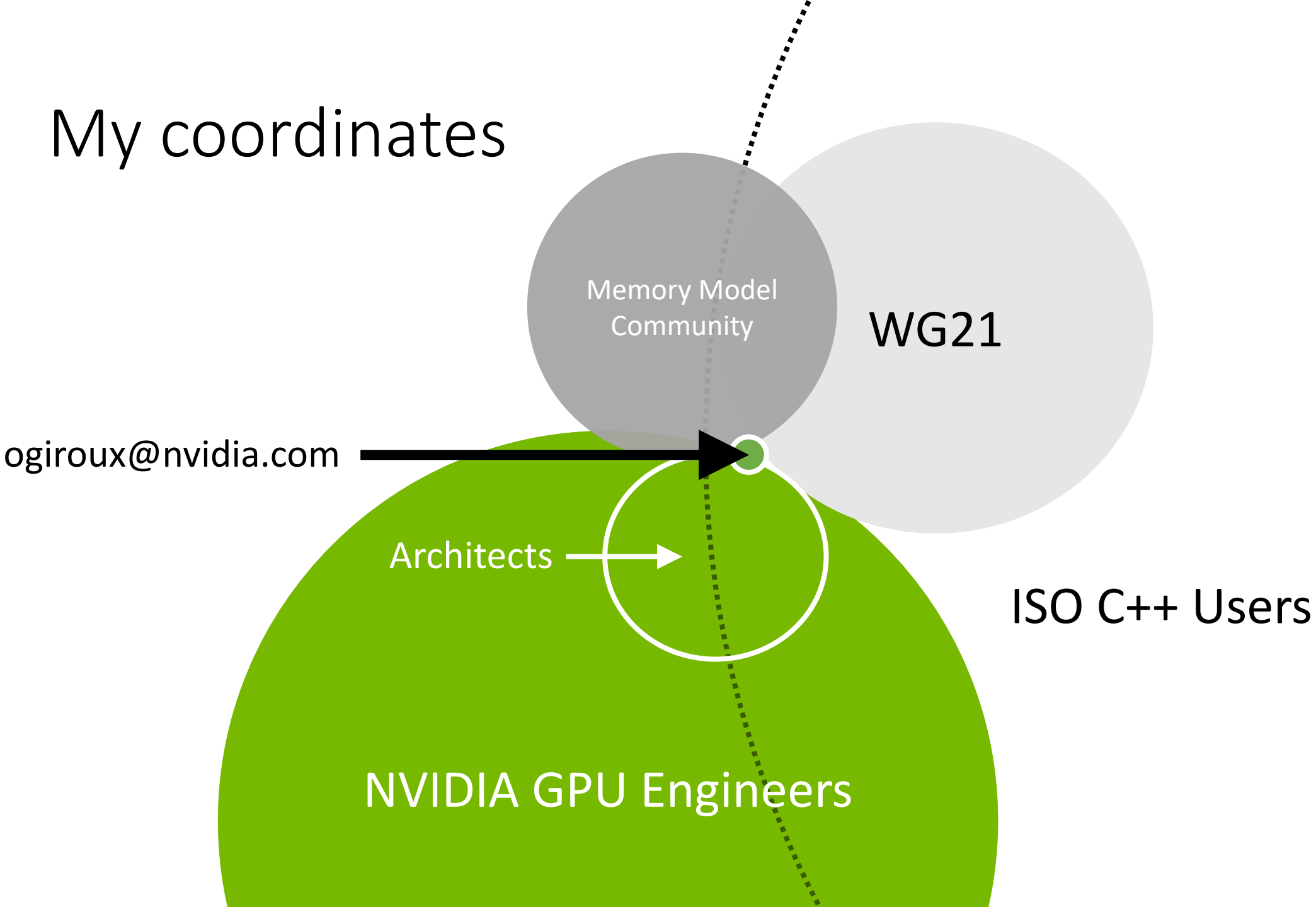
SYNCHRONIZATION IS BAD, BUT IF YOU MUST… (S9329)

Olivier Giroux, Distinguished Architect, ISO C++ Chair of Concurrency & Parallelism.

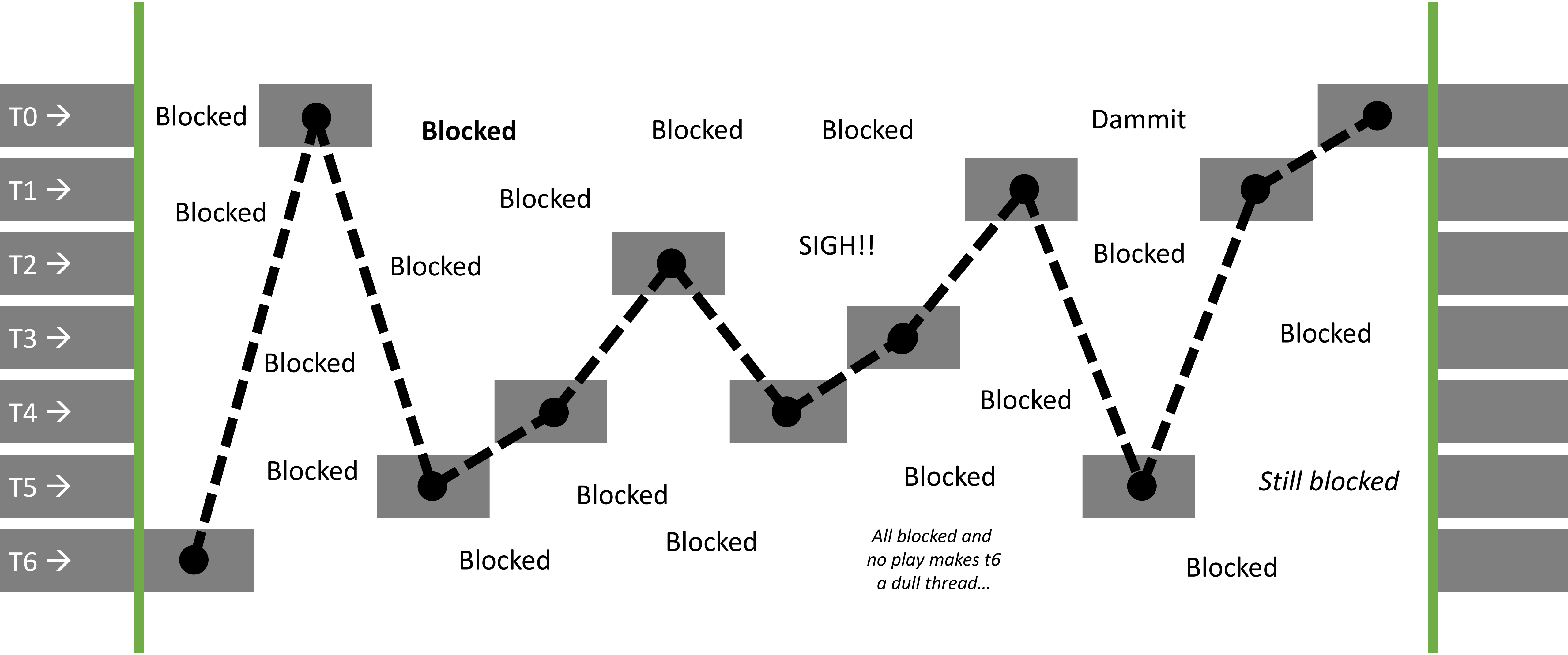
My coordinates



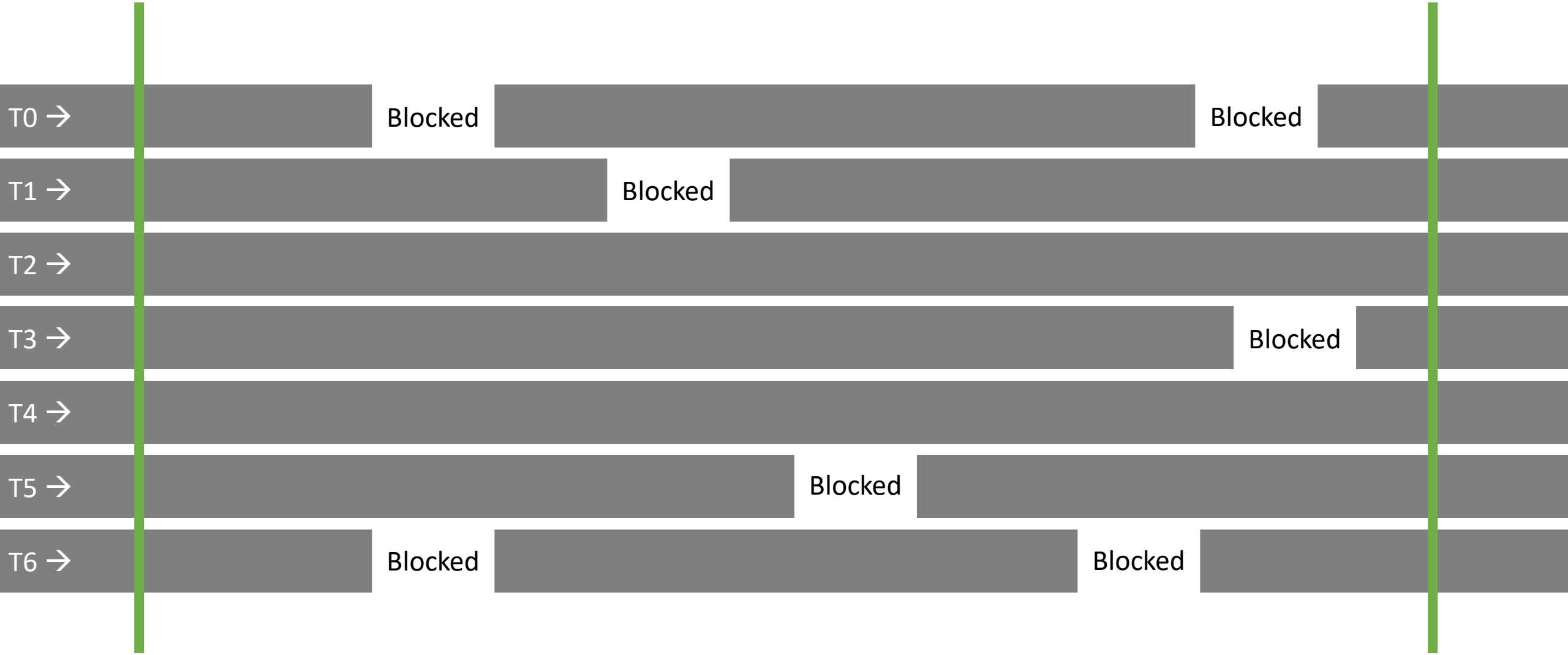
WHAT THIS TALK IS ABOUT:

- ⛔ `cudaDeviceSynchronize()`
- ⛔ `__syncthreads()`
- ⛔ `__shfl_sync()`
- ☑ Using atomics to do blocking synchronization.

