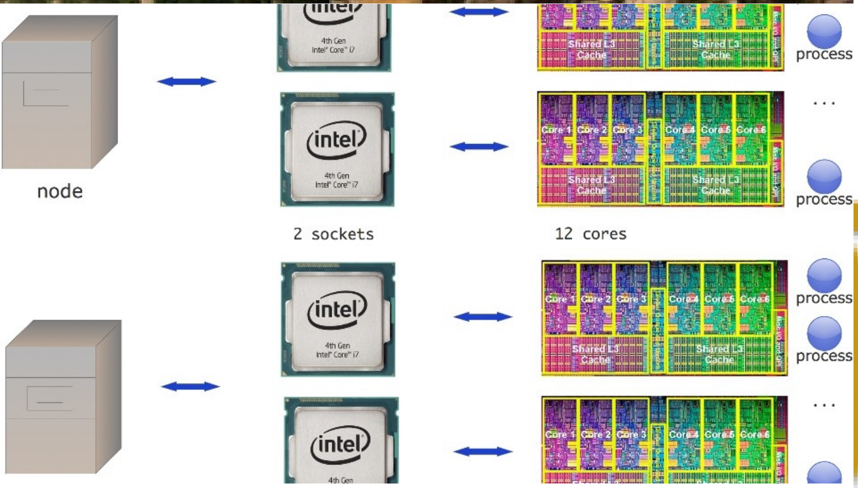
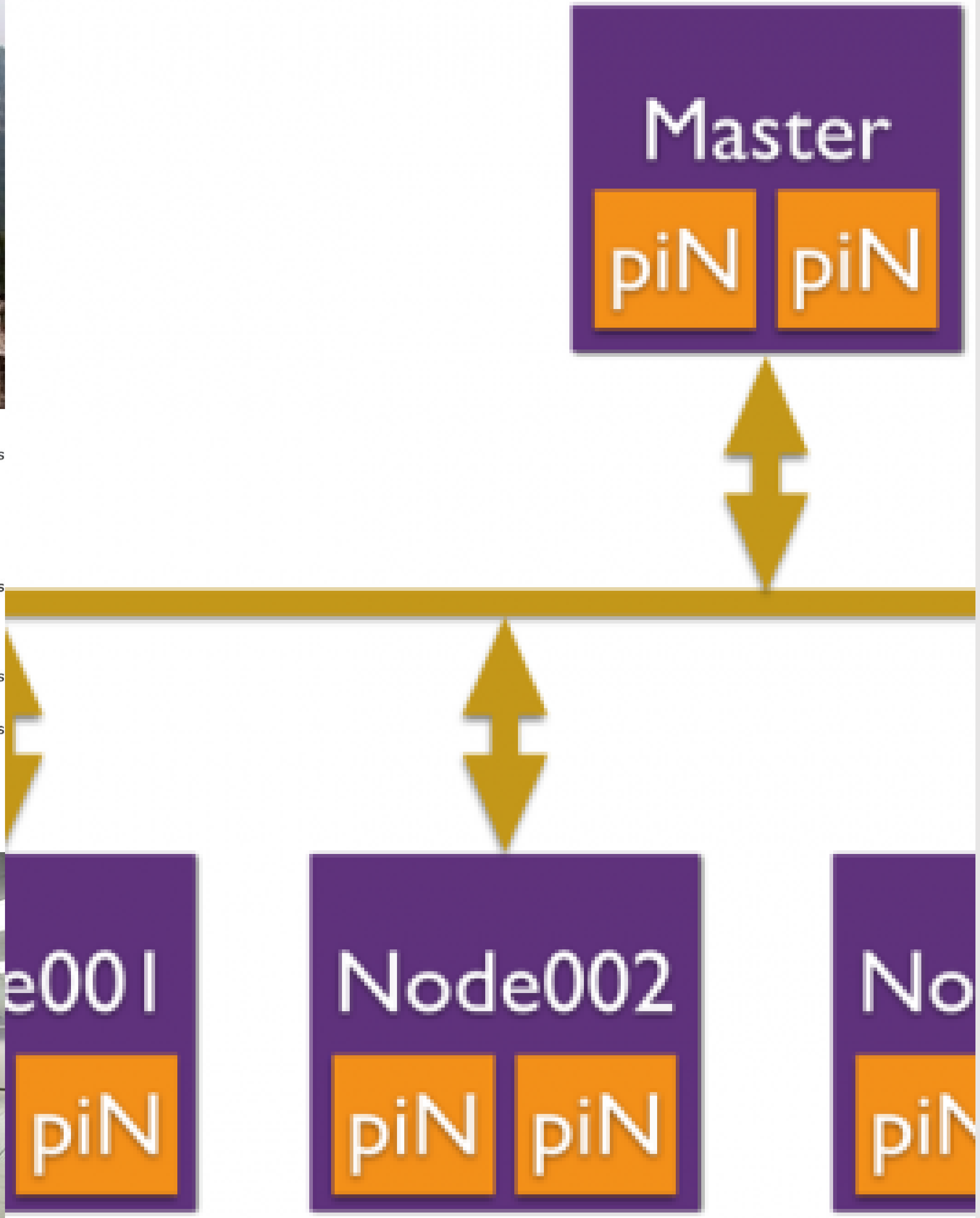
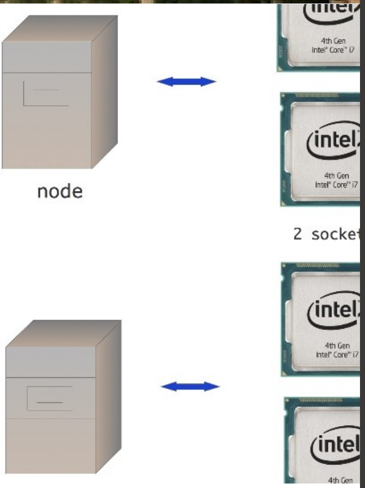
Rust + 2PC
Parallelism at Scale: MPI

