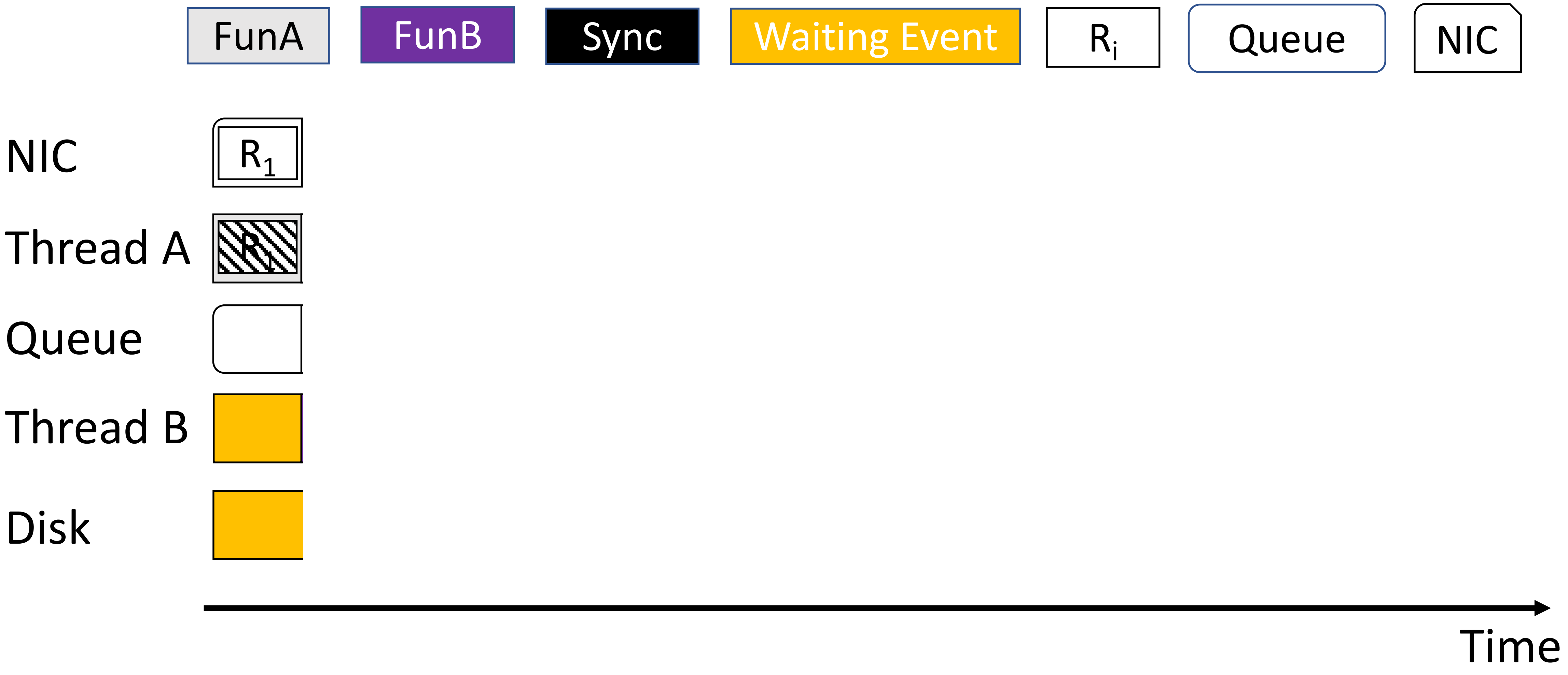
```
while (true)
  recv req from network
  funA(req)      // 2ms
  queue.enqueue(req)
```

Thread B

```
while (true)
  req = queue.dequeue()
  funB(req)      // 5ms
  log req to a file
  sync()      // 5ms
```

Queue is a producer-consumer queue with max size k.
Assume k = 1 for simplicity.
Thread A (enqueue) blocks if queue size is 1.
Thread B (dequeue) blocks if queue size is 0.

Concrete example



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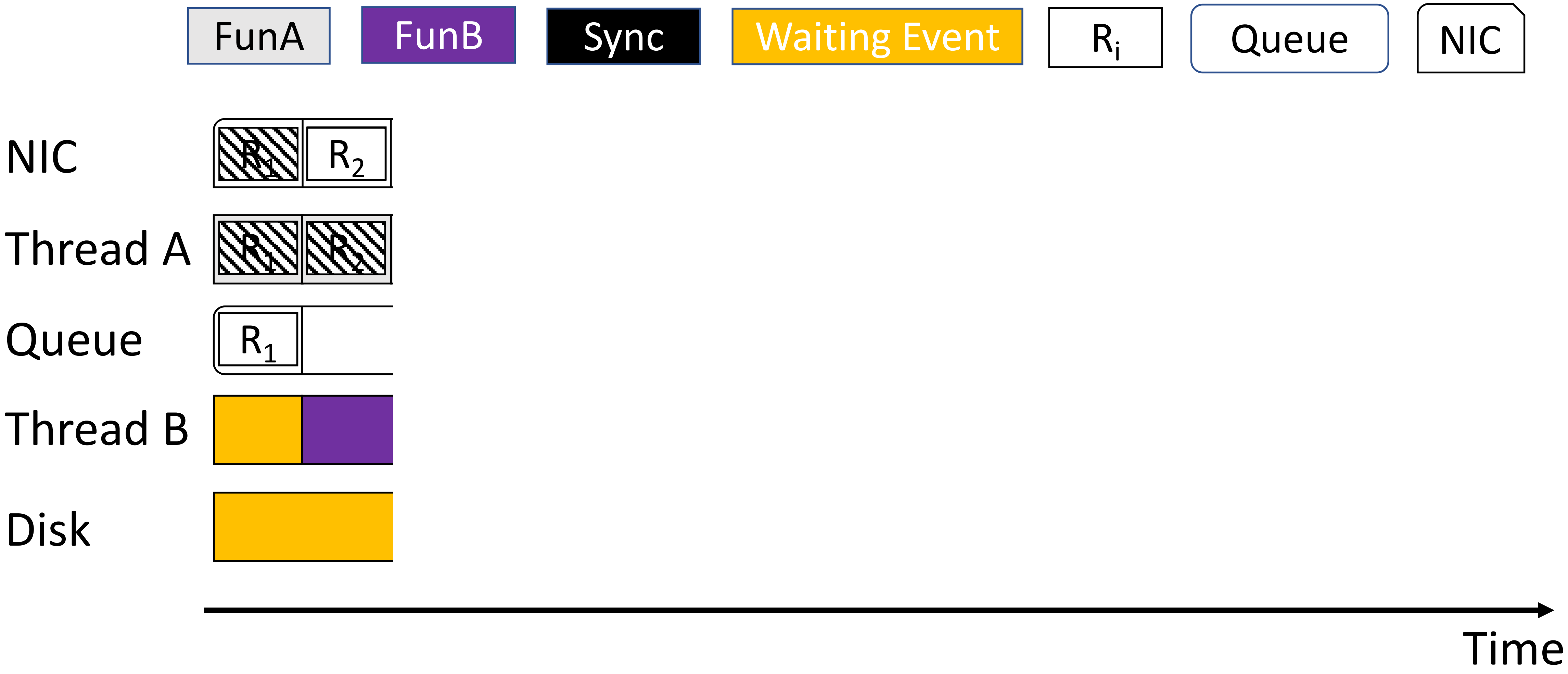

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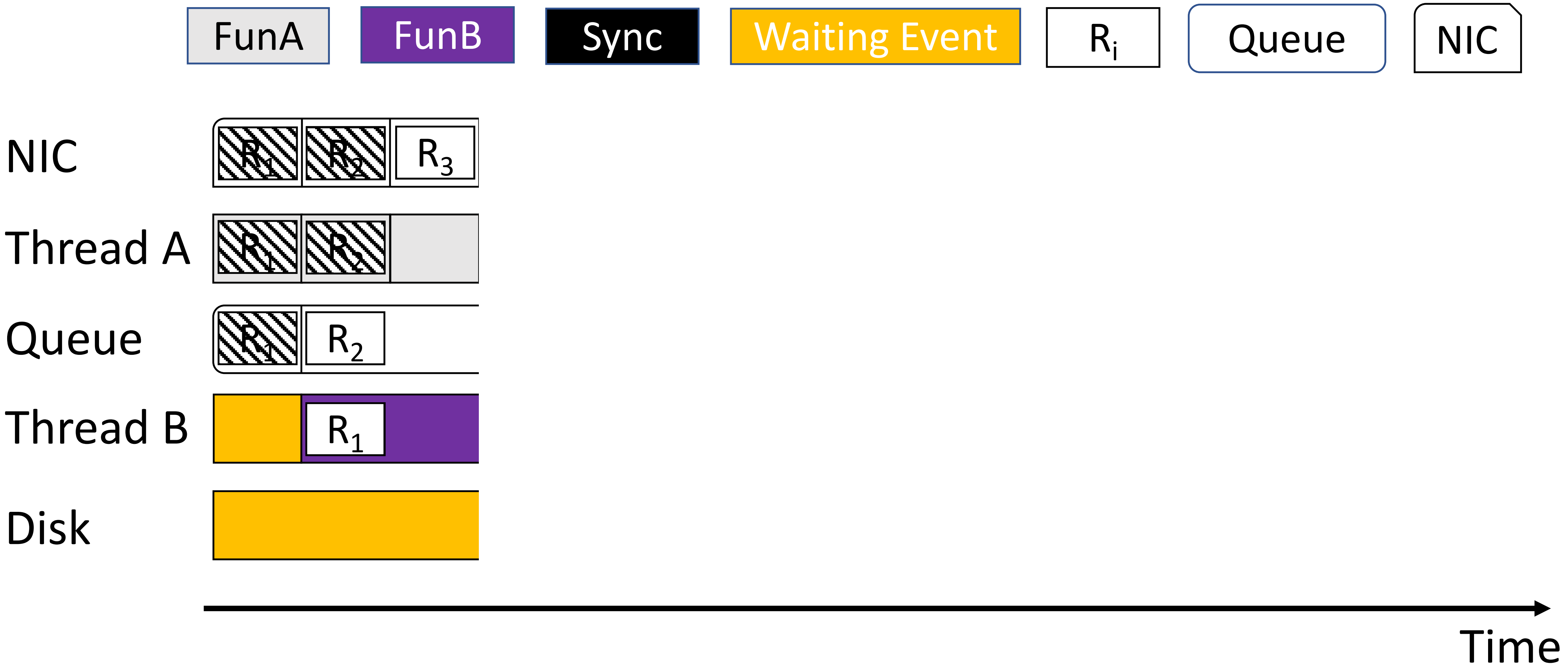