PSA: DON'T RUN SERIAL CODE IN THREADS

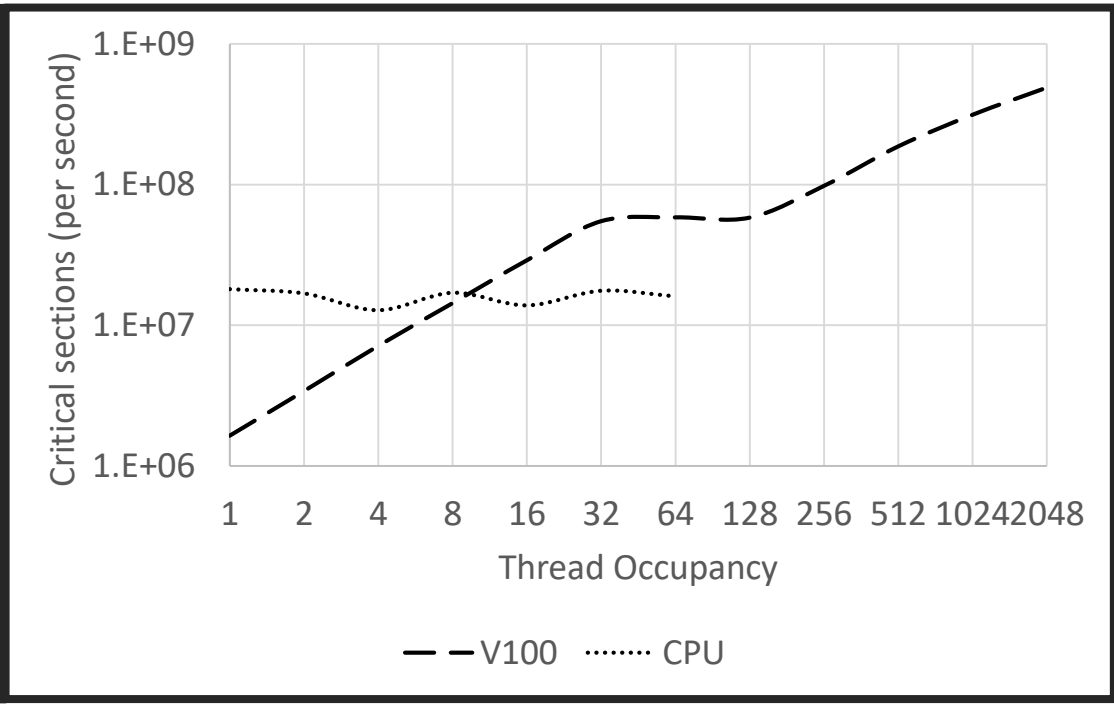


PSA: RARE CONTENTION IS FINE



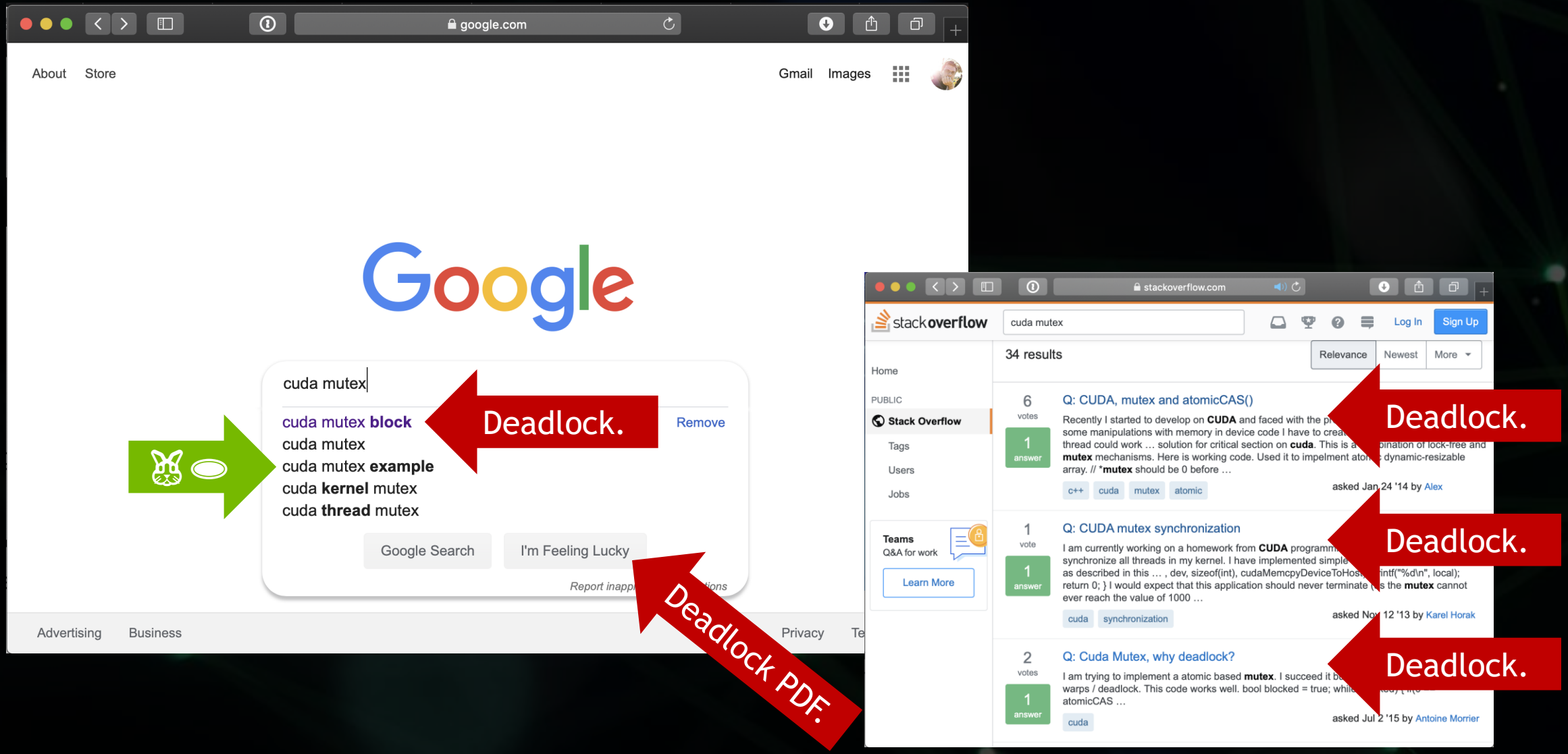
UNCONTENDED EXCHANGE LOCK

```
struct mutex { // suspend atomic<> disbelief for now

 __host__ __device__ void lock() {
  while(1 == l.exchange(1, memory_order_acquire))
    ;
 }

 __host__ __device__ void unlock() {
  l.store(0, memory_order_release);
 }

 atomic<int> l = ATOMIC_VAR_INIT(0);
};
```



Awesome.

Thanks for attending my talk.


google.com
About
Store
Gmail
Images
Google
cuda mutex
cuda mutex block
cuda mutex
cuda mutex example
cuda kernel mutex
cuda thread mutex
Remove
Deadlock.
Google Search
I'm Feeling Lucky
Advertising
Business
Privacy
Deadlock PDF.
stackoverflow.com
stackoverflow
cuda mutex
Log In
Sign Up
34 results
Relevance
Newest
More
Home
PUBLIC
Stack Overflow
Tags
Users
Jobs
Teams
Q&A for work
Learn More
6 votes
1 answer
Q: CUDA, mutex and atomicCAS()
Recently I started to develop on CUDA and faced with the pr
some manipulations with memory in device code I have to crea
thread could work … solution for critical section on cuda. This is a
mutex mechanisms. Here is working code. Used it to impelment atom
dynamic-resizable
array. // *mutex should be 0 before …
c++
cuda
mutex
atomic
asked Jan 24 '14 by Alex
Deadlock.
1 vote
1 answer
Q: CUDA mutex synchronization
I am currently working on a homework from CUDA programmi
synchronize all threads in my kernel. I have implemented simple
as described in this … , dev, sizeof(int), cudaMemcpyDeviceToHost
intf("%d\n", local);
return 0; } I would expect that this application should never terminate
s the mutex cannot
ever reach the value of 1000 …
cuda
synchronization
asked Nov 12 '13 by Karel Horak
Deadlock.
2 votes
1 answer
Q: Cuda Mutex, why deadlock?
I am trying to implement a atomic based mutex. I succeed it b
warps / deadlock. This code works well. bool blocked = true; whil
atomicCAS …
cuda
asked Jul 2 '15 by Antoine Morrier
Deadlock.

SIMT ATOMIC CONCERN SCALE :

 Atomic result feeds branch, closes loop, Volta+

 Atomic result feeds branch, closes loop

 Atomic result feeds branch, inside loop

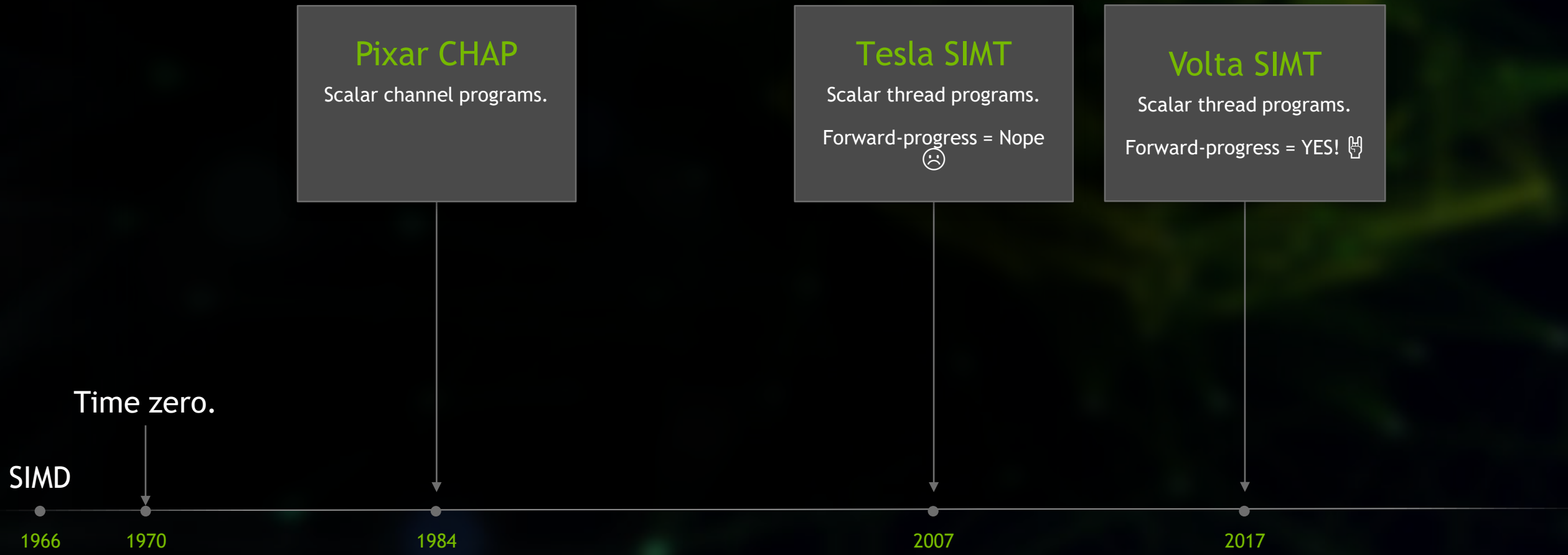
 Atomic result feeds branch, outside loop

 Atomic result feeds arithmetic

 Atomic result ignored

 No atomics

SIMT FAMILY HISTORY



Source: Wikipedia, SIGGRAPH proceedings, IEEE Micro.

APPLICABILITY

SYNCHRONIZATION DECISION CHECKLIST

CONs:

1. Serialization is bad.
2. Critical path / Amdahl's law.
3. Latency is high.

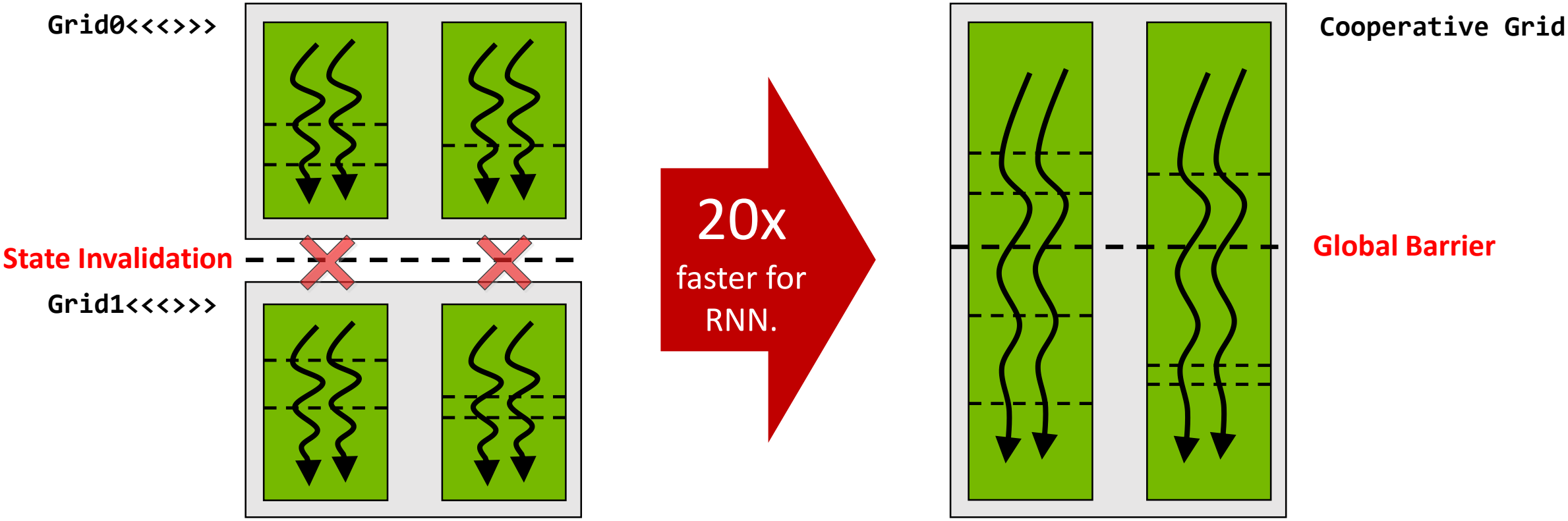
PROs

1. Algorithmic gains.
2. Latency hiding.
3. Throughput is high

TL;DR: Sometimes, it's a win.

APP #1: GPU-RESIDENT METHODS

Keep local state in registers & shared memory, with synchronization.



See Greg Diamos' GTC 2016 talk for more.

