Spin Locks and Contention

Companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit

Focus so far: Correctness and Progress

- Models
  - Accurate (we never lied to you)
  - But idealized (so we forgot to mention a few things)
- Protocols
  - Elegant
  - Important
  - But naïve

New Focus: Performance

- Models
  - More complicated (not the same as complex!)
  - Still focus on principles (not soon obsolete)
- Protocols
  - Elegant (in their fashion)
  - Important (why else would we pay attention)
  - And realistic (your mileage may vary)

Kinds of Architectures

- SISD (Uniprocessor)
  - Single instruction stream
  - Single data stream
- SIMD (Vector)
  - Single instruction
  - Multiple data
- MIMD (Multiprocessors)
  - Multiple instruction
  - Multiple data.

Kinds of Architectures

- SISD (Uniprocessor)
  - Single instruction stream
  - Single data stream
- SIMD (Vector)
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- MIMD (Multiprocessors)
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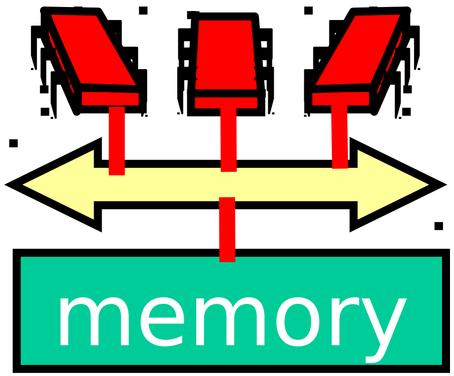
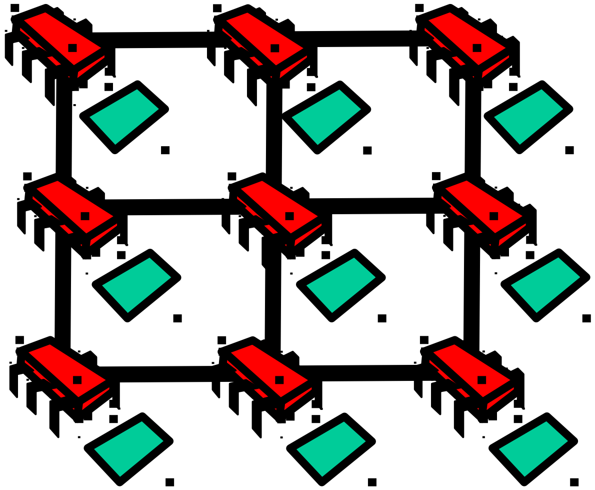
Our space

MIMD Architectures





Shared Bus

Distributed

- Memory Contention
- Communication Contention
- Communication Latency

Today: Revisit Mutual Exclusion

- Think of performance, not just correctness and progress
- Begin to understand how performance depends on our software properly utilizing the multiprocessor machine's hardware
- And get to know a collection of locking algorithms…

What Should you do if you can't get a lock?

- Keep trying
  - "spin" or "busy-wait"
  - Good if delays are short
- Give up the processor
  - Good if delays are long
  - Always good on uniprocessor

What Should you do if you can’t get a lock?

- Keep trying
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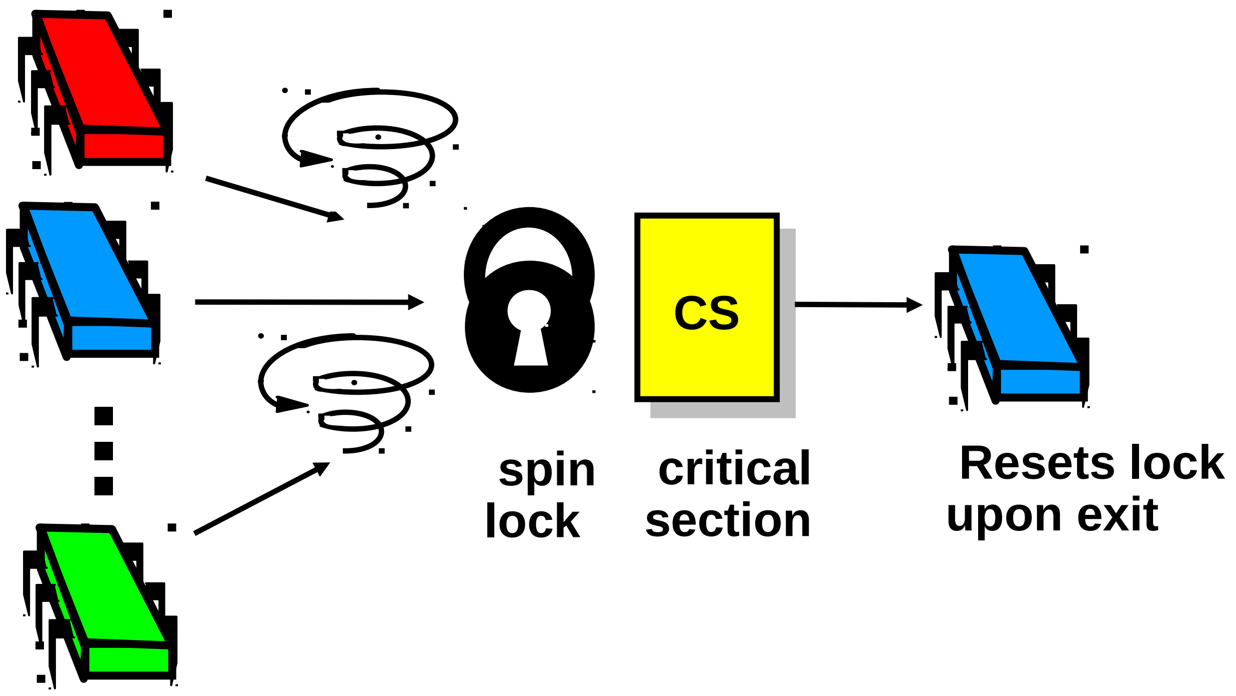
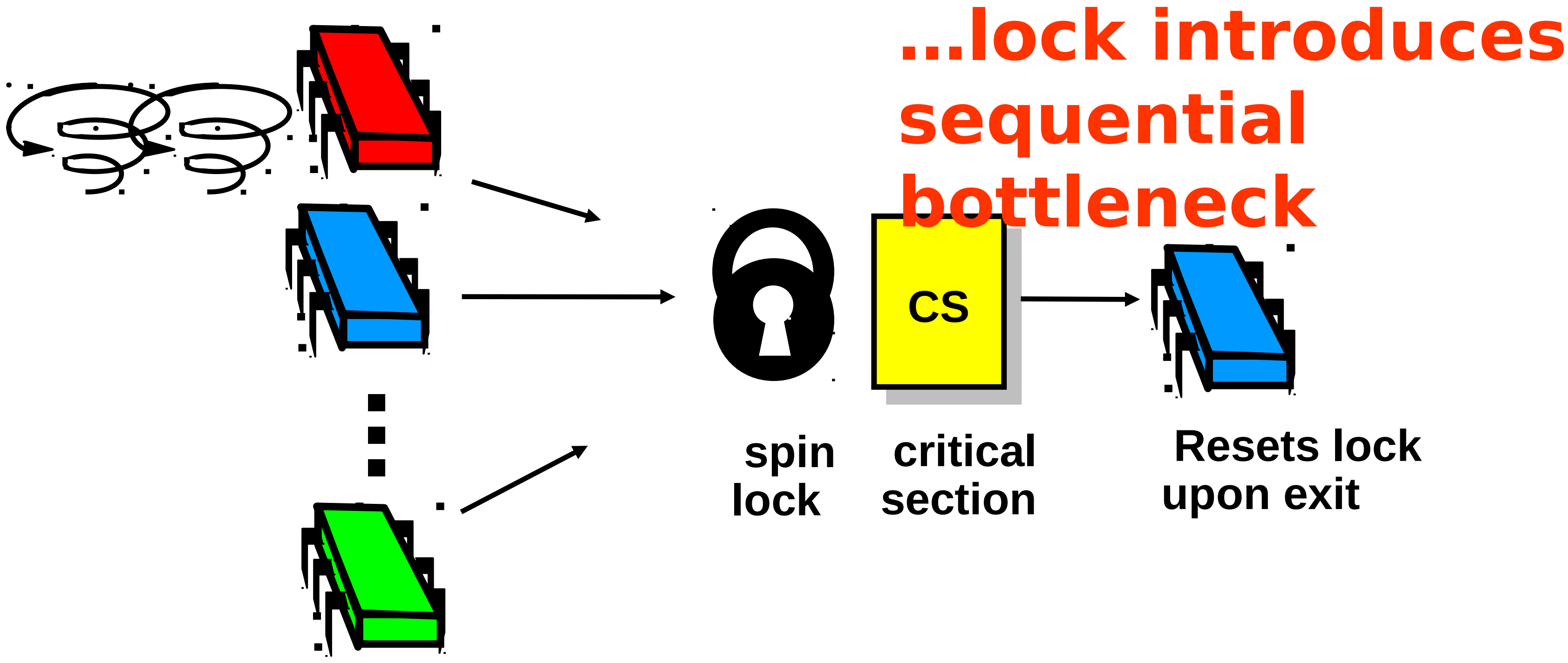
our focus

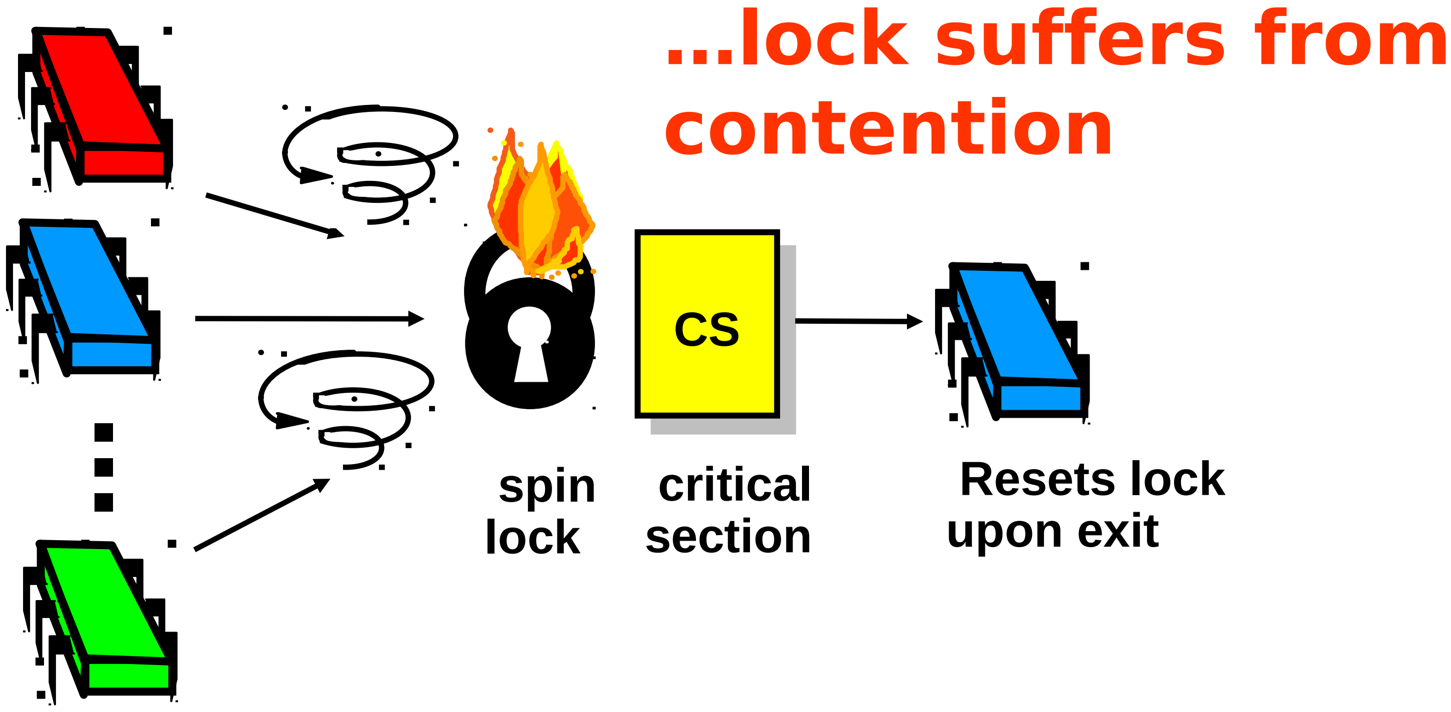
Basic Spin-Lock



Basic Spin-Lock

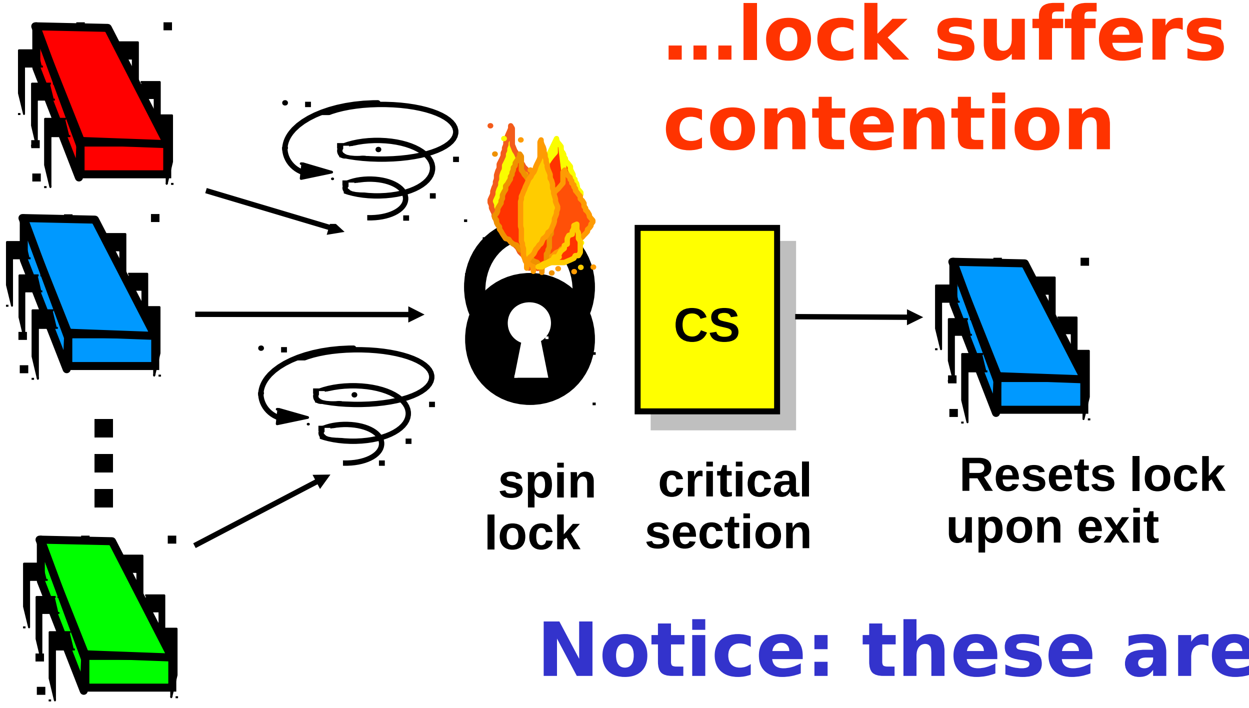


Basic Spin-Lock



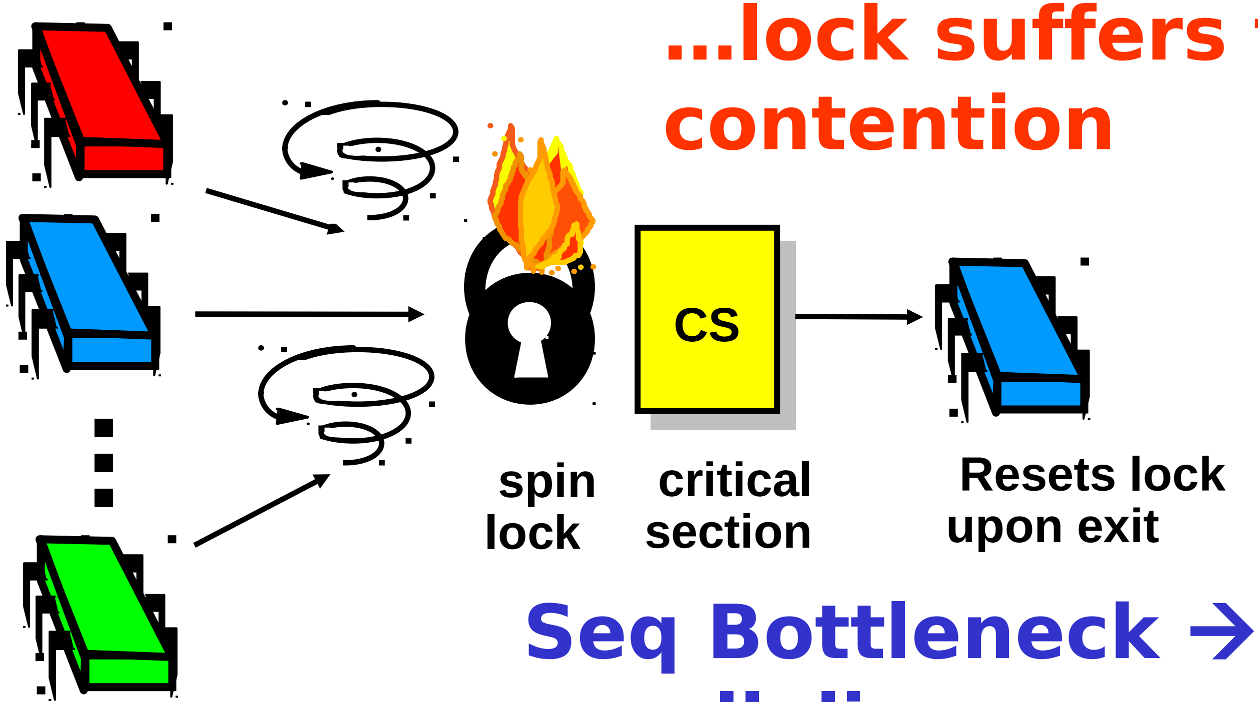
Basic Spin-Lock

...lock suffers from contention



Notice: these are distinct phenomena

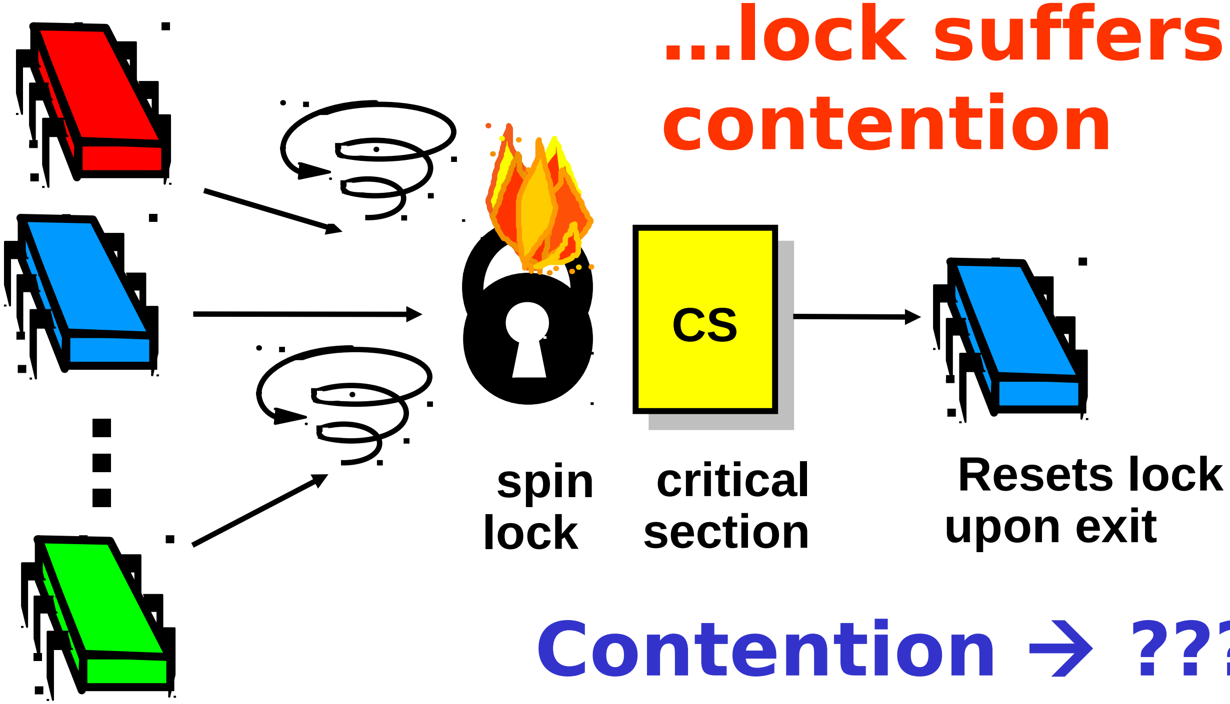
Basic Spin-Lock



...lock suffers from contention

Seq Bottleneck → no parallelism

Basic Spin-Lock



...lock suffers from contention

Contention → ???

Review: Test-and-Set

- Boolean value
- Test-and-set (TAS)
  - Swap **true** with current value
  - Return value tells if prior value was **true** or **false**
- Can reset just by writing **false**
- TAS aka “getAndSet”

Review: Test-and-Set

```
public class AtomicBoolean {
 boolean value;

 public synchronized boolean
  getAndSet(boolean newValue) {
   boolean prior = value;
   value = newValue;
   return prior;
 }
}
```

Review: Test-and-Set

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public class AtomicBoolean {
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```

Package
java.util.concurrent.atomic

Review: Test-and-Set

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public class AtomicBoolean {
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   value = newValue;
   return prior;
 }
}
```

Swap old and new values

Review: Test-and-Set

```
AtomicBoolean lock
 = new AtomicBoolean(false)
…
boolean prior = lock.getAndSet(true)
```

Review: Test-and-Set

```
AtomicBoolean lock
 = new AtomicBoolean(false)
…
boolean prior = lock.getAndSet(true)
```

Swapping in true is called "test-and-set" or TAS

Test-and-Set Locks

- Locking
  - Lock is free: value is false
  - Lock is taken: value is true
- Acquire lock by calling TAS
  - If result is false, you win
  - If result is true, you lose
- Release lock by writing false

Test-and-set Lock

```
class TASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

 void lock() {
  while (state.getAndSet(true)) {}
 }

 void unlock() {
  state.set(false);
 }}
```

Test-and-set Lock

```
class TASlock {
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 void unlock() {

