Engineering Robust Server Software

Scalability

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Brian Rogers / Duke ECE
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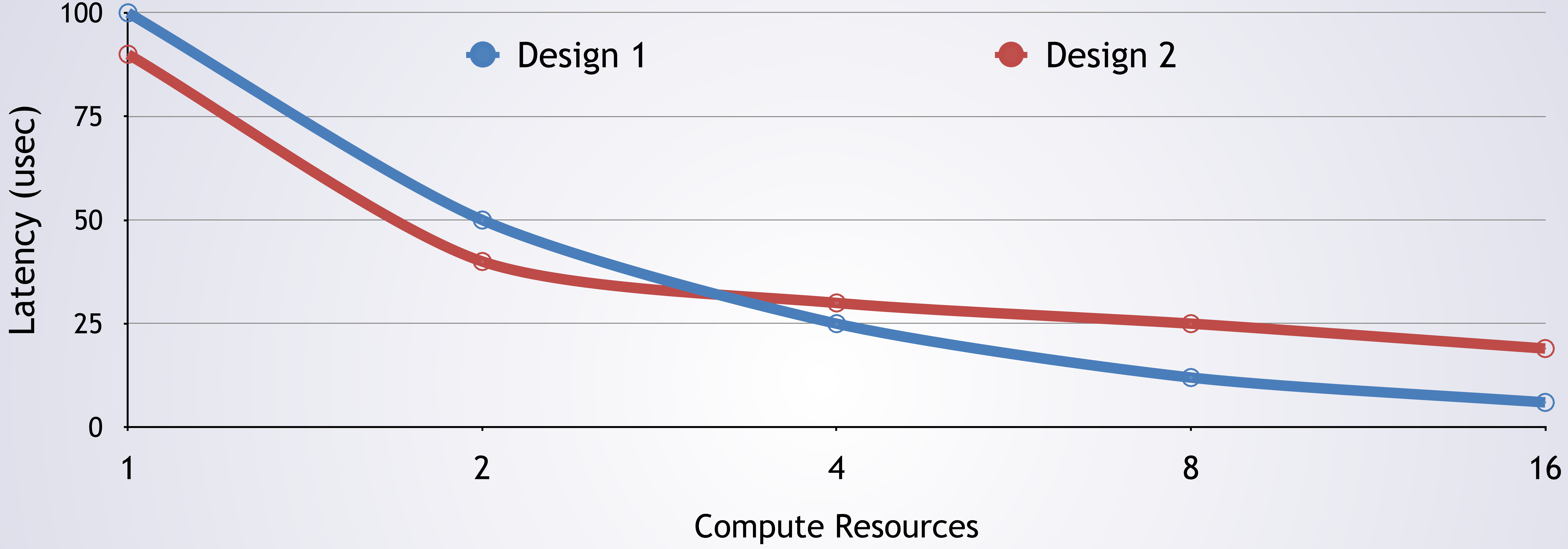
Intro To Scalability

- What does **scalability** mean?

Intro To Scalability



- What does **scalability** mean?
  - How does performance change with resources?

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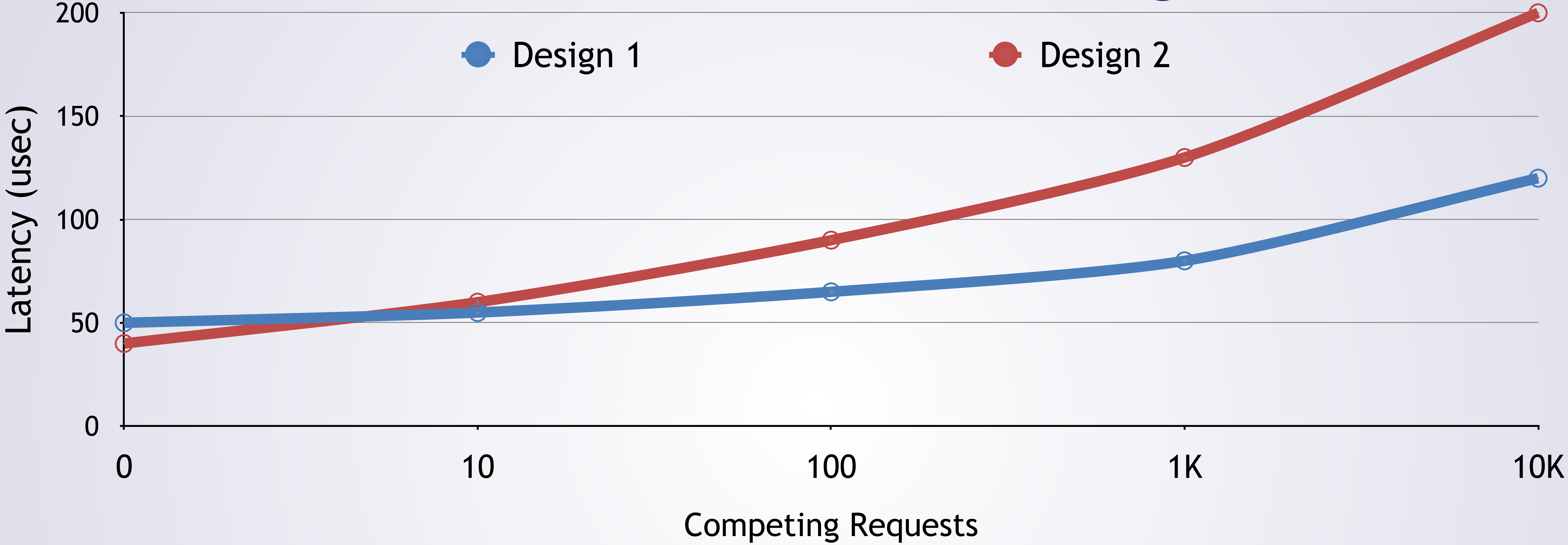
Intro To Scalability



- What does **scalability** mean?
  - How does performance change with resources?
  - How does performance change with load?

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Scalability Terms

- **Scale Out**: Add more nodes
  - More computers
- **Scale Up**: Add more stuff in each node
  - More processors in one node
- **Strong Scaling**: How does time change for fixed problem size?
  - Do 100M requests, add more cores -> speedup?
- **Weak Scaling**: How does time change for fixed (problem size/core)?
  - Do (100*N)M requests, with N cores -> speedup?

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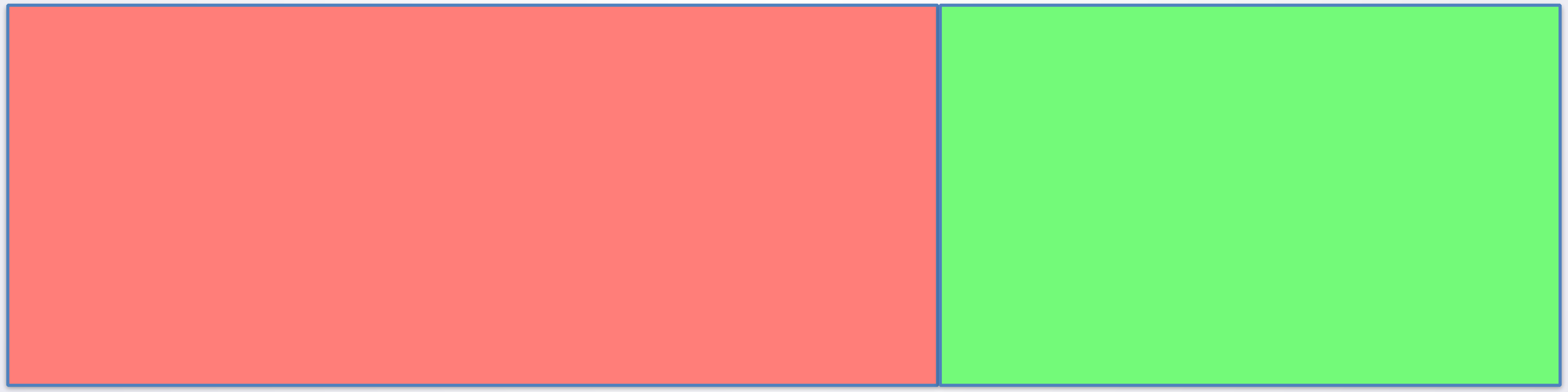
Amdahl's Law

$$\text{Speedup}(N) = \frac{S + P}{S + \frac{P}{N}}$$

Amdahl's Law

$$\text{Speedup}(N) = \frac{S + P}{S + \frac{P}{N}} = \frac{6 + 4}{6 + \frac{4}{N}}$$

Serial Portion: S = 6



Parallel Portion: P = 4

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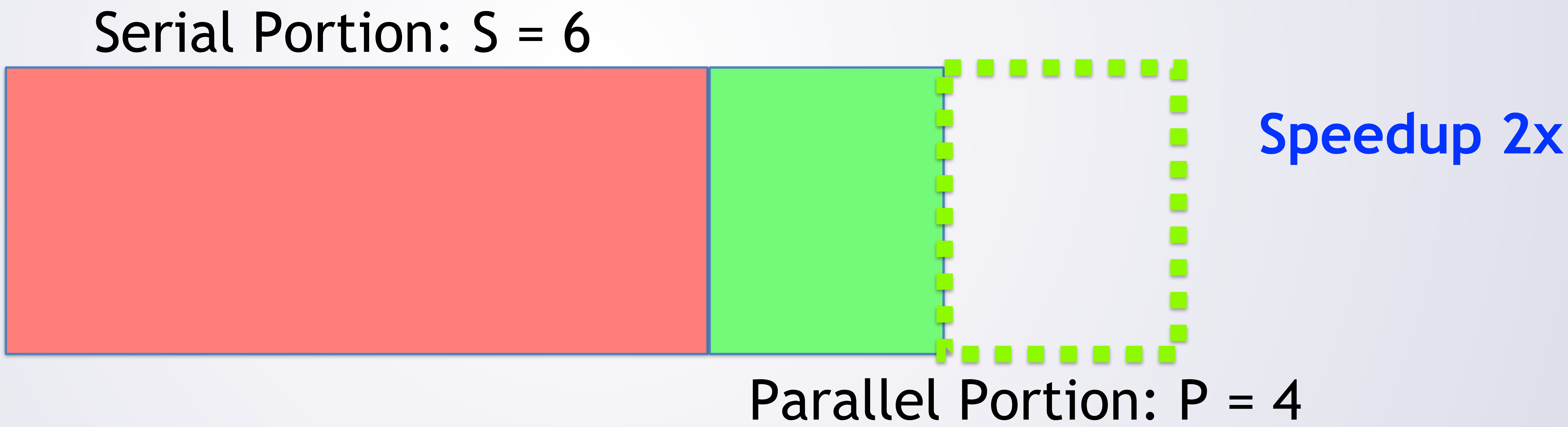
Amdahl's Law