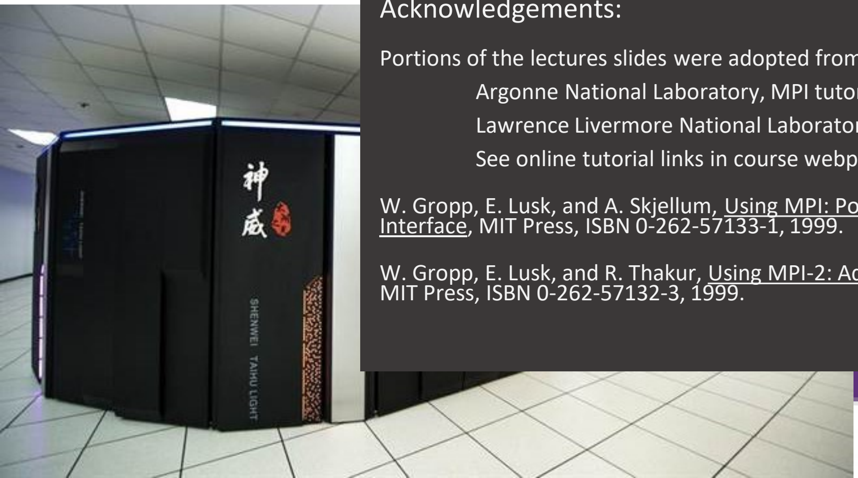
cs378h

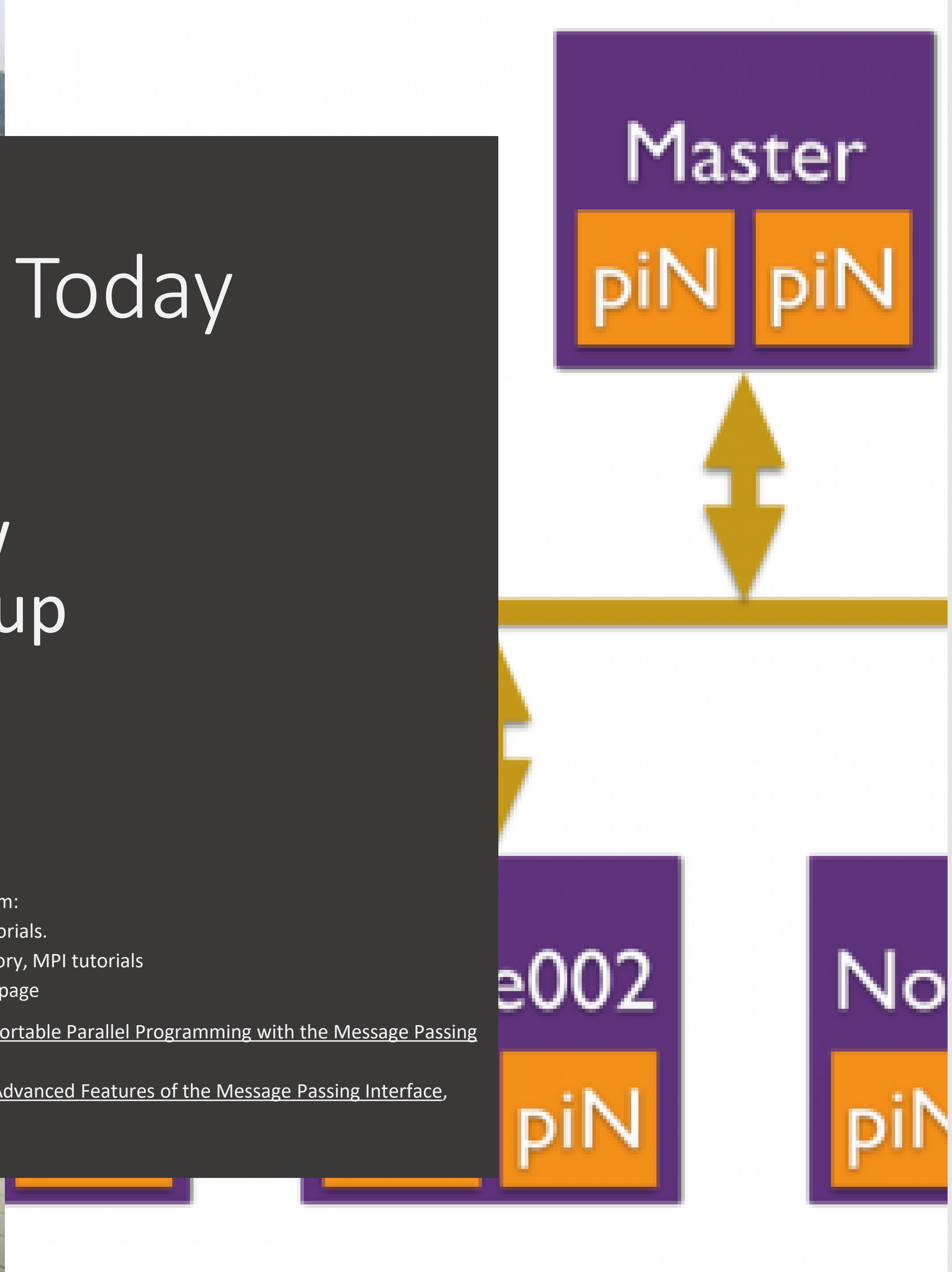

node
2 sockets
12 cores
process
process
process
process
...


神威
SHENWEI TAIHU LIGHT


Master
piN
piN
e001
piN
Node002
piN
piN
No
pi







Outline for Today

- Project
- 2PC review
- Rust Wrapup
- Scale
- MPI

Acknowledgements:

Portions of the lectures slides were adopted from:

- Argonne National Laboratory, MPI tutorials.
- Lawrence Livermore National Laboratory, MPI tutorials
- See online tutorial links in course webpage

W. Gropp, E. Lusk, and A. Skjellum, Using MPI: Portable Parallel Programming with the Message Passing Interface, MIT Press, ISBN 0-262-57133-1, 1999.

W. Gropp, E. Lusk, and R. Thakur, Using MPI-2: Advanced Features of the Message Passing Interface, MIT Press, ISBN 0-262-57132-3, 1999.

Project Proposal

CS378: Concurrency

Project Proposal

The goal of this assignment is to come up with a plan for your course project.

The project is a more open-ended assignment, where you have the flexibility to pursue an topic or area that interests you. The goal of the first part of this assignment then, is to identify roughly v

I encourage you to come up with your own project idea, but there are suggestions at the end of this assignment for projects for those wishing for more guidance.

You must submit a proposal (1-2 pages long), meeting the guidelines and answering the basic questions enumerated below:

- Provide a detailed timeline of how you plan to build the system. It is really important to have intermediate milestones where some subset of functionality is *completely working* by date X ra on the deadline. Give a list of 4 key milestones.
- What infrastructure will you have to build to run the experiments you want to run?
- What hardware will you need and where will you get it? (Talk to me early if you have an experiment that needs hardware support but you don't know where to get the hardware from.)
- What kind of experiments do you plan to run?
- How will you know if you have succeeded?
- What kind of performance or functionality problems do you anticipate?

Planning is important. So I will review your proposal and give you feedback. If signficant refinement is needed, I will ask you to hand in a revised proposal in the few weeks after the proposal d

You can work in groups for your project.

- A very good example

Project Proposal

Ideas:

- Heterogeneity
- Transactional Memory
- Julia, X10, Chapel
- Actor Models: Akka
- Dataflow Models
- Race Detection
- Lock-free data structures
- ….

The sky is the limit

CS378: Concurrency

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Questions?

Ownership/Borrowing

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  let name = format!("...");
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What kinds of problems might this prevent?

Pass by reference takes "ownership implicitly" in other languages like Java

Shared Borrowing

```
fn main() {
  let name = format!("...");
  helper(&name);
  helper(&name);
}
```

```
fn helper(name: &String) {
  println!(“{}”, name);
}
```

Shared Borrowing

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fn main() {
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Lend the string

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fn helper(name: &String) {
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Lend the string

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```

Take a reference to a String

Why does this fix the problem?

Shared Borrowing with Concurrency

```
fn main() {
  let name = format!("...");
  helper(&name);
  helper(&name);
}
```

```
fn helper(name: &String) {
  thread::spawn(||{
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Lifetime `static` required

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error[E0621]: explicit lifetime required in the type of `name`
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   |                 ------- help: add explicit lifetime `'static` to the type of `name`: `&'static std::string::String`
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Does this prevent the exact same class of problems?

Clone, Move

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fn main() {
  let name = format!("...");
  helper(name.clone());
  helper(name);
}
```

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fn helper(name: String) {
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Explicitly take ownership

Clone, Move

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Ensure concurrent owners
Work with different copies

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Is this better?

Clone, Move

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Is this better?

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Copy versus Clone:

Default: Types cannot be copied

- Values move from place to place
- E.g. file descriptor

Clone: Type is expensive to copy

- Make it explicit with clone call
- e.g. Hashtable

Copy: type implicitly copy-able

- e.g. u32, i32, f32, …

#[derive(Clone, Debug)]

Mutability

```rust
struct Structure {
    id: i32,
    map: HashMap<String, f32>,
}

impl Structure {
    fn mutate(&mut self, name: String, value: f32){
        self.map.insert(name, value);
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Key idea:

- Force mutation and ownership to be explicit
- Fixes MM *and* concurrency in fell swoop!

Sharing State

```
fn main() {
  let var = Structure::new();
  for i in 0..N {
    thread::spawn(move || {
       // ok to mutate var?
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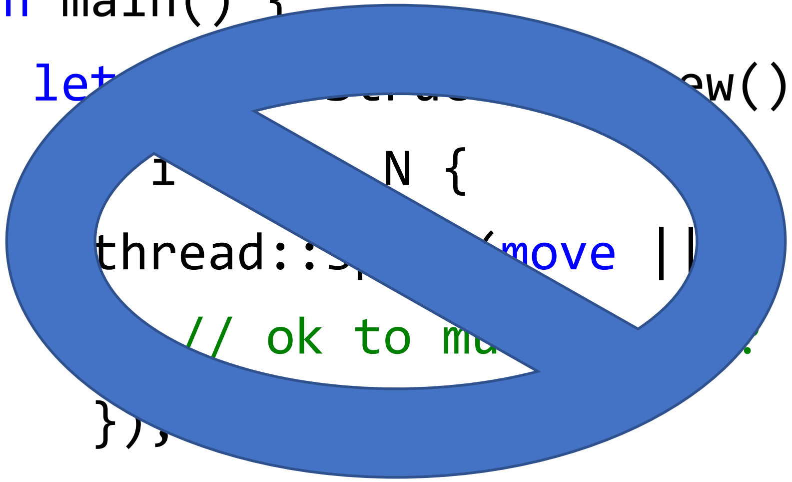
Sharing State



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Key ideas:

- Use reference counting wrapper to pass refs
- Use scoped lock for mutual exclusion
- Actually compiles → works 1st time!

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error[E0382]: use of moved value: `var_arc`
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Would cloning var_arc fix it?

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Same problem!

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    thread::spawn(move || {
      let ldata = Arc::clone(&var_arc.clone());
      let vdata = ldata.lock();
      // ok to mutate var (vdata)!
    });
```

Same problem!

What if we just don't ***move?***

```
   Compiling concurrency-2pc v0.1.0 (/u/rossbach/src/utcs-concurrency/labs/2pc/solution)
error[E0382]: use of moved value: `var_arc`
   --> src/main.rs:166:22
    |
164 |     let var_arc = Arc::new(var_lock);
    |         ------- move occurs because `var_arc` has type `std::sync::Arc<std::sync::Mutex<message::ProtocolMessage>>`, which does not implement the `Copy`
165 |     for _i in 0..N {
166 |         thread::spawn(move || {
    |                       ^^^^^^^ value moved into closure here, in previous iteration of loop
167 |             let ldata = Arc::clone(&var_arc);
    |                                     ------- use occurs due to use in closure
```

Sharing State: Arc and Mutex, *really*

```
fn test() {
  let var = Structure::new();
  let var_lock = Mutex::new(var);
  let var_arc = Arc::new(var_lock);
  for i in 0..N {
    thread::spawn(|| {
      let ldata = Arc::clone(&var_arc);
      let vdata = ldata.lock();
      // ok to mutate var (vdata)!
    });
  }
}
```

Sharing State: Arc and Mutex, *really*

```rust
fn test() {
  let var = Structure::new();
  let var_lock = Mutex::new(var);
  let var_arc = Arc::new(var_lock);
  for i in 0..N {
    thread::spawn(|| {
      let ldata = Arc::clone(&var_arc);
      let vdata = ldata.lock();
      // ok to mutate var (vdata)!
    });
```

```
[101] ~/src/utcs-concurrency/labs/2pc/solution$ cargo build
   Compiling concurrency-2pc v0.1.0 (/u/rossbach/src/utcs-concurrency/labs/2pc/solution)
error[E0373]: closure may outlive the current function, but it borrows `var_arc`, which is owned by the current function
   --> src/main.rs:166:22
    |
166 |         thread::spawn(|| {
    |                       ^^ may outlive borrowed value `var_arc`
167 |             let ldata = Arc::clone(&var_arc);
    |                                     -------- `var_arc` is borrowed here
    |
note: function requires argument type to outlive `'static`
```

Sharing State: Arc and Mutex, *really*

```rust
fn test() {
  let var = Structure::new();
  let var_lock = Mutex::new(var);
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  for i in 0..N {
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      let ldata = Arc::clone(&var_arc);
      let vdata = ldata.lock();
      // ok to mutate var (vdata)!
    });
```

What's the actual fix?