 }}
```

Lock state is AtomicBoolean

Test-and-set Lock

```
class TASlock {
 AtomicBoolean state =
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 void lock() {
  while (state.getAndSet(true)) {}
 }

 void unlock() {
```

Keep trying until lock acquired

```
 }}
```

Test-and-set Lock

```
class TA
 AtomicB
  new At

 void lock() {
  while (state.getAndSet(true)) {}
 }

 void unlock() {
  state.set(false);
 }}
```

Release lock by resetting state to false

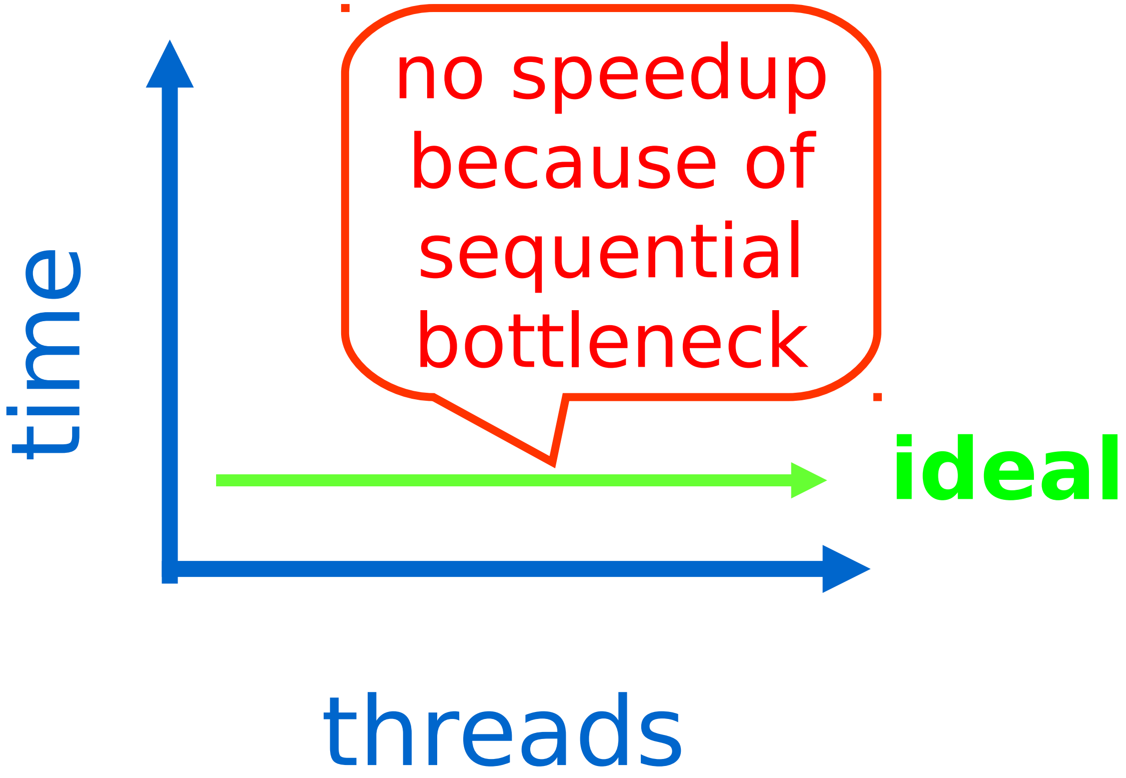
Space Complexity

- TAS spin-lock has small "footprint"
- N thread spin-lock uses O(1) space
- As opposed to O(n) Peterson/Bakery
- How did we overcome the $\Omega(n)$ lower bound?
- We used a RMW operation…

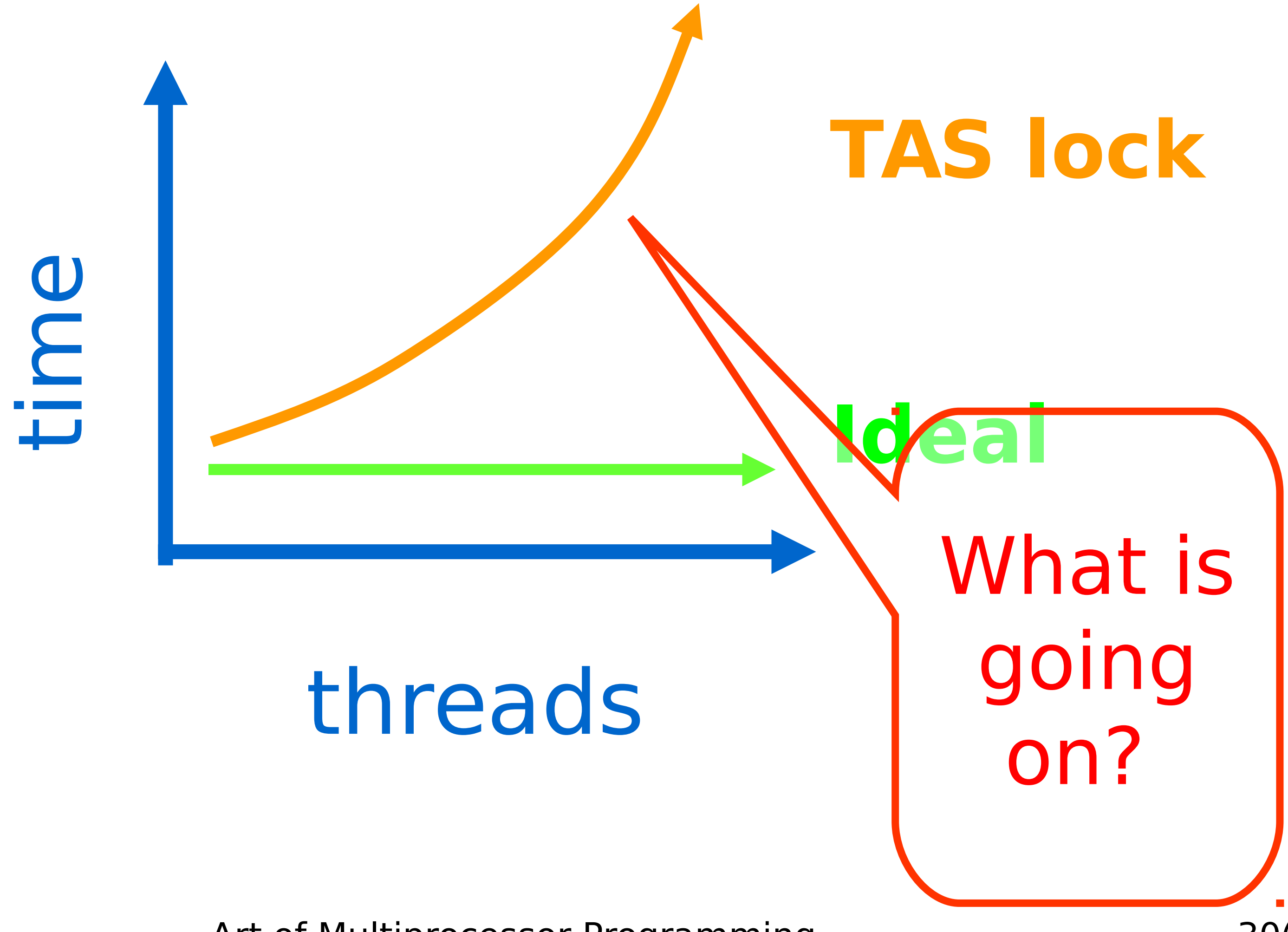
Performance

- Experiment
  - n threads
  - Increment shared counter 1 million times
- How long should it take?
- How long does it take?

Graph


no speedup because of sequential bottleneck
ideal
time
threads

Mystery #1



Test-and-Test-and-Set Locks

- Lurking stage
  - Wait until lock “looks” free
  - Spin while read returns true (lock taken)
- Pouncing state
  - As soon as lock “looks” available
  - Read returns false (lock free)
  - Call TAS to acquire lock
  - If TAS loses, back to lurking

Test-and-test-and-set Lock

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class TTASlock {
 AtomicBoolean state =
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 void lock() {
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Test-and-test-and-set Lock

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Wait until lock looks free

Test-and-test-and-set Lock

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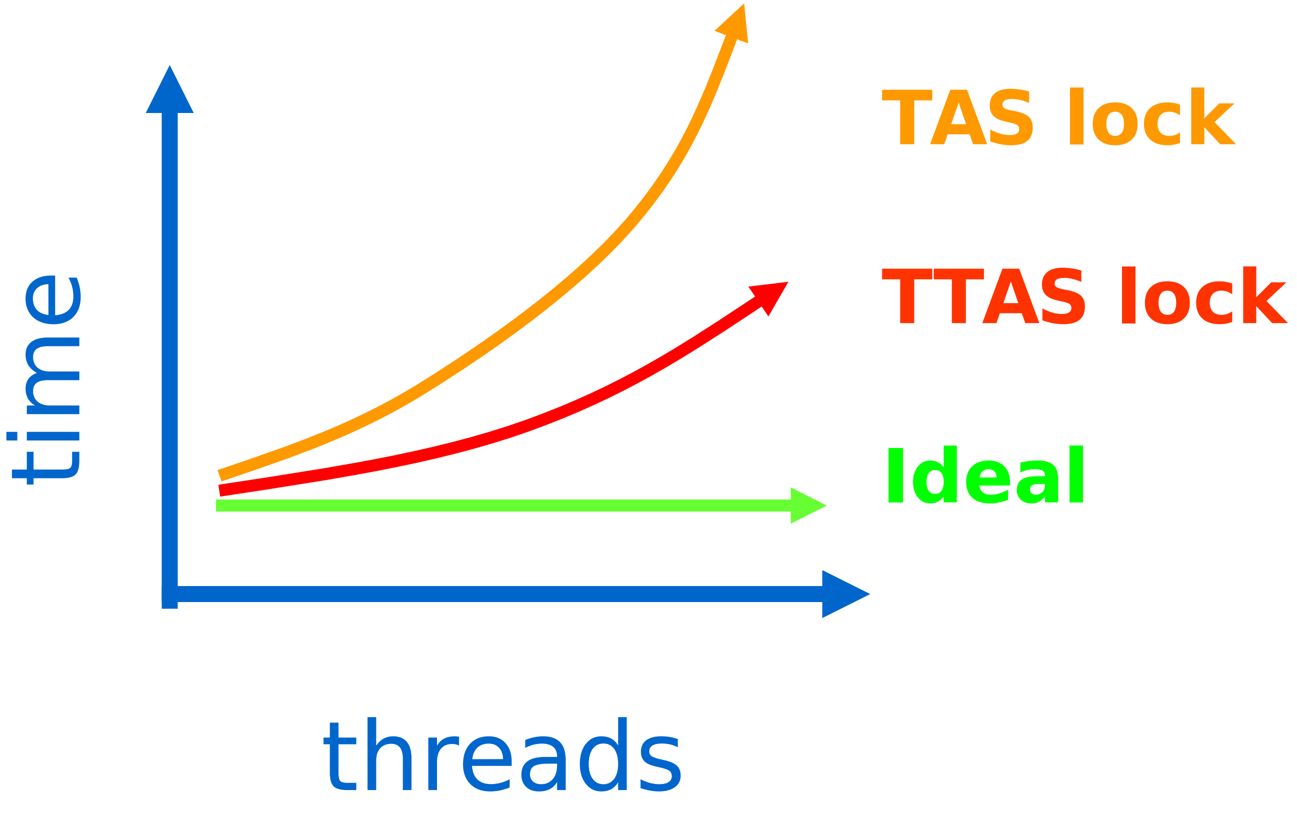
class TTASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

 void lock() {
  while (true) {
   while (state.get()) {}
   if (!state.getAndSet(true))
    return;
 }
}
```

Then try to acquire it

Mystery #2



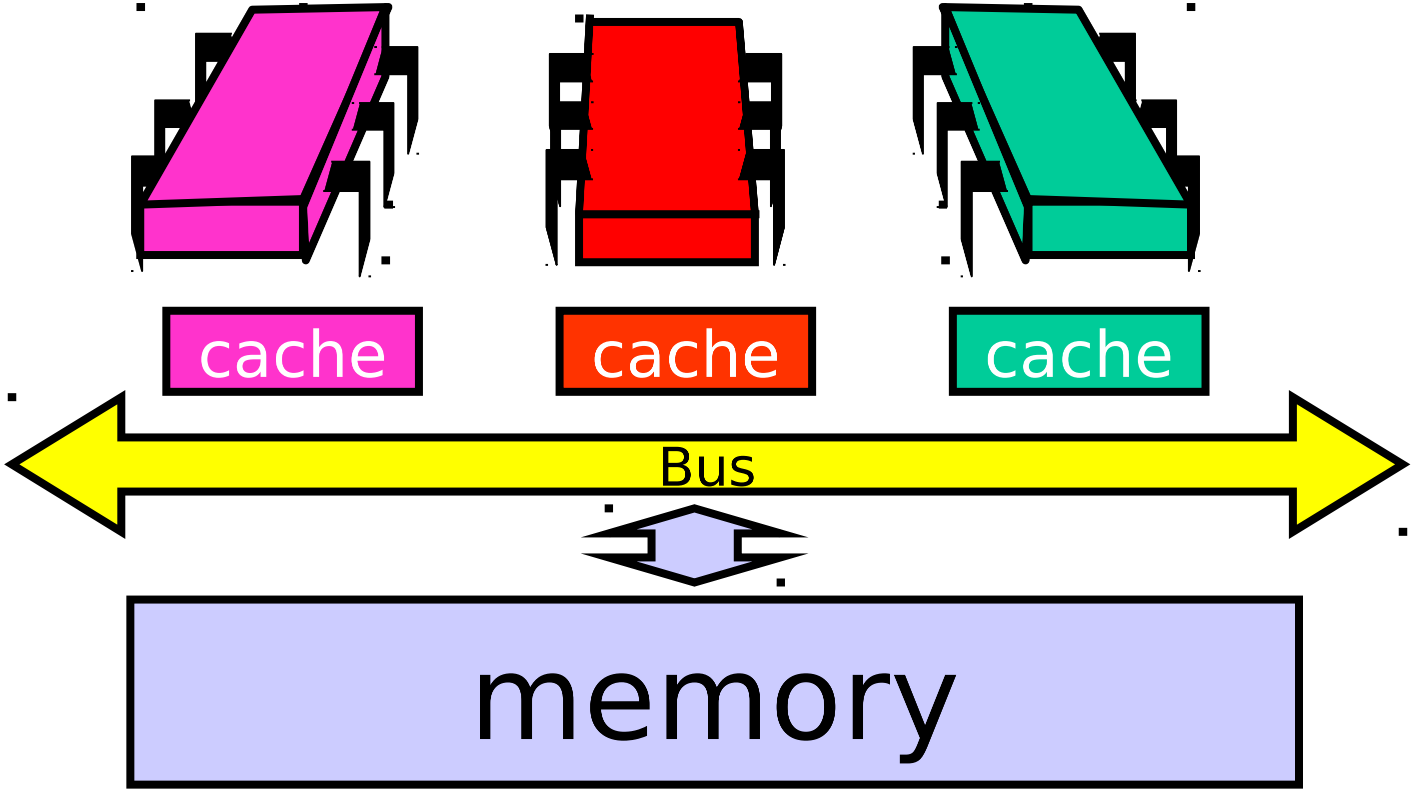
Mystery

- Both
  - TAS and TTAS
  - Do the same thing (in our model)
- Except that
  - TTAS performs much better than TAS
  - Neither approaches ideal

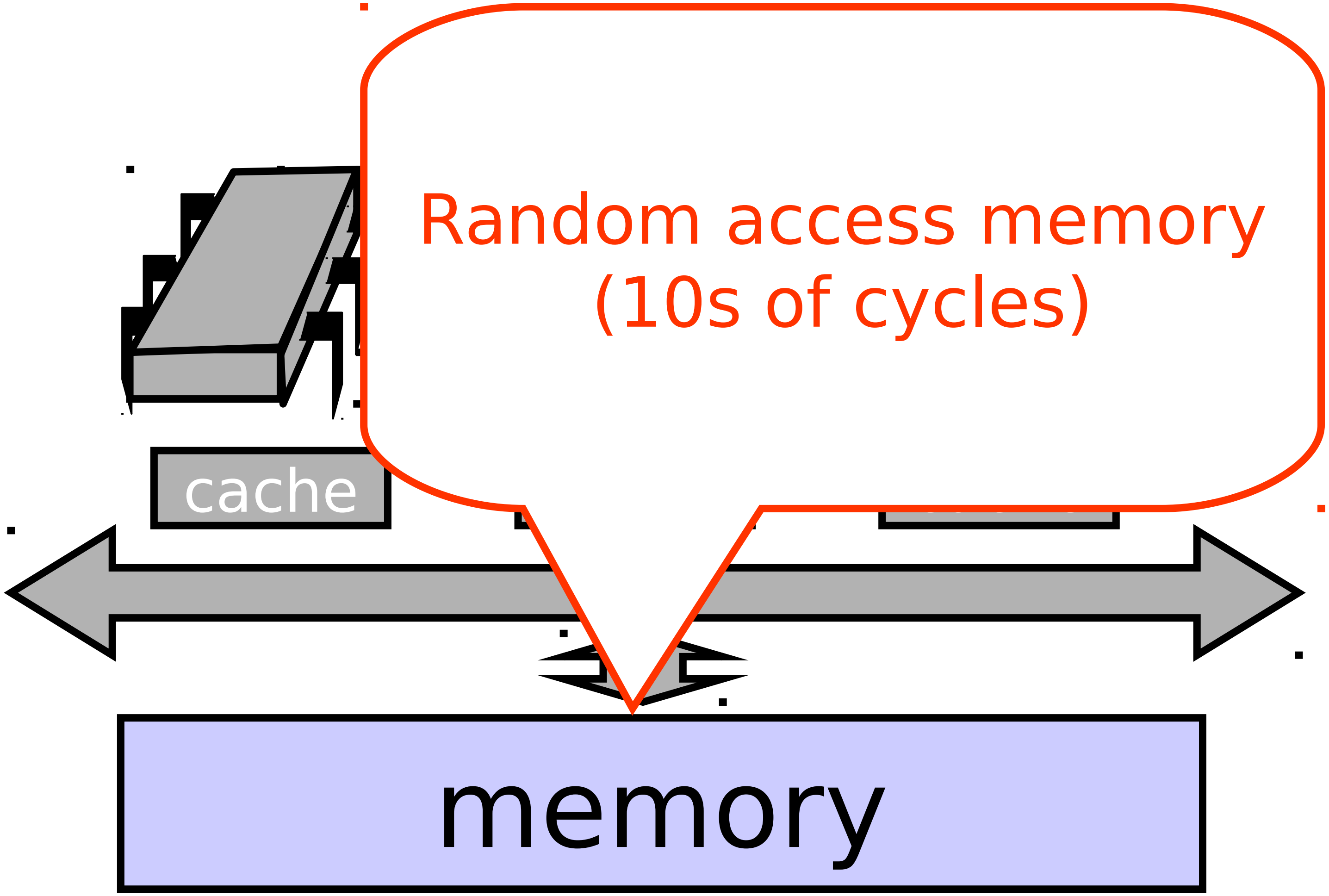
Opinion

- Our memory abstraction is broken
- TAS & TTAS methods
  - Are provably the same (in our model)
  - Except they aren't (in field tests)
- Need a more detailed model …

Bus-Based Architectures



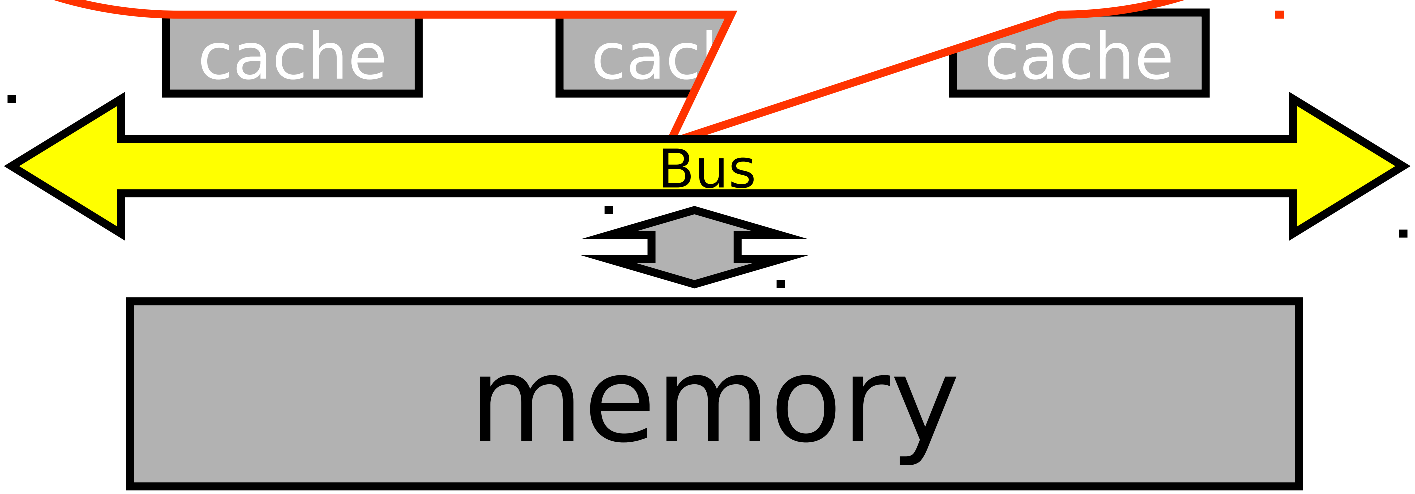
Bus-Based Architectures



Bus-Based Architectures

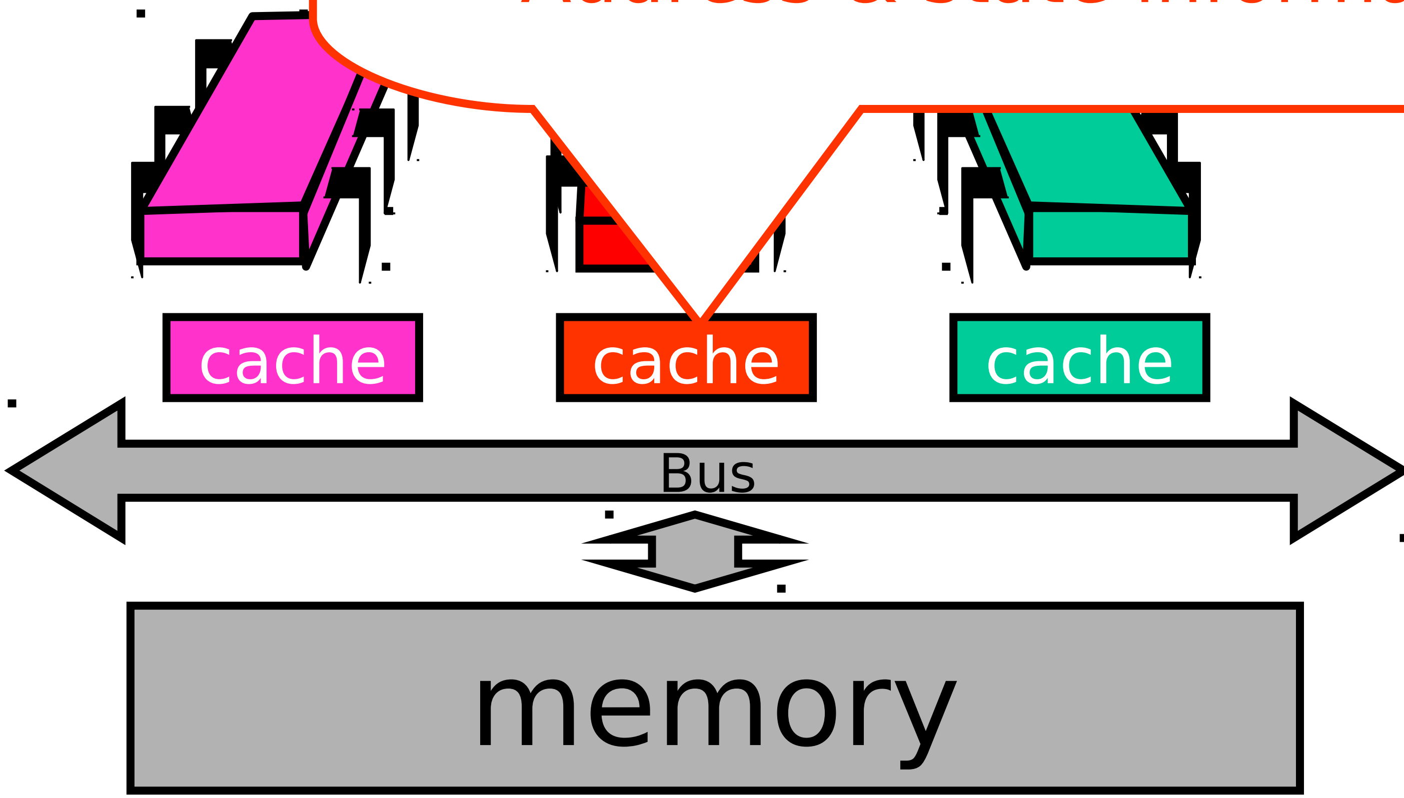
Shared Bus

- Broadcast medium
- One broadcaster at a time
- Processors and memory all "snoop"



Bus-B

Per-Processor Caches
- Small
- Fast: 1 or 2 cycles
- Address & state information



Jargon Watch

- Cache hit
  - "I found what I wanted in my cache"
  - Good Thing™

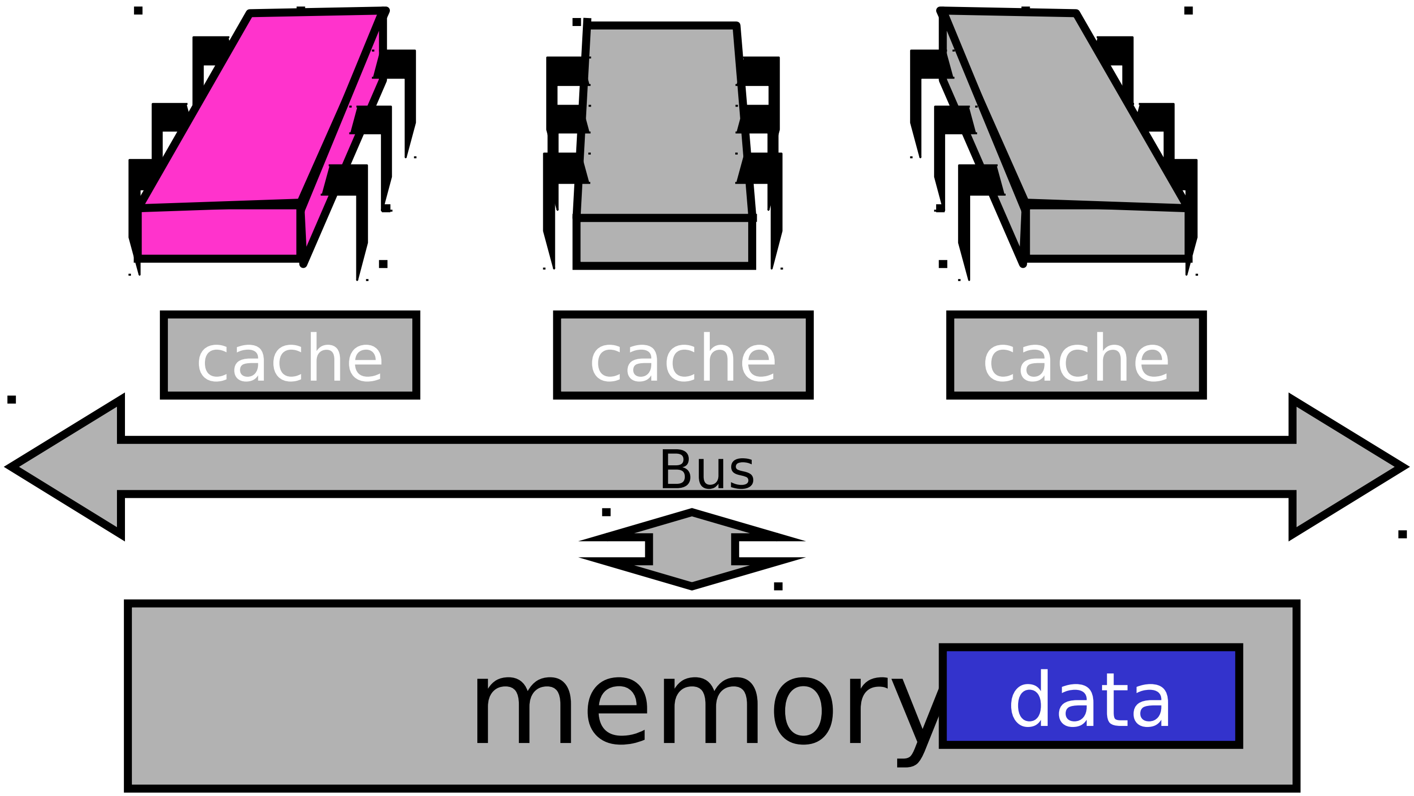
Jargon Watch

- Cache hit
  - "I found what I wanted in my cache"
  - Good Thing™
- Cache miss
  - "I had to shlep all the way to memory for that data"
  - Bad Thing™

