Fine-Grained Multiprocessor Real-Time Locking with Improved Blocking

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Motivation

- Locks can be used to control access to:
  - Shared memory objects
  - Shared hardware resources (e.g., buses, GPUs, shared caches, etc.)
- However, locks cause blocking.
- Our goal: improve worst-case blocking so as to improve real-time schedulability.

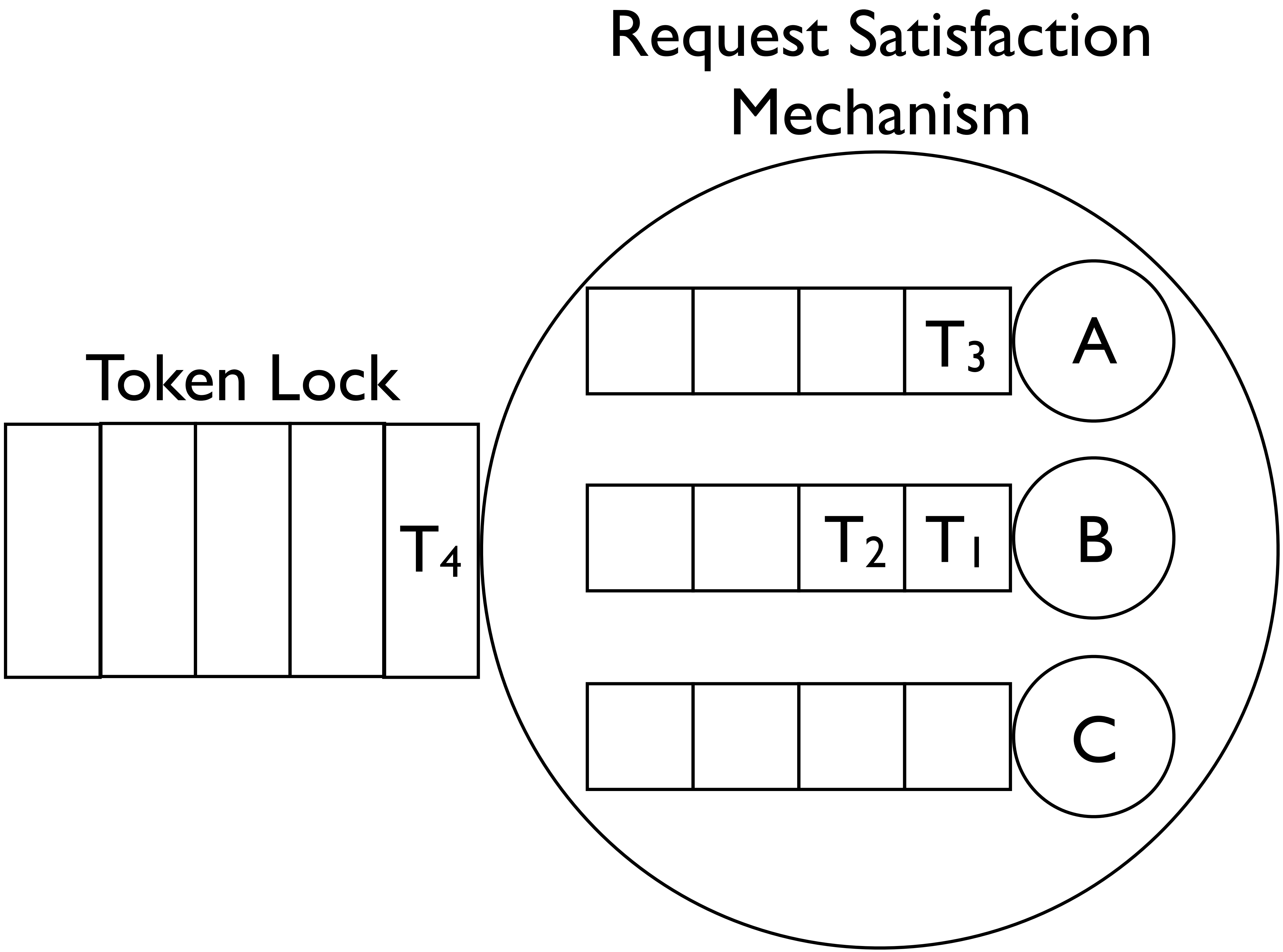
Multi-Resource Locking

- Sometimes jobs need to access multiple shared resources concurrently.
- Two general approaches:
  - Coarse-grained locking.
  - Fine-grained locking.
- The Real-Time Nested Locking Protocol (RNLP) was the first fine-grained locking protocol for multicore real-time systems.

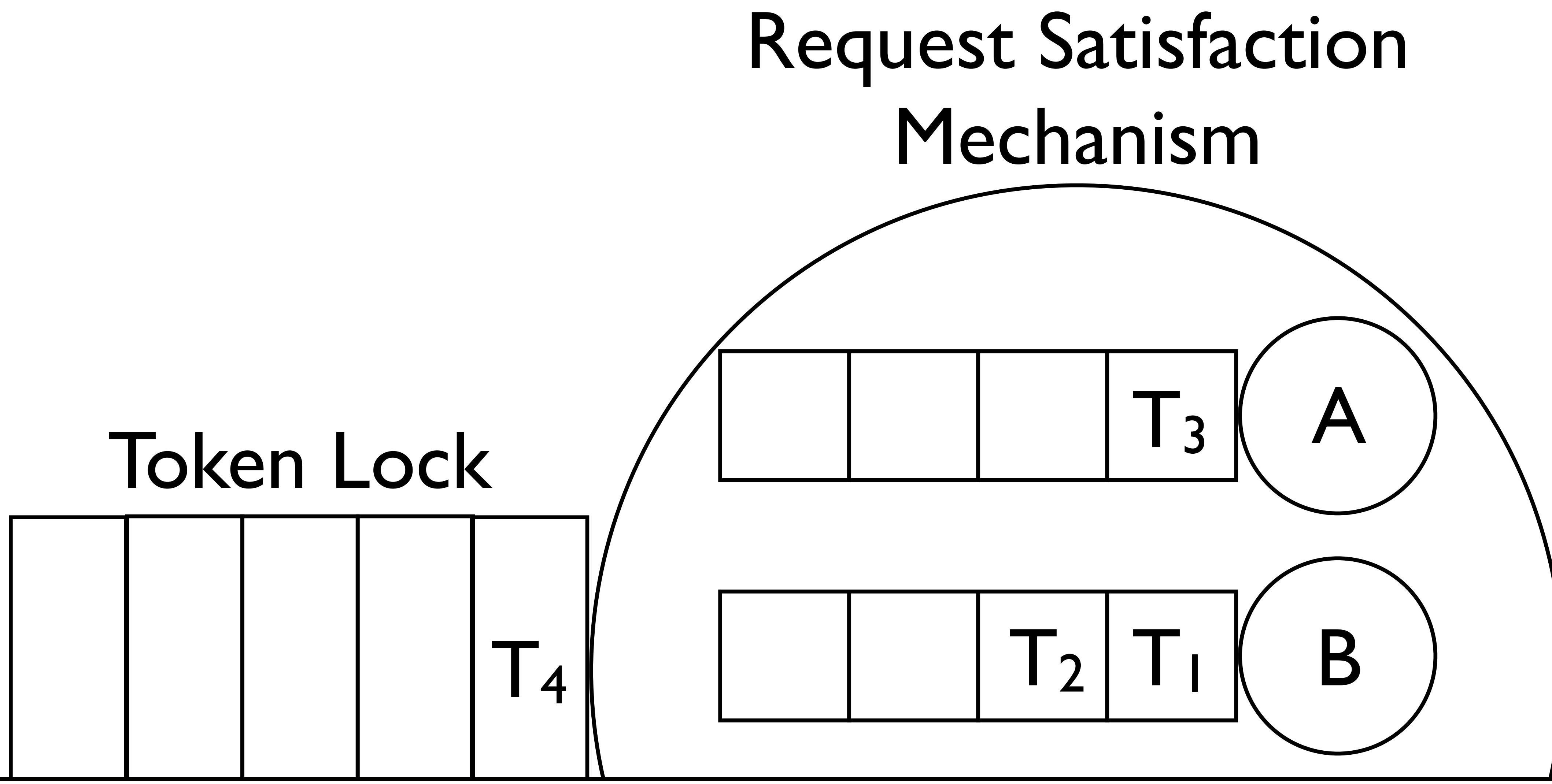
Our Contributions

- We extend the RNLP in three ways:
  1. Reduce system-call overhead.
  2. Improve worst-case blocking when critical sections have different lengths.
  3. Support replicated resources.
- Techniques can be combined, but presented separately (unless noted).

RNLP Background

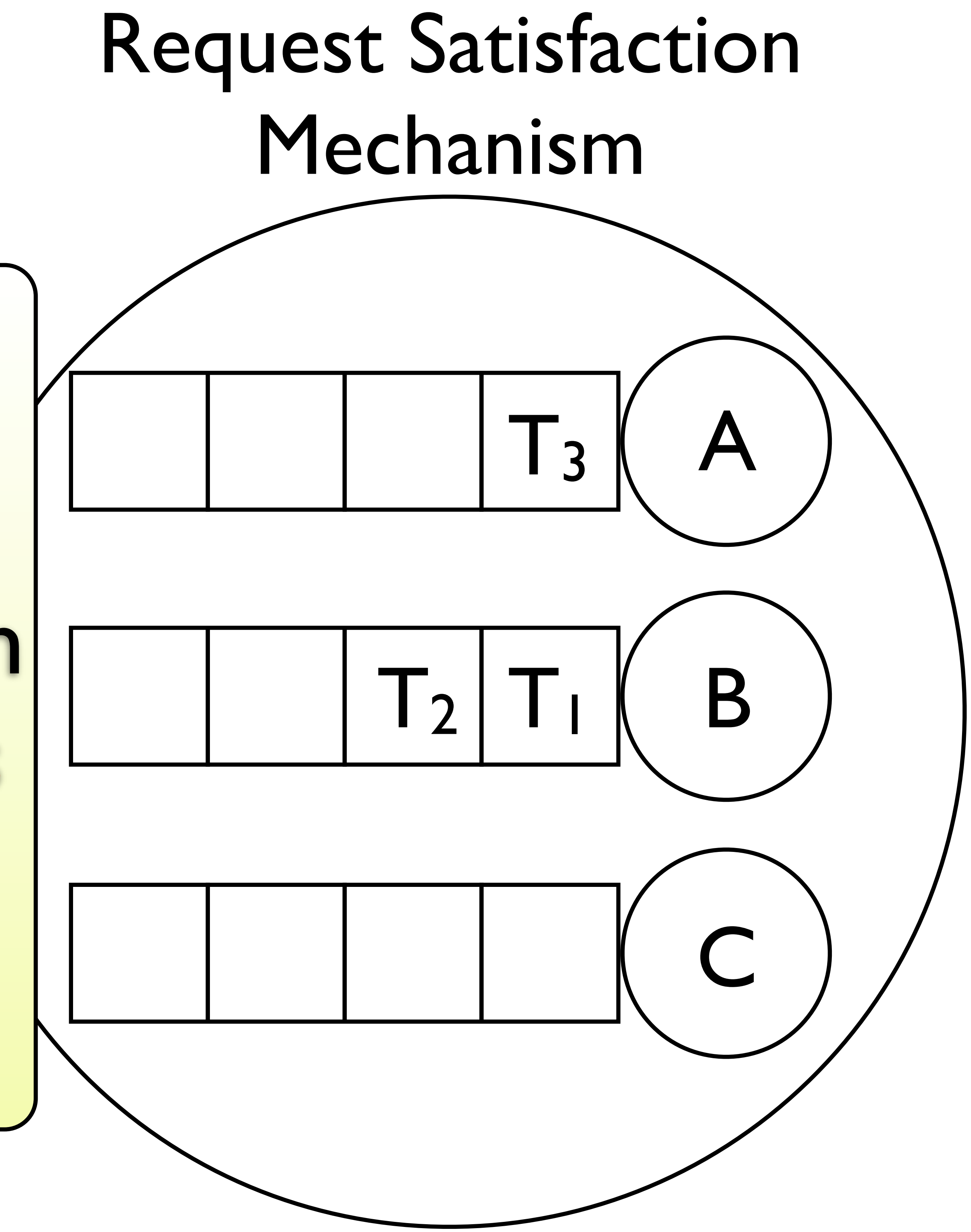


RNLP Background



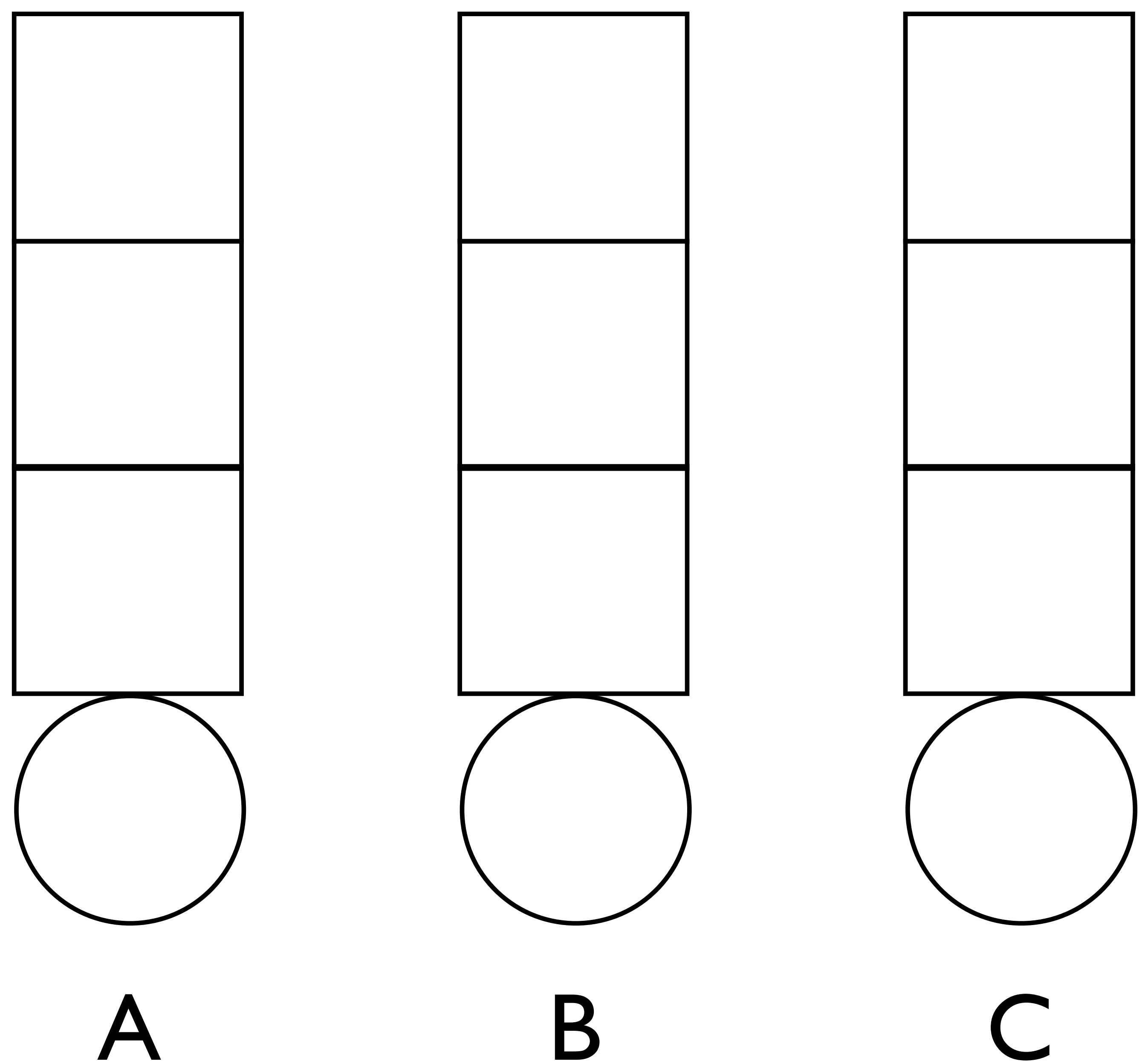
Different token locks can be used to achieve better blocking bounds under different schedulers and analysis assumptions.

RNLP Background



Request satisfaction mechanism (RSM) orders the satisfaction of requests. We focus exclusively on it for the rest of the talk.

Fine-Grained Locking Challenge



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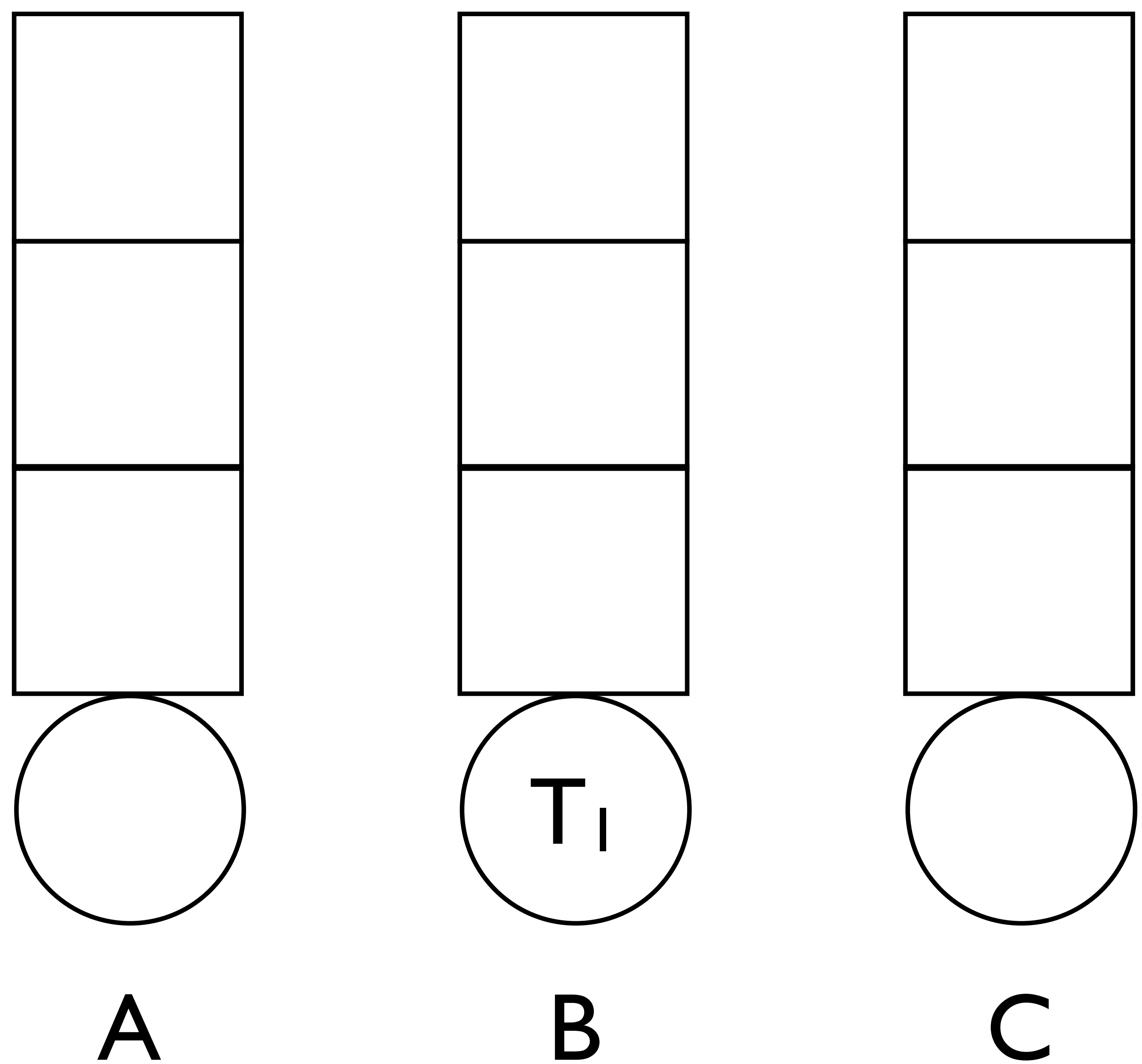

