Making Lockless Synchronization Fast: Performance Implications of Memory Reclamation

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Outline

- **Motivation**
- Memory Reclamation Schemes
- Results
- Conclusions

My Laptop Has Two Cores

- Multiprocessing becoming mainstream.
- Synchronization must be fast.
- Locks create problems:
  - Overhead
  - Serialization Bottleneck
  - Deadlock
  - Priority Inversion

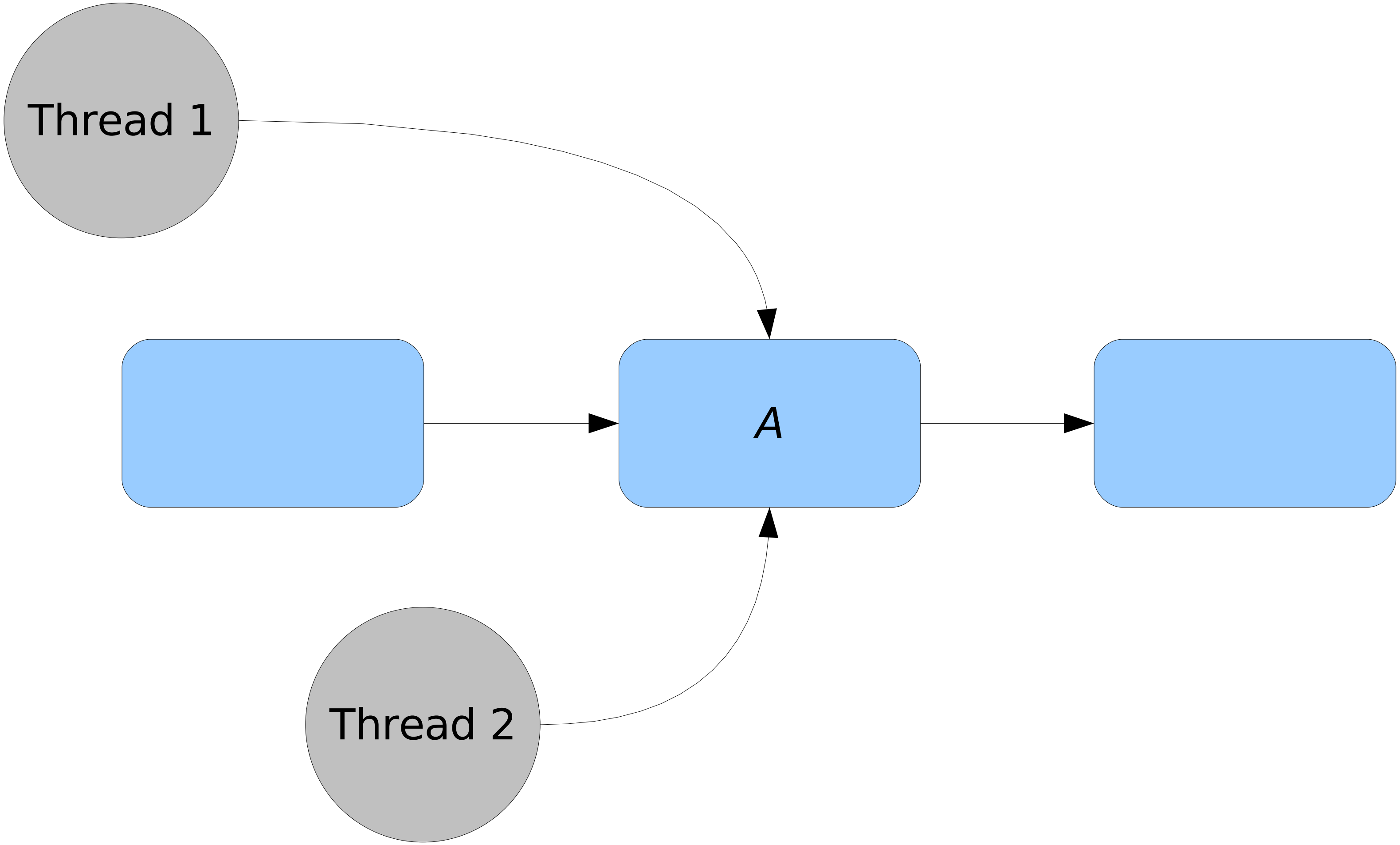
Lockless Synchronization

- Using a shared object *without* locking.
  - Non-blocking synchronization.
  - Read-copy update.

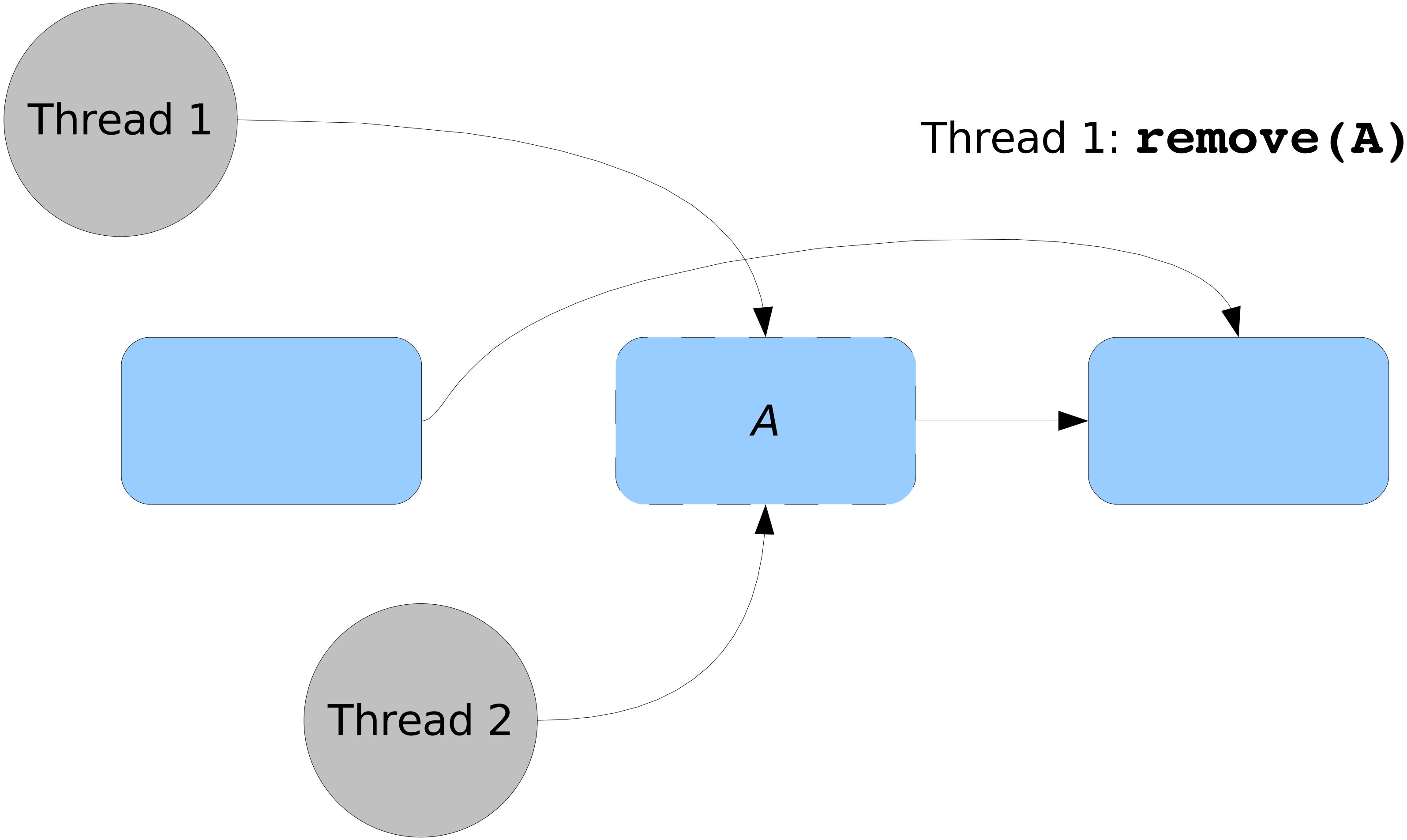
✔ Can drastically improve performance. ☺