Cave Canem

- This model is still a simplification
  - But not in any essential way
  - Illustrates basic principles
- Will discuss complexities later

Processor Issues Load Request



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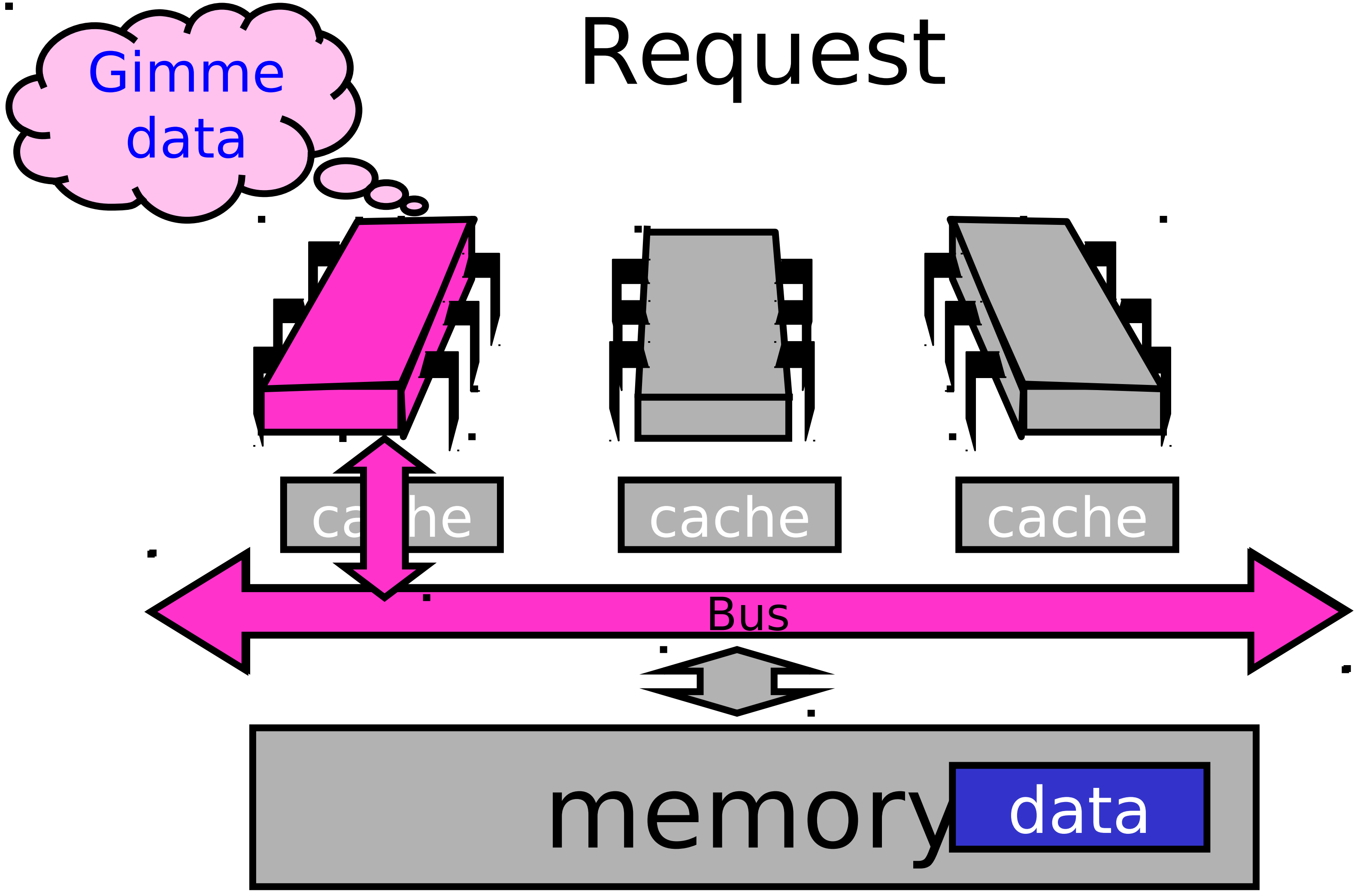
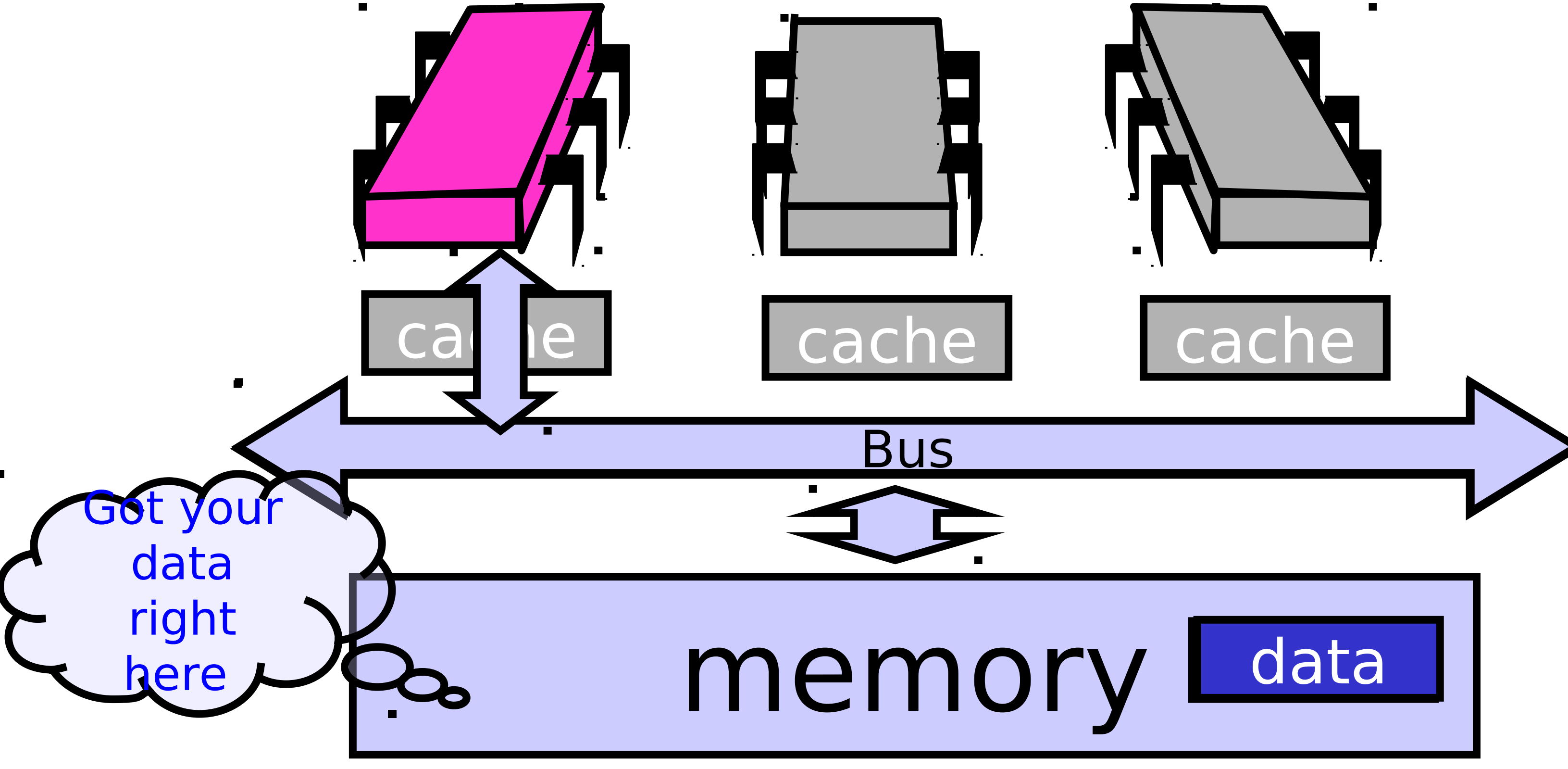


Memory Responds



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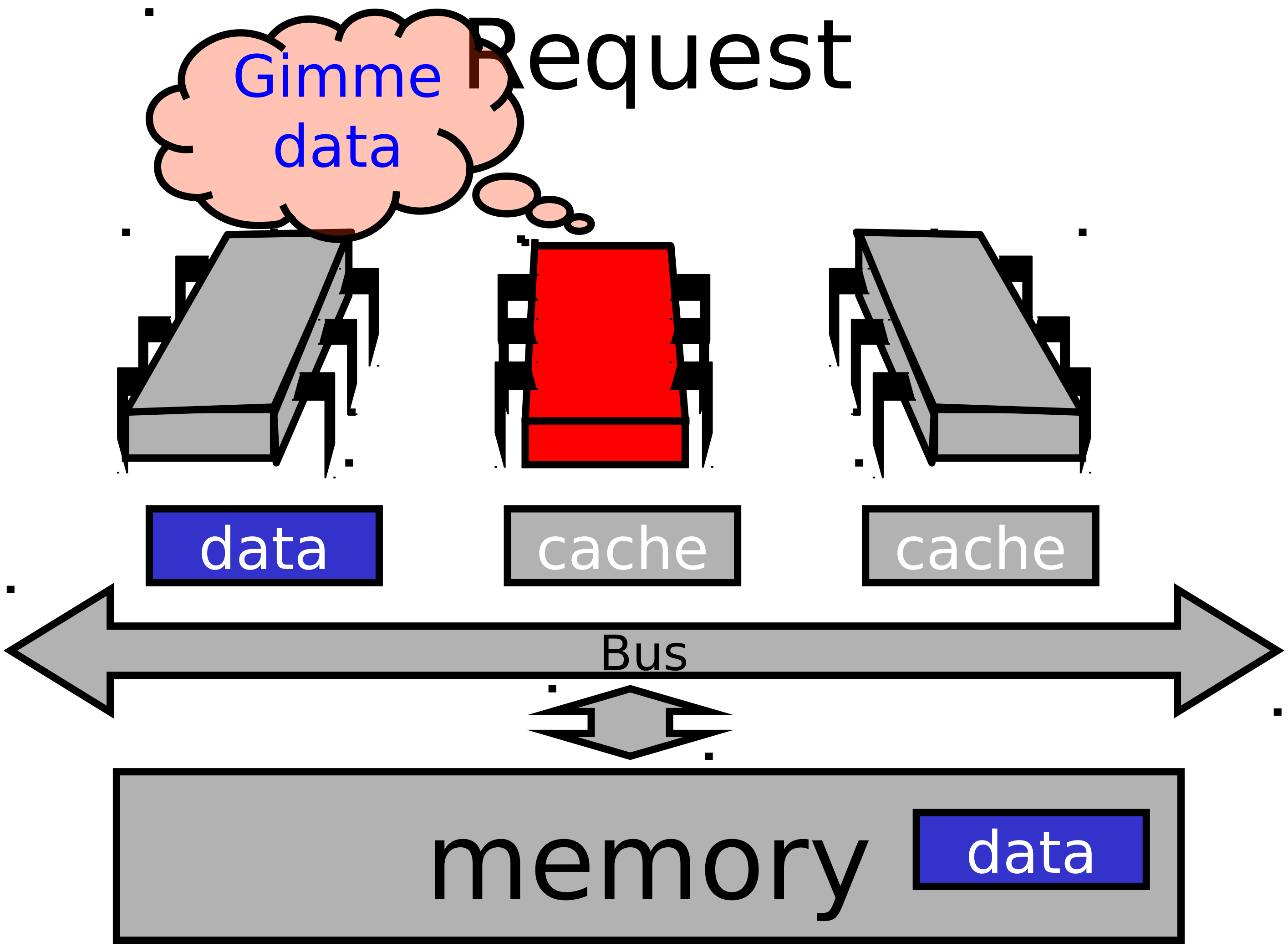

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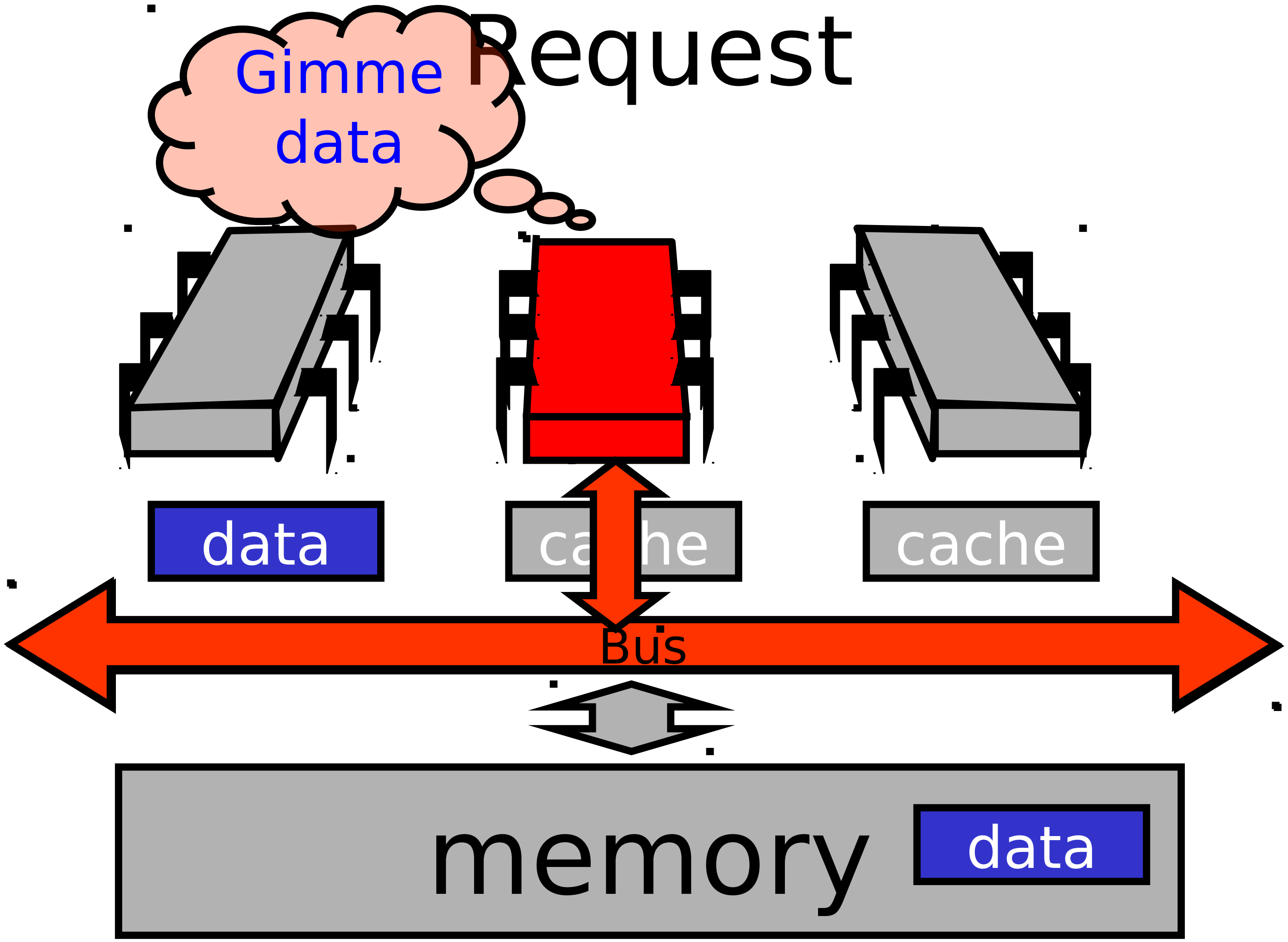

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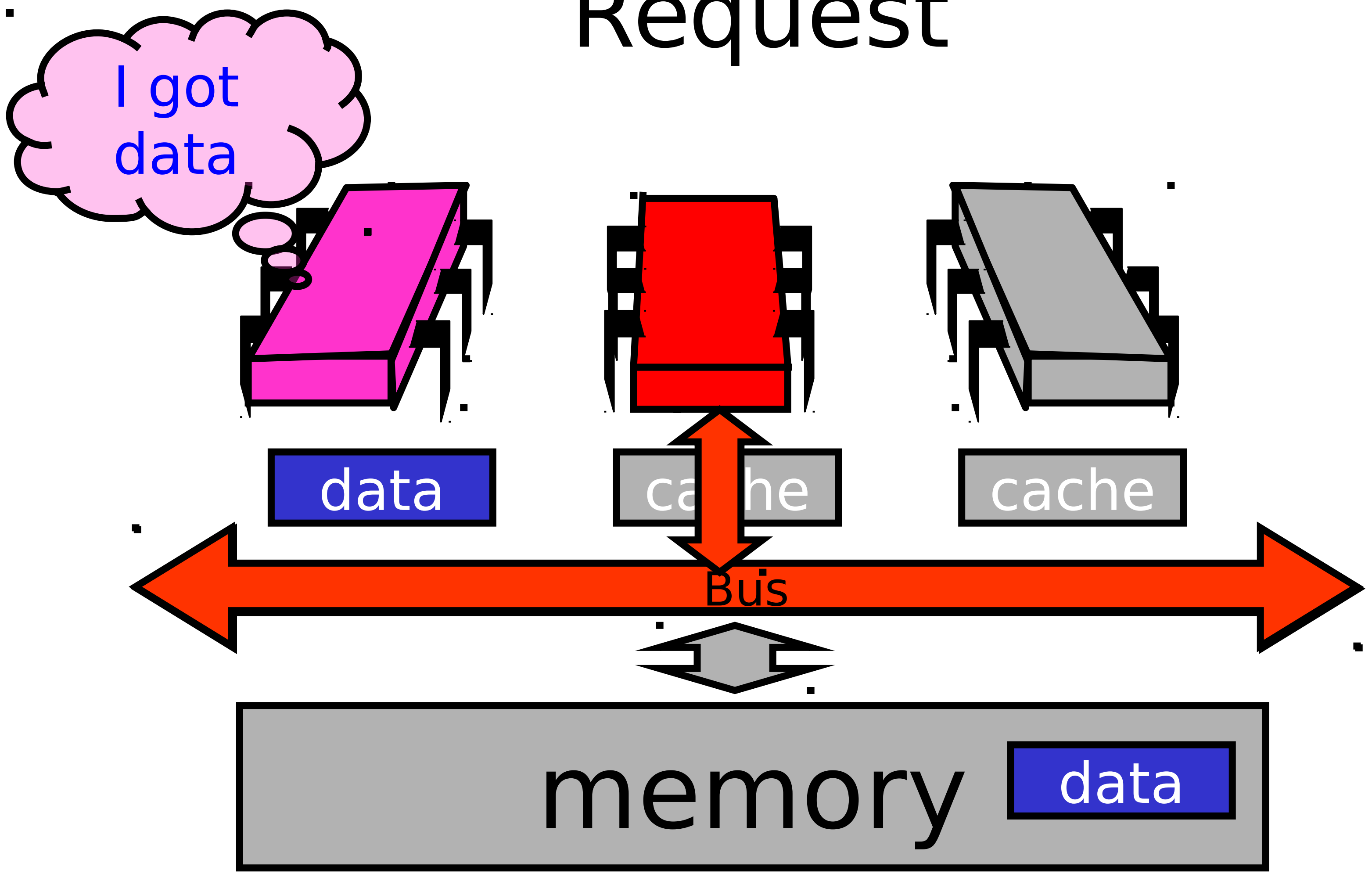
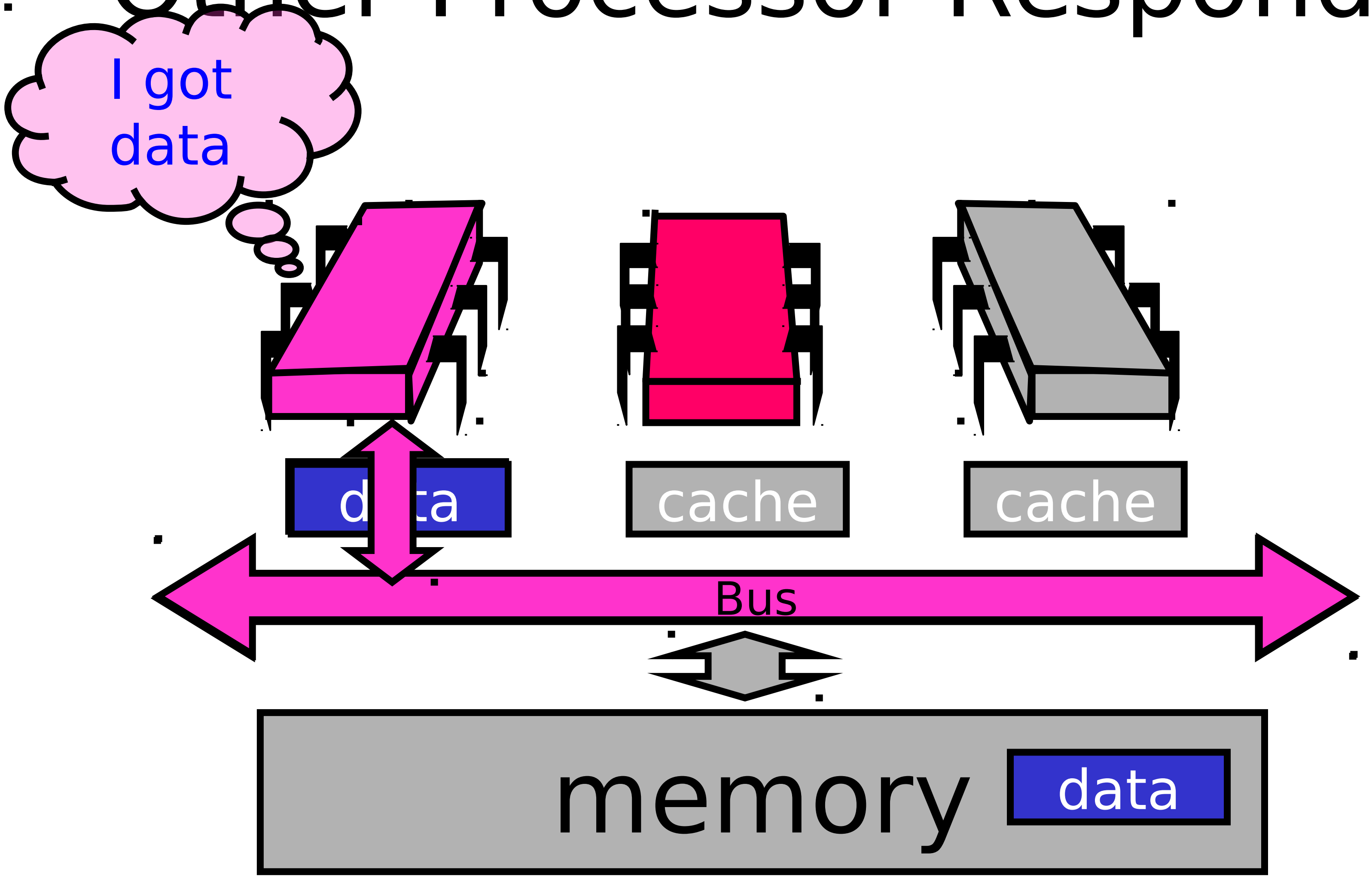