APP #2: LOCK-FREE IS NOT ALWAYS FASTER

```
// *continue* to suspend atomic<> disbelief for now
__host__ __device__ bool lock_free_writer_version(atomic<int>& a, atomic<int>& b) {
  int expected = -1;
  if(a.compare_exchange_strong(expected, 1, memory_order_relaxed))
    b.store(1, memory_order_relaxed);
  return expected == -1;
}

// This version is a ~60% speedup at GPU application level, despite progress hazards.
__host__ __device__ bool starvation_free_writer_version(atomic<int>& a, atomic<int>& b) {
  int expected_a = -1,
      expected_b = -1;
  bool success_a = a.compare_exchange_strong(expected_a, 1, memory_order_relaxed),
       success_b = b.compare_exchange_strong(expected_b, 1, memory_order_relaxed);
  if(success_a) // Note: we almost always succeed at both.
    while(!success_b) // <-- This loop makes this a deadlock-free algorithm.
      success_b = b.compare_exchange_strong(expected_b = -1, 1, memory_order_relaxed);
  else if(success_b)
    b.store(-1, memory_order_relaxed);
  return expected_a == -1;
}
```

Exposed dependent latency

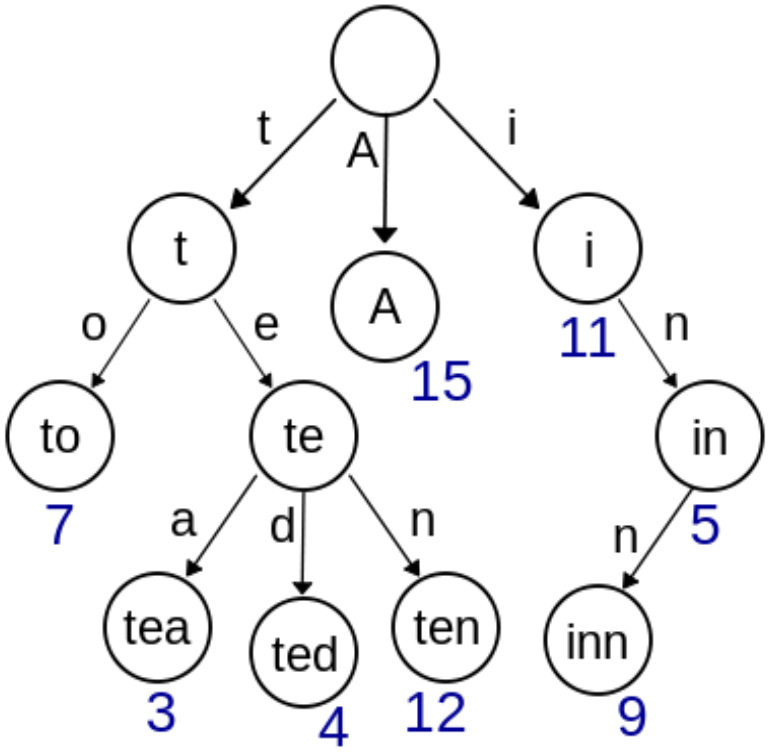
Overlapped

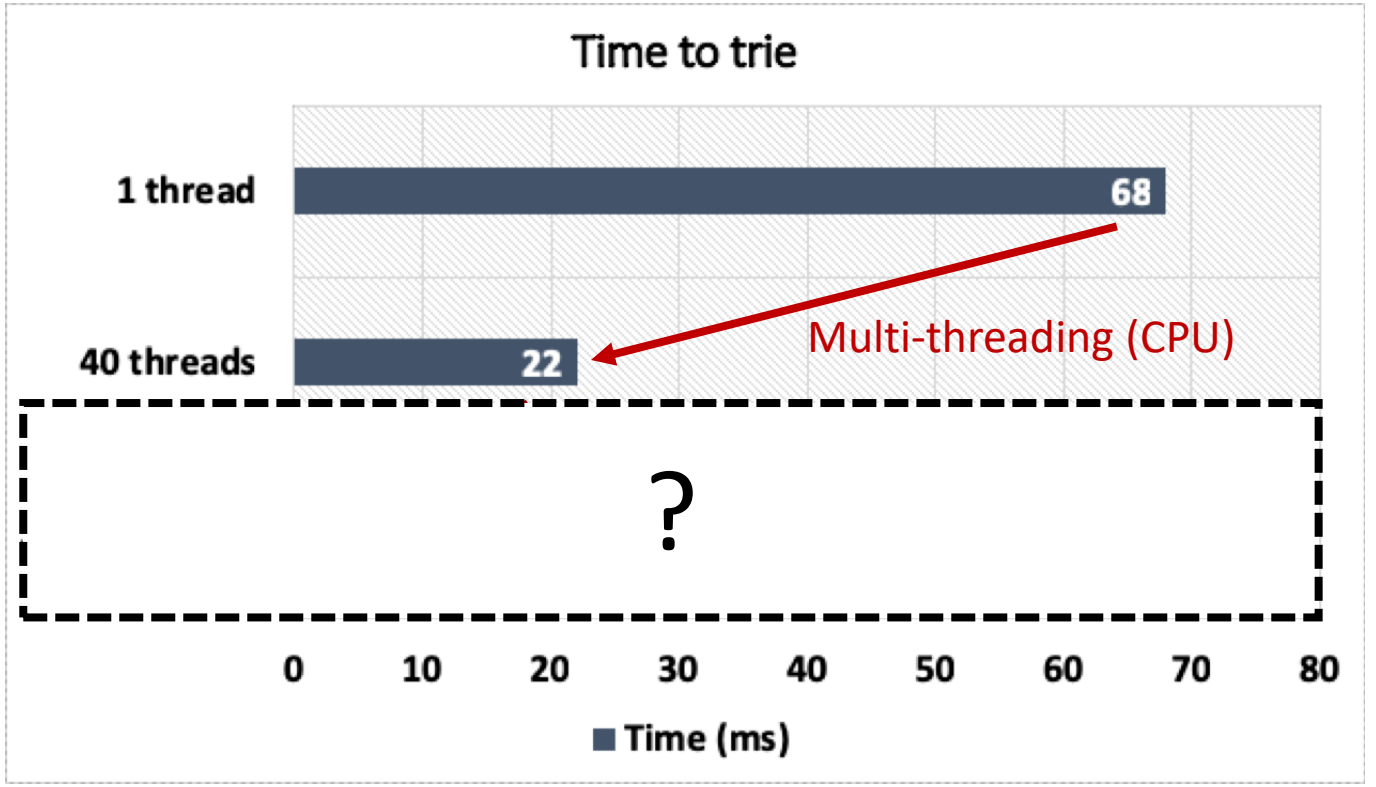
Rarely-taken loop changes this algorithm to a different category.

APP #3: CONCURRENT DATA STRUCTURES

Even if mutexes hide in every node, GPUs can build tree structures fast.

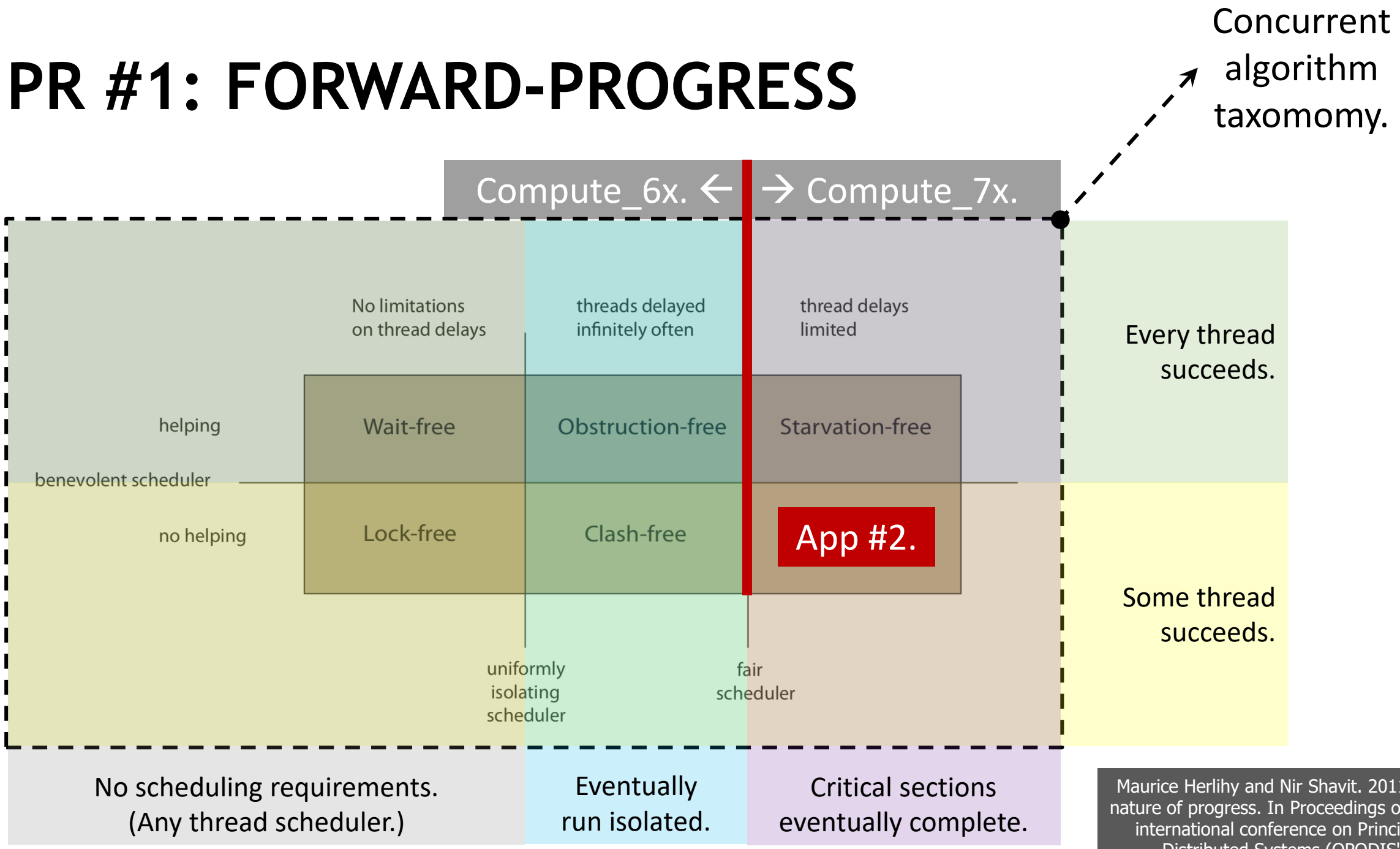
For more, see my CppCon 2018 talk on YouTube, *and* 'Parallel Forall' blog post.





PRE-REQUISITES

PR #1: FORWARD-PROGRESS



Maurice Herlihy and Nir Shavit. 2011. On the nature of progress. In Proceedings of the 15th international conference on Principles of Distributed Systems (OPODIS'11)

PR #2: MEMORY CONSISTENCY

Classic CUDA C++.

Our ASPLOS 2019 paper: https://github.com/NVlabs/ptxmemorymodel.

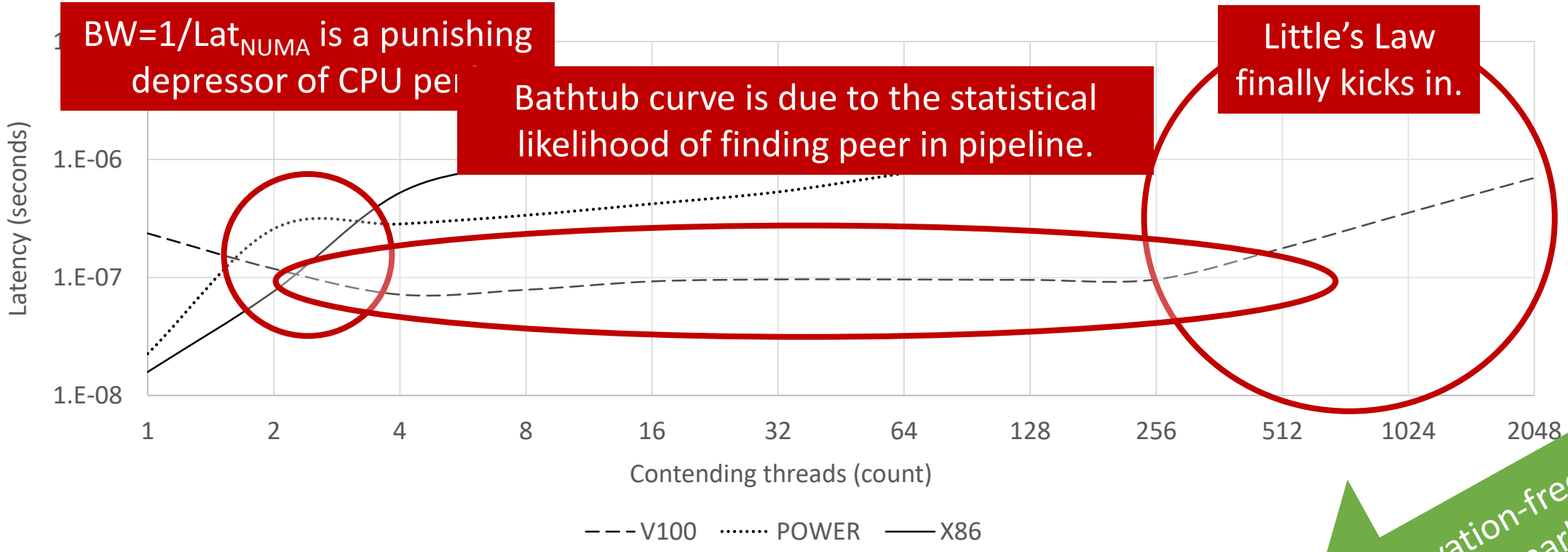
PR #3: TRUE SHARING

- Concurrent data sharing between CPU and GPU is a new possibility.
- Real usefulness has some more conditions.

Platform / allocator	Load/store sharing Atomic (low cont'n)	Atomic (high cont'n)
Any: ARM/Windows/Mac/Unmanaged		
x86 Linux (CPU/GPU) Managed		
x86 Linux (GPU/GPU) Managed		
POWER Linux (all pairs) Managed		

PRELIMINARIES

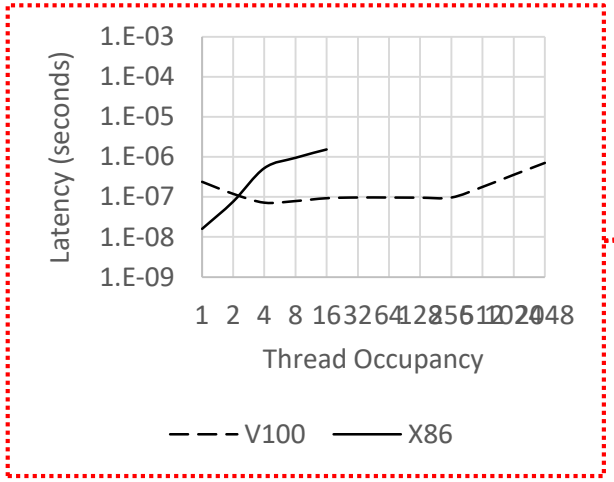
CONTENTION IS THE ISSUE, DIFFERENTLY.