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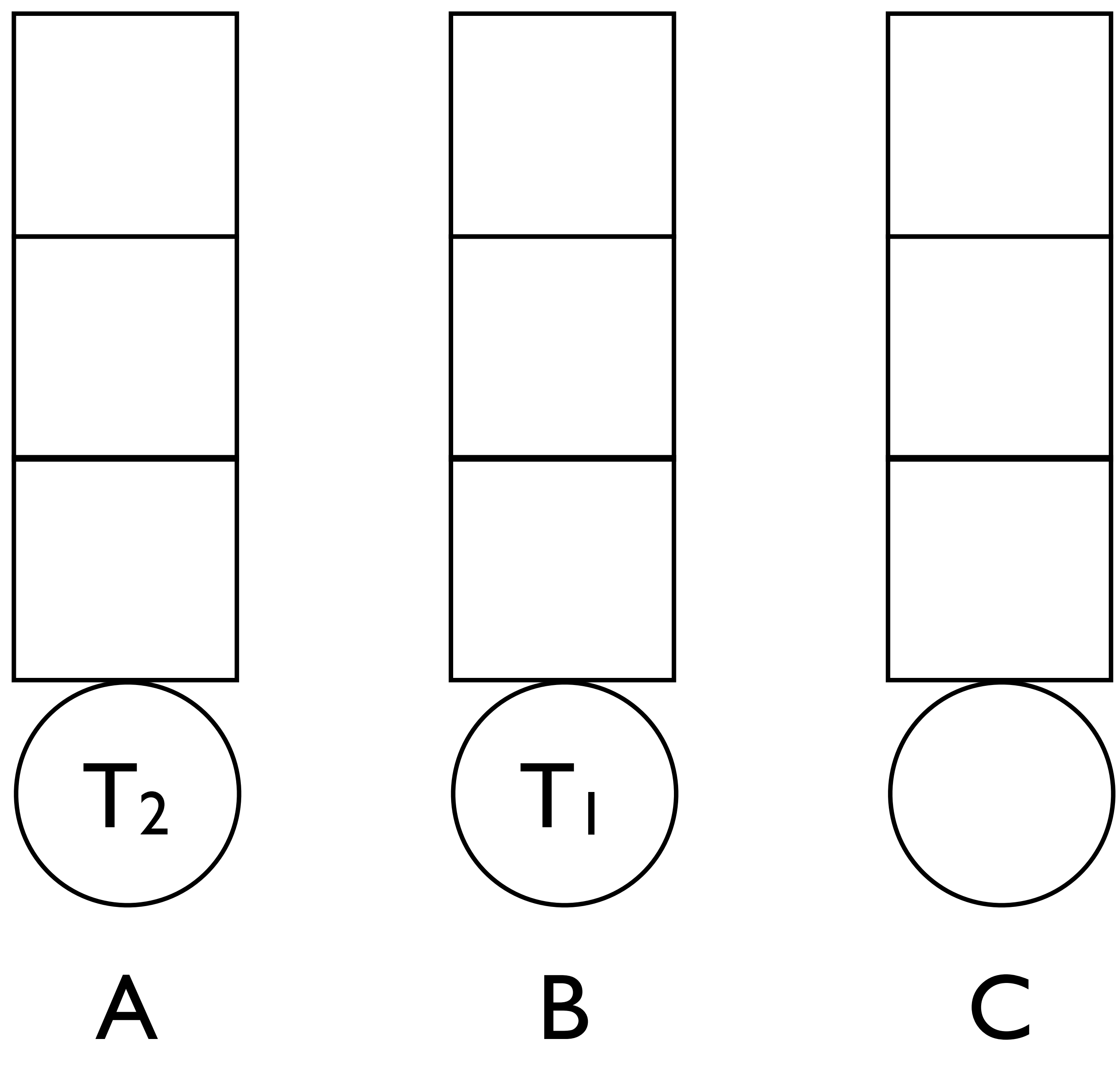

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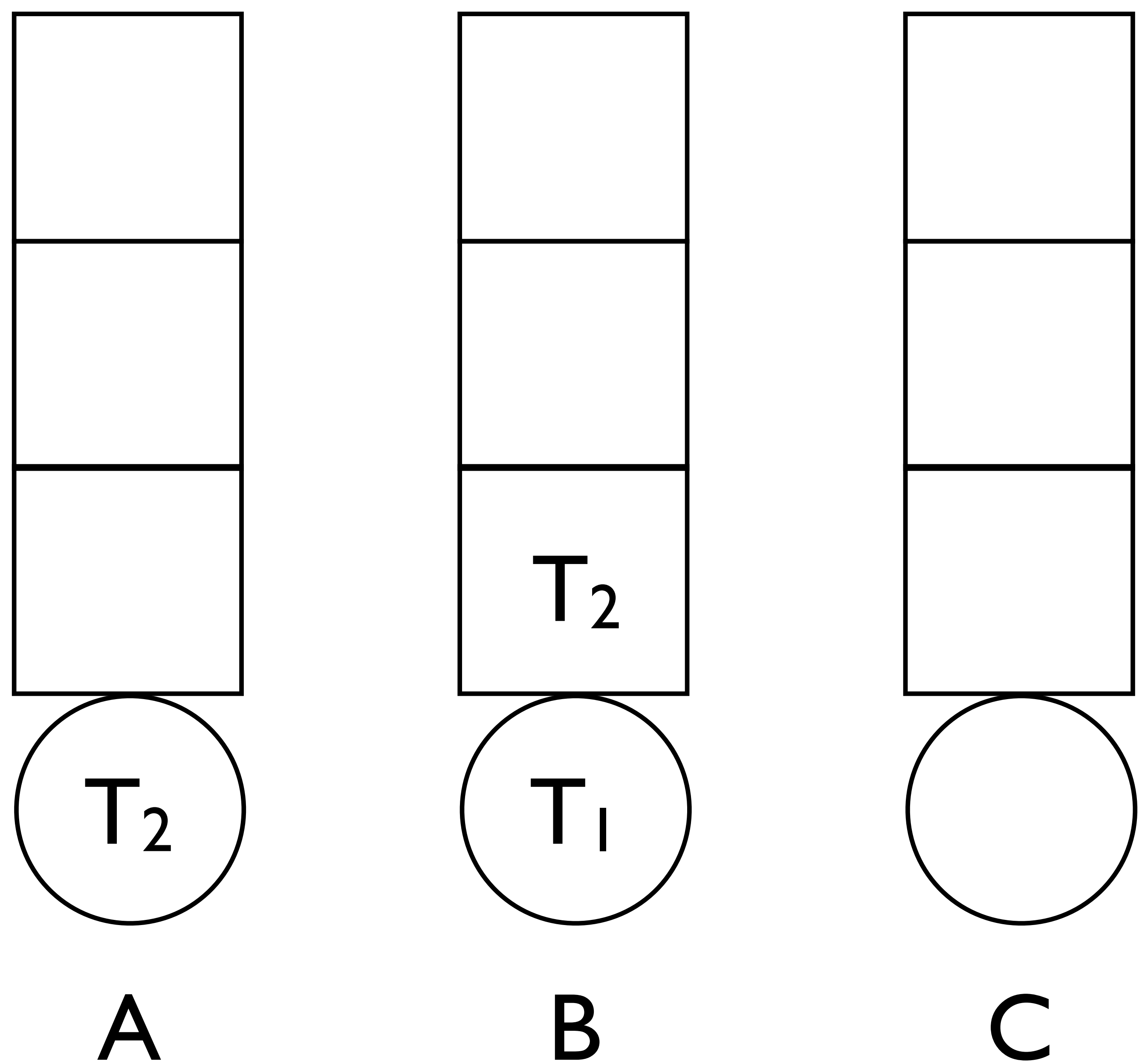

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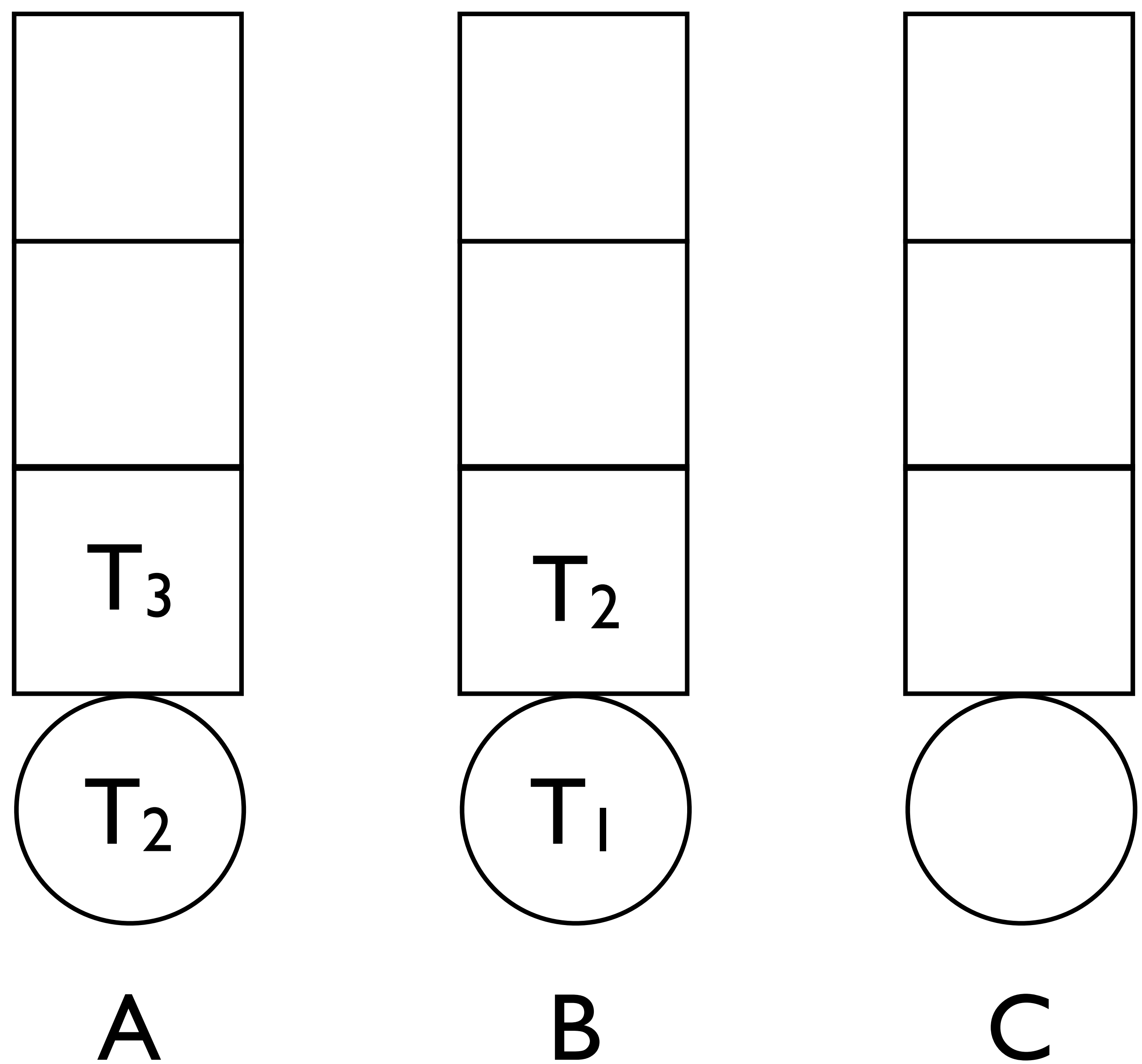

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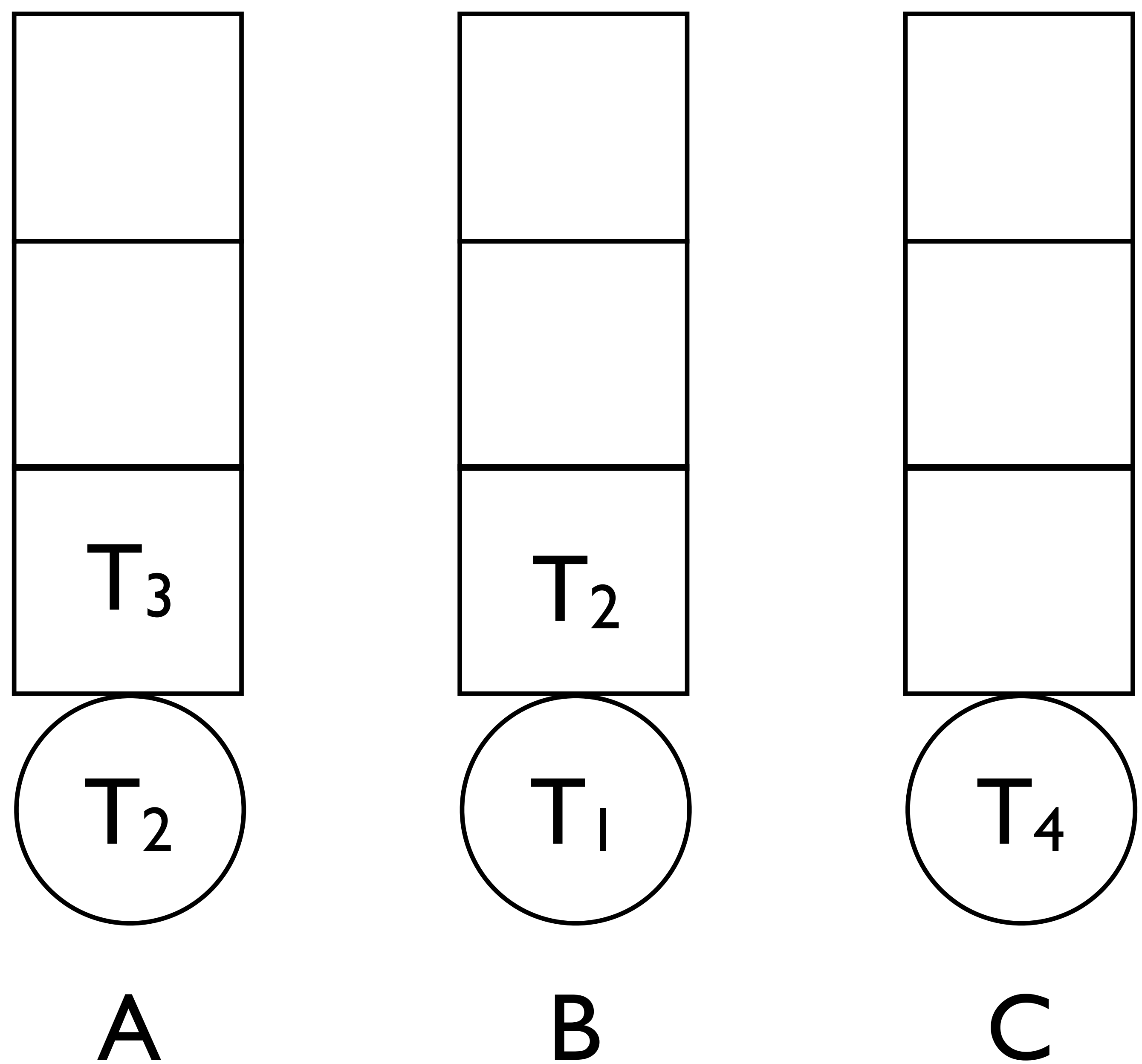

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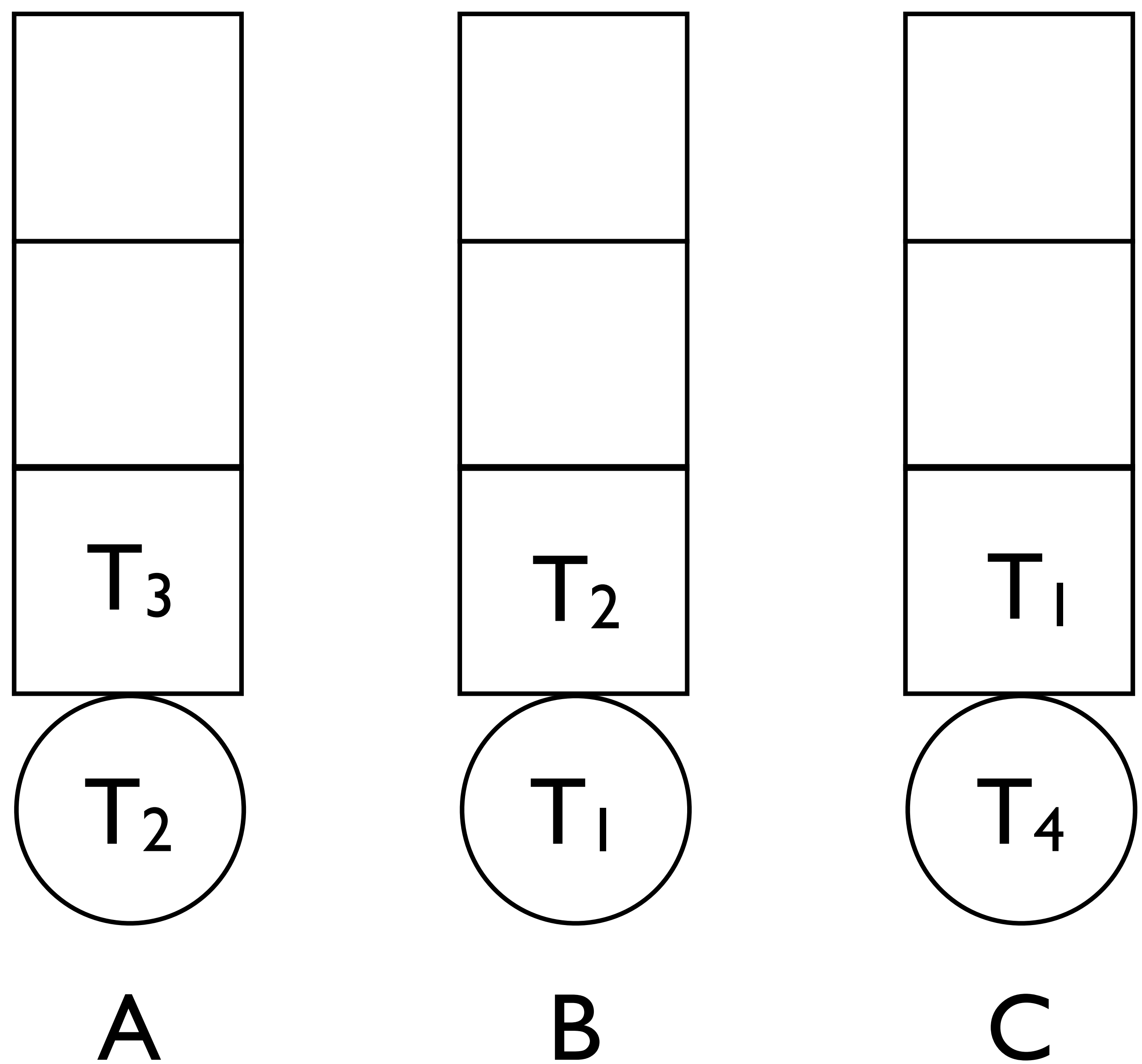