✗ Can lead to *read-reclaim races*. ☹

Read-Reclaim Races

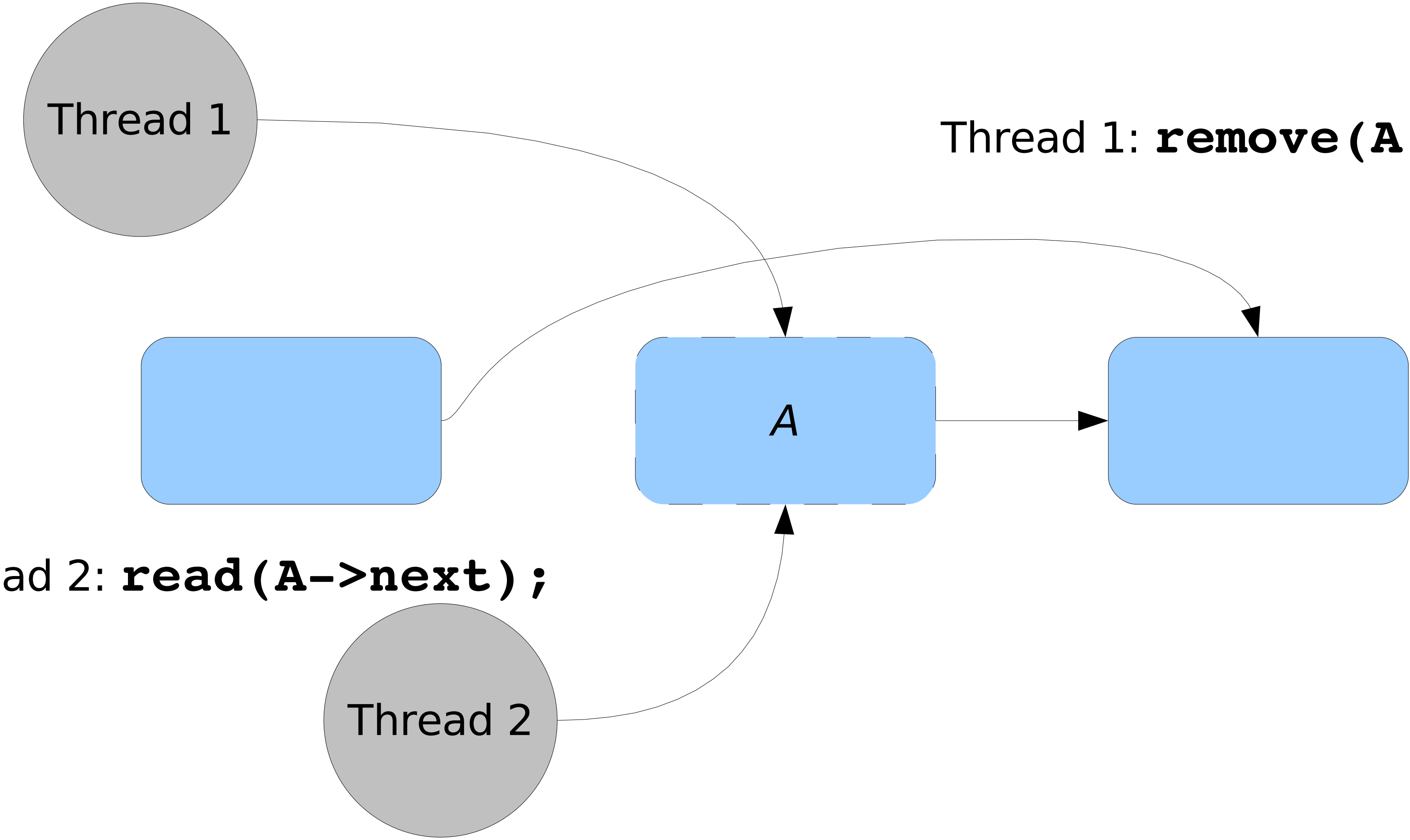


Read-Reclaim Races



Thread 1: **`remove(A);`**

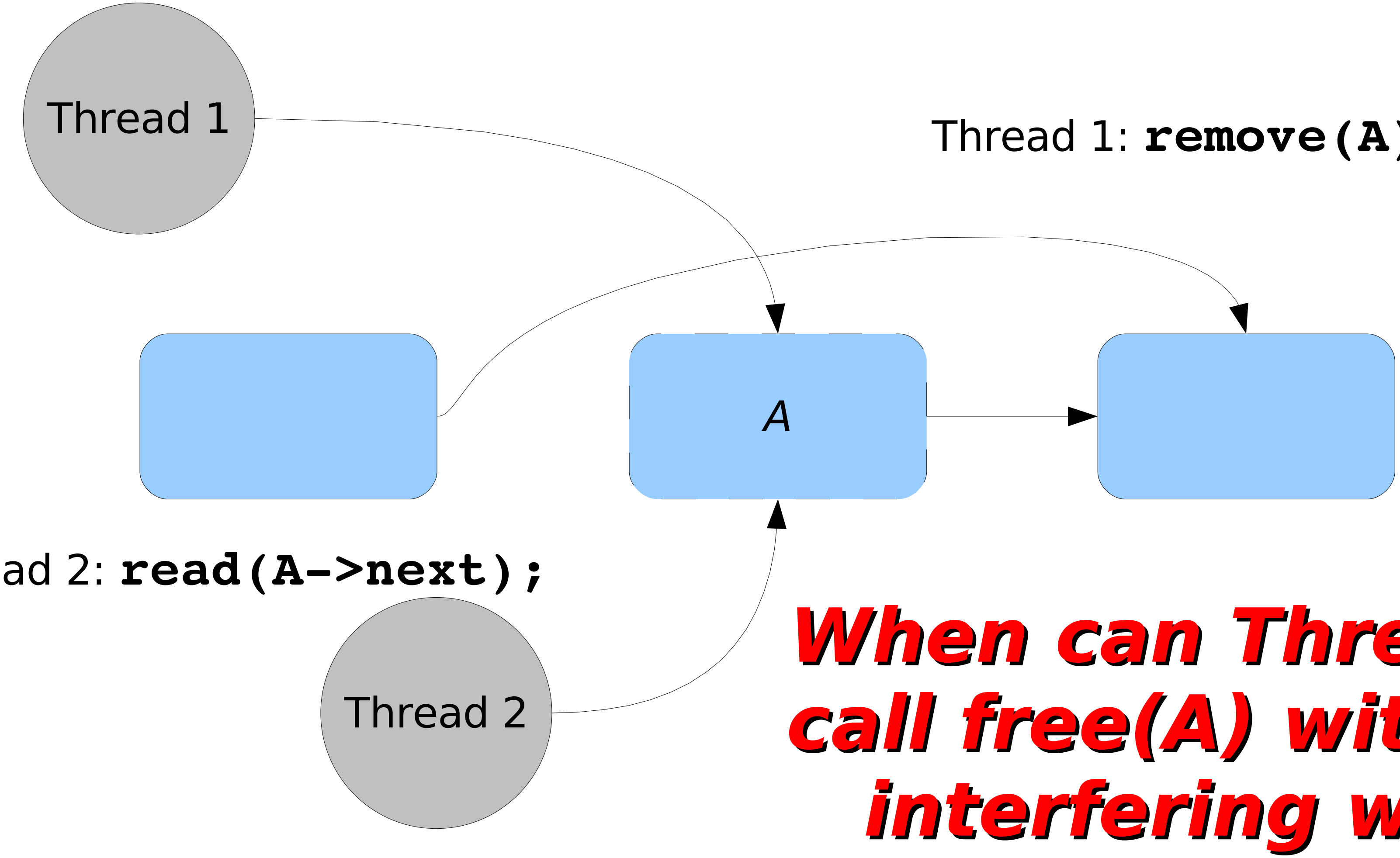
Read-Reclaim Races



Thread 1: **`remove(A);`**

Thread 2: **`read(A->next);`**

Read-Reclaim Races



Thread 1: **`remove(A);`**

Thread 2: **`read(A->next);`**

When can Thread 1 call free(A) without interfering with Thread 2?

Contribution

- Much prior work solves read-reclaim races, but...
  - How do these solutions perform?
  - What *factors* determine performance?
  - Is the performance impact significant?
- Investigate with a microbenchmark:
  - Vary factors independently.

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Memory Reclamation Schemes

- Mediate read-reclaim races.
- Many have been proposed:
  - Quiescent-State-Based Reclamation [M&S]
    - Used with Read-Copy Update (RCU)
  - Epoch-Based Reclamation [Fraser]
  - Hazard Pointers [Michael]
  - Lock-Free Reference Counting [Valois, D. et. al.]

Memory Reclamation Schemes

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  - **Hazard Pointers** [Michael]
  - Lock-Free Reference Counting [Valois, D. et. al.]

Assumption!

- For the purposes of this presentation:
  - A thread accesses the elements of a shared data structure *only* through a well-defined set of operations.
- Operations:
  - find()
  - insert()
  - enqueue()
  - dequeue()
  - etc.

Quiescent-State-Based Reclamation

```
for (i=0;i<100;i++)
   if(list_find(L, i))
      break;



/* Do other work.... */
```

Thread has no references to any element in list `L`.

Quiescent-State-Based Reclamation

Introduce application-dependent *quiescent states*.

```
for (i=0;i<100;i++)
   if(list_find(L, i))
      break;

quiescent_state();
/* Do other work.... */
```

Thread has no references to any element in list `L`.

Quiescent-State-Based Reclamation

- *Grace period*: *any* interval in which each thread passes through a quiescent state.


Thread 1

Thread 2

Thread 3

QS

Execution Time

Quiescent-State-Based Reclamation

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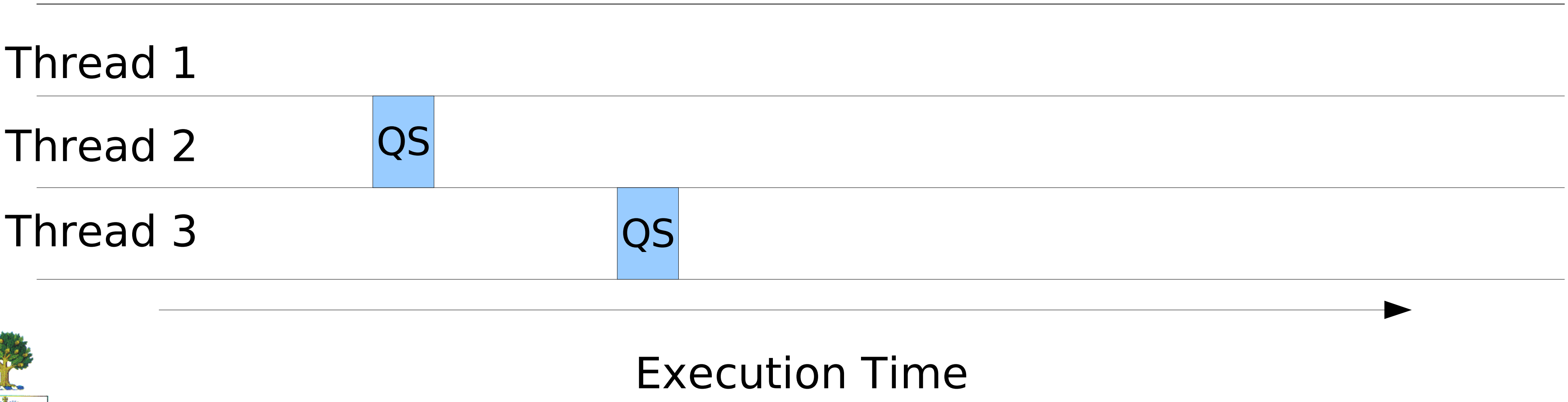