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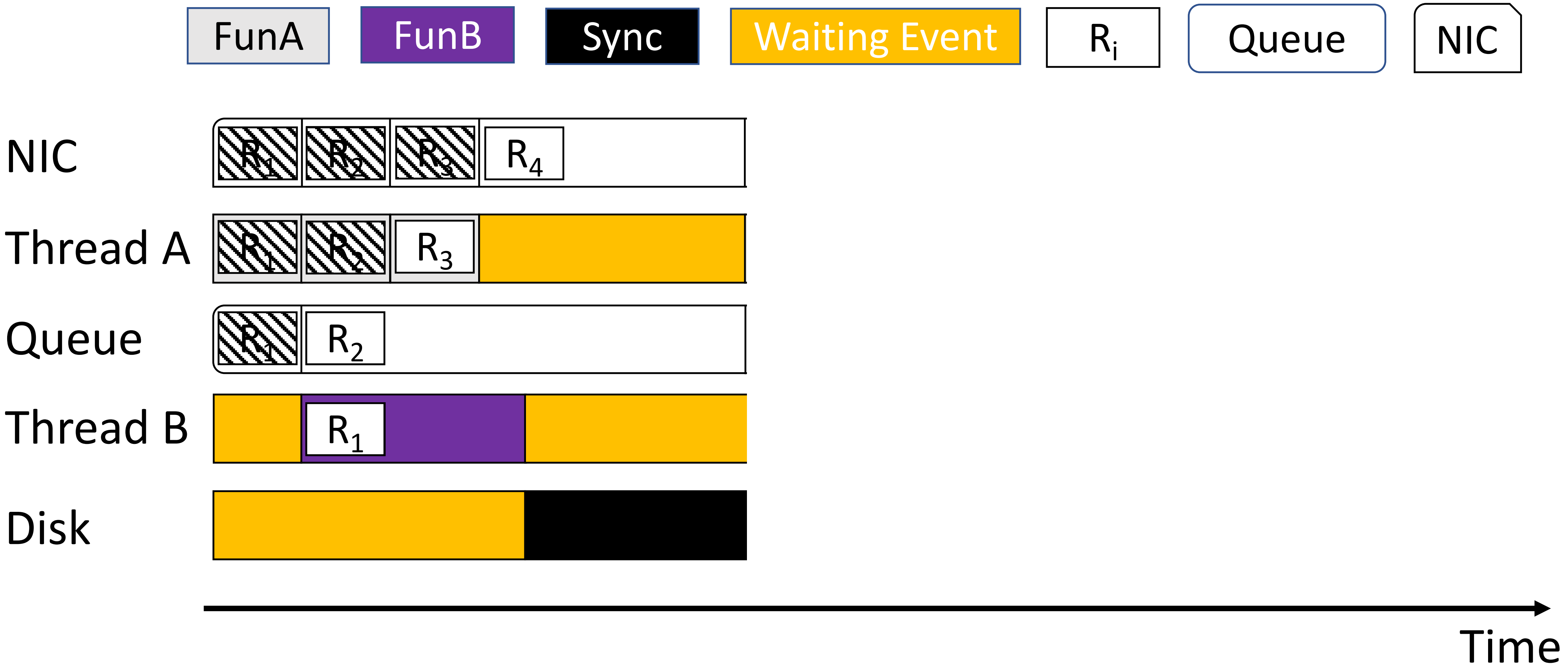

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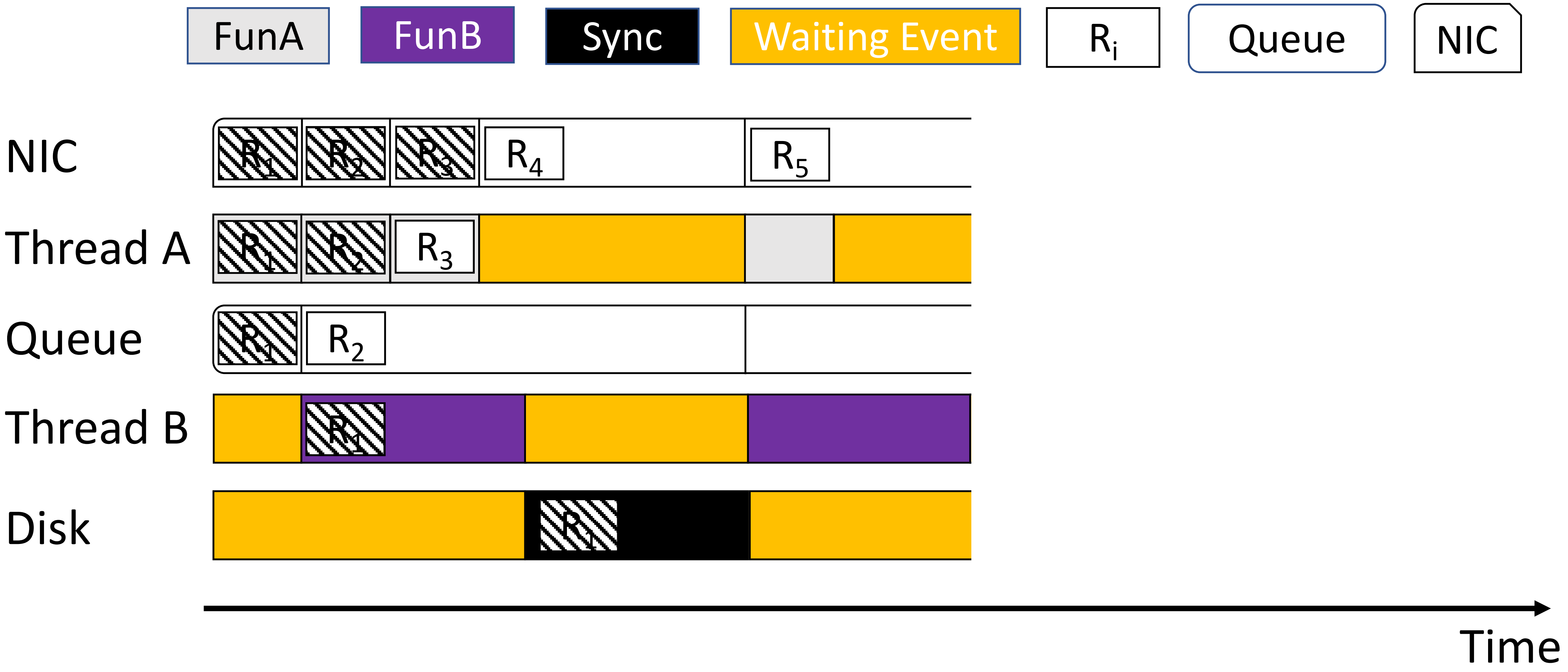

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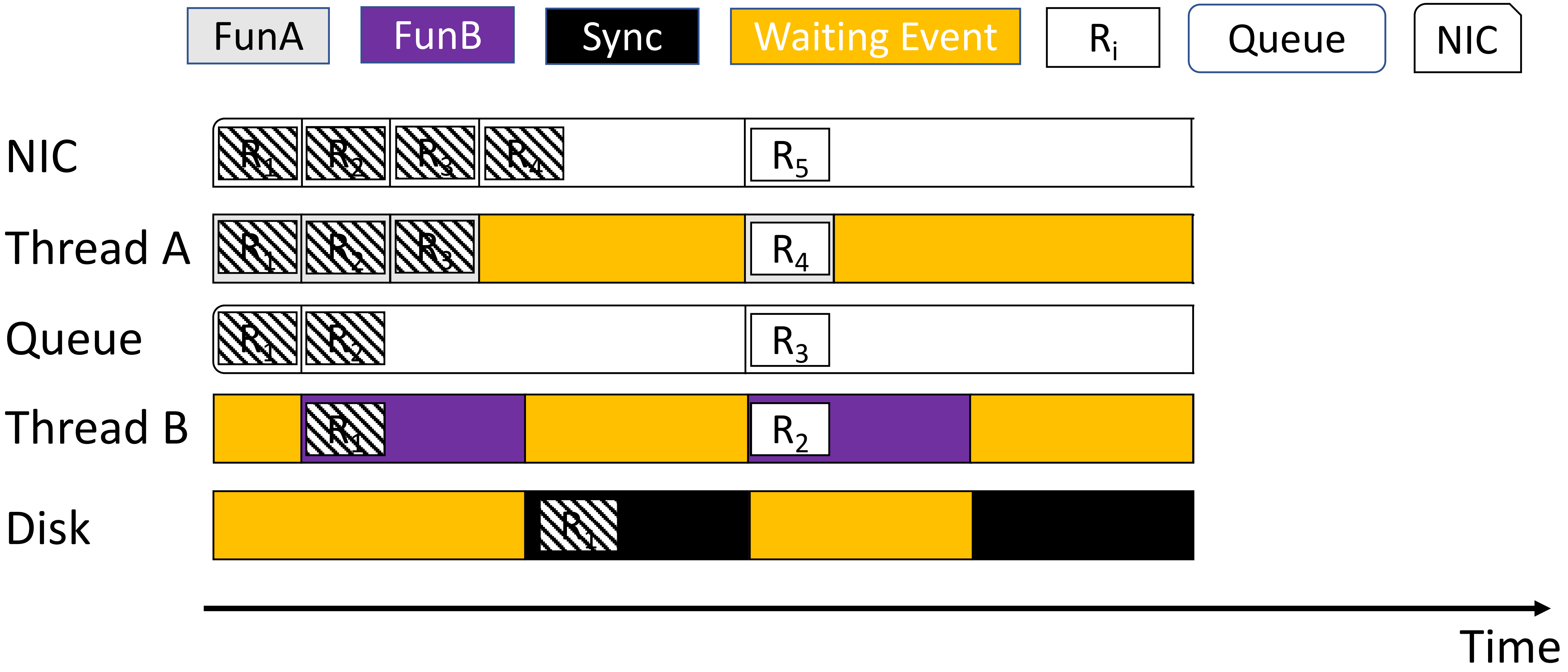