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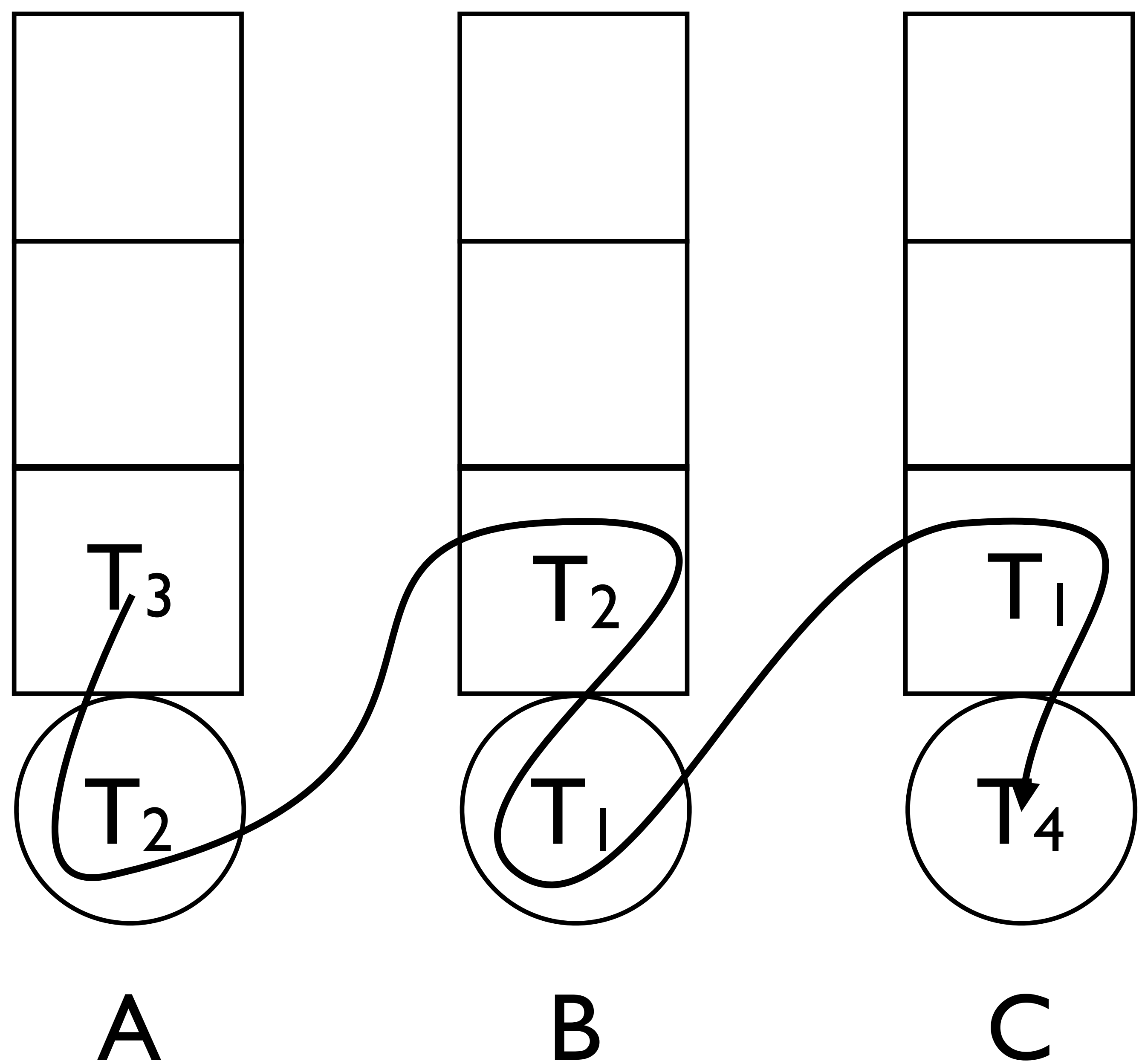
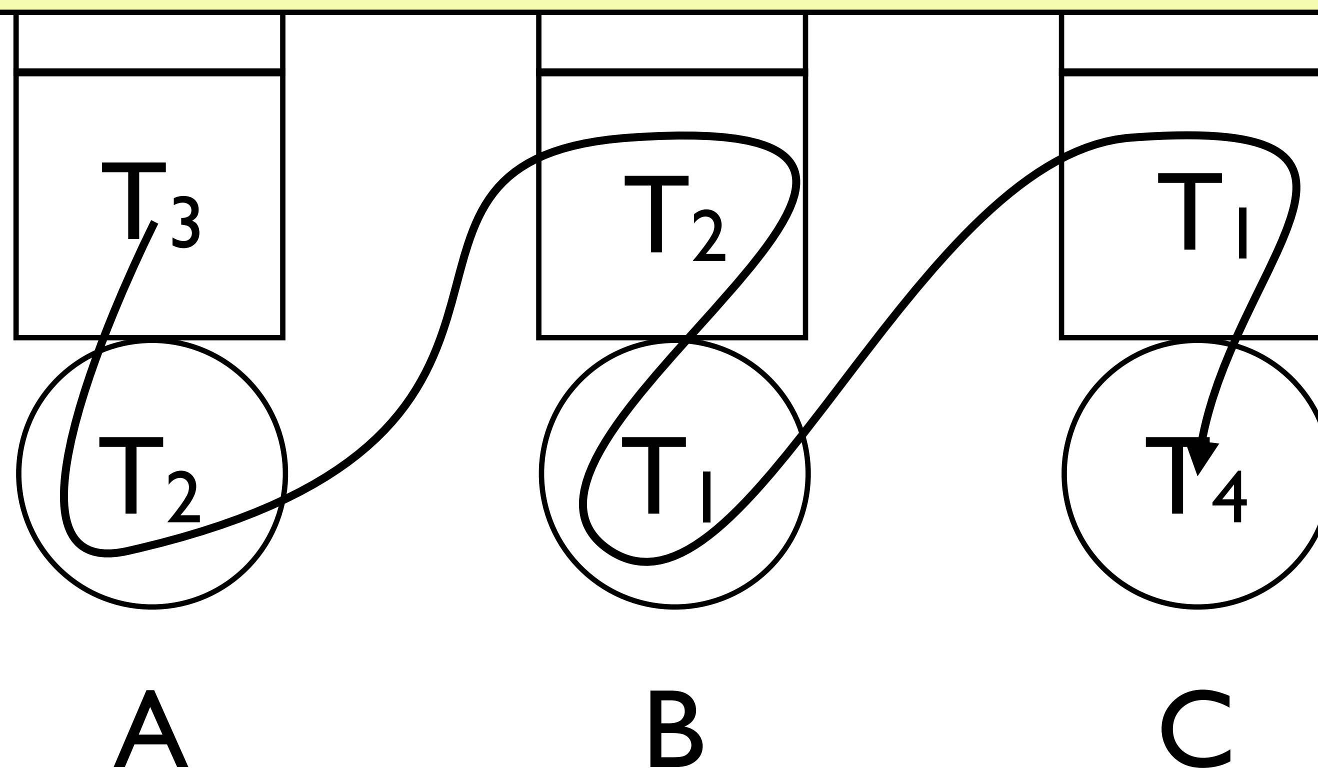
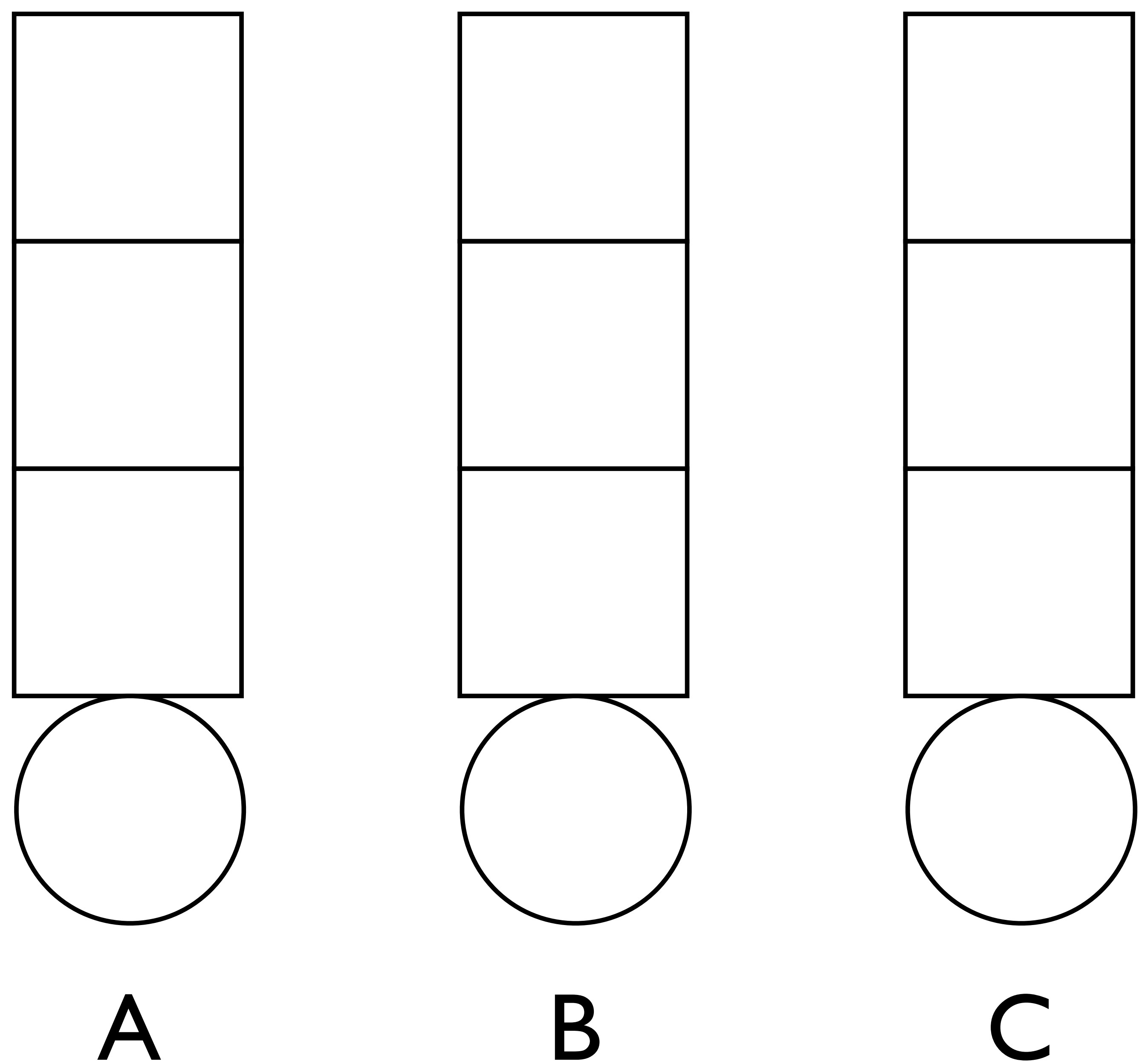


Fine-Grained Locking Challenge

Observation: A later-issued request (T_4) blocks earlier-issued requests (T_1-T_3).



RNLP Solution



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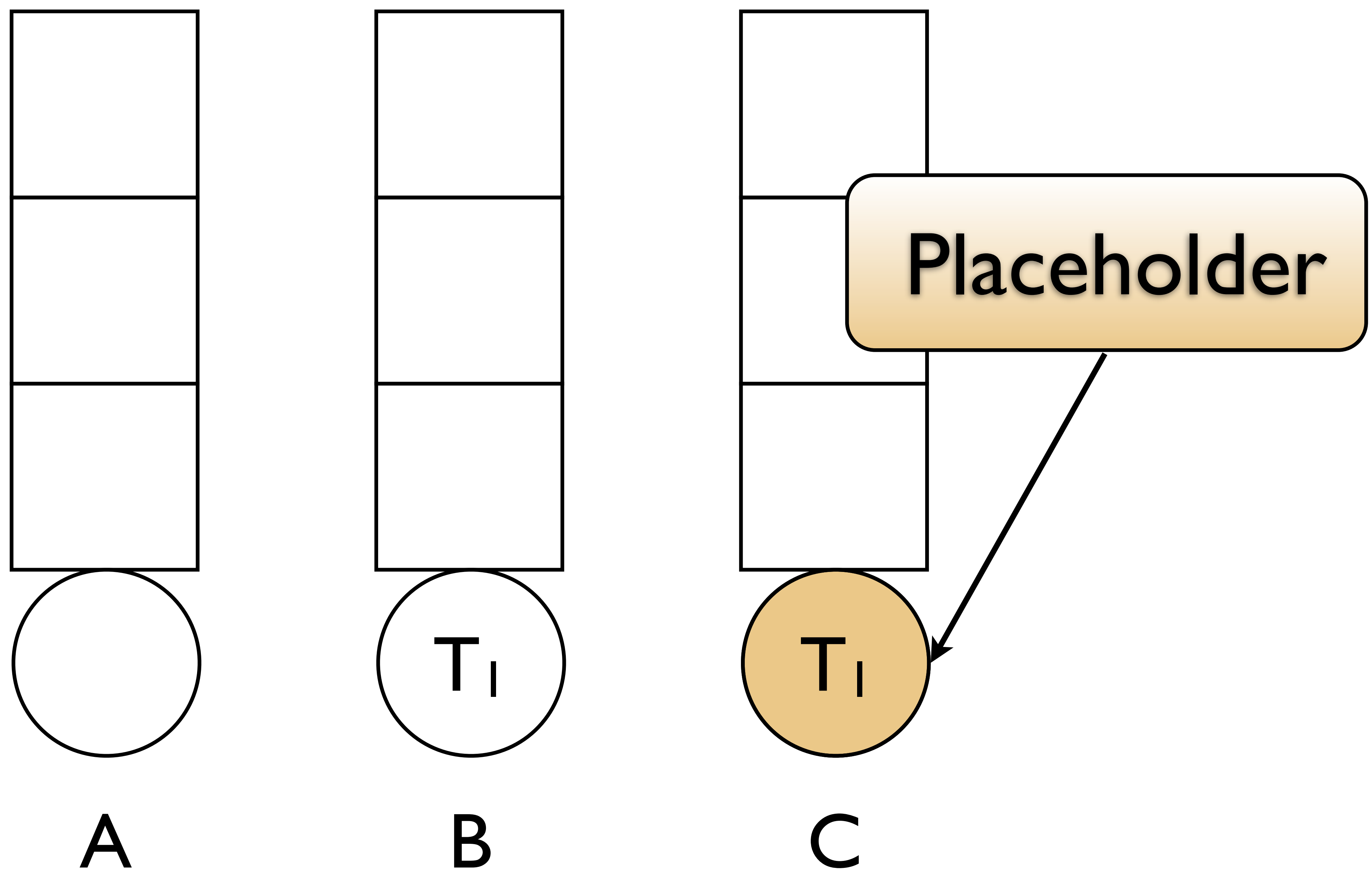

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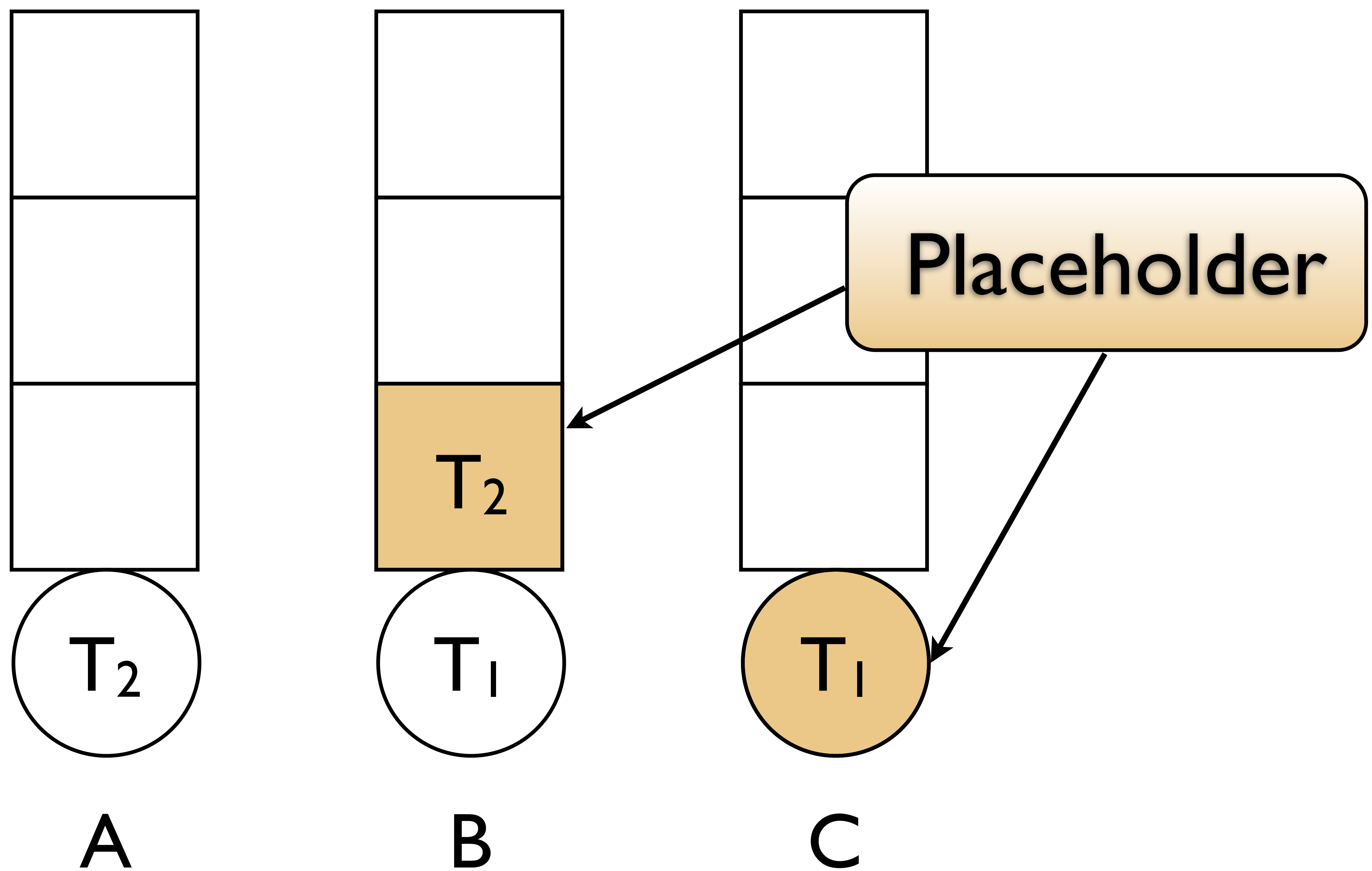