```
[101] ~/src/utcs-concurrency/labs/2pc/solution$ cargo build
   Compiling concurrency-2pc v0.1.0 (/u/rossbach/src/utcs-concurrency/labs/2pc/solution)
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   --> src/main.rs:166:22
    |
166 |         thread::spawn(|| {
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note: function requires argument type to outlive `'static`
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Sharing State: Arc and Mutex, *really*

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fn test() {
  let var = Structure::new();
  let var_lock = Mutex::new(var);
  let var_arc = Arc::new(var_lock);
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    thread::spawn(move || {
      let ldata = Arc::clone(&clone_arc);
      let vdata = ldata.lock();
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}
```

Sharing State: Arc and Mutex, *really*

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    thread::spawn(move || {
      let ldata = Arc::clone(&clone_arc);
      let vdata = ldata.lock();
      // ok to mutate var (vdata)!
    });
  }
}
```

Compiles! Yay!
Other fixes?

Sharing State: Arc and Mutex, *really*

```
fn test() {
  let var = Structure::new();
  let var_lock = Mutex::new(var);
  let var_arc = Arc::new(var_lock);
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}
```

Why does this compile?

Sharing State: Arc and Mutex, *really*

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  }

}
```

Could we use a vec of JoinHandle to keep var_arc in scope?

Sharing State: Arc and Mutex, *really*

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      let ldata = Arc::clone(&var_arc);
      let vdata = ldata.lock();
      // ok to mutate var (vdata)!
    });
  }
  for i in 0..N { join(); }
}
```

Could we use a vec of JoinHandle
to keep var_arc in scope?

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What if I need my lambda to own some things and borrow others?

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Parameters!

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Sharing State: Arc and Mutex, *really*

```
fn test() {
  let var = Structure::new();
  let var_lock = Mutex::new(var);
  let var_arc = Arc::new(var_lo...
```

```
// Closures are anonymous, here we are binding them to references
// Annotation is identical to function annotation but is optional
// as are the `{}` wrapping the body. These nameless functions
// are assigned to appropriately named variables.
let closure_annotated = |i: i32| -> i32 { i + 1 };
let closure_inferred  = |i     |          i + 1  ;
```

```
      // ok to mutate var (vdata)!
    });
  }
  for i in 0..N { join(); }
}
```

Parameters!

Could we use a vec of JoinHandle to keep var_arc in scope?

What if I need my lambda to own some things and borrow others?

Discussion

GC lambdas, Rust C++

- This is pretty nuanced:
- Stack closures, owned closures, managed closures, exchg heaps

Ownership and Macros

Macros use regexp and expand to closures

Summary

Rust: best of both worlds

- systems vs productivity language

Separate sharing, mutability, concurrency

Type safety solves MM and concurrency

Have fun with the lab!

Transactions

Core issue: multiple updates

Canonical examples:

```
move(file, old-dir, new-dir) {
    delete(file, old-dir)
    add(file, new-dir)
}
```

```
create(file, dir) {
    alloc-disk(file, header, data)
    write(header)
    add (file, dir)
}
```

Transactions

Core issue: multiple updates

Canonical examples:

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- Modified data in memory/caches
- Even if in-memory data is durable, multiple disk updates

Transactions

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Problem: crash in the middle

- Modified data in memory/caches
- Even if in-memory data is durable, multiple disk updates

Transactions: Implementation

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- Key idea: turn multiple updates into a single one

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- Many implementation Techniques
  - Two-phase locking
  - Timestamp ordering
  - Optimistic Concurrency Control
  - Journaling
  - 2,3-phase commit
  - Speculation-rollback
  - Single global lock
  - Compensating transactions

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Key problems:
- output commit
- synchronization

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Key problems:
- output commit
- synchronization

Two-phase commit

- N participants agree or don’t (atomicity)
- Phase 1: everyone “prepares”
- Phase 2: Master decides and tells everyone to actually commit
- What if the master crashes in the middle?

2PC: Phase 1

1. Coordinator sends REQUEST to all participants
2. Participants receive request and
3. Execute locally
4. Write VOTE_COMMIT or VOTE_ABORT to local log
5. Send VOTE_COMMIT or VOTE_ABORT to coordinator

Example—move: C→S1: delete foo from /, C→S2: add foo to /

Failure case:
S1 writes rm /foo, VOTE_COMMIT to log
S1 sends VOTE_COMMIT
S2 decides permission problem
S2 writes/sends VOTE_ABORT

Success case:
S1 writes rm /foo, VOTE_COMMIT to log
S1 sends VOTE_COMMIT
S2 writes add foo to /
S2 writes/sends VOTE_COMMIT

2PC: Phase 2

- Case 1: receive VOTE_ABORT or timeout
    - Write GLOBAL_ABORT to log
    - send GLOBAL_ABORT to participants
- Case 2: receive VOTE_COMMIT from all
    - Write GLOBAL_COMMIT to log
    - send GLOBAL_COMMIT to participants
- Participants receive decision, write GLOBAL_* to log

2PC corner cases

Phase 1

1. Coordinator sends REQUEST to all participants
X 2. Participants receive request and
3. Execute locally
4. Write VOTE_COMMIT or VOTE_ABORT to local log
5. Send VOTE_COMMIT or VOTE_ABORT to coordinator

Phase 2

- Y Case 1: receive VOTE_ABORT or timeout
  - Write GLOBAL_ABORT to log
  - send GLOBAL_ABORT to participants
- Case 2: receive VOTE_COMMIT from all
  - W Write GLOBAL_COMMIT to log
  - send GLOBAL_COMMIT to participants
- Z Participants recv decision, write GLOBAL_* to log

- What if participant crashes at X?
- Coordinator crashes at Y?
- Participant crashes at Z?
- Coordinator crashes at W?

2PC limitation(s)

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- Coordinator crashes at W, never wakes up

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- All nodes block forever!

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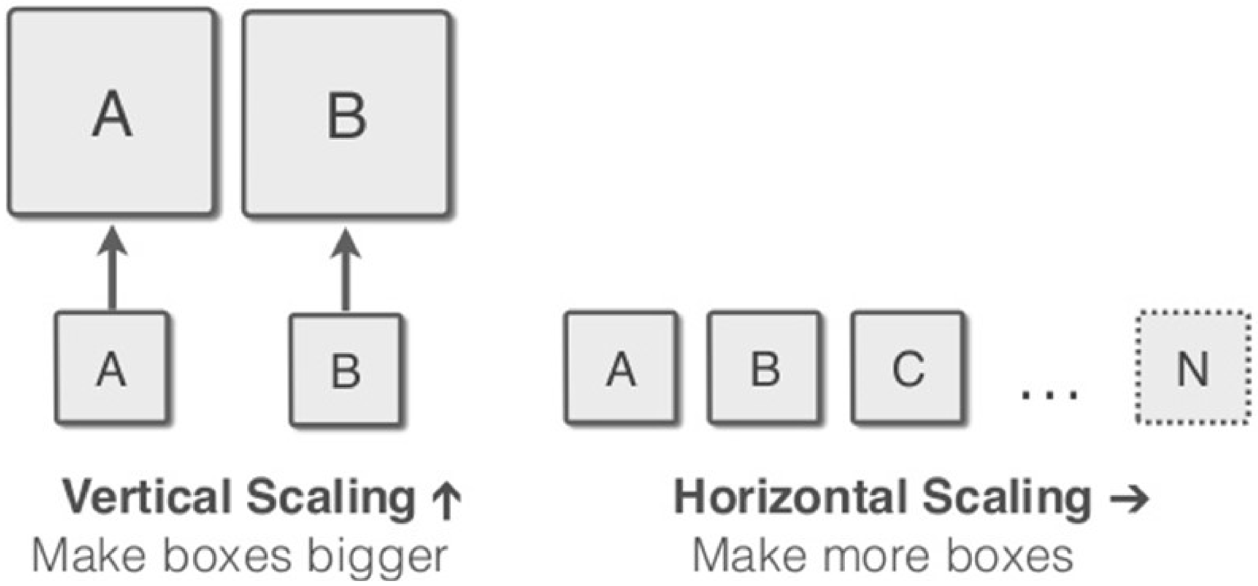
2PC limitation(s)

- Coordinator crashes at W, never wakes up
- All nodes block forever!
- Can participants ask each other what happened?
- 2PC: always has risk of indefinite blocking
- Solution: (yes) 3 phase commit!
  - Reliable replacement of crashed “leader”
  - 2PC often good enough in practice

