LFthreads: A lock-free thread library

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Outline

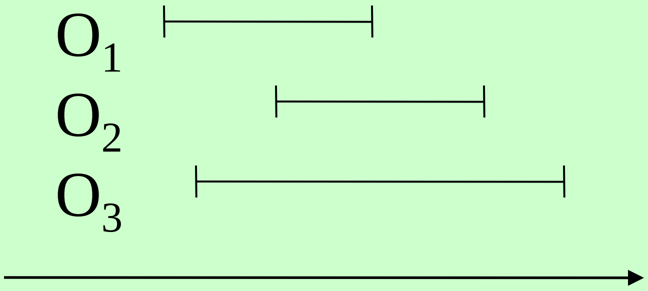
- Introduction
  - Lock-free synchronization
  - The Problem & Background
- LFthreads
  - Overview
  - Lock-free thread-blocking synchronization
- Experiments
- Conclusions

Synchronization on a shared object

- Lock-free synchronization
  - Concurrent operations without enforcing mutual exclusion
  - Avoids:
    - Blocking (or busy waiting), convoy effects and priority inversion
  - *Progress Guarantee*
    - At least one operation always makes progress
- Synchronization primitives
  - Built into CPU and memory system
    - Atomic read-modify-write (i.e. a critical section of one instruction)
  - Examples: Compare-and-Swap, Load-Linked / Store-Conditional

Correctness of a concurrent object

- Desired semantics of a shared data object
  - Linearizability [Herlihy & Wing, 1990]
    - For each operation invocation there must be one single time instant during its duration where the operation appears to take effect.
    - The observed effects should be consistent with a sequential execution of the operations in that order.



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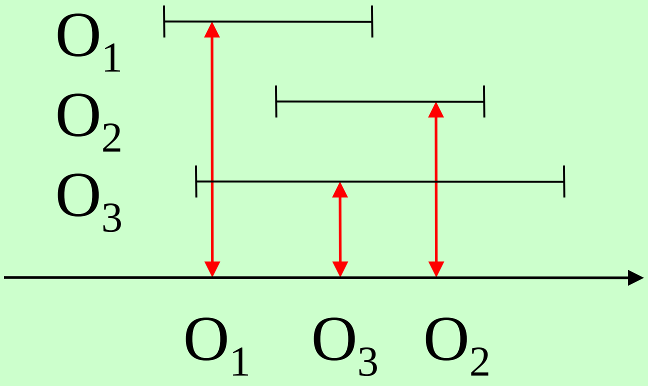
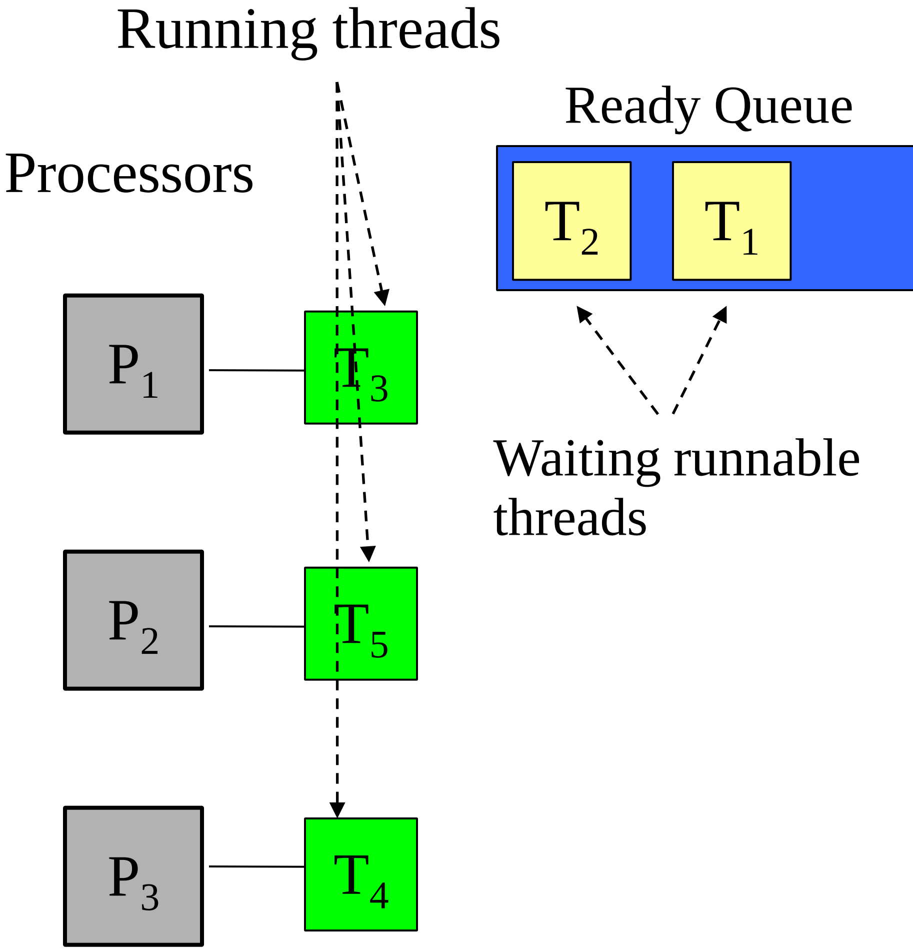


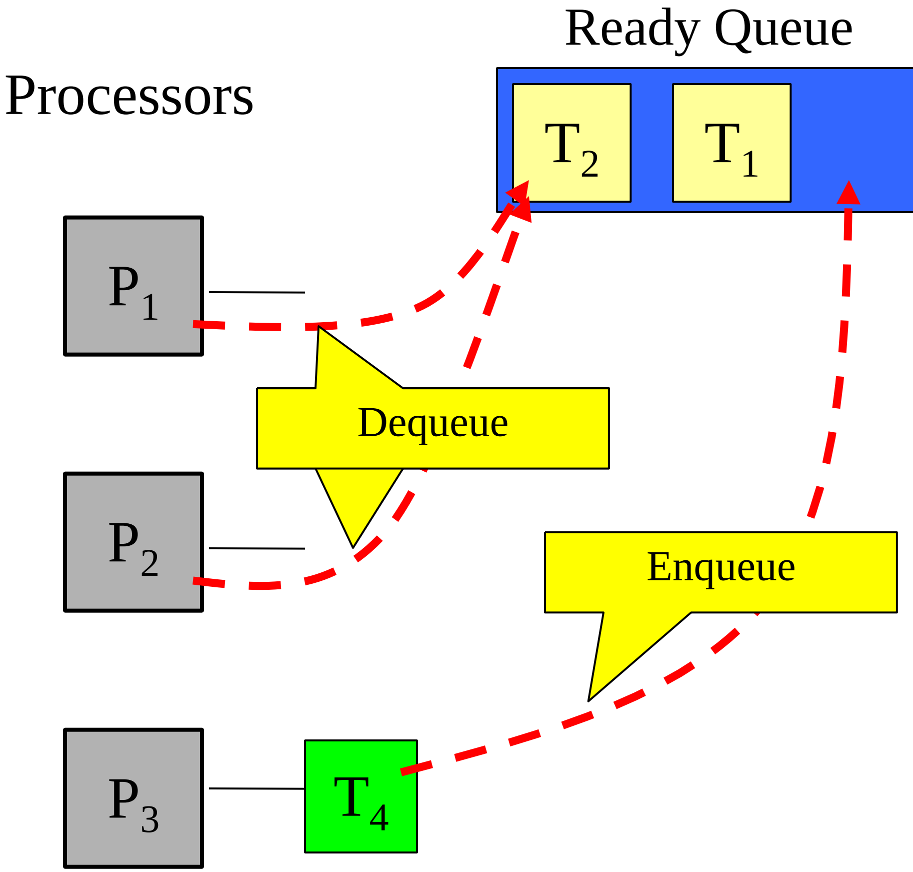
The Problem

- Multithreading on a multiprocessor
  - Thread multiplexing and scheduling
  - Thread synchronization objects
  - Aim: The POSIX pthread API implemented in a lock-free way
- Motivation: Why lock-free?
  - Processors should always be able to do useful work
    - In spite of others being slow: page faults, interrupts, h/w problems
  - Improved performance?



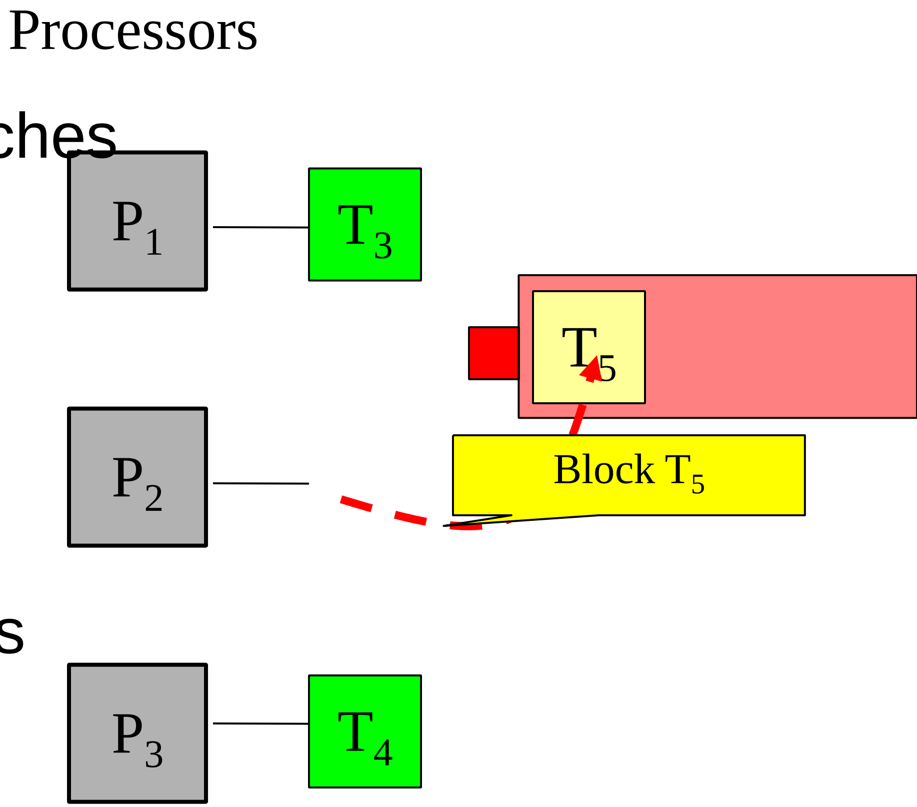
The Problem(s)

- Contention on the ready queue
  - Non-blocking work-stealing; Hood, [Blumhofe et al, 1994], [Blumhofe et al, 1998]
  - Lesser Bear, [Oguma et al, 2001]
  - In LFthreads: a lock-free queue



The Problem(s)

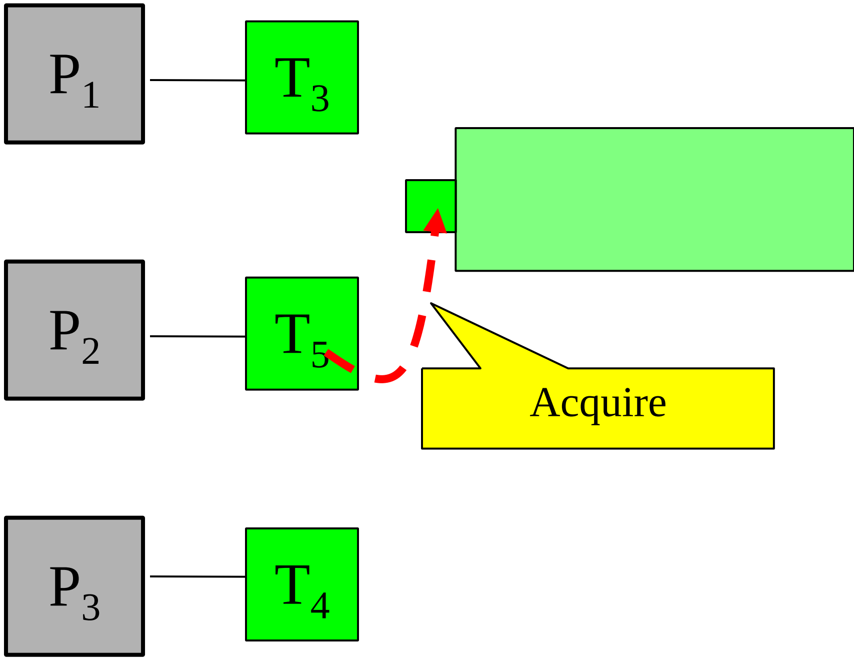
- Blocking synchronization
  - Often undesirable
    - Hinders progress
    - Expensive context switches
  - Sometimes required
    - Waiting for some event
    - Legacy applications
  - Goal in LFthreads:
    - Lock-free for processors
    - Resilience to slow operations/processors



The Problem(s)

- Implementing blocking synchronization
  - Keep common case fast
    - Often no contention
    - User / kernel level split implementation
      - E.g. Linux, Solaris
  - Critical sections are short
    - Spinning v.s. blocking [Zahorjan et al, 1991]

Processors



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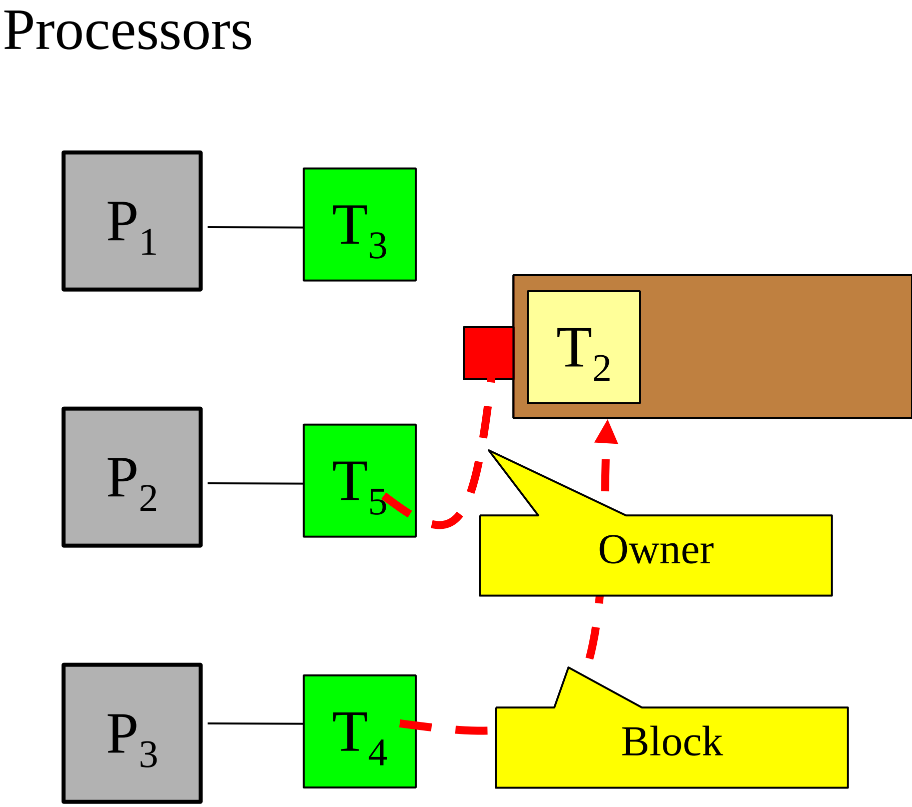
  - Enlisting the scheduler
    - [Devi et al, 2006]
    - [Kontothanassis et al, 1997]