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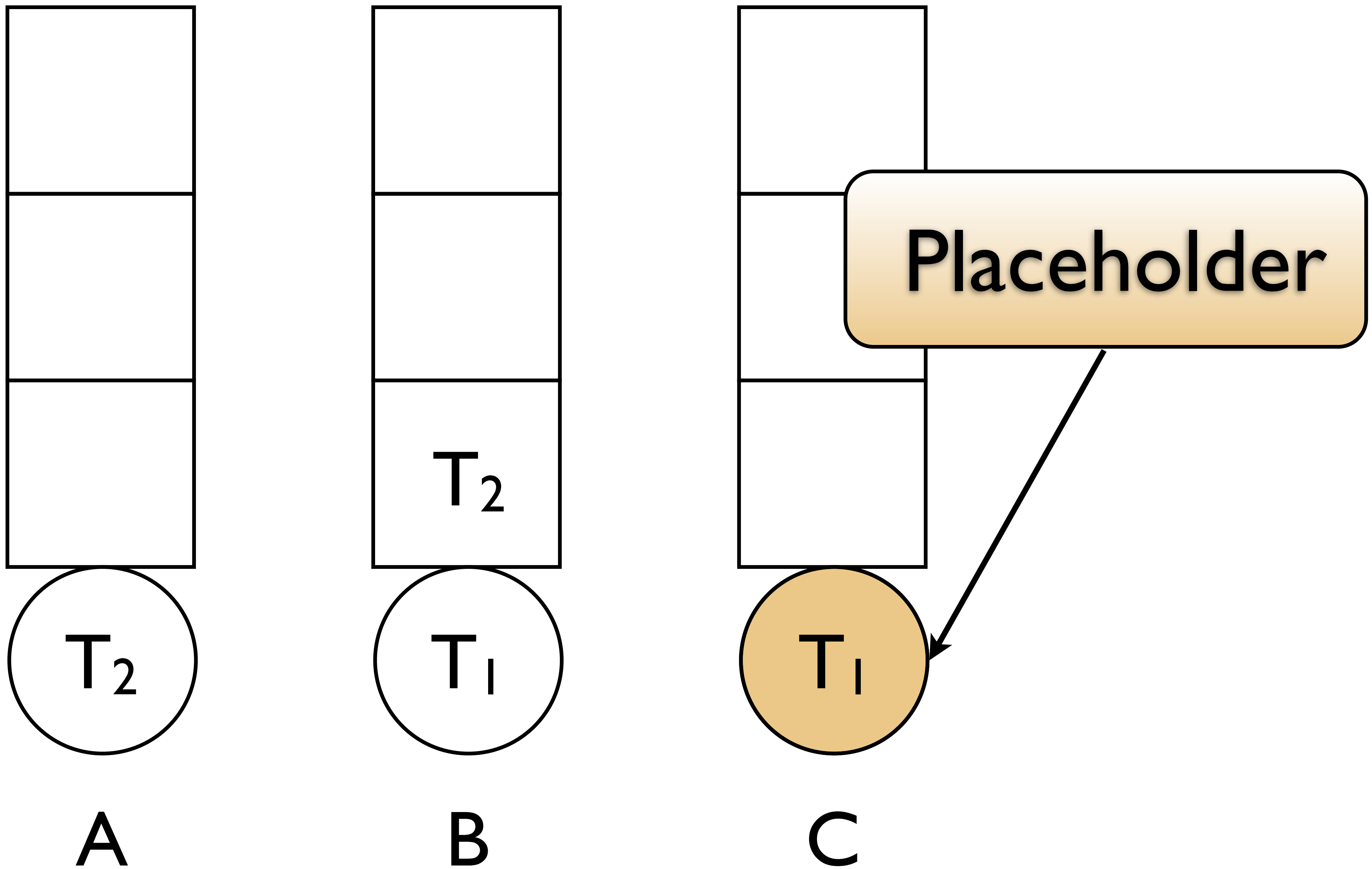

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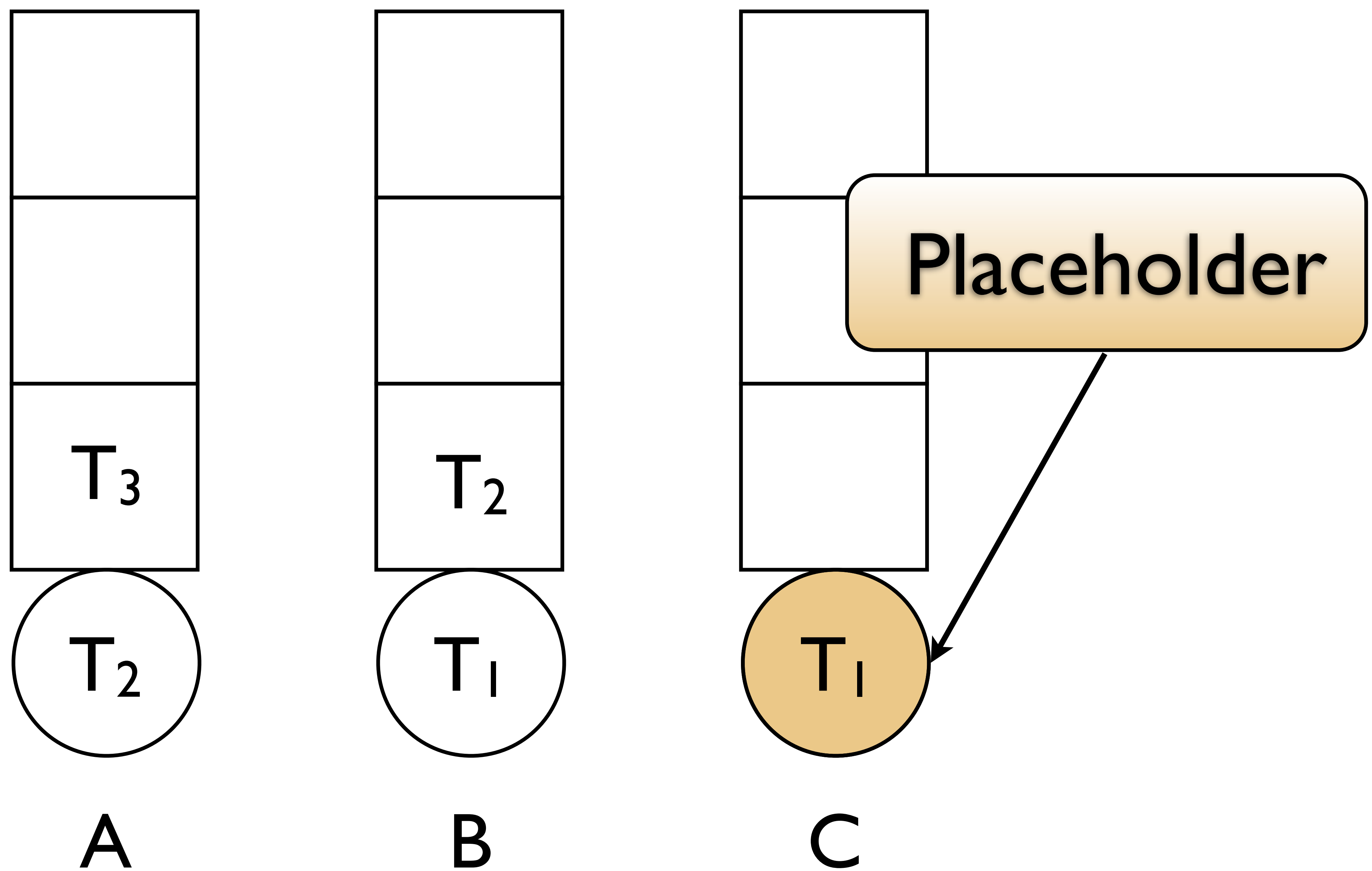

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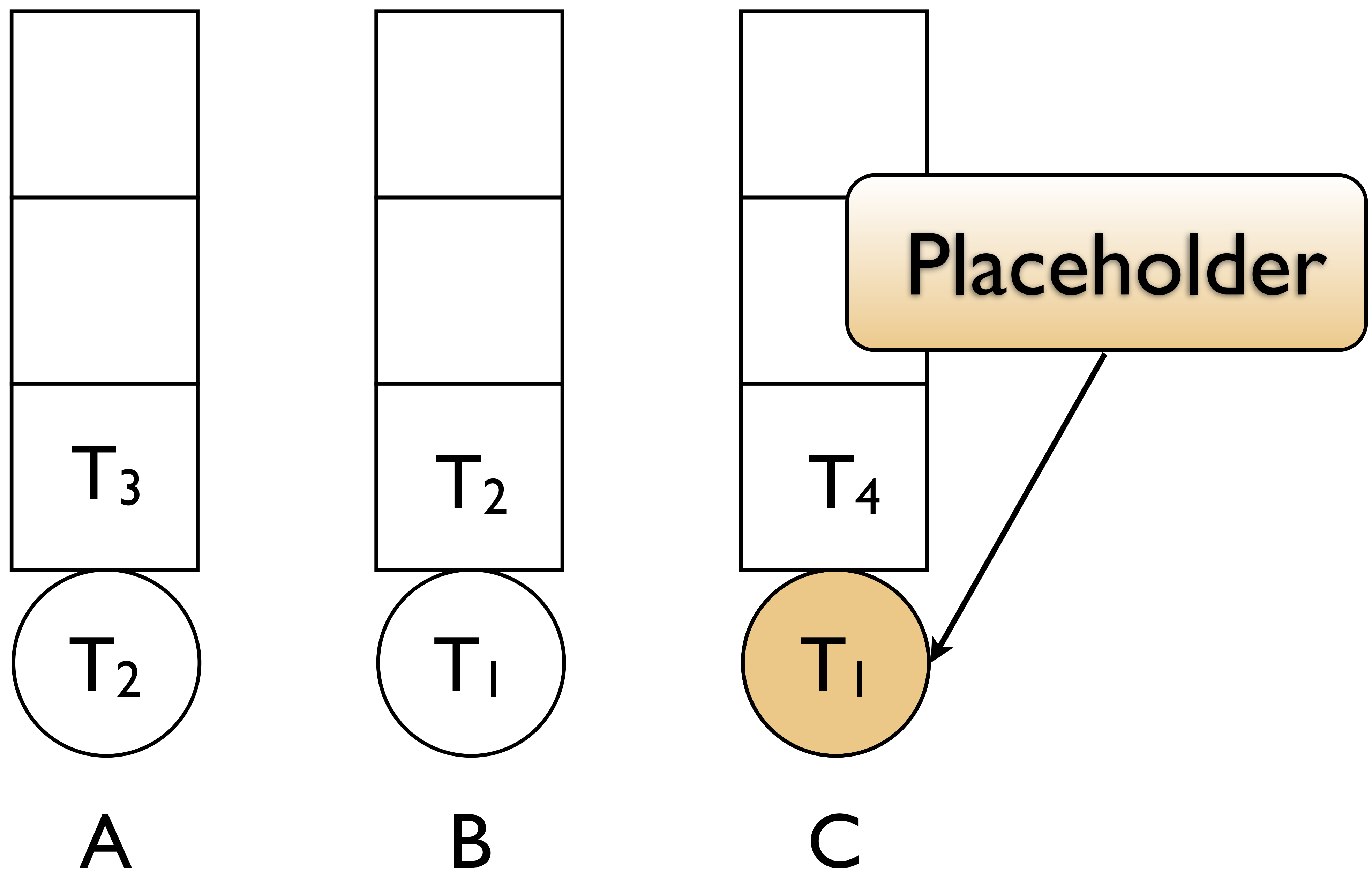
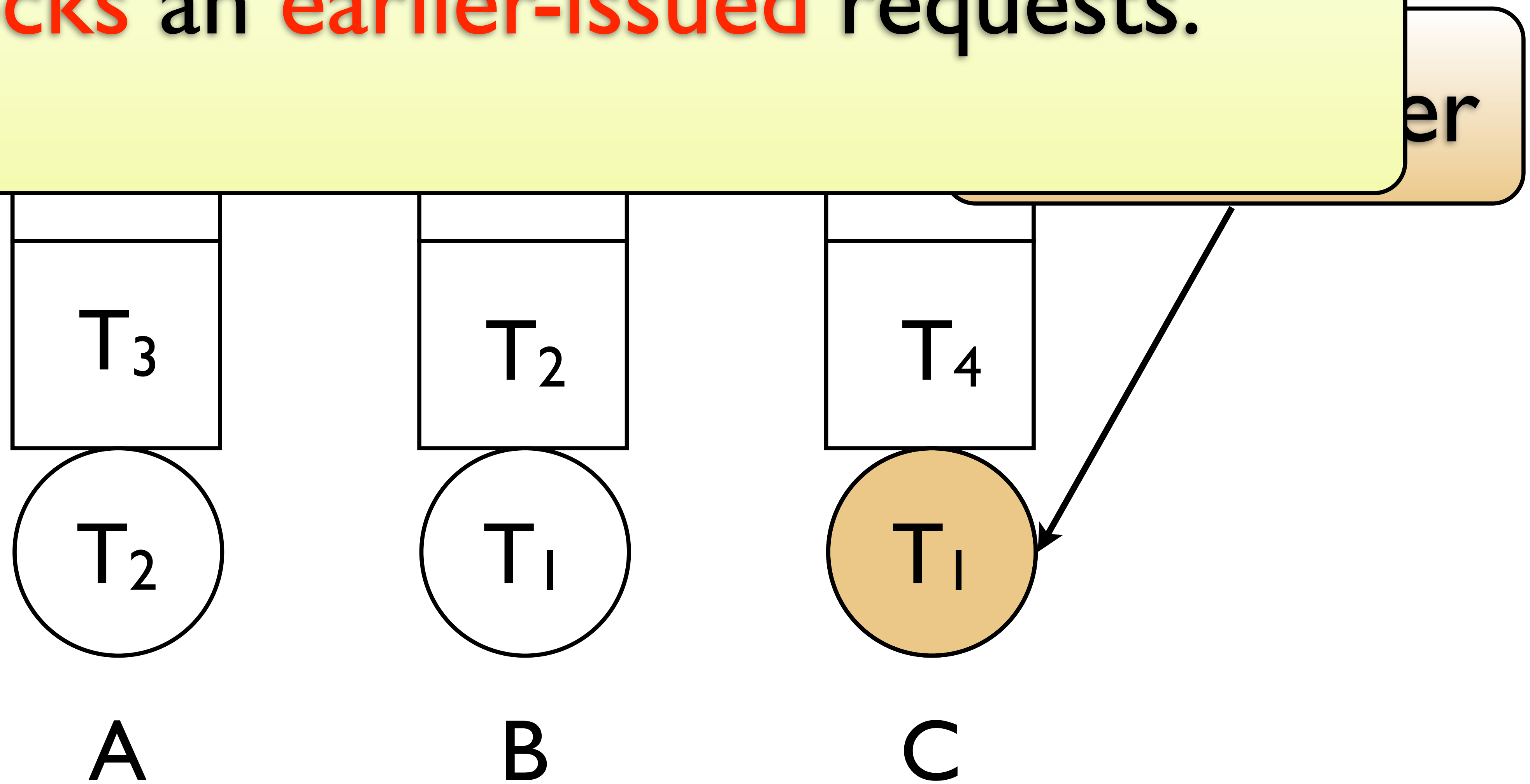


RNLP Solution

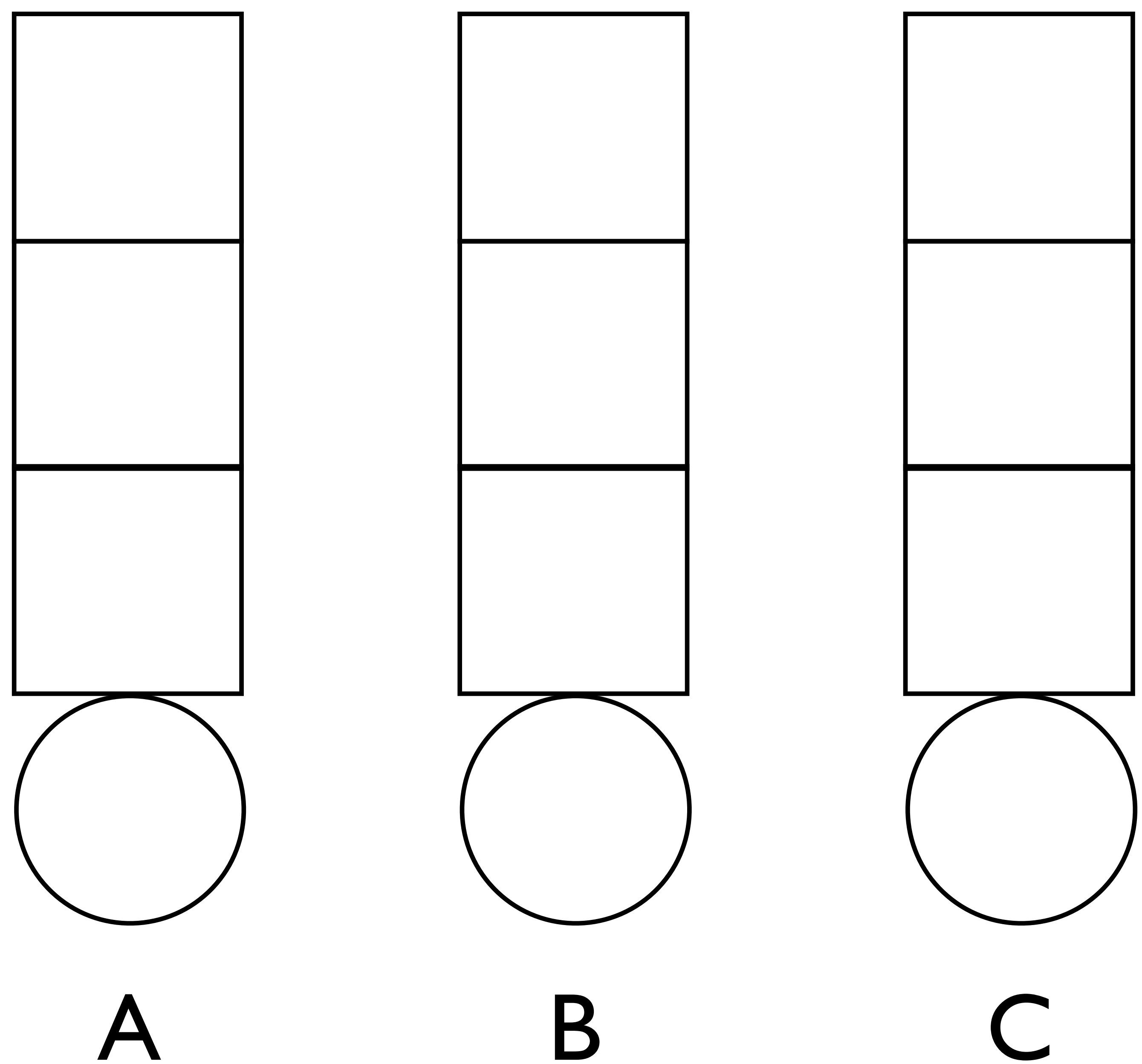
Invariant: A later-issued request never blocks an earlier-issued requests.