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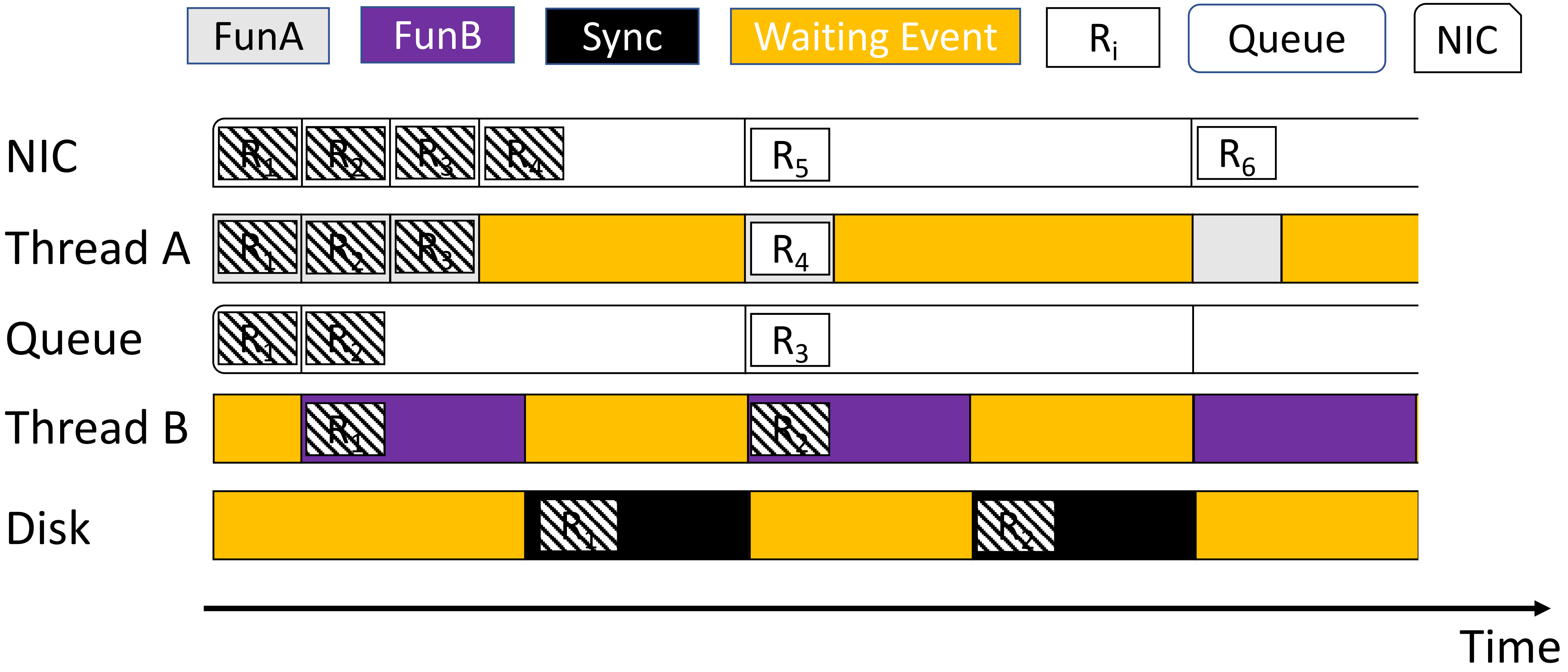

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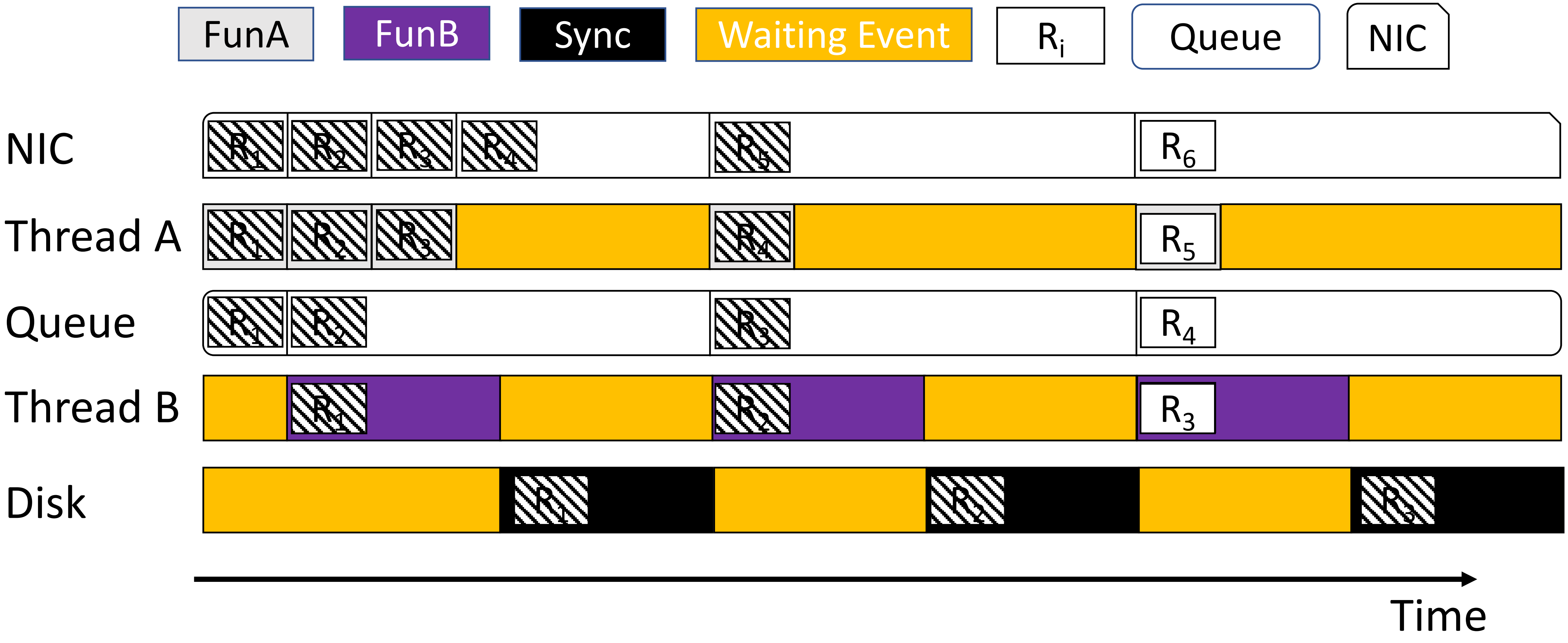