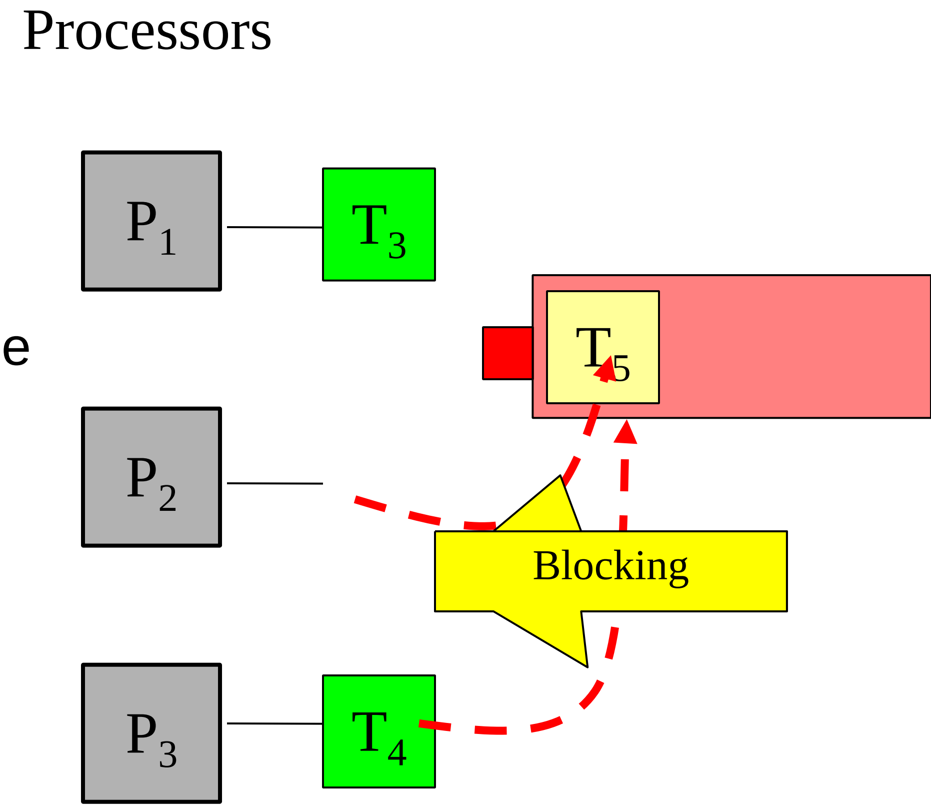


The Problem(s)

- Implementing blocking synchronization
  - There can be concurrent operations – synchronization needed
    - Mutual exclusion?
    - A slow processor could force others to spin
    - Slow: e.g. page faults, interrupts, h/w problems

Kernel partial solution:

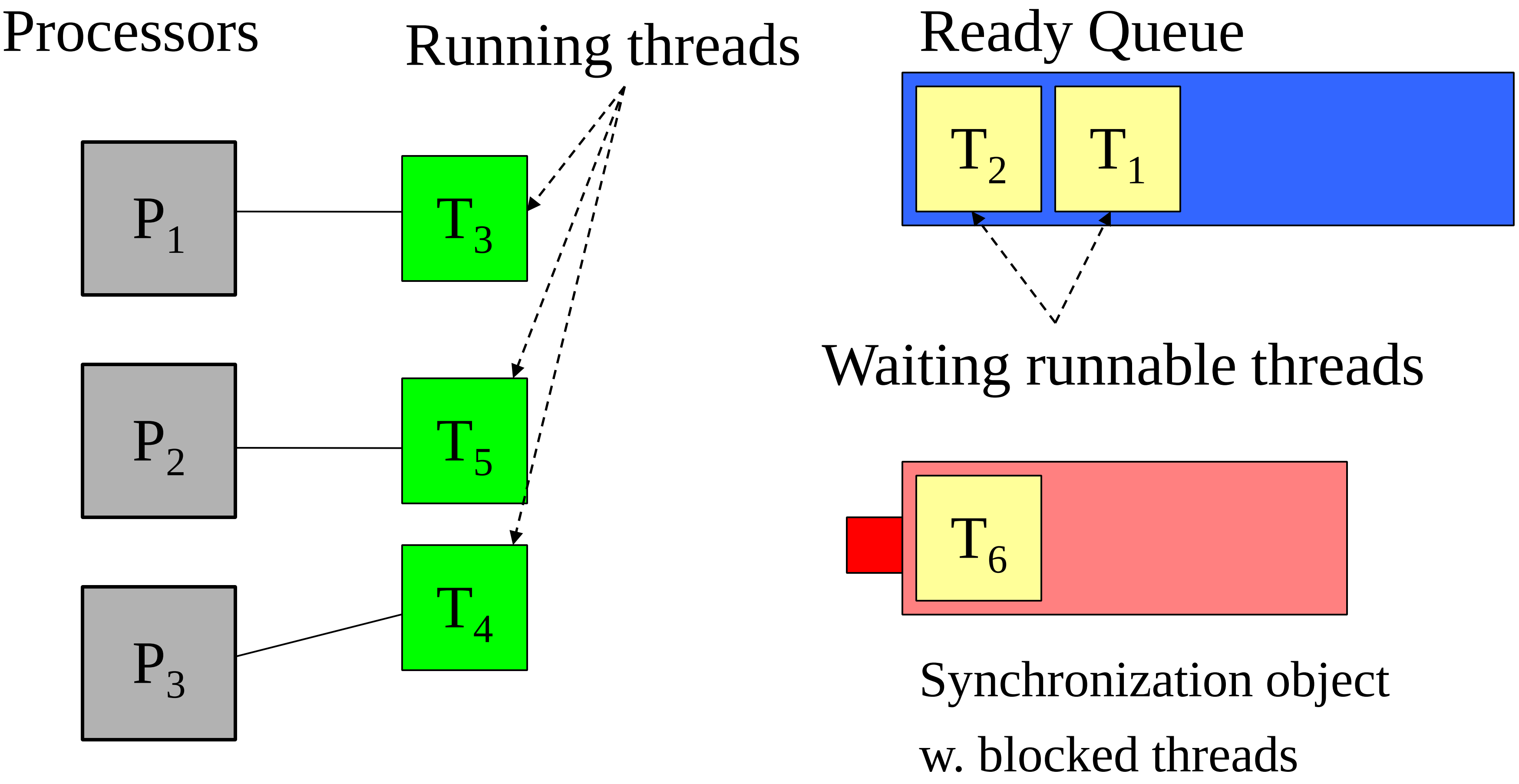
- spin lock + disable IRQ



More Related Work

- Lock-free threading
  - Hood. R. Blumofe, D. Papadopoulos, 1998.
  - Lesser Bear. H. Oguma, Y. Nakayama, 2001.
- Lock-free operating systems kernels
  - Synthesis. H. Massalin, 1992.
  - Cache Kernel. M. Greenwald, D. Cheriton, 1999.
  - A. Gavare, P. Tsigas, 2005.

LFthreads – system overview



Thread synchronization objects

- Mutual exclusion object – mutex
  - Two states: unlocked / locked
  - Three operations for threads
    - lock(m) - Locks m. If m is already locked the thread is blocked.
    - trylock(m) - Tries to lock m. Returns false if m is already locked.
    - unlock(m) - Unlocks m.

Mutex implementation

- “Typical” mutex implementation

```
type mutex_t is record
state : enum (UNLOCKED, LOCKED);
waiting : Queue of thread_t;
slock : spin_lock_t;
```

- Note: The spin-lock protects the mutex_t record from concurrent updates by different processors
  - Operations cannot overlap
  - Processors might be forced to spin waiting for others

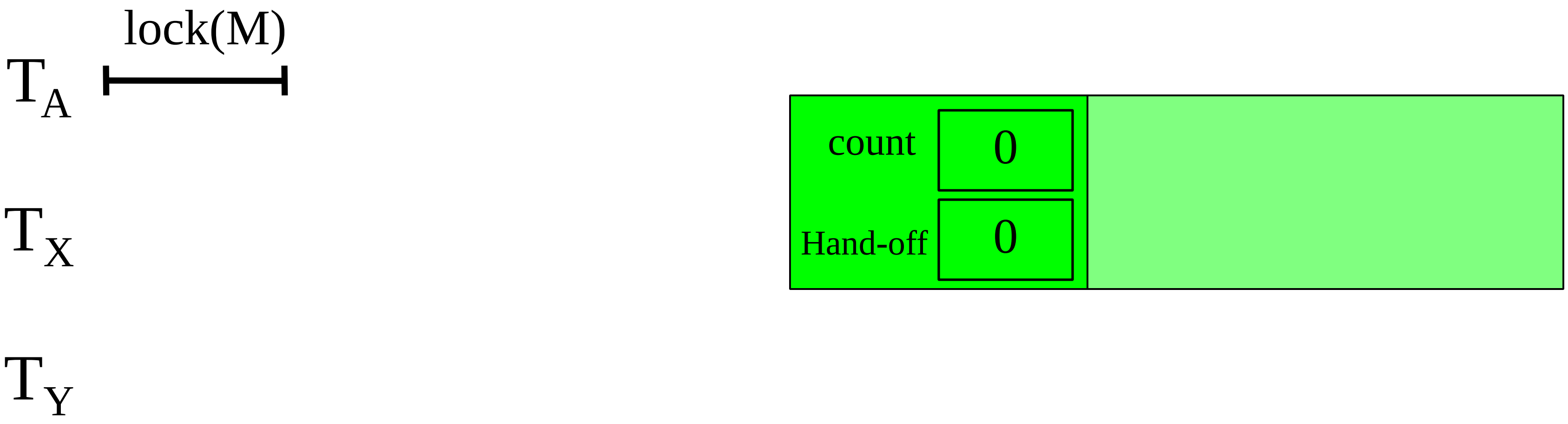
Lock-free mutex implementation
The Hand-off method

type mutex_t **is record**

count : integer;

waiting : *Lock-free Queue* of thread_t;

hand-off : integer;



lock(M)

T_A

T_X

T_Y

count 0

Hand-off 0

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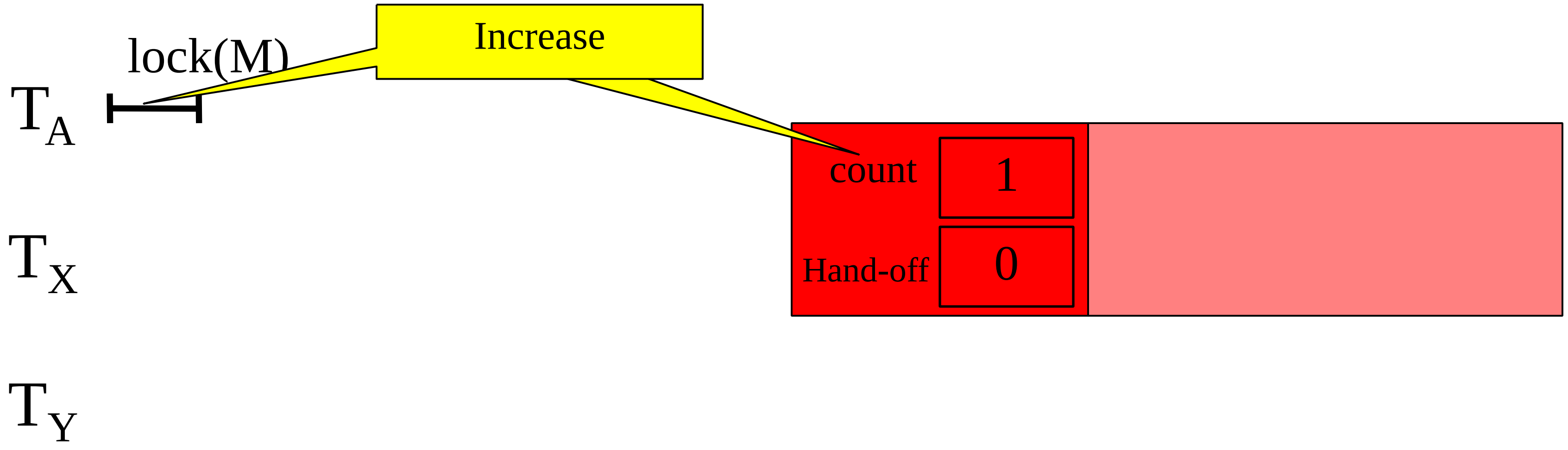

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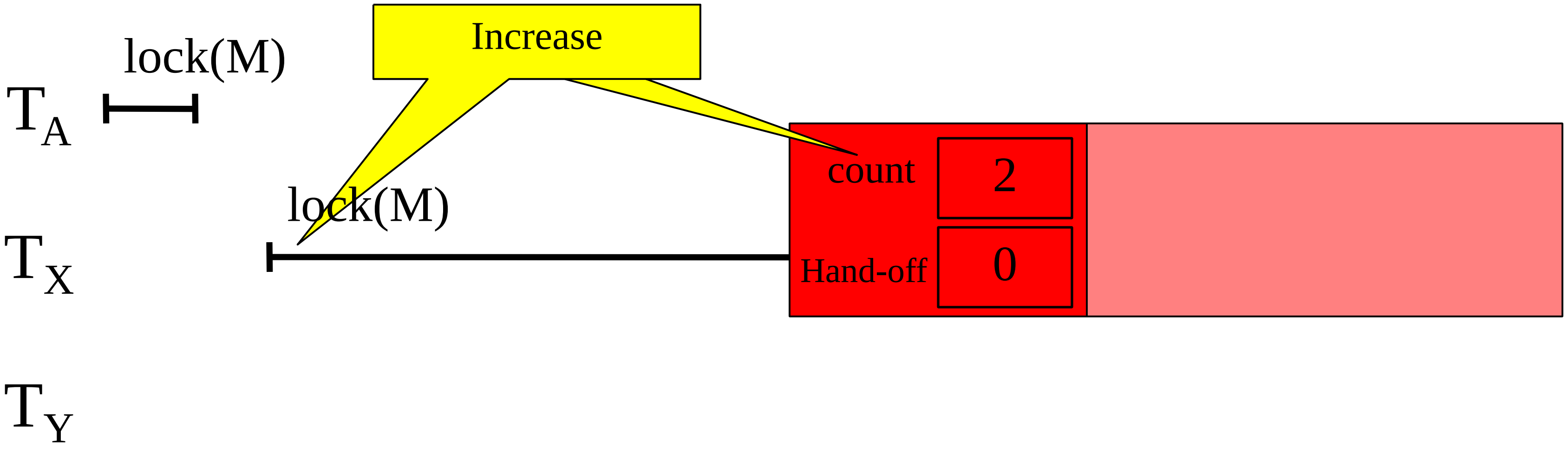