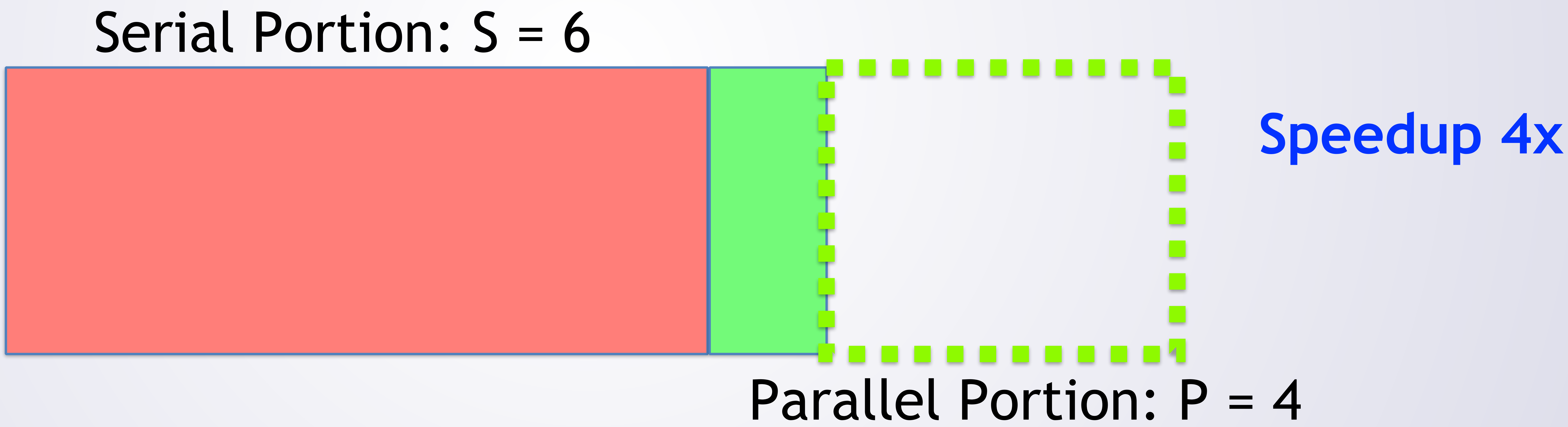
$$\text{Speedup}(N) = \frac{S + P}{S + \frac{P}{N}} = \frac{6 + 4}{6 + \frac{4}{2}} = \frac{10}{8}$$



- 10/8 = 1.25x speedup = 25% increase in **throughput**.
  - 8/10 = 0.8x = 20% reduction in **latency**

Amdahl's Law

$$\text{Speedup}(N) = \frac{S + P}{S + \frac{P}{N}} = \frac{6 + 4}{6 + \frac{4}{4}} = \frac{10}{7}$$



- 10/7 = 1.42x speedup = 42% increase in **throughput**.
  - 7/10 = 0.7x = 30% reduction in **latency**

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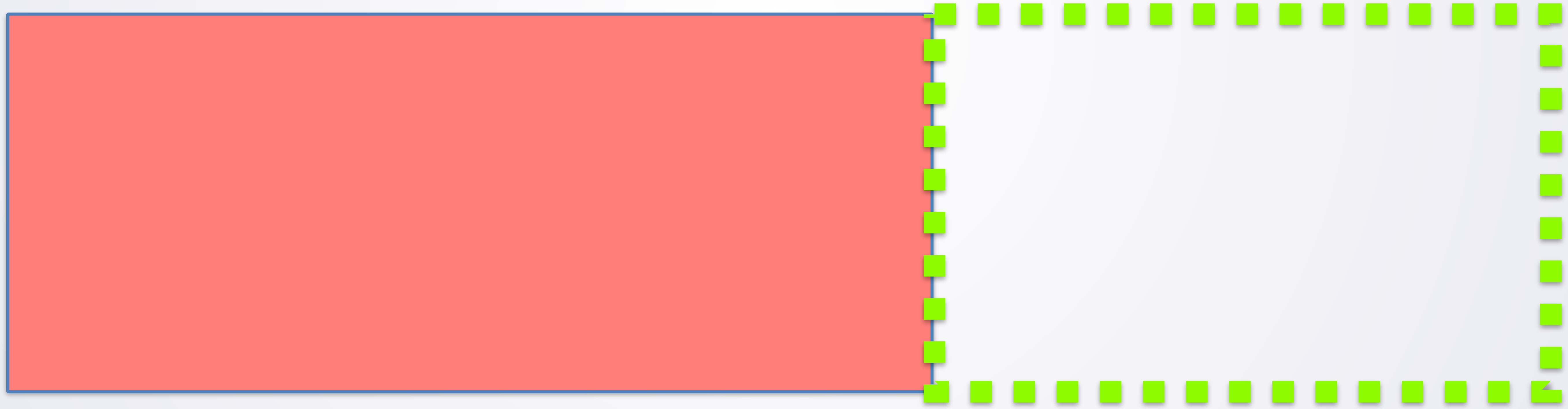
Amdahl's Law

$$\text{Speedup (N)} = \frac{S + P}{S + \frac{P}{N}} = \frac{6 + 4}{6 + \frac{4}{\infty}} = \frac{10}{6}$$

Serial Portion: S = 6

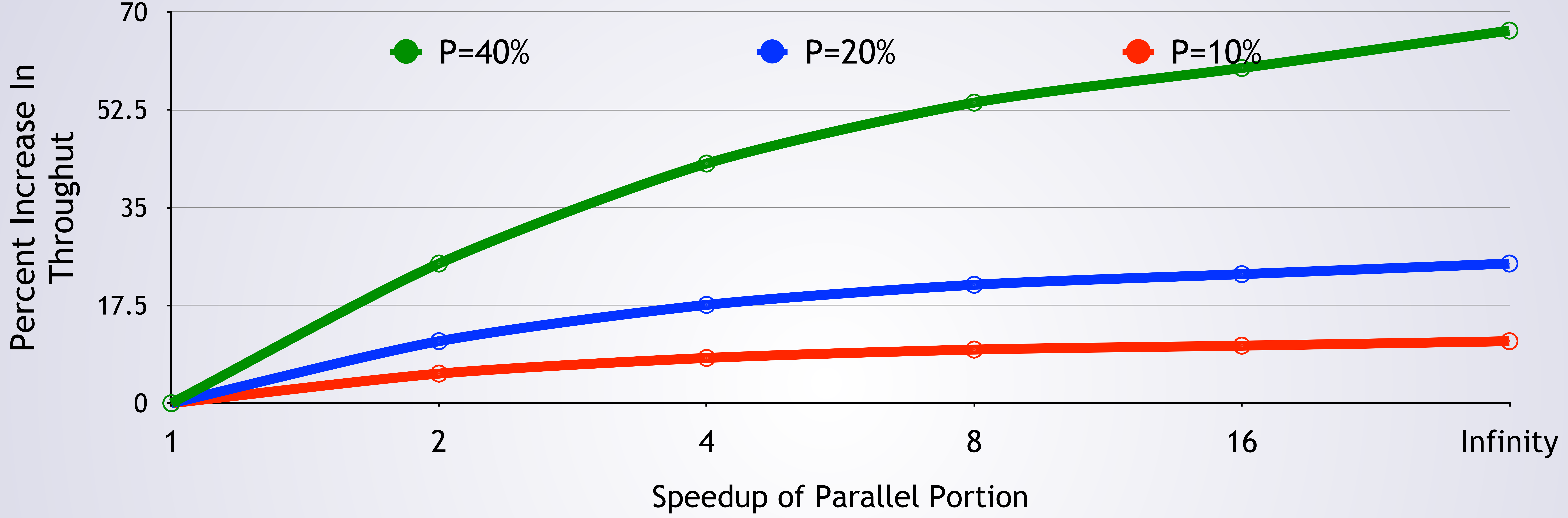


Speedup ∞x

Parallel Portion: P = 4

- 10/6 = 1.67x speedup = 67% increase in **throughput**.
  - 6/10 = 0.6x = 40% reduction in **latency**

Amdahl's Law



- Anne Bracy: "Don't try to speed up brushing your teeth"
  - What does she mean?

Brushing your teeth doesn’t take long, so you can’t save much total time by optimizing it.

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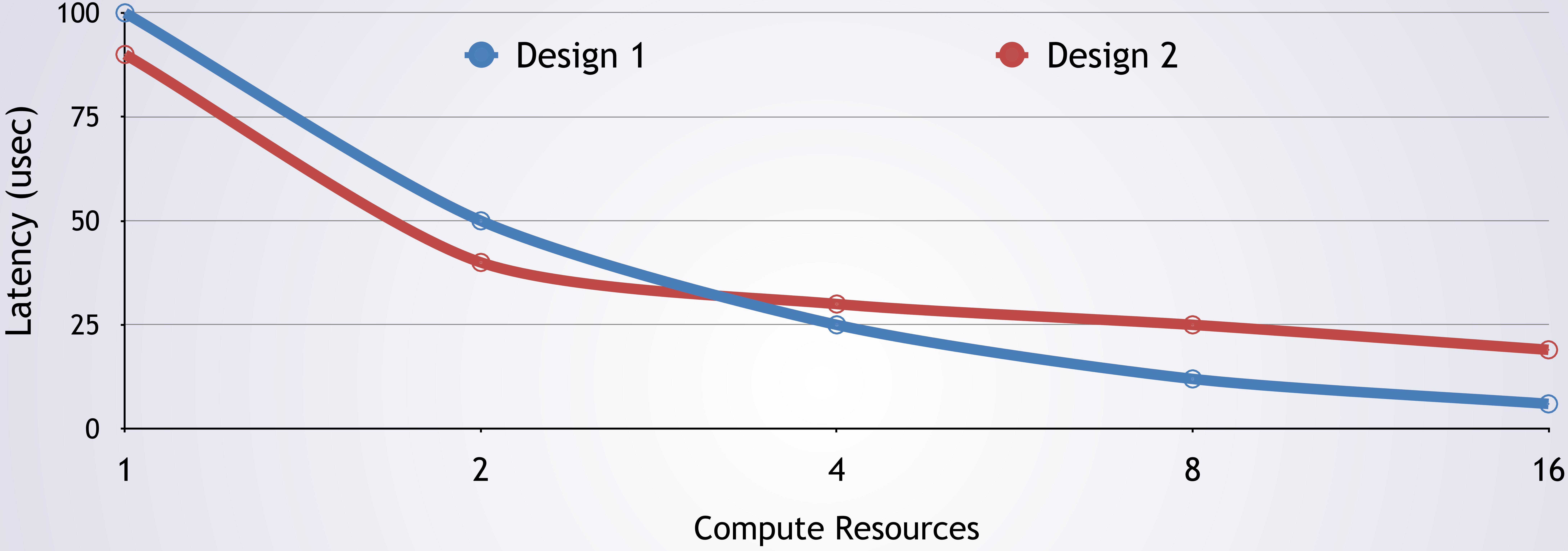
Why Not Perfect Scalability?



- Why don't we get (Nx) speedup with N cores?
  - What prevents ideal speedups?