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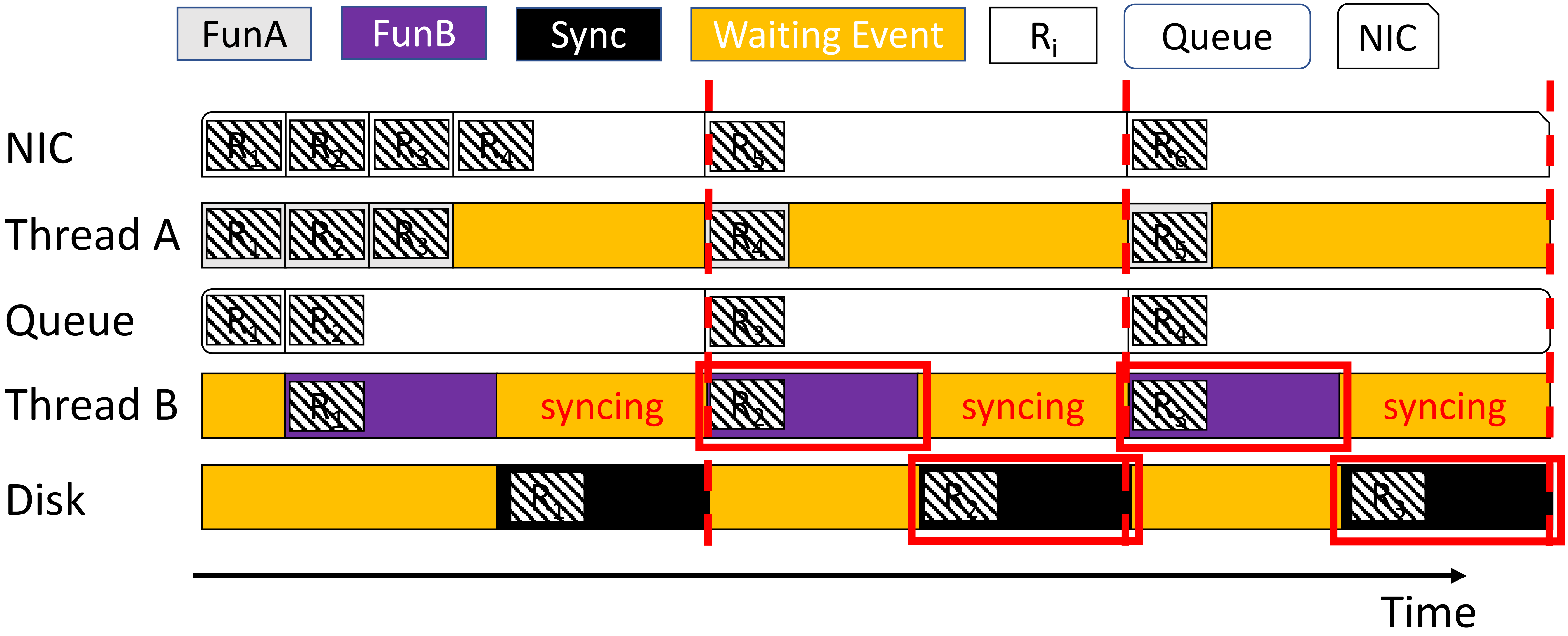
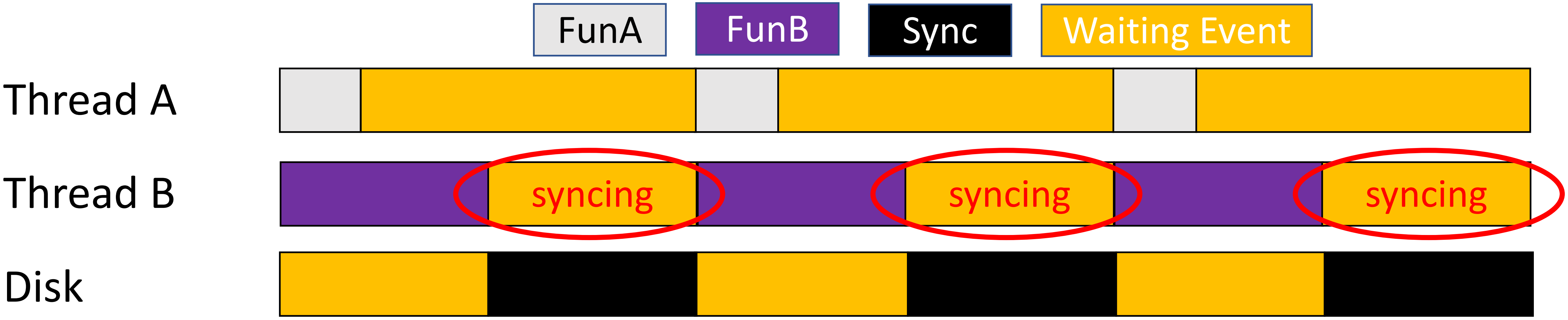


Observation: waiting is important



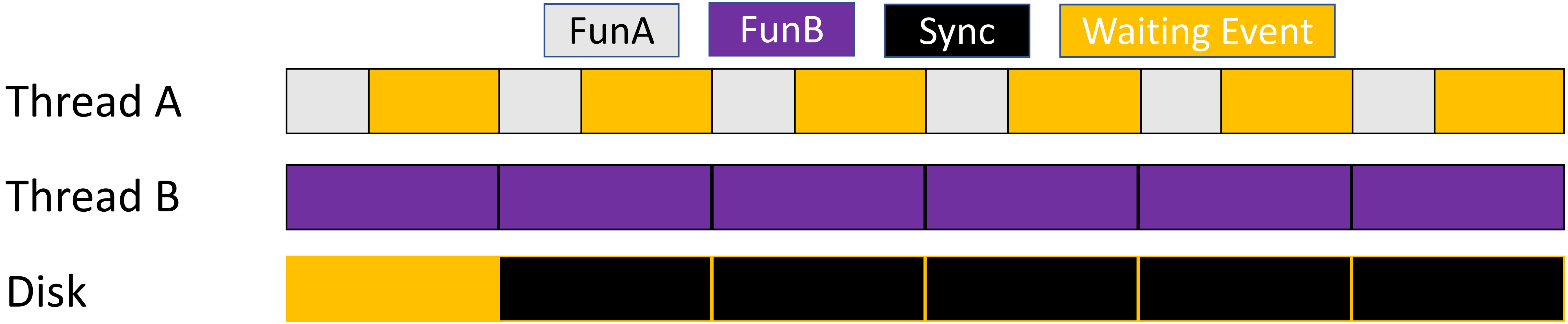
Observations:

Waiting can have a large impact on throughput.

Longer waiting events may not be more important.

Contention is not the only waiting event that matters.

Observation: waiting is important



Observations :

Waiting can have a large impact on throughput.

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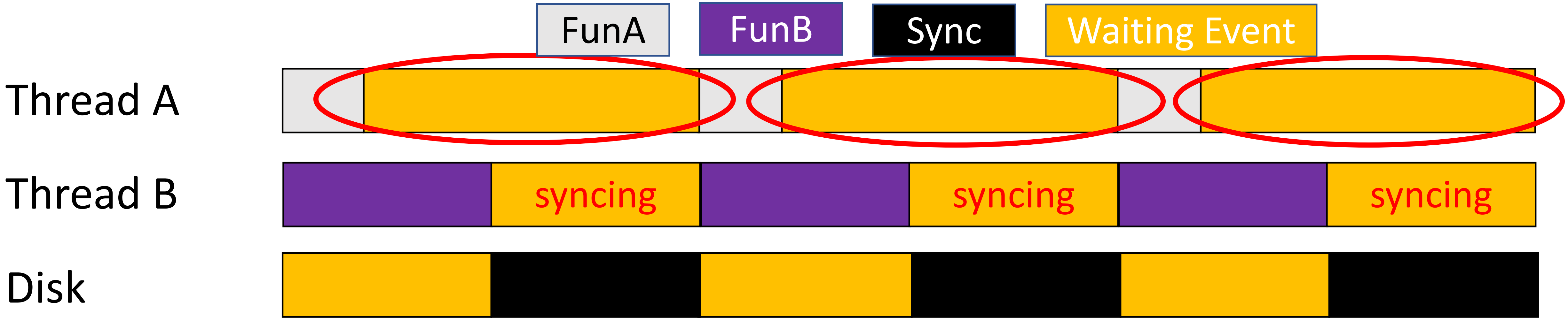
Observation: long waiting may not be important



Observations :

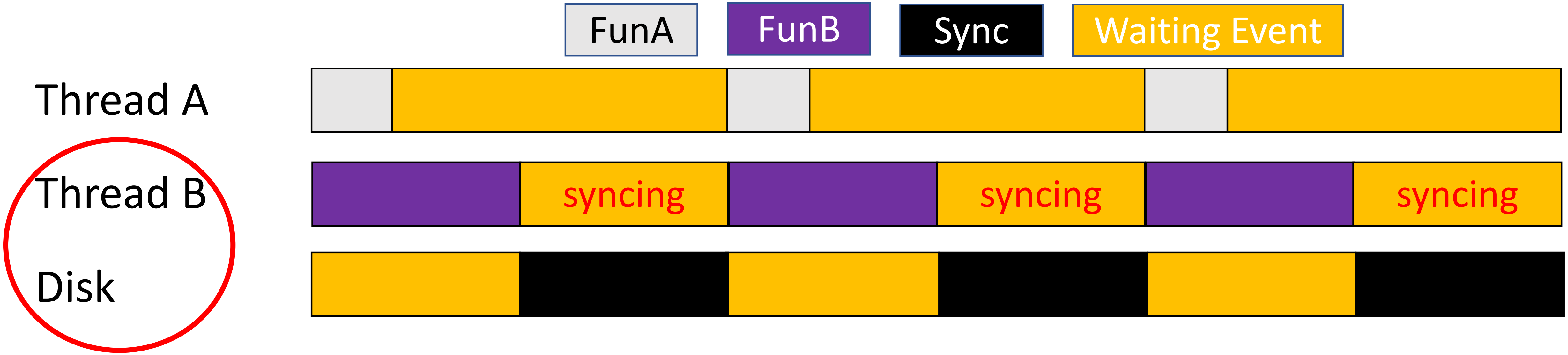
Waiting can have a large impact on throughput.

Longer waiting events may not be more important.

- Large local impact does not mean large global impact.

Contention is not the only waiting event that matters.

Observation: contention is not everything



Observations:

- Waiting can have a large impact on throughput.
- Longer waiting events may not be more important.
- Contention is not the only waiting event that matters.

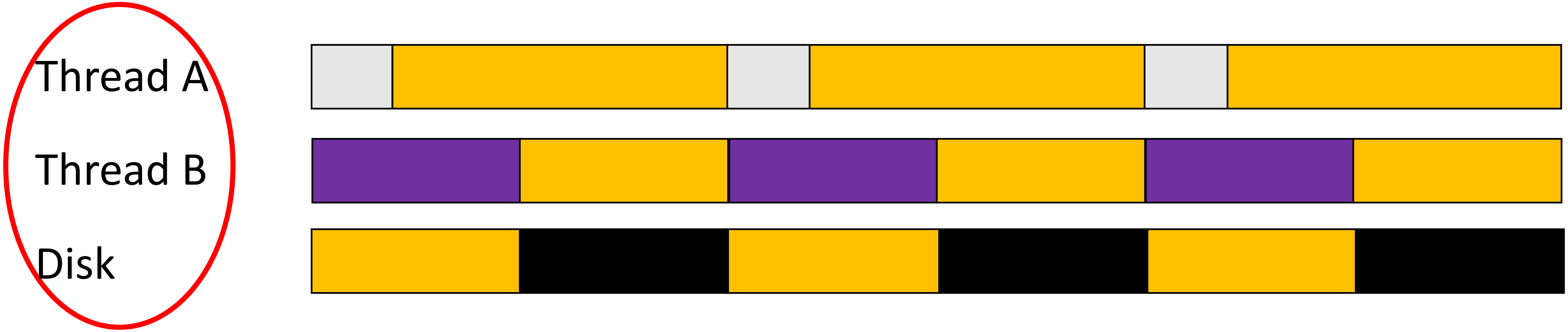
Key insights of wPerf

- Insight 1: to improve the throughput, we need to improve all the threads involved in request processing (worker threads).
  - Worker threads: request handling, disk flushing, garbage collection, etc.
  - Background threads: heartbeat processing, deadlock checking, etc.
  - See formal definition in the paper.