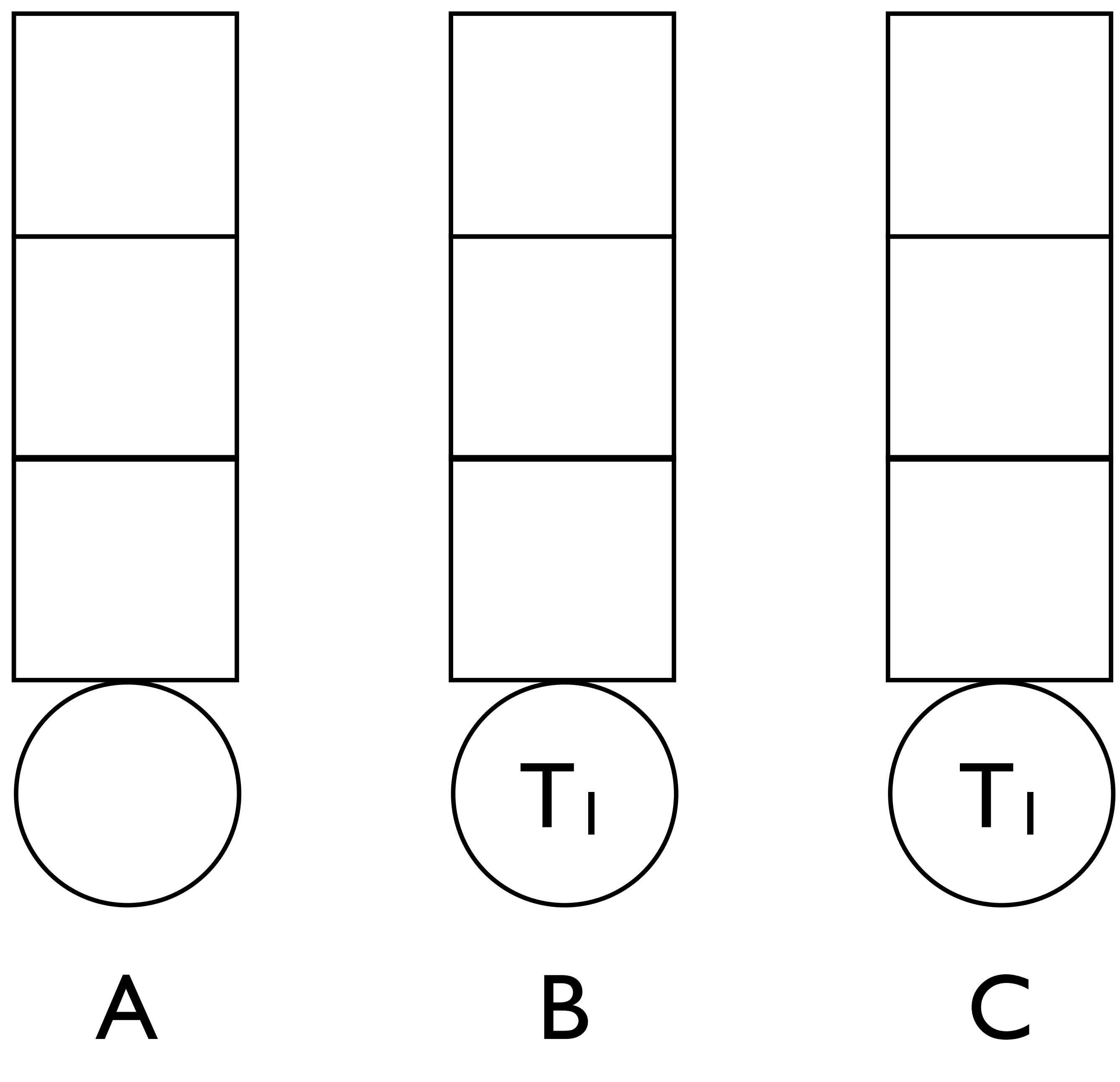
Dynamic Group Locks (DGLs)

- Goal: reduce number of lock/unlock calls.
- A job requests all potentially needed resources at once.
  - Request a subset of all resources.
  - Job may have to request resources that it doesn't use.
- Scheduled when all resources available.

DGL Example



DGL Example



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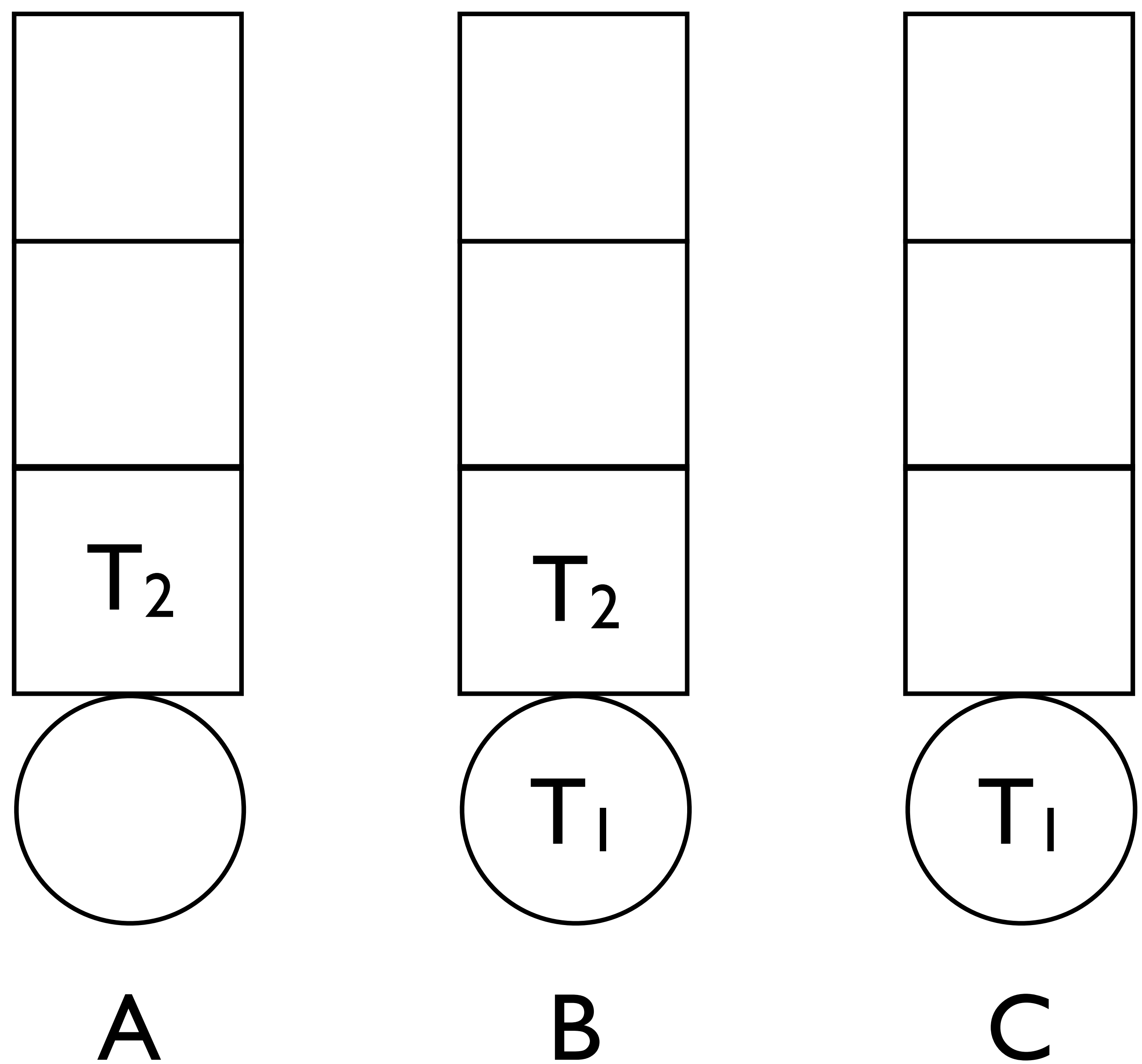

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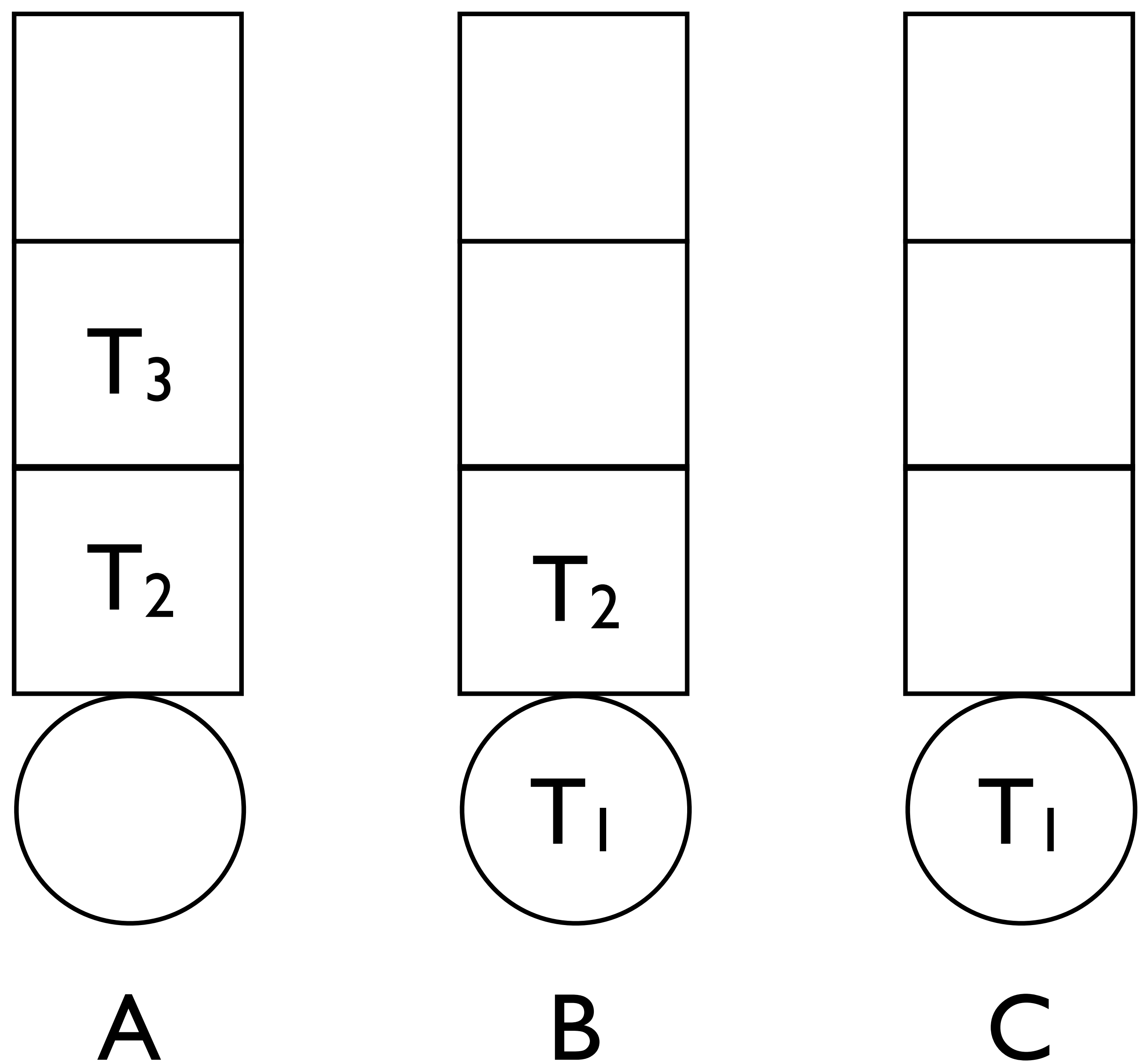
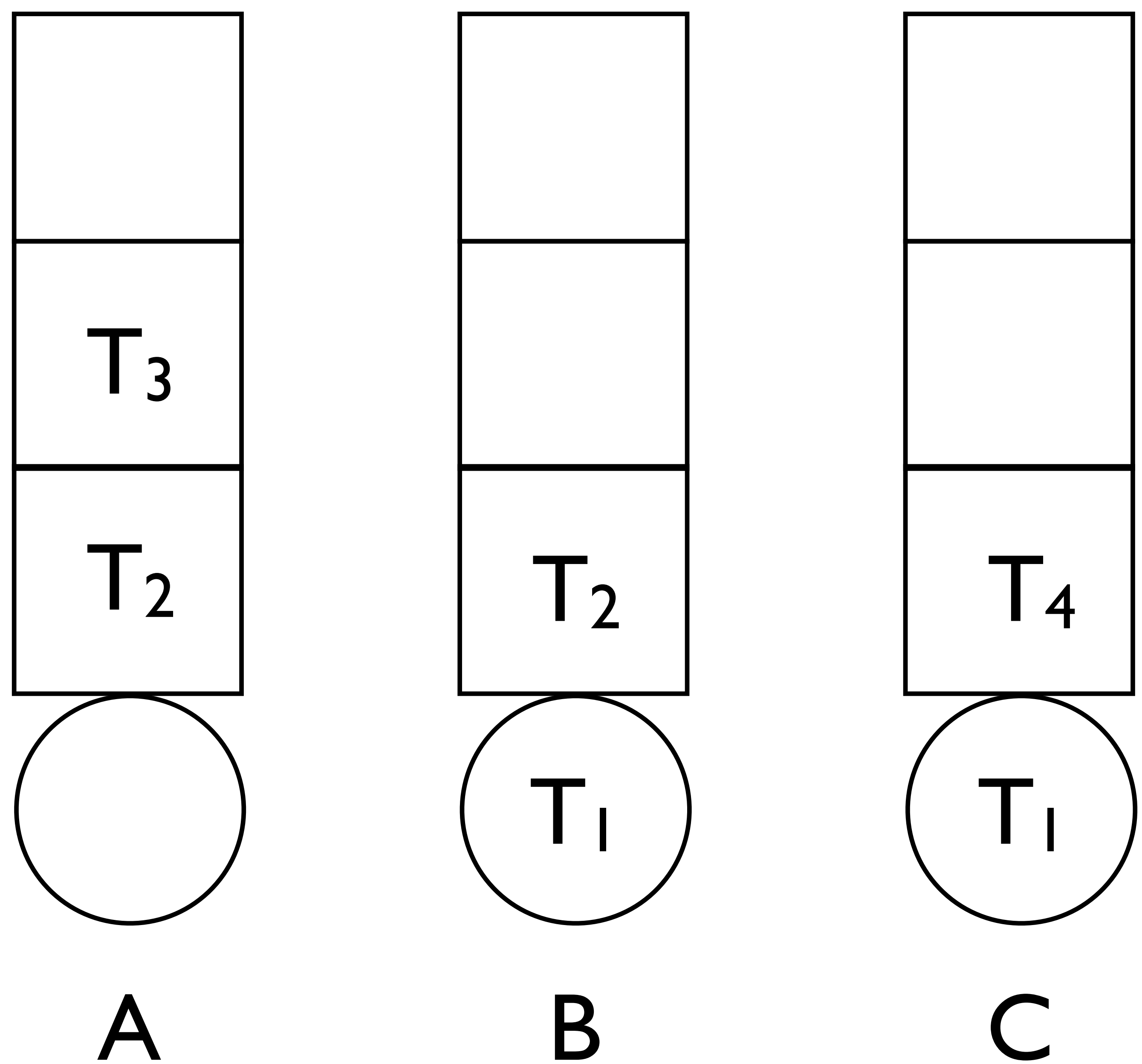


DGL Example



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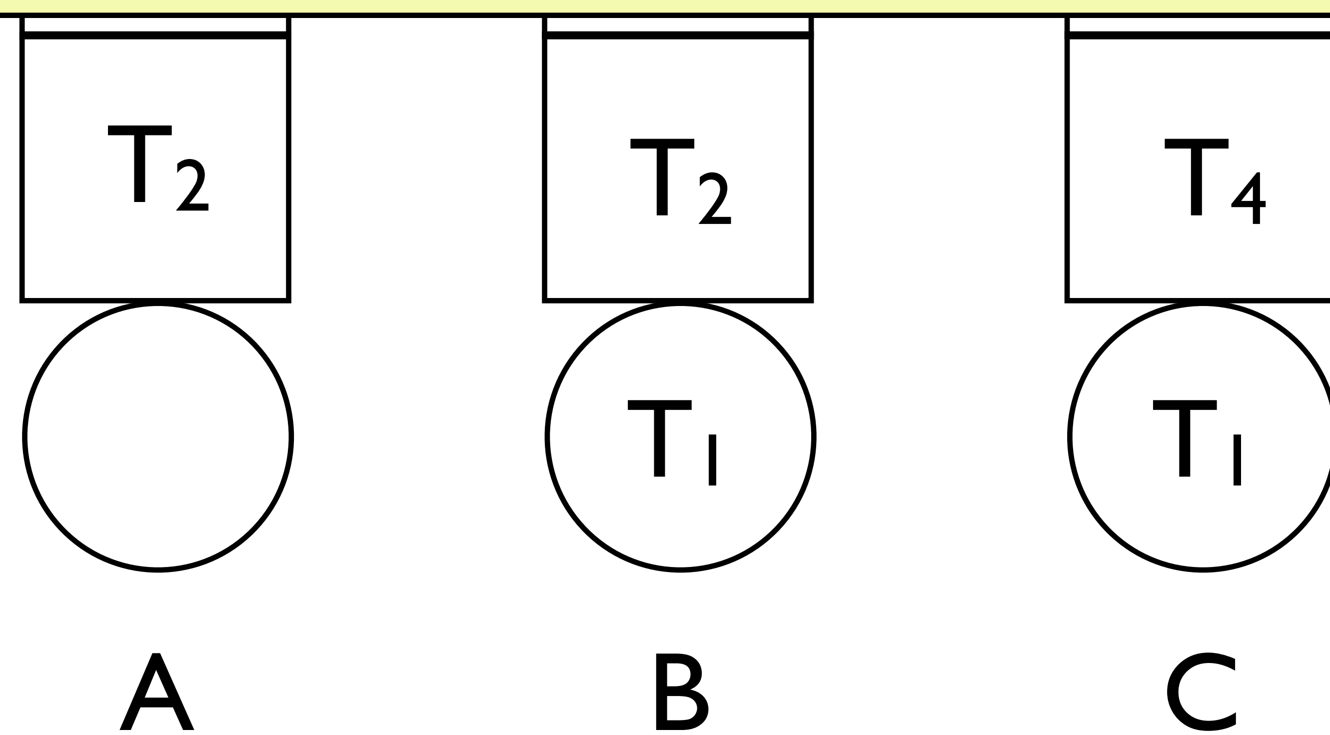


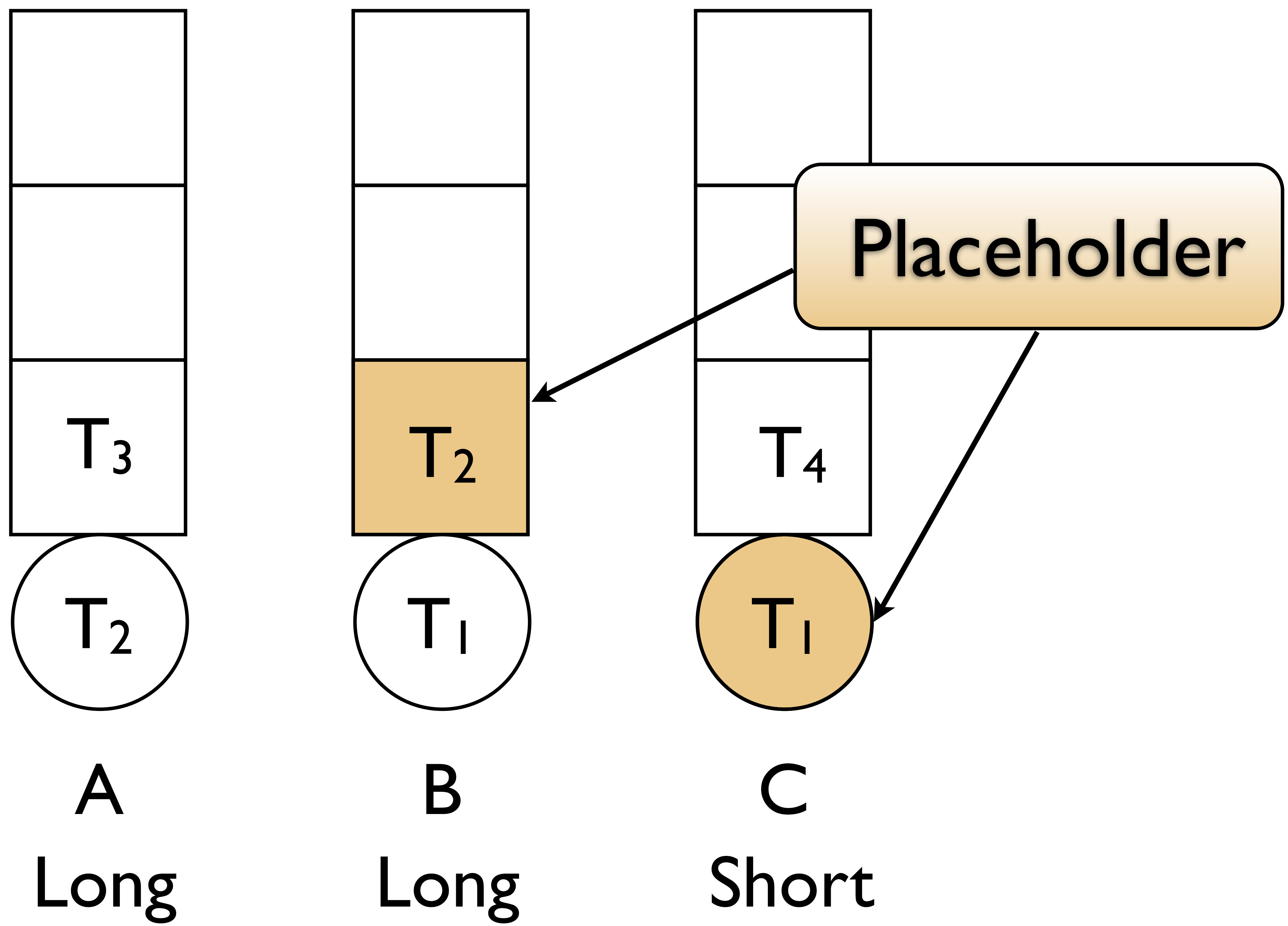
DGLs vs. RNLP

- Same worst-case blocking behavior.
- DGLs require only one lock and unlock call per outermost request instead of one per resource.
- RNLP may provide better observed blocking behavior.