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Impediments to Scalability

- Shared Hardware
  - Functional Units
  - Caches
  - Memory Bandwidth
  - IO Bandwidth
  - …
- Data Movement
  - From one core to another
- Blocking
  - Locks (and other synchronization)
  - Blocking IO

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Impediments to Scalability

- Shared Hardware
  - Functional Units
  - Caches
  - Memory Bandwidth
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  - …
- Data Movement
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  - Blocking IO
  - Locks (and other synchronization)

Let's talk about these for now

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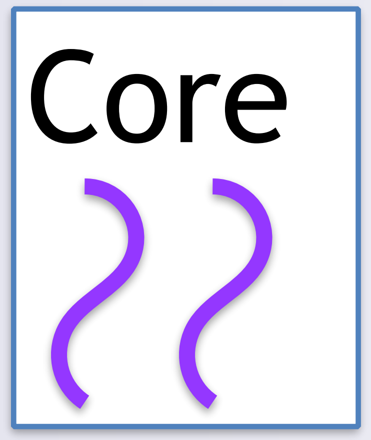
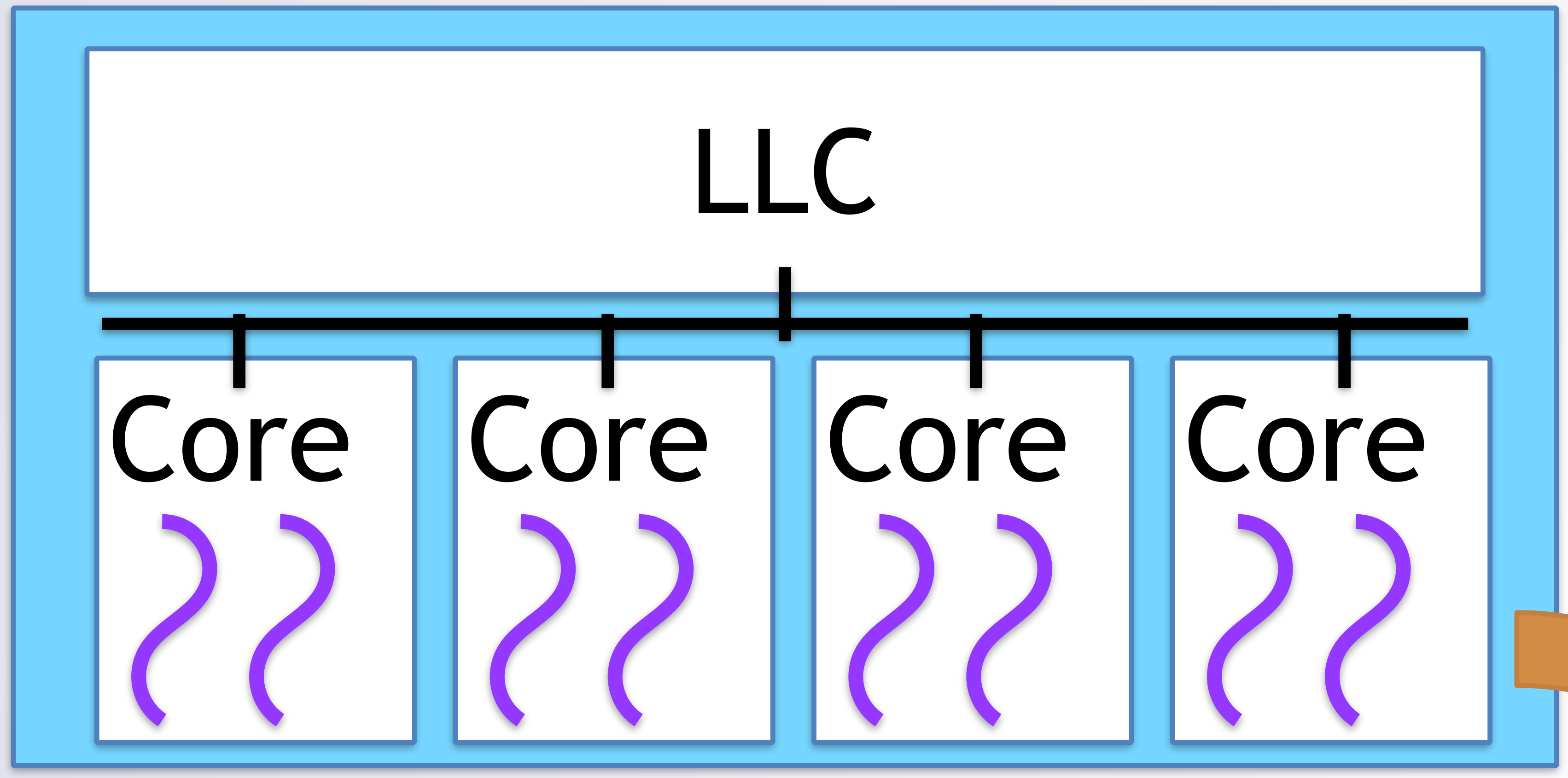
Hypothetical System



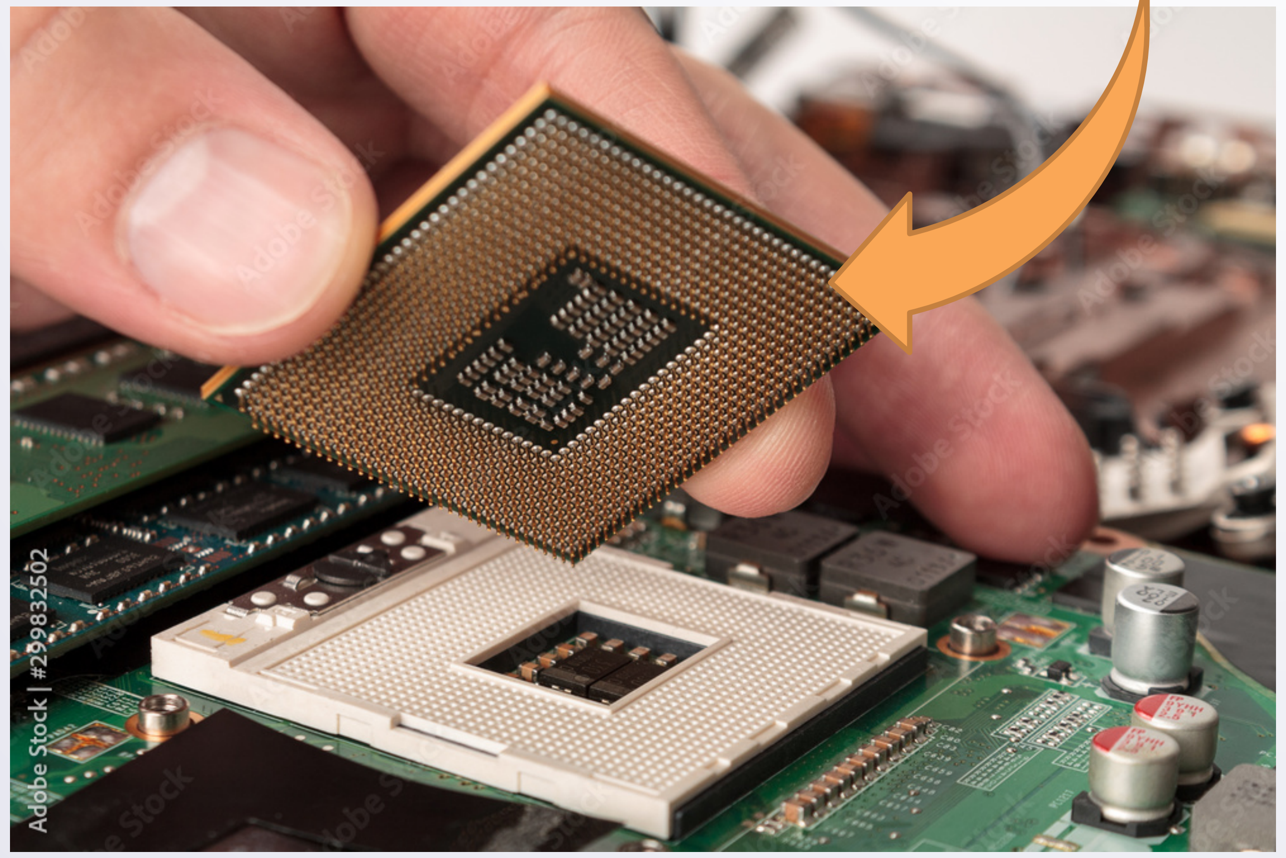
A core has 2 threads (2-way SMT)

- Also private L1 + L2 caches (not shown)