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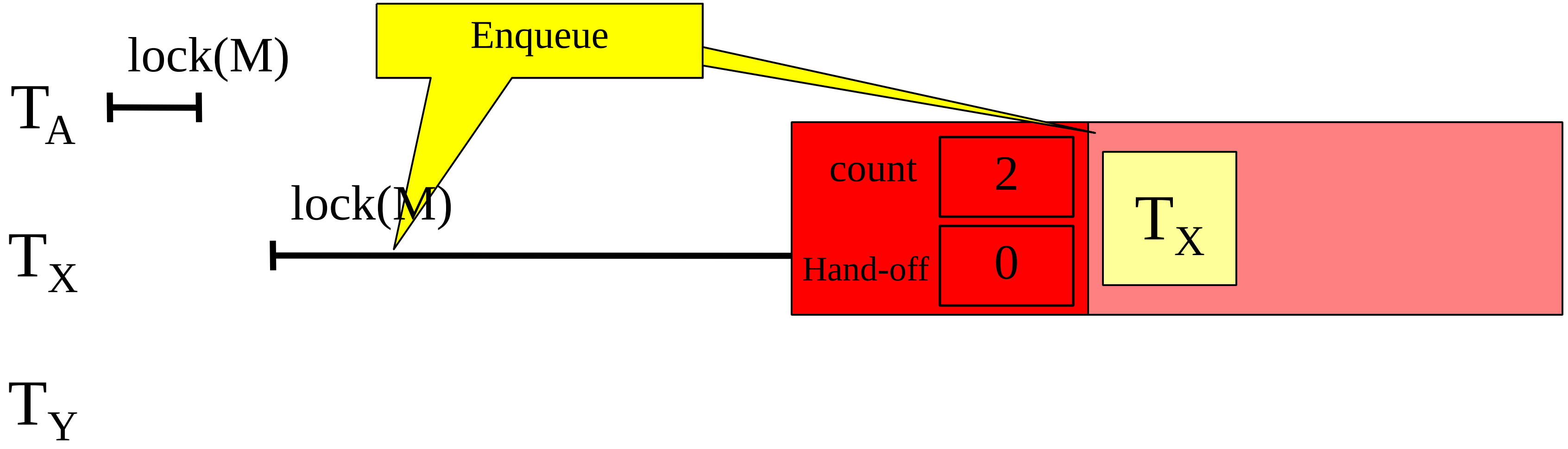

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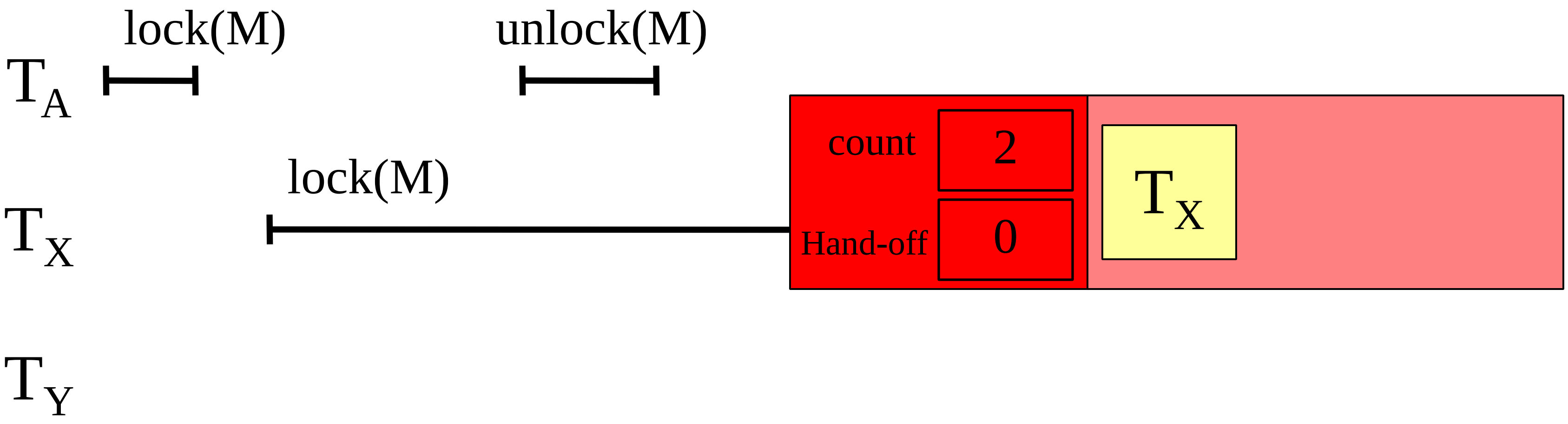

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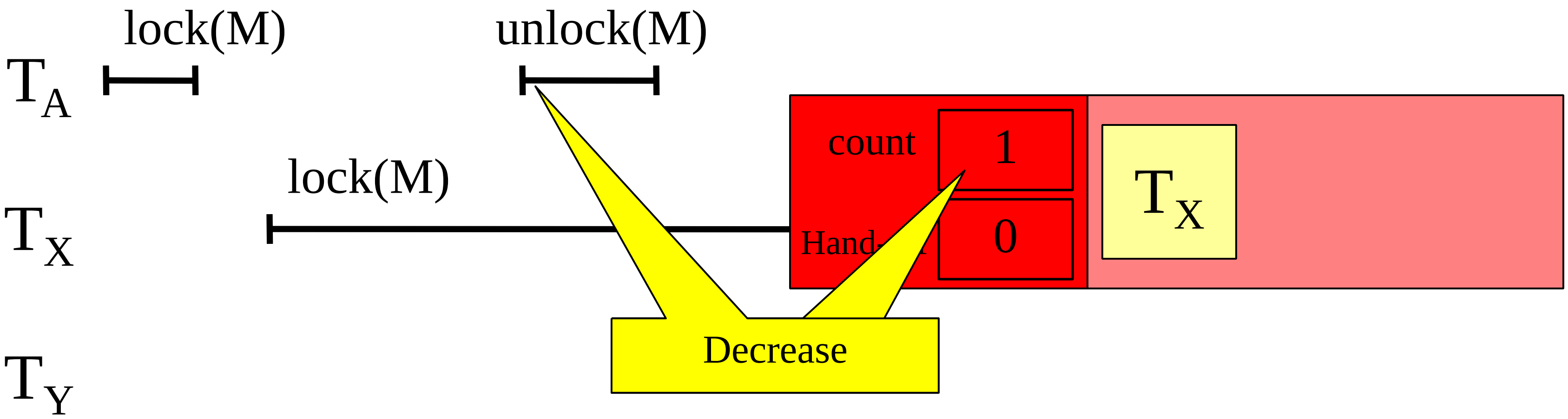

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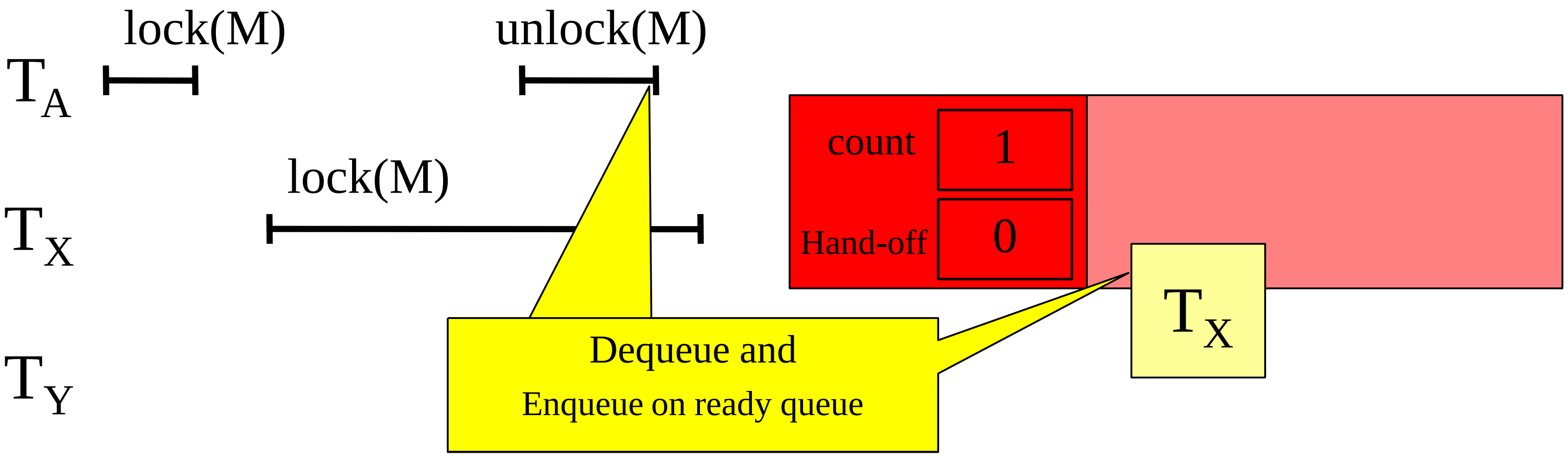

Dequeue and

Enqueue on ready queue

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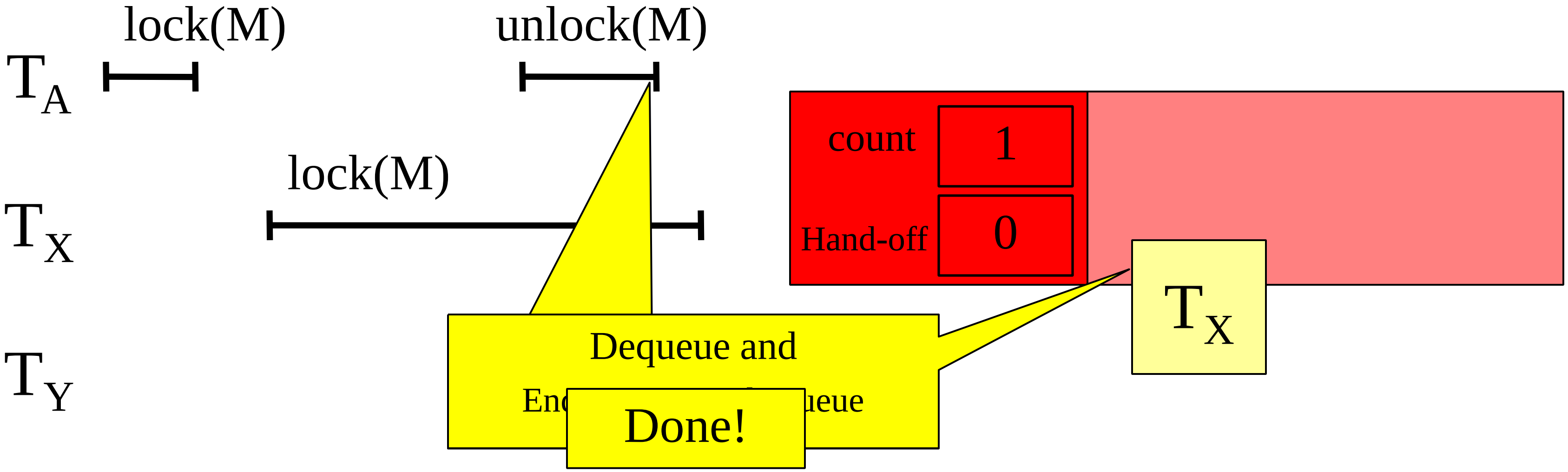

Lock-free mutex implementation: Slow lock (i)

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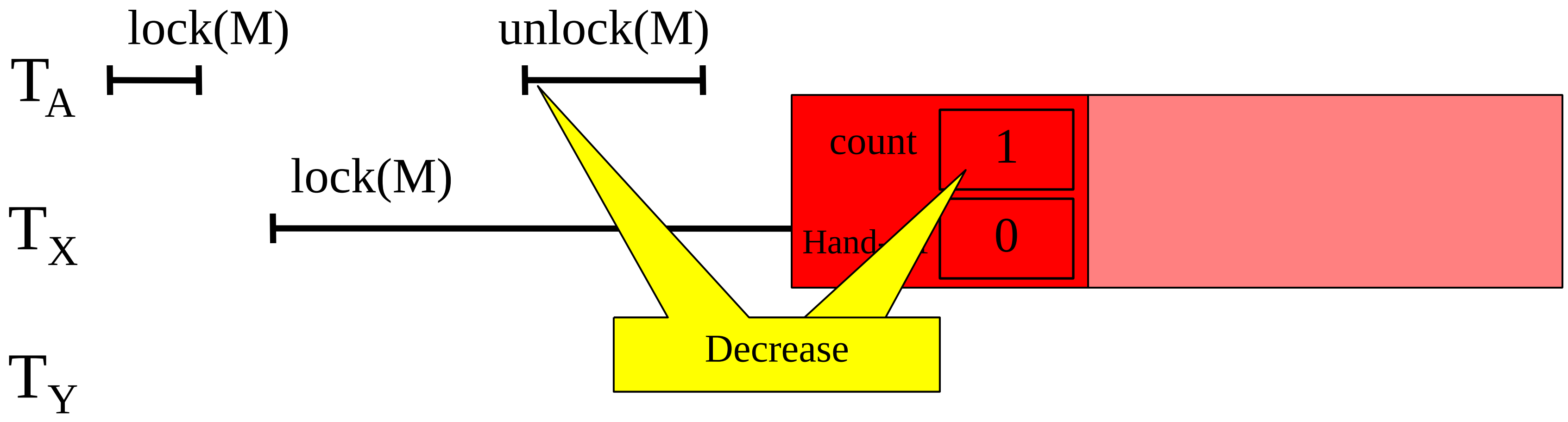

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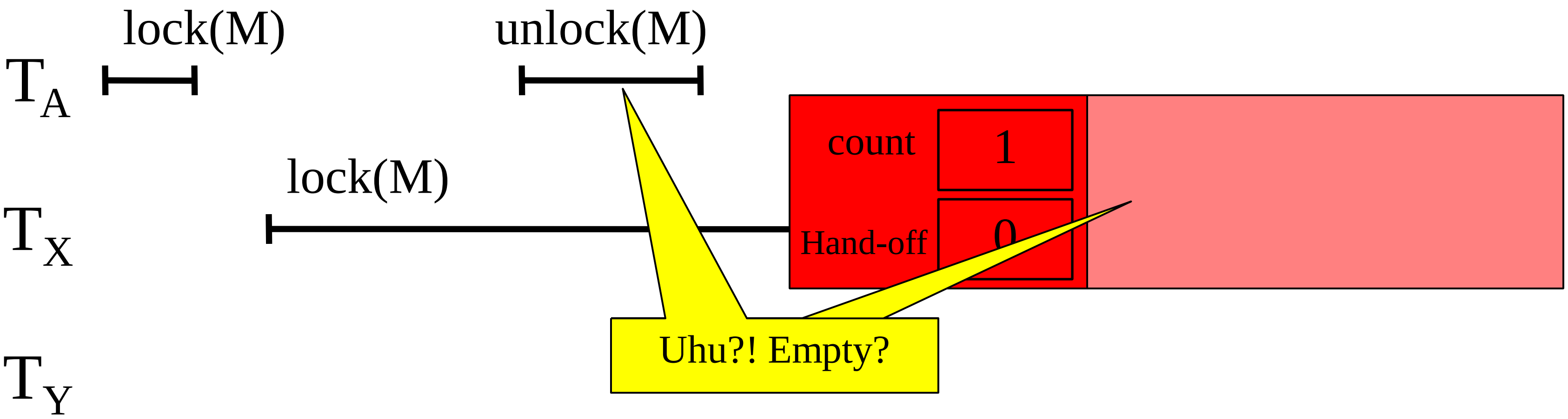