- Implication:
  - Bottleneck is an event whose optimization can improve all worker threads

Key insights of wPerf

Insight 1: a bottleneck is an event whose optimization can improve all worker threads.



Key insights of wPerf

Before optimization:

Thread A
Thread B
Disk

After optimization:

Thread A
Thread B
Disk

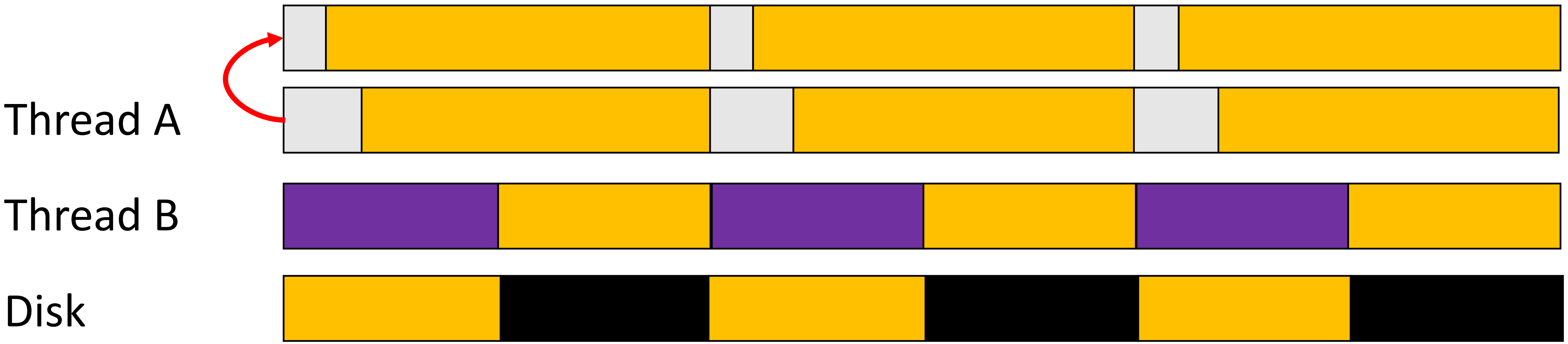
Optimizing sync can double the throughputs of all worker threads, so sync is a bottleneck.

Key insights of wPerf

- Insight 1: a bottleneck is an event whose optimization can improve all worker threads
- Insight 2: if thread B never waits for A, either directly or indirectly, then optimizing A's event will not help B.
  - Implication: A's event is not a bottleneck, if B is a worker thread.

Key insights of wPerf

Insight 2: if thread B never waits for A, either directly or indirectly, then optimizing A's event will not help B.

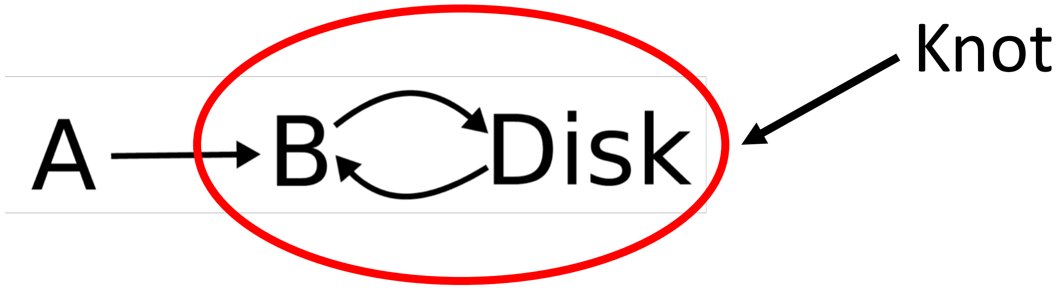


Key idea of wPerf

- Insight 1: a bottleneck is an event whose optimization can improve all worker threads
- Insight 2: if thread B never waits for A, either directly or indirectly, then optimizing A’s event will not help B.
  - Implication: A’s event is not a bottleneck, if B is a worker thread.
- Key idea: narrow down the search space by excluding non-bottlenecks

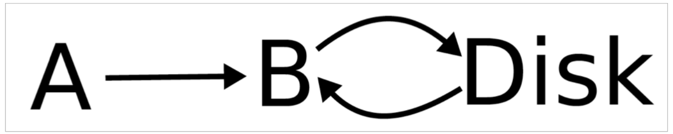
Key idea of wPerf

- Construct a holistic view of the application using wait-for graph:
  - Each thread is a vertex.
  - A directed edge (A->B) means thread A sometimes is waiting for thread B.
- Theorem: Each knot with at least one worker contains a bottleneck.
  - A knot is a strongly connected component with no outgoing edges.
  - Optimizing events outside of knot cannot improve worker in the knot.