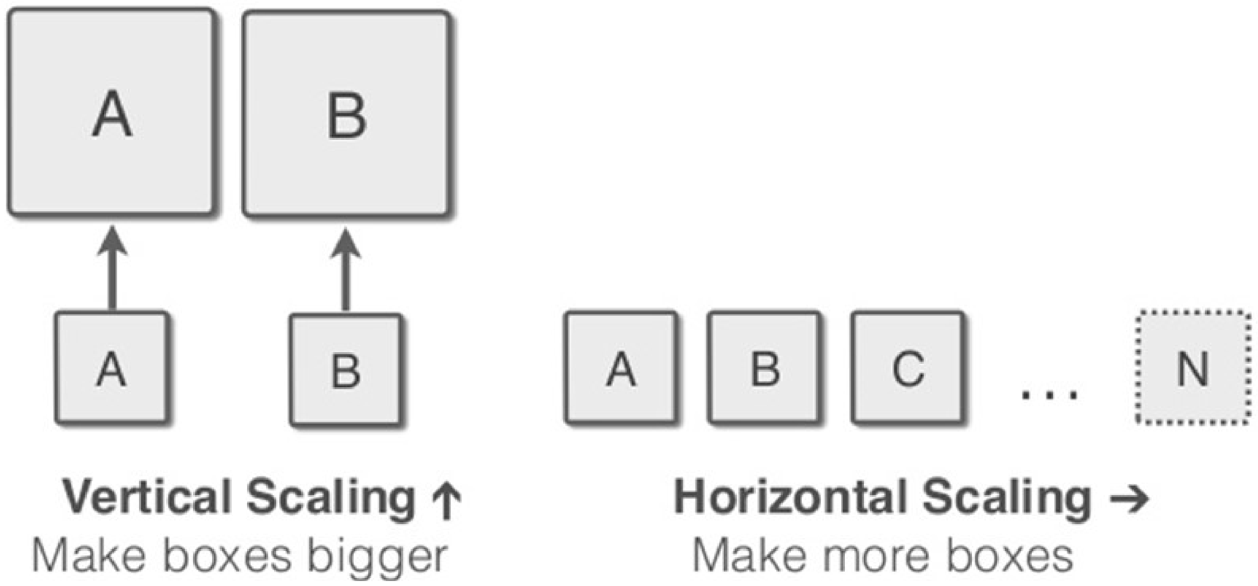
Questions?

Scale Out vs Scale Up

Scale Out vs Scale Up



Scale Out vs Scale Up



Vertical Scaling	Horizontal Scaling
Higher Capital Investment	On Demand Investment
Utilization concerns	Utilization can be optimized
Relatively Quicker and works with the current design	Relatively more time consuming and needs redesigning
Limiting Scale	Internet Scale

Parallel Systems Architects Wanted

Parallel Systems Architects Wanted

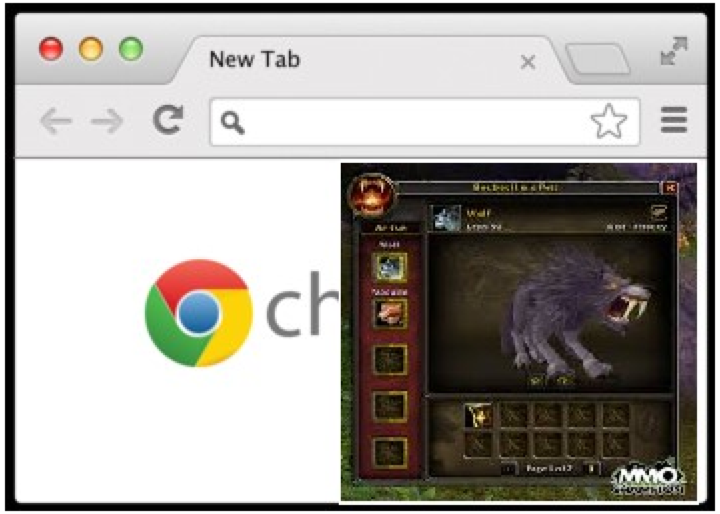
Hot Startup Idea:

www.purchase-a-pooch.biz

Parallel Systems Architects Wanted

Parallel Systems Architects Wanted

1. User Browses Potential Pets



Parallel Systems Architects Wanted

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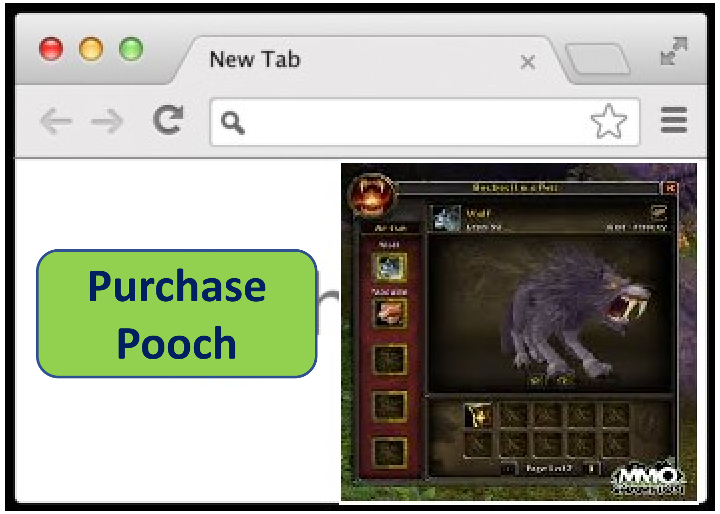

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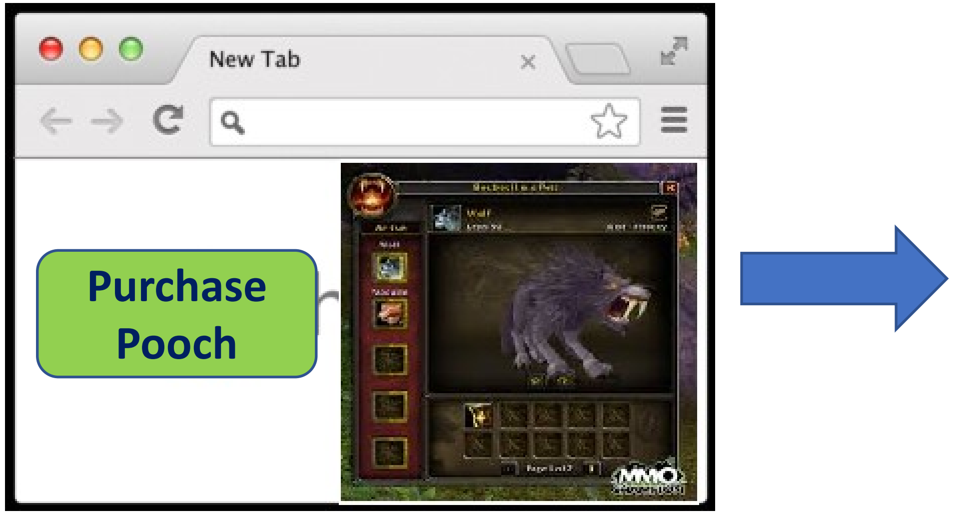

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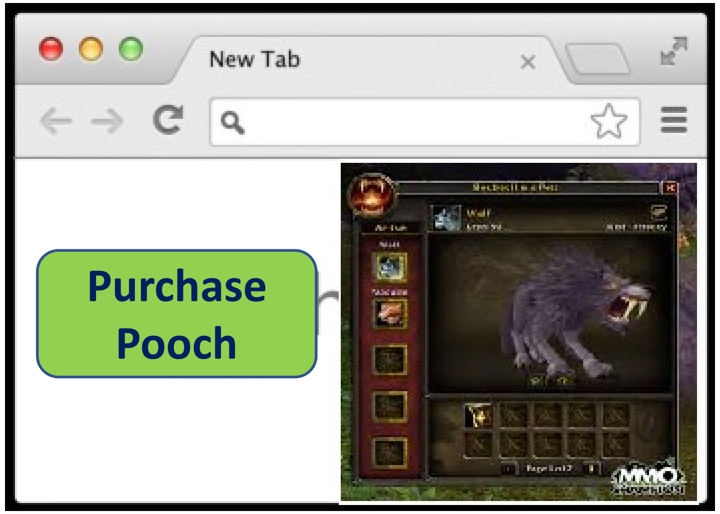

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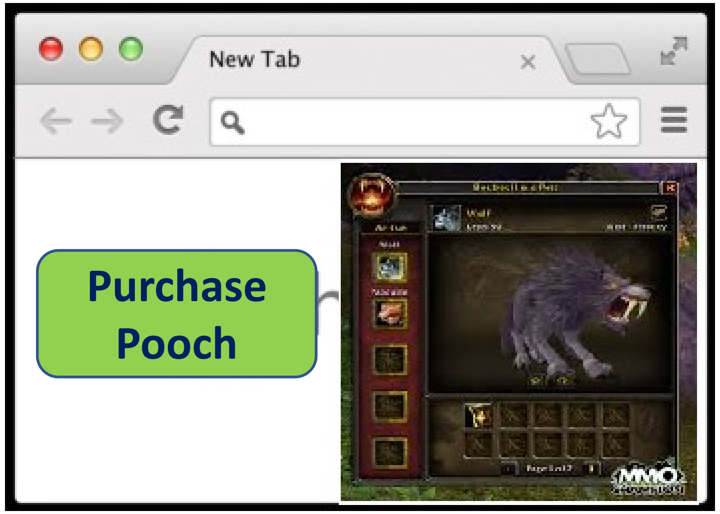
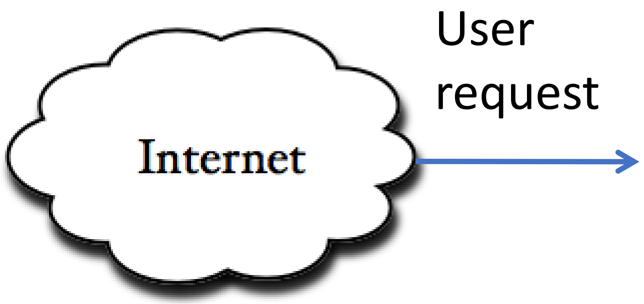
How to handle lots and lots of dogs?