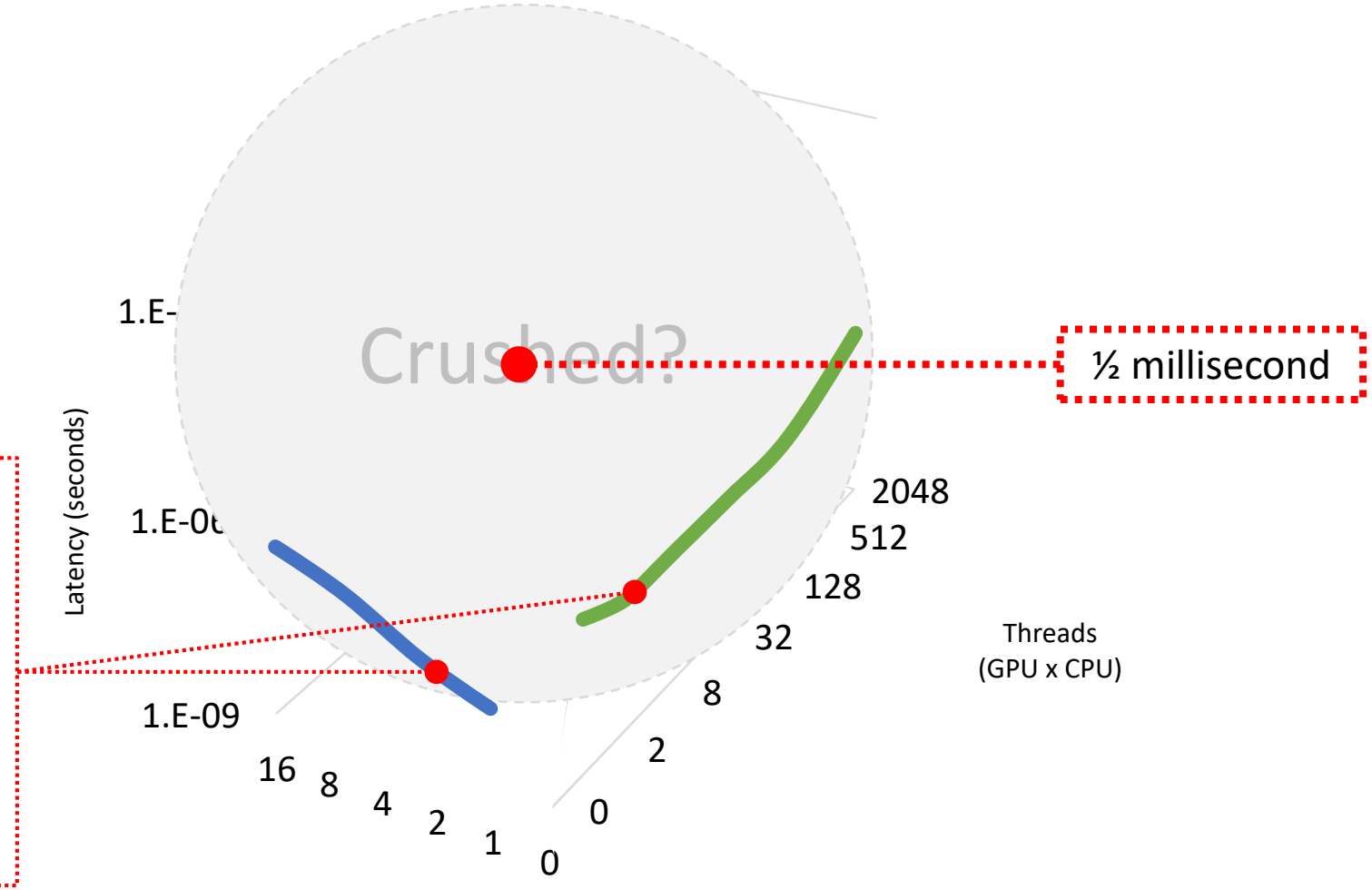



```
__host__ __device__ void test(int my_thread, int total_threads, int final_value) {
  for(int old ; my_thread < final_value; start += total_threads)
    while(!a.compare_exchange_weak(old = my_thread, my_thread + 1,
                                   memory_order_relaxed))
      ;
}
```

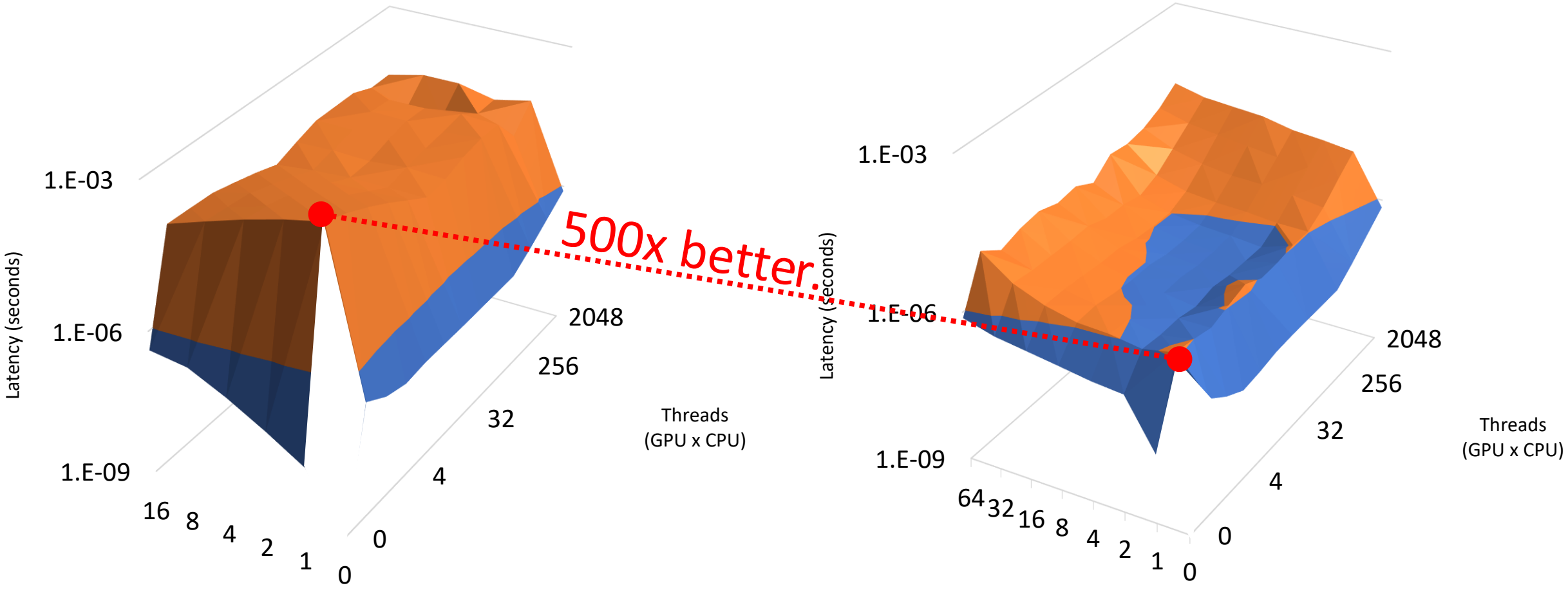
Starvation-free µbenchmark.

CONTENDING PROCESSORS ARE CRUSHED…





…UNLESS THE PROCESSORS ARE NVLINK'ED.

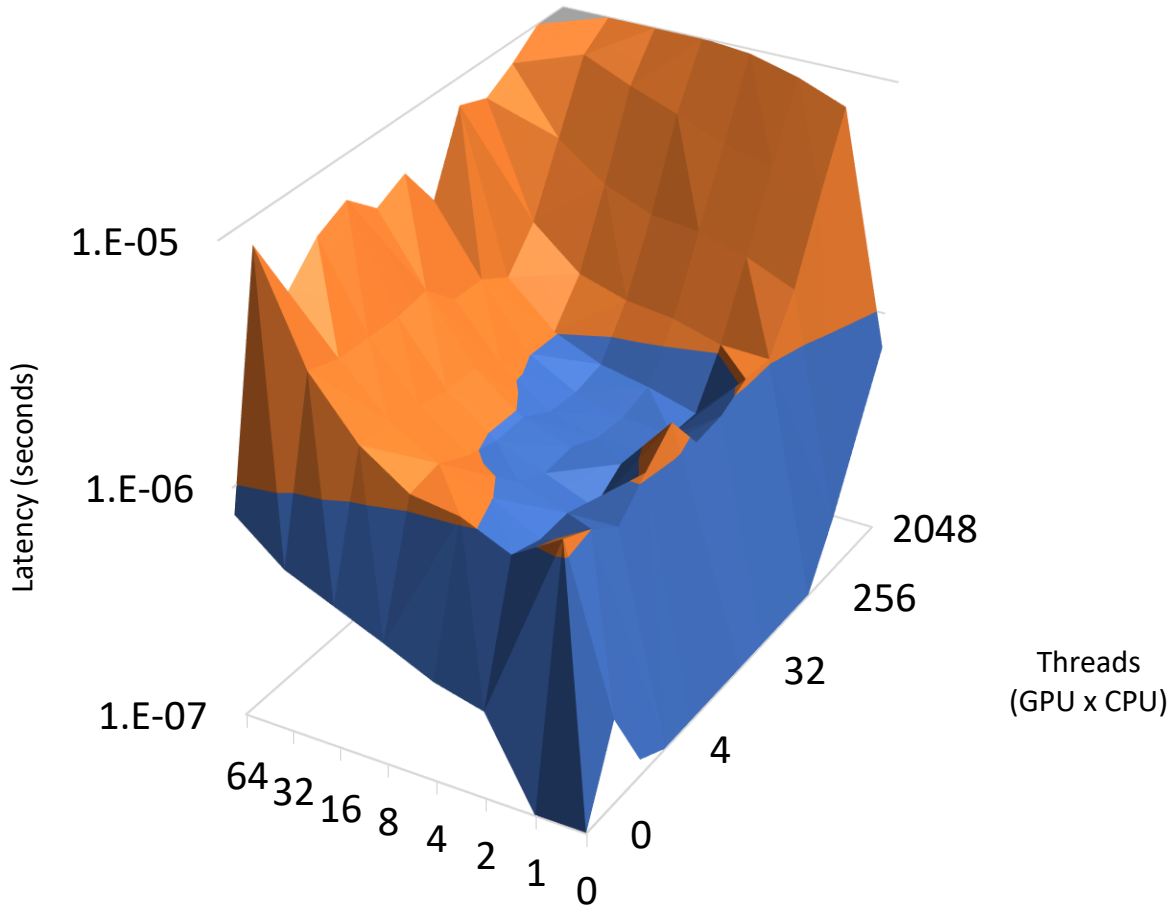


x86 + V100 (PCIE)

POWER + V100 (NVLINK)

ALL OF THE FOLLOWING SLIDES ARE NVLINK'ED.

And not log scale,
because it's legible in
linear scale now.
Thanks.

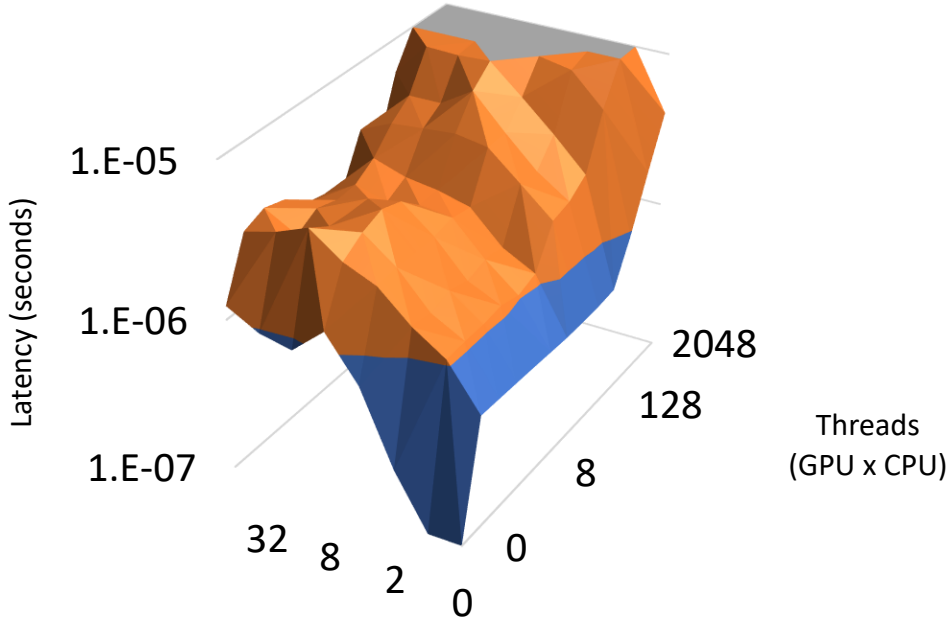


CONTENDED MUTEXES


CONTENDED MUTEXES
AS AN EXERCISE TO THINK ABOUT
THROUGHPUT AND FAIRNESS

CONTENDED EXCHANGE LOCK

```
struct mutex {

 __host__ __device__ void lock() {
  while(1 == l.exchange(1, memory_order_acquire))
    ;
 }

 __host__ __device__ void unlock() {
  l.store(0, memory_order_release);
 }

 atomic<int> l = ATOMIC_VAR_INIT(0);
};
```