Other Processor Responds



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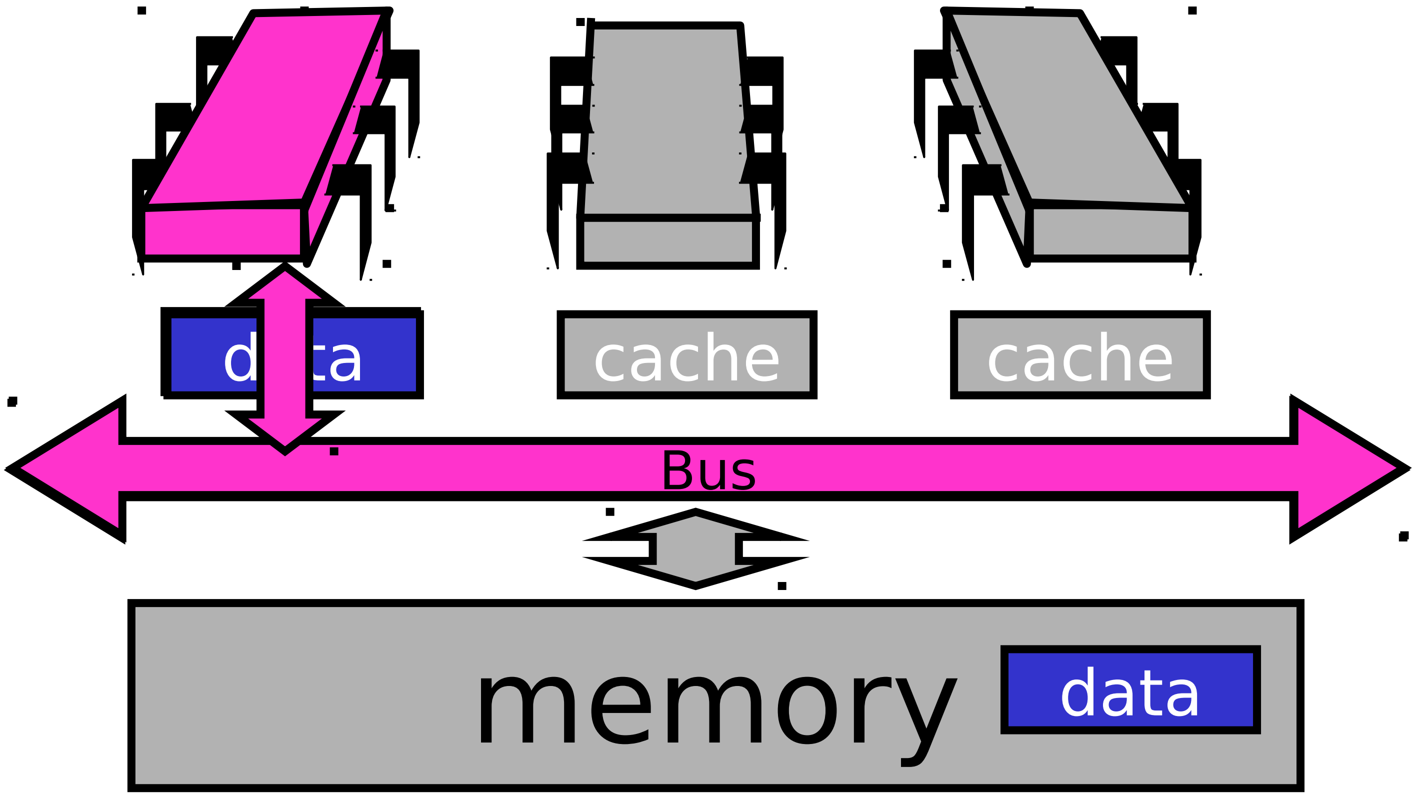
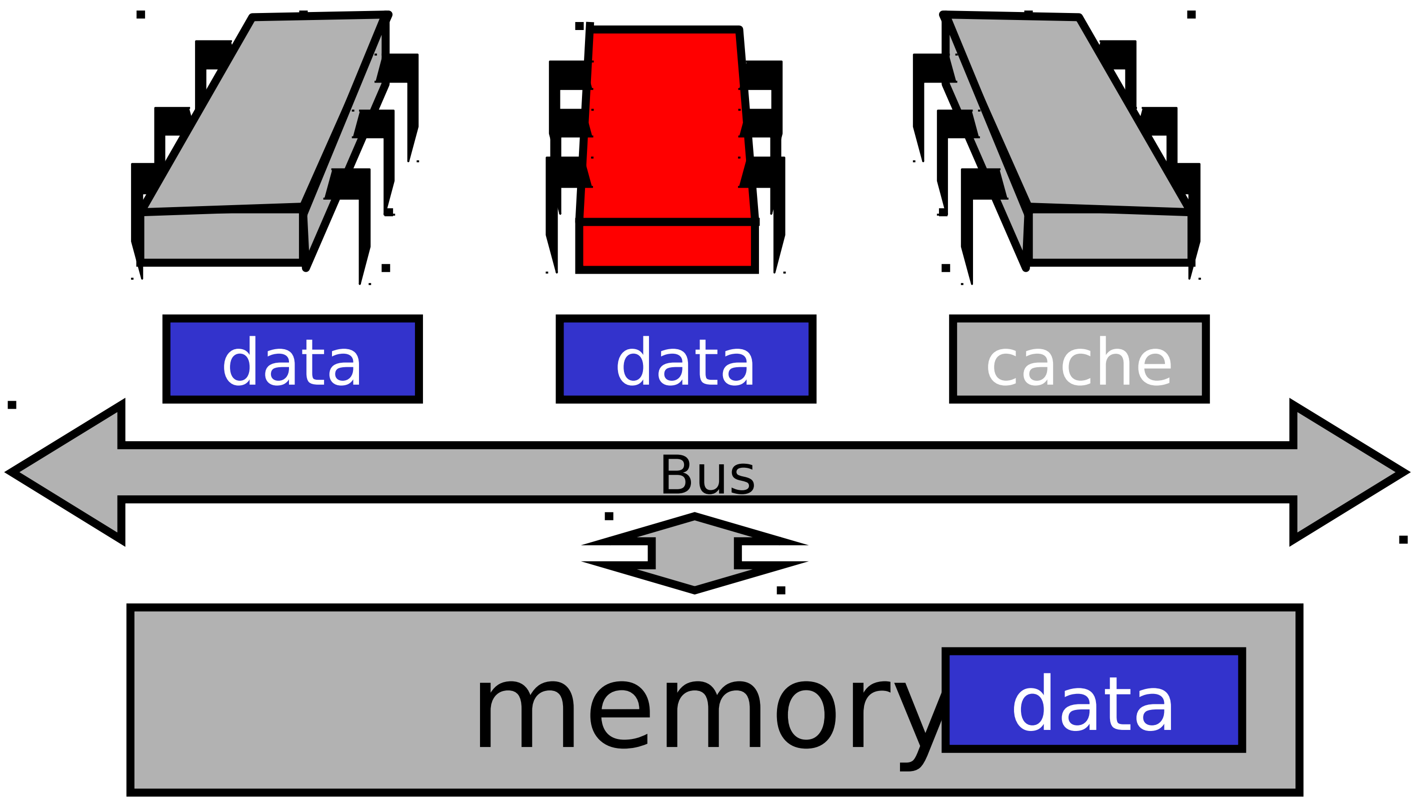


Modify Cached Data



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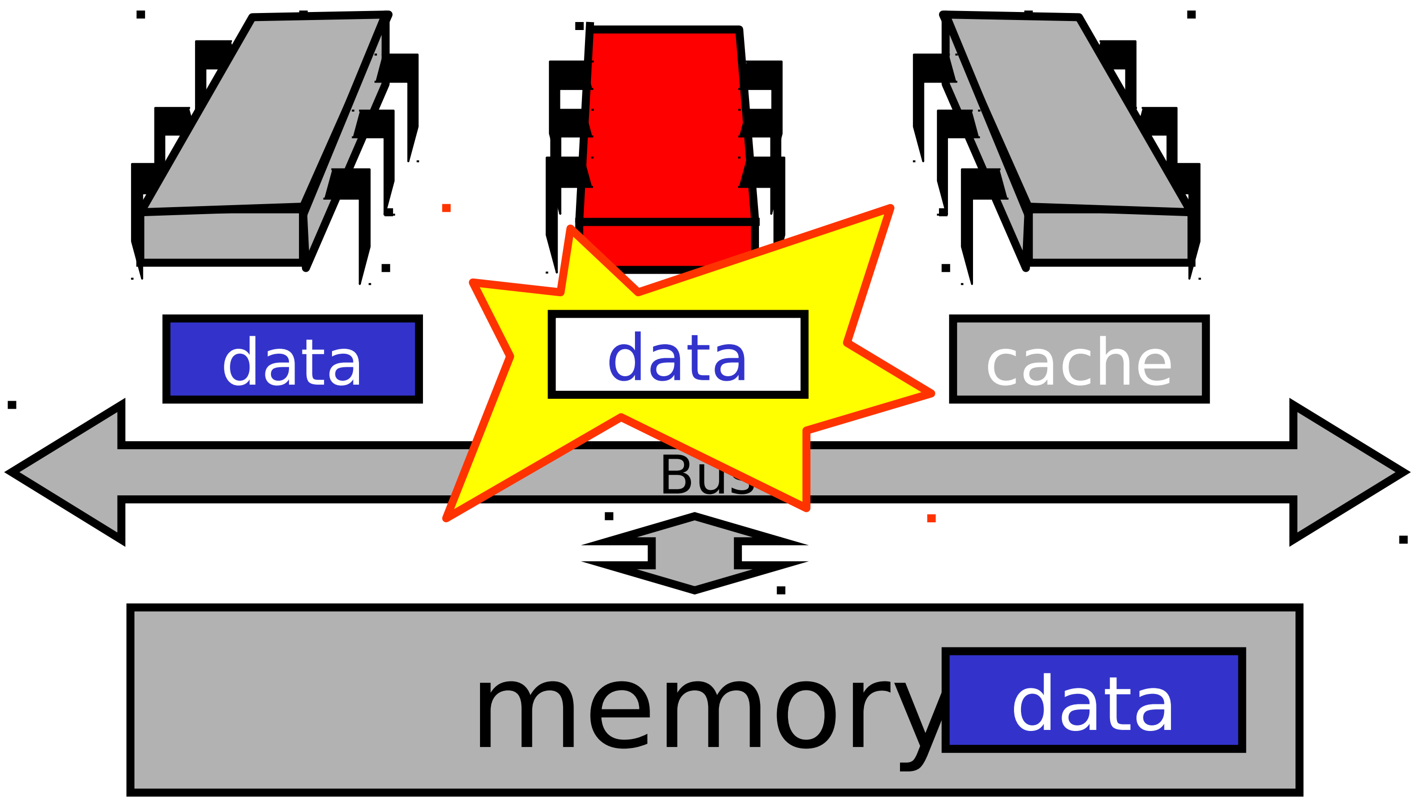

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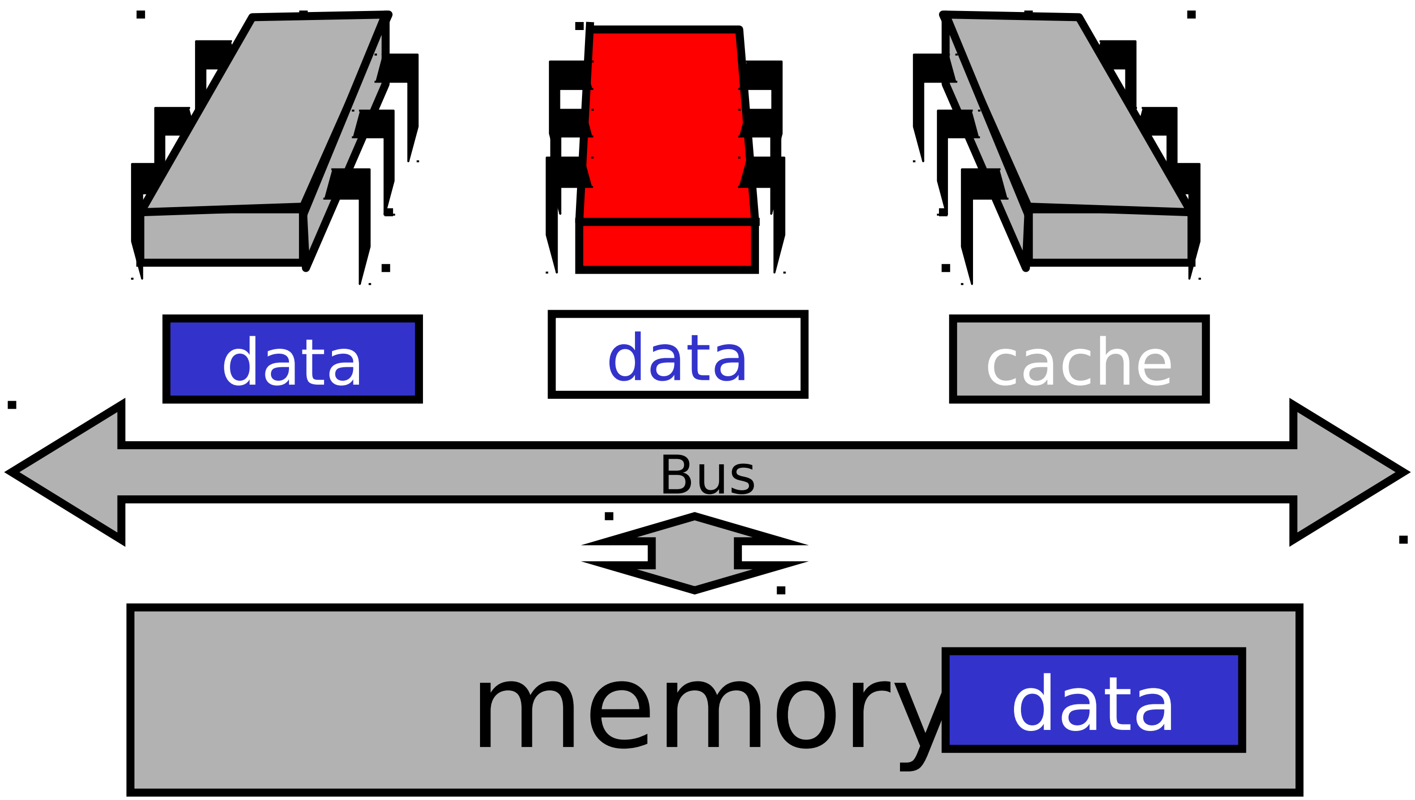

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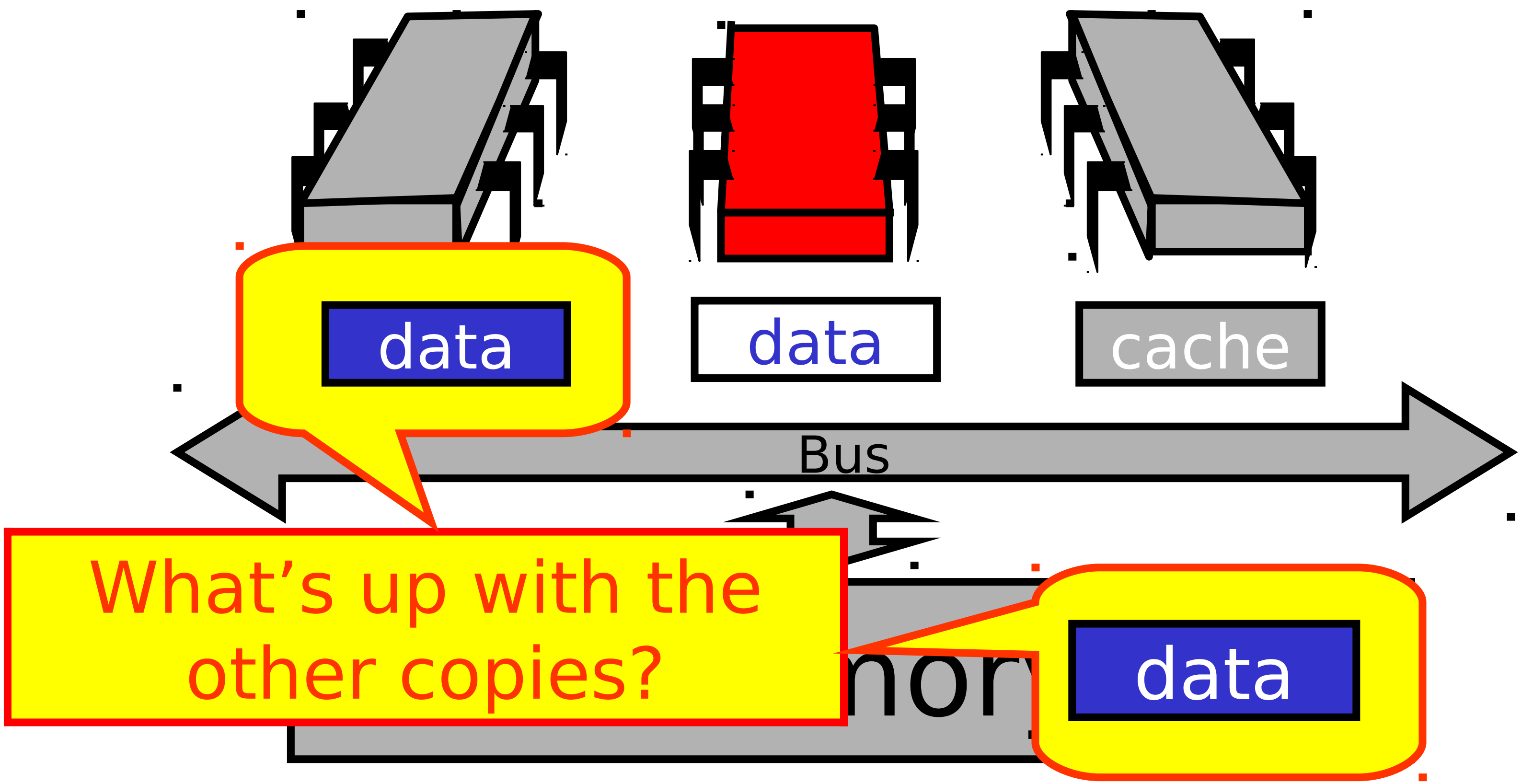


Cache Coherence

- We have lots of copies of data
  - Original copy in memory
  - Cached copies at processors
- Some processor modifies its own copy
  - What do we do with the others?
  - How to avoid confusion?

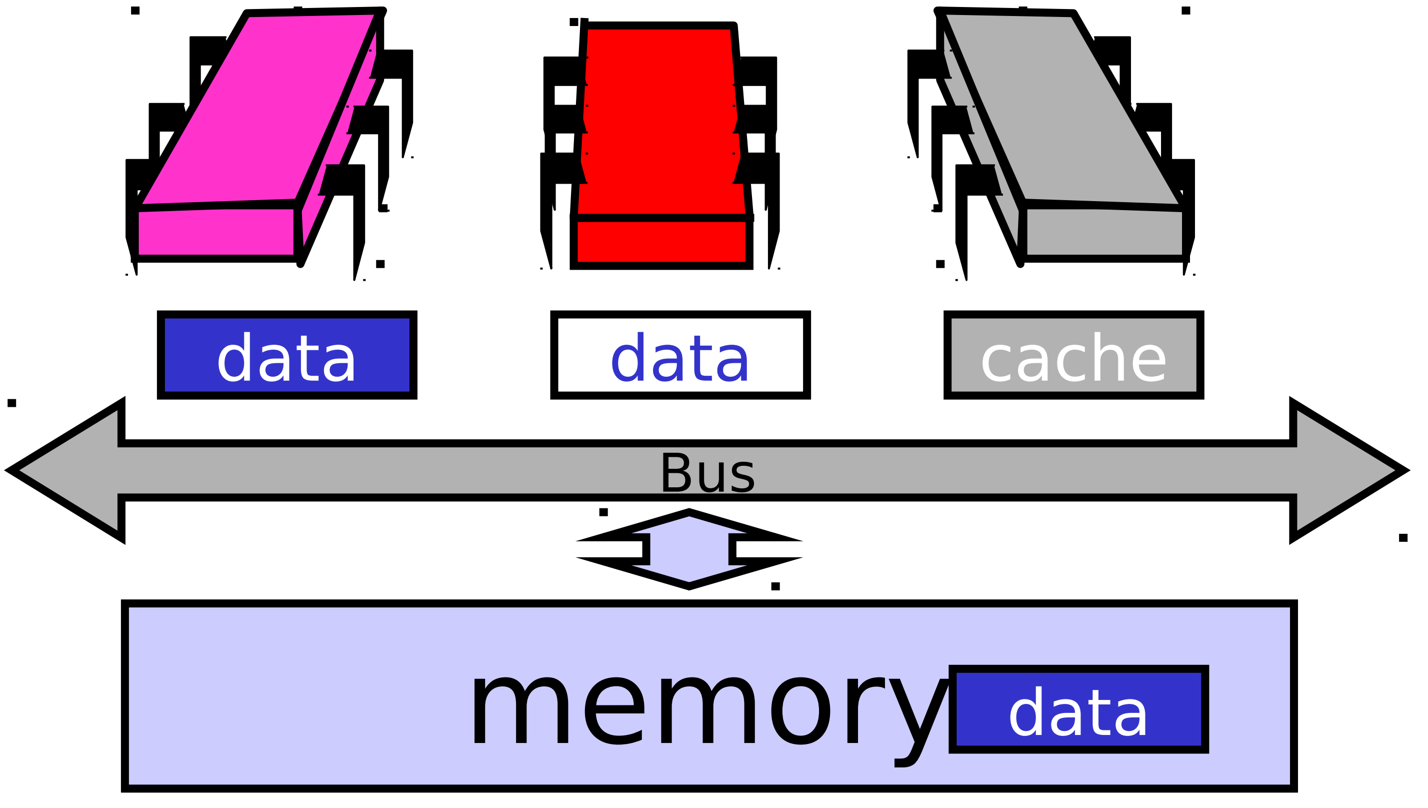
Write-Back Caches

- Accumulate changes in cache
- Write back when needed
  - Need the cache for something else
  - Another processor wants it
- On first modification
  - Invalidate other entries
  - Requires non-trivial protocol …

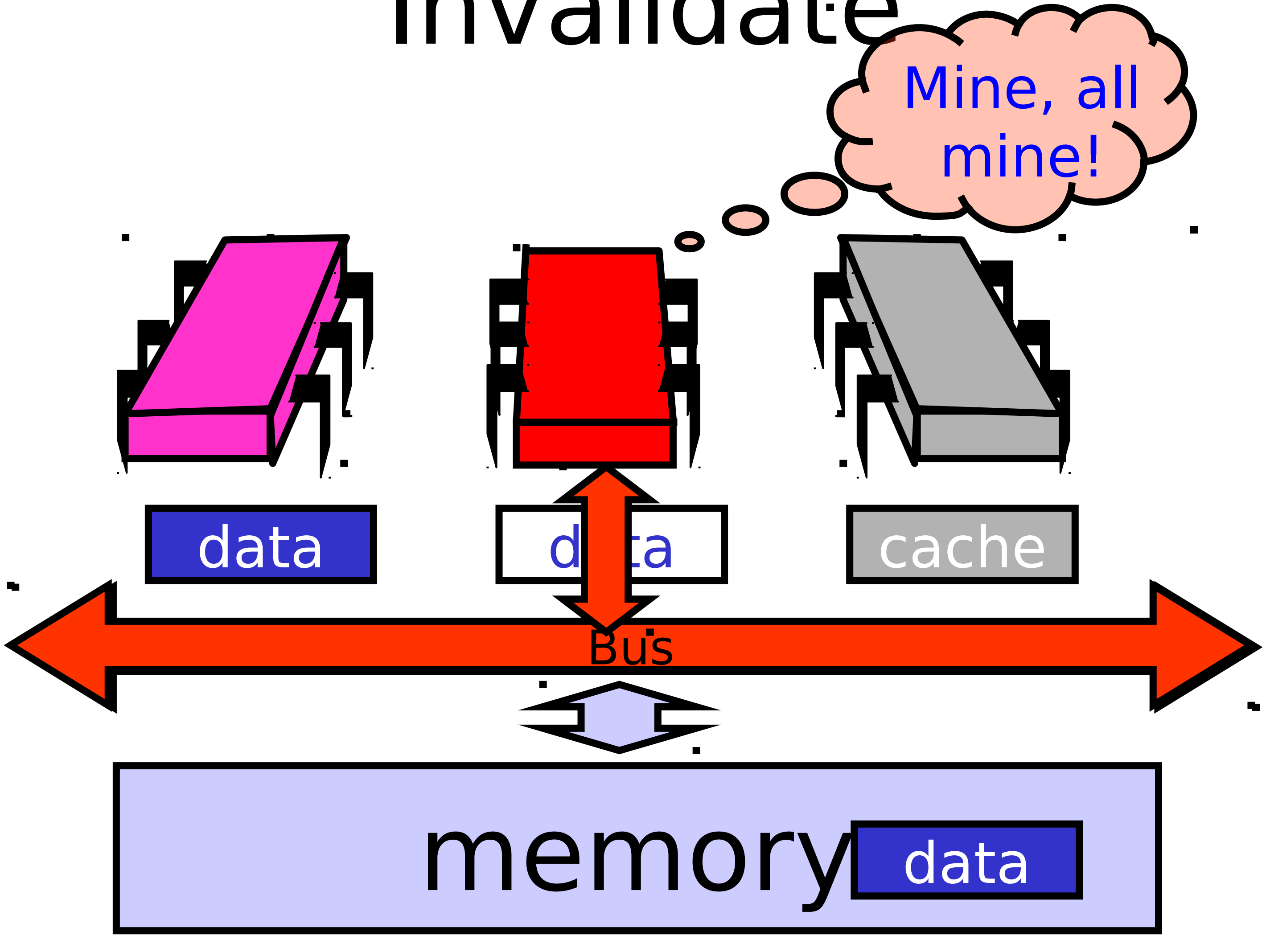
Write-Back Caches

- Cache entry has three states
  - Invalid: contains raw seething bits
  - Valid: I can read but I can't write
  - Dirty: Data has been modified
    - Intercept other load requests
    - Write back to memory before using cache