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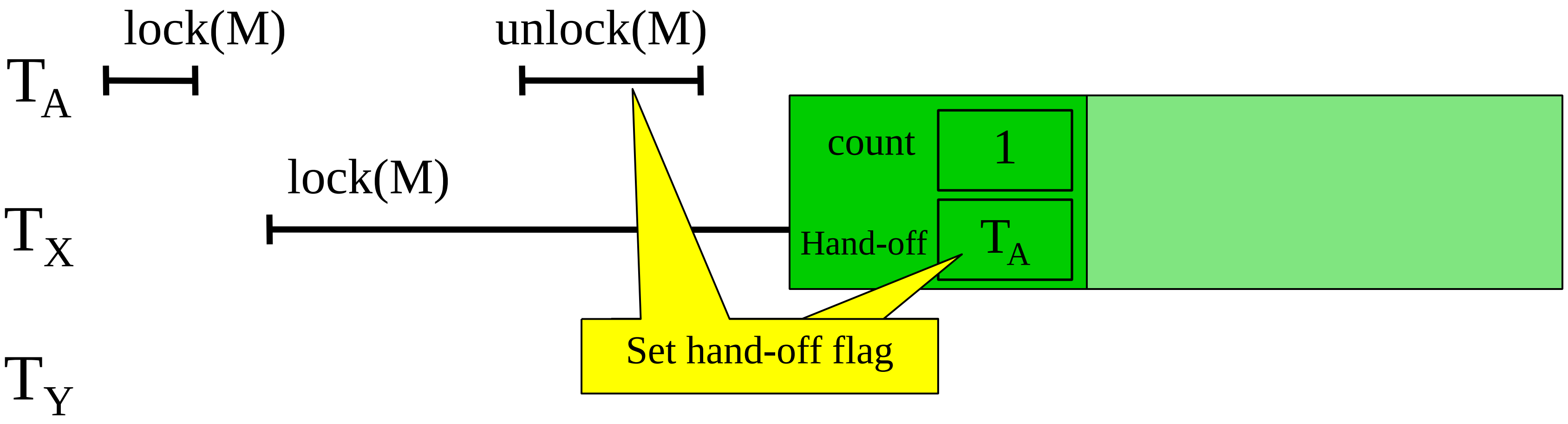

Set hand-off flag

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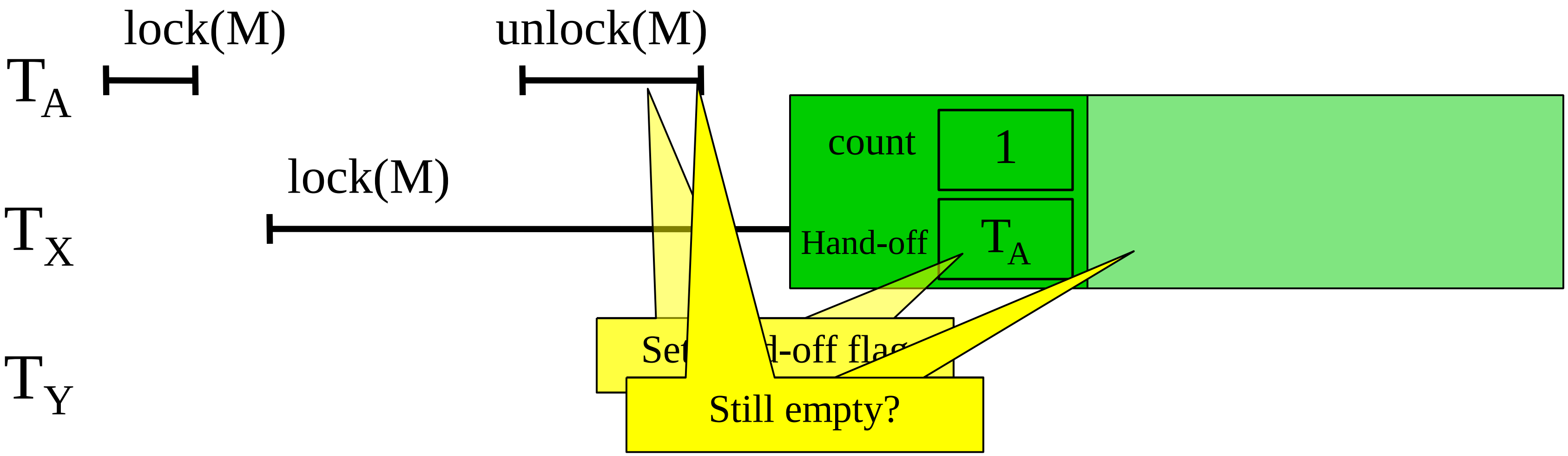

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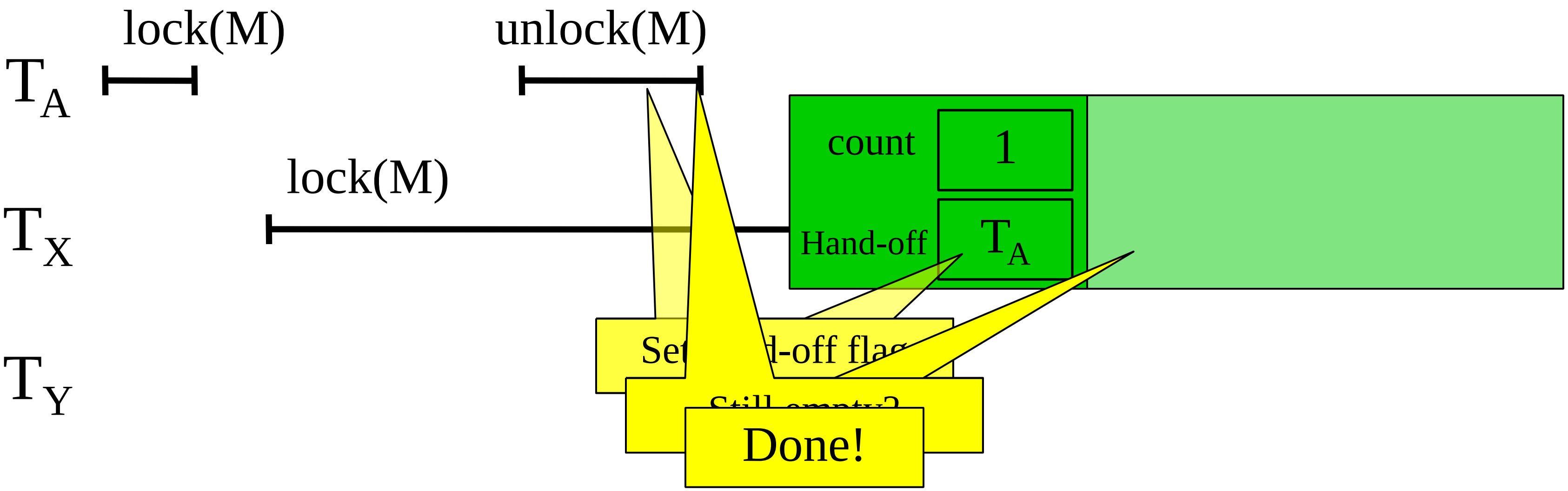

Lock-free mutex implementation: Slow lock (ii)

type mutex_t **is record**

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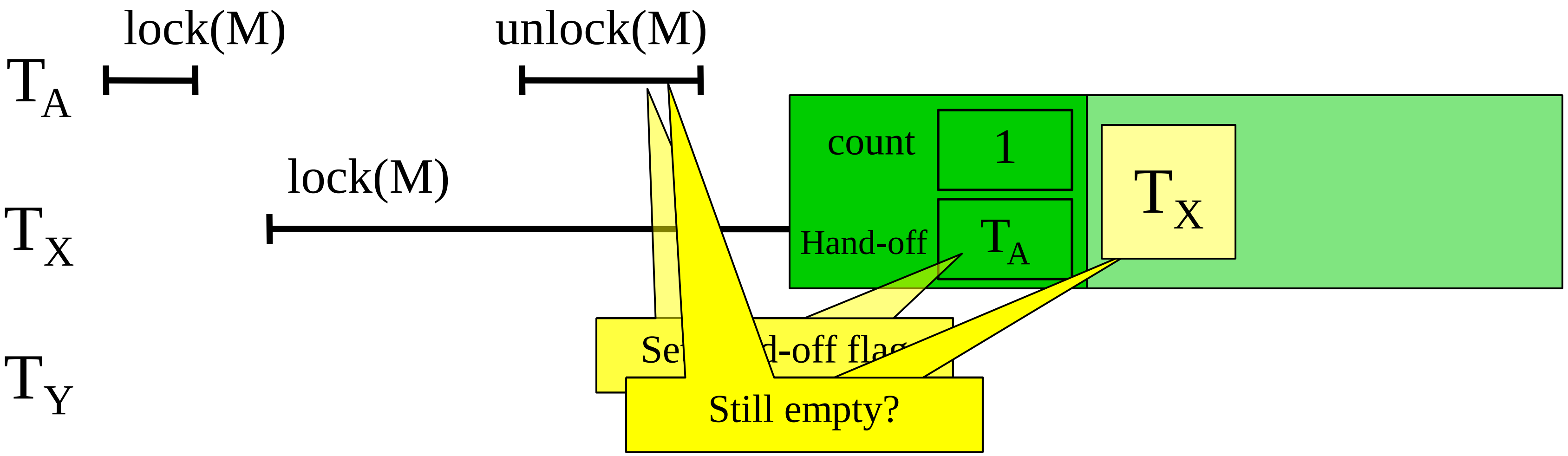
waiting : Lock-free Queue of thread_t;

hand-off : integer;



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count : integer;

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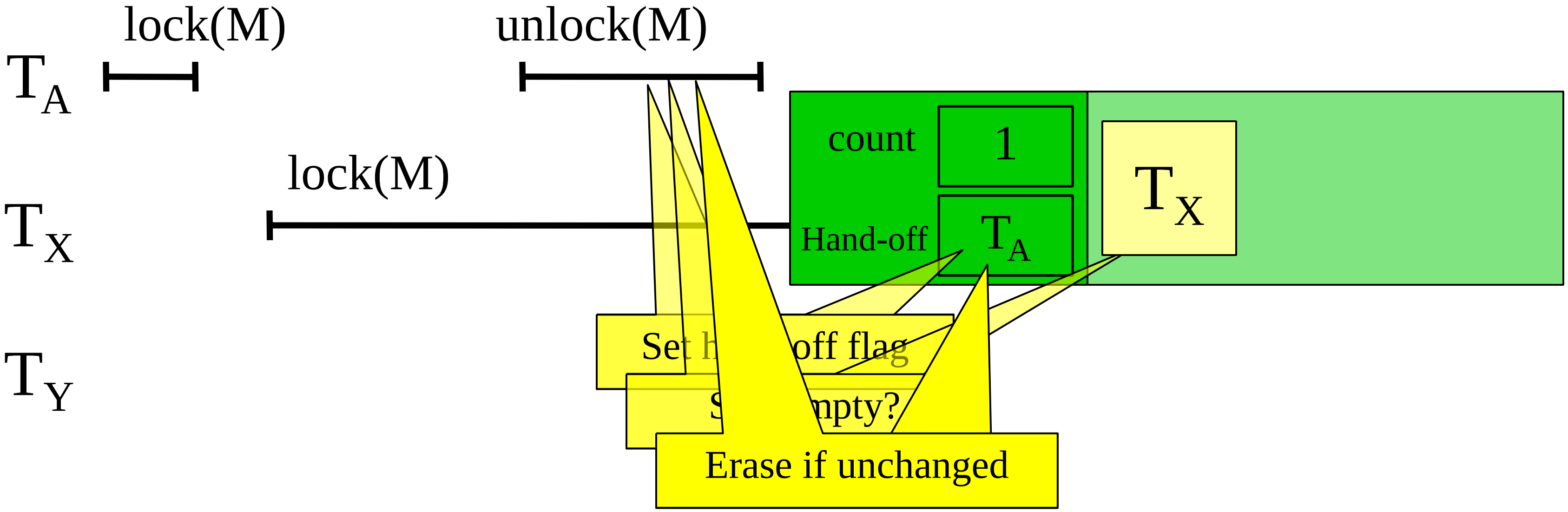
hand-off : integer;



lock(M)

unlock(M)

lock(M)

T_A

T_X

T_Y

count

1

Hand-off

T_A

T_X

Set h off flag

S mpty?

Erase if unchanged

Lock-free mutex implementation: Slow lock (ii)

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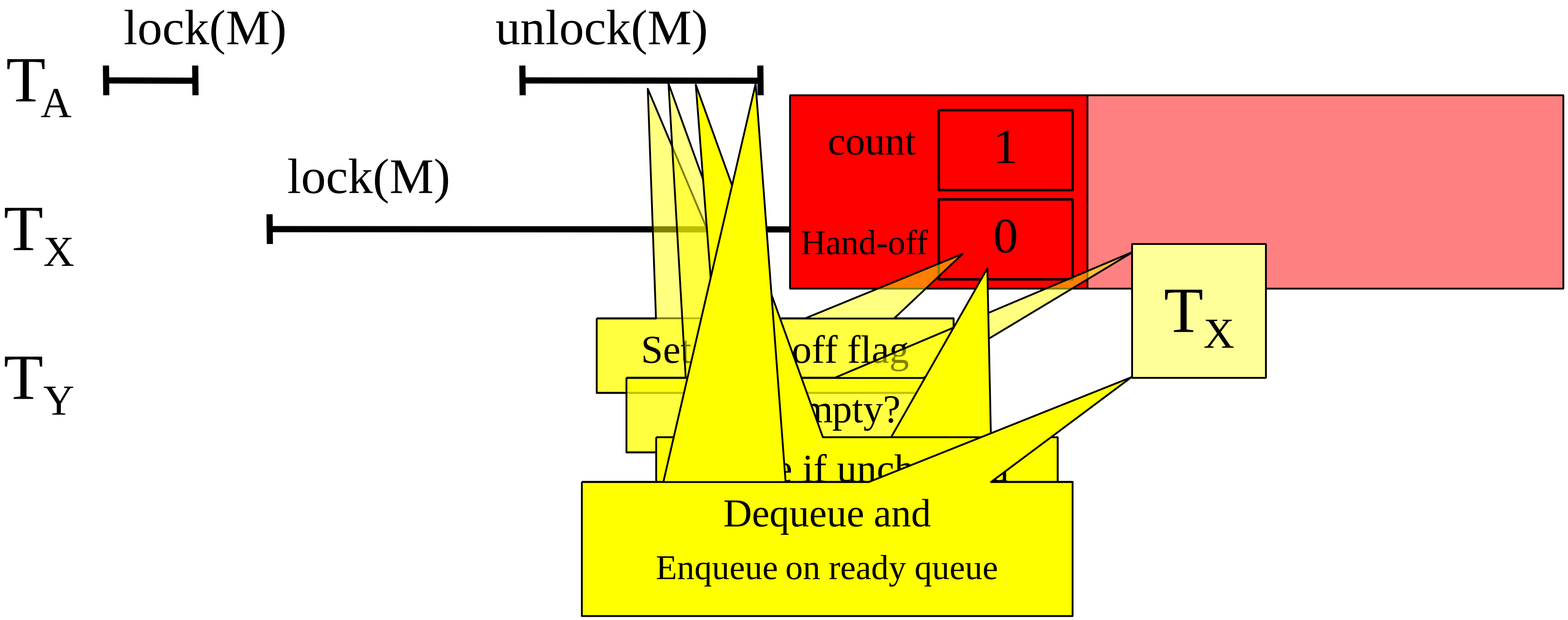
count : integer;

waiting : Lock-free Queue of thread_t;

hand-off : integer;



Lock-free mutex implementation: Slow lock (ii)