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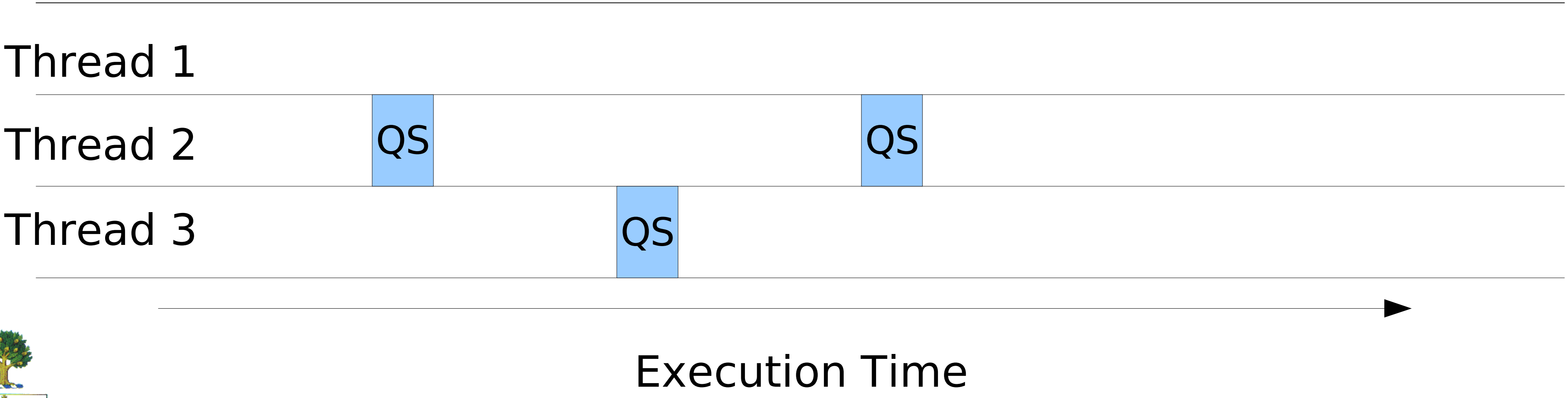

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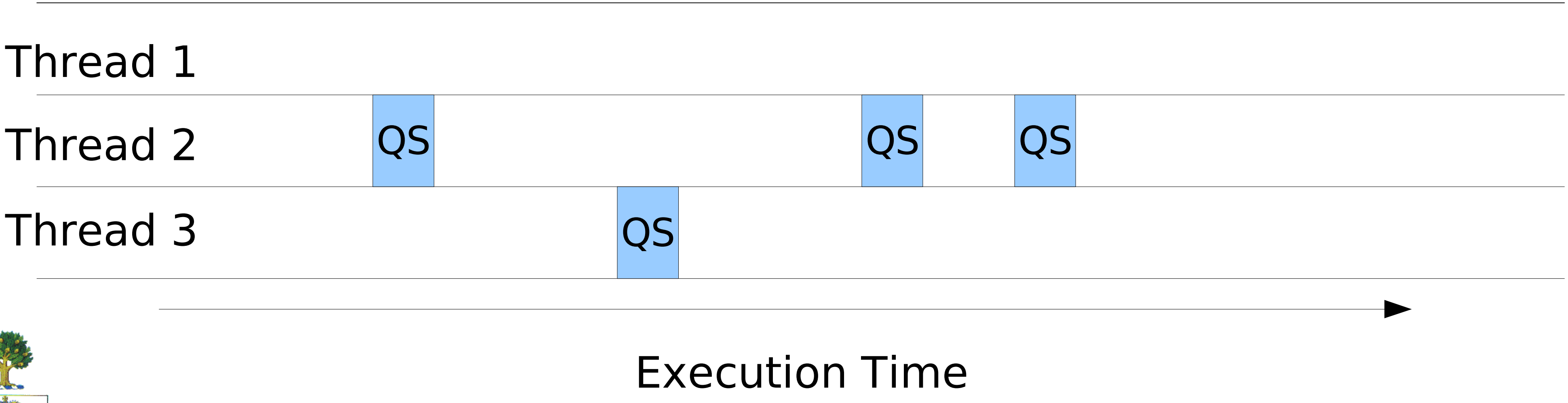

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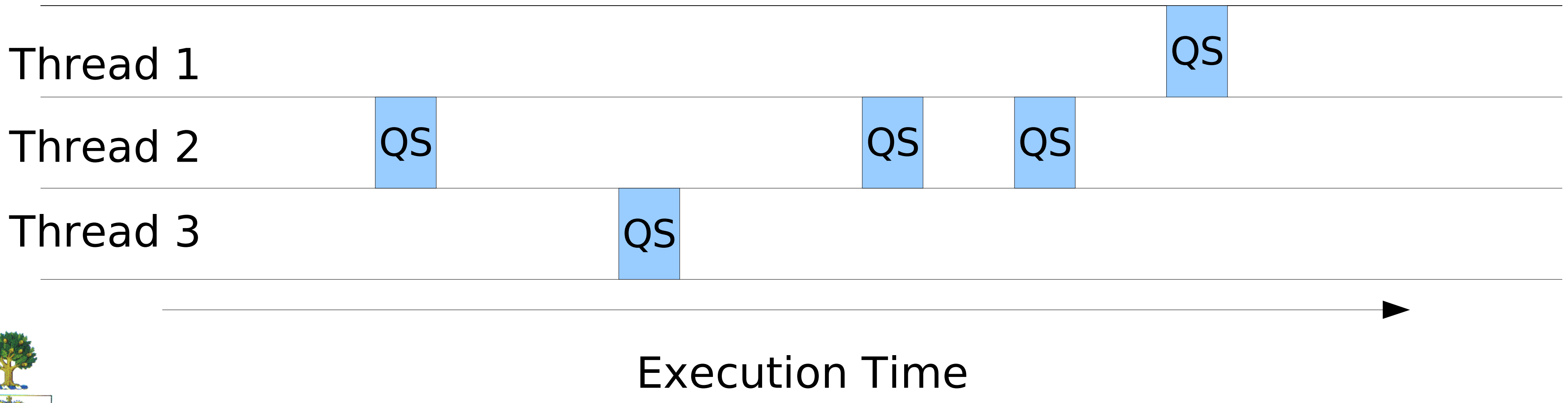
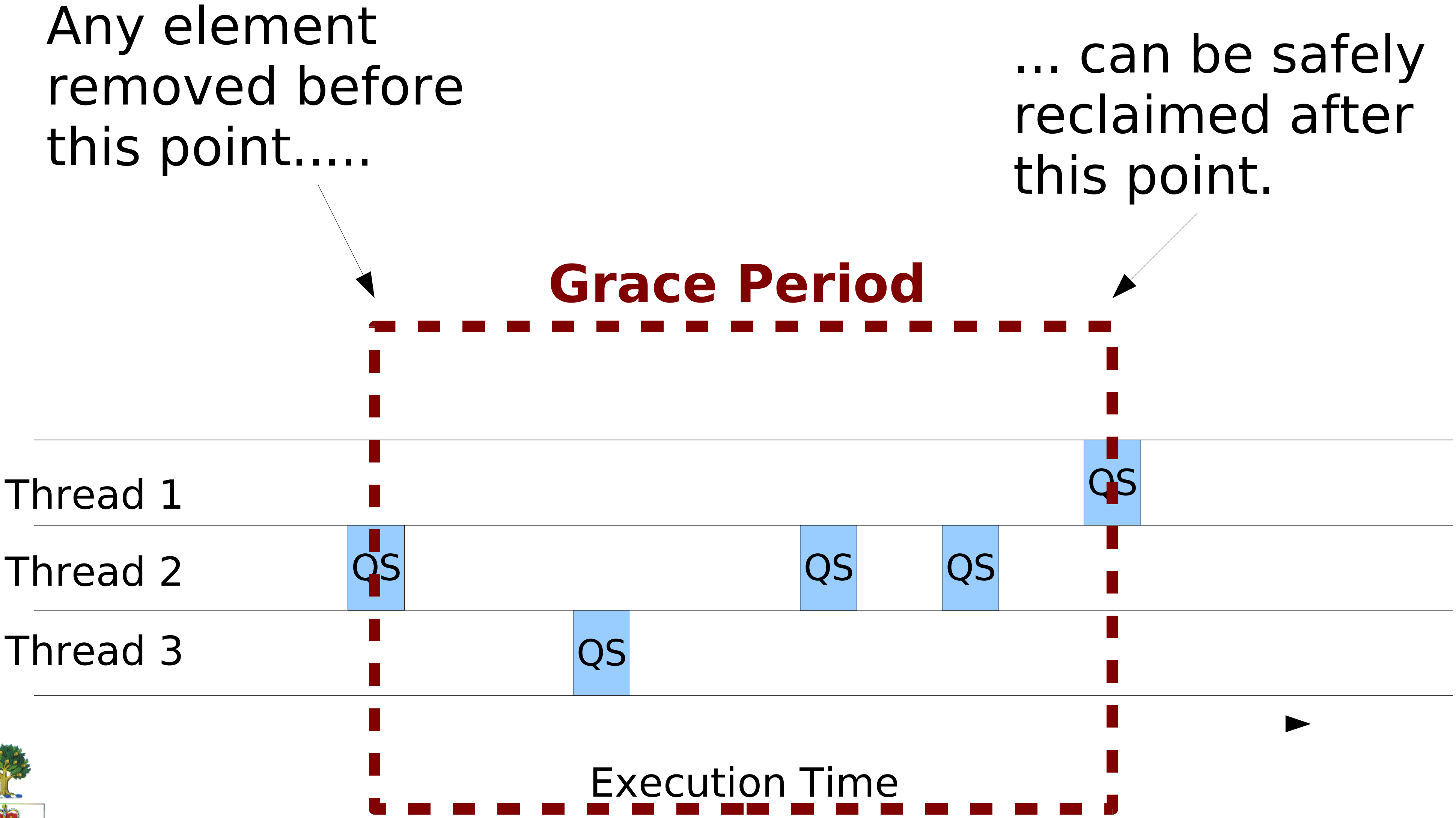