3 Tier architecture



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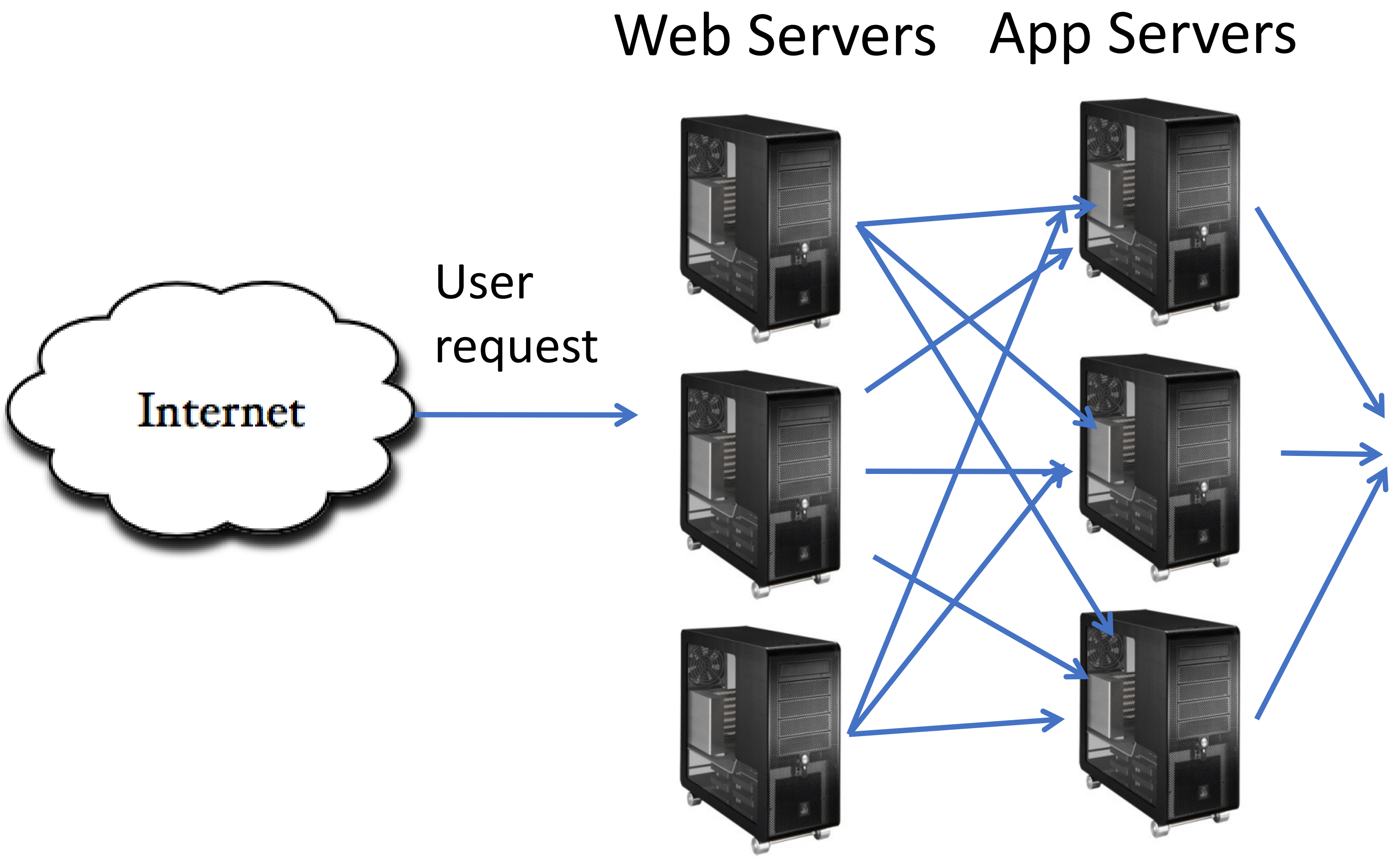
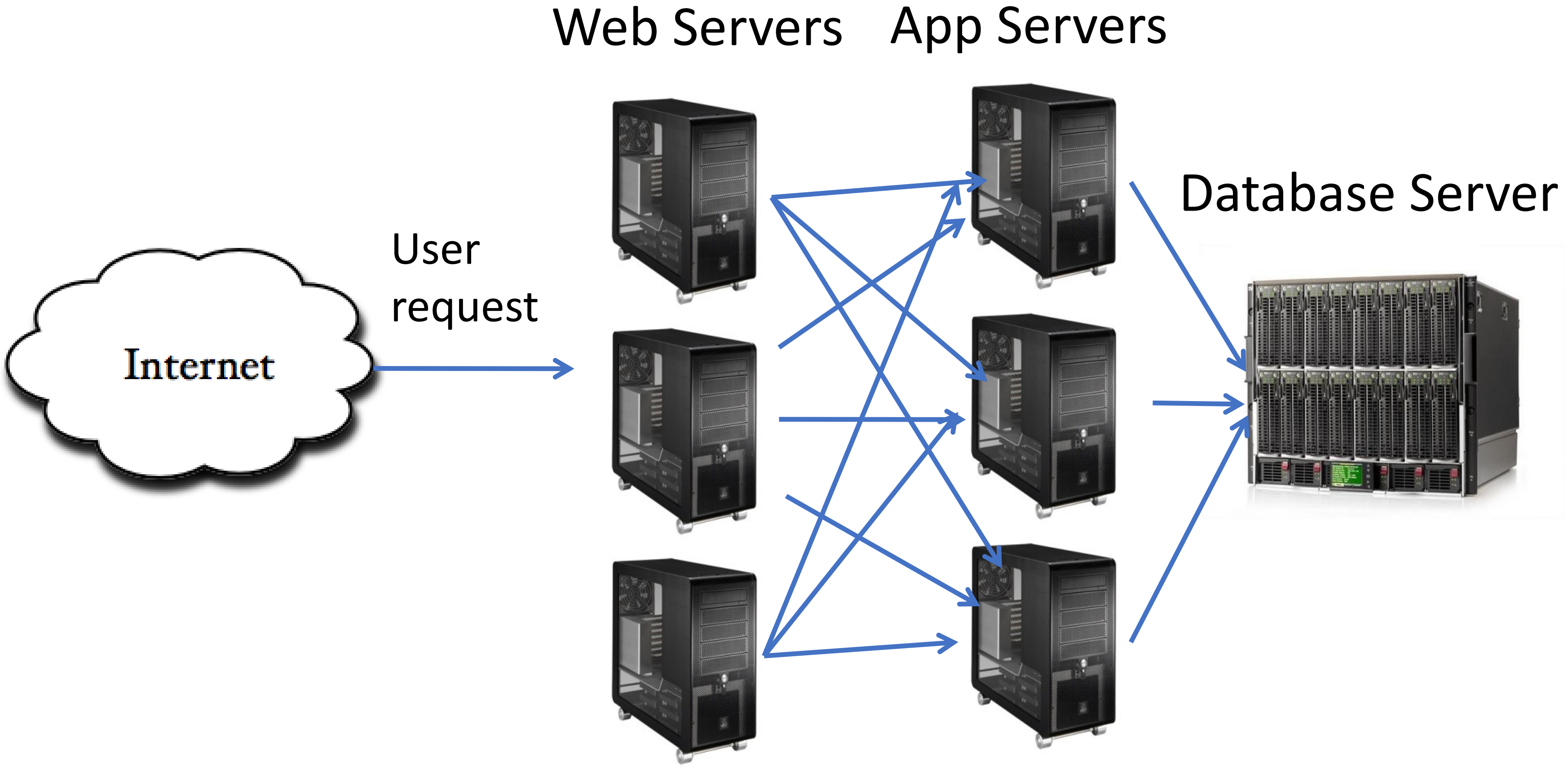