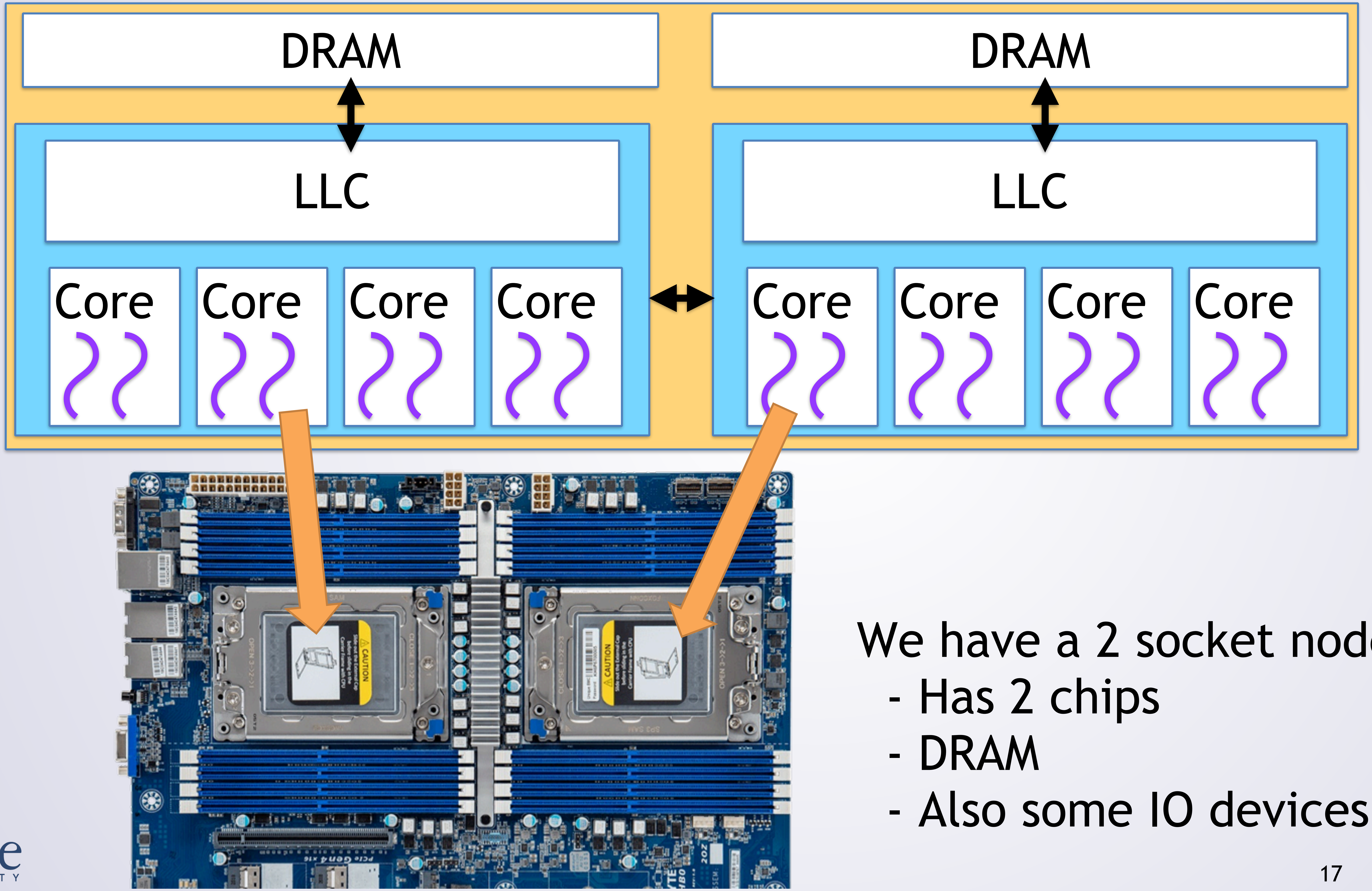
Hypothetical System



4 cores share an LLC
- Connected by on chip interconnect



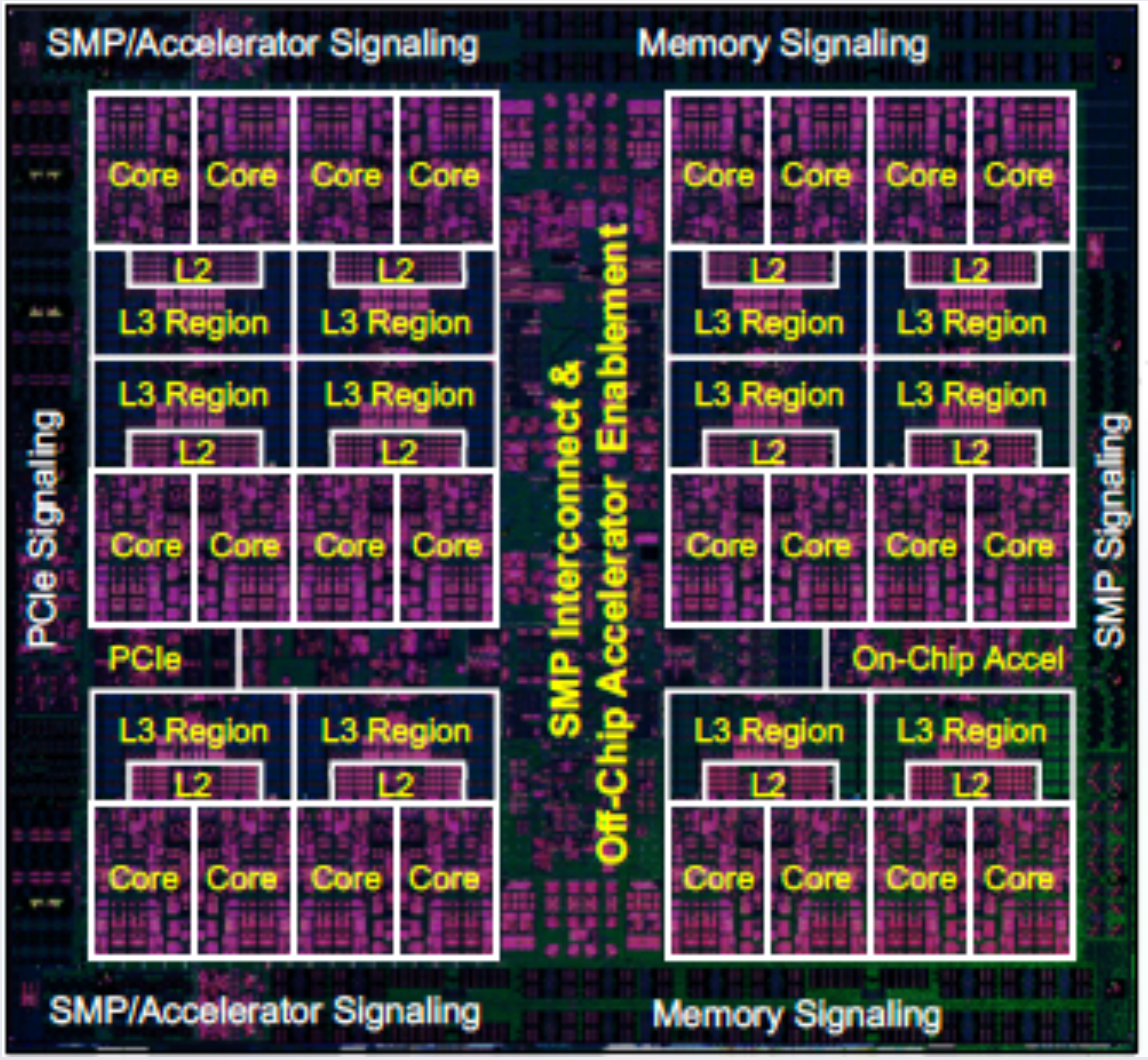
Hypothetical System



We have a 2 socket node

- Has 2 chips
- DRAM
- Also some IO devices (not shown)

And a Real Example (IBM POWER9 CPU)



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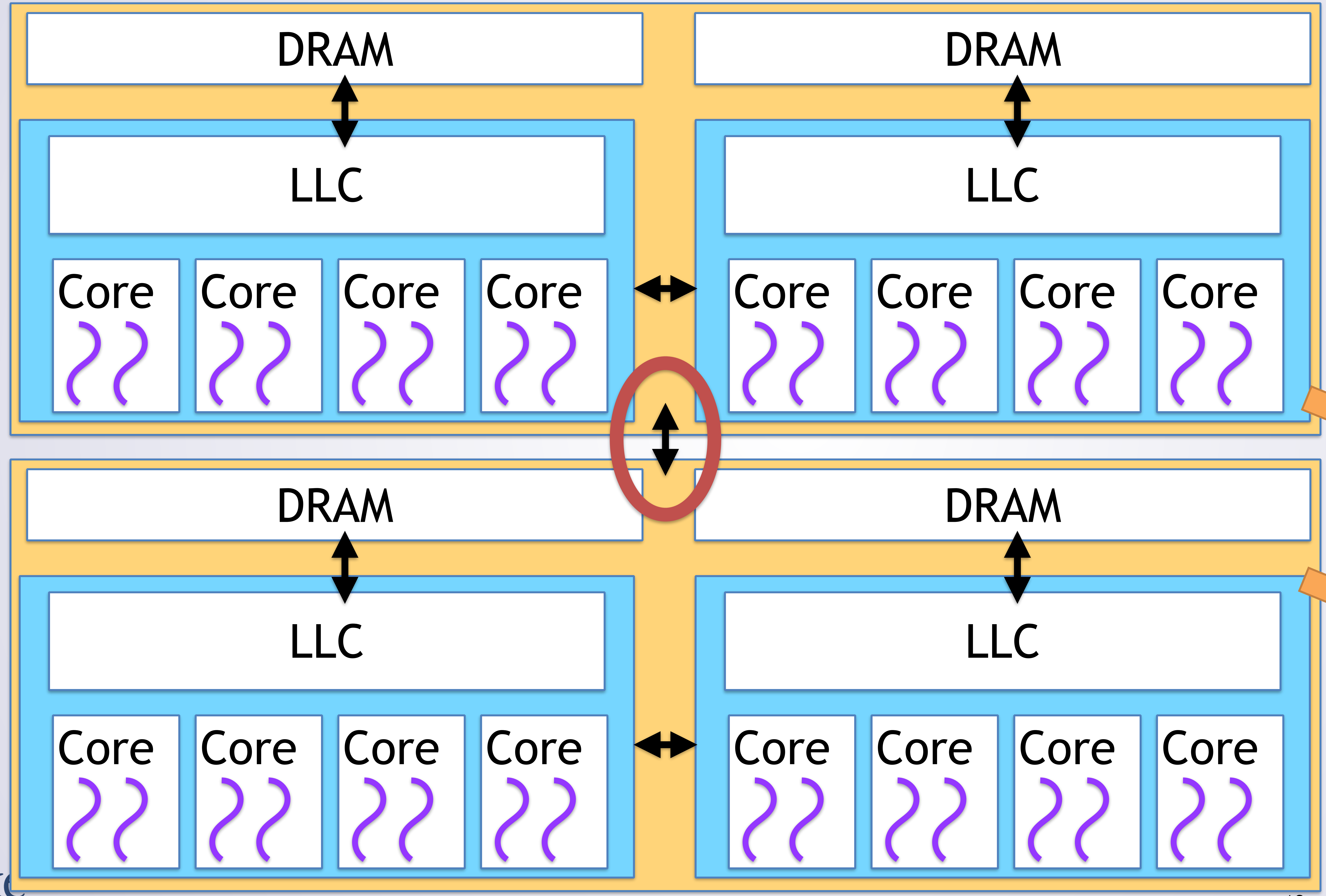
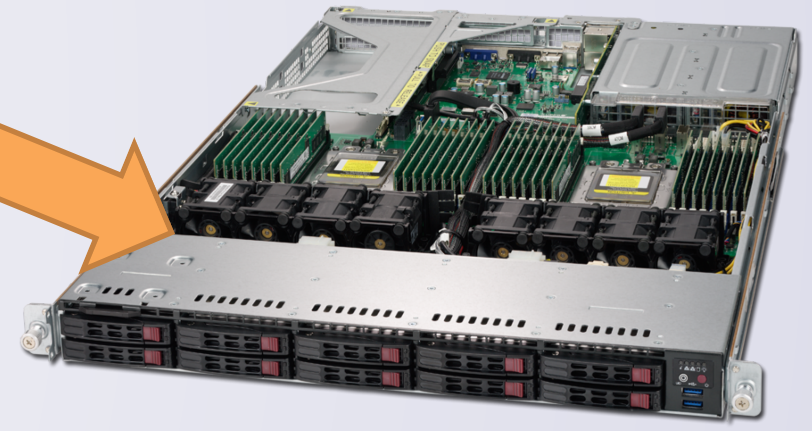
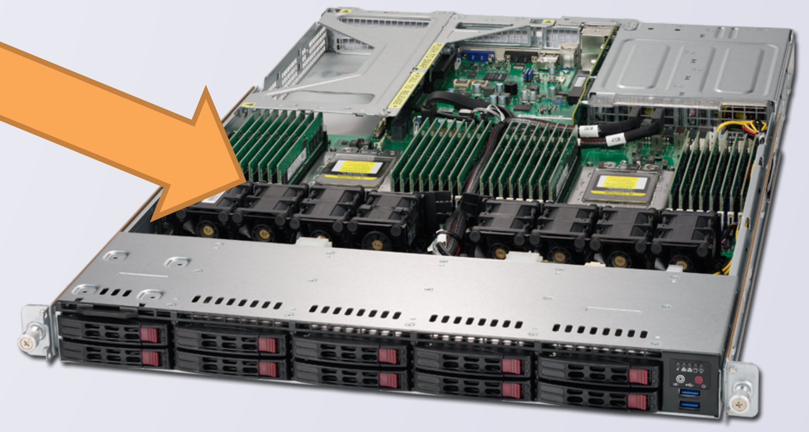
Hypothetical System