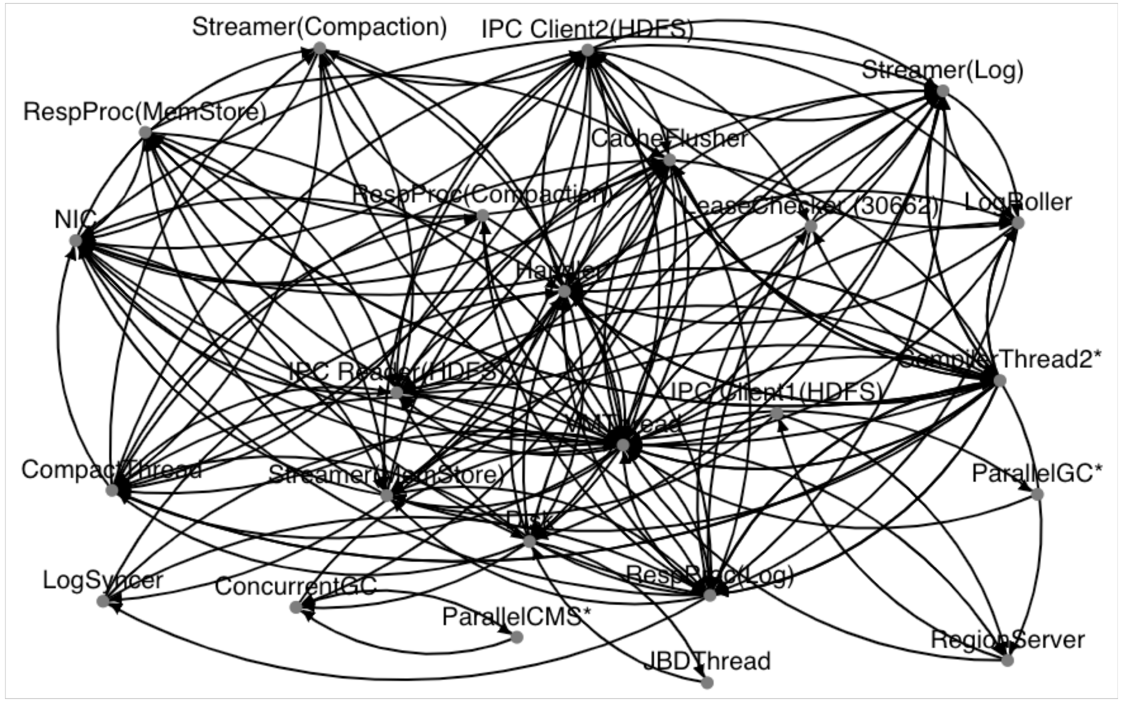


The wait-for graph of the example

Theory vs Practice



Theory

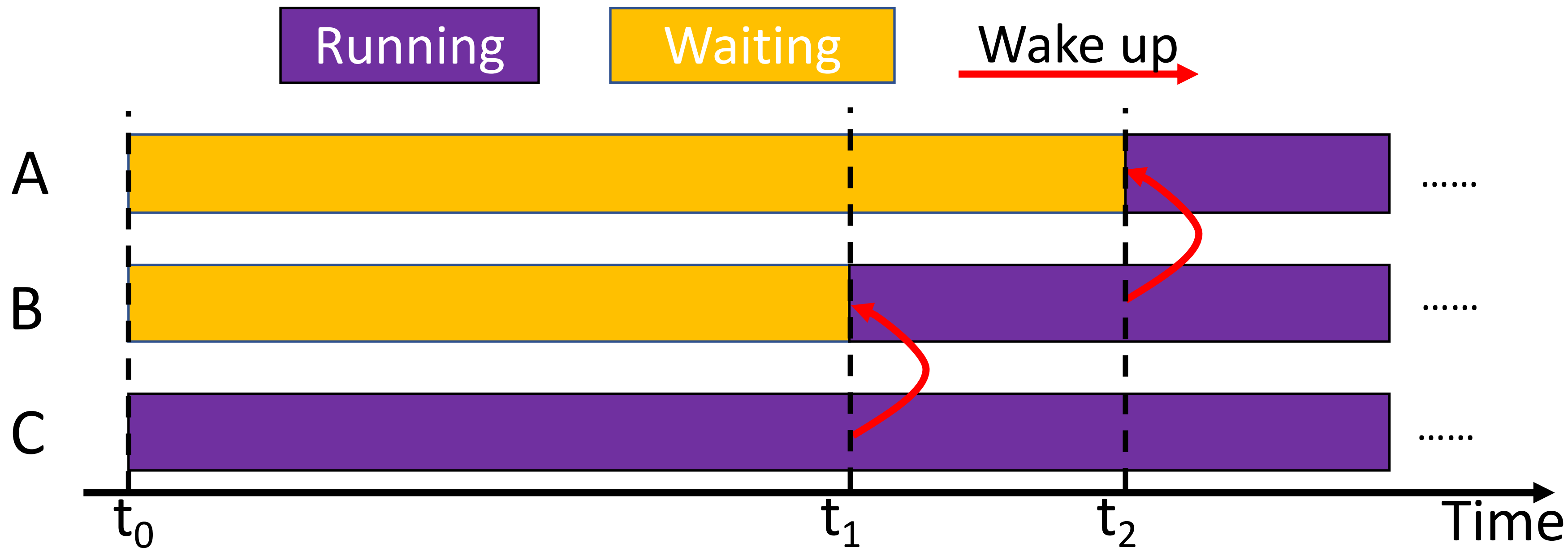


Practice

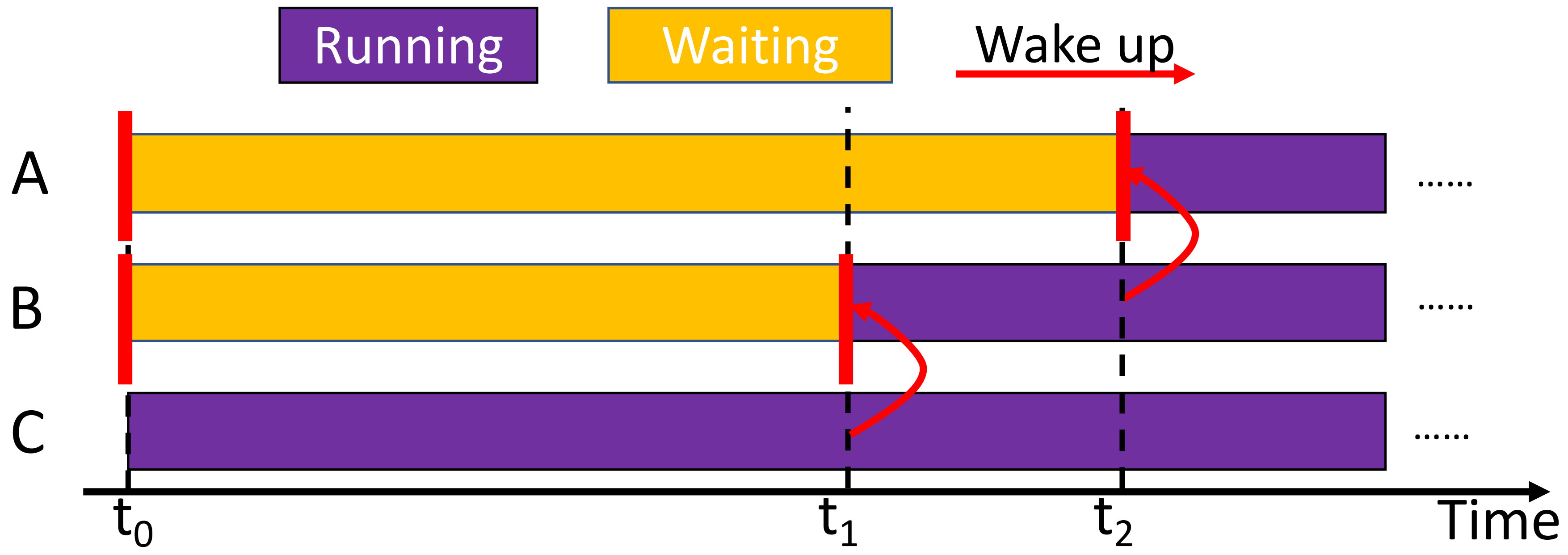
Solution: trim unimportant edges

- wPerf trims edges with little impact on throughput.
  - However, computing global impact is a challenging problem in the first place.
- Solution: use the waiting time spent on an edge to estimate the upper bound of the benefit of optimizing the edge.
- Challenge: nested waiting

An example of nested waiting



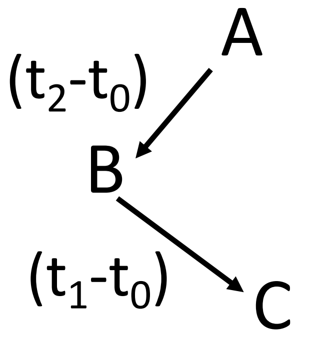
Naïve approach to compute waiting time



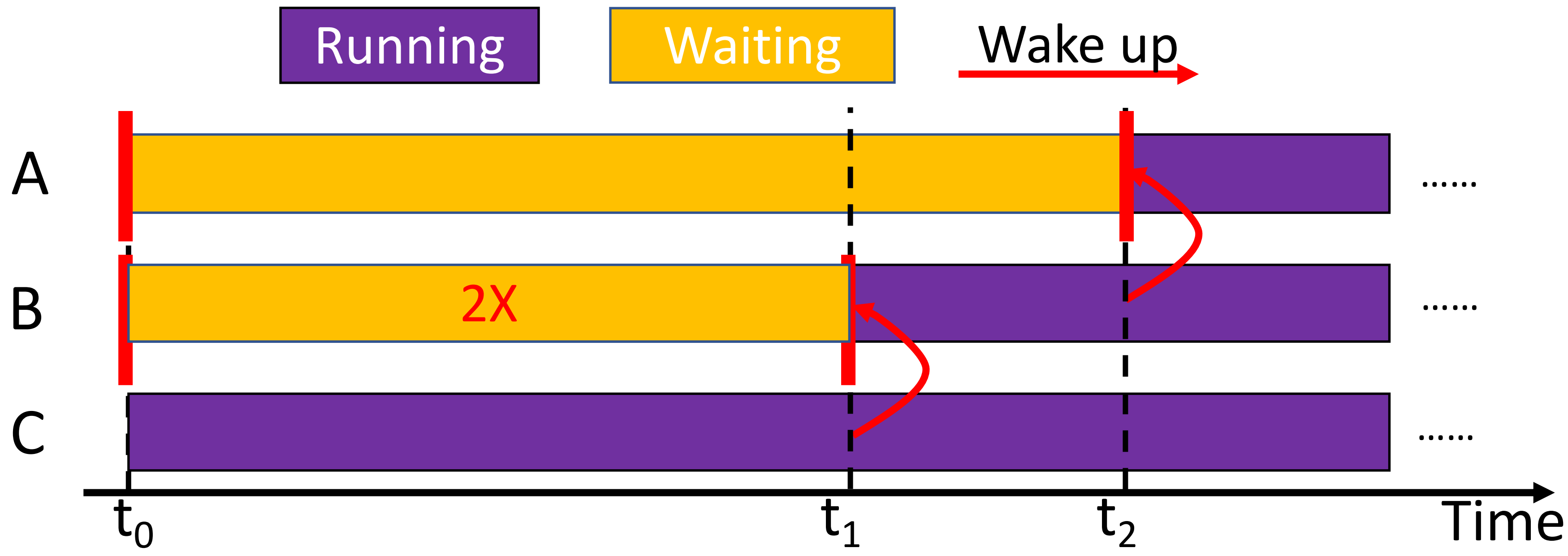
Naïve approach:
A waits for B from t0 to t2, add (t2-t0) to A->B.
B waits for C from t0 to t1, add (t1-t0) to B->C.