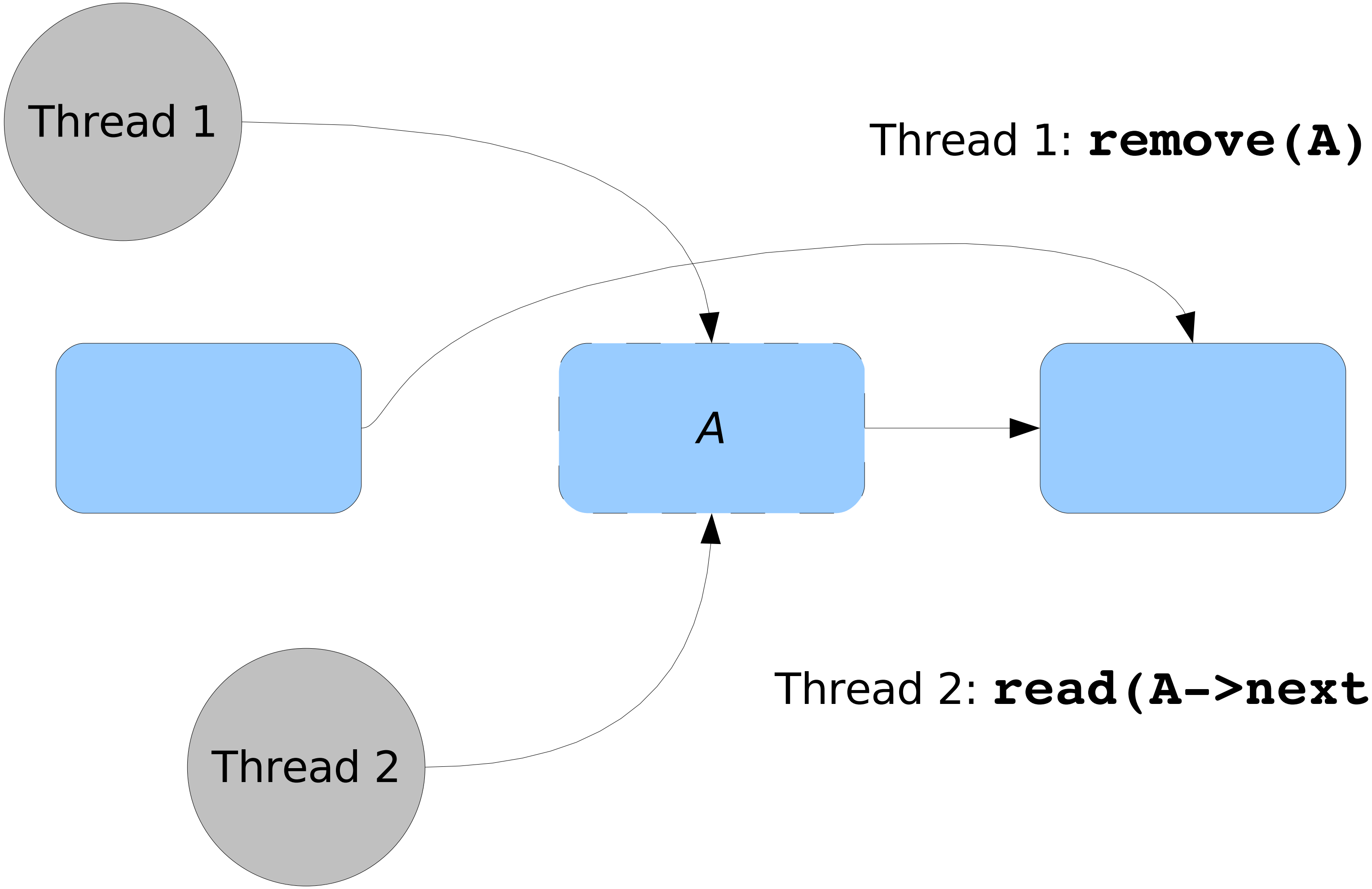
Quiescent-State-Based Reclamation



Epoch-Based Reclamation

- Similar to quiescent-state-based scheme.
- Instead of `quiescent_state()`, uses:
  - `lockless_begin()`
  - `lockless_end()`
- *Within* the body of an operation.
  - Application-independent.

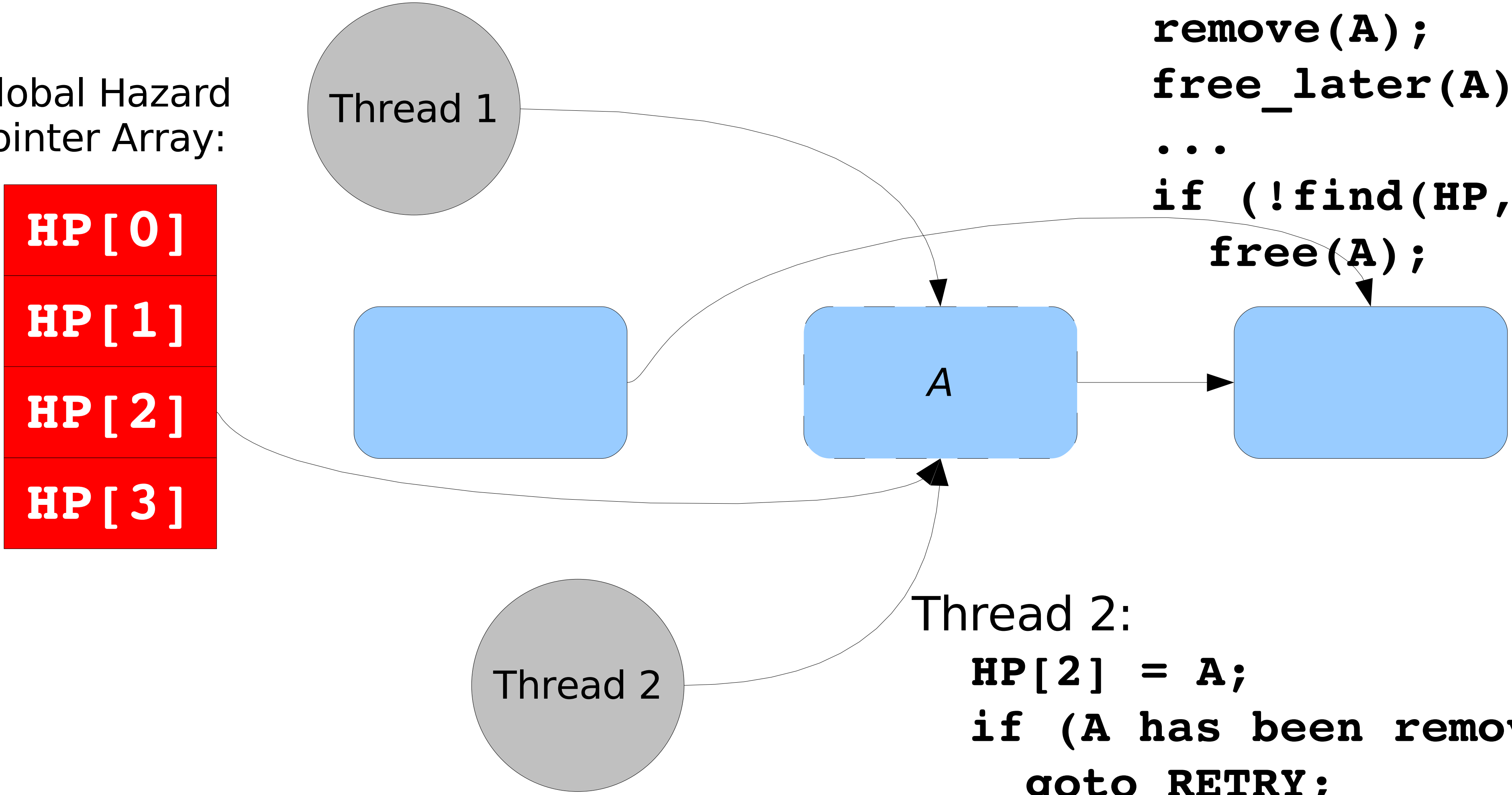
Hazard Pointers



Thread 1: **`remove(A);`**

Thread 2: **`read(A->next);`**

Hazard Pointers



Global Hazard
Pointer Array:

HP[0]
HP[1]
HP[2]
HP[3]

Thread 1

A

Thread 2

Thread 1:

```
remove(A);
free_later(A);
...
if (!find(HP,A))
  free(A);
```

Thread 2:

```
HP[2] = A;
if (A has been removed)
  goto RETRY;
read(A->next);
```

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Performance Factors

- In our paper, we consider:
  - Number of CPUs
  - Number of threads
  - Choice of data structure
  - Workload (read-to-update ratio)
  - Length of chains of elements
  - Memory constraints
- Look at a few in this presentation.

Performance Factors

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Sequential Consistency

- Parallel schedule of instructions is equivalent to a legal serial schedule; ie.
  - Machine instructions are not reordered.
  - Memory references are globally ordered.

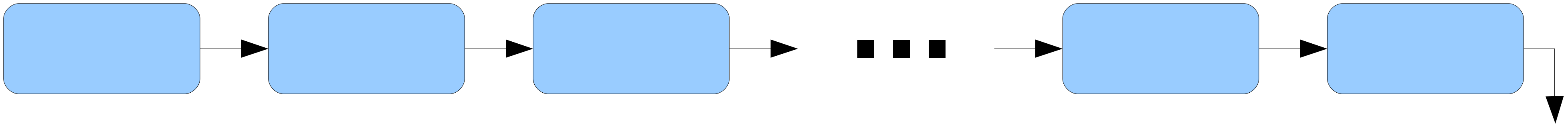
~~Sequential Consistency~~

Don't Bet On It!!!

- Hardware is *not* sequentially-consistent.
  - CPUs can reorder instructions for performance.
- Must force sequential consistency.
  - Use a *memory fence*.
- Fences affect relative performance:
  - Fences are expensive (orders of magnitude).
  - Reclamation schemes need **different numbers of fences**!

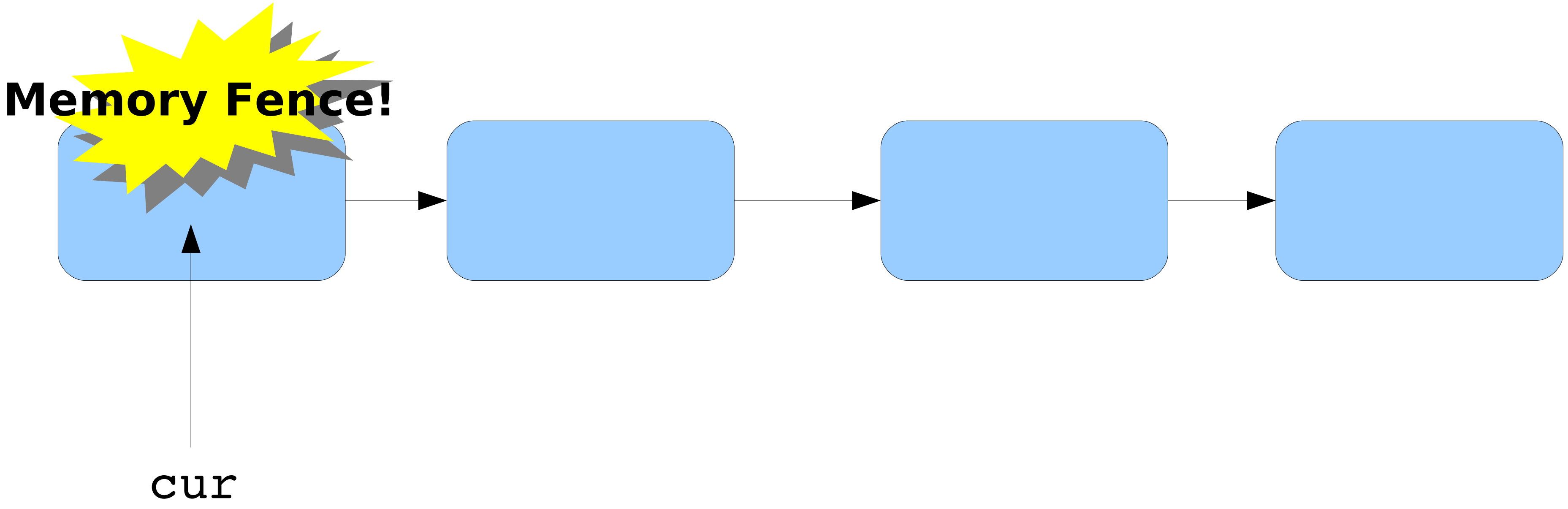
Data Structures and List Length

- Can affect the number of fences needed.
  - Linked lists have long chains of elements.