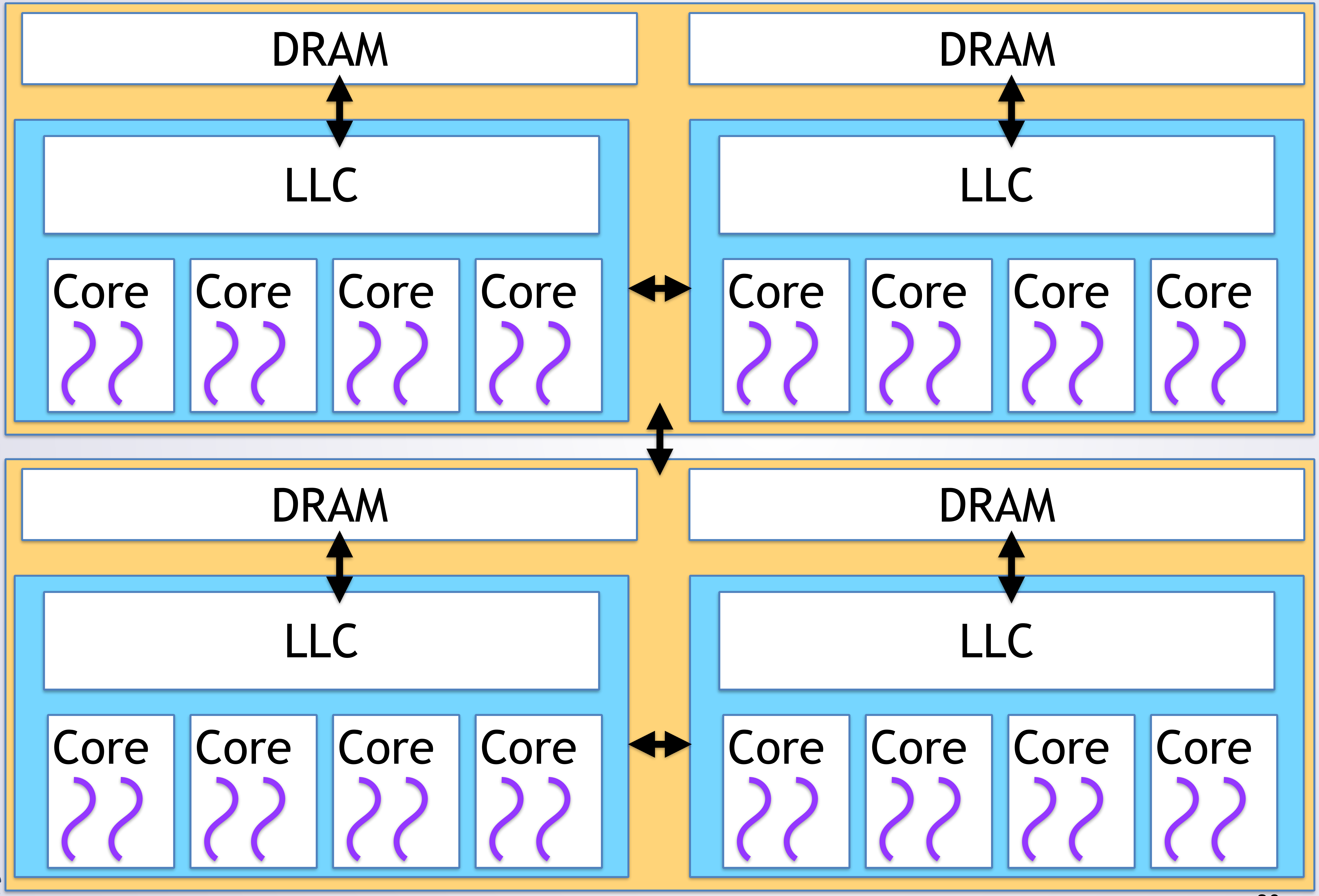


We have 2 nodes





Hypothetical System



Suppose we have 2 requests: where best to run them?

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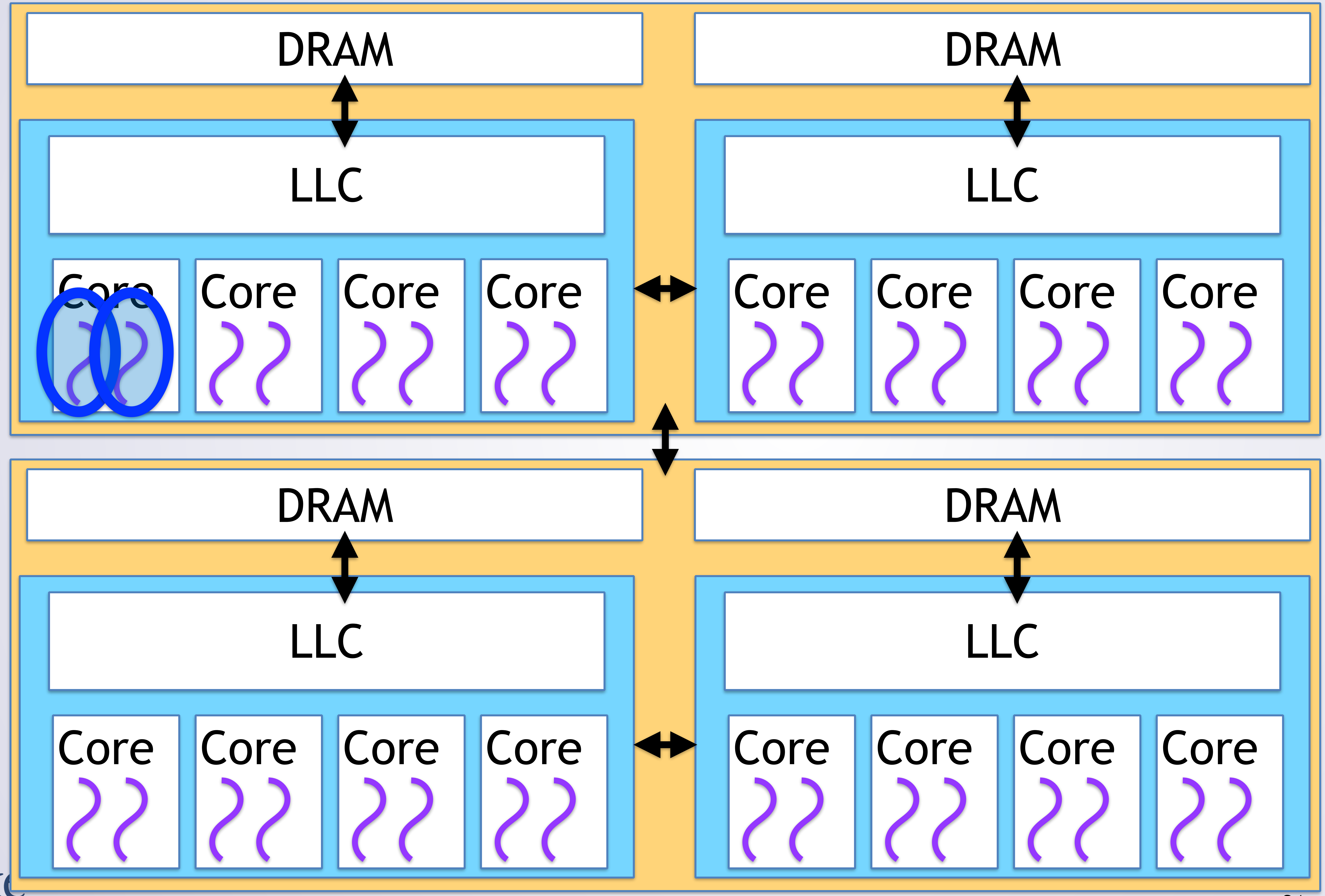
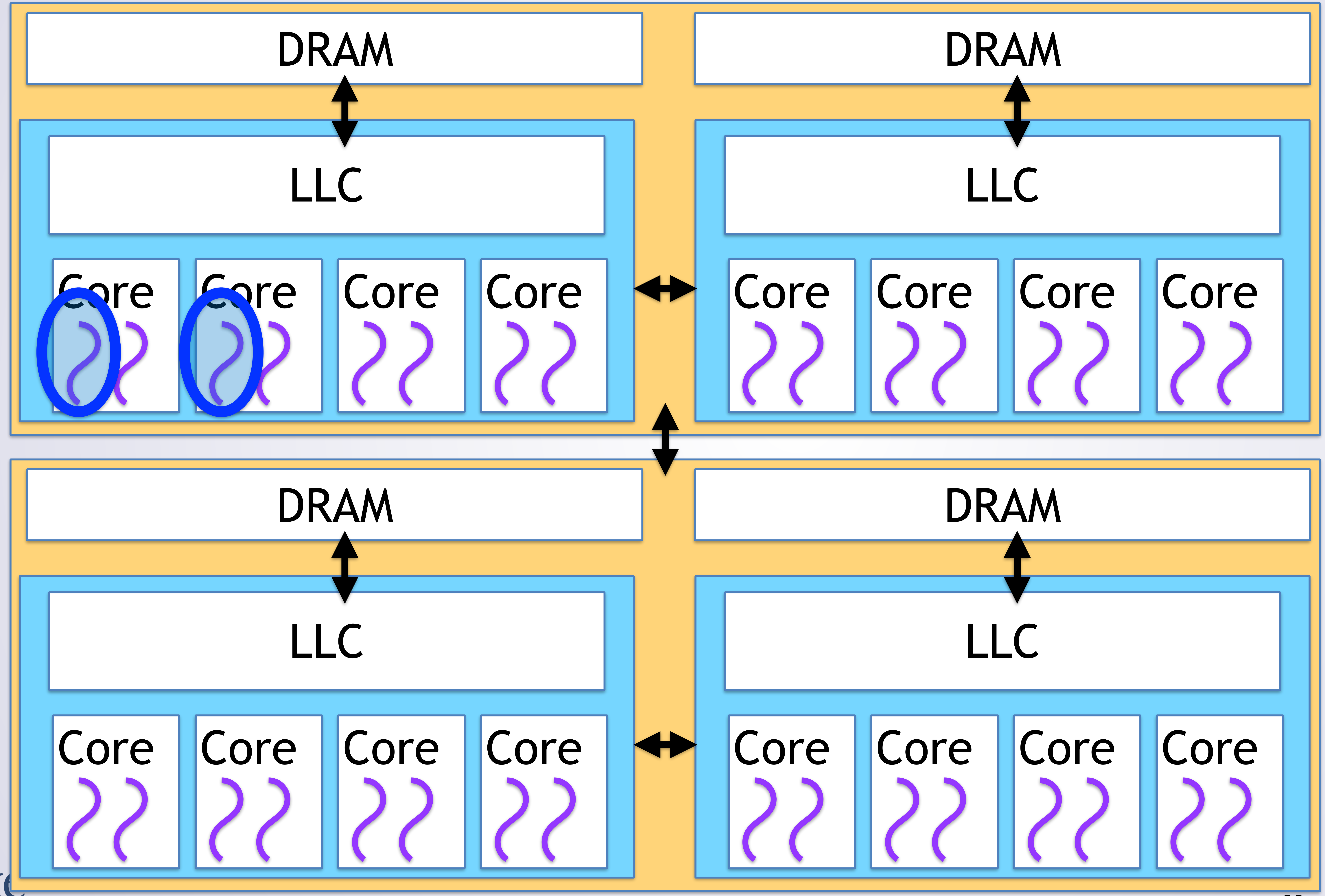
Hypothetical System



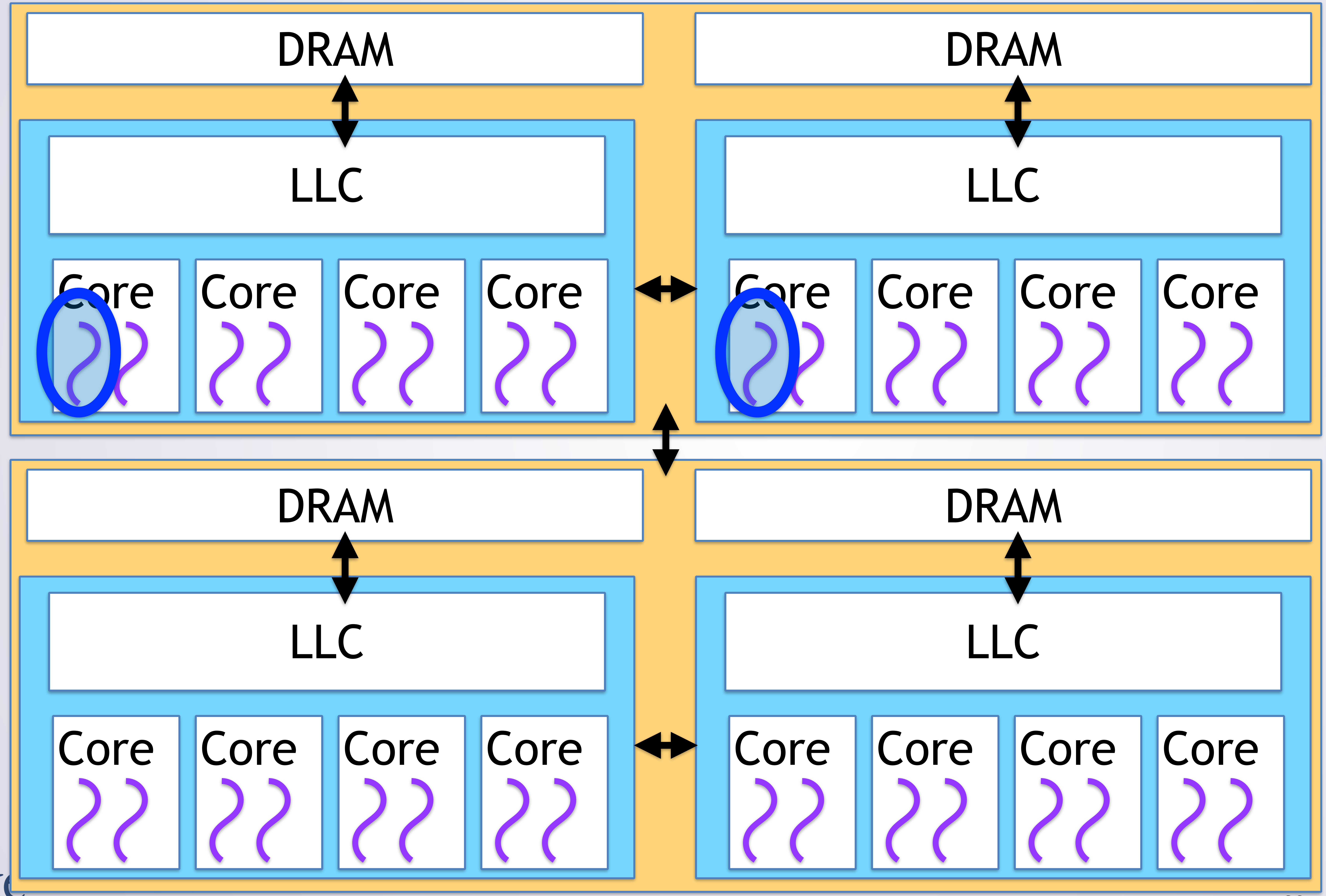
Different threads on same core?