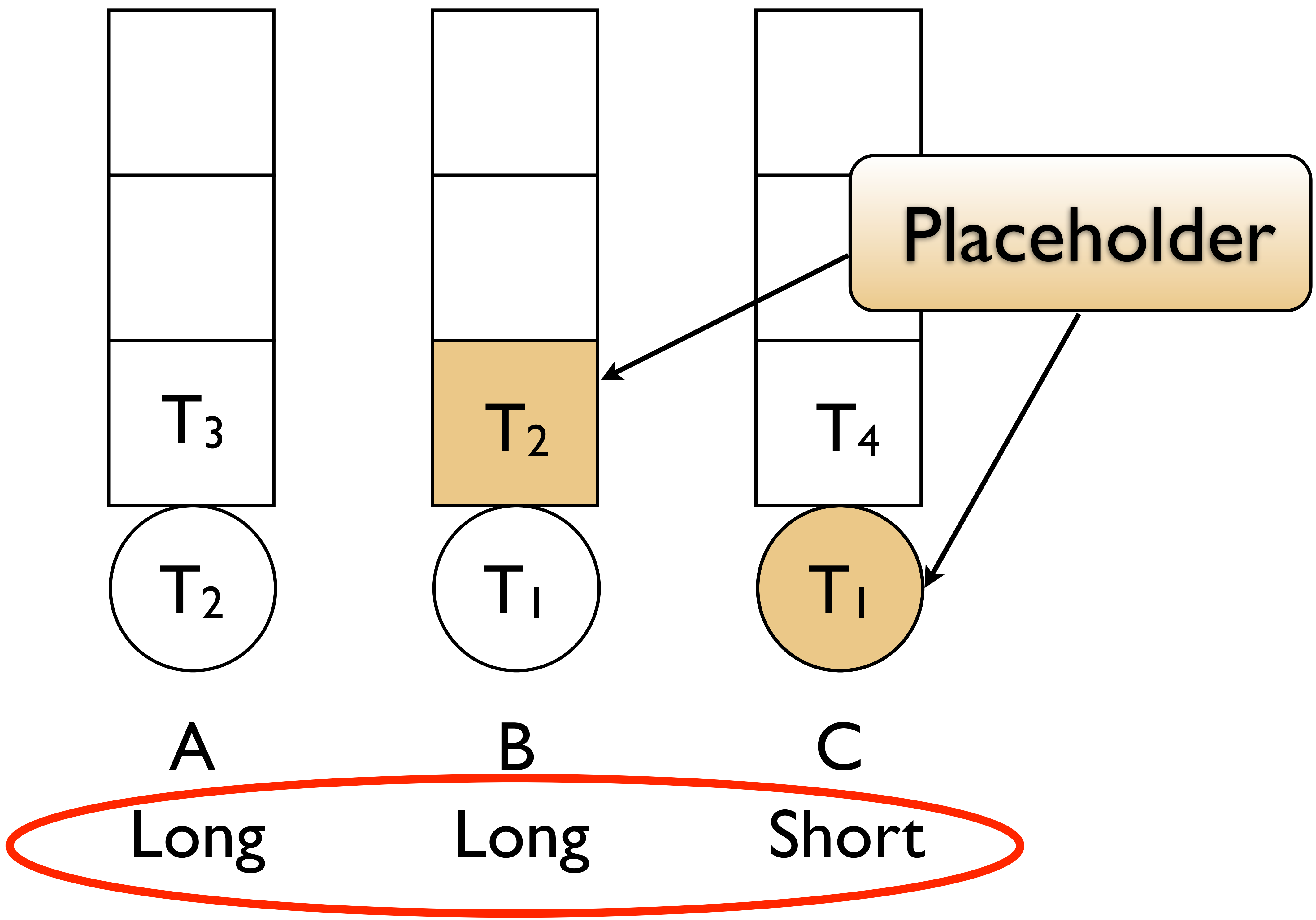
Short vs. Long

- Critical sections may take longer for some resources than others. For example:
  - GPUs = long (milliseconds).
  - Shared memory objects = short (microseconds).

Short vs. Long Problem

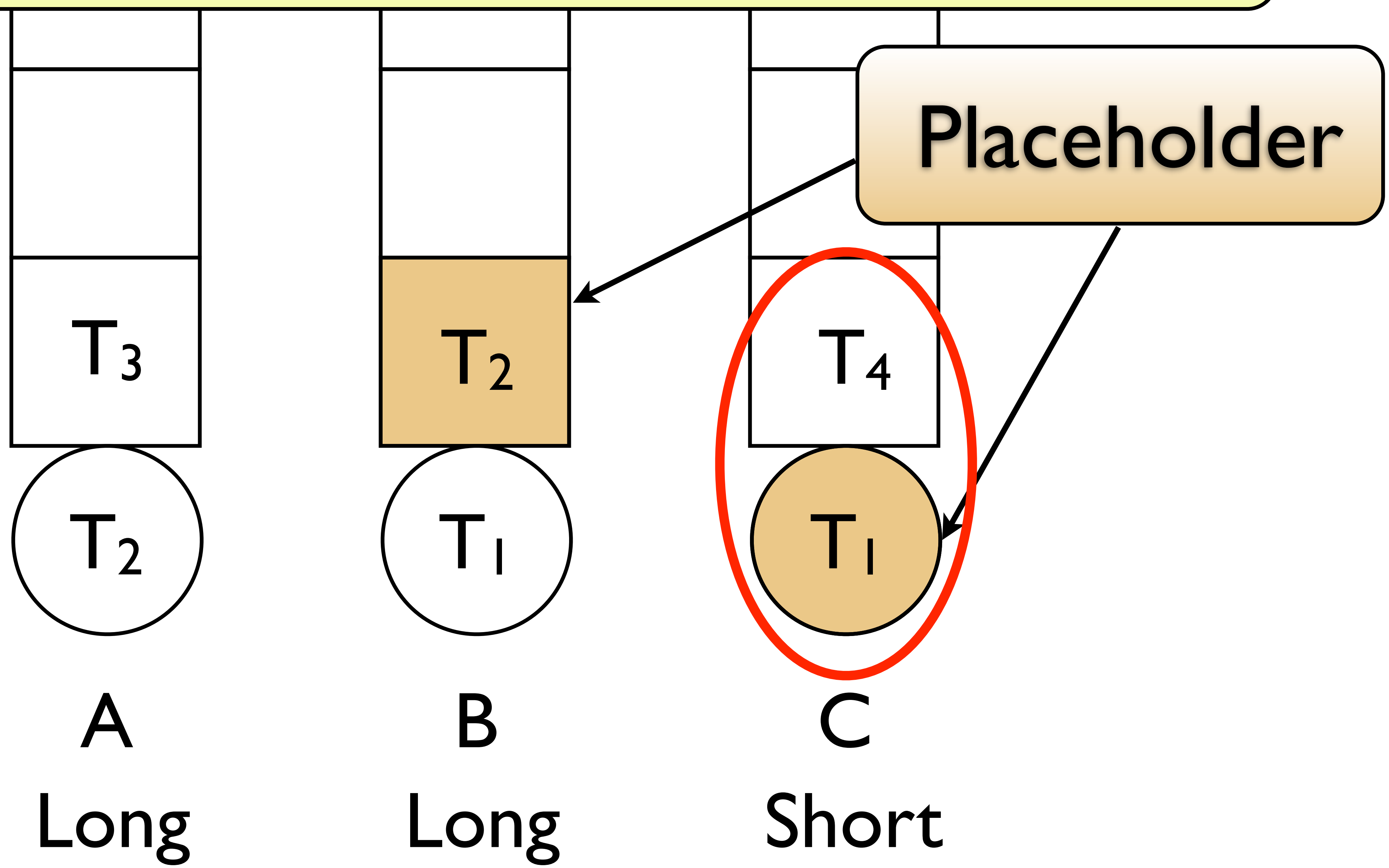


Short vs. Long Problem



Short vs. Long Problem

Problem: A short request (T_4) is blocked by the placeholder of a long request (T_1)



Eliminating Short-on-Long Blocking

- Key ideas:
  - Long requests do not insert placeholders for short resources.
  - Long requests enqueue in short resource queues based on outermost lock request time.
- Details in the paper show how different waiting mechanisms (spin vs. suspend) can be used for short and long resources.
- Asymptotic optimality retained.

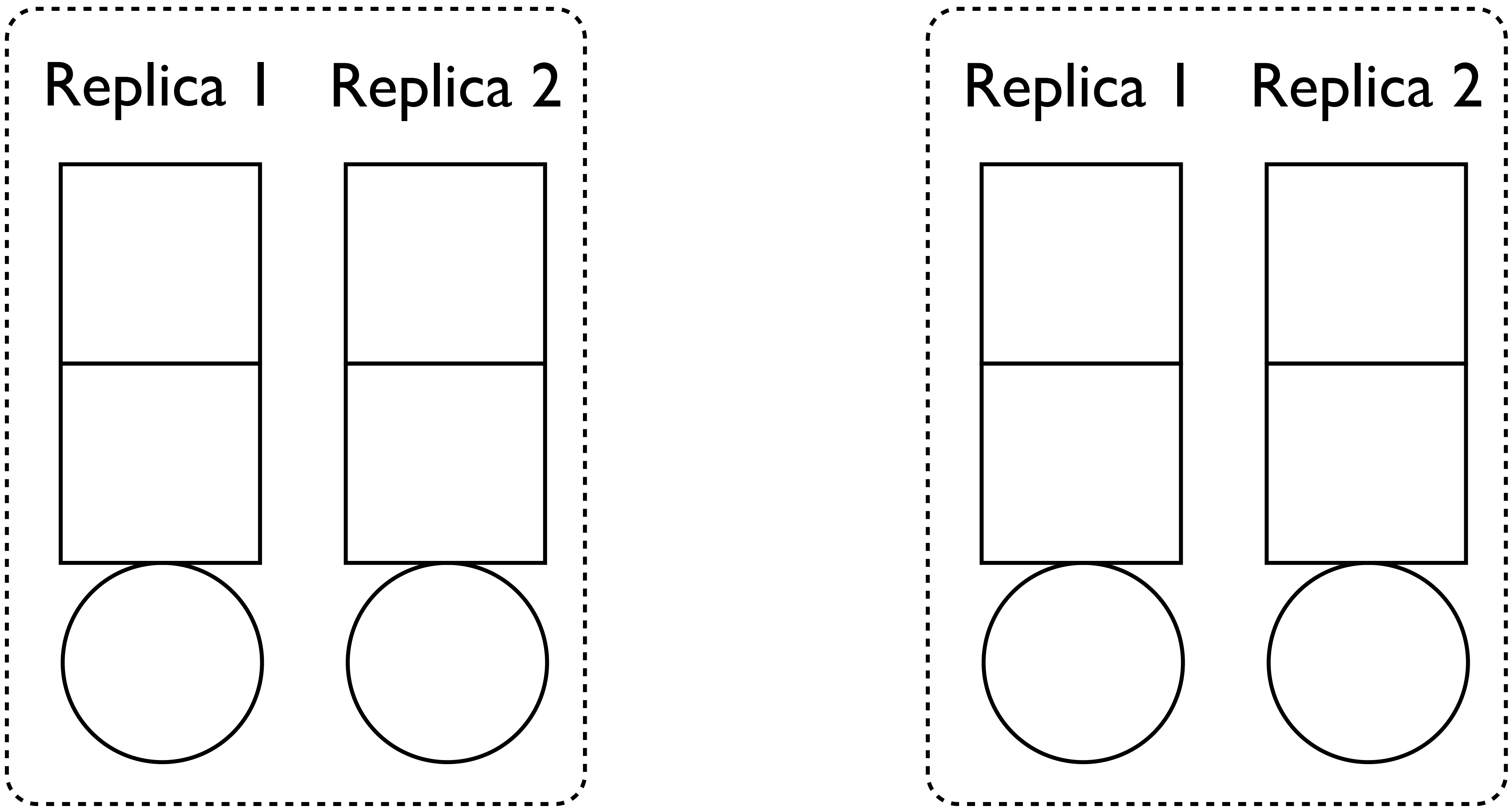
Multi-unit Locking

- Resource model:
  - For each resource, there are *k* replicas.
  - Jobs require access to any of the *k* replicas.
- Example use:
  - Shared hardware (e.g. GPUs).

k-RNLP

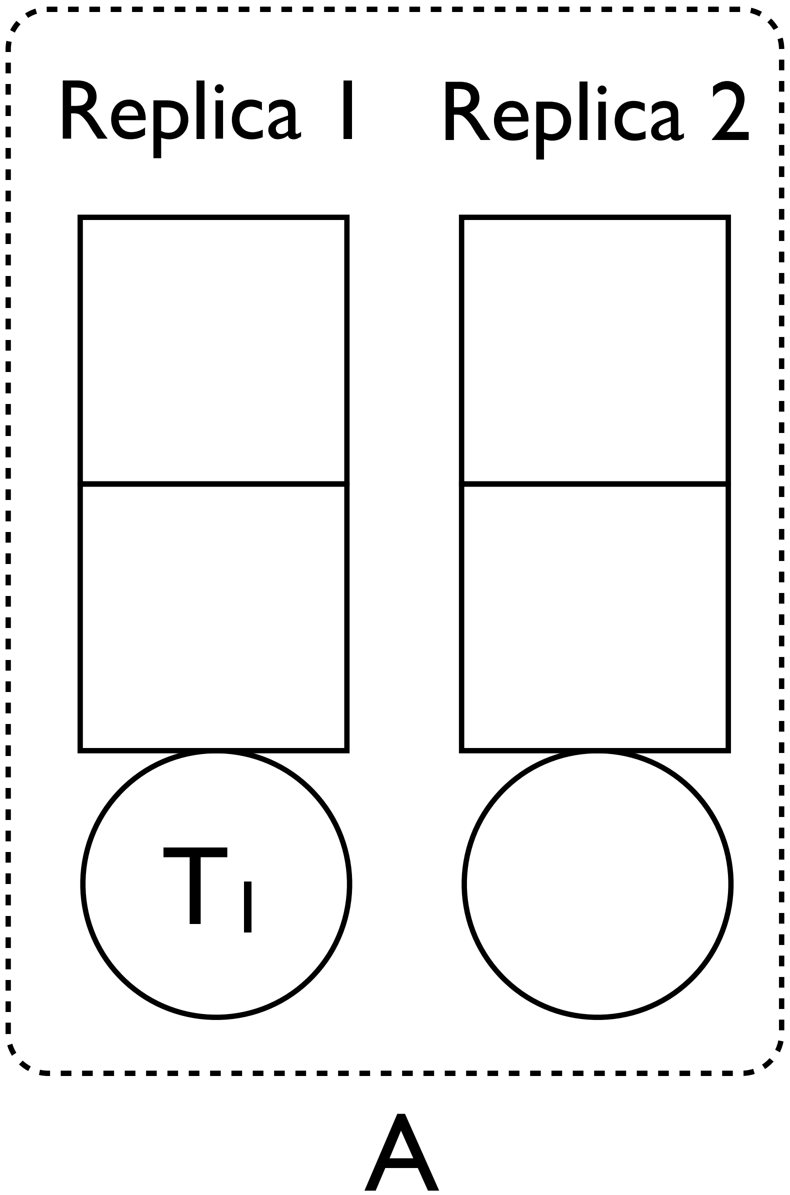
- FIFO-ordered queue per replica.
- At request time, the job is enqueued in the shortest replica queue for each potentially required resource.
  - Could insert a placeholder for potentially needed resources.