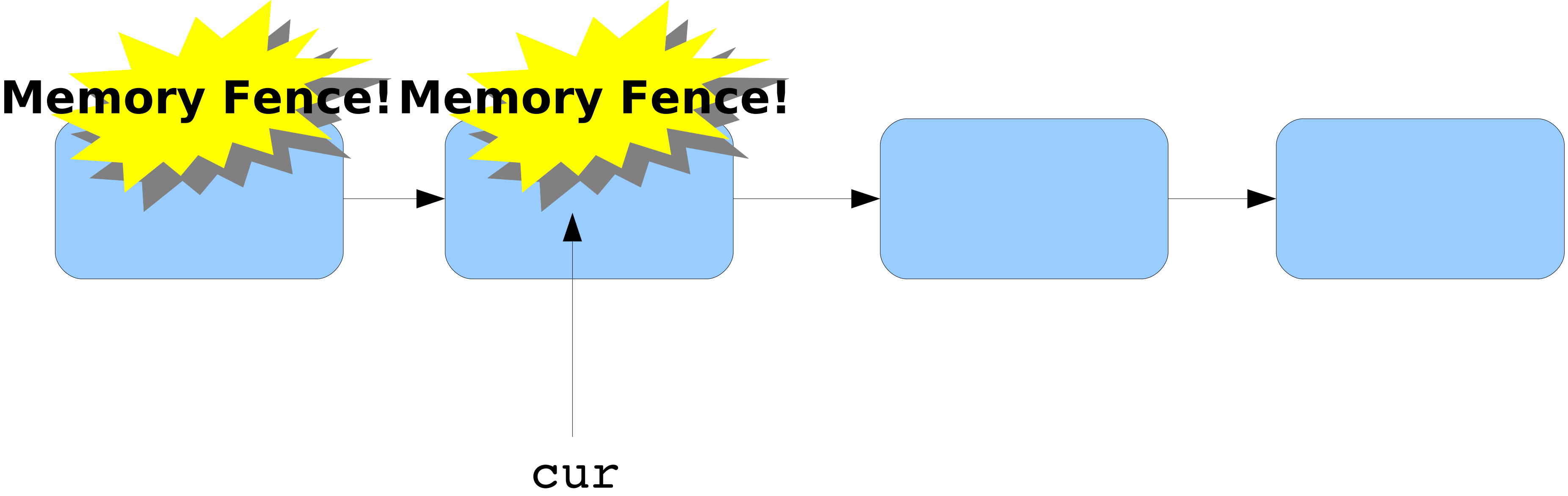
  - Well-designed hash tables have short chains.

Example – Hazard Pointers



```
for (cur = list->head; cur != NULL; cur = cur->next) {
    *hazard_ptr = list->cur;
    memory_fence();
    /* continue...*/
}
```

Example – Hazard Pointers



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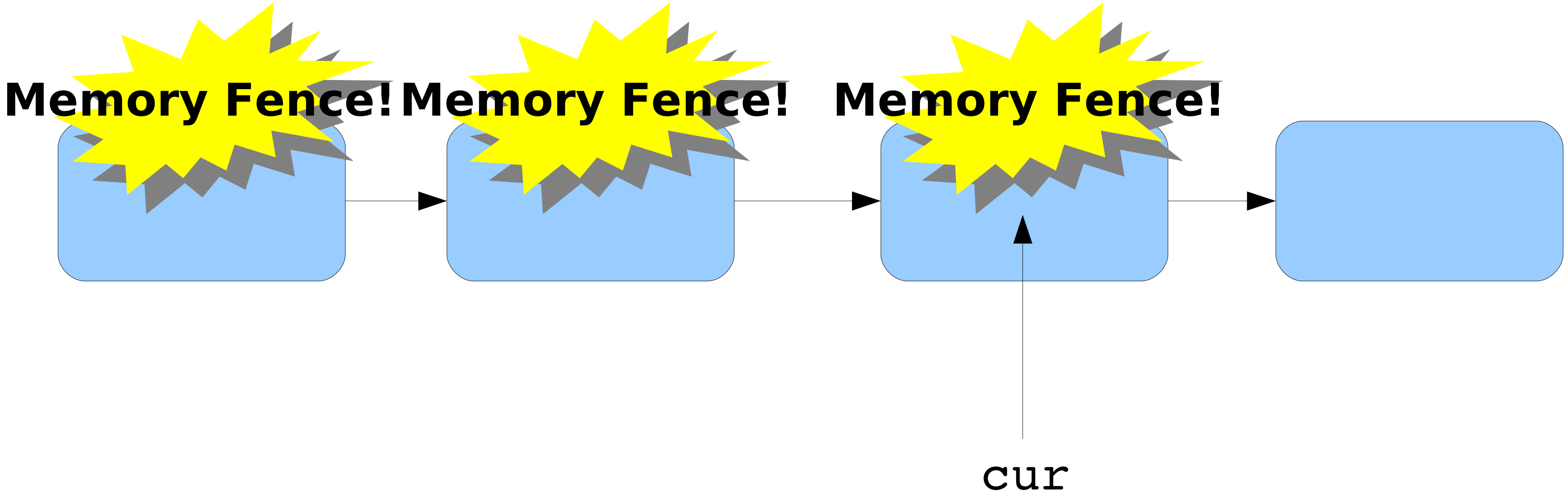

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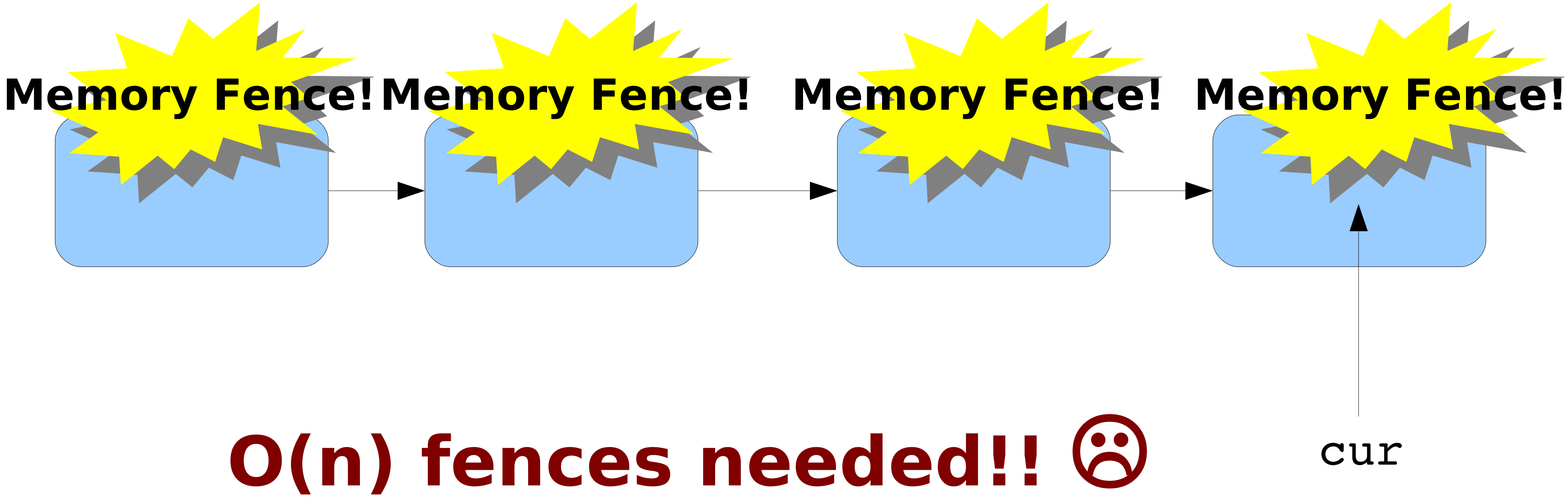

Memory Fence! Memory Fence! Memory Fence! Memory Fence!