Problem: underestimate B->C

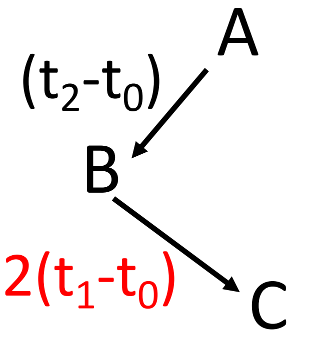
Wait-for graph



wPerf's solution



Wait-for graph



Detailed algorithm: cascaded re-distribution

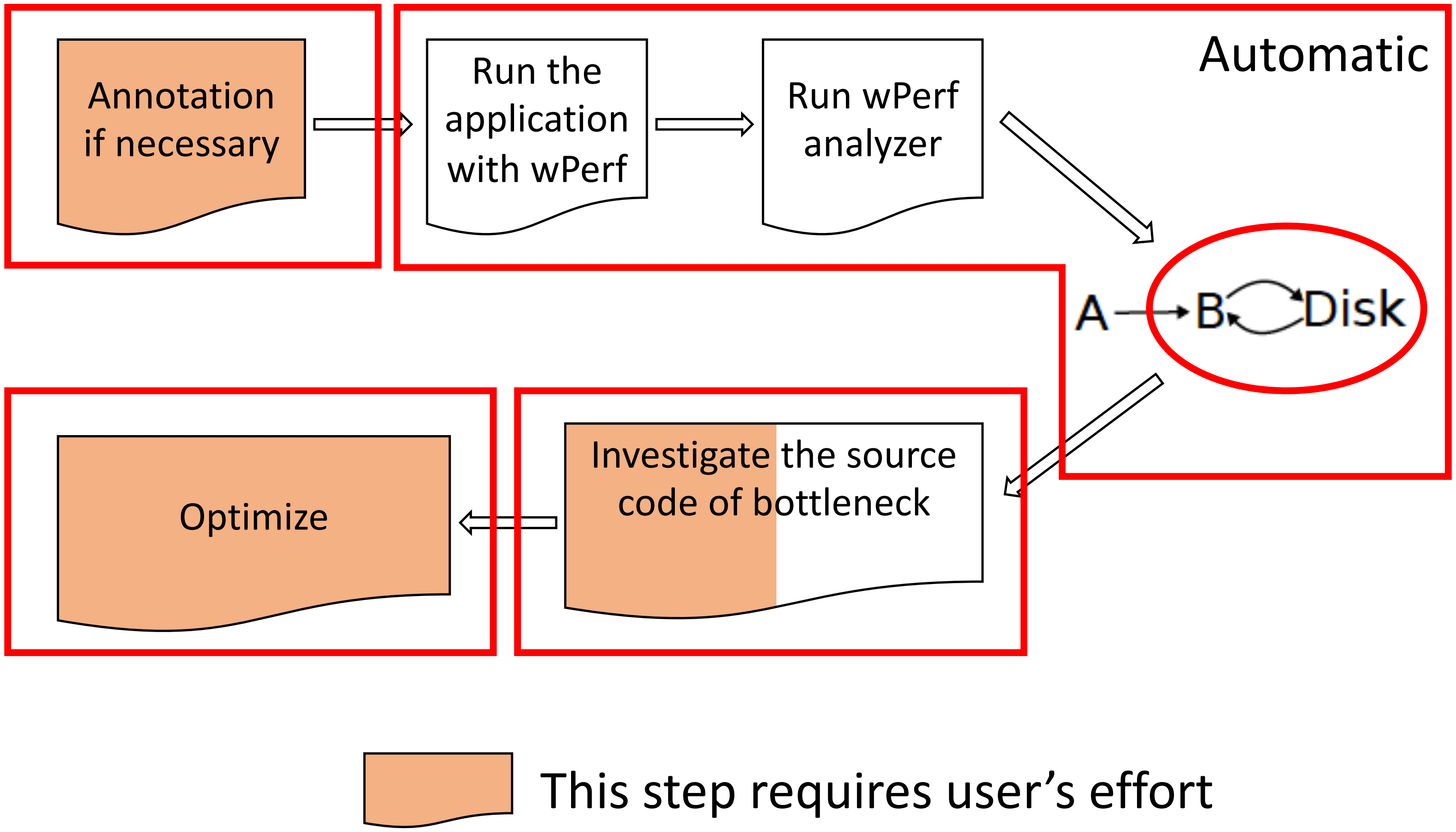
wPerf's overall algorithm

1. Build the wait-for graph with weights.
2. Identify knot.
3. If the knot is smaller than a threshold, terminate.
4. Otherwise remove the edge with the lowest weight.
5. Go to 2.

Termination condition: smallest weight in the knot is larger than a threshold

-Threshold value depends on how much improvement the user expects.

Overall procedure of using wPerf



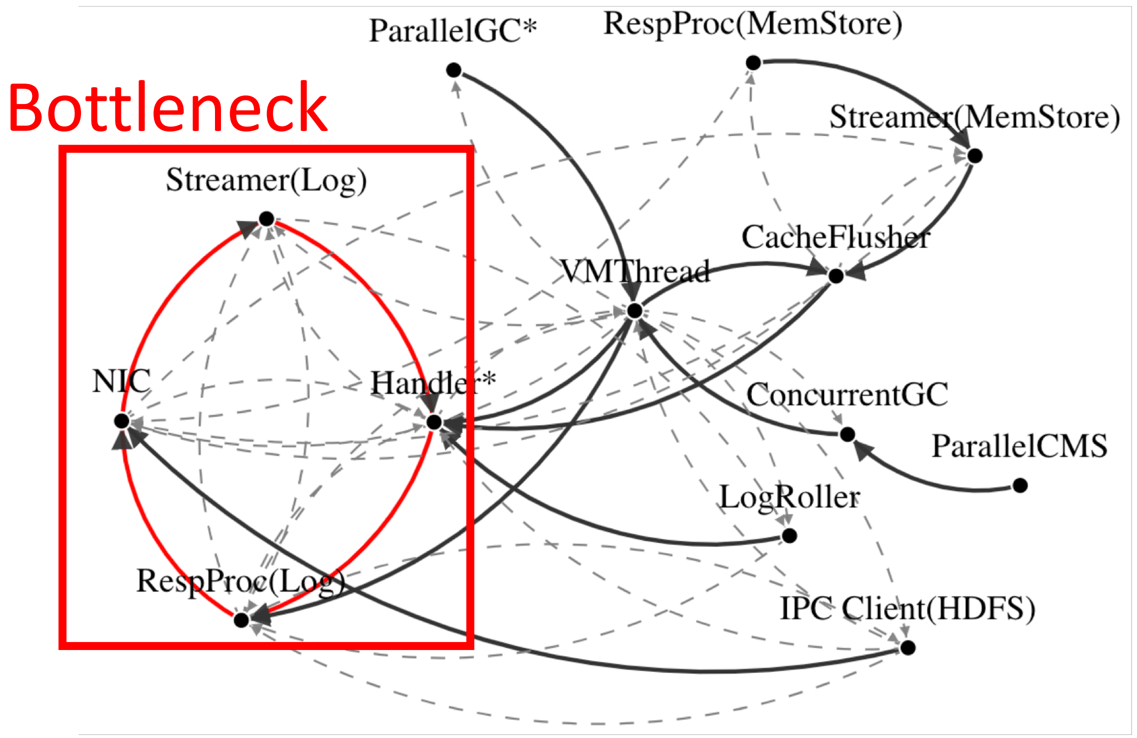
Evaluation

- Case studies: Can wPerf identify bottlenecks in real applications?
  - We apply wPerf to seven open-source applications.
  - To confirm wPerf’s accuracy, we tried to investigate and optimize the bottlenecks reported by wPerf.
- Overhead:
  - How much does recording slow down the application?
  - Required user’s effort?

Summary of case studies

Application	Problem	Speedup after Optimization	Recording Overhead	Known fixes?
HBase 0.92	Blocking write	2.74x	3.37%	Yes
ZooKeeper 3.4.11	Blocking write	4.83x	2.84%	No
HDFS 2.70	Blocking write	2.56x	3.40%	Yes
grep over NFS	Blocking read	3.9x	0.77%	No
BlockGrace	Load imbalance	1.44x	8.04%	No
Memcached	Lock contention	1.64x	2.43%	Partially
MySQL	Lock contention	1.42x	14.64%	Yes

Case study: HBase



Wait-for graph of original RegionServer

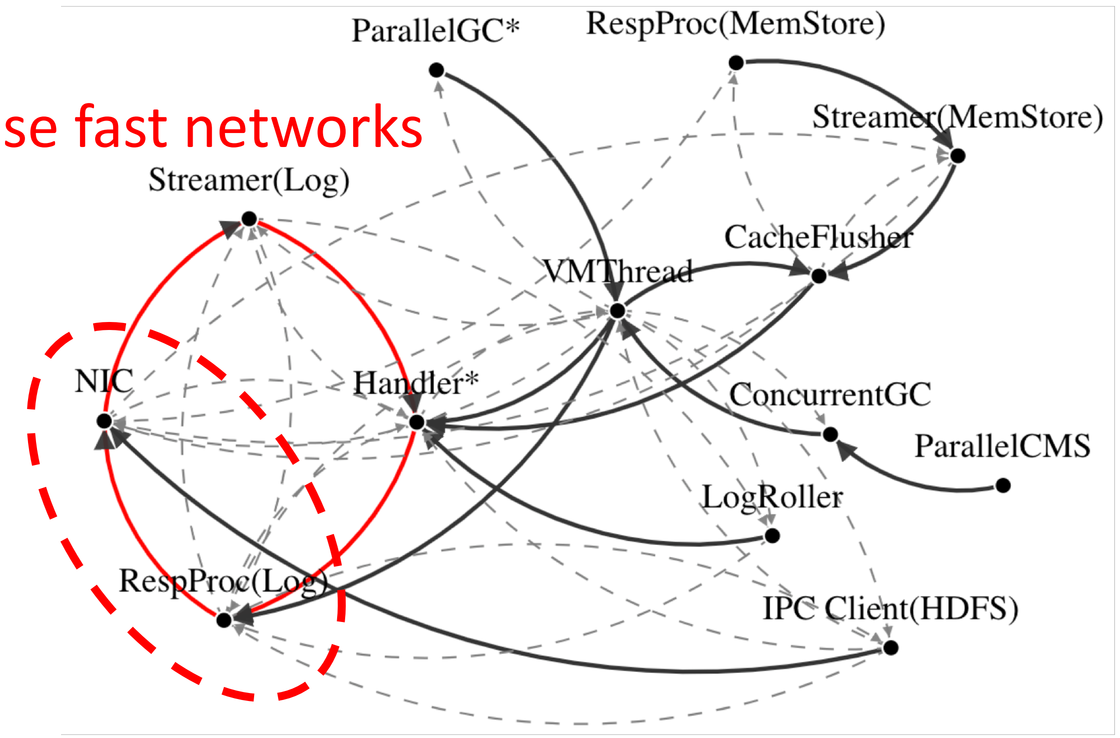
Workload: write workload with 1KB KV pairs.

Our solution: reducing blocking between Handler and RespProc

HBase uses parallel flushing to alleviate this problem, but the default setting of 10 handler threads is not enough.