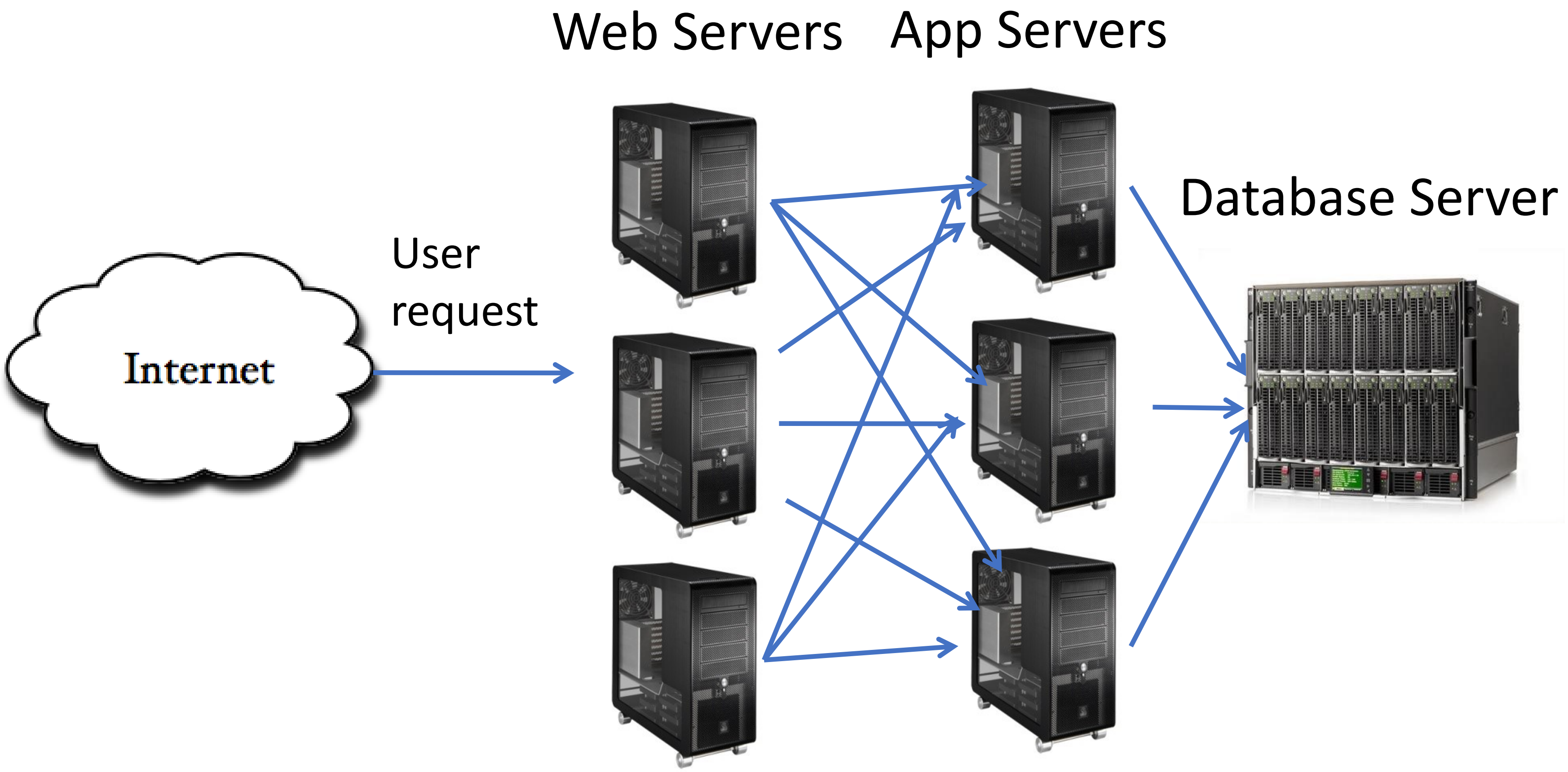
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

3 Tier architecture



Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*
Database Server → scales *vertically*
Horizontal Scale → "Shared Nothing"

3 Tier architecture



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Why is this a good arrangement?

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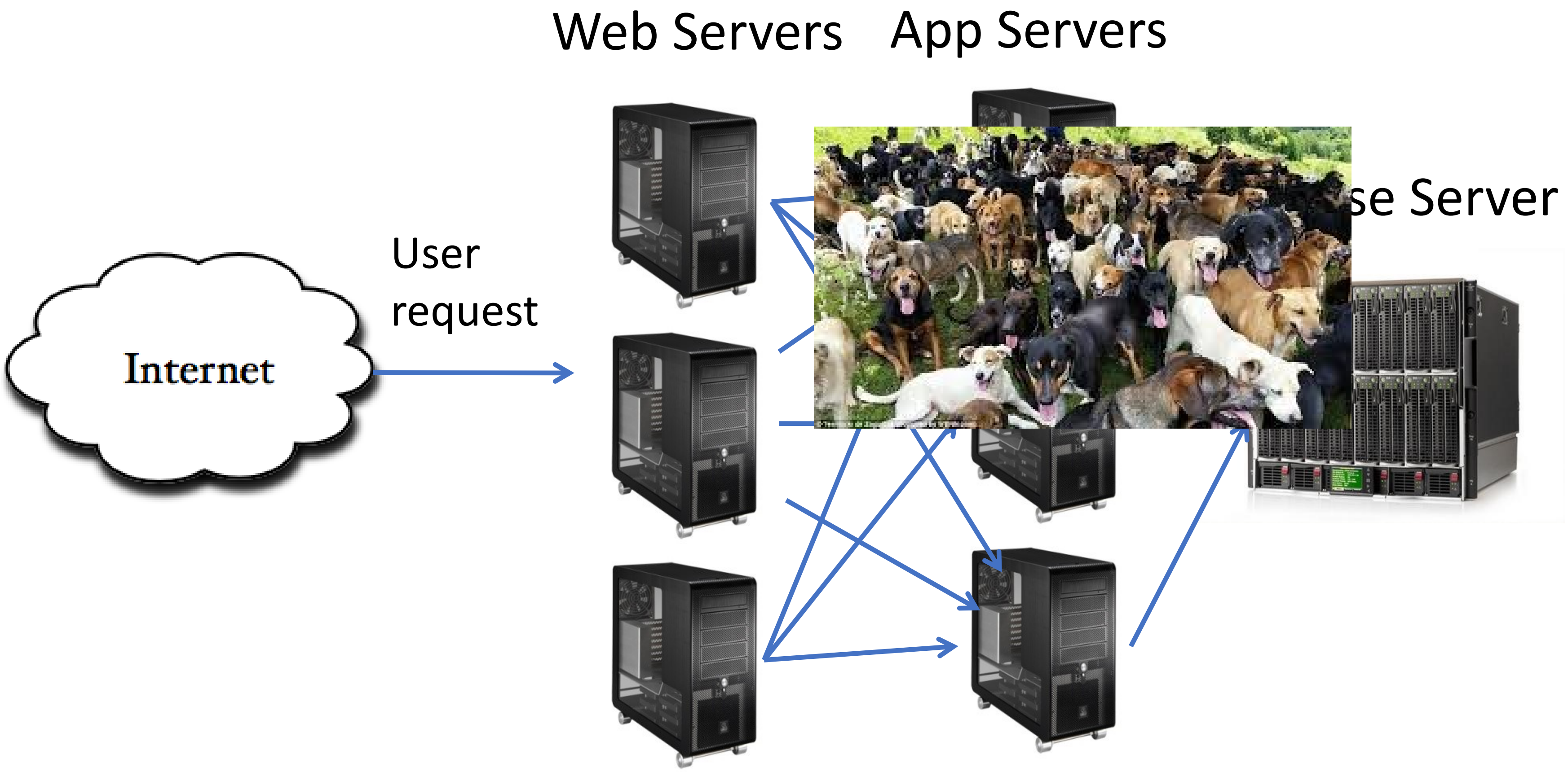

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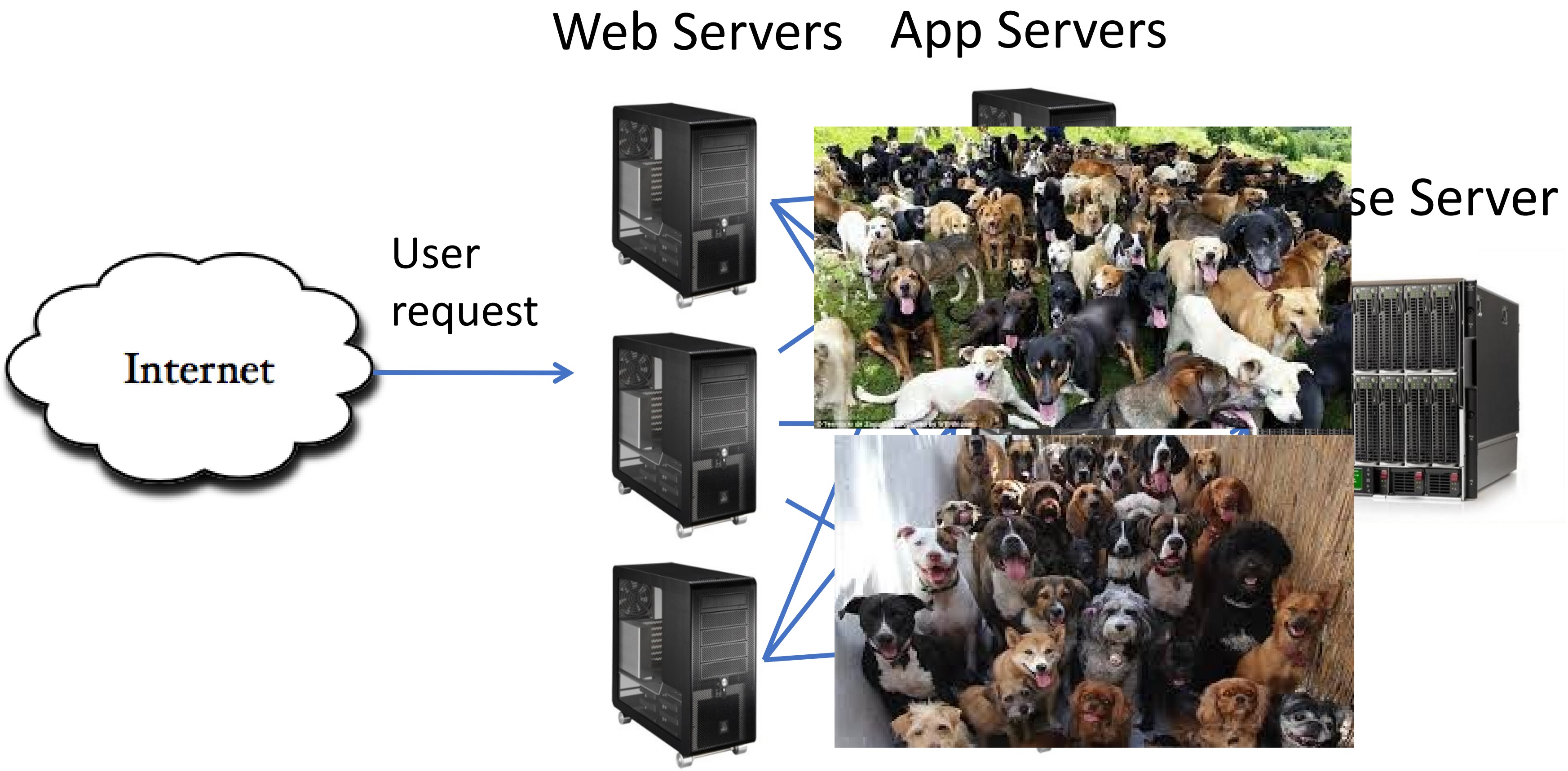