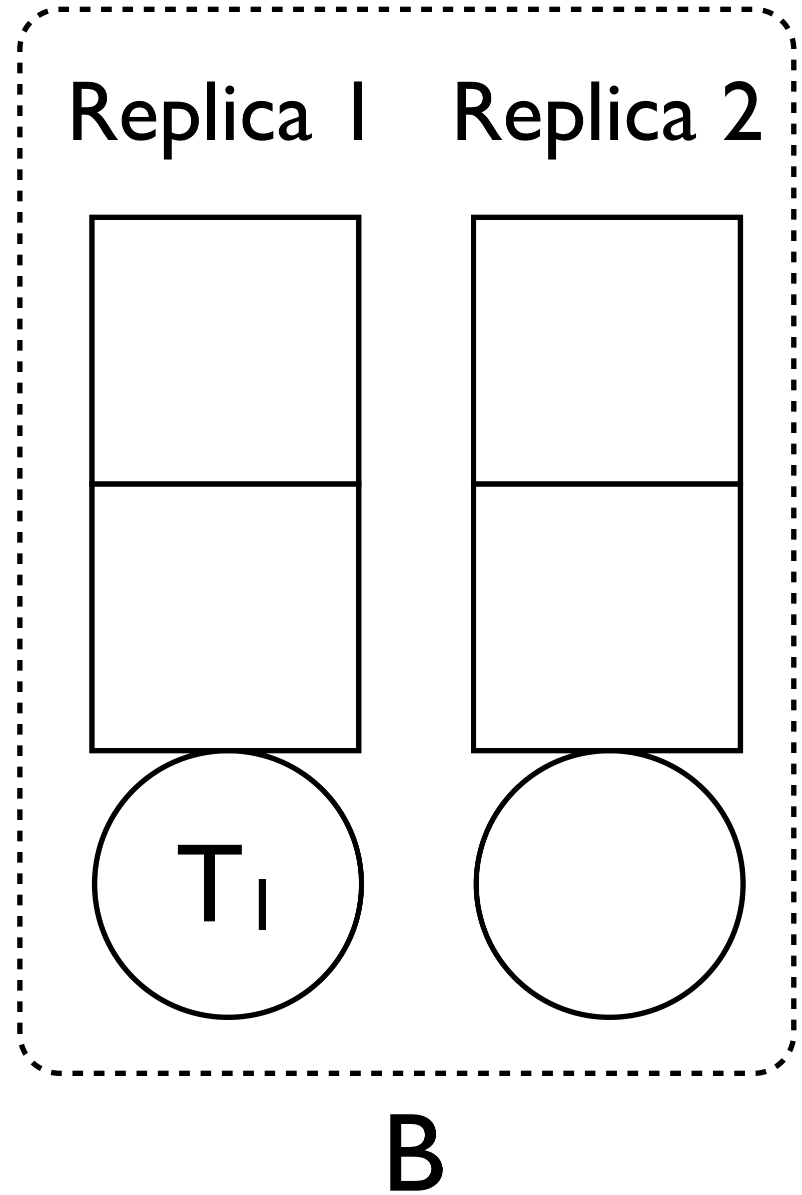
Queue Structure



A B

Queue Structure





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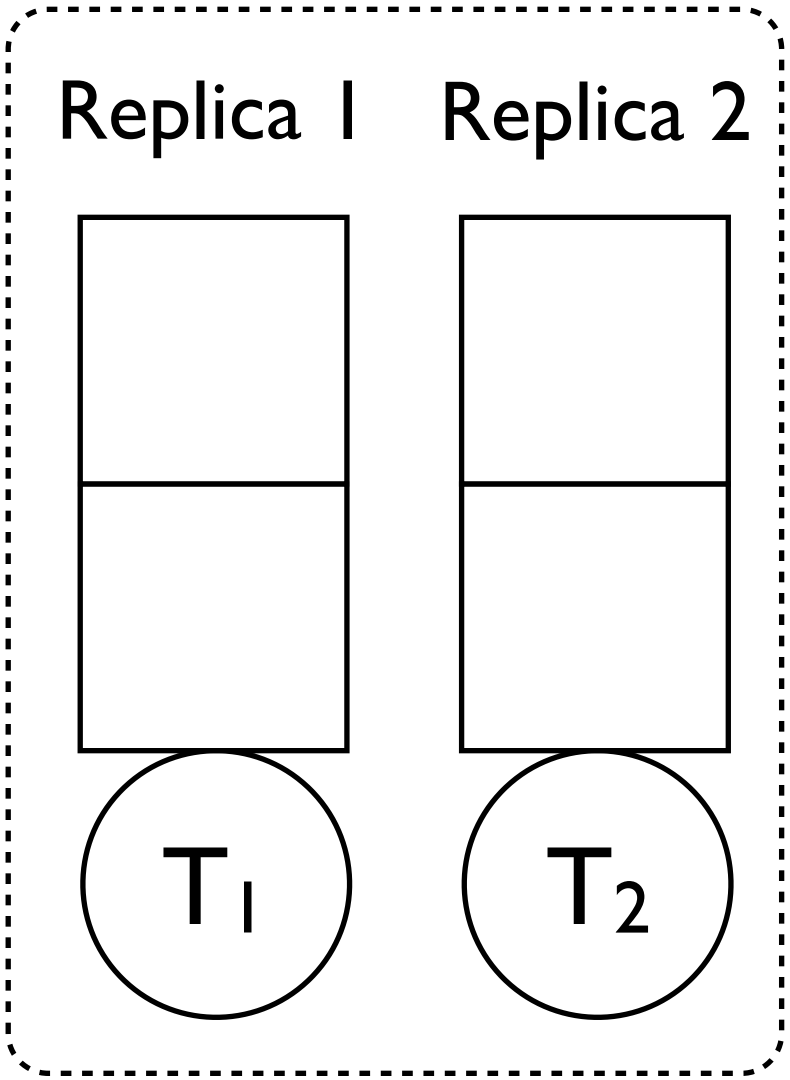
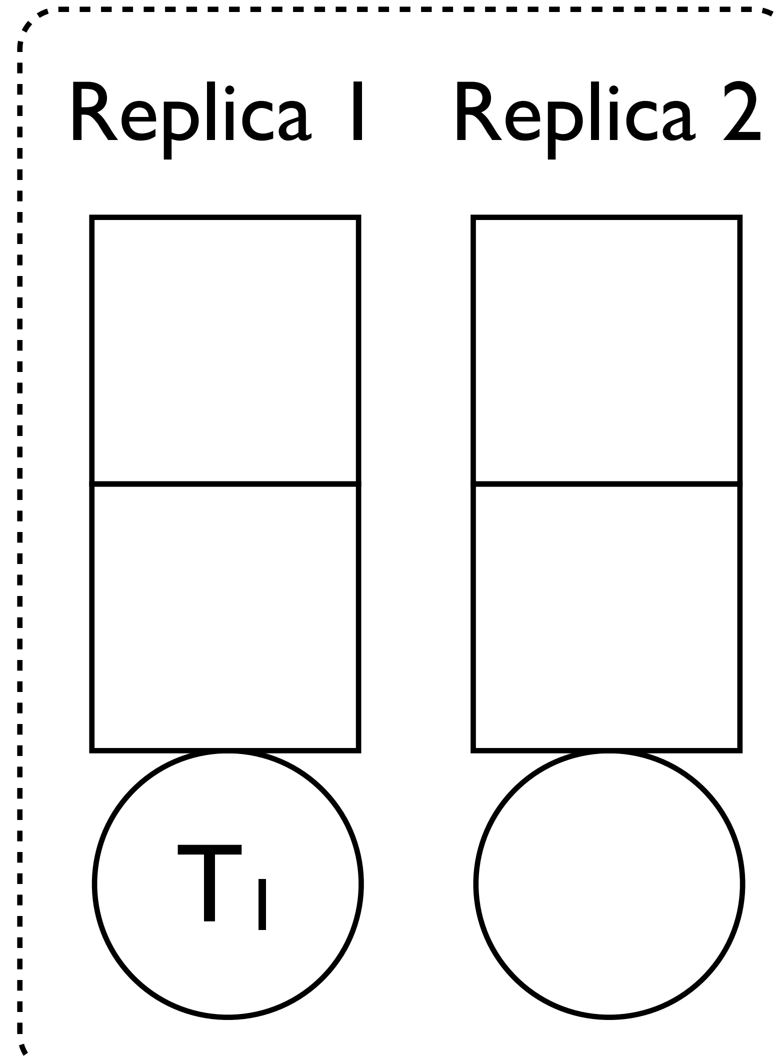
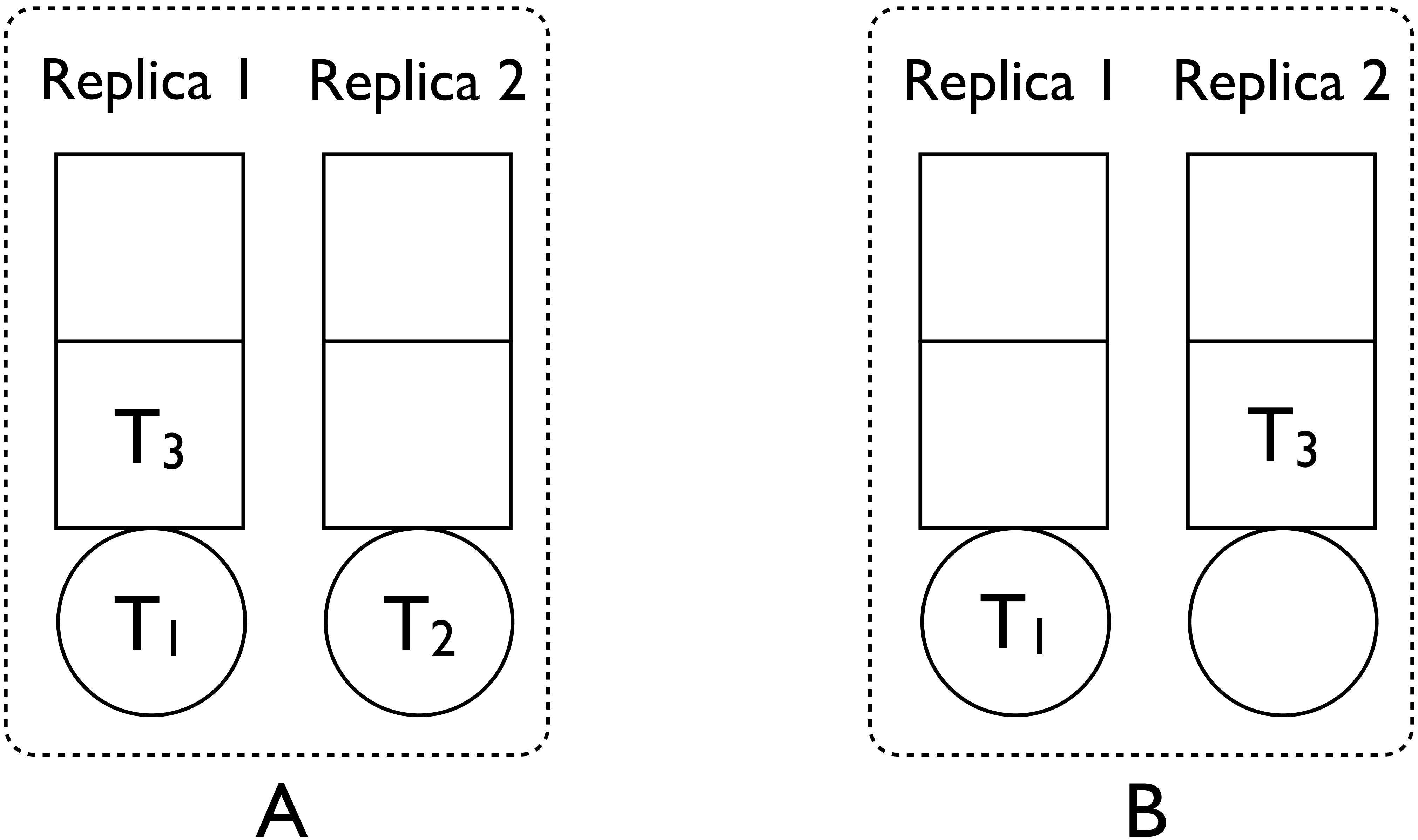


A



B

Queue Structure



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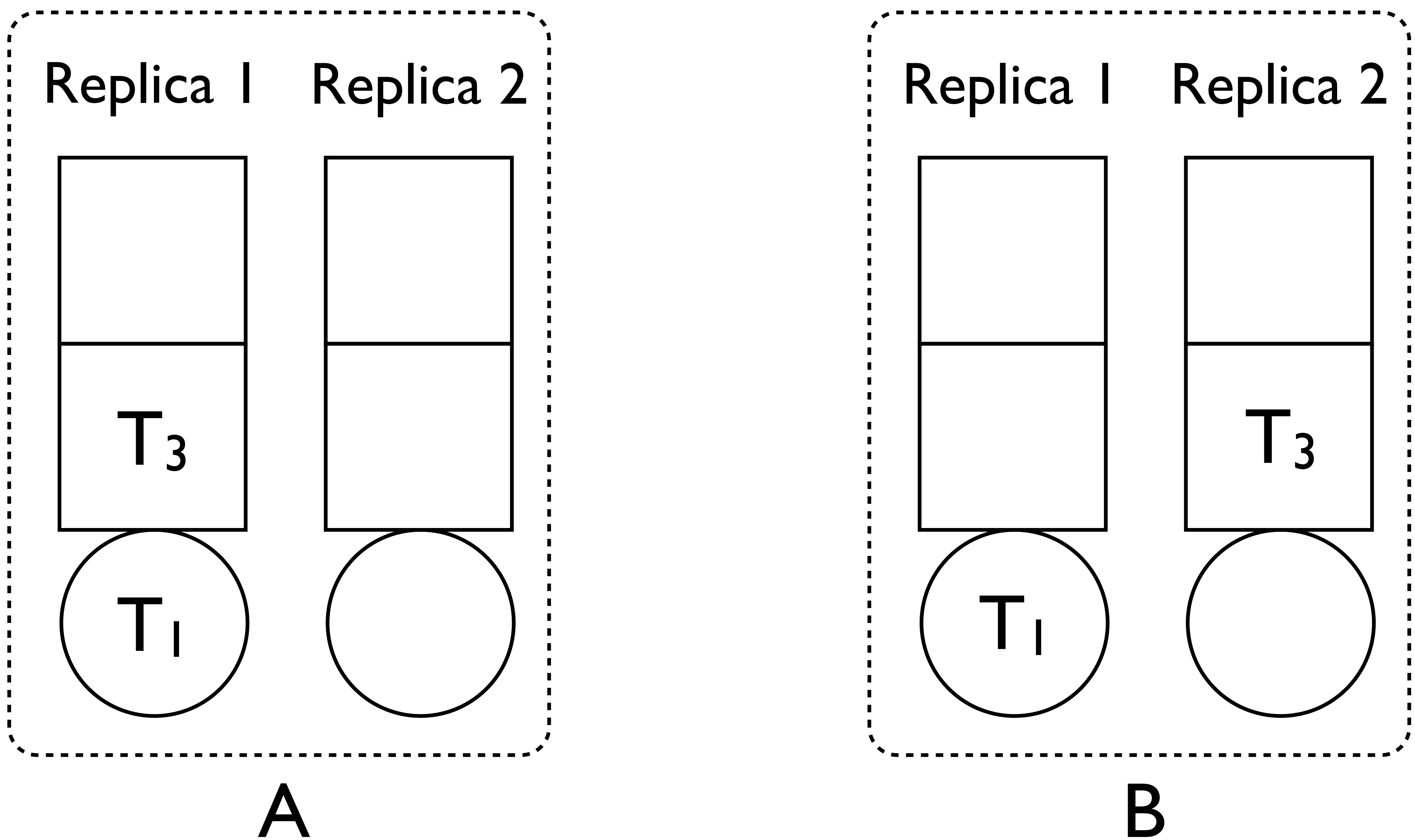

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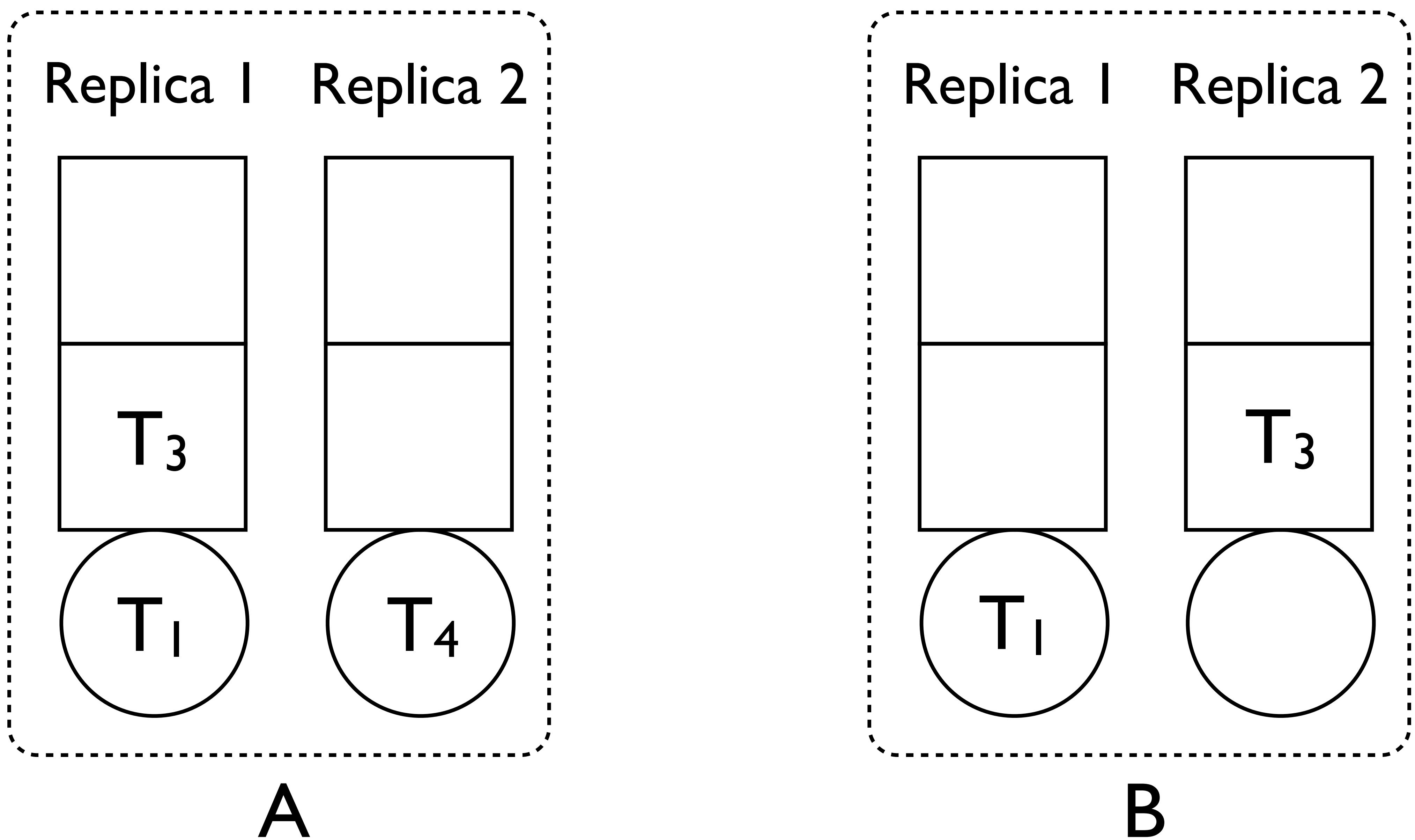
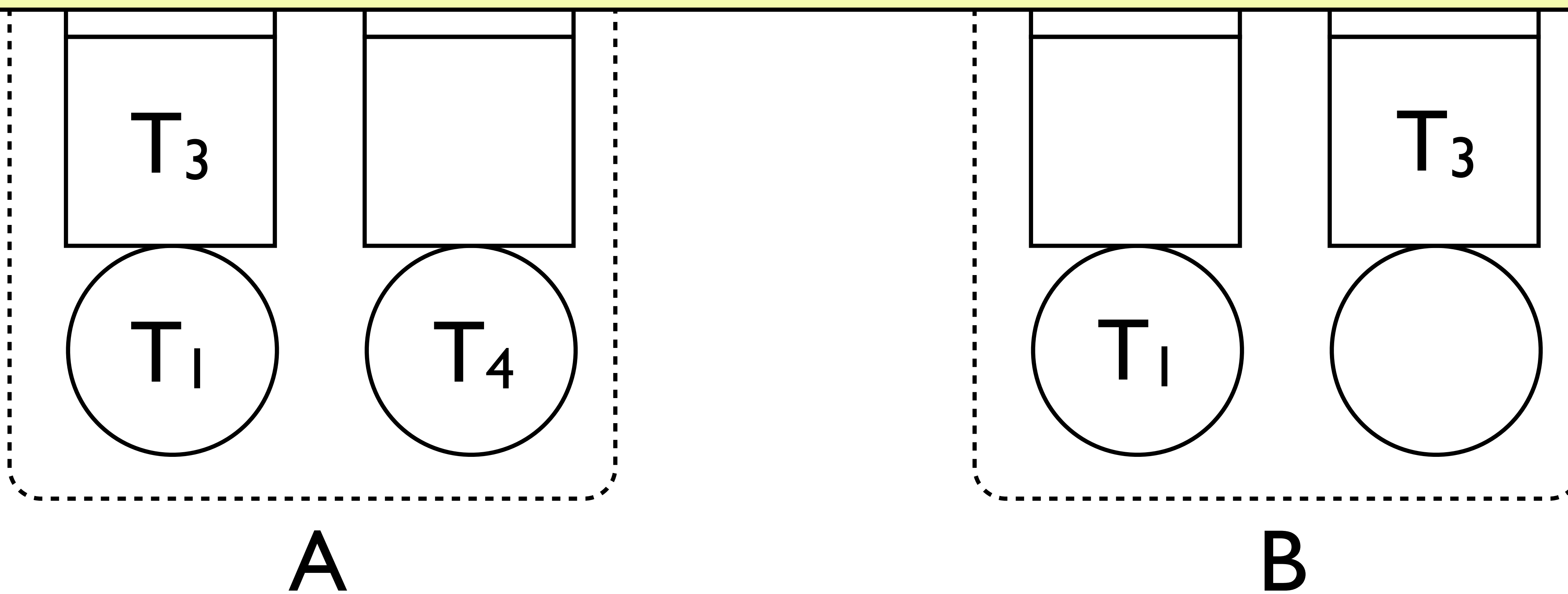


Queue Structure

Observation: Later-issued requests (T_4) may be satisfied **earlier** by acquiring a different replica.