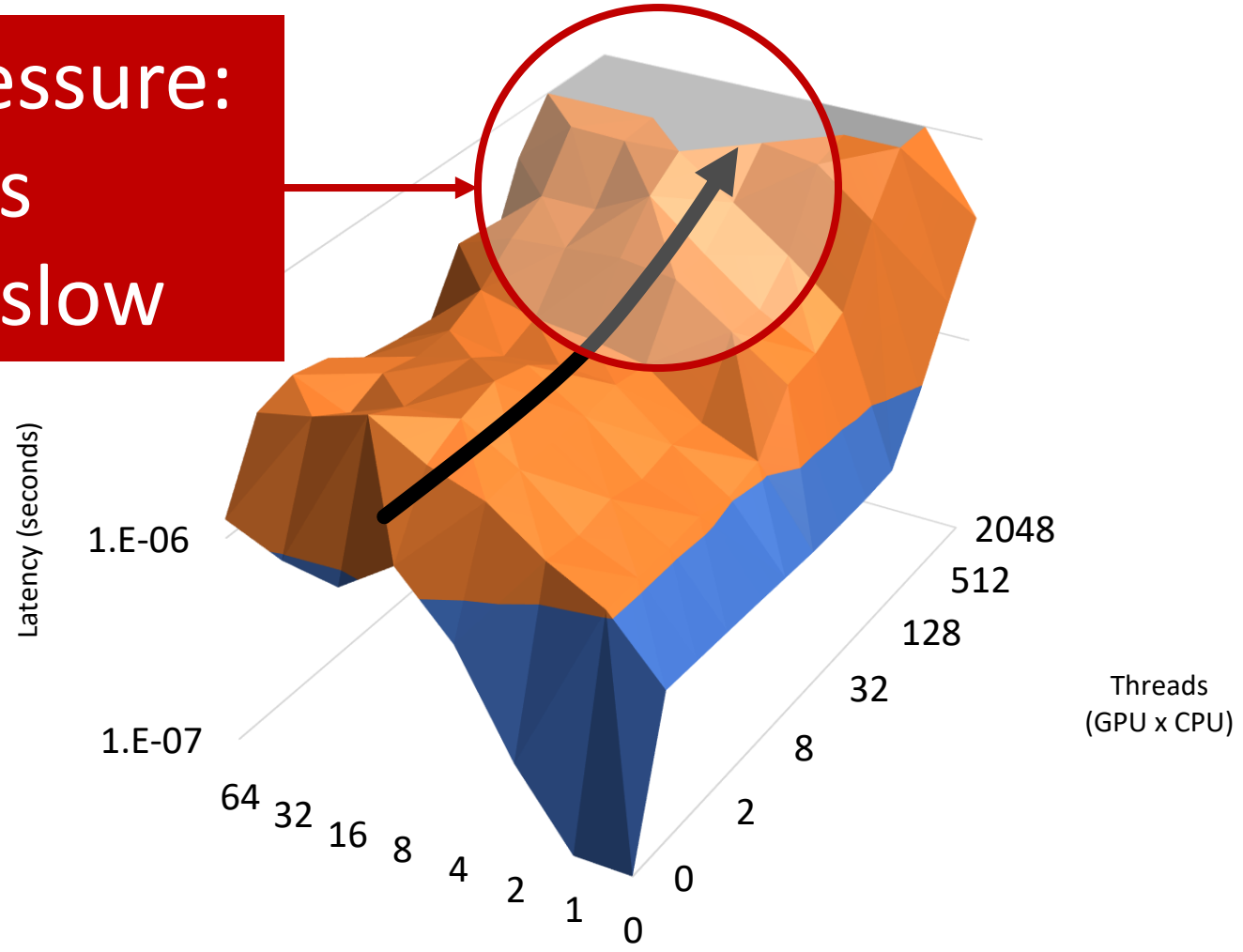
Not awesome.

Stay. Keep attending my talk.

CONTENDED EXCHANGE LOCK

Heavy system pressure:

- A lot of requests
- Each request is slow

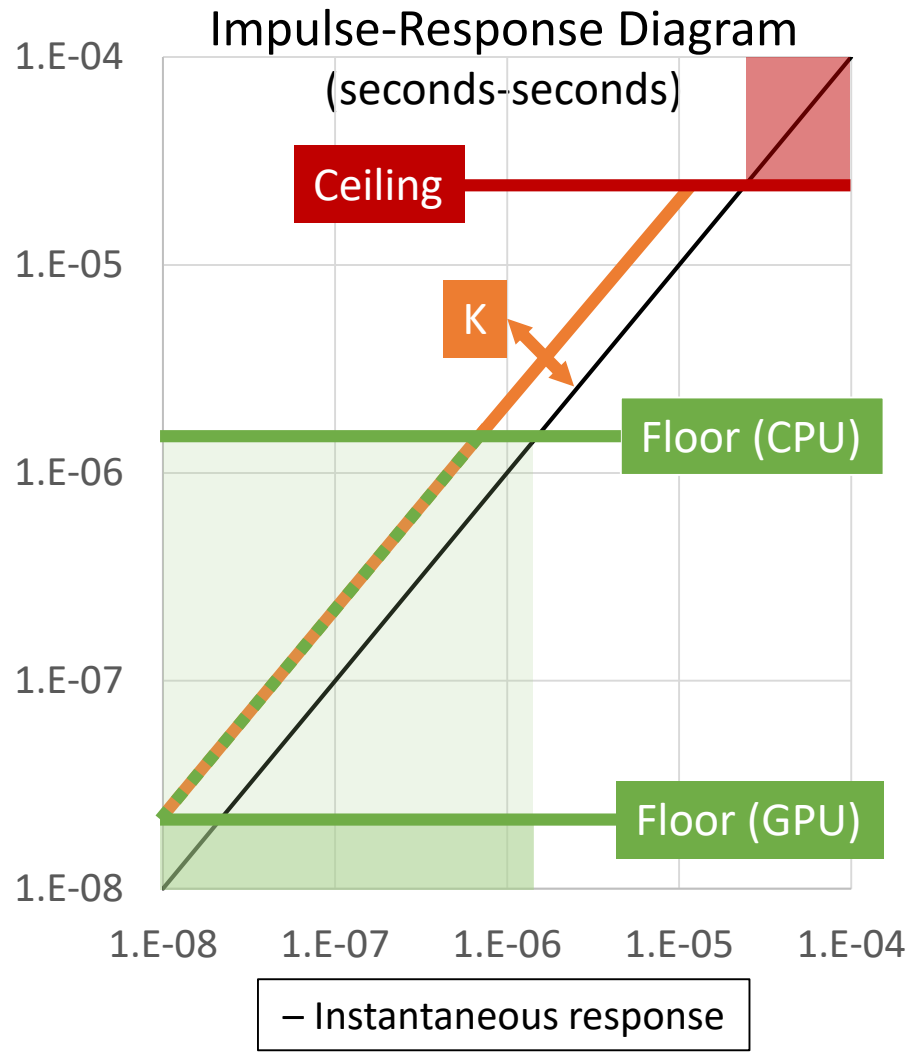


BACKOFF : LESS PRESSURE VIA FORECASTING

- **K** bounds forecast relative error (orange line):
  $Latency_{response} > K_{delay} * Latency_{impulse}$
  - Pick arbitrary K_{delay}; say 1.5 for 50% error.
  - Some benefit to stochastic choice, avoid coupling.

- **Ceiling** trades bandwidth & maximum error:
  $t_{polling} / (lat_{loaded} + lat_{backoff}) > BW_{polling}$
  - Pick arbitrary $BW_{polling}$; say 0.5 * $Bw_{contended}$

- **Floor** protects the fast corner (green box):
  $Latency_{response} > Latency_{floor}$
  - Minimum CPU sleep (Linux) is ~= 50000ns.
  - Minimum sleep on V100 is ~= 0ns.



CONTENDED EXCHANGE LOCK + BACKOFF

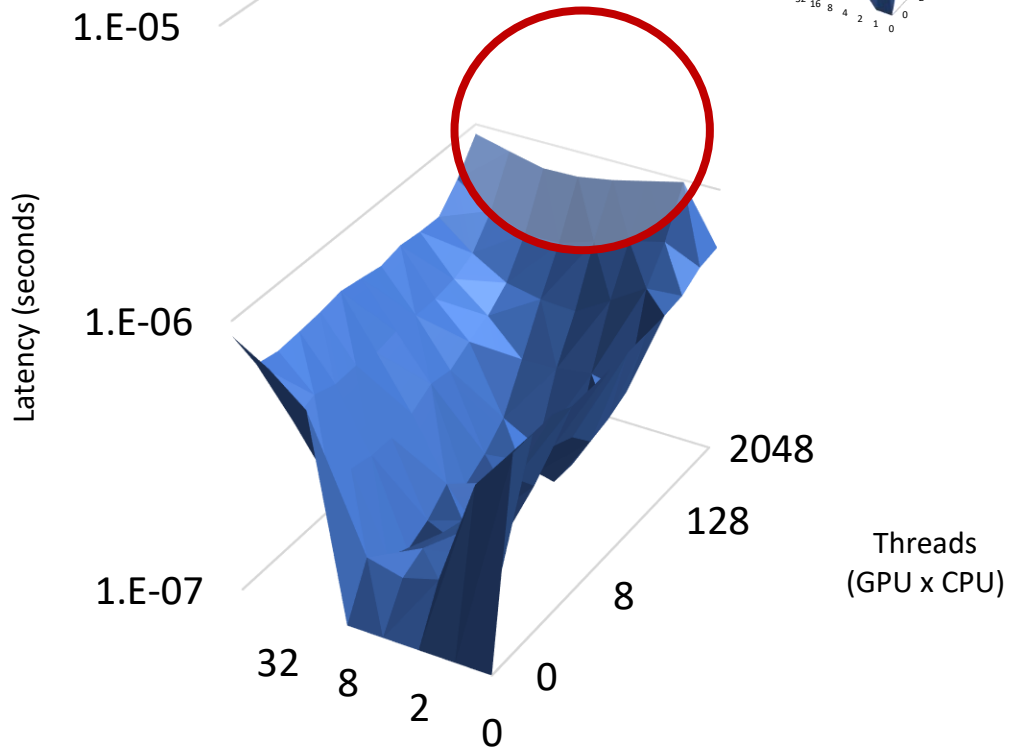
```
__host__ __device__ void lock() {
  uint32_t history = 1<<8; // 256ns
  while(1 == l.exchange(1, memory_order_acquire)) {
    uint32_t delay = history >> 1; // 50%
#ifdef __CUDA_ARCH__
    __nanosleep(delay);
#else
    if(delay > (1<<15)) // 32us
      std::this_thread::sleep_for(
        std::chrono::nanoseconds(delay));
    else {
      std::this_thread::yield();
      delay = 0;
    }
#endif
    history += (1<<8) + delay;
    if(history > (1<<18)) // 256us
      history = 1<<18;
  }
}
```