Invalidate



Invalidate



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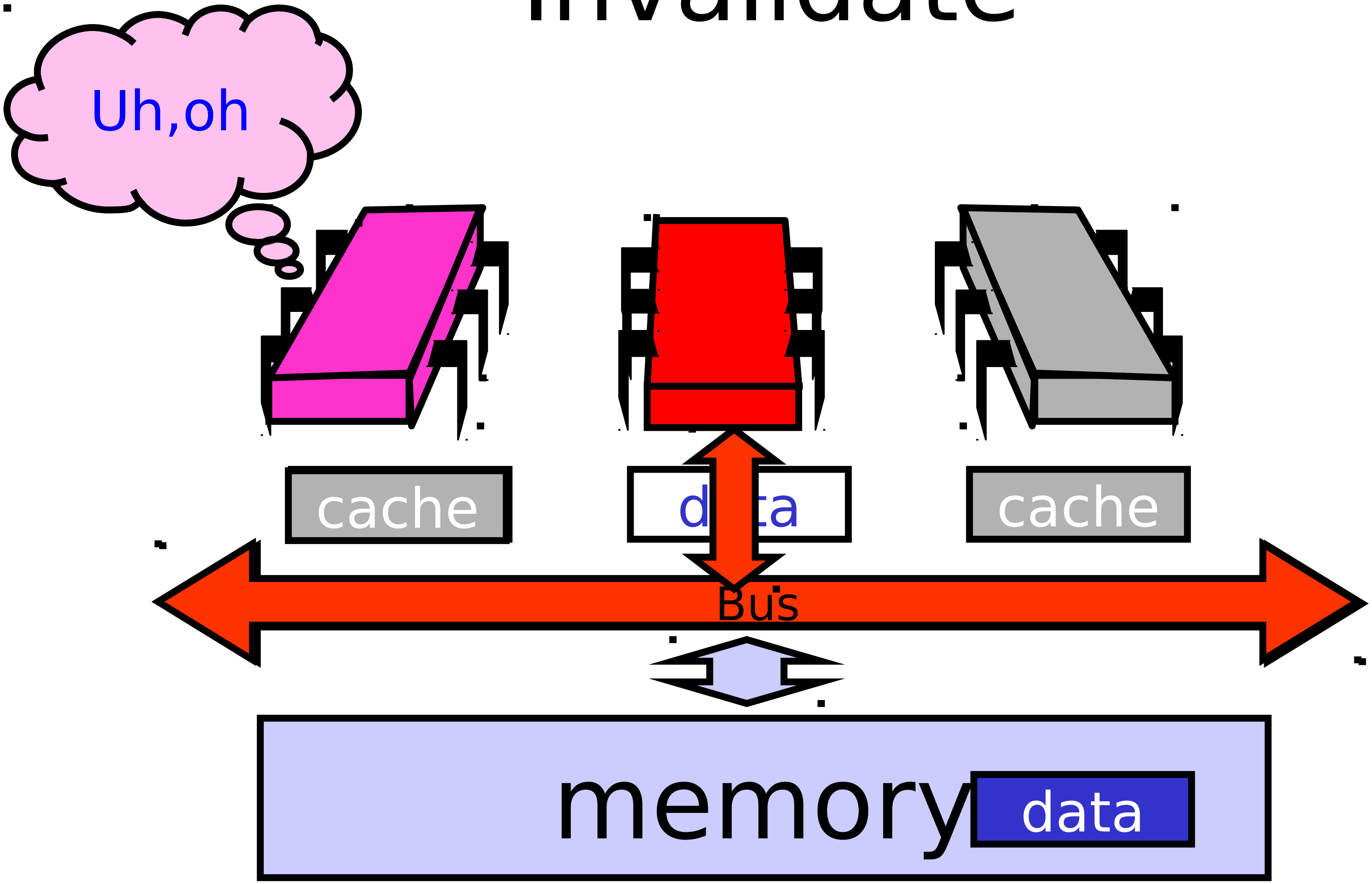

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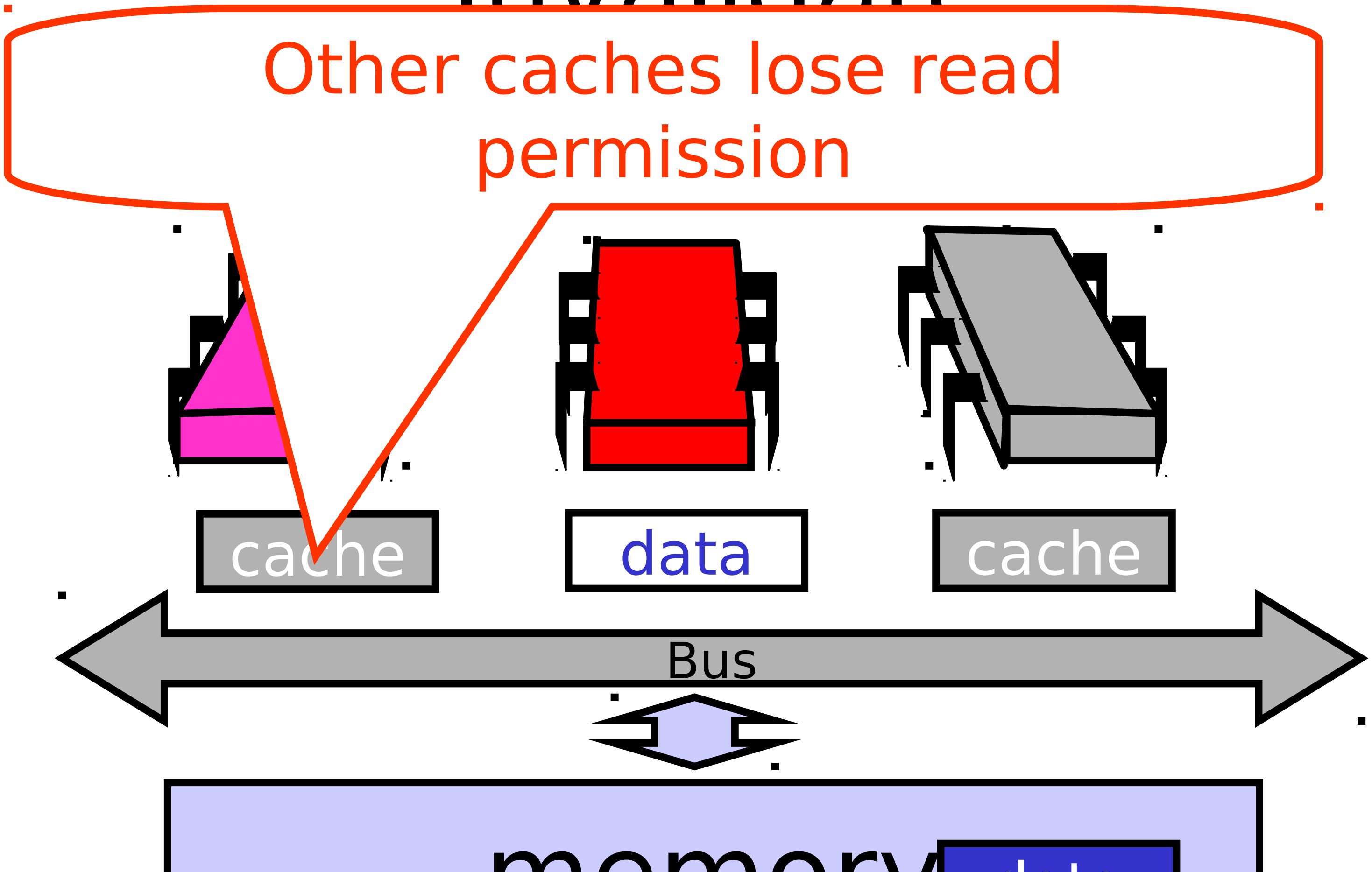
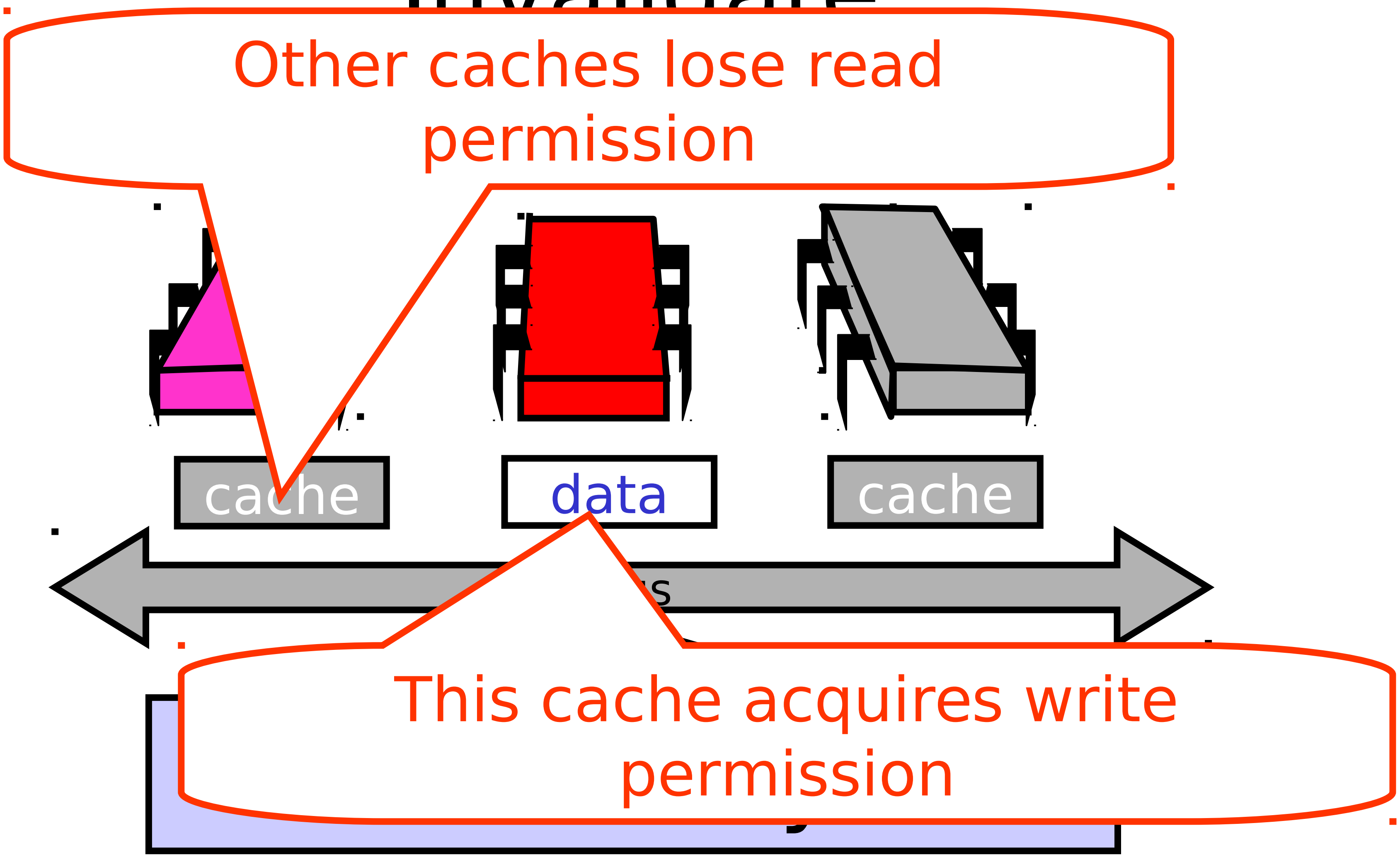
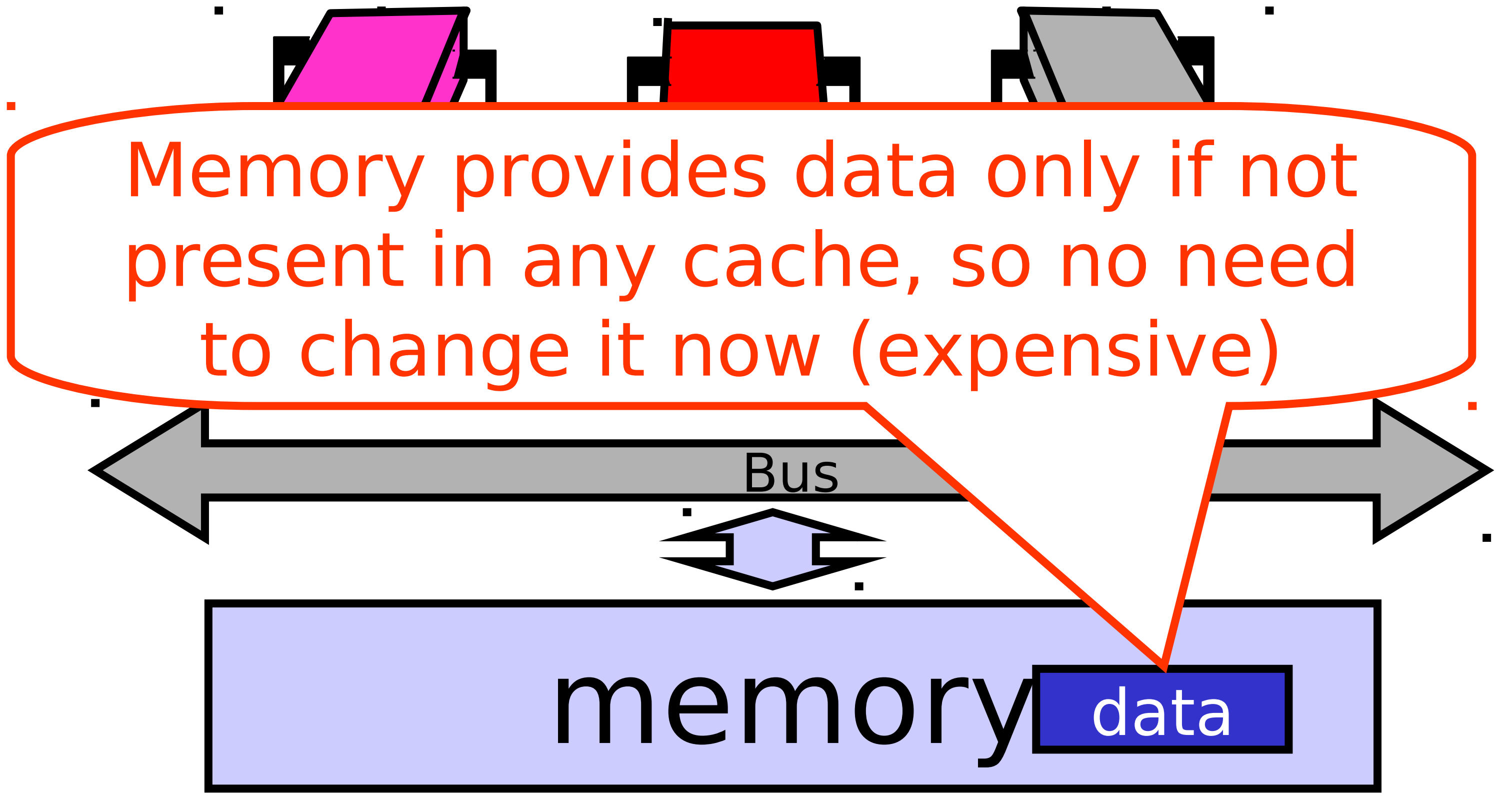

Other caches lose read permission
cache
data
cache
Bus
memory
data

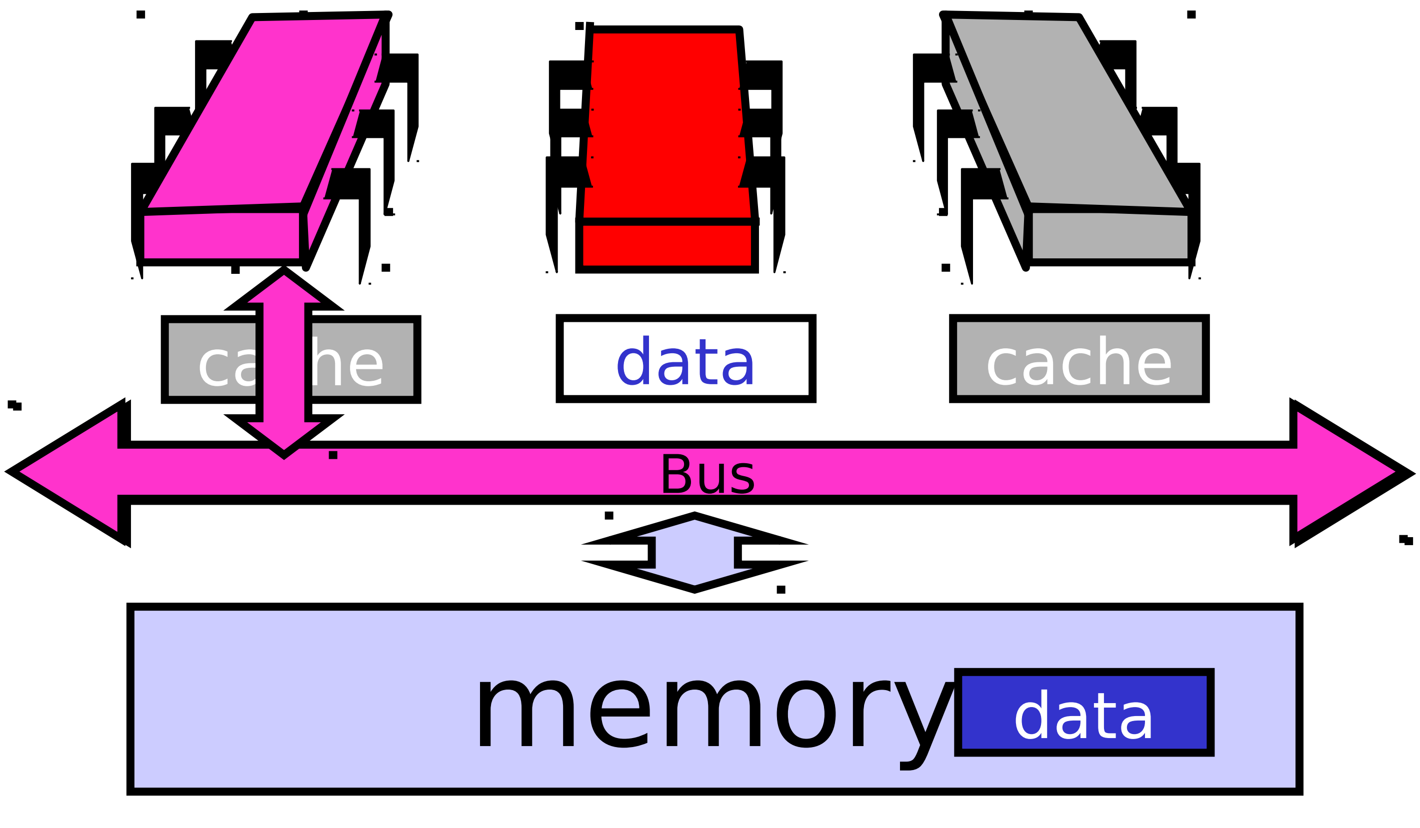
Invalidate


Other caches lose read permission
cache
data
cache
This cache acquires write permission

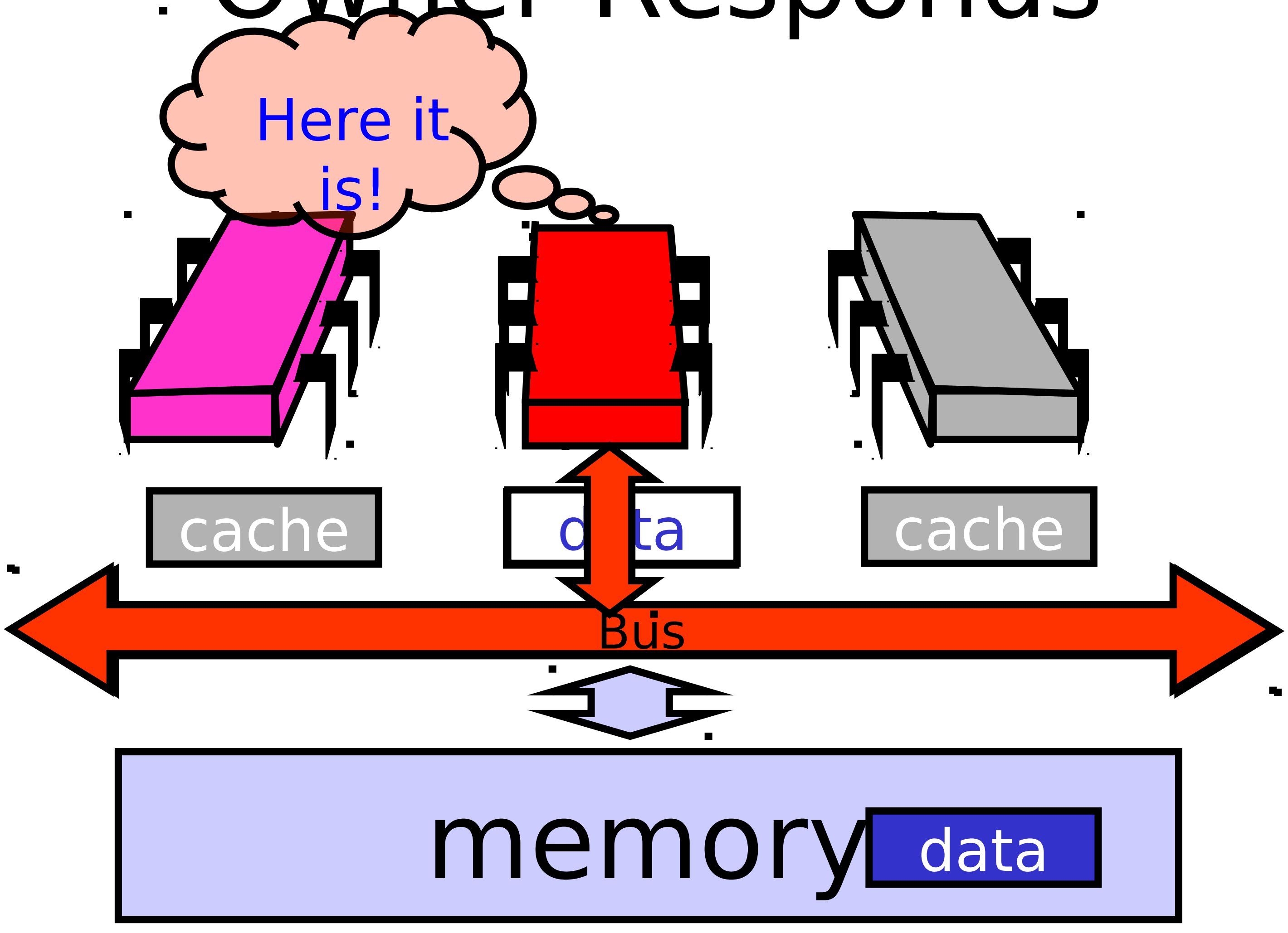
Invalidate


Memory provides data only if not present in any cache, so no need to change it now (expensive)
Bus
memory
data