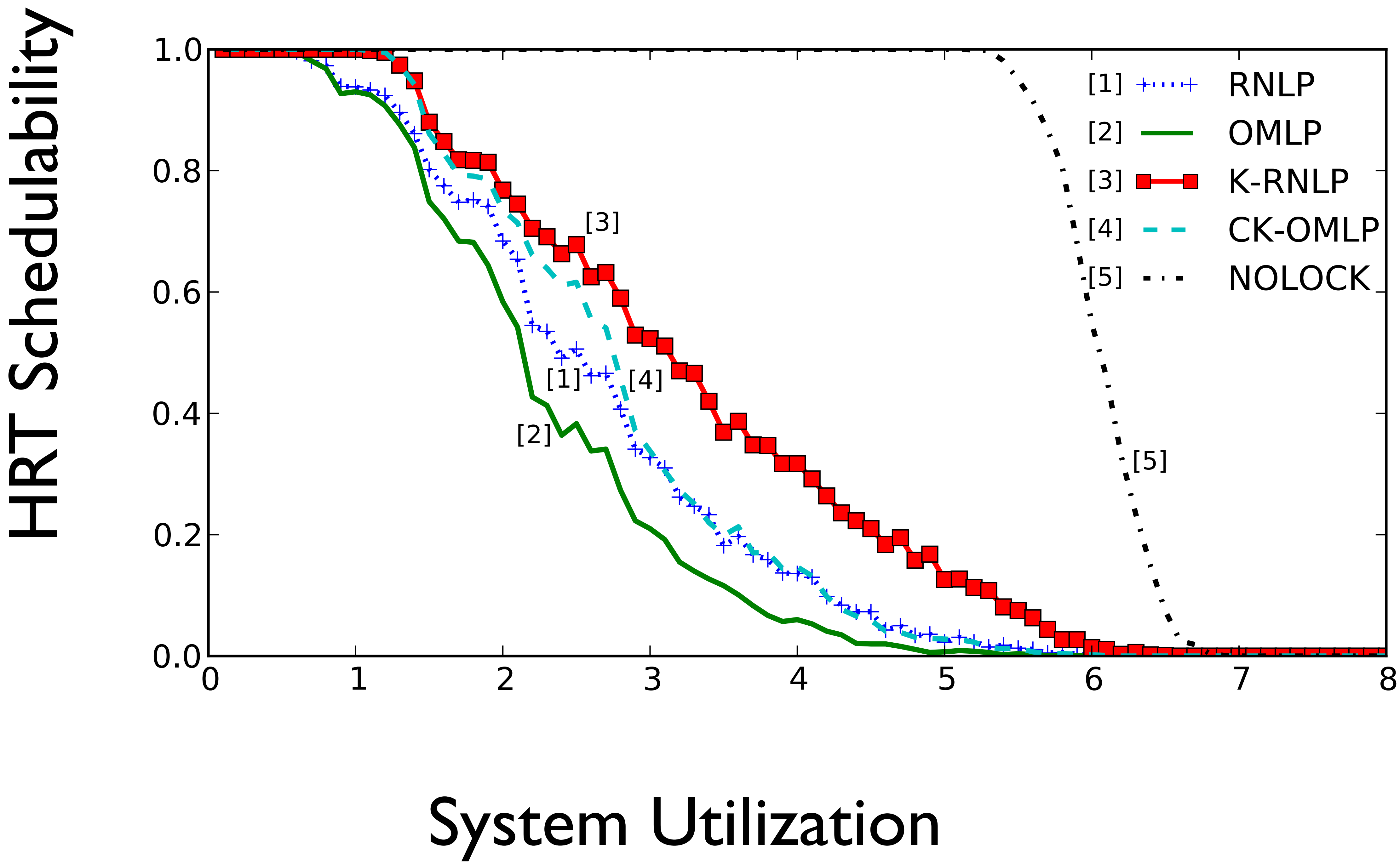


k-RNLP Blocking Analysis

- Queue length reduced by factor of k.
- Worst-case blocking is at most the maximum queue length.
- In the paper, we show that the *k*-RNLP can be configured for $O(m/k)$ or $O(n/k)$ blocking under different analysis assumptions.
- Asymptotically optimal.

Schedulability

k = 2



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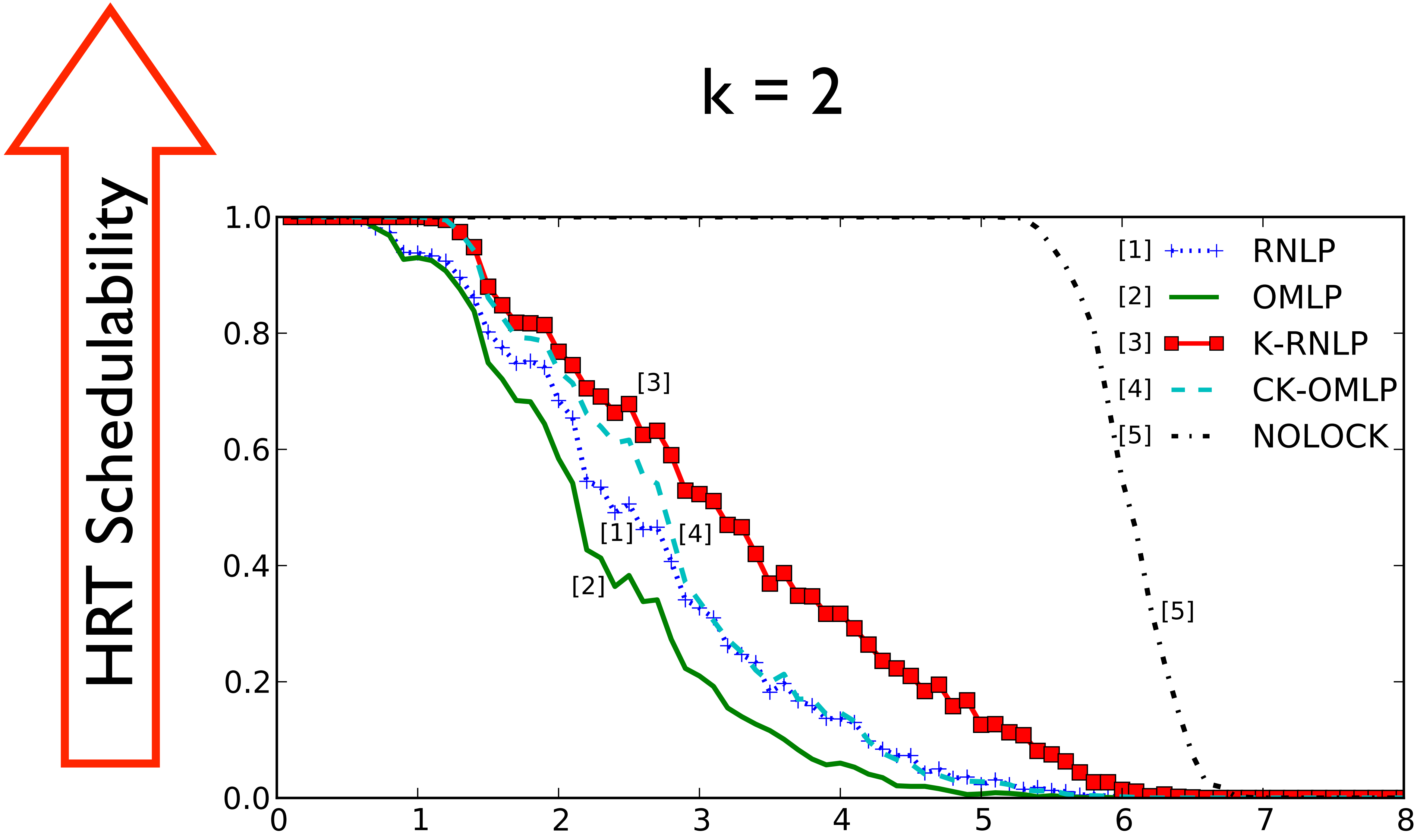
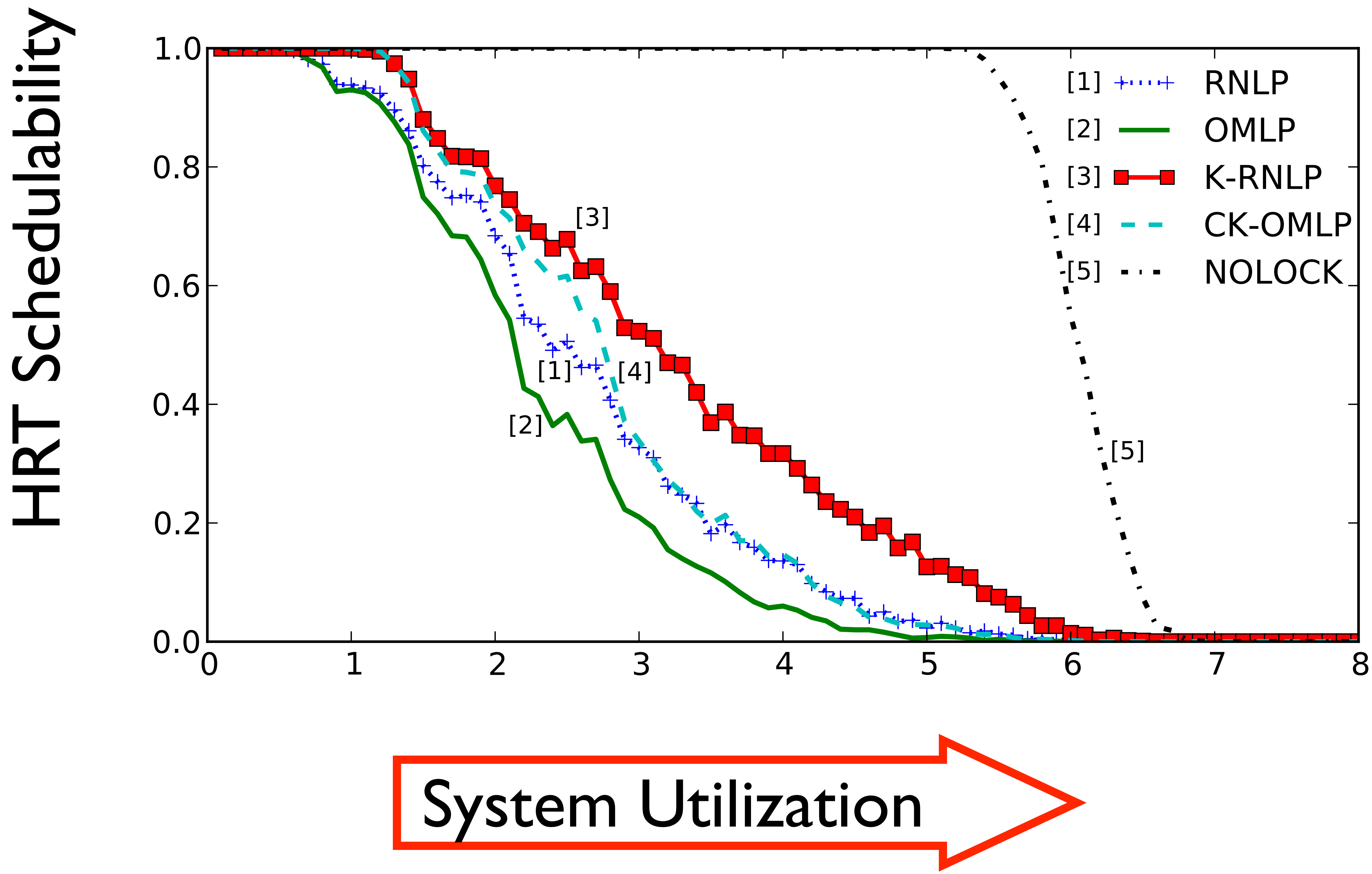


System Utilization

Schedulability

k = 2



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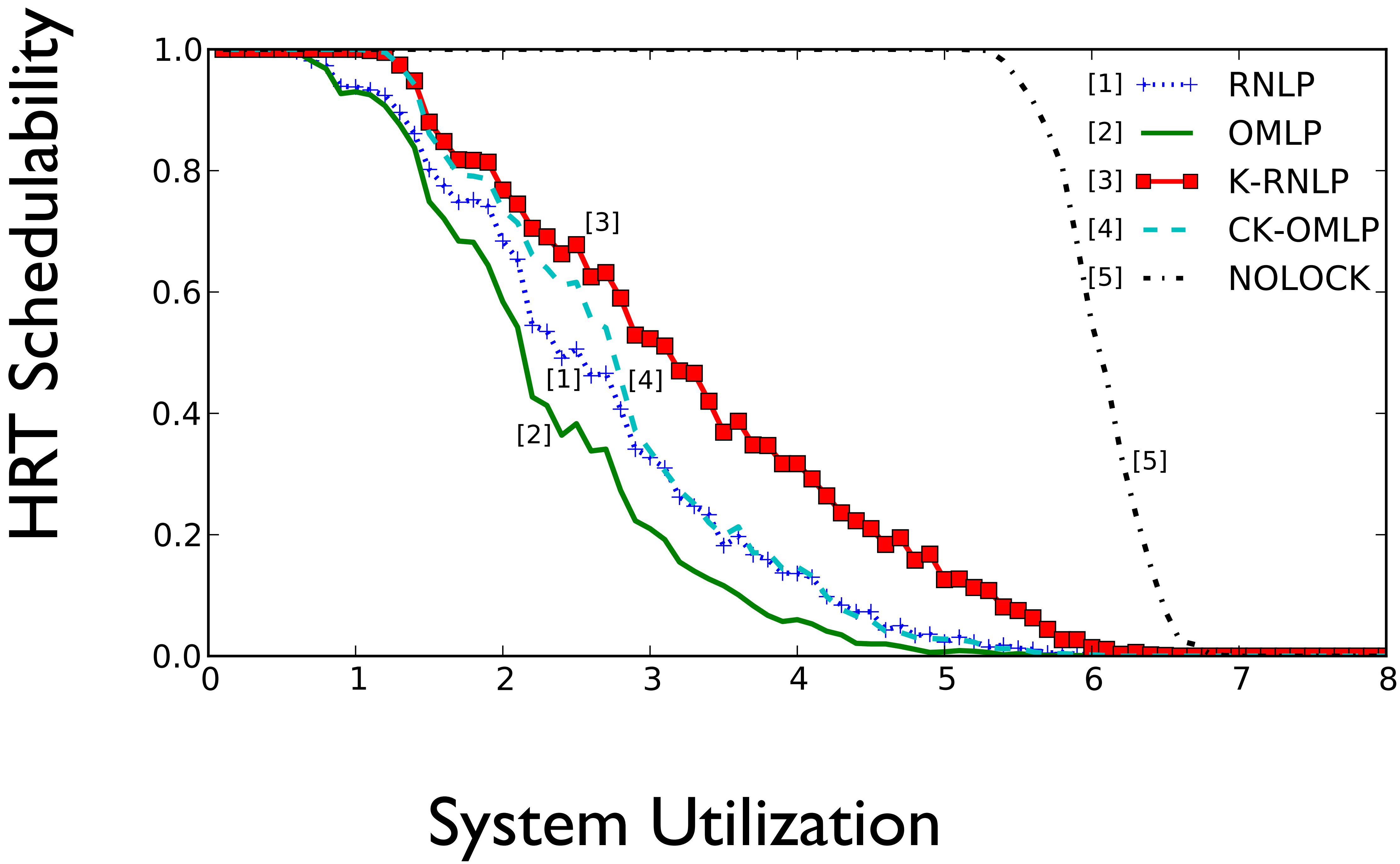

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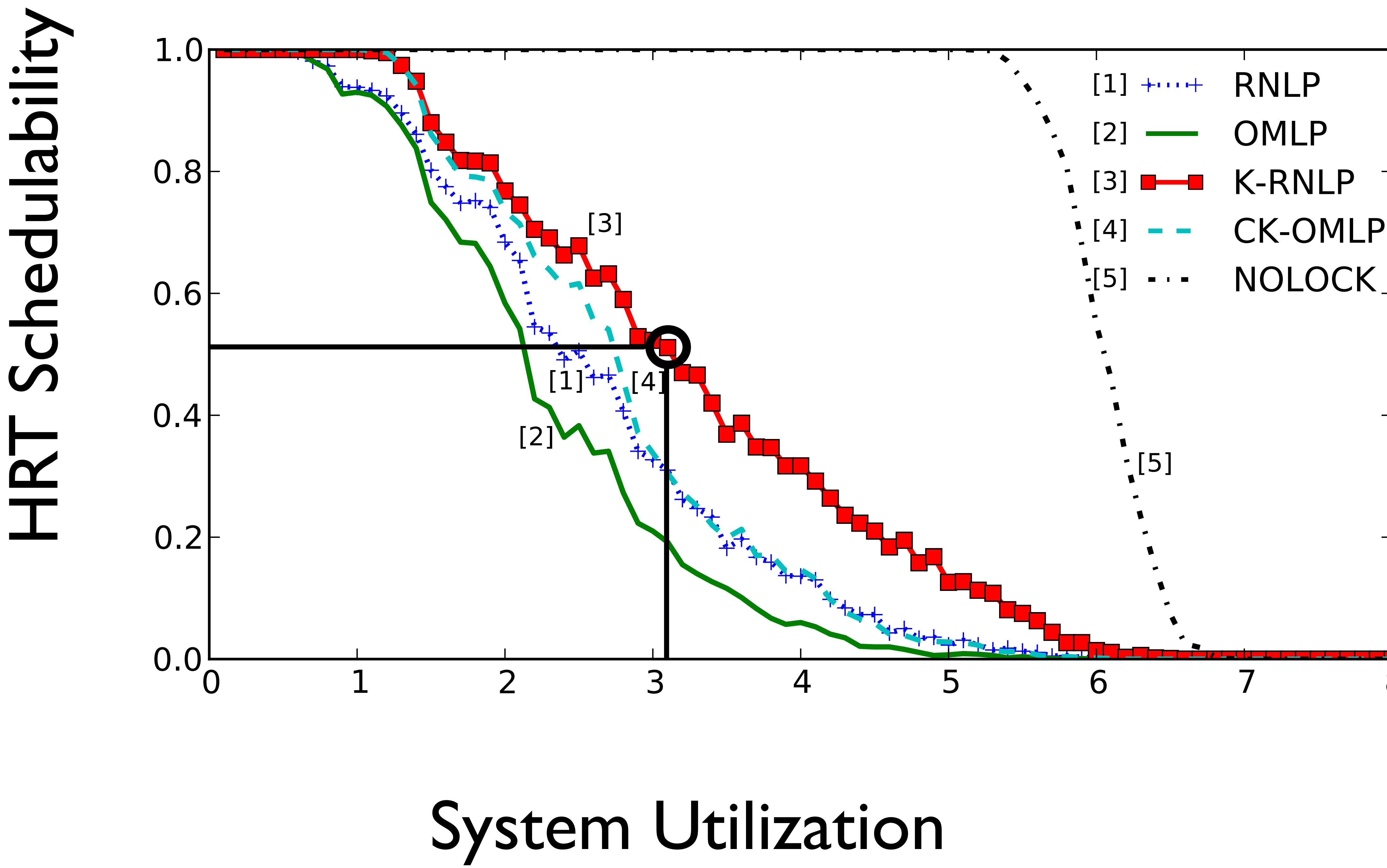

Conclusions

- We presented three RNLP modifications:
  - DGLs - reduce system-call overhead.
  - Eliminate short-on-long blocking.
  - Support for multi-unit resources.
- Modifications improve real-time schedulability.
- Maintain asymptotic optimality.

Questions?