Hypothetical System



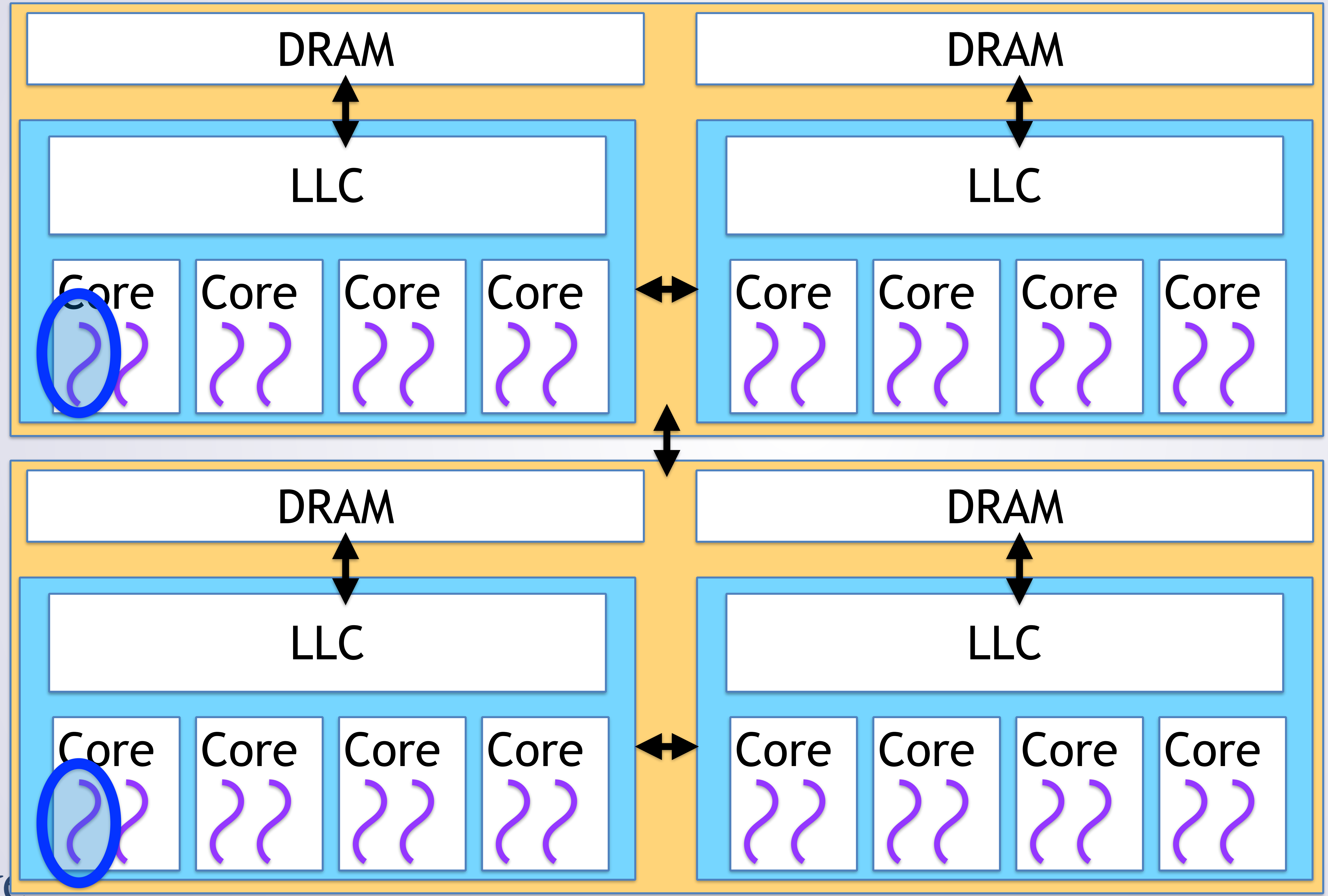
Different cores on same chip?

Hypothetical System



Different chips on same node?

Hypothetical System

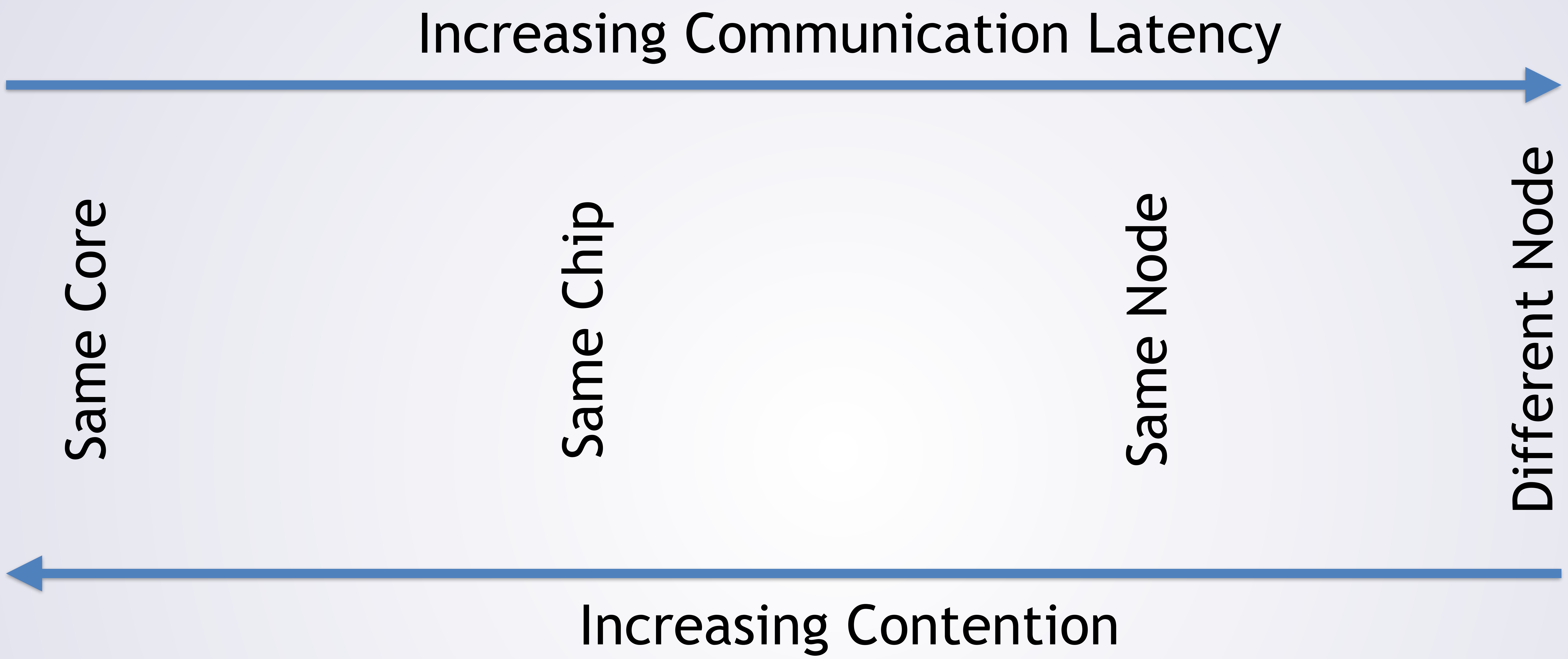


Different nodes?

How To Control Placement?

- Within a node: `sched_setaffinity`
  - Set mask of CPUs that a thread can run on
  - SMT contexts have different CPU identifiers
  - In pthreads, library wrapper: pthread_setaffinity_np
- Across nodes: depends..
  - Daemons running on each node? Direct requests to them
  - Startup/end new services? Software management
  - Load balancing becomes important here

Tradeoff: Contention vs Locality



- Trade off:
  - Contend for shared resources?
  - Longer/slower communication?

Tradeoff: Contention vs Locality

Increasing Communication Latency →

Same Core	Same Chip	Same Node	Different Node
Loads + Stores	Loads + Stores	Loads + Stores	IO Operations
Same Cache	On Chip Coherence	Off Chip Coherence	Network
1s of cycles	10s of cycles	100s cycles	Ks-Ms of cycles

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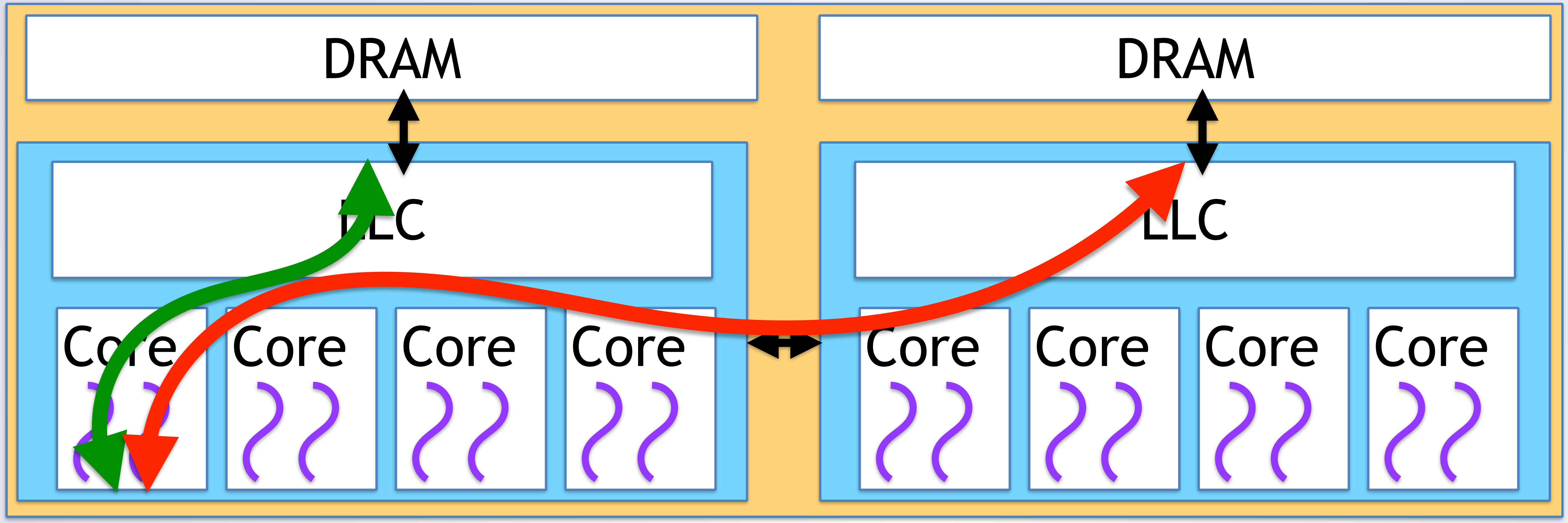
NUMA