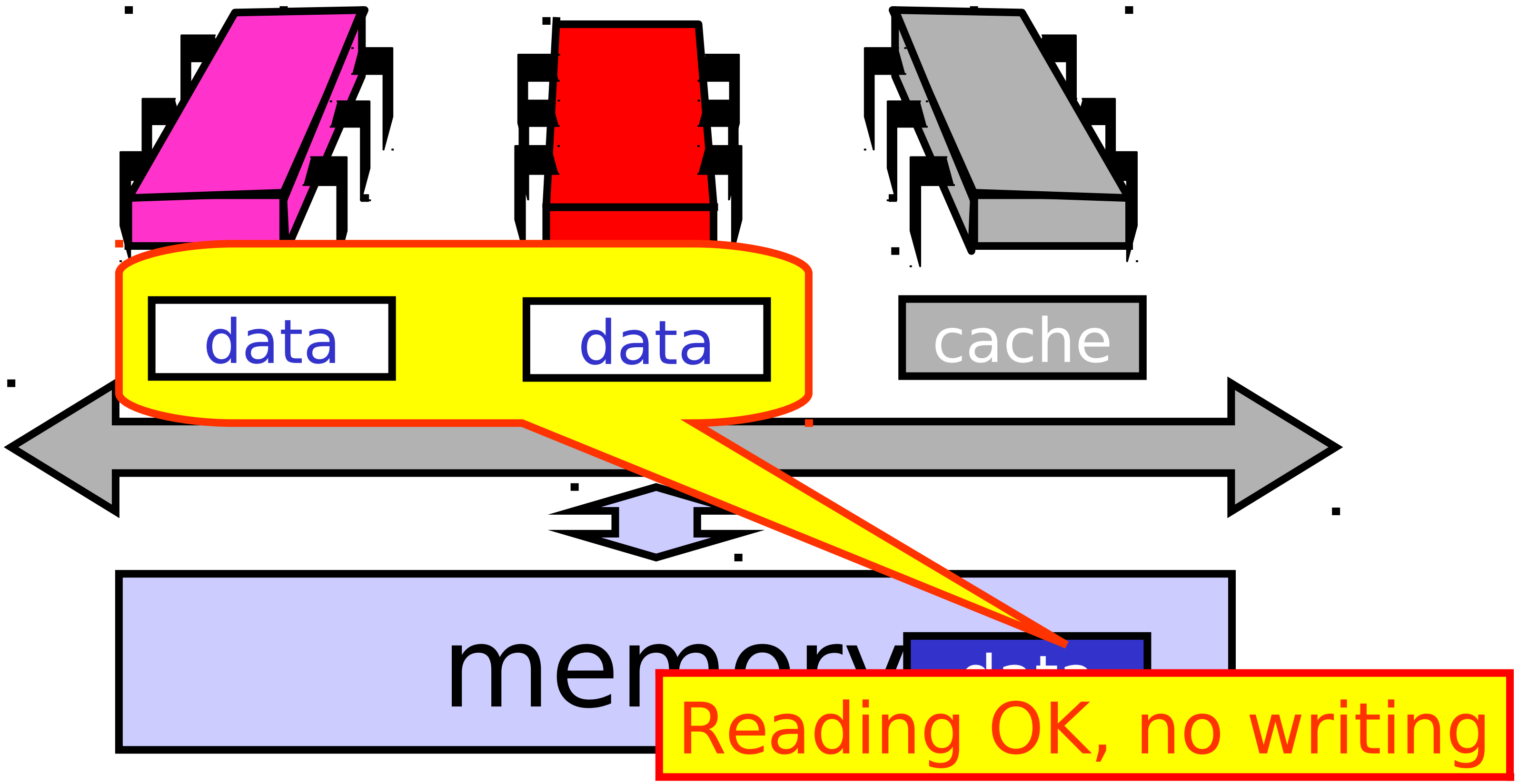
Another Processor Asks for Data



Owner Responds



End of the Day …



Mutual Exclusion

- What do we want to optimize?
  - Bus bandwidth used by spinning threads
  - Release/Acquire latency
  - Acquire latency for idle lock

Simple TASLock

- TAS invalidates cache lines
- Spinners
  - Miss in cache
  - Go to bus
- Thread wants to release lock
  - delayed behind spinners

Test-and-test-and-set

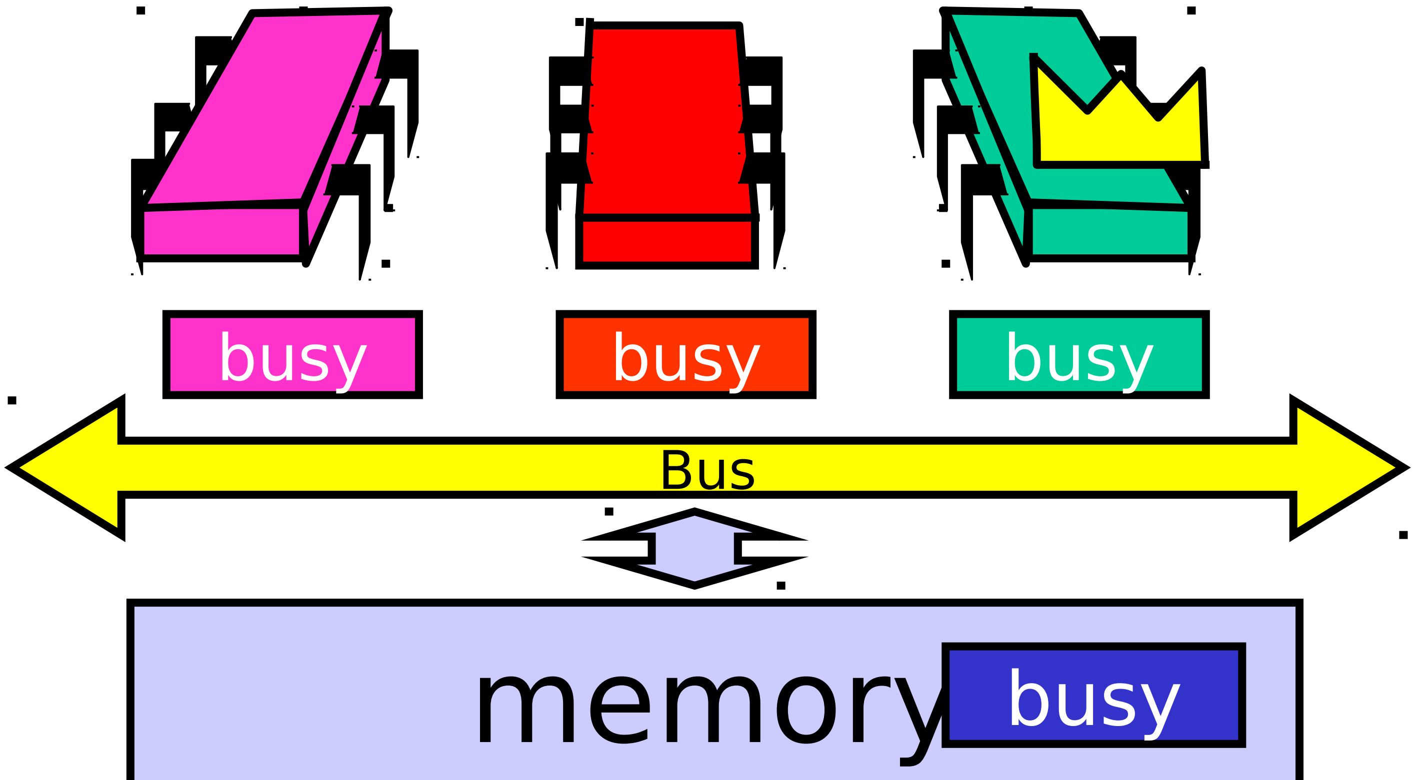
- Wait until lock “looks” free
  - Spin on local cache
  - No bus use while lock busy
- Problem: when lock is released
  - Invalidation storm …

Test-and-test-and-set Lock

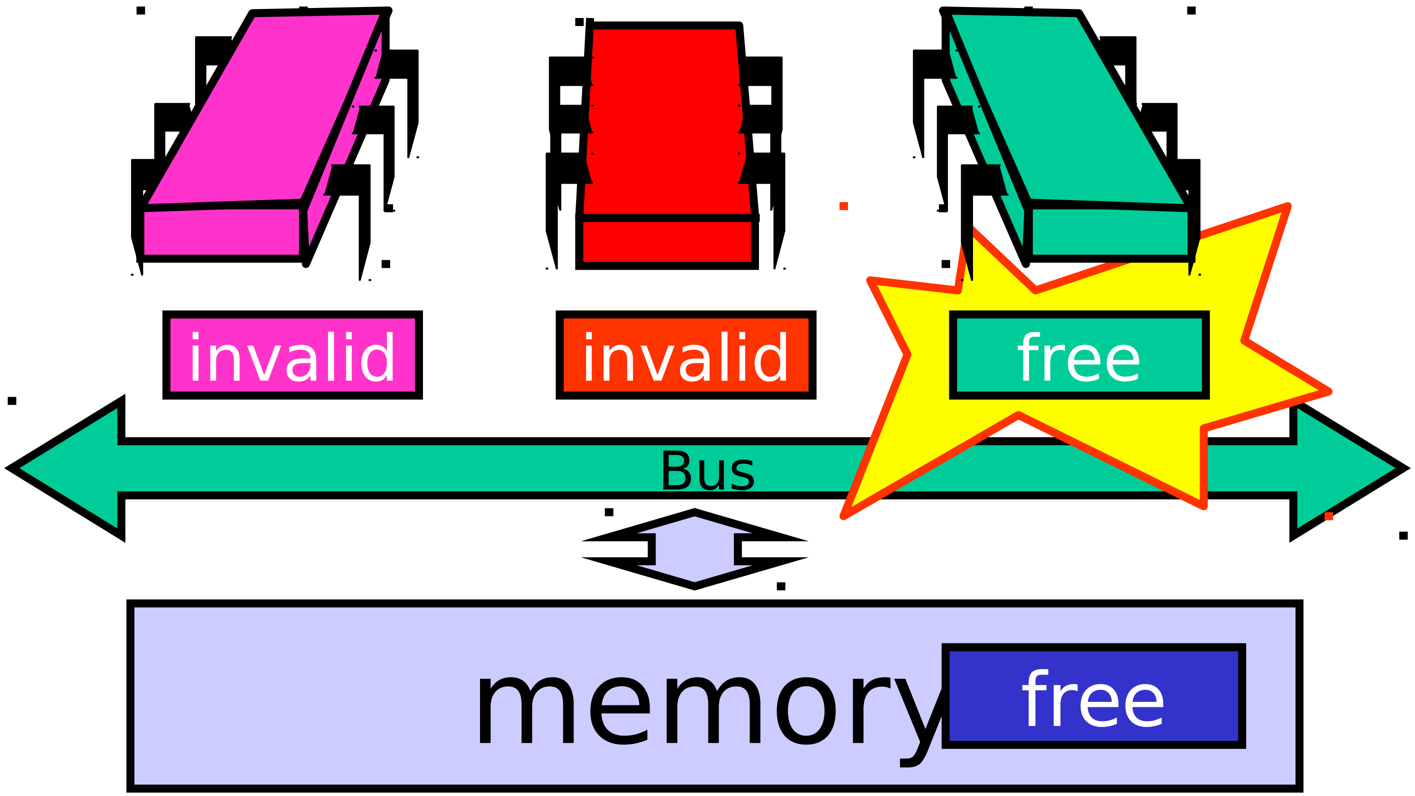
```
class TTASlock {
 AtomicBoolean state =
  new AtomicBoolean(false);

 void lock() {
  while (true) {
   while (state.get()) {}
   if (!state.getAndSet(true))
    return;
 }
}
```

Local Spinning while Lock is Busy

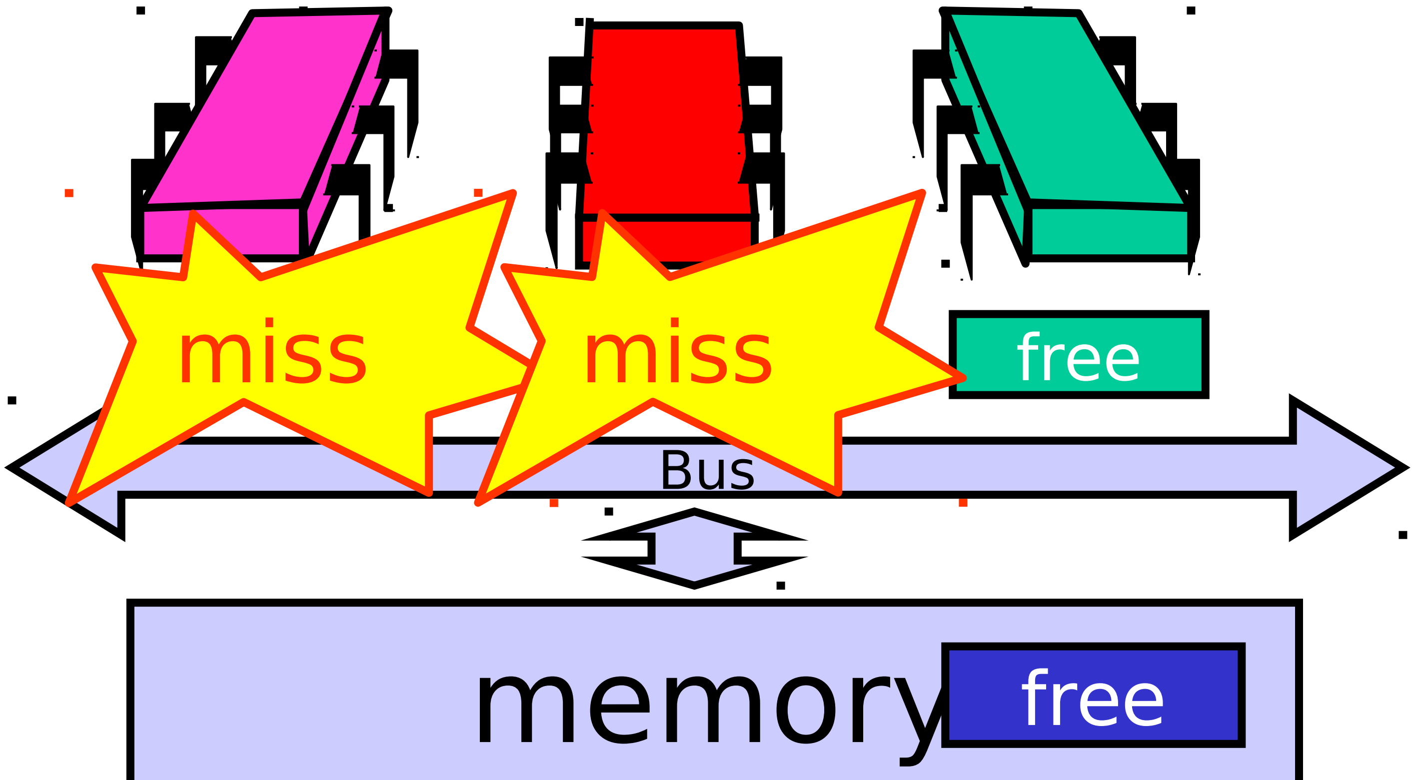


On Release



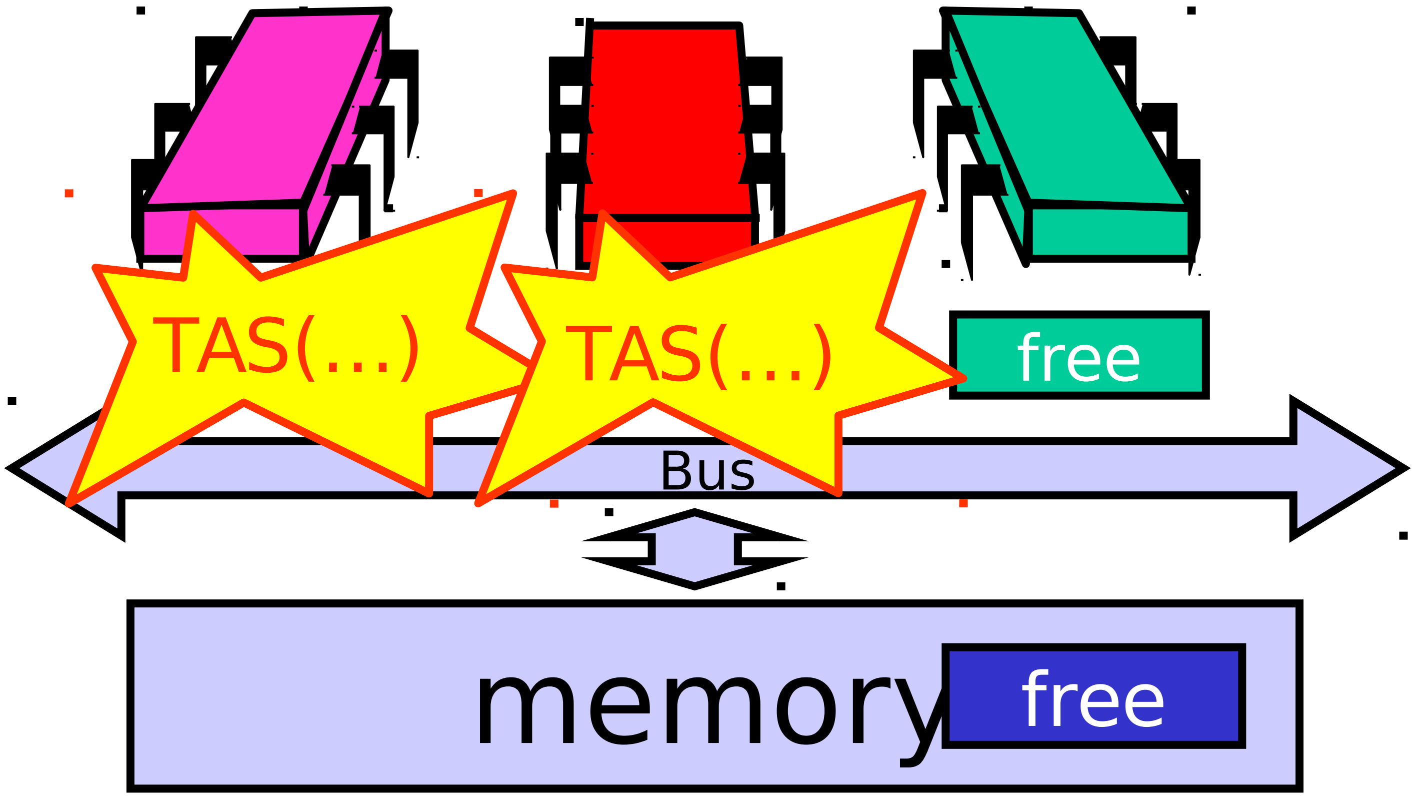
On Release

Everyone misses, rereads



On Release

Everyone tries TAS



Test-and-test-and-set Lock

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 void lock() {
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    return;
 }
}
```

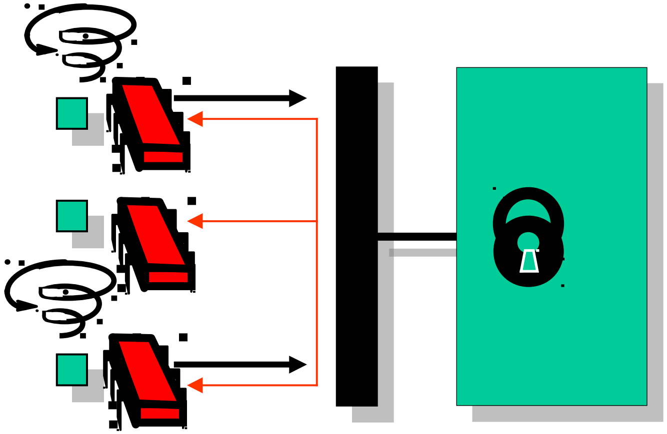
Problems

- Everyone misses
  - Reads satisfied sequentially
- Everyone does TAS
  - Invalidates others' caches
- Eventually quiesces after lock acquired
  - How long does this take?

Measuring Quiescence Time

X = time of ops that don't use the bus

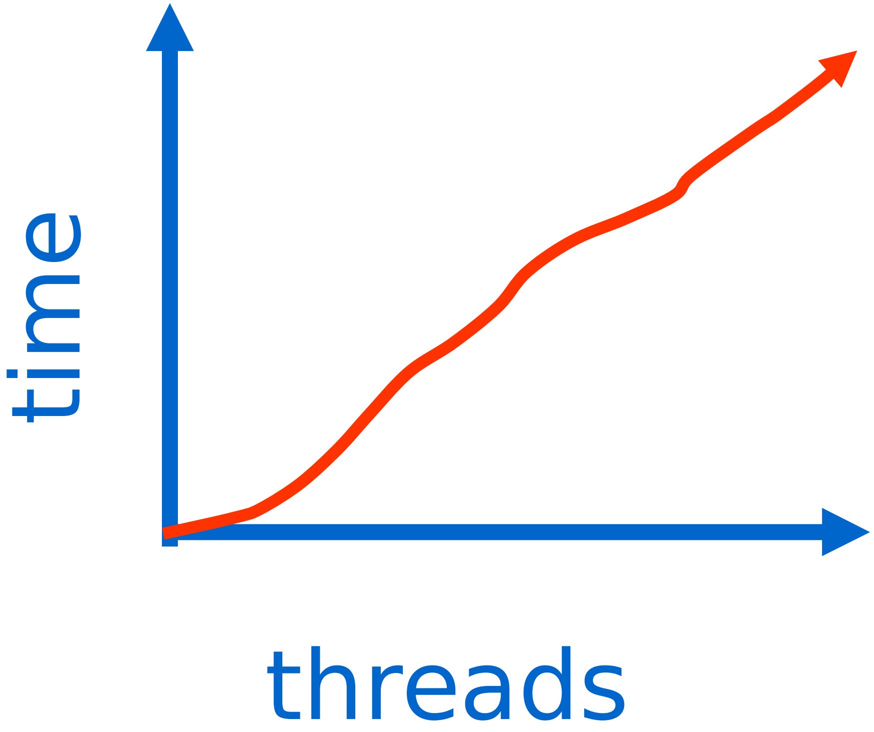
Y = time of ops that cause intensive bus traffic



In critical section, run ops X then ops Y. As long as Quiescence time is less than X, no drop in performance.

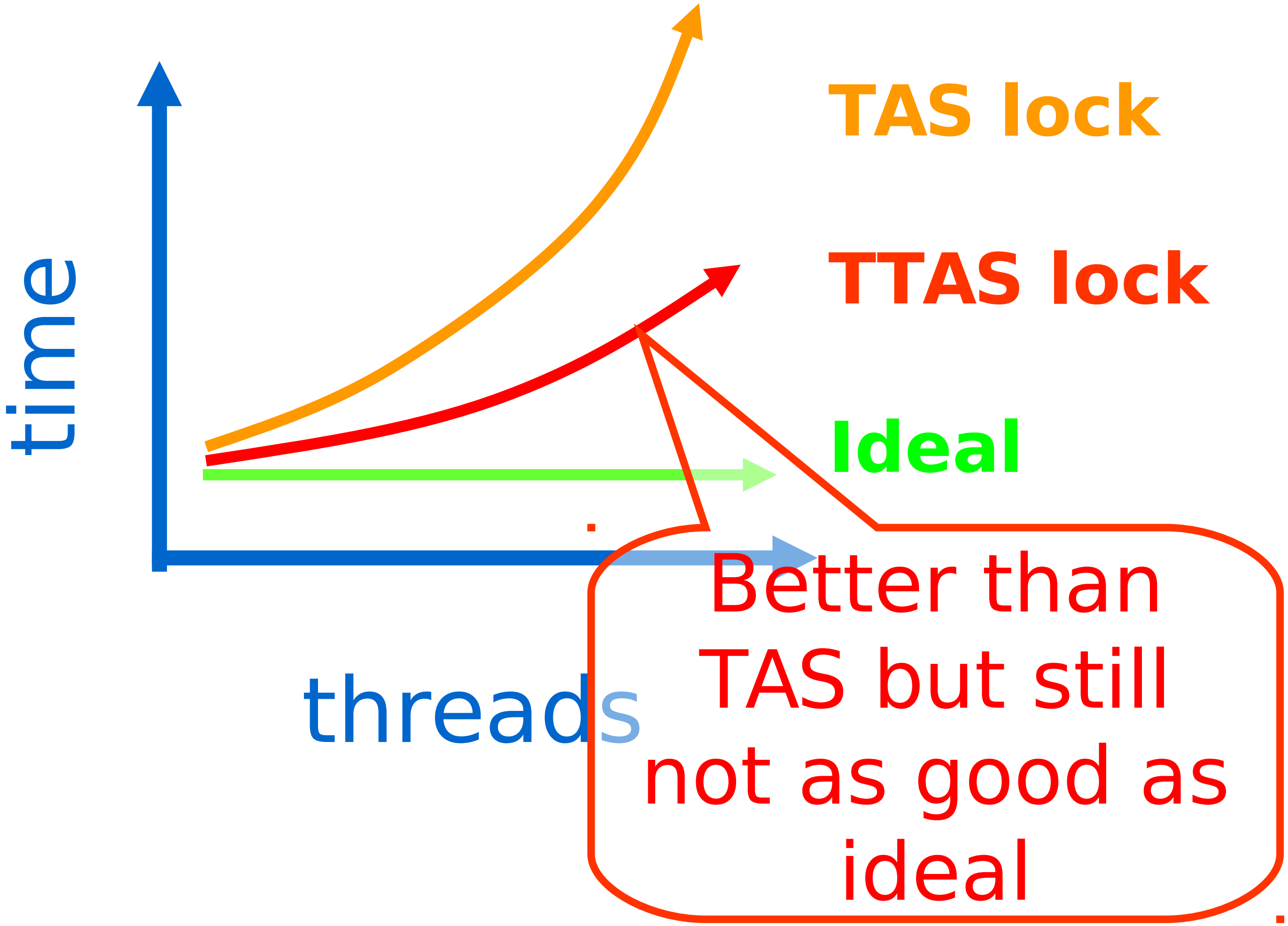
By gradually varying X, can determine the exact time to quiesce.

Quiescence Time



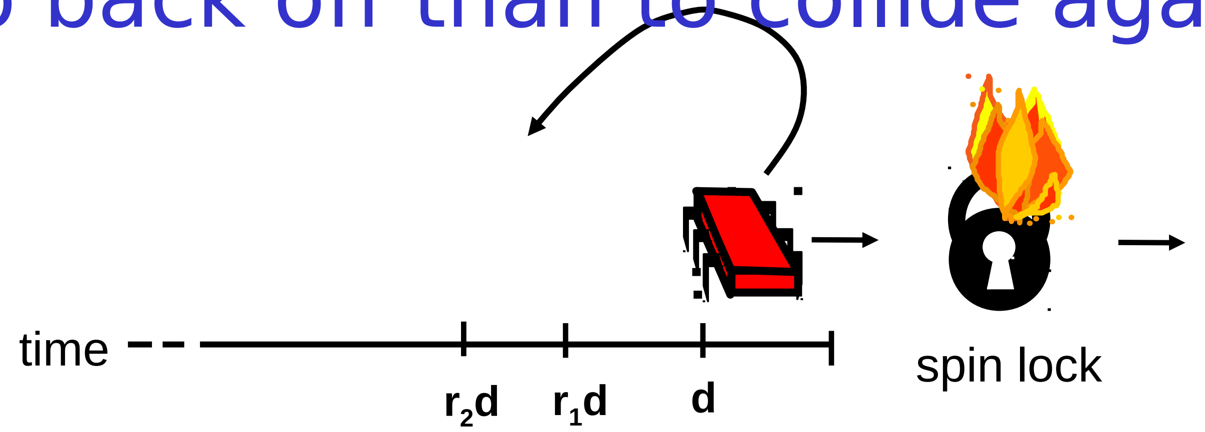
Increses linearly with the number of processors for bus architecture

Mystery Explained

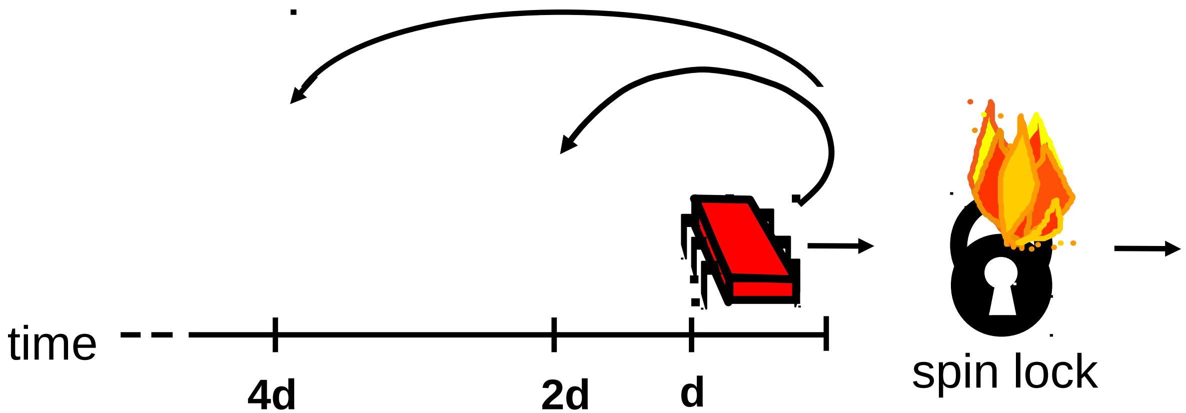


Solution: Introduce Delay

- If the lock looks free
  - But I fail to get it
- There must be lots of contention
  - Better to back off than to collide again



Dynamic Example: Exponential Backoff



If I fail to get lock
- **wait random duration before retry**
- **Each subsequent failure doubles expected wait**

Exponential Backoff Lock