`cur`

O(n) fences needed!! ☹

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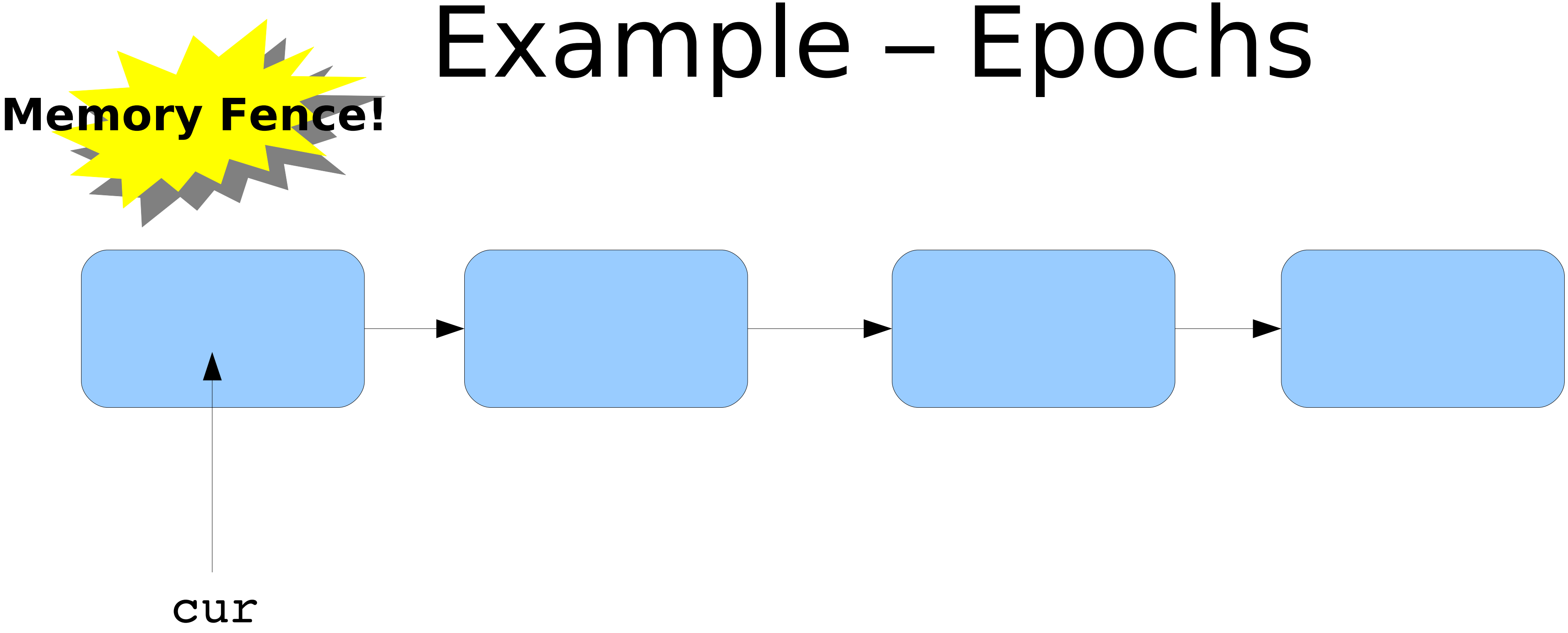
```

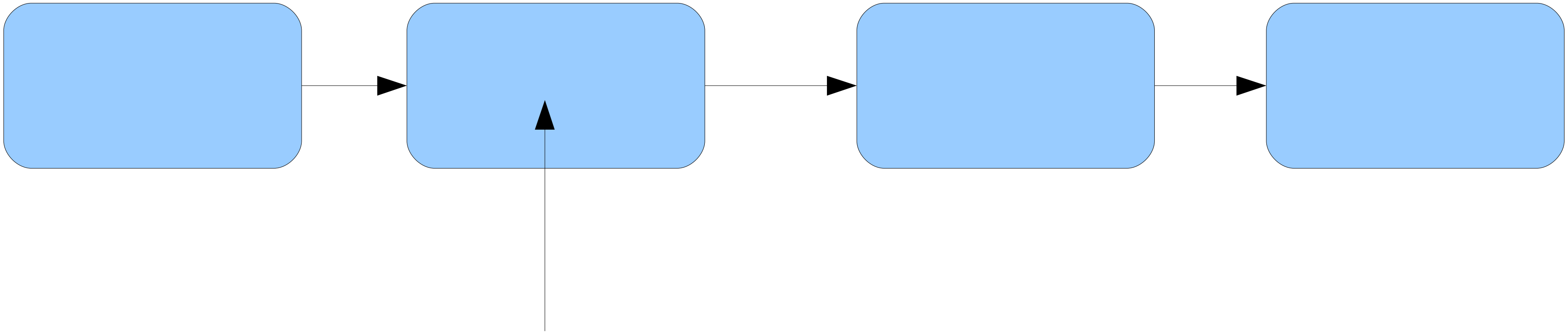
Example – Epochs