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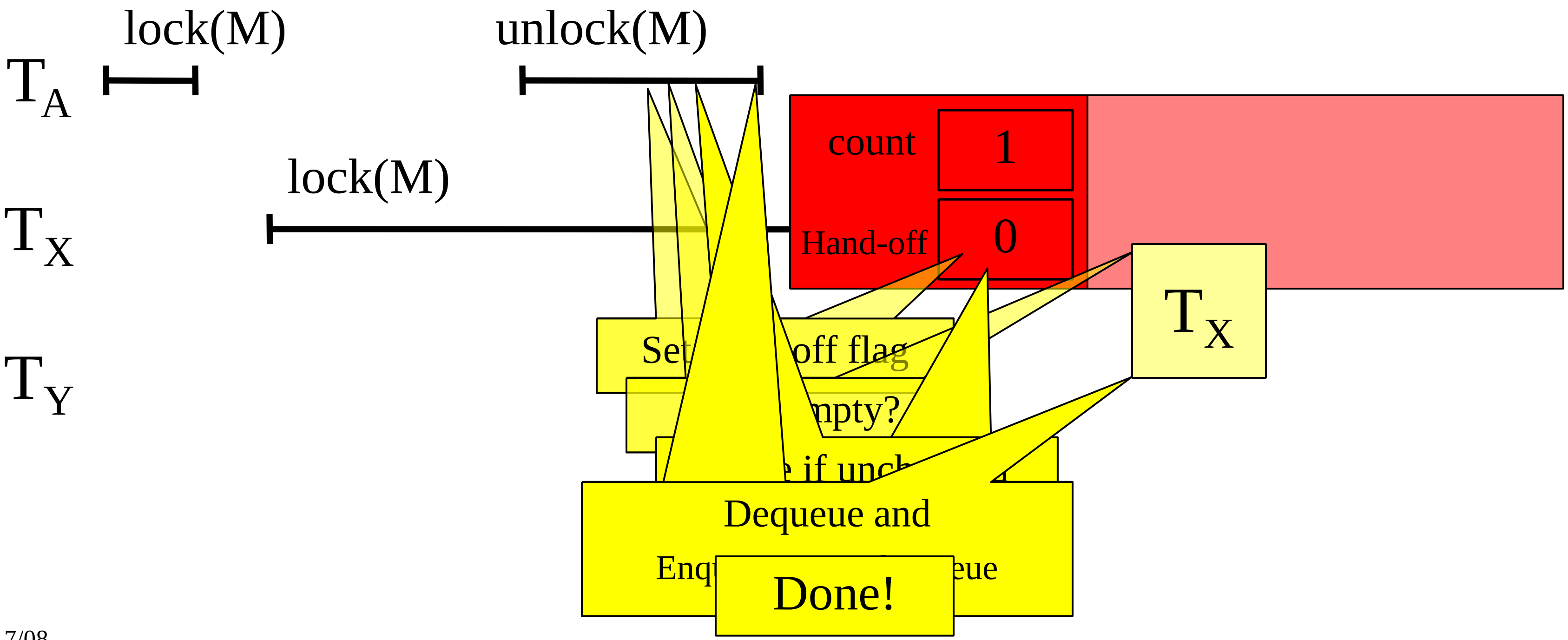

Lock-free mutex implementation: Slow lock (iii)

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waiting : Lock-free Queue of thread_t;

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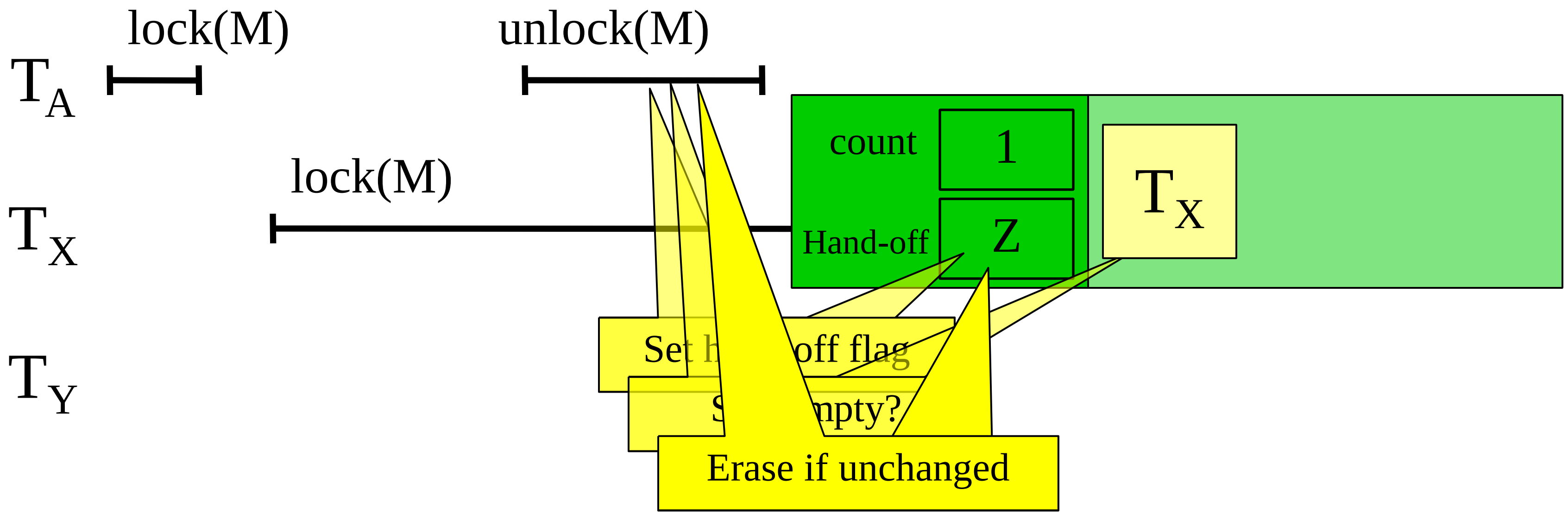

Lock-free mutex implementation: Slow lock (iii)

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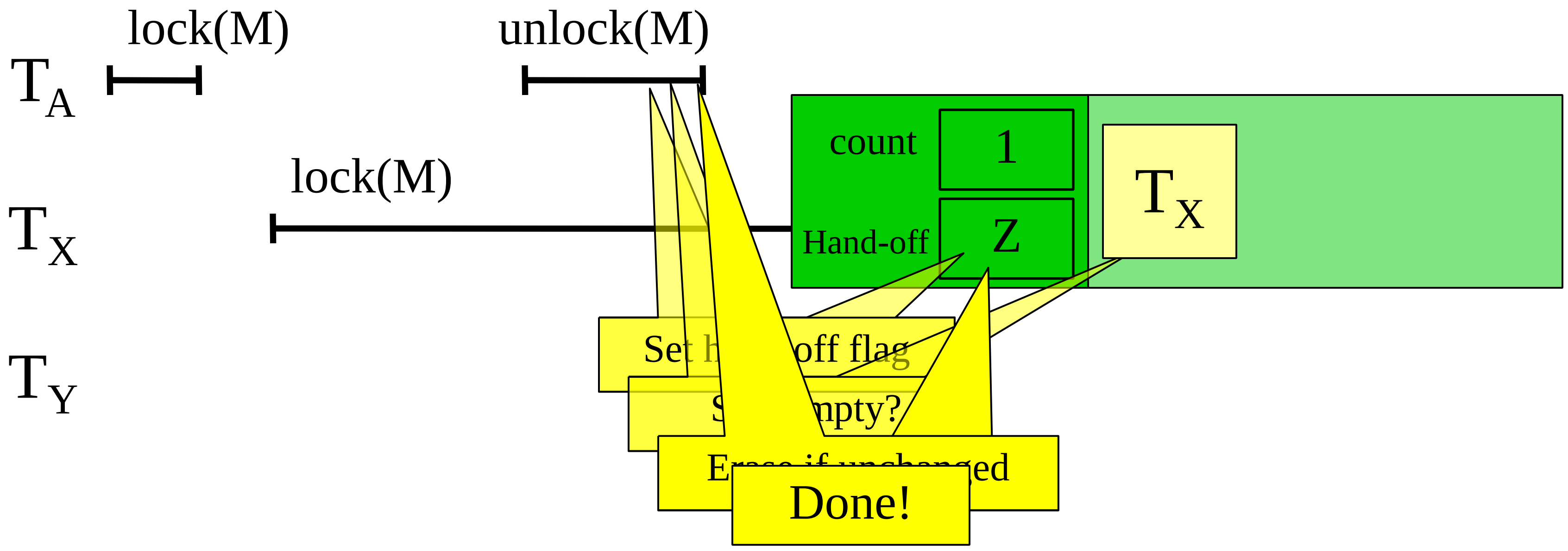
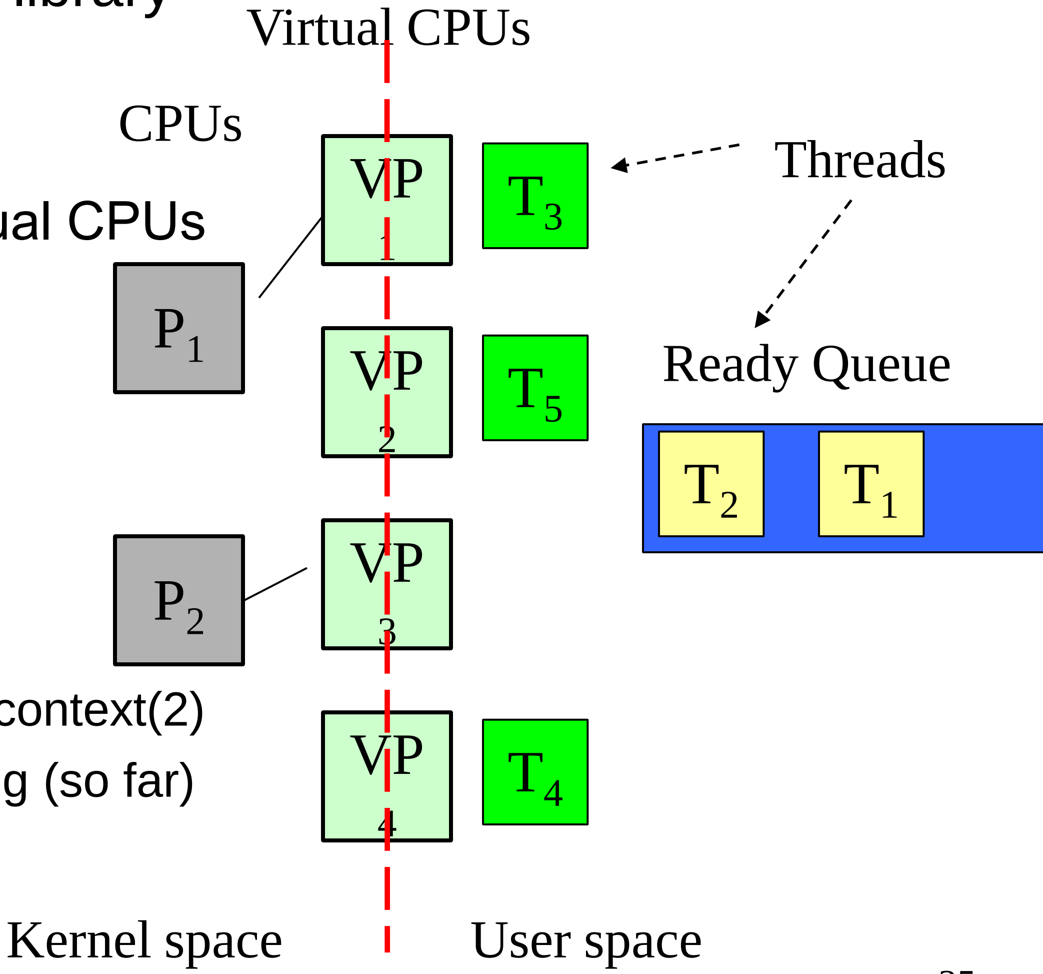
hand-off : integer;



Proof-of-concept implementation

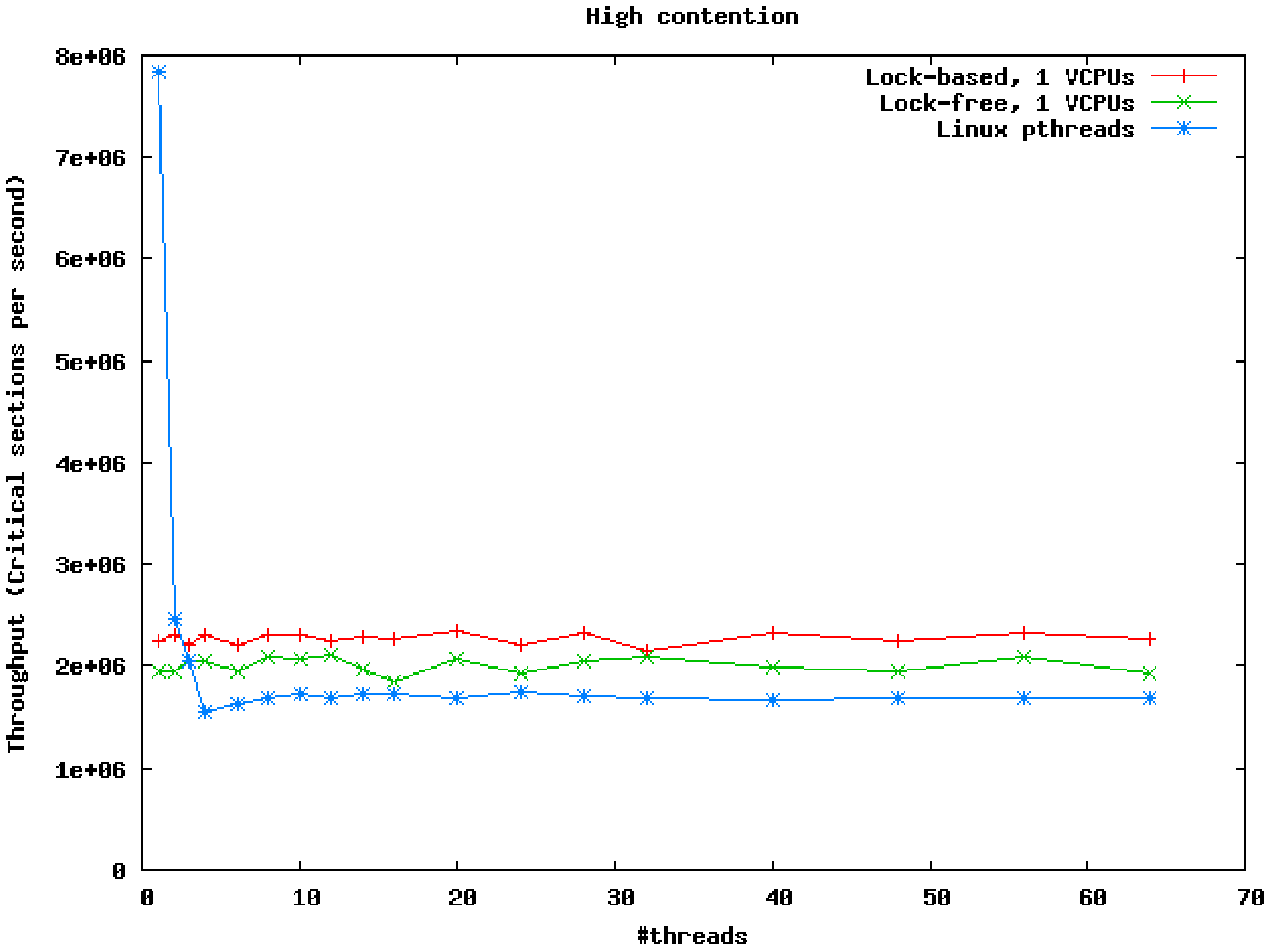
- LFthreads user-level thread library
  - Linux/IA32 platform
  - “Cloned” processes as virtual CPUs
    - Share the same address space, file descriptor table etc
  - User-level thread contexts based on
    - SUSv2 setcontext(2) / getcontext(2)
    - Non-preemptive scheduling (so far)
  - POSIX compliance a goal