K

FLOOR

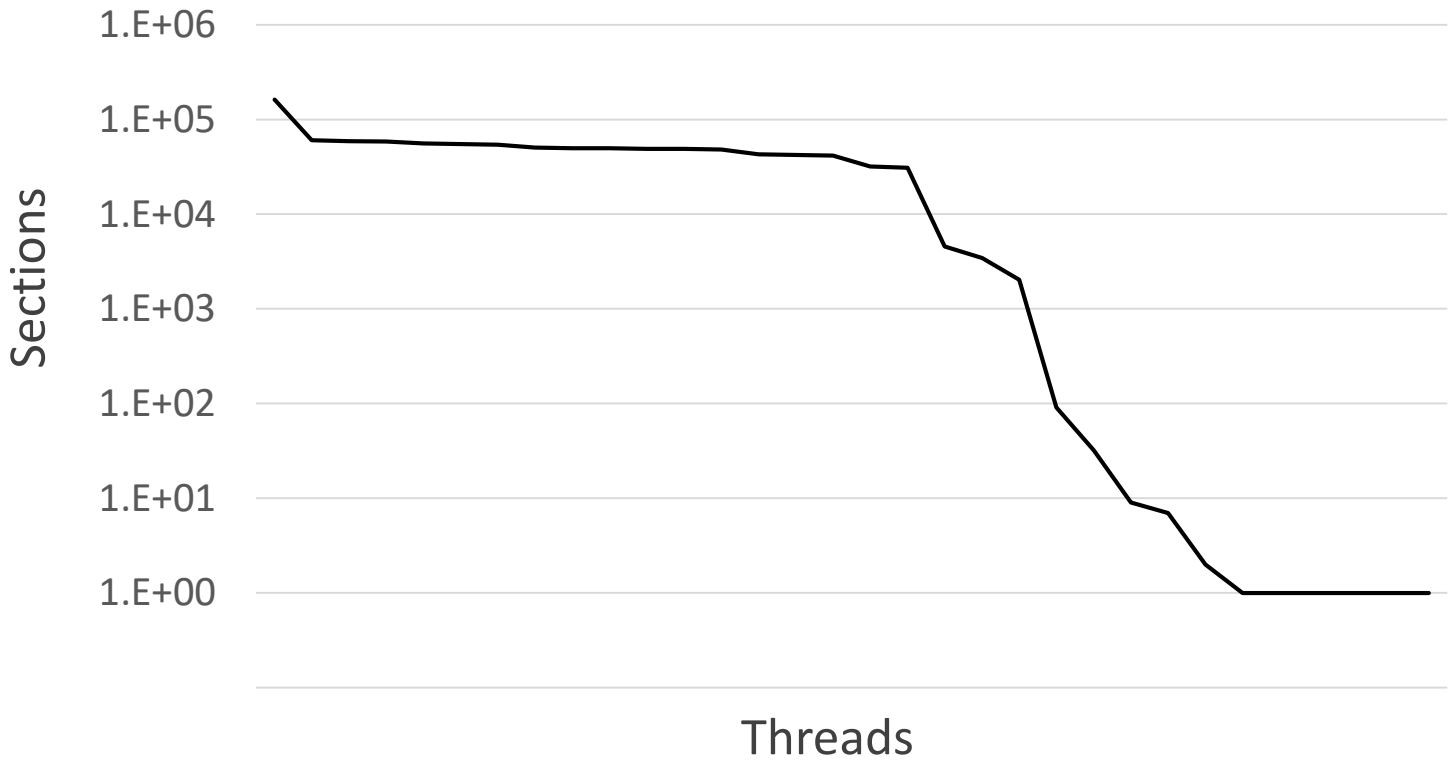
CEILING

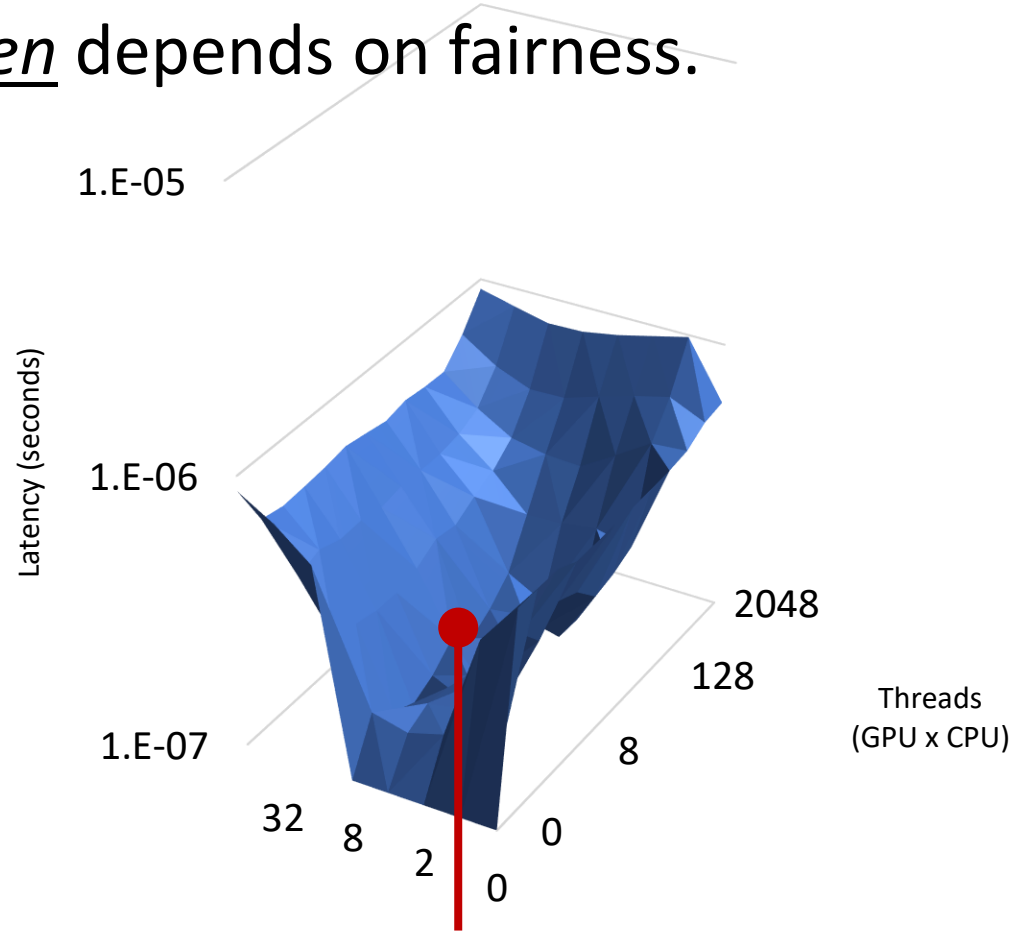
We seem to have fixed the slow corner.



FAST LOCKS, SLOW APPLICATIONS

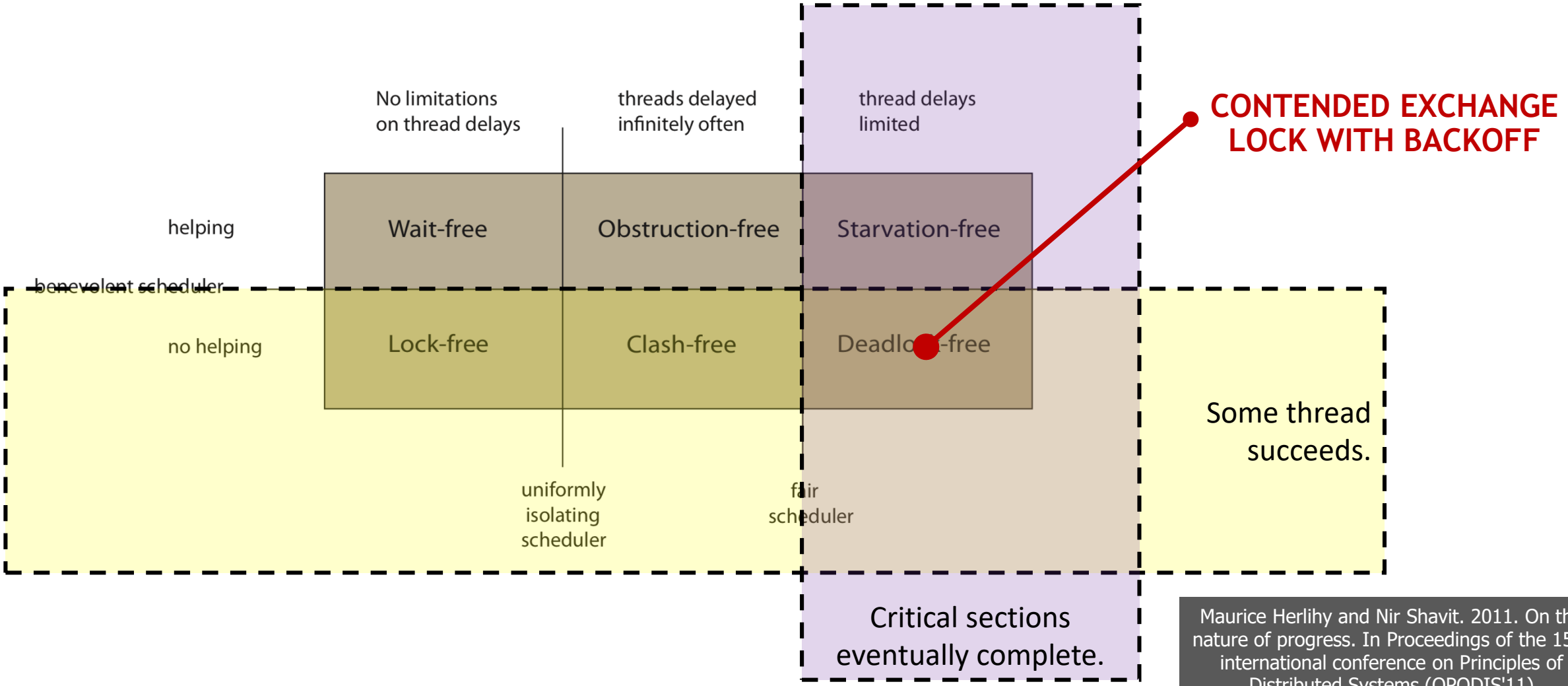
- Fast because: lock *disproportionally* granted to some threads.
- Slow because: top-level performance *often* depends on fairness.





Single-thread rate is a strong attractor.

RECALL : FORWARD-PROGRESS



Maurice Herlihy and Nir Shavit. 2011. On the nature of progress. In Proceedings of the 15th international conference on Principles of Distributed Systems (OPODIS'11)

WHEN IS DEADLOCK-FREE SUITABLE?

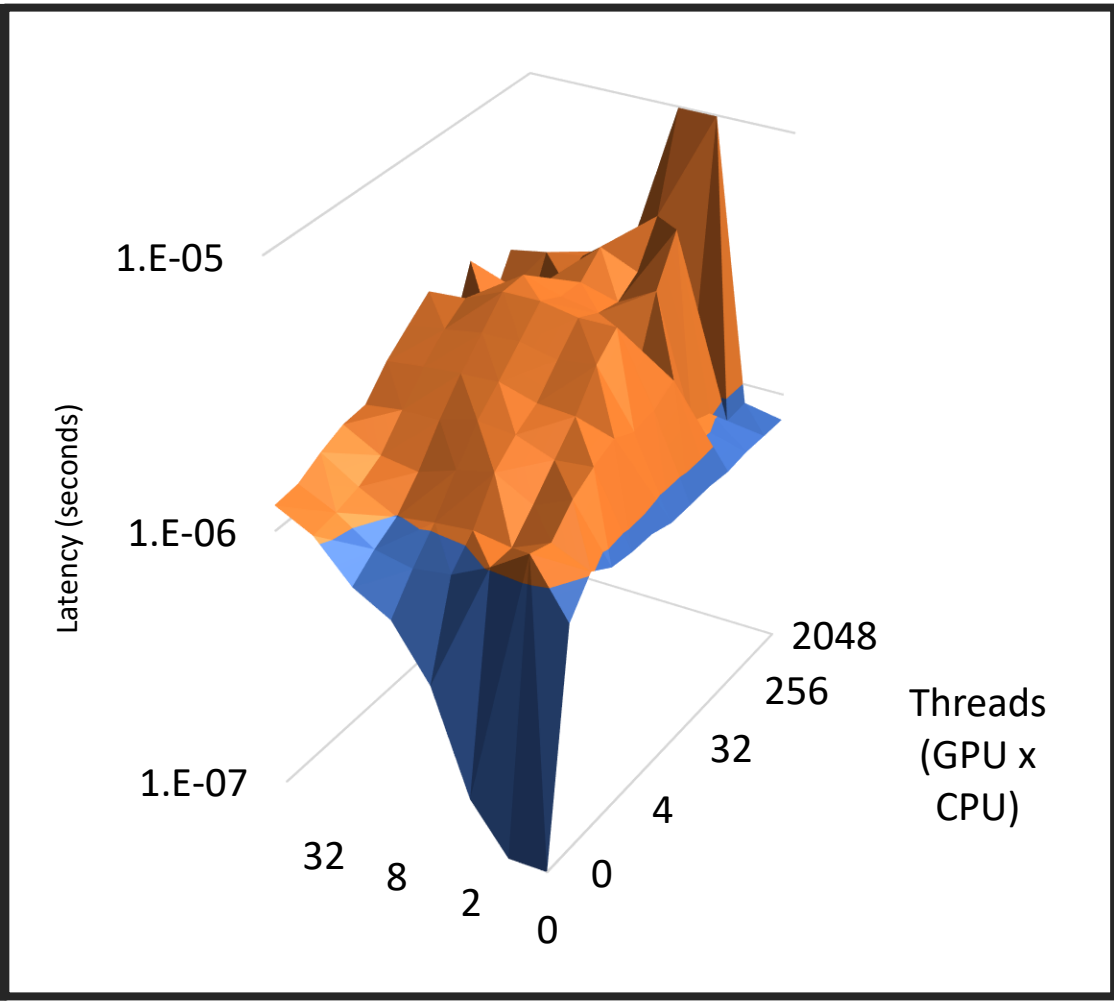
Enumerated list:

1. Very low contention.
2. Top-level algorithms resilient to tail effects.

Luckily, this is still pretty common!