```
public class Backoff implements lock {
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

Exponential Backoff Lock

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public class Backoff implements lock {
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

Fix minimum delay

Exponential Backoff Lock

```
public class Backoff implements lock {
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2
 }}}
```

Wait until lock looks free

Exponential Backoff Lock

```
public class Backoff implements lock {
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

If we win, return

Exponential Backoff Lock

Back off for random duration

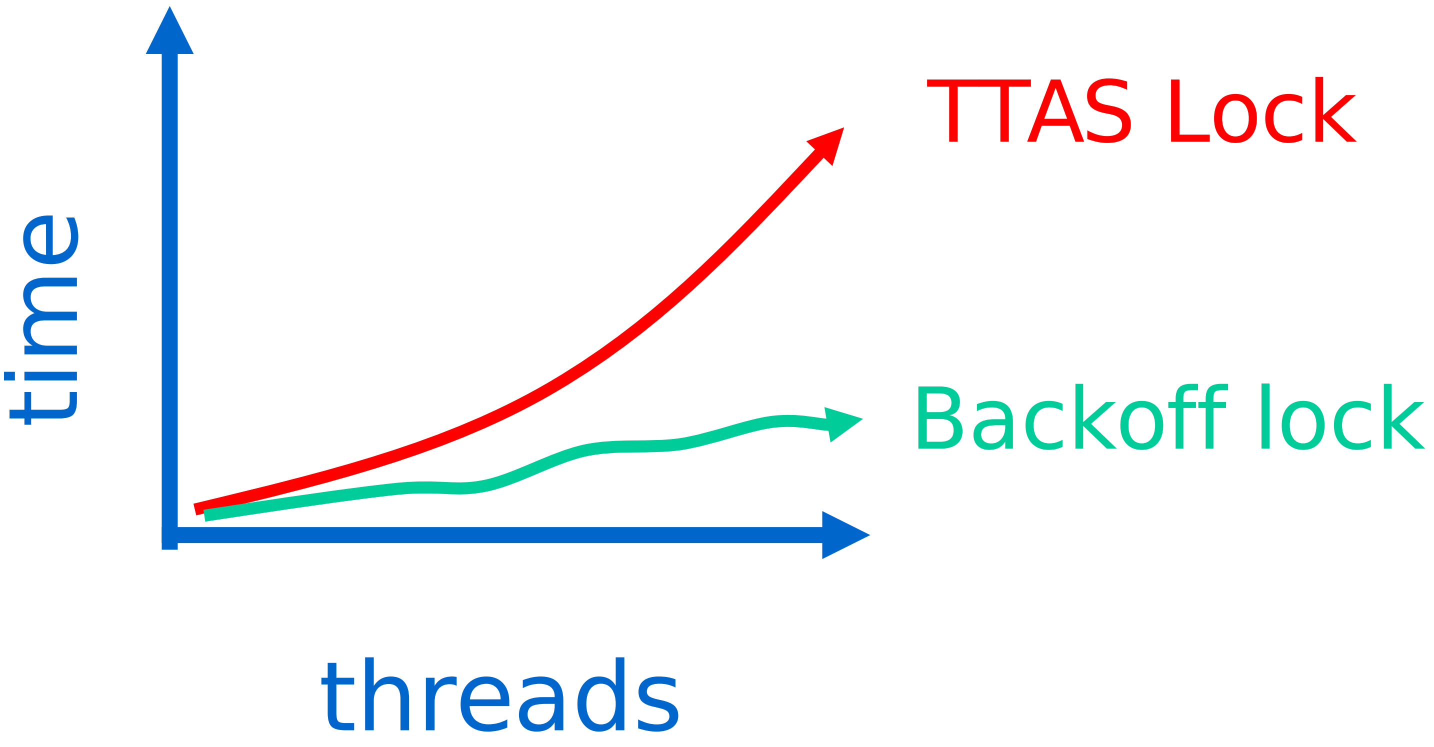
```
public
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

Exponential Backoff Lock

```
pu
 public void lock() {
  int delay = MIN_DELAY;
  while (true) {
   while (state.get()) {}
   if (!lock.getAndSet(true))
    return;
   sleep(random() % delay);
   if (delay < MAX_DELAY)
    delay = 2 * delay;
 }}}
```

Double max delay, within reason

Spin-Waiting Overhead



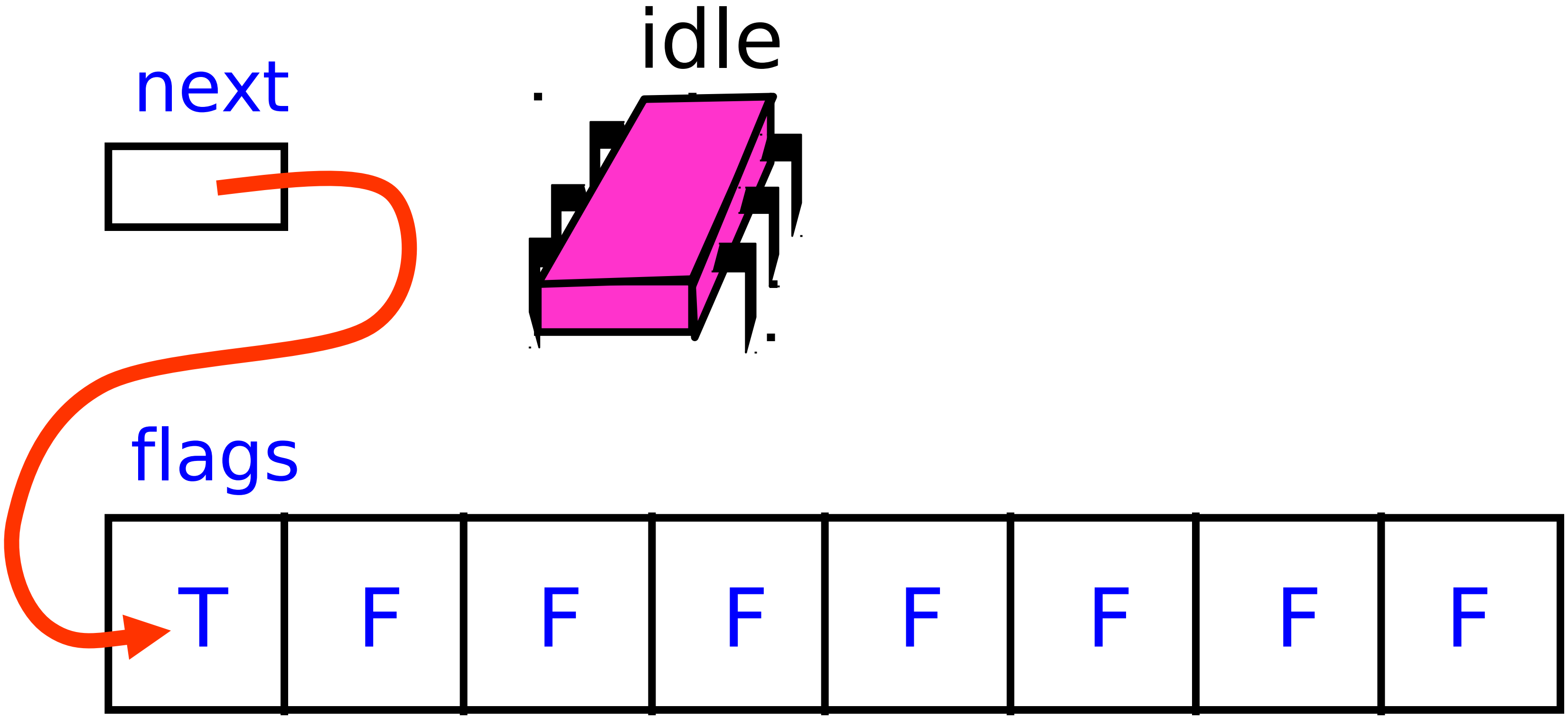
Backoff: Other Issues

- Good
  - Easy to implement
  - Beats TTAS lock
- Bad
  - Must choose parameters carefully
  - Not portable across platforms

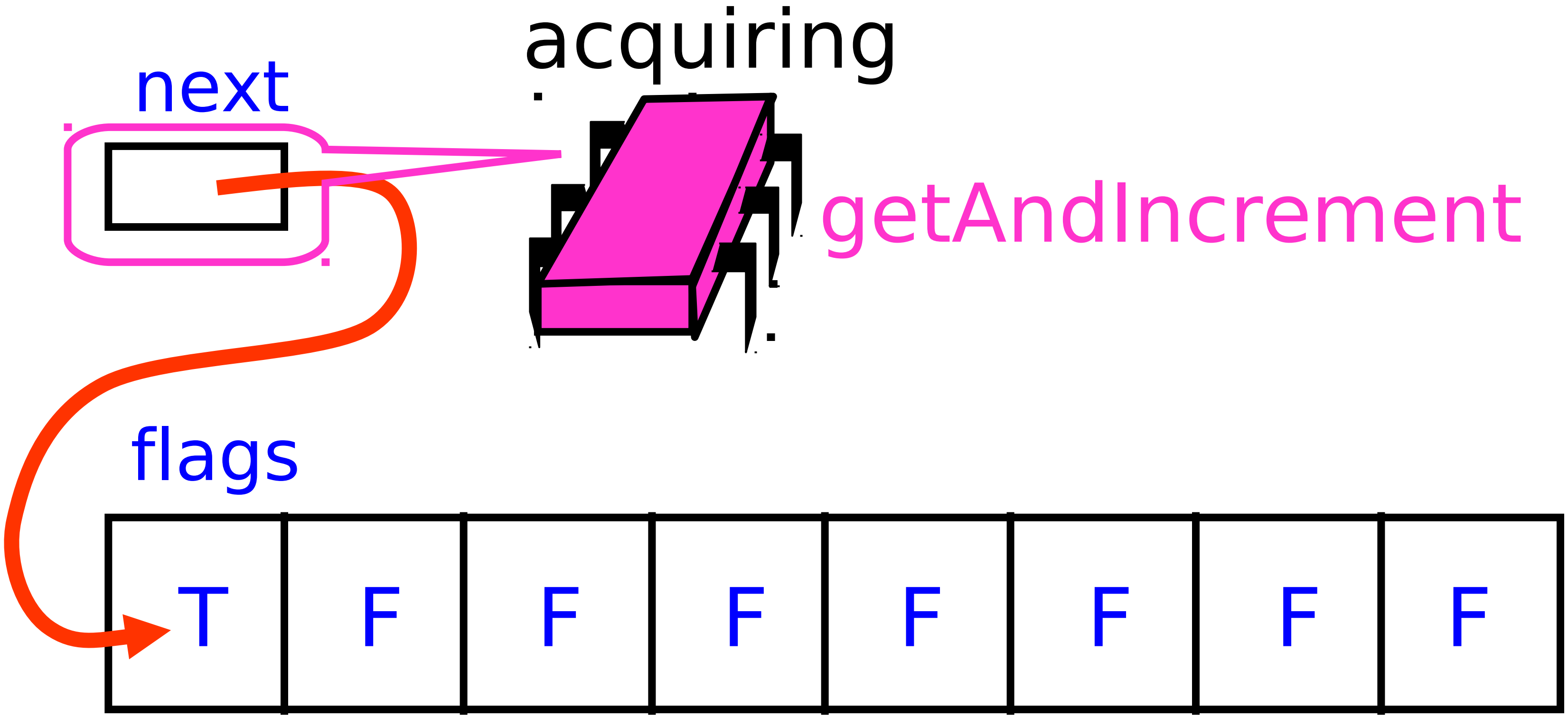
Idea

- Avoid useless invalidations
  - By keeping a queue of threads
- Each thread
  - Notifies next in line
  - Without bothering the others