Experimental evaluation

- Micro benchmark
  - Threads competing for a critical section
    - High contention
      - Work: 1 -1
    - Low contention
      - Work: 1 - 1000
  - Configurations
    - LFthreads with 1, 2, 4, 8,16 virtual CPUs
      - lock-free mutex
      - spin-lock-based mutex
    - Platforms standard pthreads (2.6.x kernel)
  - 2x dual AMD Opteron processors

Experimental evaluation (i)



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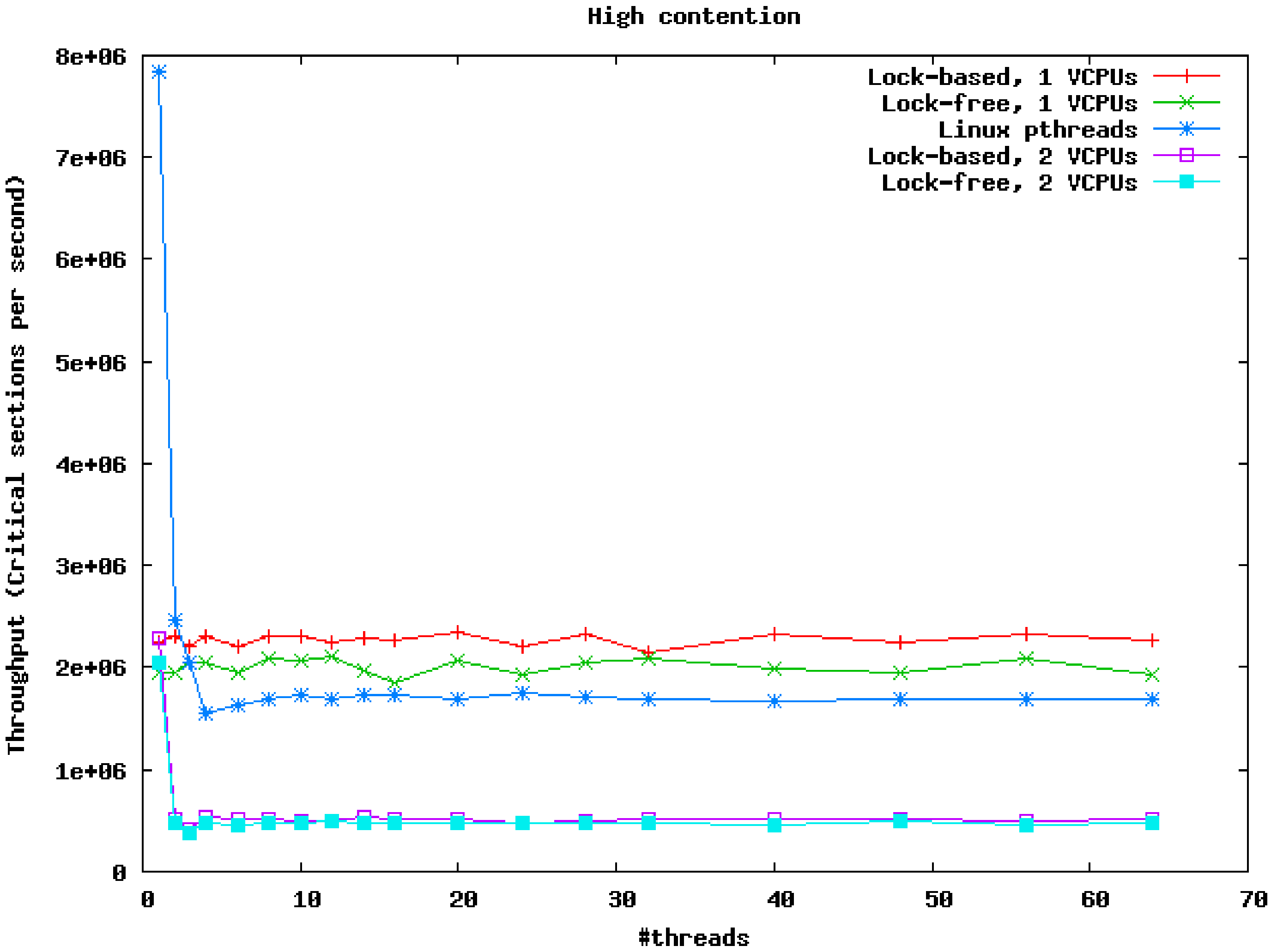

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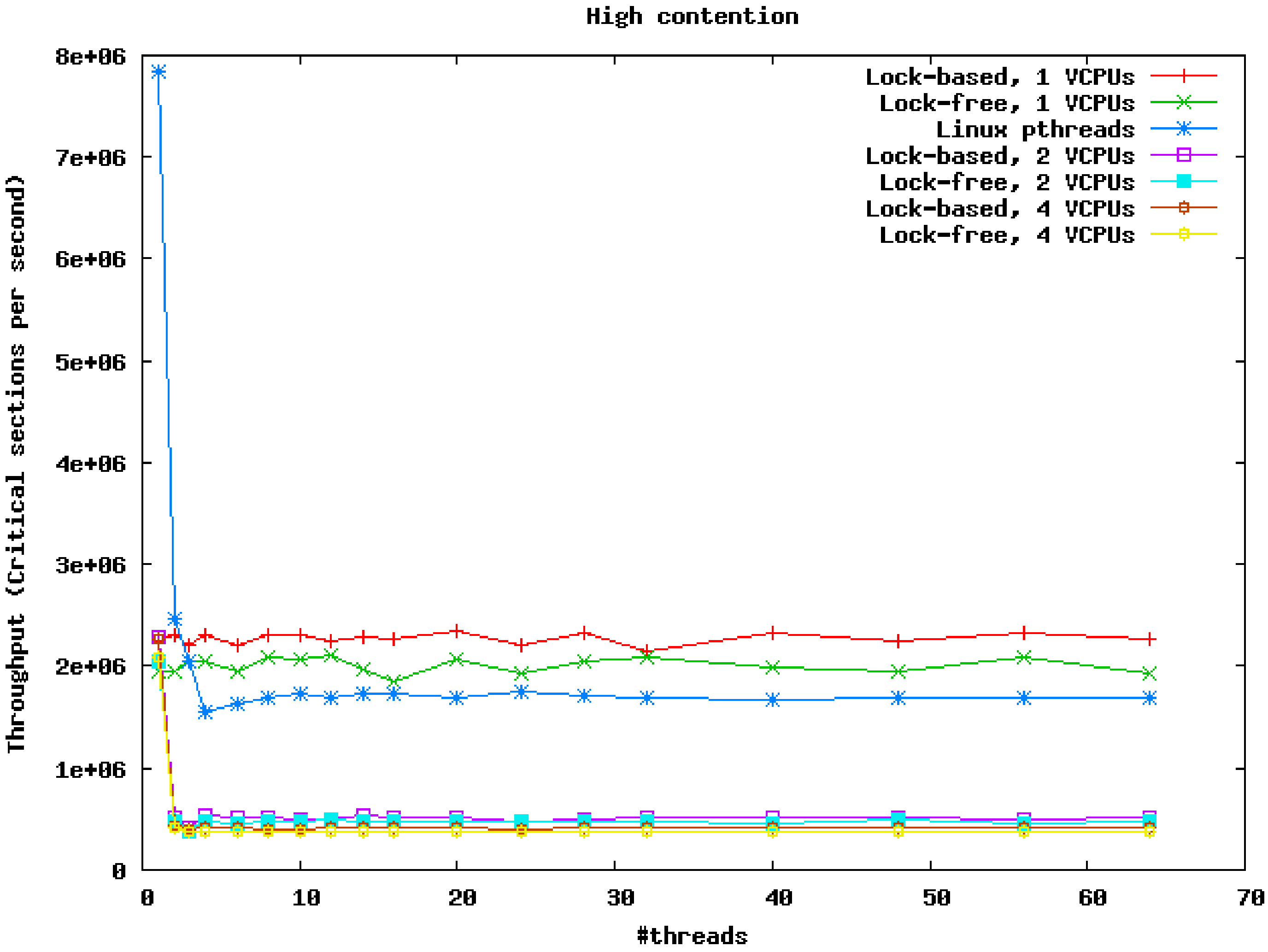

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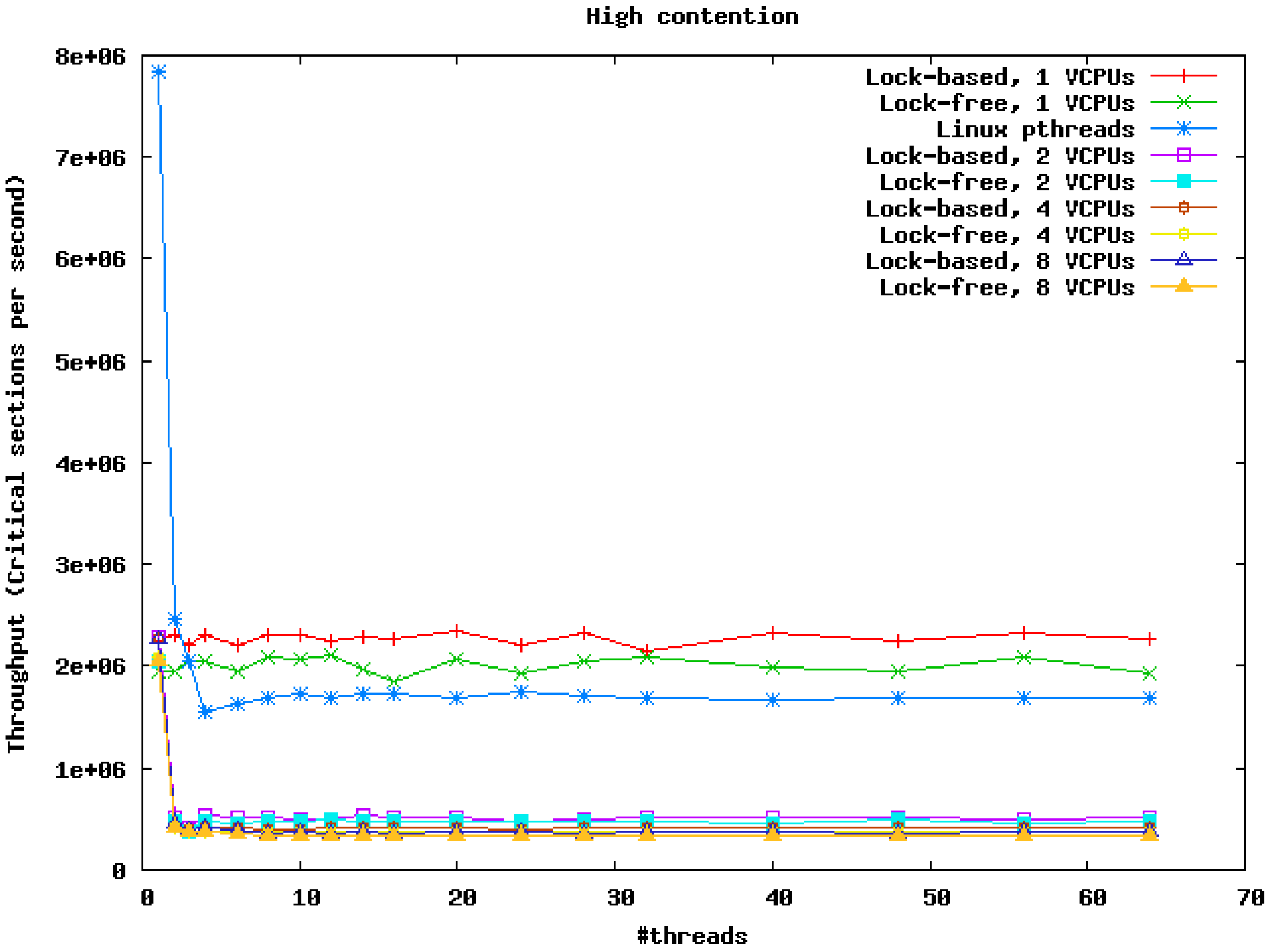

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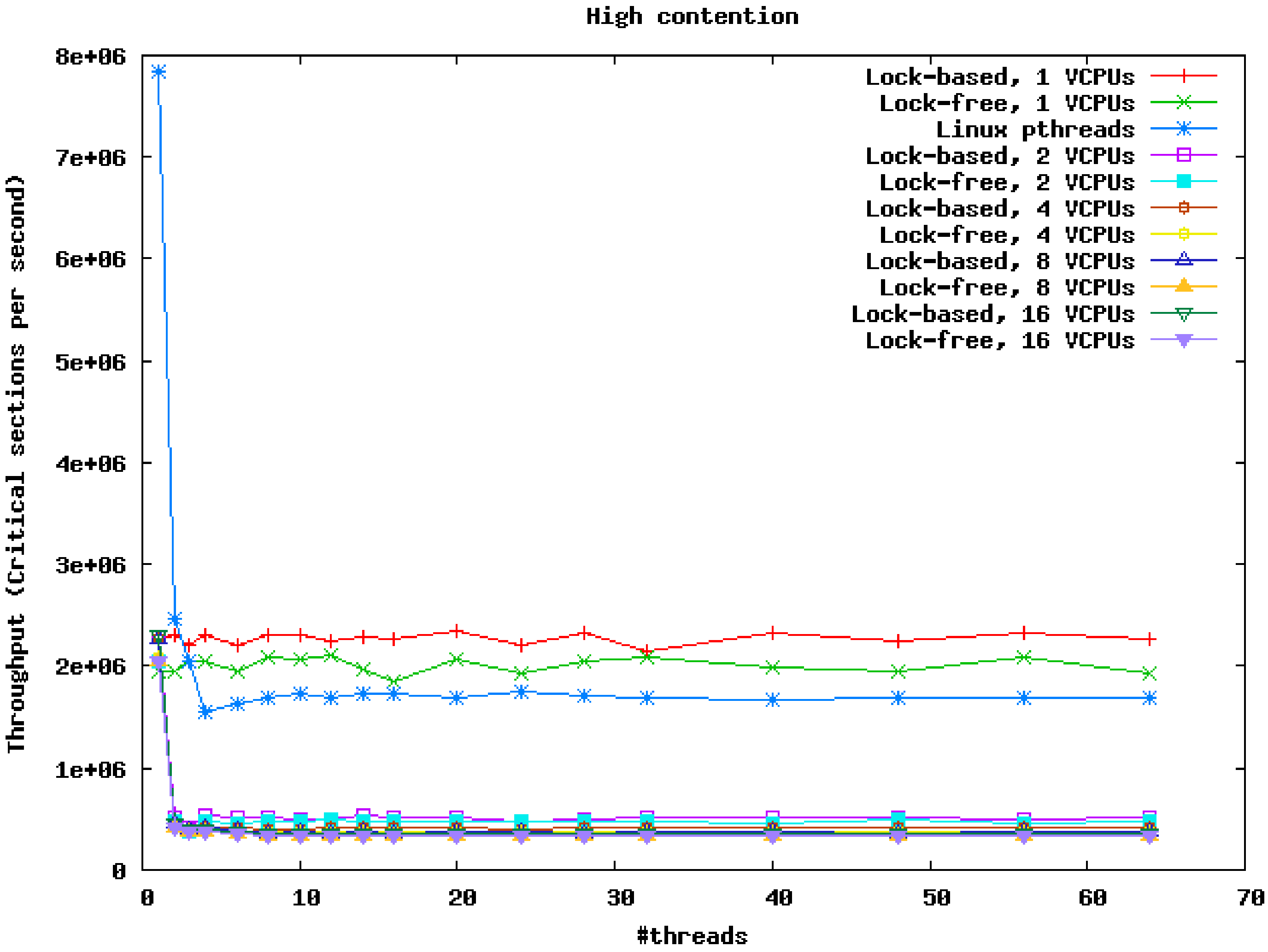