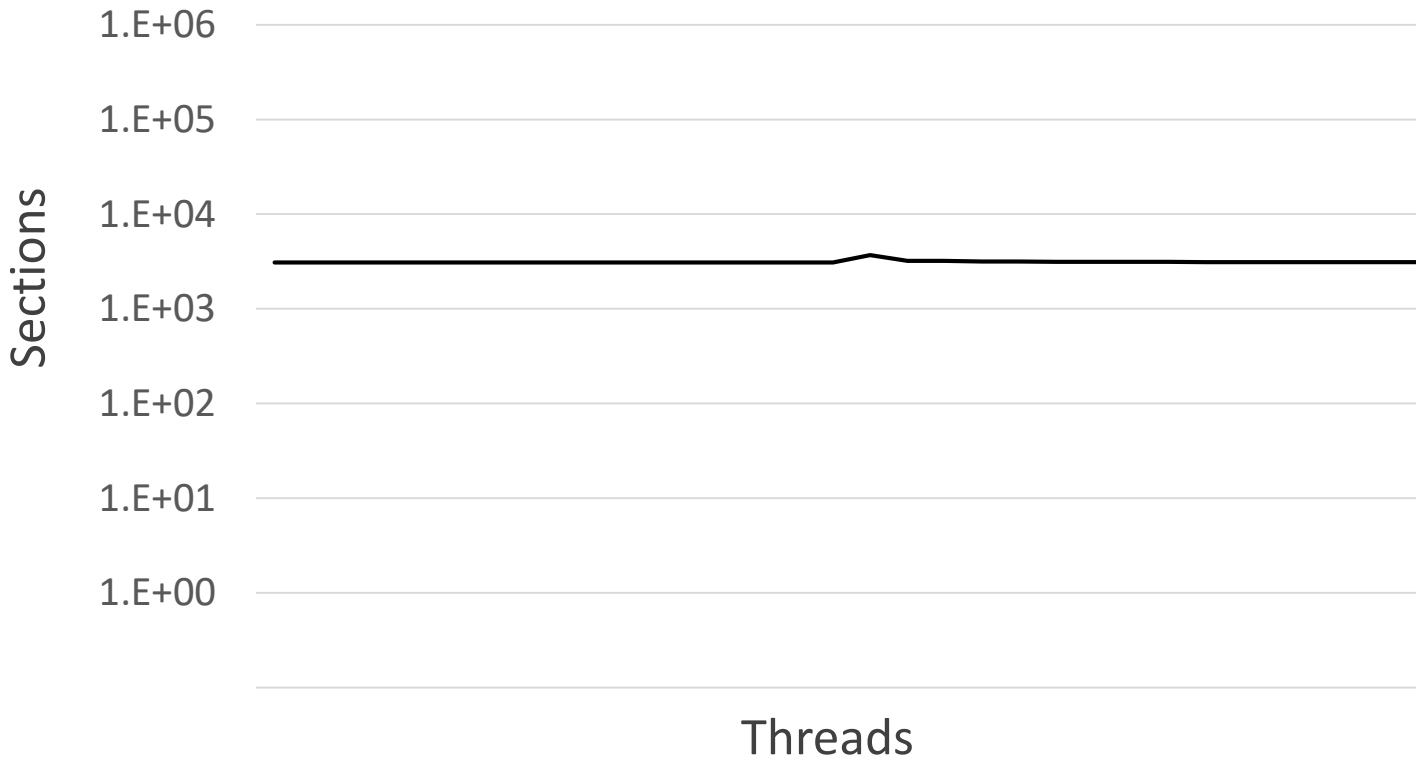
TICKET LOCK + PROPORTIONAL BACKOFF

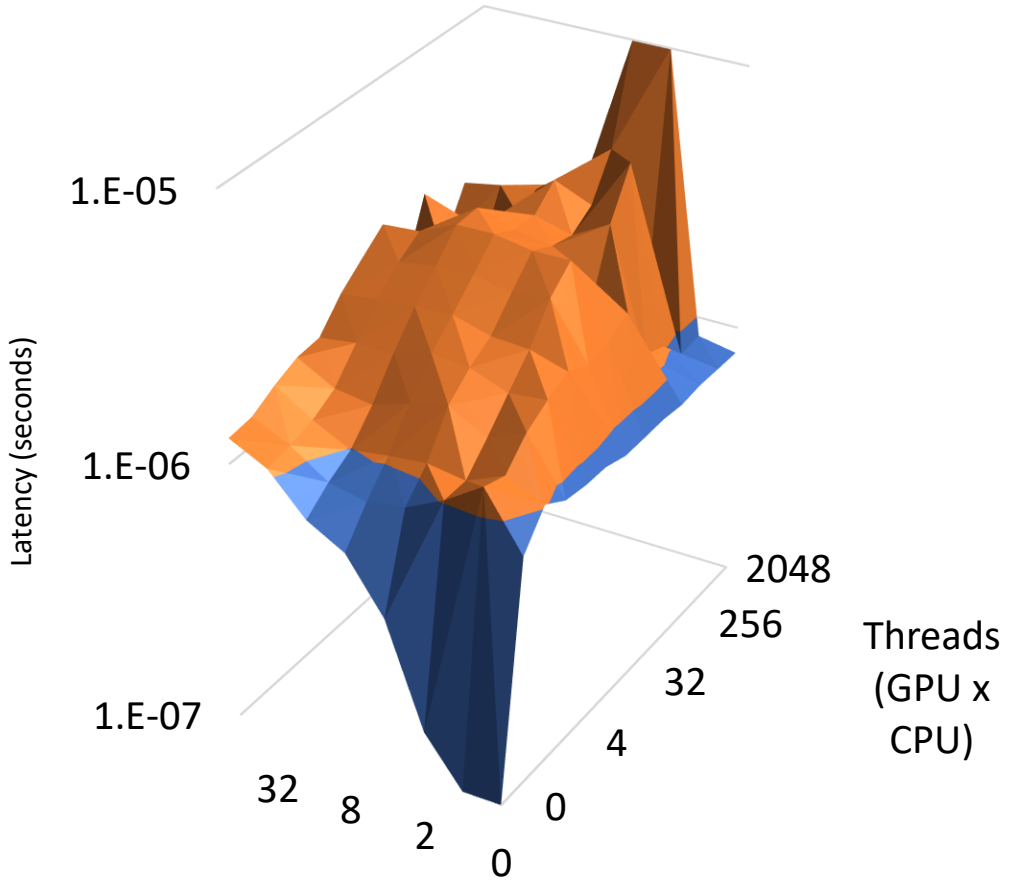
```
struct alignas(128) ticket_mutex {
  __host__ __device__ void lock() {
    auto const my = in.fetch_add(1, memory_order_acquire);
    while(1) {
      auto const now = out.load(memory_order_acquire);
      if(now == my)
        break;
      auto const delta = my - now;
      auto const delay = (delta << 8); // * 256
#ifdef __CUDA_ARCH__
      __nanosleep(delay);
#else
      if(delay > (1<<15)) // 32us
        std::this_thread::sleep_for(std::chrono::nanoseconds(delay));
      else
        std::this_thread::yield();
#endif
    }
  }
  __host__ __device__ void unlock() {
    out.fetch_add(1, memory_order_release);
  }
  atomic<unsigned> in = ATOMIC_VAR_INIT(0);
  atomic<unsigned> out = ATOMIC_VAR_INIT(0);
};
```



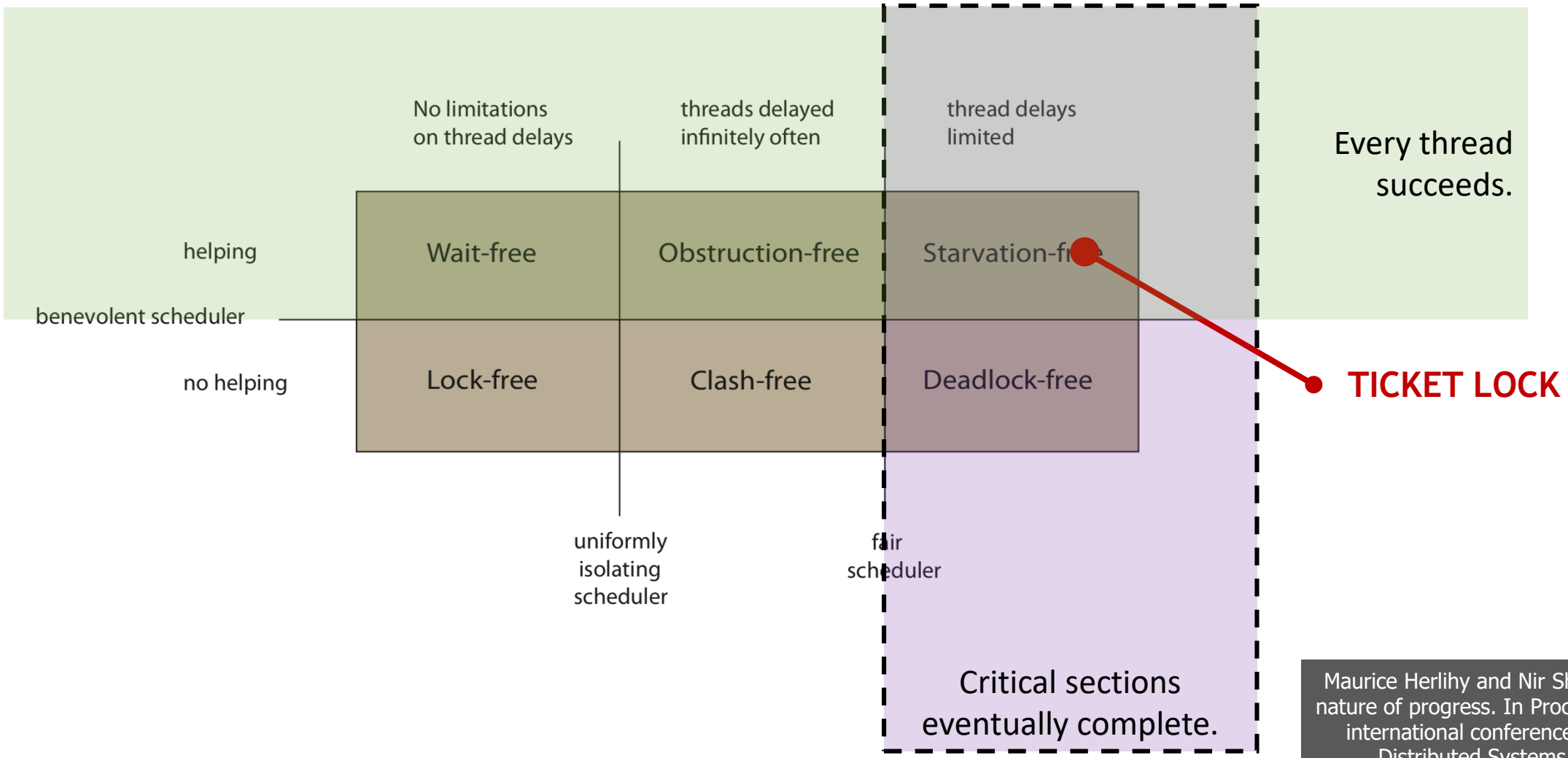
Don’t need either K or ceiling here, `delta` is an accurate forecast! ☺

TICKET LOCK + PROPORTIONAL BACKOFF





AGAIN : FORWARD-PROGRESS



Maurice Herlihy and Nir Shavit. 2011. On the nature of progress. In Proceedings of the 15th international conference on Principles of Distributed Systems (OPODIS'11)

WHEN IS STARVATION-FREE SUITABLE?

This is your default, when deadlock-free is unsuitable.

WHAT ELSE IS THERE FOR MUTEXES?

Wish we could use **queue locks** (e.g. MCS) but we can’t.

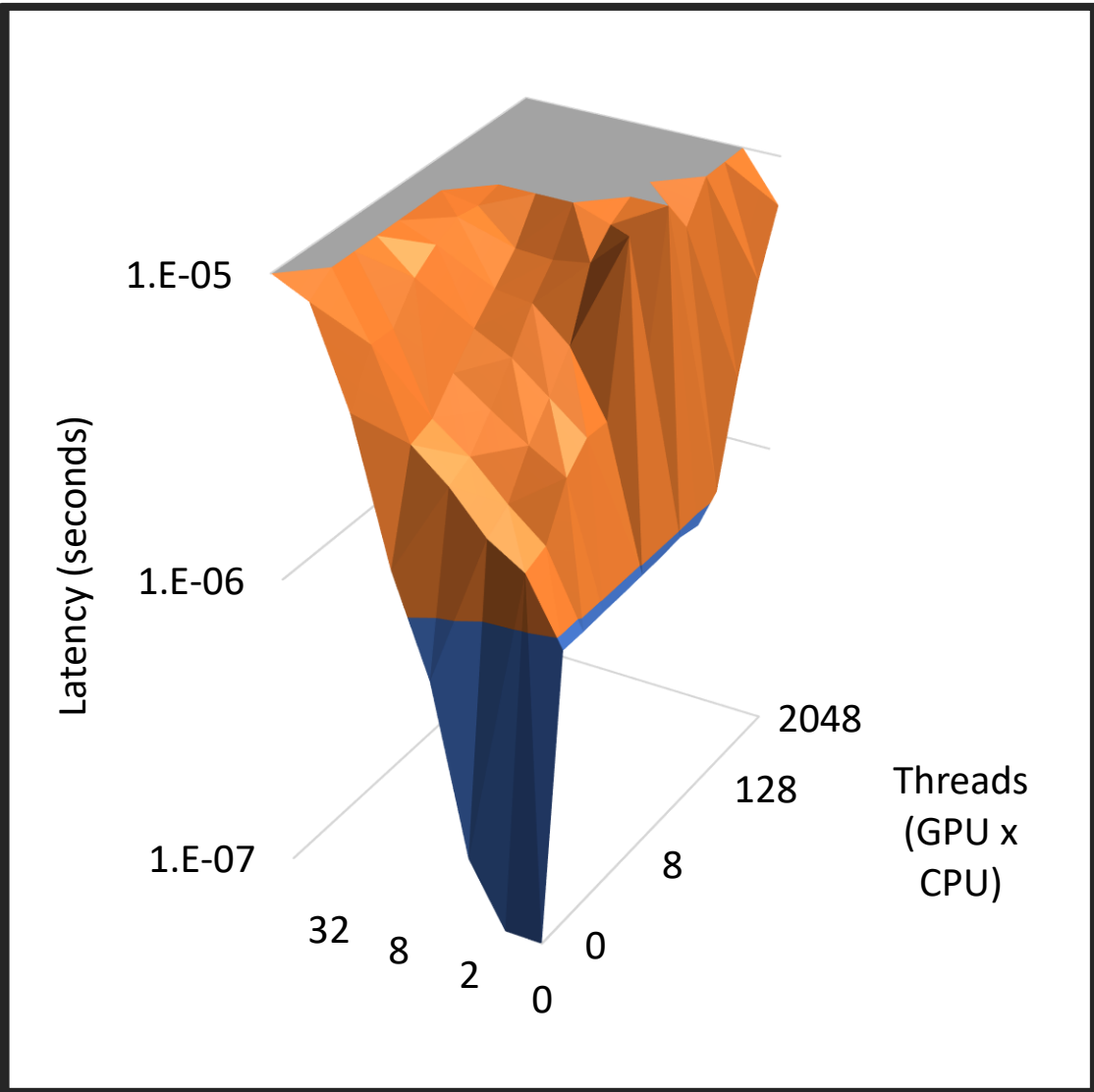
These use O(P) storage 😱 and local stack pointers (MCS).