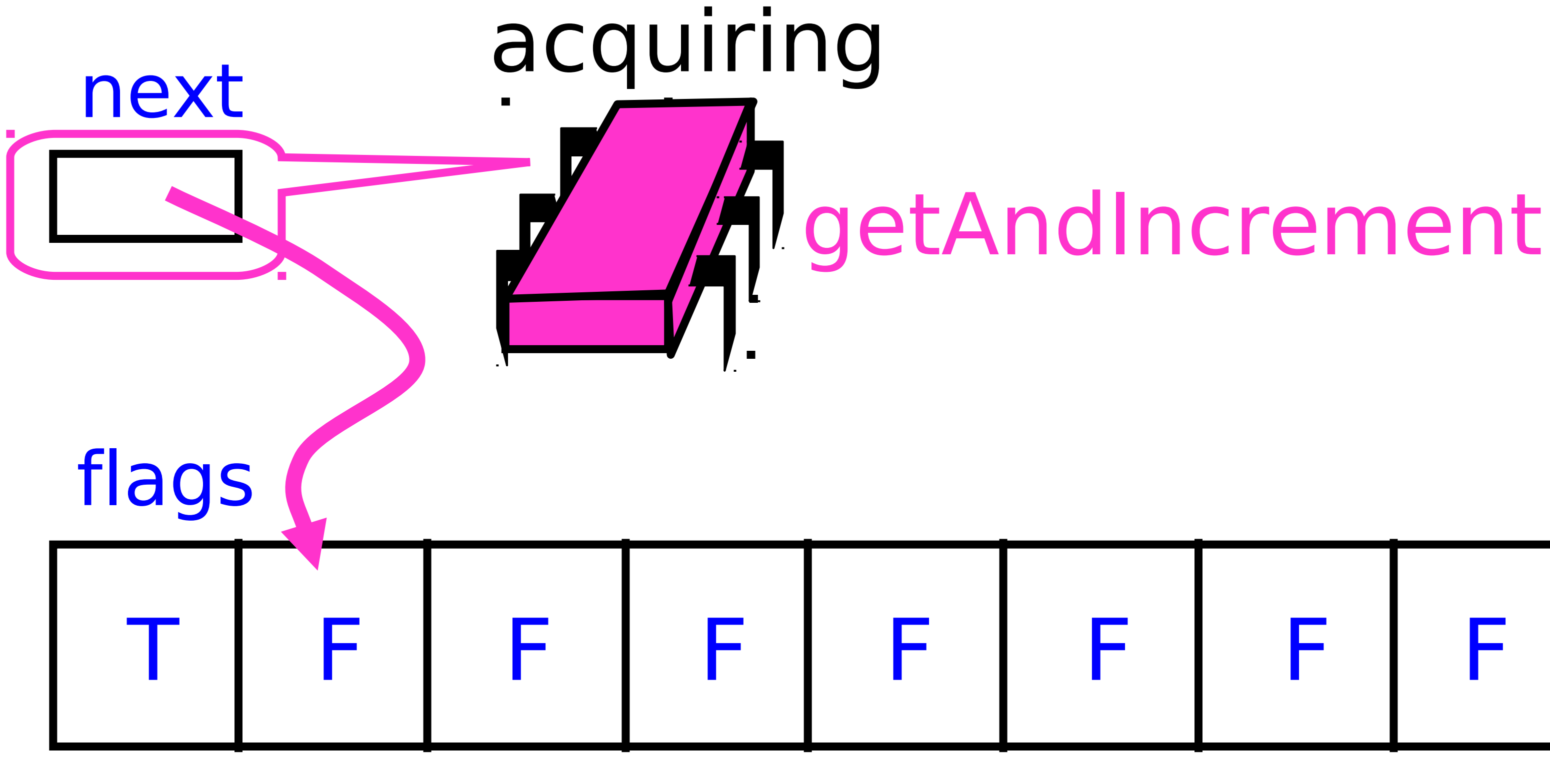
Anderson Queue Lock



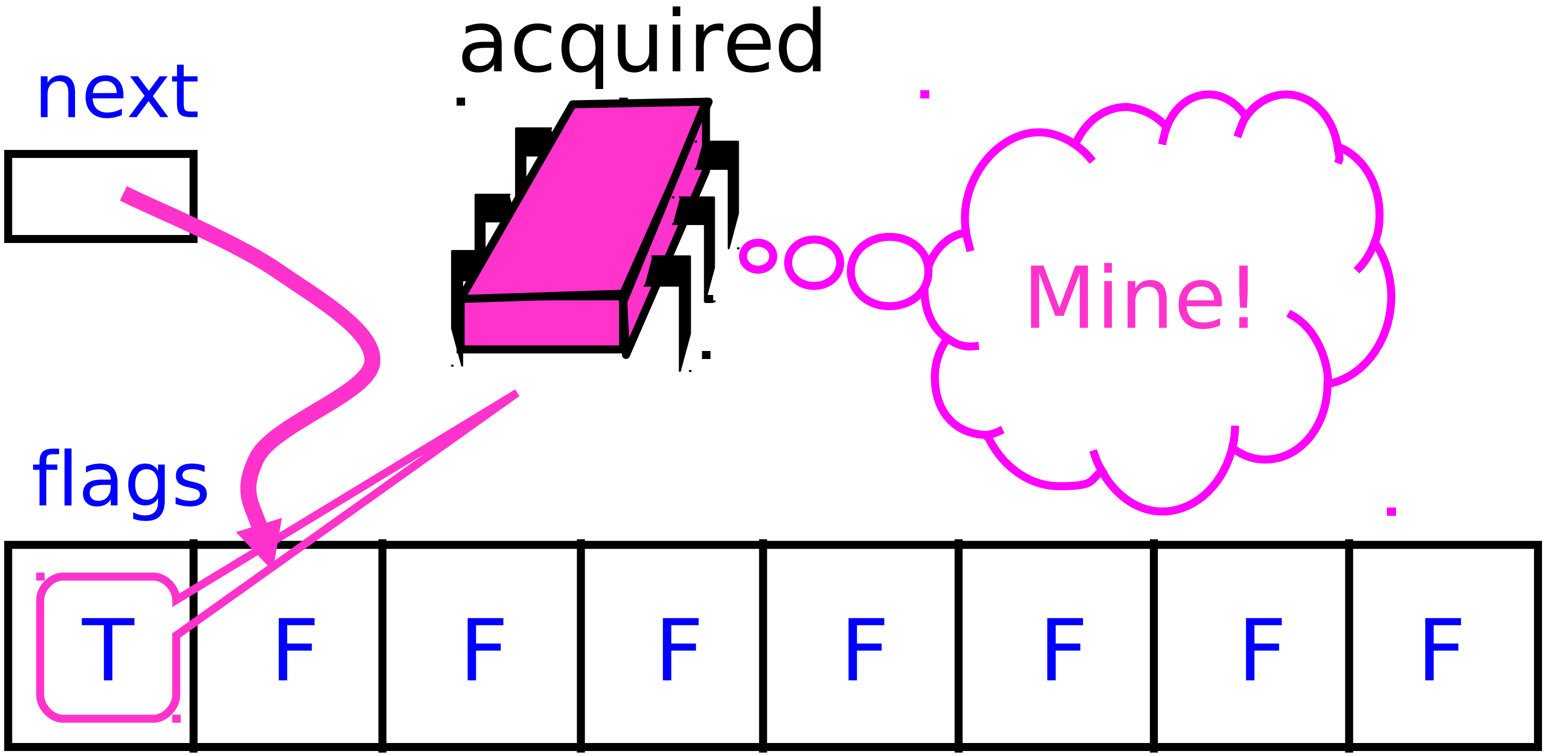
Anderson Queue Lock



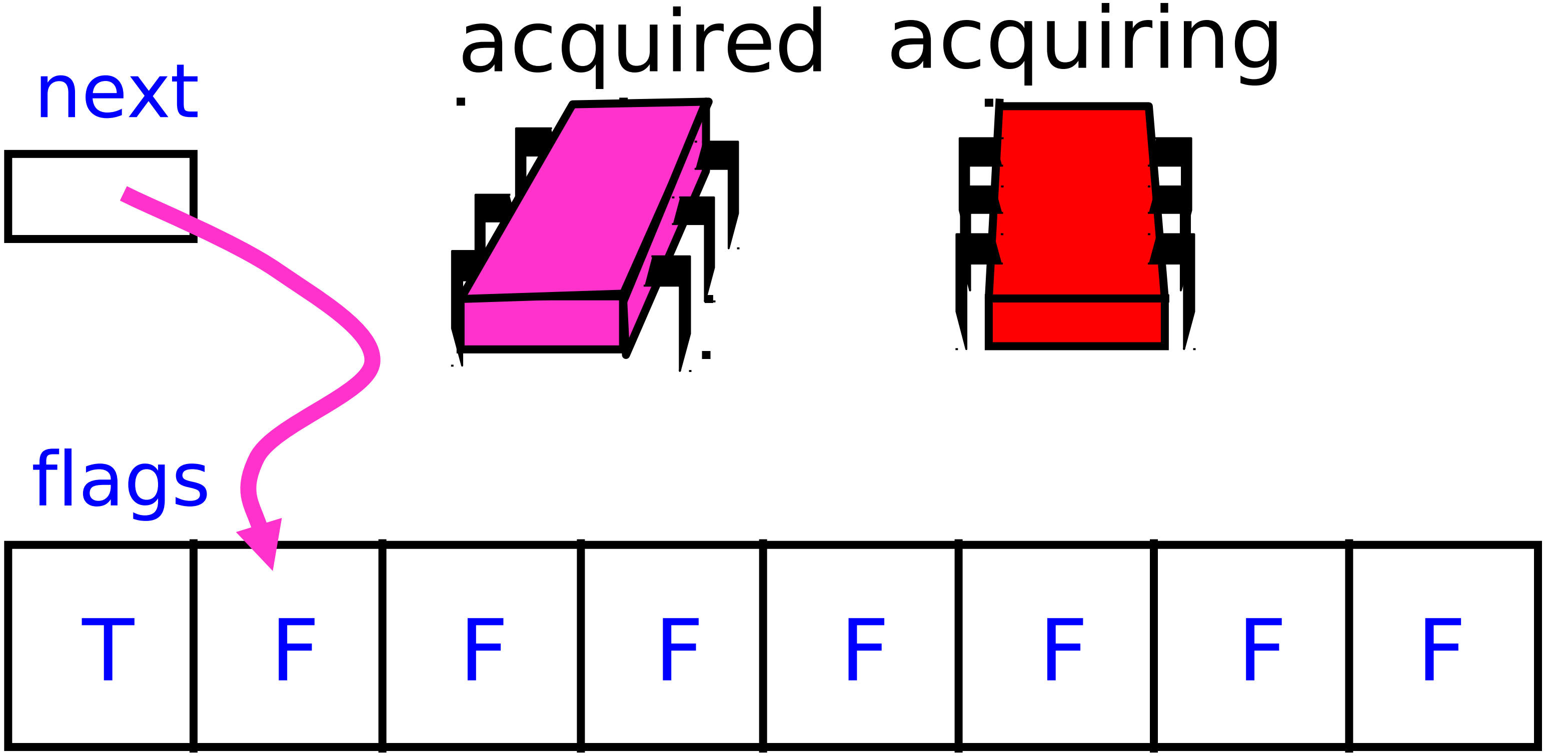
Anderson Queue Lock



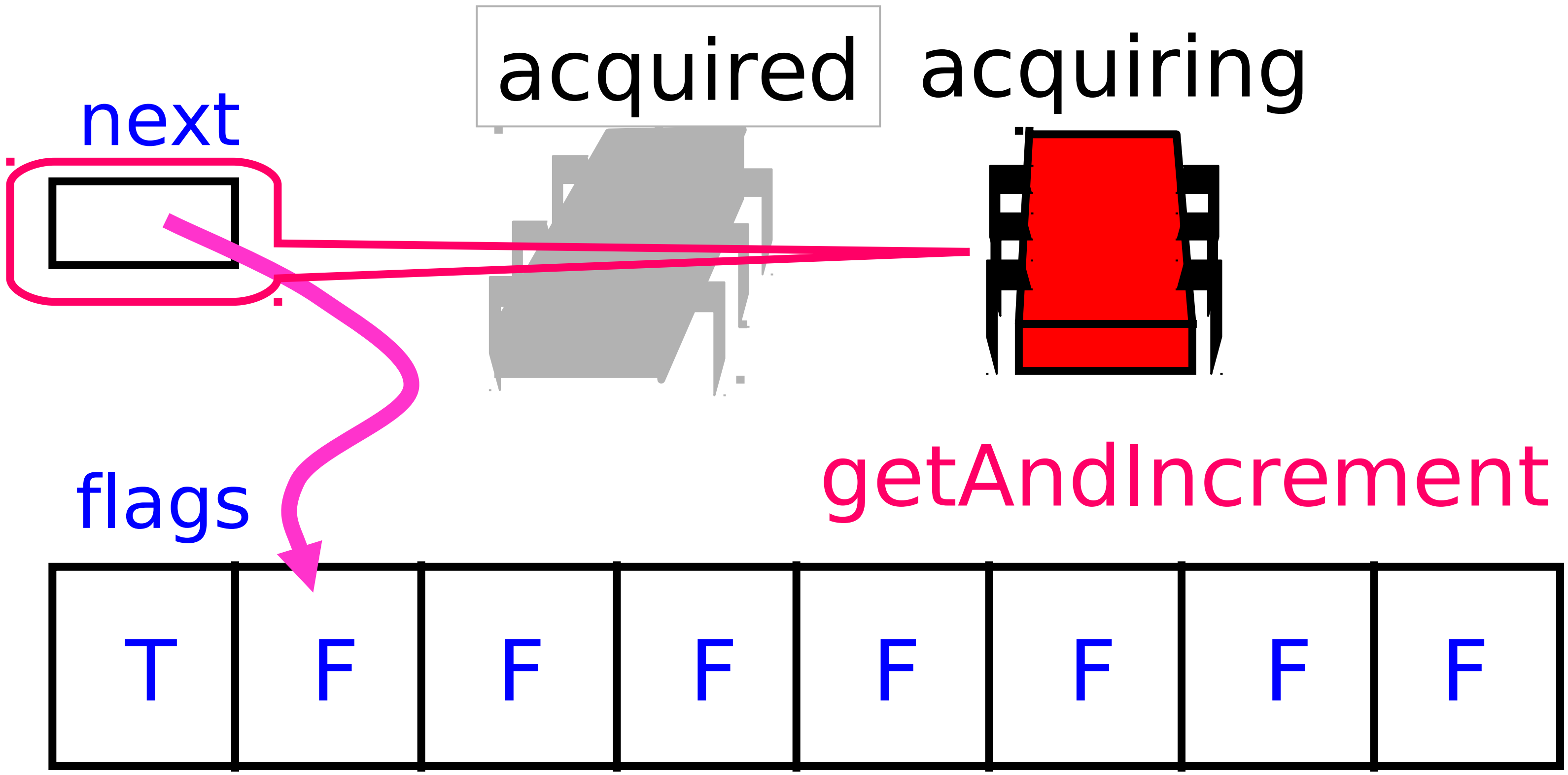
Anderson Queue Lock



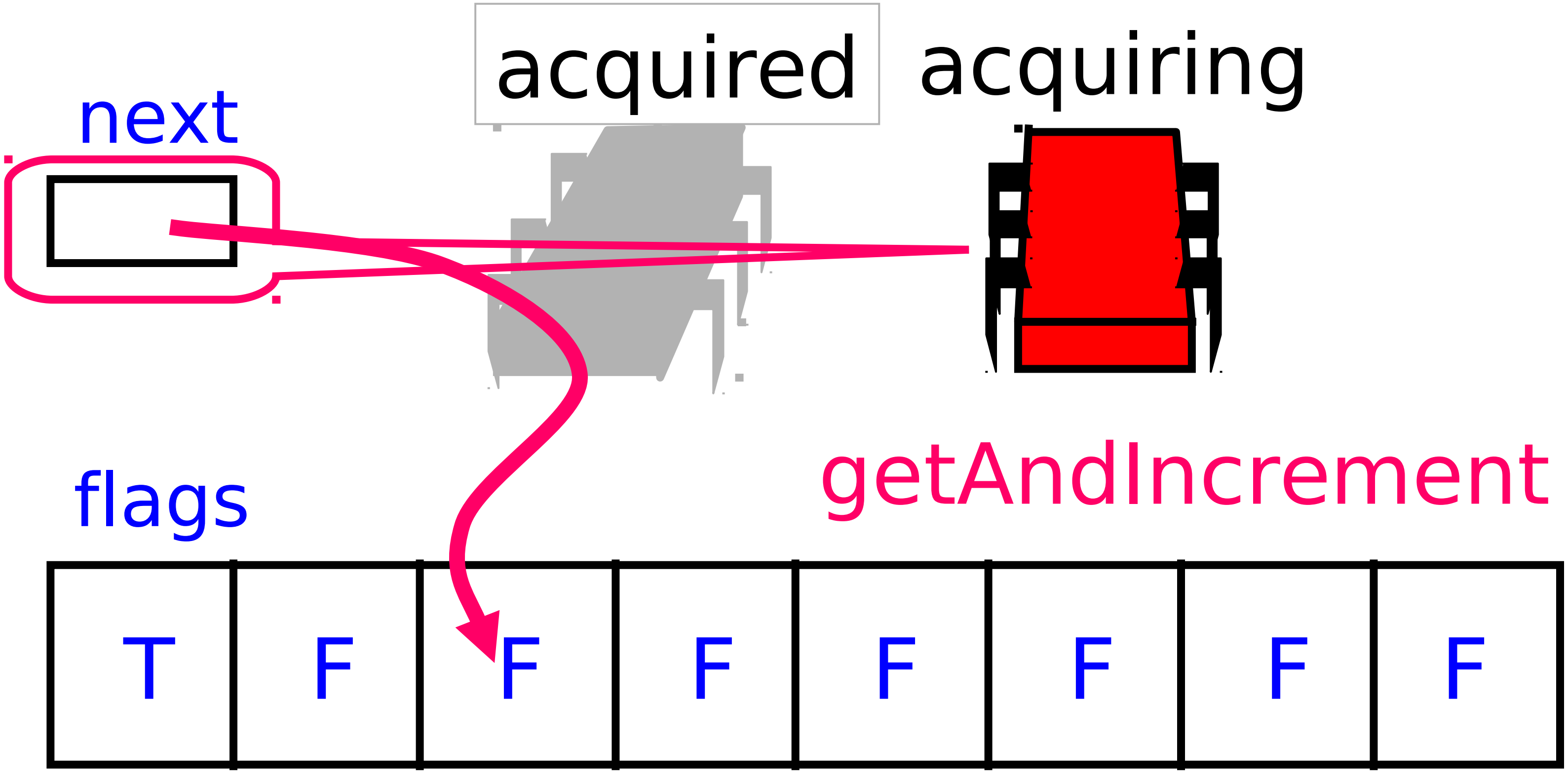
Anderson Queue Lock



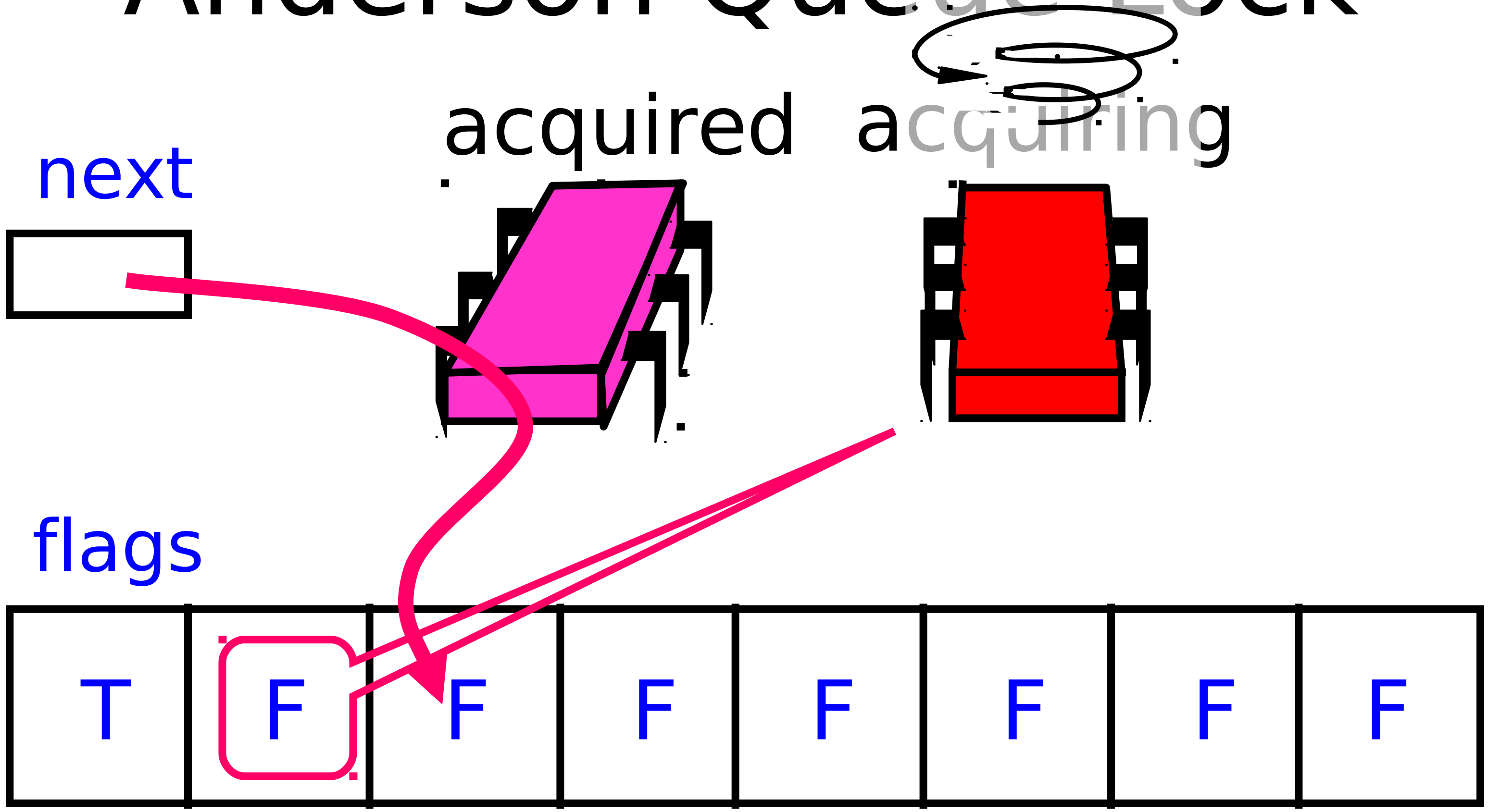
Anderson Queue Lock



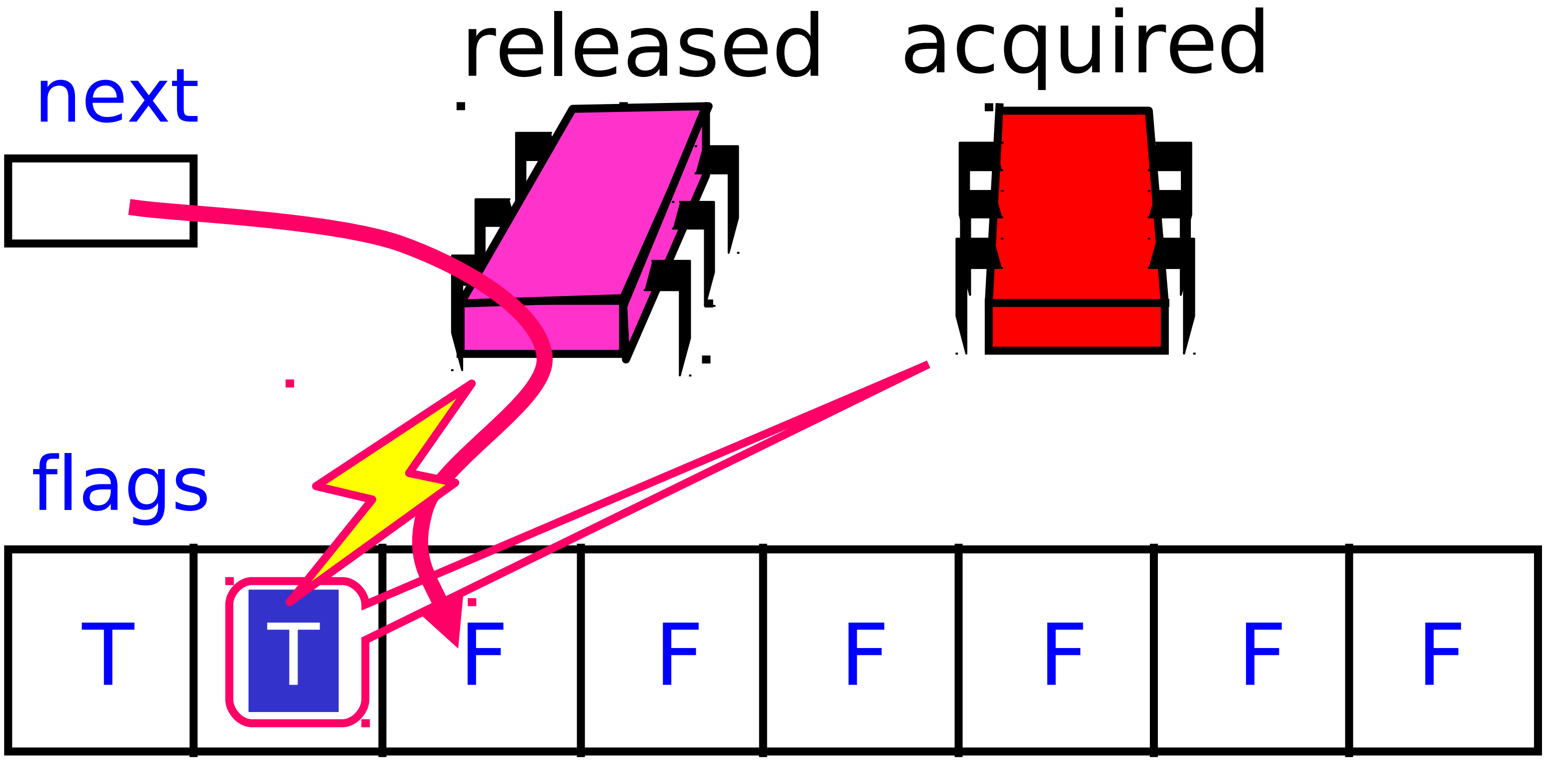
Anderson Queue Lock



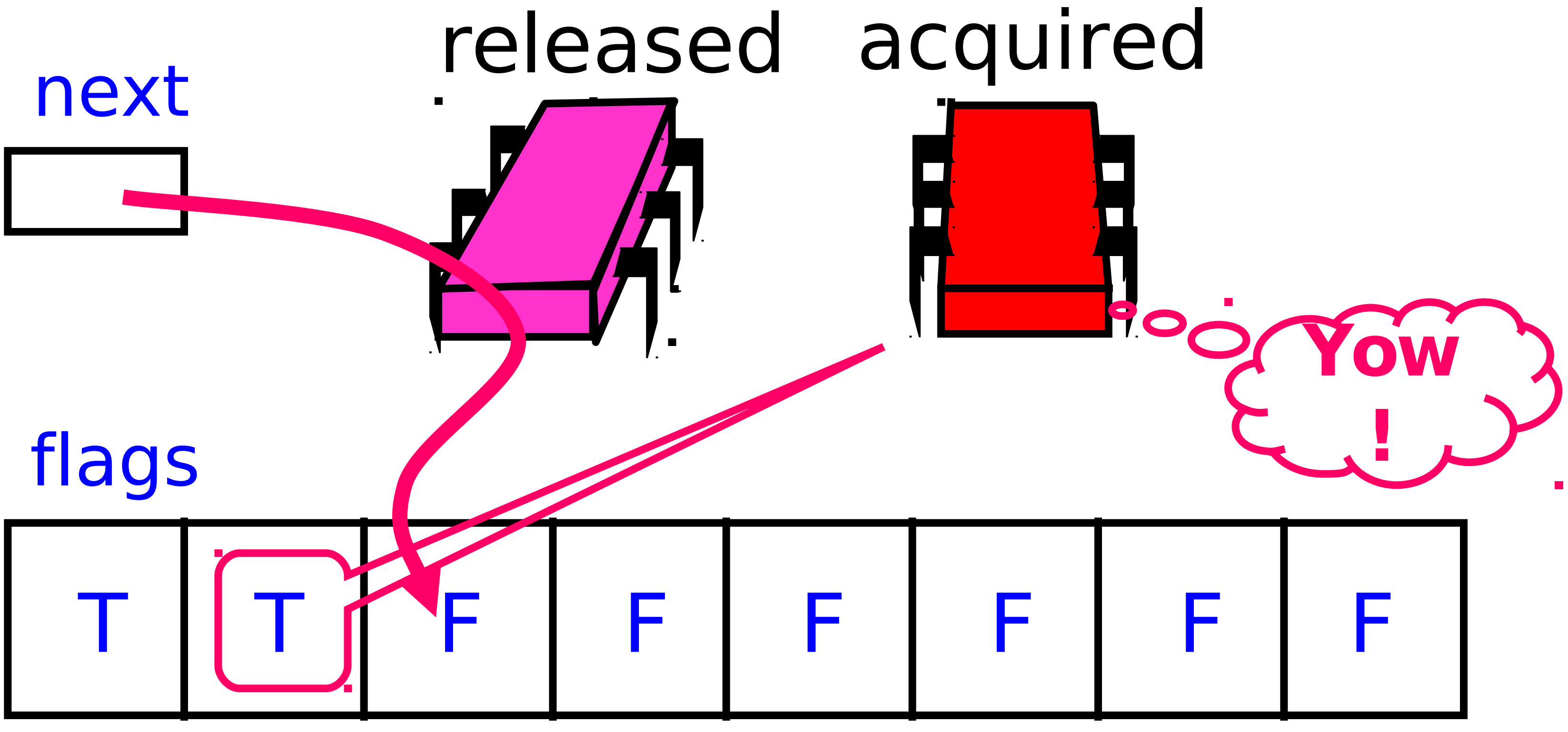
Anderson Queue Lock



Anderson Queue Lock



Anderson Queue Lock



Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 int[] slot = new int[n];
```

Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 int[] slot = new int[n];
```

One flag per thread

Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 int[] slot = new int[n];
```

Next flag to use

Anderson Queue Lock

```
class ALock implements Lock {
 boolean[] flags={true,false,…,false};
 AtomicInteger next
  = new AtomicInteger(0);
 ThreadLocal<Integer> mySlot;
```

Thread-local variable

Anderson Queue Lock

```
public lock() {
 mySlot = next.getAndIncrement();
 while (!flags[mySlot % n]) {};
 flags[mySlot % n] = false;
}

public unlock() {
 flags[(mySlot+1) % n] = true;
}
```

Anderson Queue Lock

```
public lock() {
 mySlot = next.getAndIncrement();
 while (!flags[mySlot % n]) {};
 flags[mySlot % n] = false;
}

public unlock() {
 flags[(mySlot+1) % n]
}
```

Take next slot

Anderson Queue Lock

```
public lock() {
 mySlot = next.getAndIncrement();
 while (!flags[mySlot % n]) {};
 flags[mySlot % n] = false;
}

public unlock() {
 flags[(mySlot+1
}
```

Spin until told to go

Anderson Queue Lock

```
public lock() {
 myslot = next.getAndIncrement();
 while (!flags[myslot % n]) {};
 flags[myslot % n] = false;
}

public unlock() {
 flags[(myslot+1) % n] = true;
}
```

Prepare slot for re-use

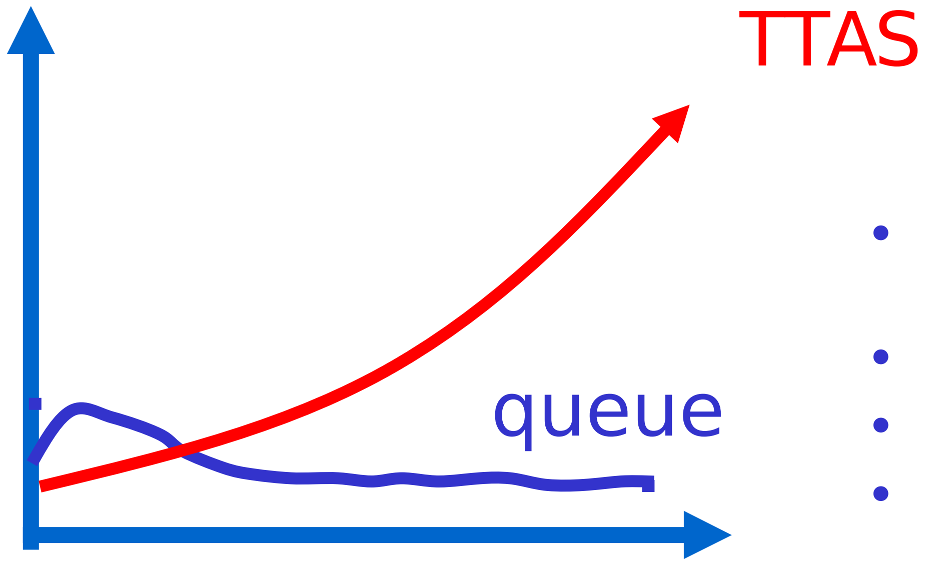
Anderson Queue Lock

```
public lock()
 mySlot = next.getAndIncrement();
 while (!flags[mySlot % n]) {};
 flags[mySlot % n] = false;
}

public unlock() {
 flags[(mySlot+1) % n] = true;
}
```

Tell next thread to go

Performance



- **Shorter handover than backoff**
- **Curve is practically flat**
- **Scalable performance**
- **FIFO fairness**

Anderson Queue Lock

- Good
  - First truly scalable lock
  - Simple, easy to implement
- Bad
  - Space hog
  - One bit per thread
    - Unknown number of threads?
    - Small number of actual contenders?

CLH Lock

- FIFO order
- Small, constant-size overhead per thread

See part 2