- Non Uniform Memory Access (NUMA—technically, ccNUMA)
  - Memory latency differs depending on physical address
  - migrate_pages, mbind: control physical memory placement

Tradeoff: Contention vs Locality

Same Core

Same Chip

Same Node

Different Node

← Increasing Contention

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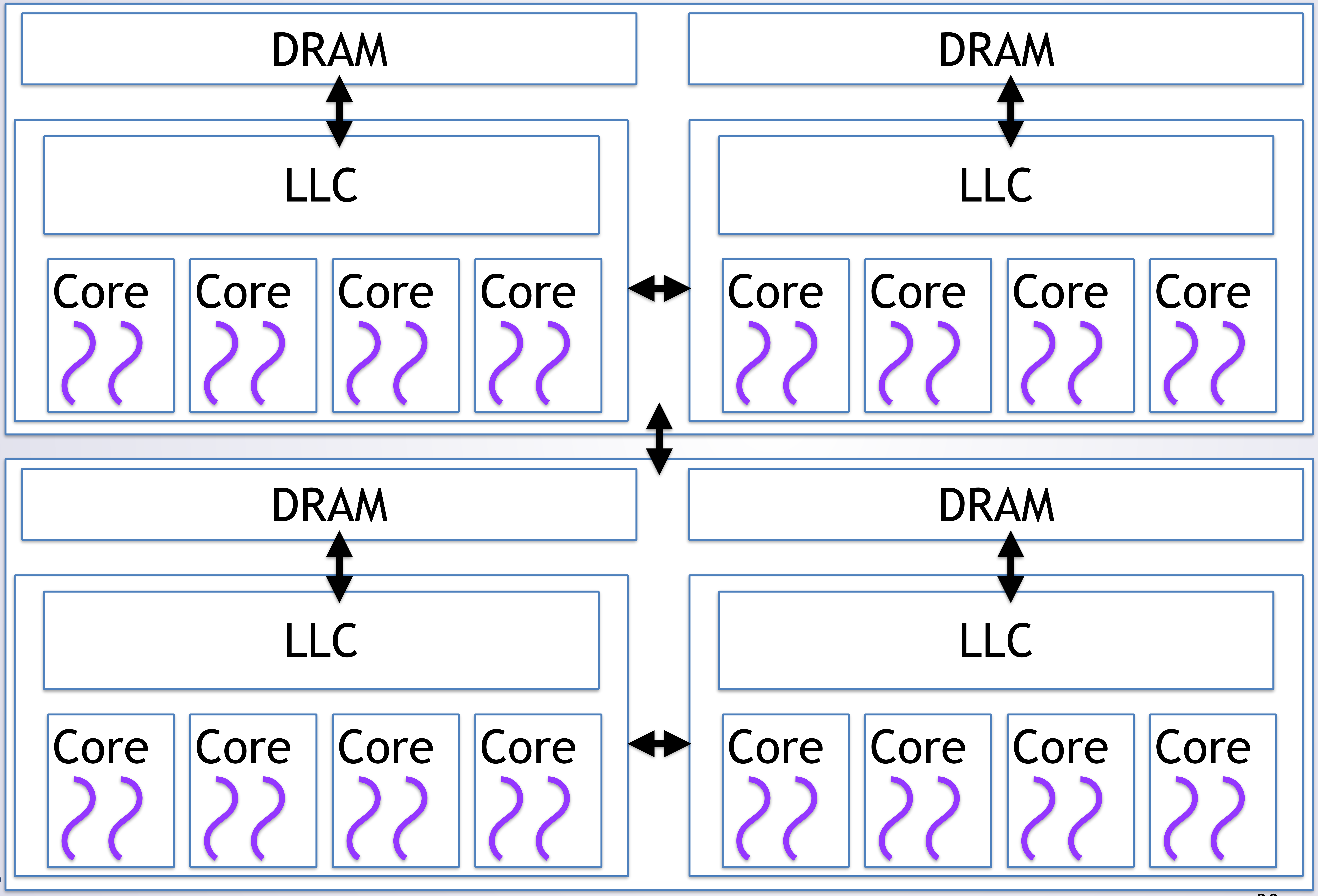
Re-examine Our Hypothetical System



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Tradeoff: Contention vs Locality

- External network b/w
- Datacenter cooling

- Memory b/w
- Chip<-> chip b/w
- IO b/w

- On chip b/w
- LLC capacity
- On chip cooling

- L1/L2 capacity
- Functional Units

Same Core

Same Chip

Same Node

Different Node

Increasing Contention

Interactions Between Resource Contention

- Suppose two threads need + are sensitive to:
  - LLC Capacity
  - Memory bandwidth
- What happens when we run them together?

Interactions Between Resource Contention

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  - Contention for LLC -> more cache misses
    - Slows down program, but also…

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Interactions Between Resource Contention

- Suppose two threads need + are sensitive to:
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- What happens when we run them together?
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    - Increases memory bandwidth demands
        - Which we already need and are contending for :(

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Interactions Between Resource Contention

- Suppose two threads need and are sensitive to:
  - LLC Capacity
  - Memory bandwidth
- What happens when we run them together?
  - Contention for LLC -> more cache misses
    - Slows down program, but also…
  - Increases memory bandwidth demands
    - Which we already need and are contending for :(
- Interactions can make contention even worse!
  - Is there a flip side?

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Improved Utilization

- Can improve utilization of resources
  - One thread executes while another stalls
  - One thread uses FUs that the other does not need
  - Pair large cache footprint with small cache footprint
  - Shared code/data: one copy in cache

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Performance/Scalability 1

- So how do we improve things?

Performance/Scalability 1

- So how do we improve things?
  - Profile our system! Understand **what** is slow and **why**
  - Remember: Ahmdal's law!

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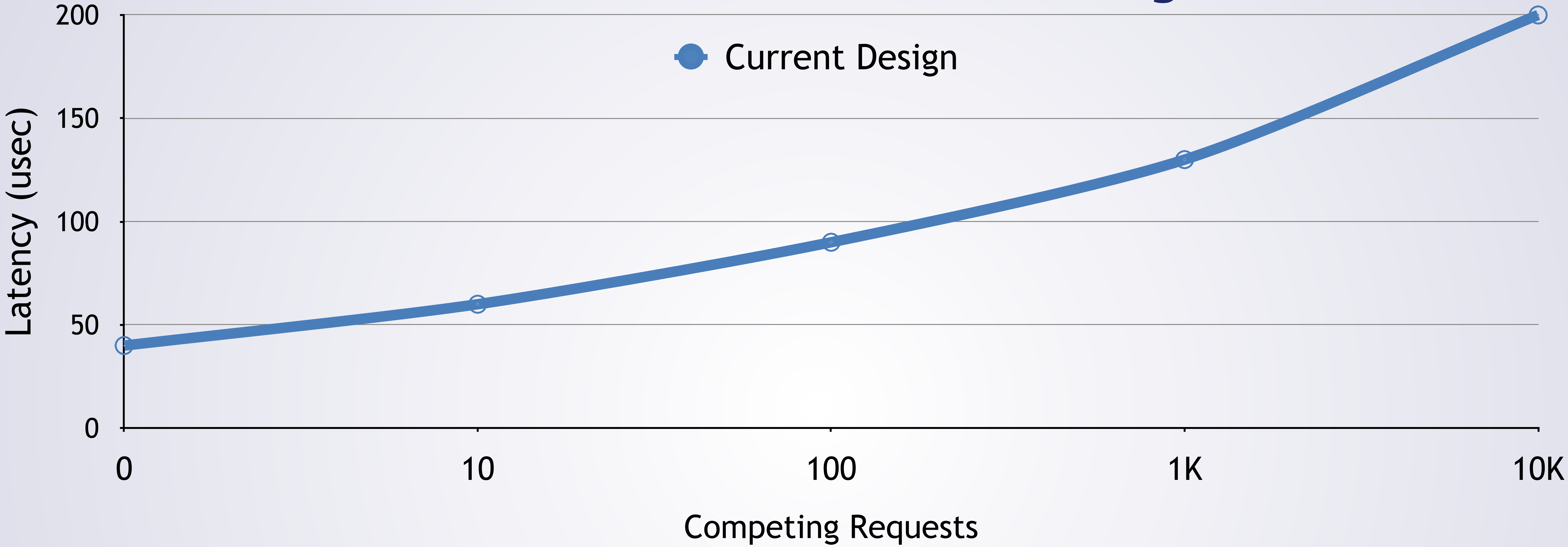
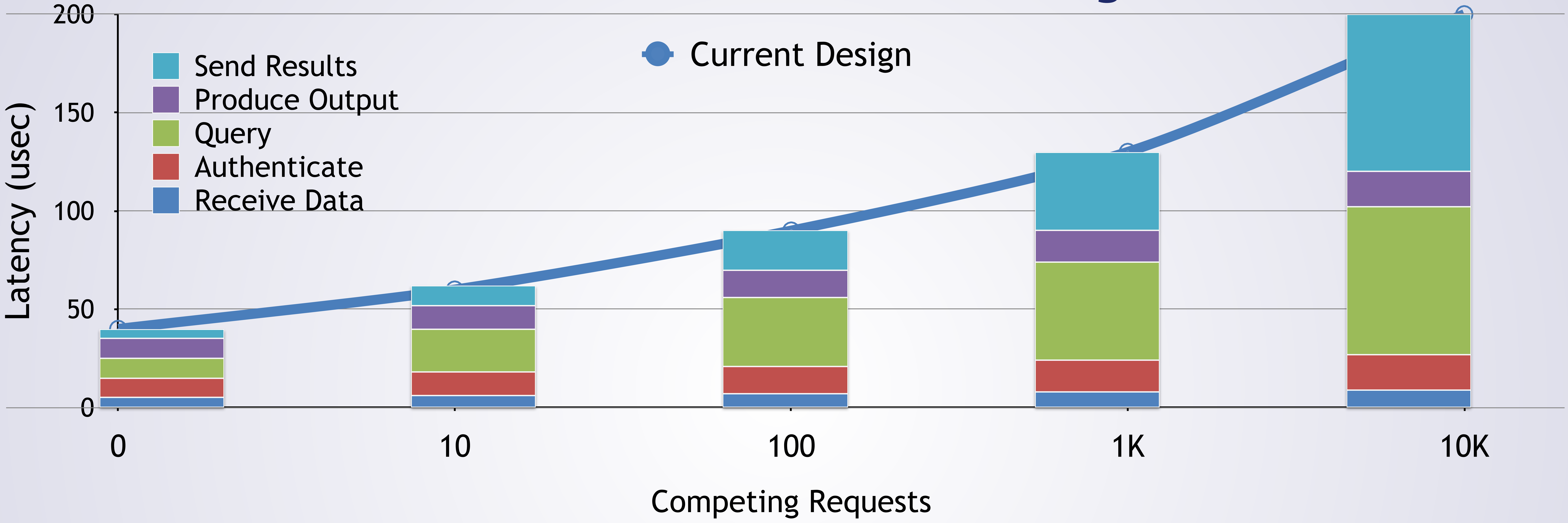


This graph hides a lot of important detail

Intro To Scalability



Breaking it down shows WHERE to focus our optimization efforts

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Performance/Scalability 1

- So how do we improve things?
  - Profile our system! Understand **what** is slow and **why**
  - Remember: Ahmdal's law!
- After making a change, what do we do?