Case study: HBase

Use fast networks



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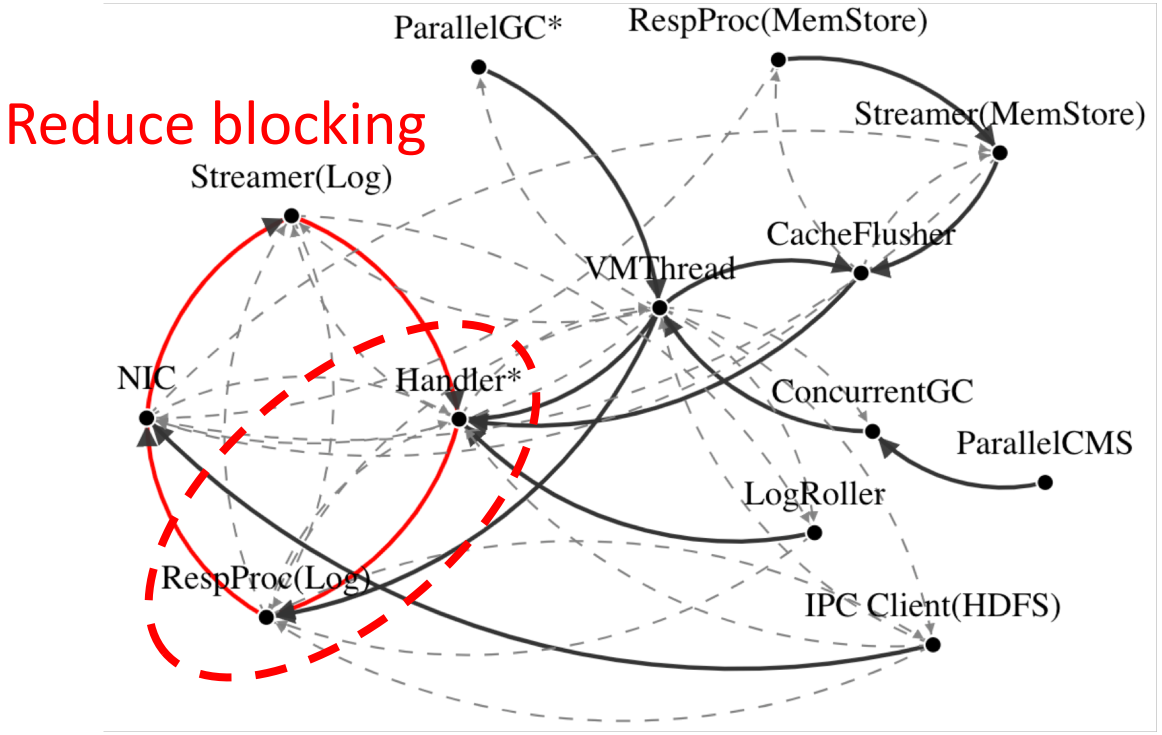

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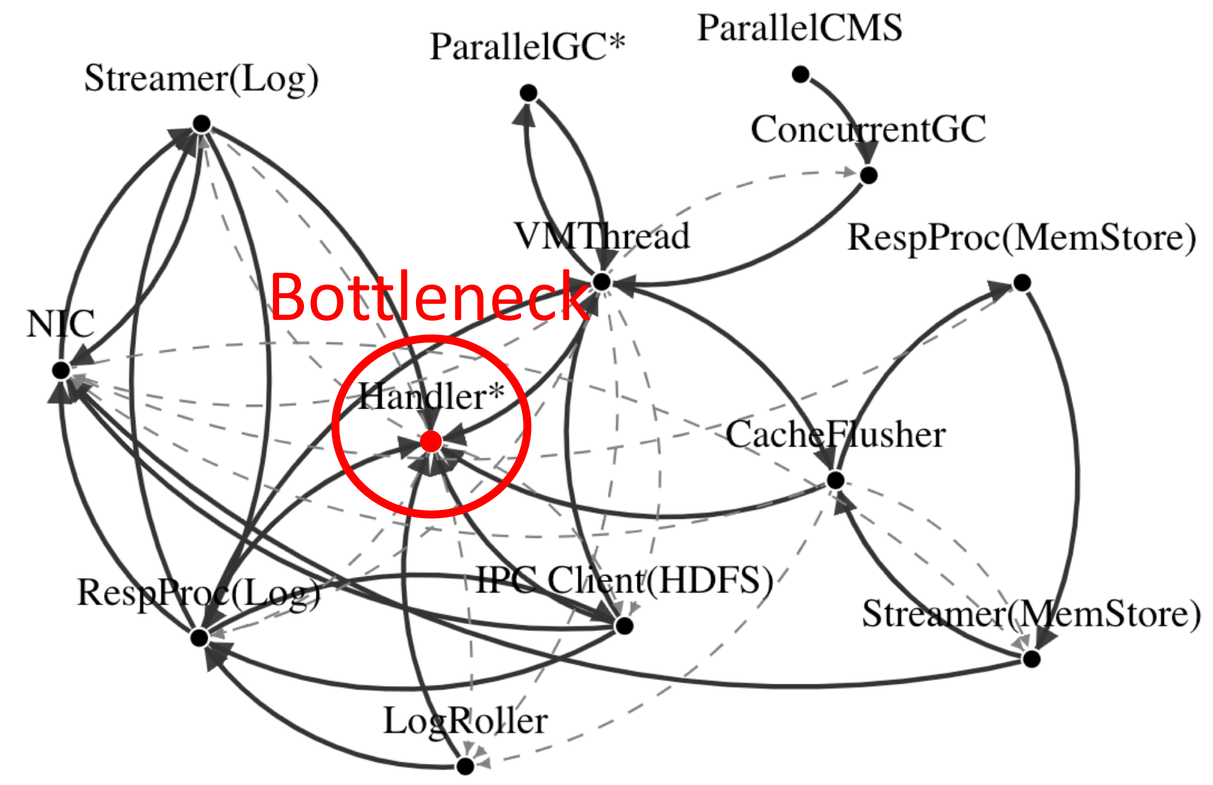


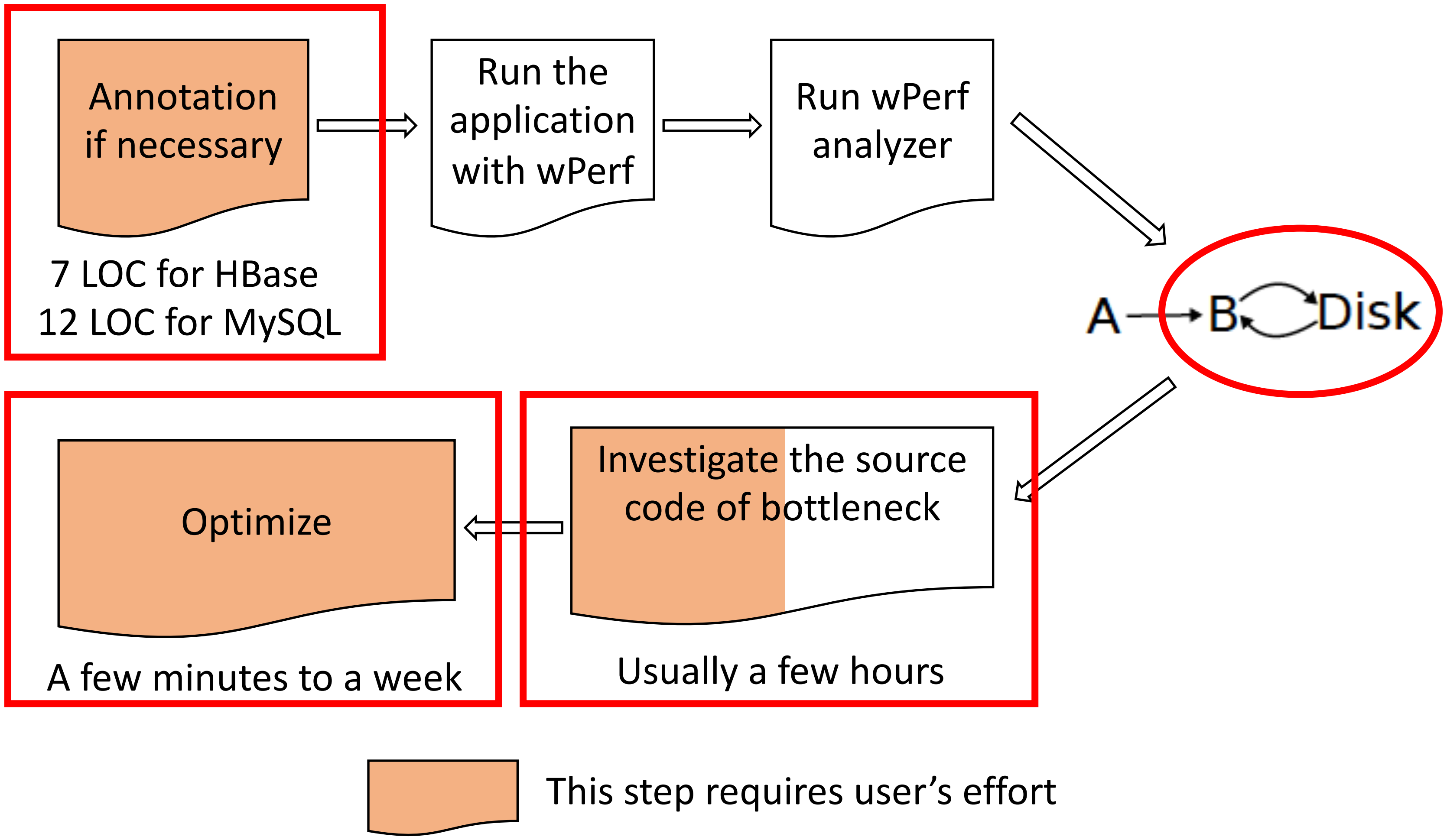
New wait-for graph of RegionServer after optimization

Increasing handler count to 60 can improve throughput by 41%.

Comparing to the previous one, the weight of Handler->RespProc is much smaller (87.42 -> 16.54).

Optimize Handlers can further improve throughput.

Users’ efforts when using wPerf



Summary and future work

- wPerf identifies events with large impacts on all worker threads.
- wPerf can find bottlenecks others cannot find.
- In the future, we plan to extend wPerf to distributed systems.
- You can find the source code of wPerf in github.
  https://github.com/OSUSysLab/wPerf
- Poster number: 12

wPerf