BARRIERS


BARRIERS
AS A TYPICALLY-GPU THING
AND ALSO TO THINK ABOUT LATENCY

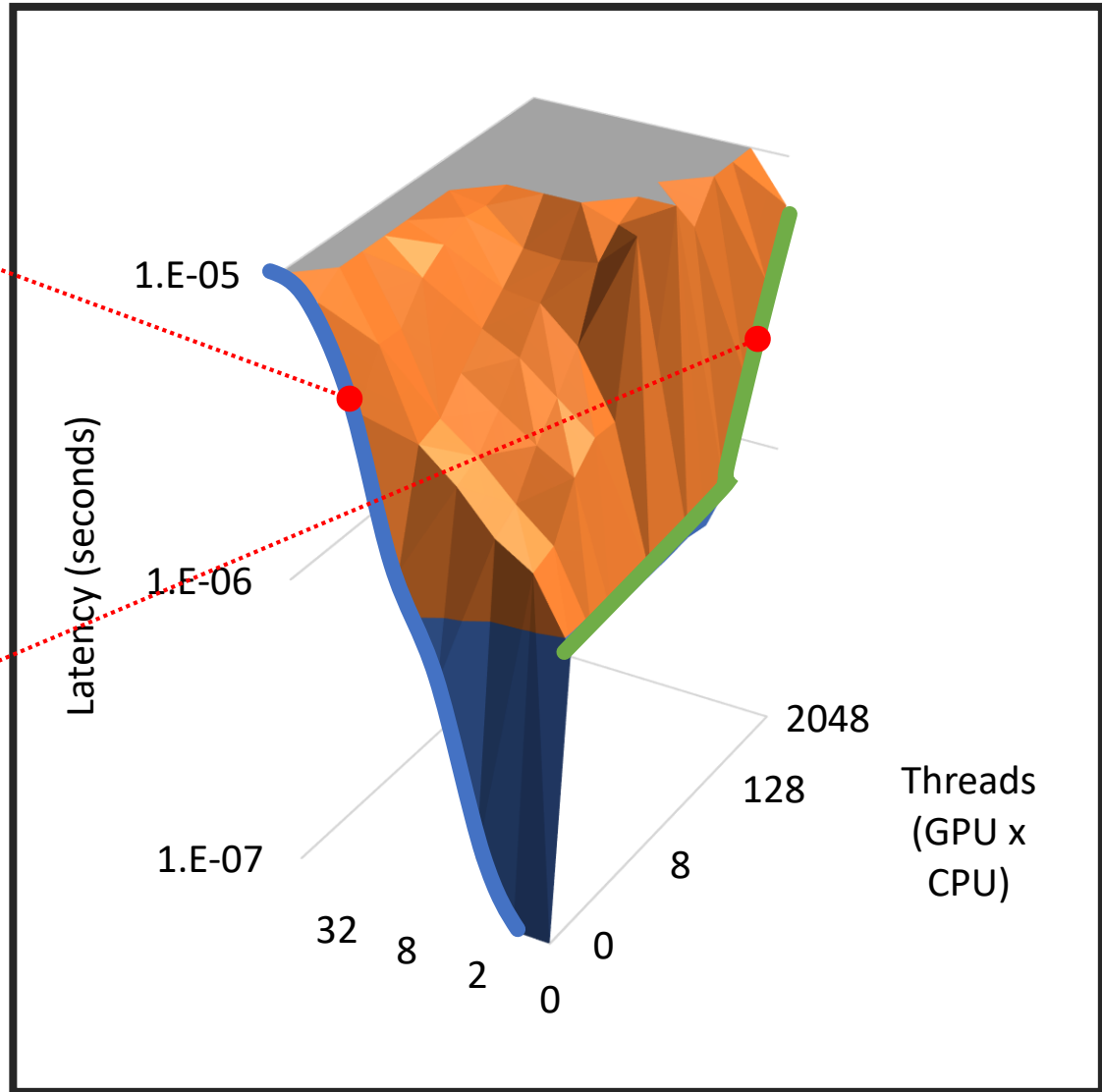
CENTRAL BARRIER + PROPORTIONAL BACKOFF

```
__host__ __device__ void arrive_and_wait() {

 auto const _expected = expected;
 auto const old = phase_arrived.fetch_add(1, memory_order_acq_rel);
 auto current = old + 1;
 if((old & phase_bit) != (current & phase_bit)) {
  phase_arrived.fetch_add(phase_bit - _expected);
 }
 else
  while(1) {
   current = phase_arrived.load(memory_order_acquire);
   if((old & phase_bit) != (current & phase_bit))
    break;
   auto const delta = phase_bit - (current & ~phase_bit);
   auto const delay = (delta << 8); // * 256
#ifdef __CUDA_ARCH__
   __nanosleep(delay);
#else
   if(delay > (1<<15)) // 32us
    std::this_thread::sleep_for(std::chrono::nanoseconds(delay));
   else
    std::this_thread::yield();
#endif
  }
}
uint32_t const expected = 0;
atomic<uint32_t> phase_arrived = ATOMIC_VAR_INIT(0);
```



CENTRAL BARRIER + PROPORTIONAL BACKOFF

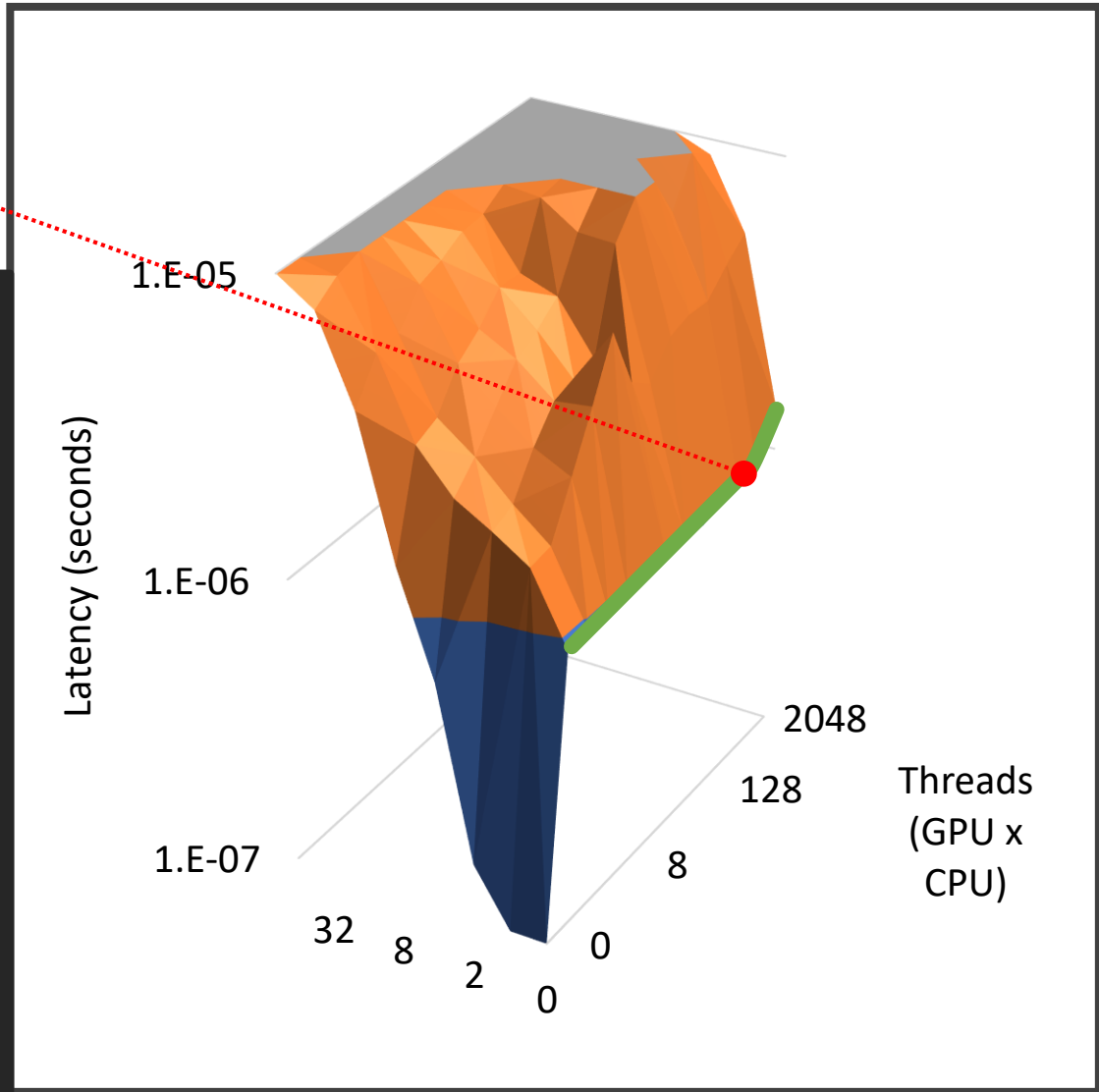
- Centralized barrier is bad for the CPU.
  - Coherence protocols strongly prefer fancy barrier algorithms: *tree, tournament, dissemination…*
  - Because: $BW_{contended} = 1/Lat_{NUMA}$.
- GPU just hangs-on for a while longer.
  - But: fancy algorithms introduce high-latency, levels of indirection.
  - Each indirection needs 1:100x .. 1:1000x improvement in BW to justify itself.



EASY AND EFFECTIVE GPU TREE BARRIER

- 2nd level of hierarchy is ~free, in blocks.
- Up to 1:1024 bandwidth reduction!

```
__host__ __device__ void arrive_and_wait() {
#ifdef __CUDA_ARCH__
 auto const c = __syncthreads_count(1);
 if(threadIdx.x == 0)
  __arrive_and_wait(c);
 __syncthreads();
#else
 __arrive_and_wait();
#endif // __CUDA_ARCH__
}

__host__ __device__ void __arrive_and_wait(int c = 1) {

 auto const _expected = expected;
 auto const old = phase_arrived.fetch_add(c, memory_order_acq_rel);
 auto current = old + c;

//...

}
```



“Remember, if you actually need a GPU barrier, then you should use cooperative groups instead.”

https://devblogs.nvidia.com/cooperative-groups/

- My inner CUDA engineer voice.

WHAT ABOUT CPU-GPU BARRIERS, THOUGH?

- As you can see, a new barrier algorithm is necessary.
- Perhaps partitioned strategies, by processor type?

Seriously, I'm asking. Somebody should try it! 

- I don't know what it would be for, though. So no rush.

WHAT ELSE IS THERE FOR BARRIERS?

For multi-GPU systems:

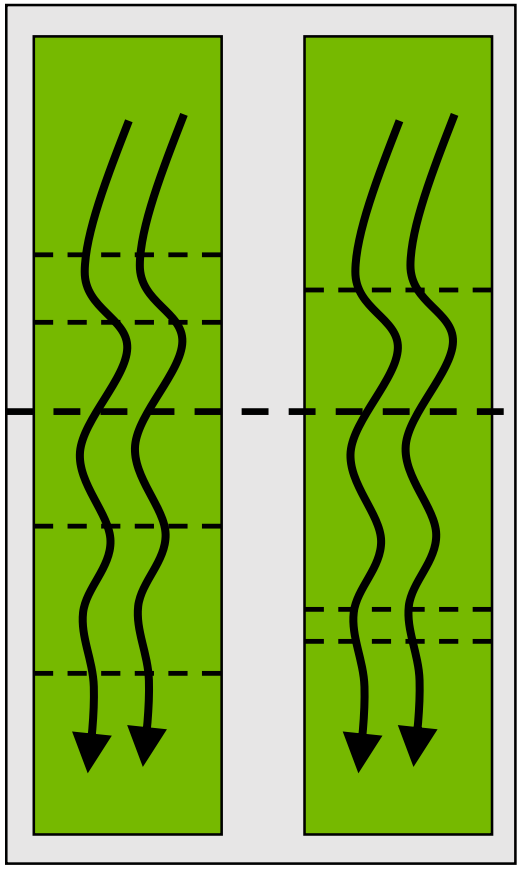
- You can replicate arrivals to trade atomics vs. polling.
- Not done by CG but it has been done at NVIDIA.

For a DGX-2 (2.6 million threads):

- You *might* benefit from 3rd level of barrier, barely.
- I don’t think it’s been done at NVIDIA yet.

IN SHORT

USE CASES



PRE-REQS

→ Compute_7x.

Critical sections
eventually complete.

KEEP IN MIND

1. Contention bandwidth is a major issue for synchronization.
   See: atomic story.

2. If you use back-offs, keep an eye on fairness.
   See: mutex story.

3. If you use indirection, the GPU needs a 100..1000x saving.
   See: barrier story.

CUDA::STD::ATOMIC<T> IS COMING SOON

Should come to the CUDA C++ toolkit this year, in 2019.

A preview is here:
https://github.com/ogiroux/freestanding.

My CppCon 2018 talk has more, stream it on YouTube.

EXTREME SHARED-MEMORY CONCURRENCY

Concurrency at this scale has never been easier.

If you have IBM + V100 systems, try new algorithms!

We want to see what you'll do with them.


NVIDIA