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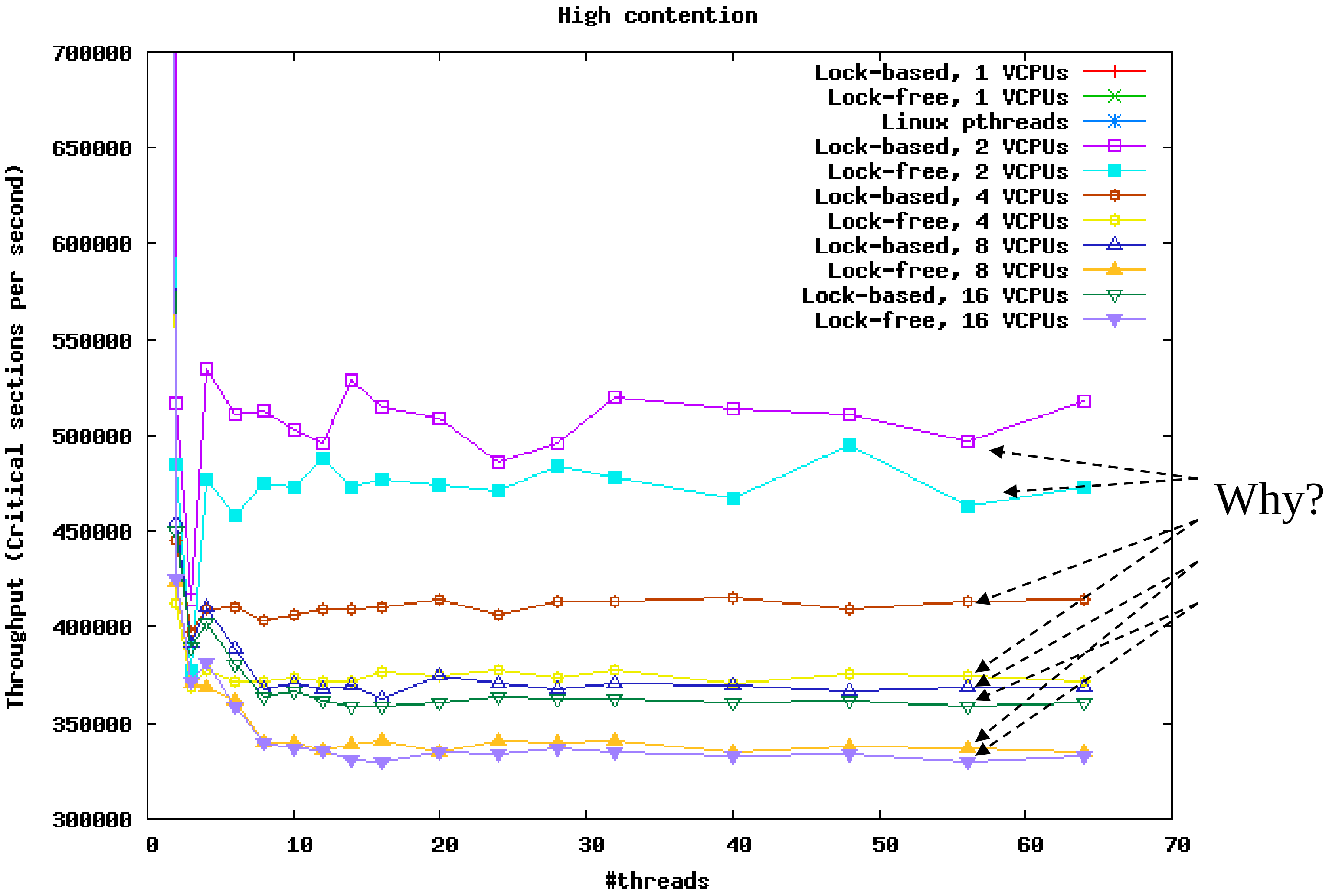

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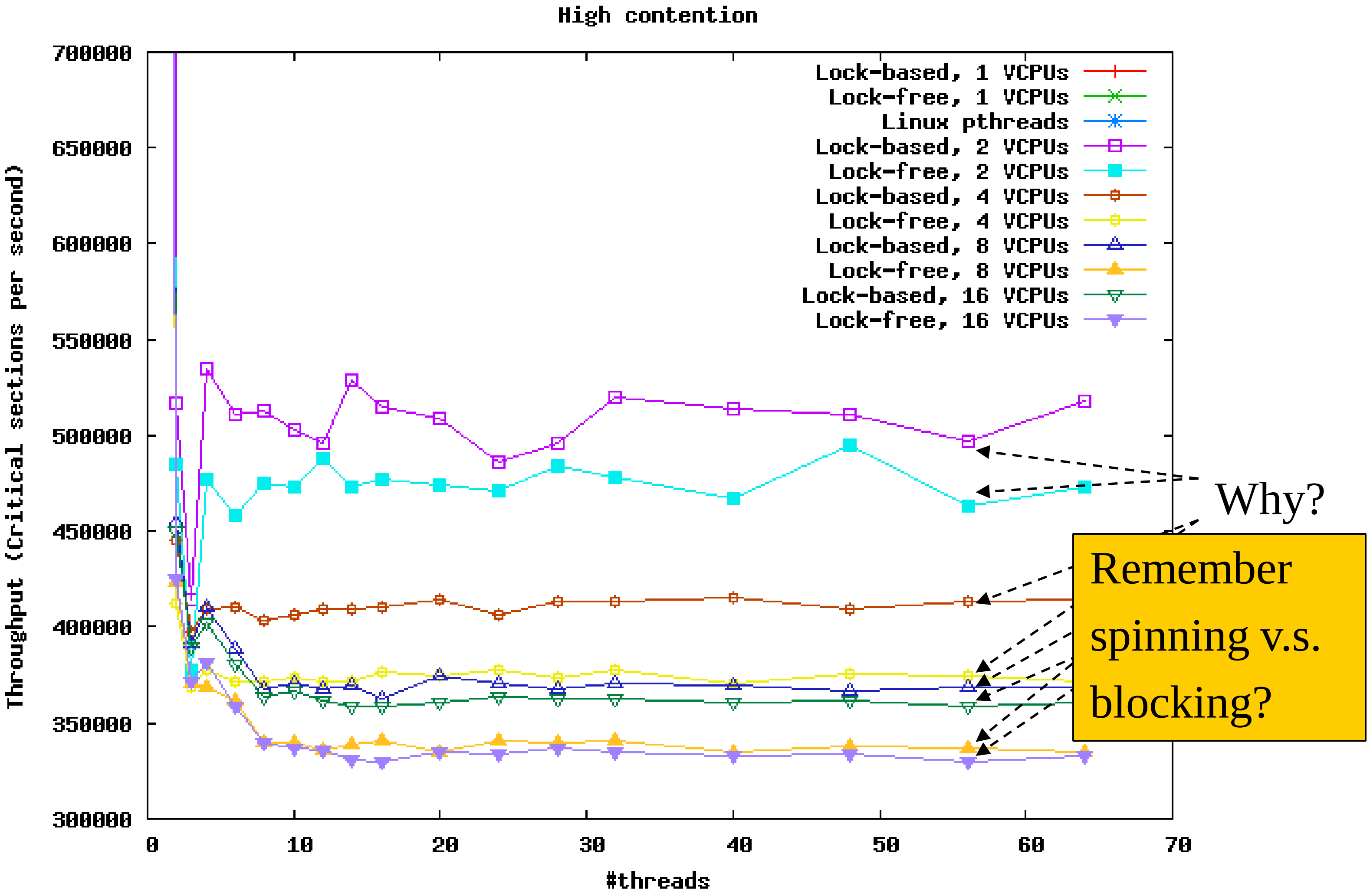
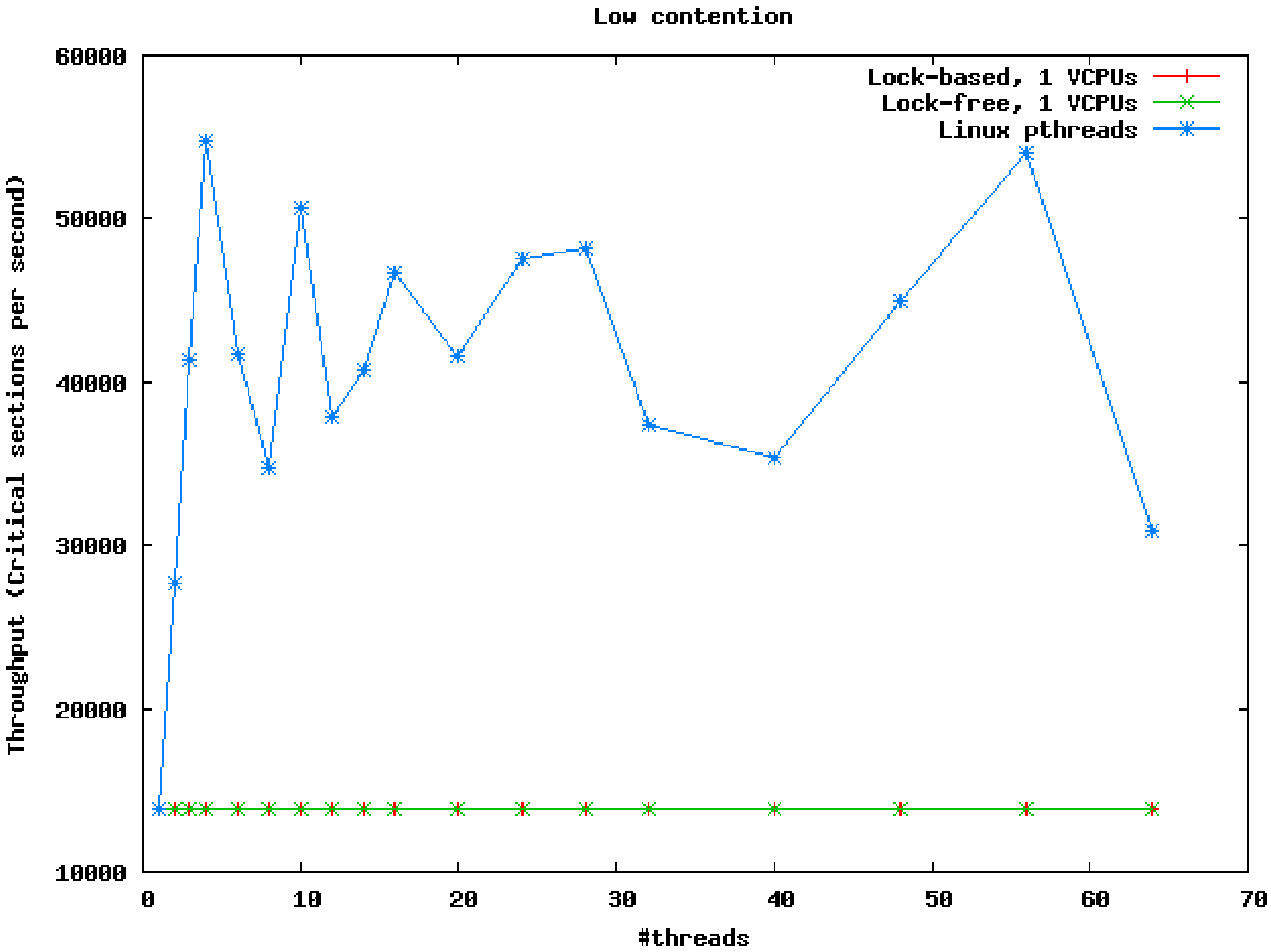


Why?

Remember spinning v.s. blocking?

Experimental evaluation (ii)



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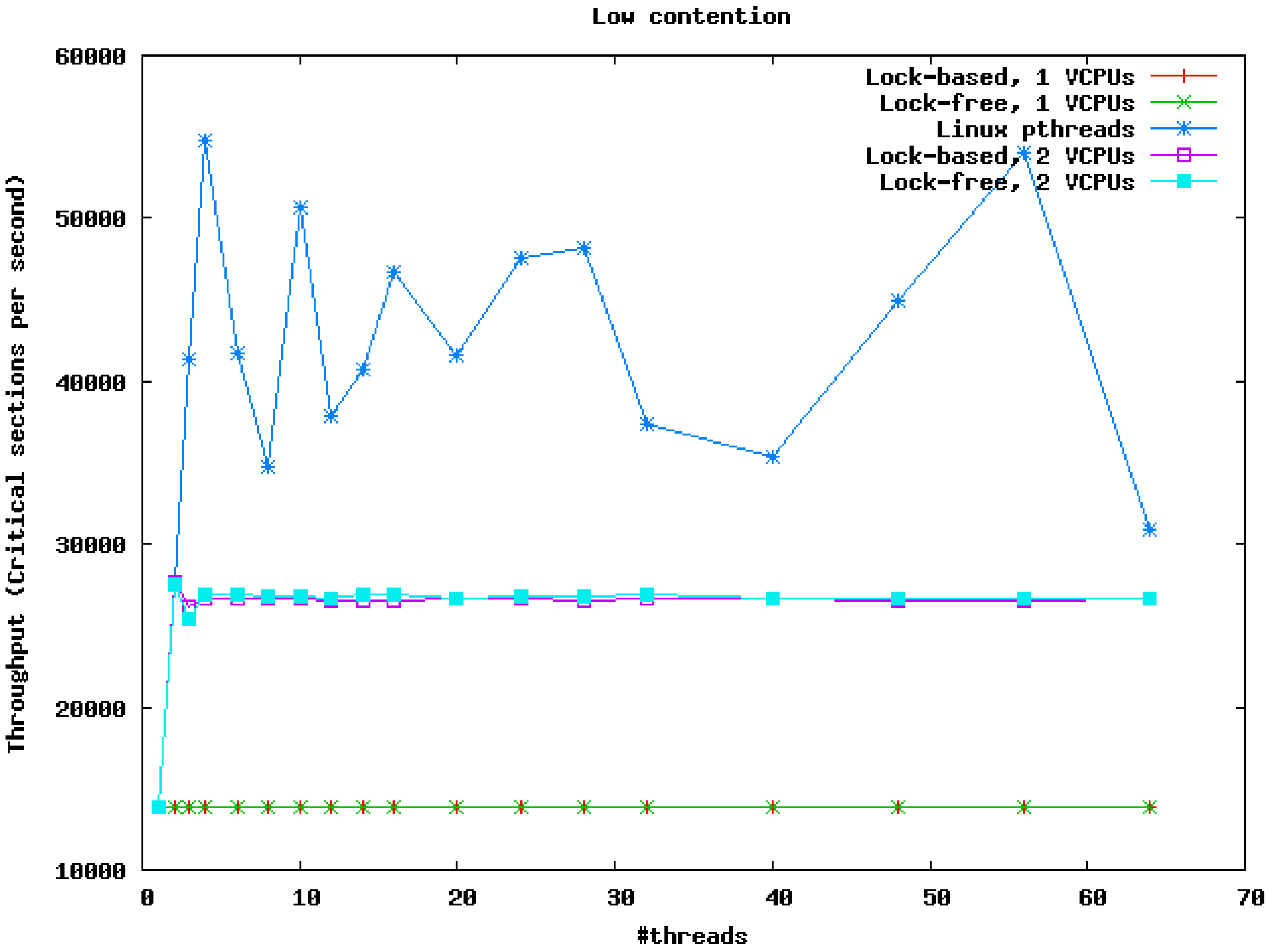