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Performance/Scalability 1

- So how do we improve things?
  - Profile our system! Understand **what** is slow and **why**
  - Remember: Ahmdal's law!
- After making a change, what do we do?
  - Measure impact: did we make things better? How much?

Performance/Scalability 1

- So what can we do?
  - Optimize code to improve its performance
  - Transform code to improve resource usage (e.g. cache space)
  - Pair threads with complementary resource usage

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Performance/Scalability 1

- So what can we do?
  - Optimize code to improve its performance
  - Transform code to improve resource usage (e.g. cache space)
  - Pair threads with complementary resource usage
- Sounds complicated?
  - Learn more about hardware (e.g., ECE 552)
  - Take Performance/Optimization/Parallelism (ECE 565)

Impediments to Scalability

- Shared Hardware
  - Functional Units
  - Caches
  - Memory Bandwidth
  - IO Bandwidth
  - …
- Data Movement
  - From one core to another
- Blocking
  - Blocking IO
  - Locks (and other synchronization)

Let's talk about this next

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Never Block

- Critical principle: never block
  - Why not?

Never Block

- Critical principle: never block
  - Why not?
- Can't we just throw more threads at it?
  - One thread per request (or even a few per request)
  - Just block whenever you want

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Never Block

- Critical principle: never block
  - Why not?
- Can't we just throw more threads at it?
  - One thread per request (or even a few per request)
  - Just block whenever you want
- Nice in theory, but has overheads
  - Context switching takes time
  - Switching threads reduces temporal locality
    - Threads not blocked? May thrash if too many
  - Threads use resources

Non-Blocking IO

- IO operations often block (we never want to block)
  - Can use non-blocking IO

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Non-Blocking IO

- IO operations often block (we never want to block)
  - Can use non-blocking IO
- Set FD to non-blocking using fcntl:

```
int x = fcntl(fd, F_GETFL, 0);
x |= O_NONBLOCK;
fcntl(fd, F_SETFL, x);
```

- Now reads/writes/etc won't block
  - Just return immediately if can't perform IO immediately
  - Note: not magic
    - **ONLY** means that IO operation returns without waiting

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Non-Blocking IO: Continued

```
int x = read (fd, buffer, size);
if (x < 0) {
    if (errno == EAGAIN){
        //no data available
    }
    else {
        //error
    }
}
```

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Non-Blocking IO: Continued

```
while (size > 0) {
    int x = read (fd, buffer, size);
    if (x < 0) {
        if (errno == EAGAIN){
            //no data available
        }
        else {
            //error
        }
    }
    else {
      buffer += x;
      size -= x;
    }
}
```

What if we just wrap this up in a while loop?

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Non-Blocking IO: Continued

```
while (size > 0) {
    int x = read (fd, buffer, size);
    if (x < 0) {
        if (errno == EAGAIN){
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        }
        else {
            //error
        }
    }
    else {
        buffer += x;
        size -= x;
    }
}
```

What if we just wrap this up in a while loop?

Now we just made this blocking!
We are just doing the blocking ourselves…

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Busy Wait

- This approach is **worse** than blocking IO
    - Why?

Busy Wait

- This approach is **worse** than blocking IO
  - Why?
- Busy waiting
  - Code is "actively" doing nothing
  - Keeping CPU busy, consuming power, contending with other threads
- Blocking IO:
  - At least OS will put thread to sleep while it waits

So What Do We Do?

- Need to do **something else** while we wait
  - Like what?

So What Do We Do?

- Need to do **something else** while we wait
  - Like what?
- It depends….
  - On what?

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So What Do We Do?

- Need to do **something else** while we wait
  - Like what?
- It depends….
  - On what?
- On what our server does
- On what the demands on it are
- On the model of parallelism we are using
  - Who can name some models of parallelism? [AoP Ch 28 review]

Data parallelism, Pipeline parallelism, Task parallelism, etc.

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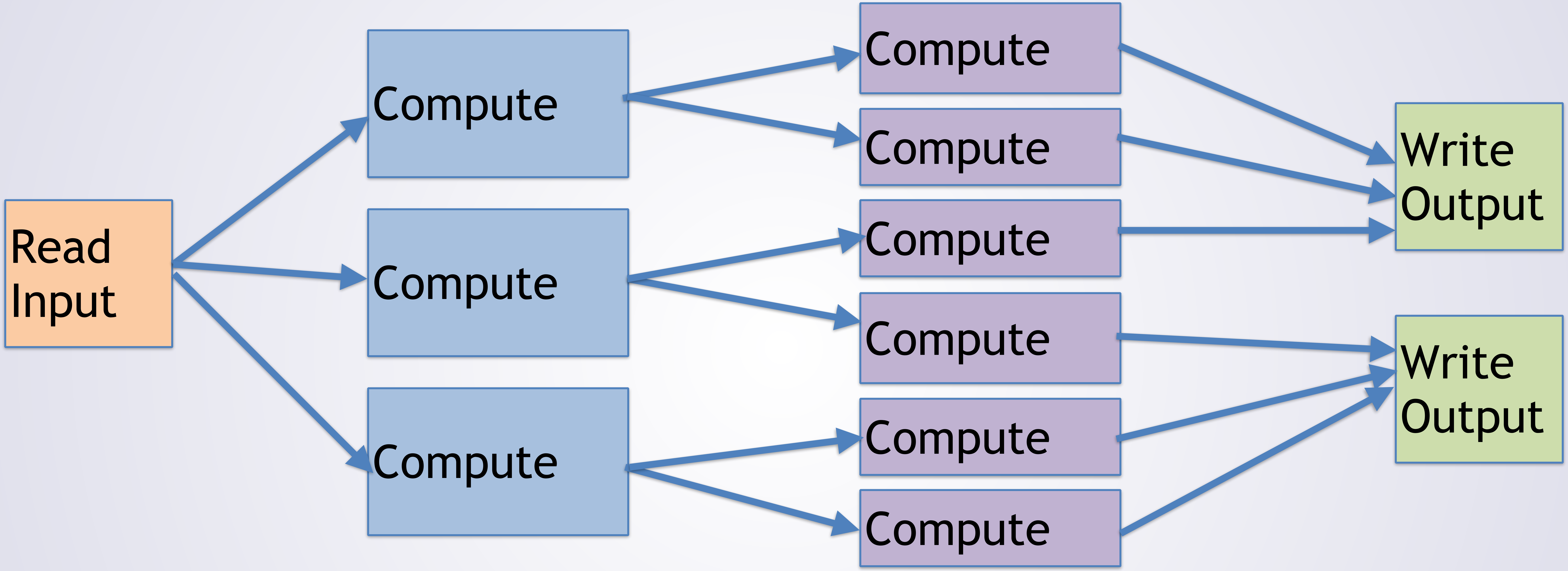
Pipeline Parallelism



- When would this be appropriate?
- What do our IO threads do for "something else"?

Pipeline Parallelism

- When appropriate: Can keep IO thread(s) busy
  - Heavy IO to perform
  - Might have one thread do reads and writes
- What is "something else"?
  - Other IO requests
  - Do whichever one is ready to be done

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Pipeline Parallelism

- When appropriate: Can keep IO thread(s) busy
  - Heavy IO to perform
  - Might have one thread do reads and writes
- What is "something else"?
  - Other IO requests
  - Do whichever one is ready to be done
- Making hundreds of read/write calls to see which succeeds = inefficient
  - Use `poll` or `select`

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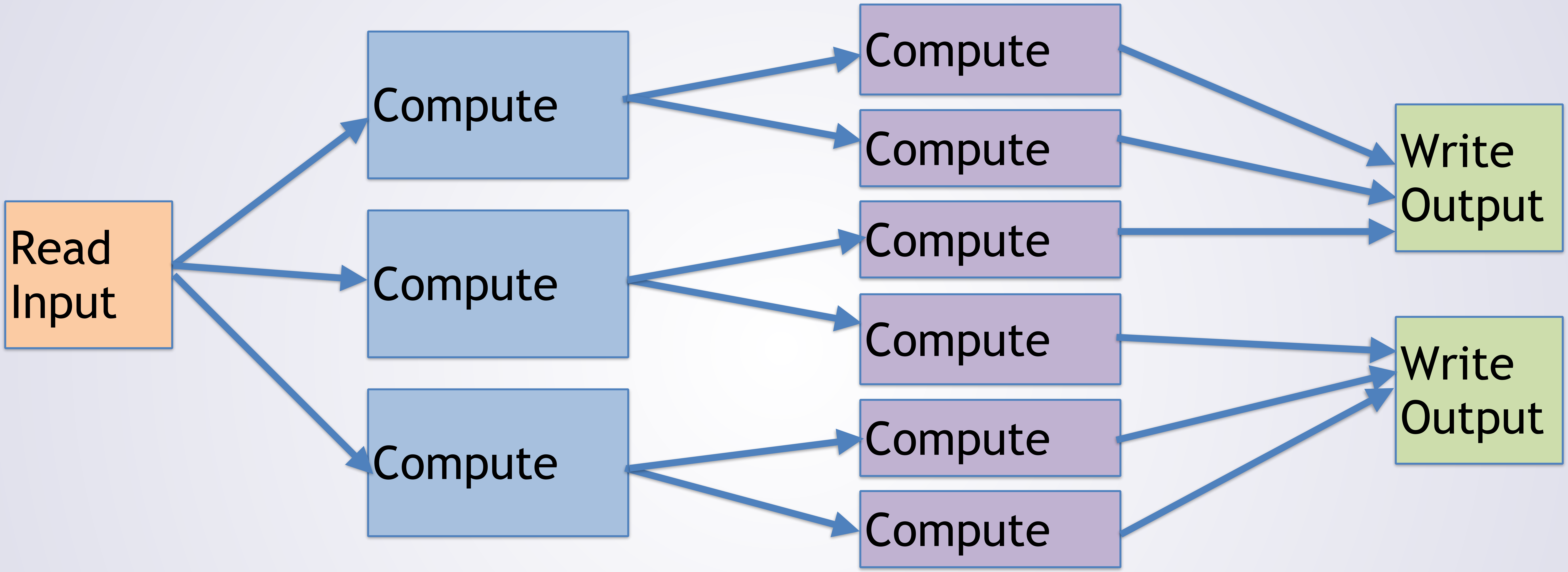
Pipeline Parallelism



- What can you say about data movement in this model? There's lots of it ☹
- What can you say about load balance? It's pretty easy to balance (just profile it) ☺

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Another Option

- Could have one thread work on many requests

```
while(1) {
  Accept new requests
  Do any available reads/writes
  Do any available compute
}
```

- What can you say about data movement in this model?

There's less of it ☺

- What can you say about load balance?

It's harder: a thread can end up with imbalanced tasks ☹

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A Slight Variant

- Slightly different inner loop:

```
while(1) {
  Accept new requests
  For each request with anything to do
       Do any available IO for that request
       Do any compute for that request
}
```

- What can you say about data movement in this model?
- What can you say about load balance?

In between ☹
(We do compute on the IO we just did, so less movement there)

Good, all threads can hit all request ☺

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