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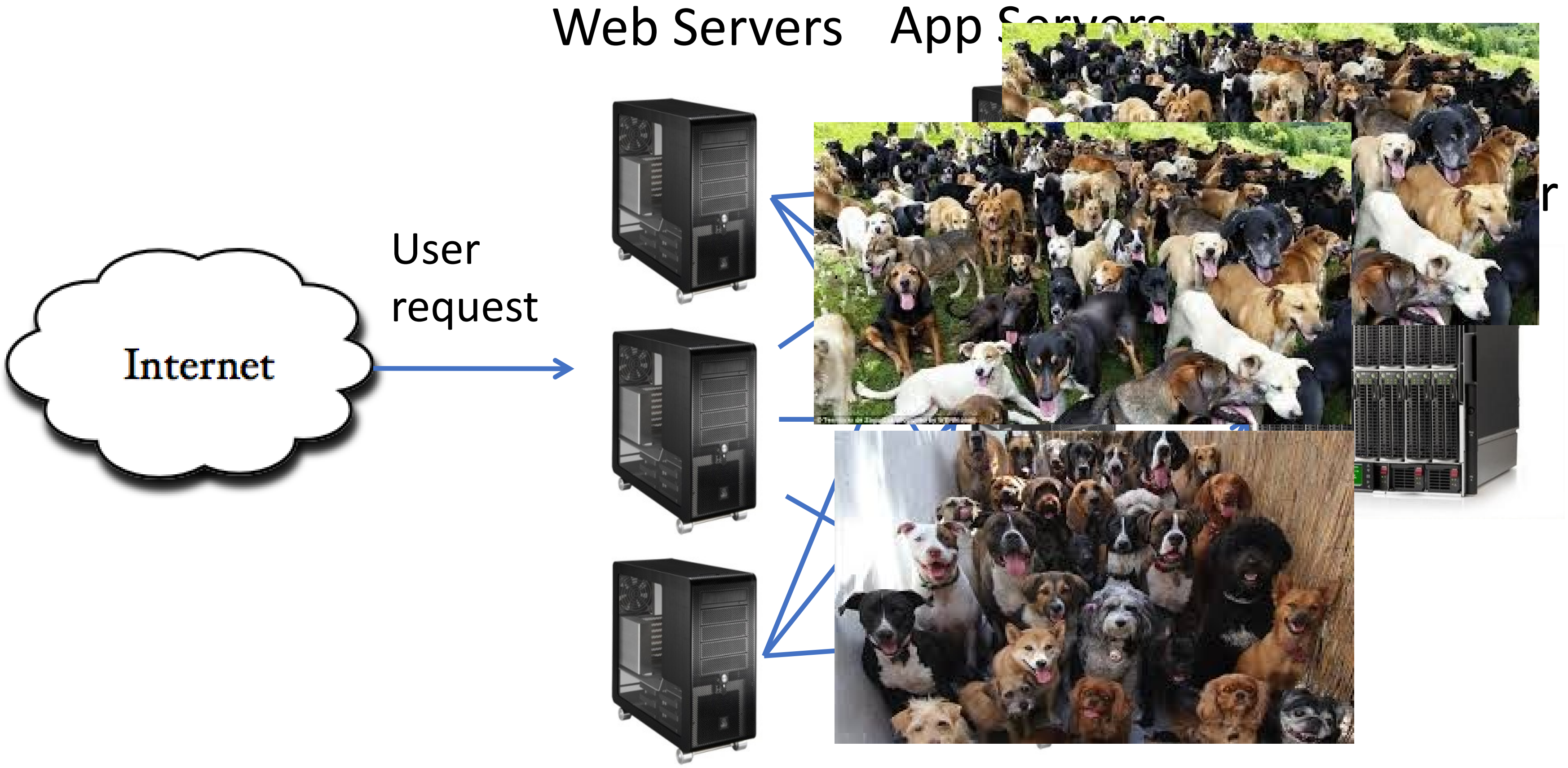

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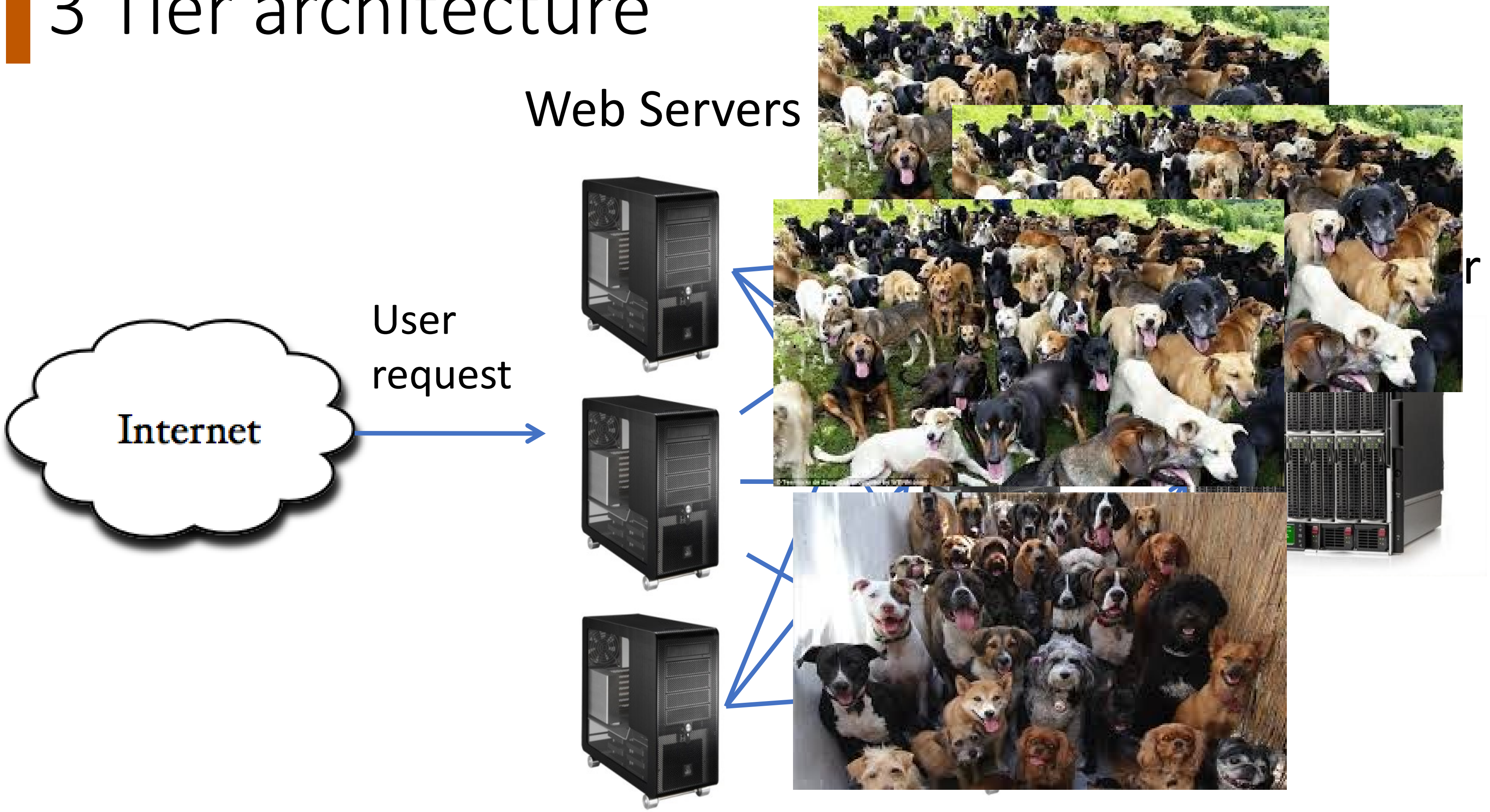