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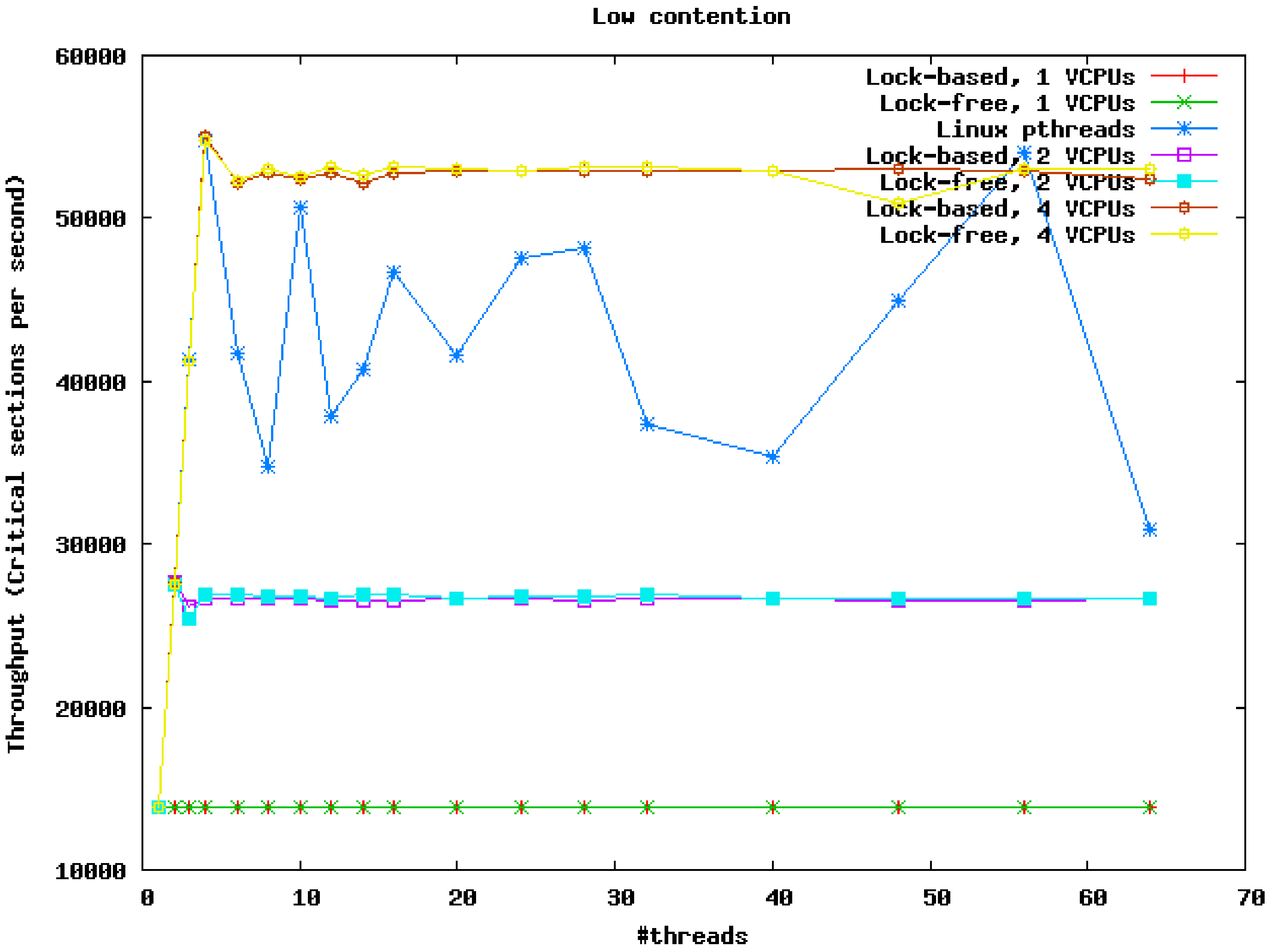

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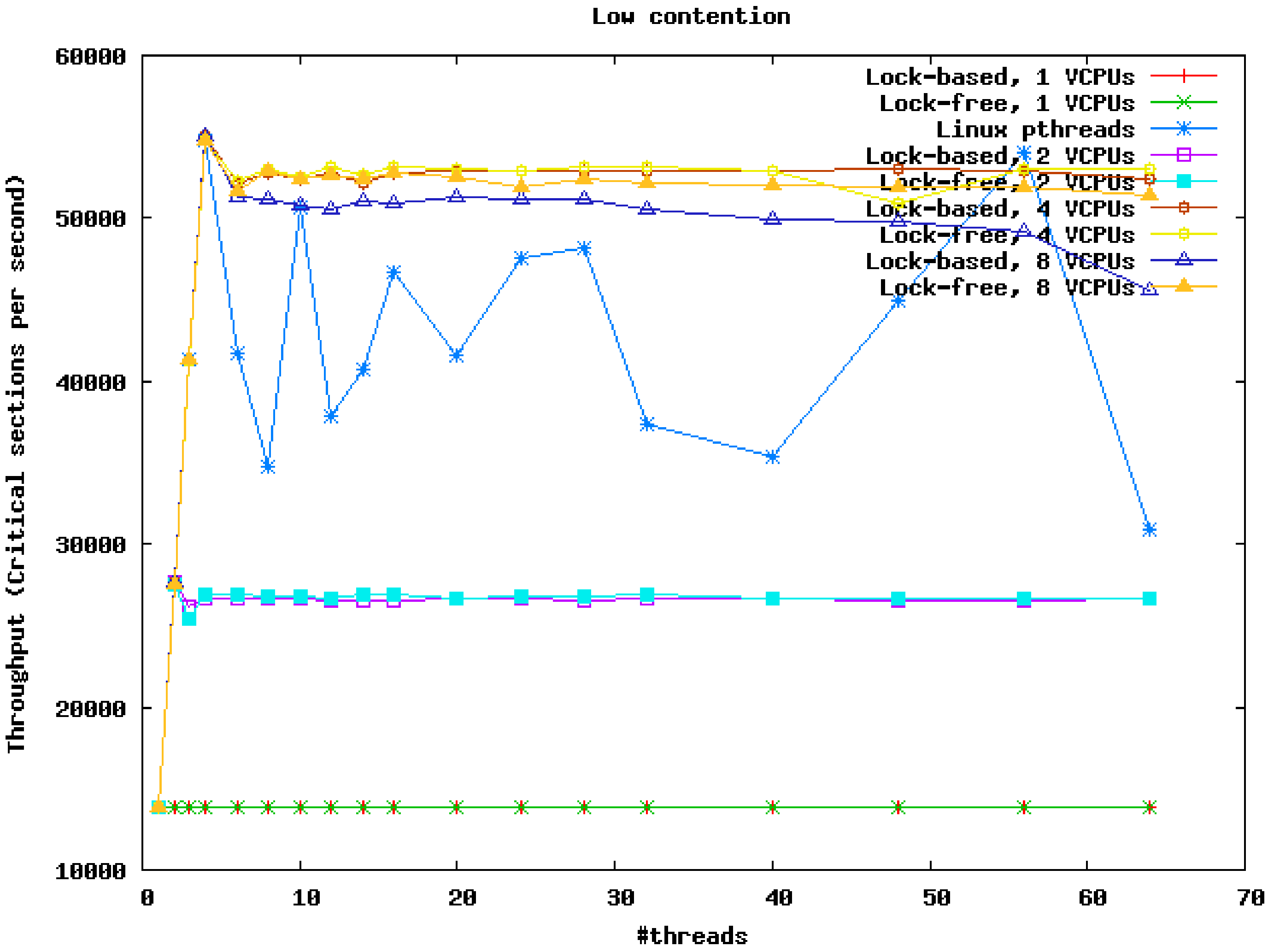

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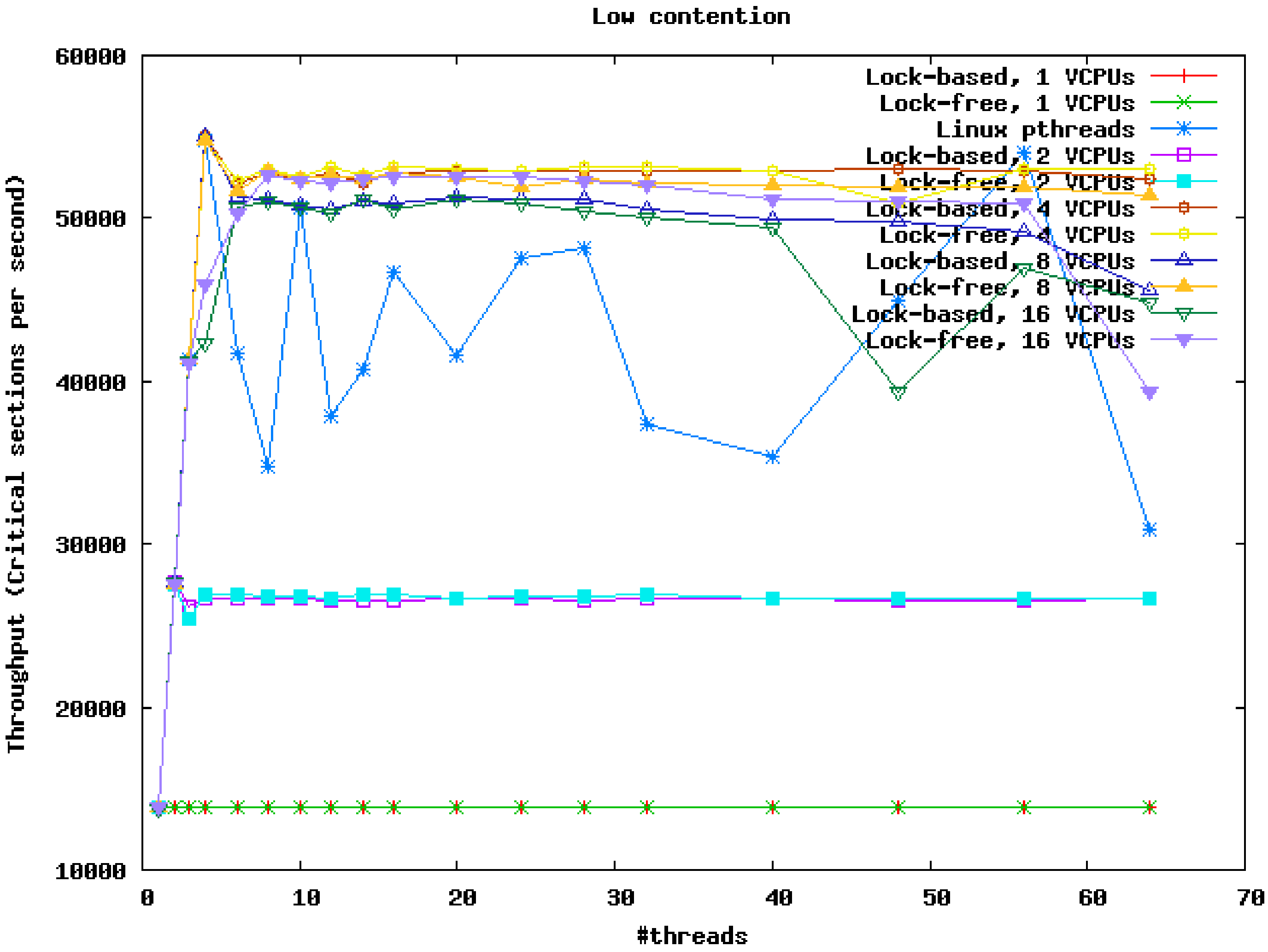

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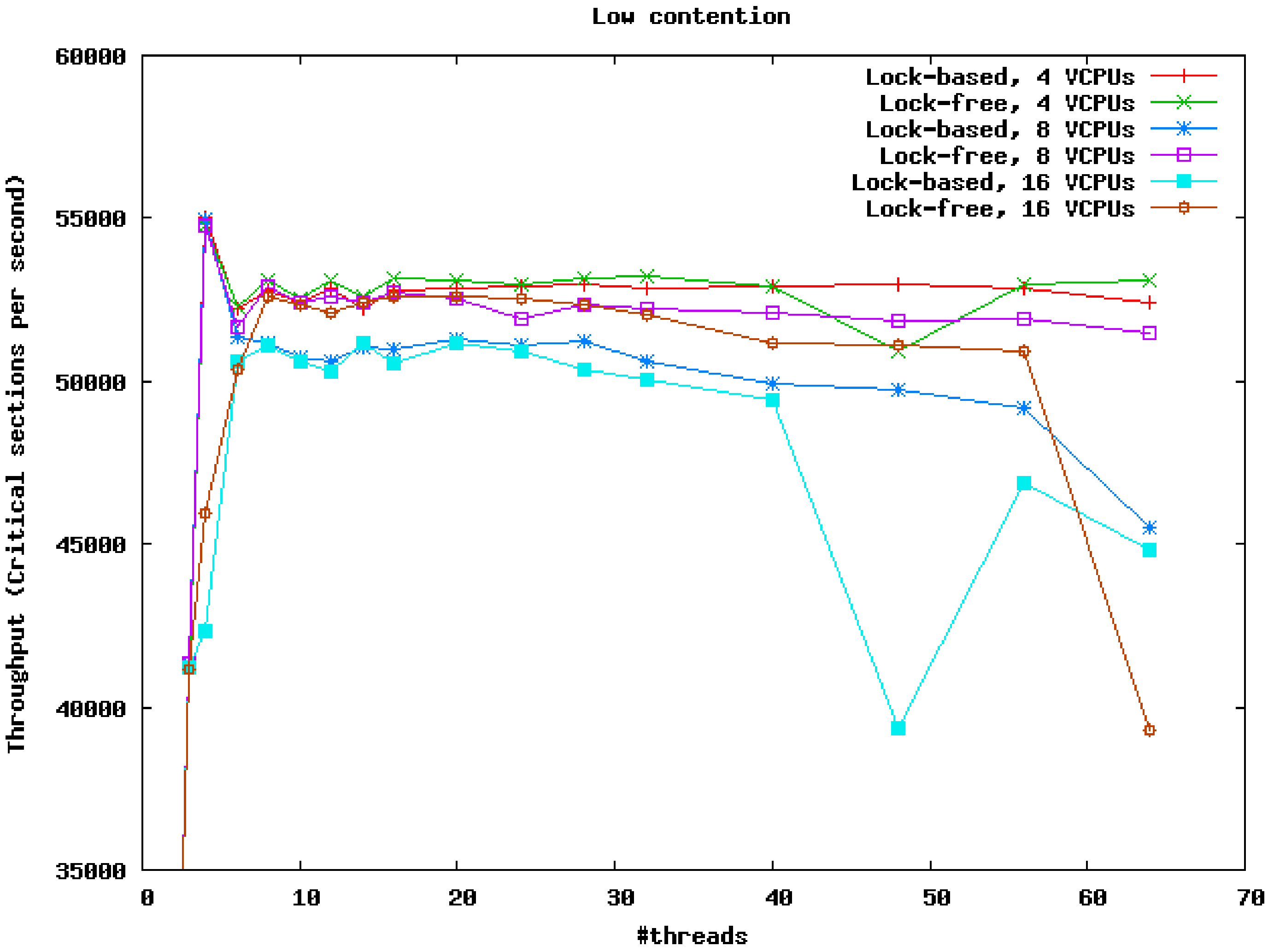

Conclusions and future work

- LFthreads: Lock-free user-level thread library
  - Lock-free thread-blocking synchronization object
  - The hand-off method
- Future work:
  - More synchronization objects
    - Condition variable
    - Semaphore
    - Read-Write locks
    - Signals, Cancellation etc
  - More POSIX pthread compliance
  - Improved scheduling – e.g. lock-free work-stealing

Thank you for listening!

Questions?