```
lockless_begin();   /* calls memory_fence() */
for (cur = list->head; cur != NULL; cur = cur->next) {
    /* continue...*/
}
lockless_end();     /* calls memory_fence() */
```

Example – Epochs

Memory Fence!



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Example – Epochs

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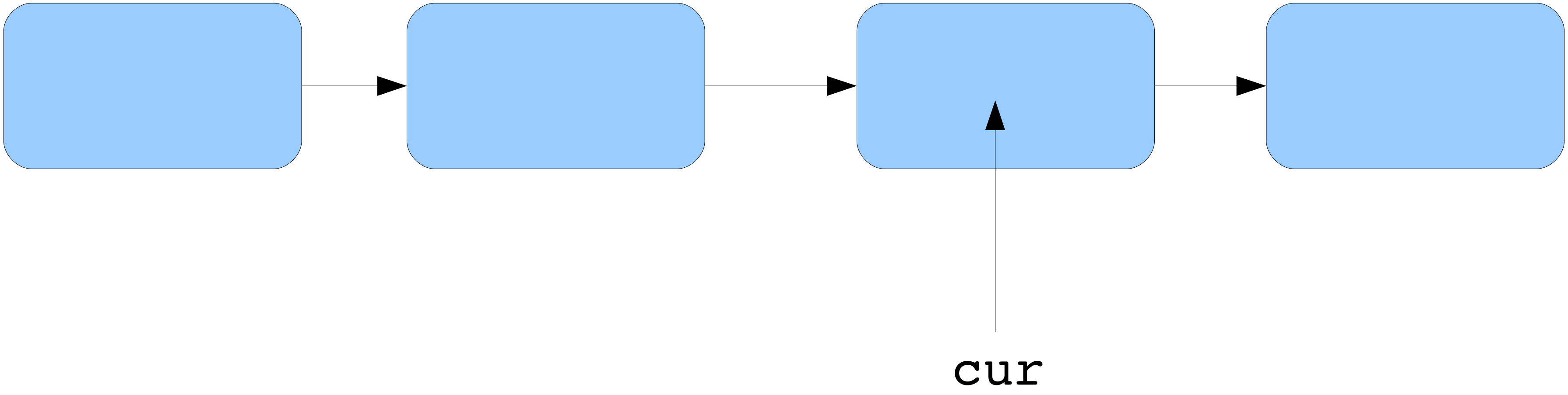

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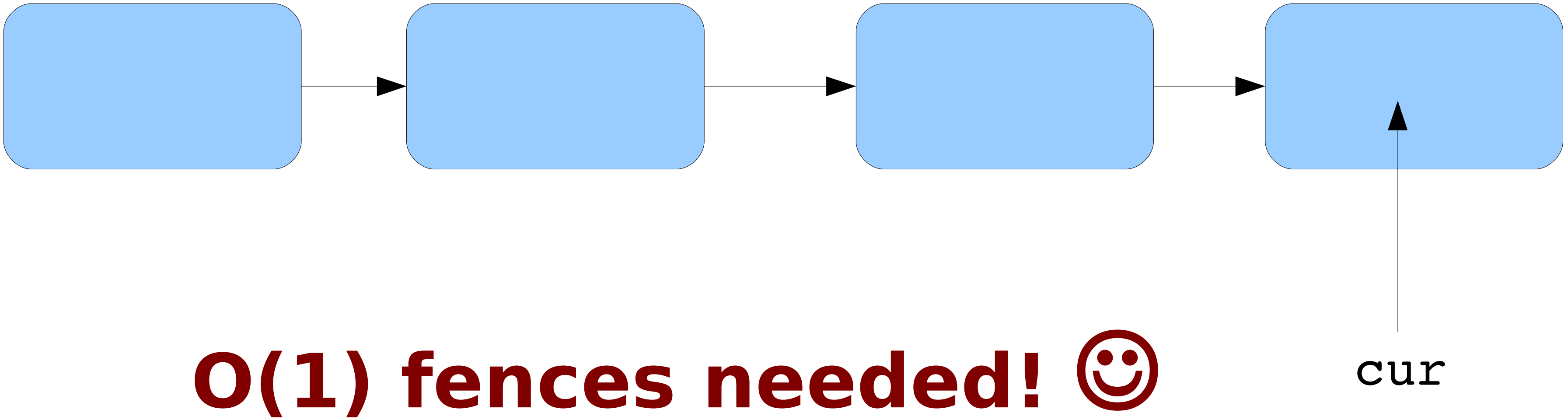
Memory Fence!

Example – Epochs

Memory Fence!



O(1) fences needed! ☺

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```
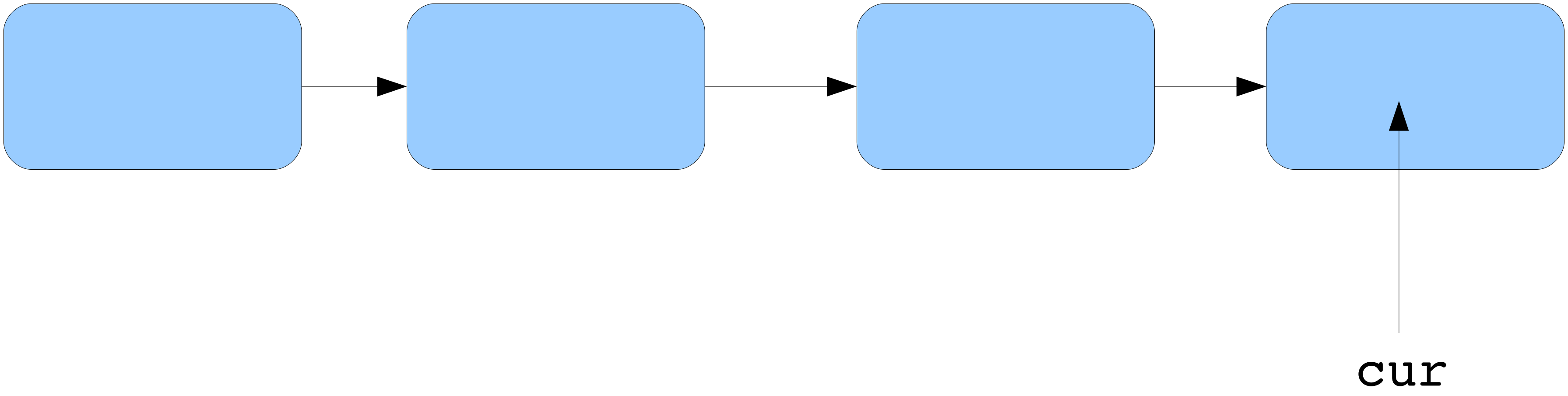
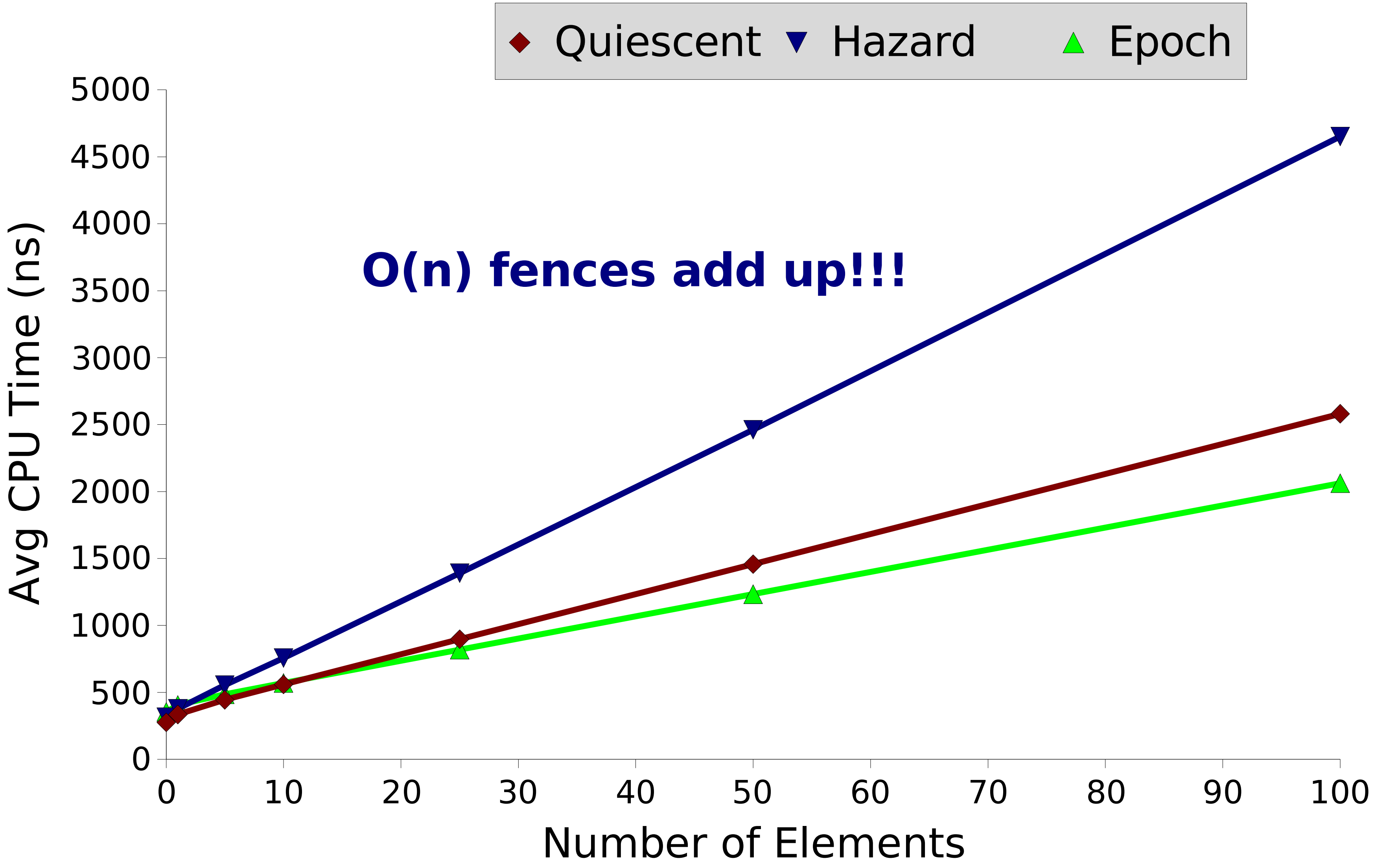

Example – Quiescent States



One fence per *several* operations. ☺☺☺

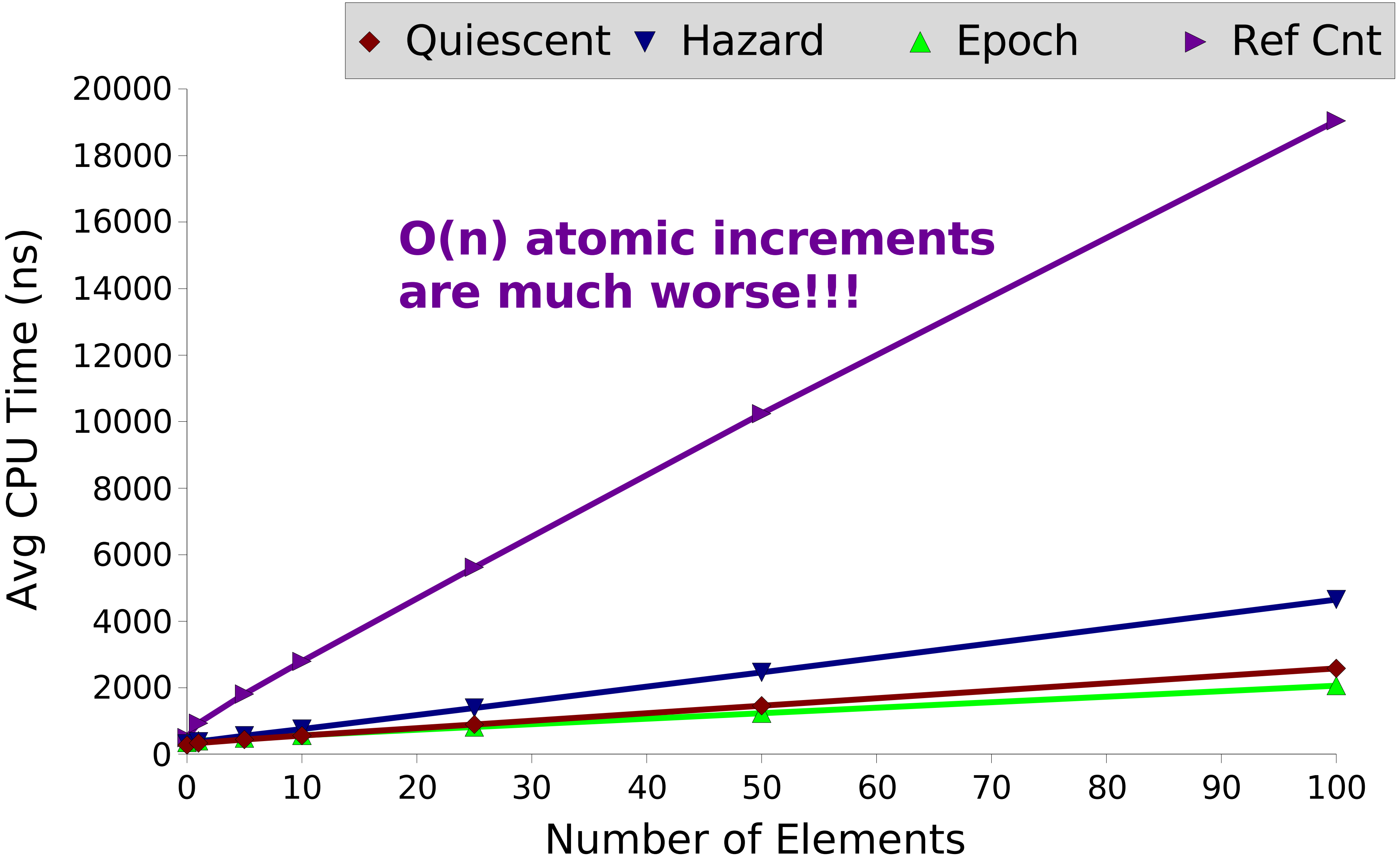
```
for (cur = list->head; cur != NULL; cur = cur->next) {
    /* continue...*/
}
```

Traversal Length



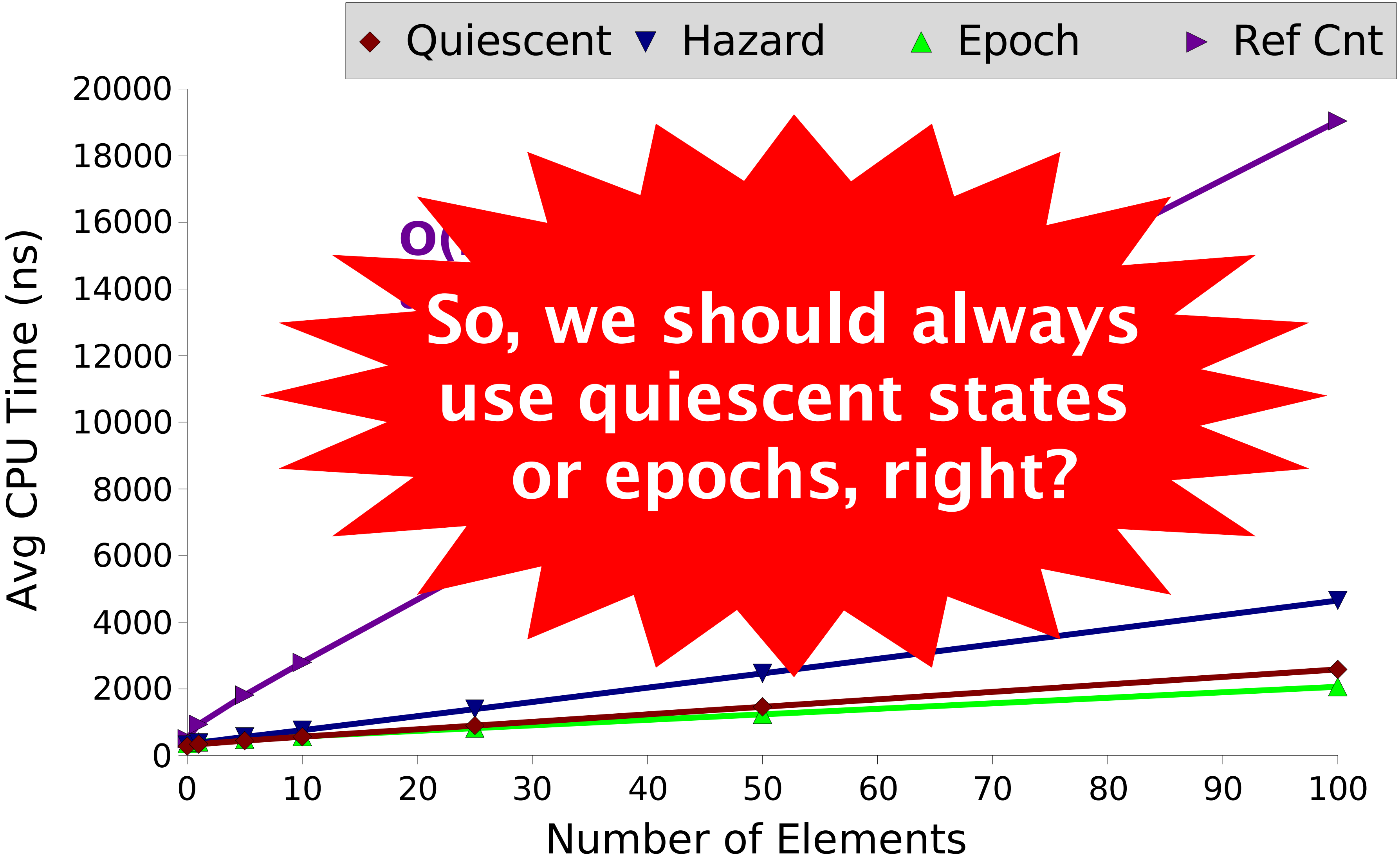
O(n) fences add up!!!

Traversal Length - LFRC



O(n) atomic increments are much worse!!!

Traversal Length - LFRC

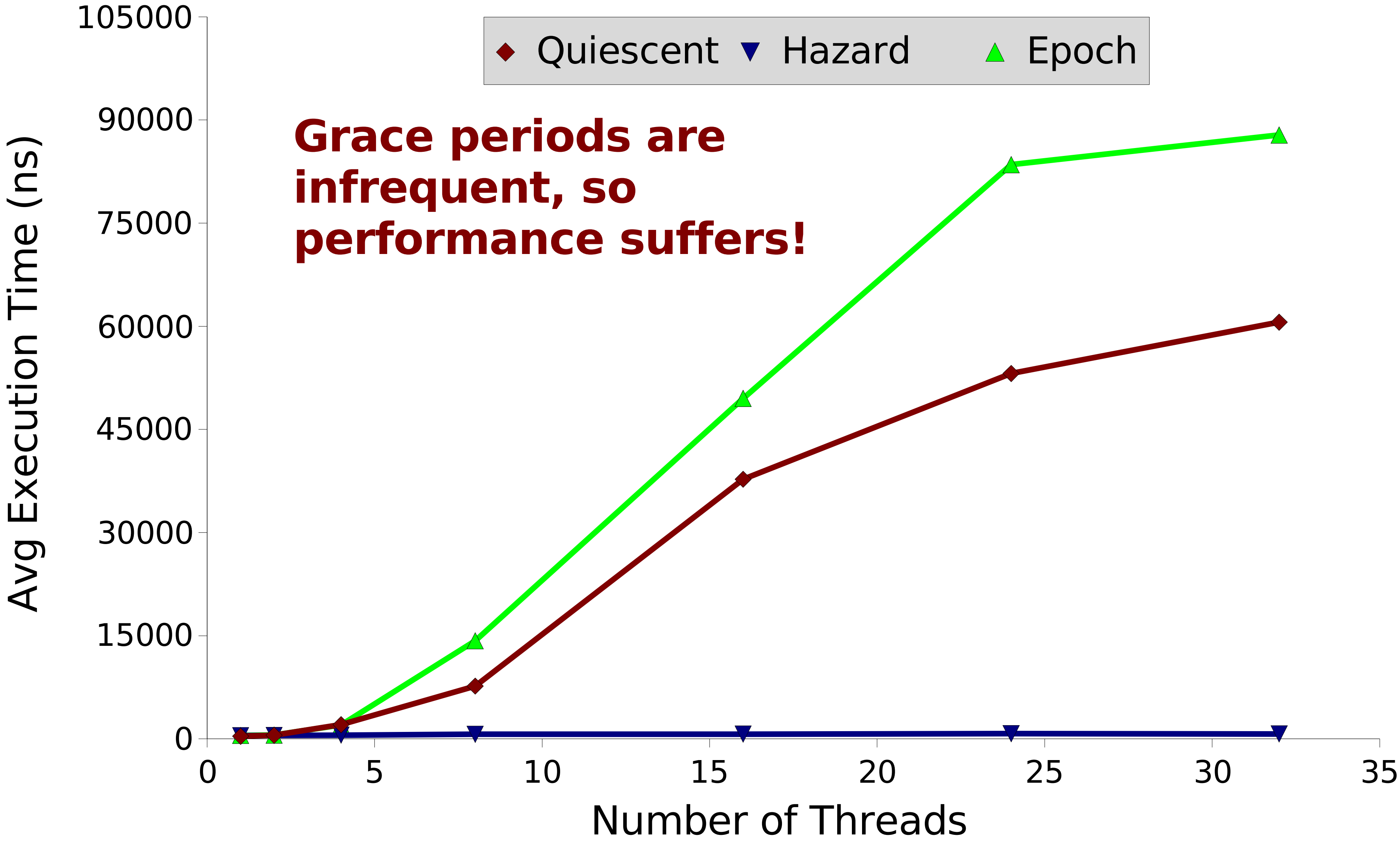


So, we should always use quiescent states or epochs, right?

Threads and Memory

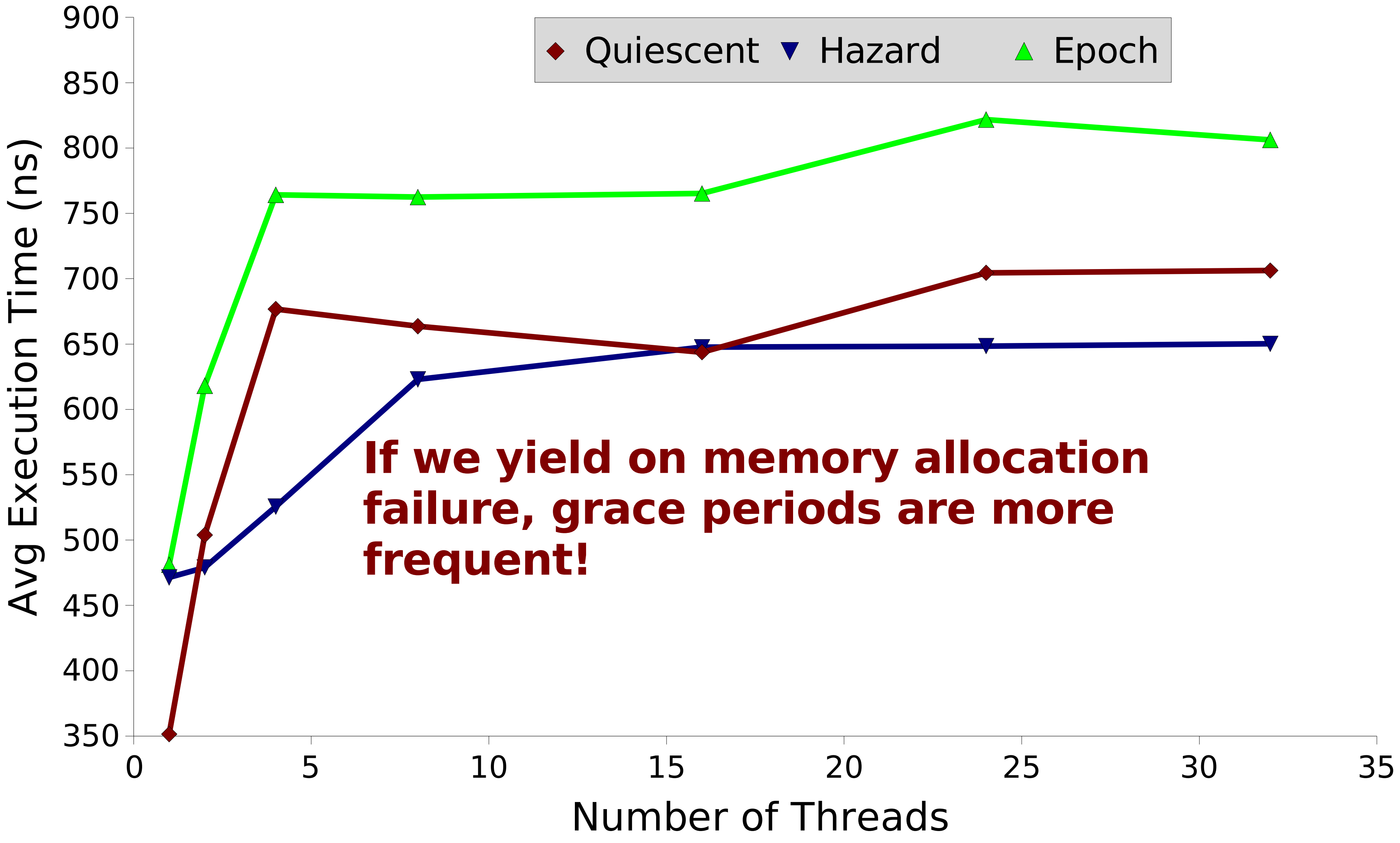
- Hazard pointers *bound* unfreed memory.
  - (Provided number of hazard pointers is finite.)
  - Everything with no hazard pointer can be freed.
  - Other schemes are more memory-hungry.
- What happens when there are *many* threads?
  - More threads than CPUs ⇒ Preemption.

Preemption



Grace periods are infrequent, so performance suffers!

Preemption With Yielding



If we yield on memory allocation failure, grace periods are more frequent!

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Summary of Results

- Schemes have *very different* overheads.
  - Difference between “faster than locking” and “slower than locking.”
- No scheme is always best.
- Quiescent-state-based reclamation has the lowest best-case overhead.
  - No per-operation fences. ☺
- Hazard pointers are good when there is preemption and many updates.

Significance

- Understanding performance factors lets us:
  - ✔Choose the right scheme for a program.
  - ✔Design new, faster schemes.

Future Work

Future Work

- Macrobenchmark
- Use lockless synchronization with SPLASH-2
- Quiescent-State-Based Reclamation with realtime workloads

Questions?

- Tom Hart
  - http://www.cs.toronto.edu/~tomhart
- Angela Demke Brown
  - http://www.cs.toronto.edu/~demke
- Paul McKenney
  - http://www.rdrop.com/users/paulmck/RCU