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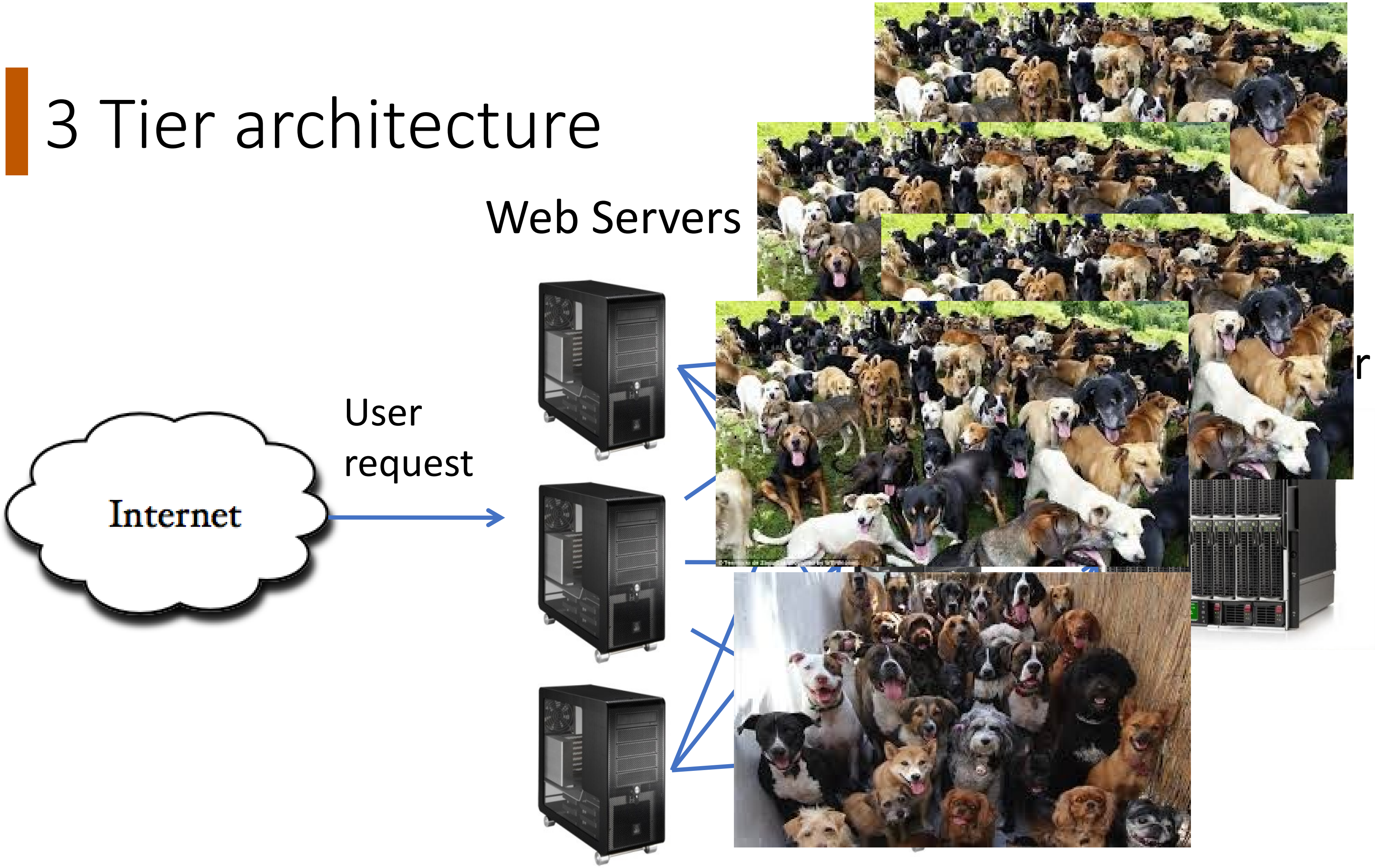

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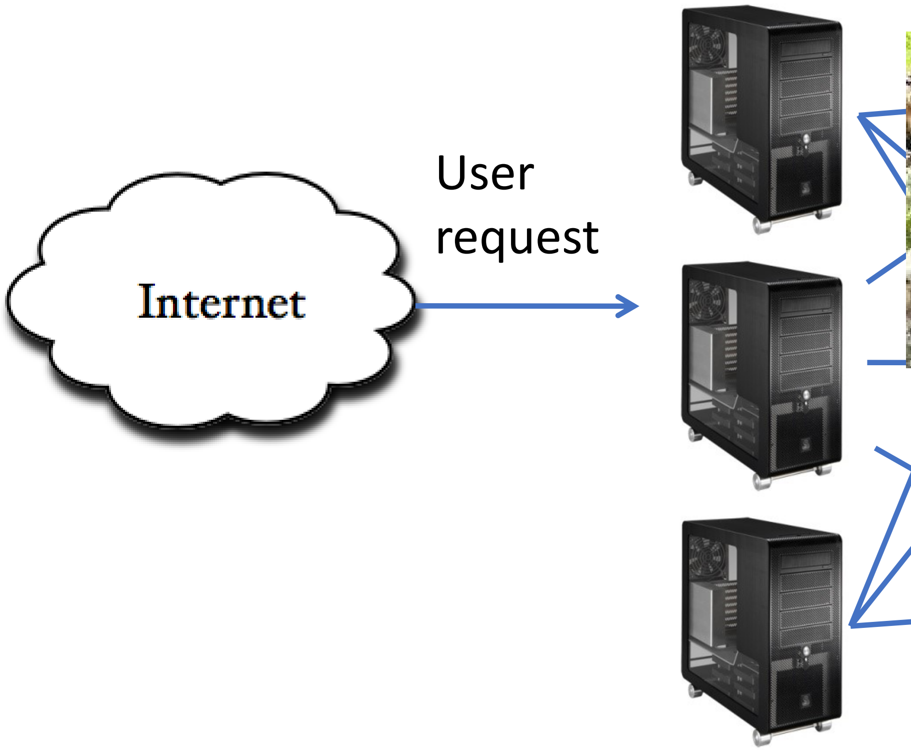
3 Tier architecture

Web Servers

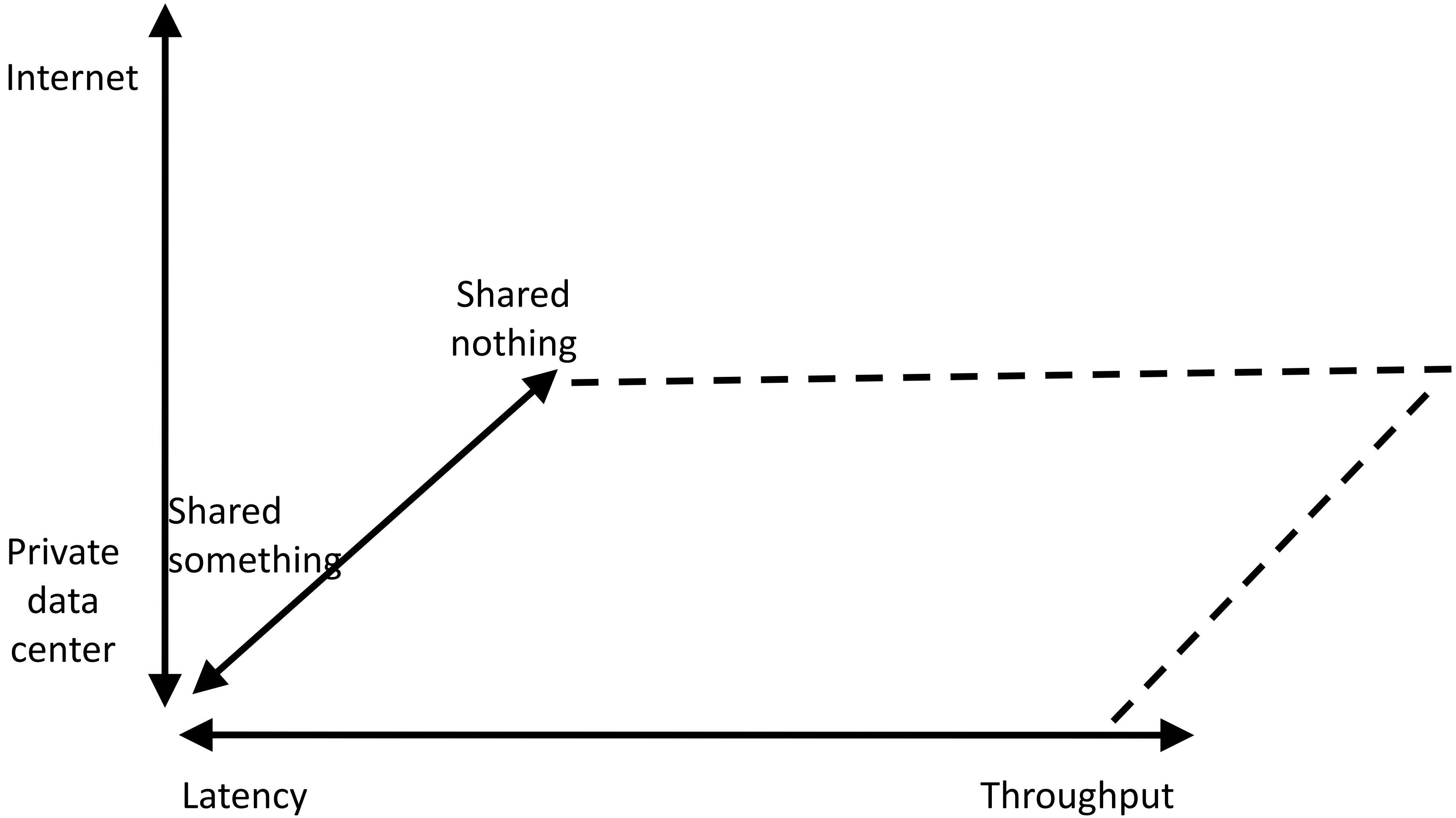


Web Servers (Presentation Tier) and Ap… *…izontally*
Database Server → scales *vertically*
Horizontal Scale → "Shared Nothing"
Why is this a good arrangement?

Vertical scale gets you a long way, but there is always a bigger problem size

Horizontal Scale: Goal

Design Space



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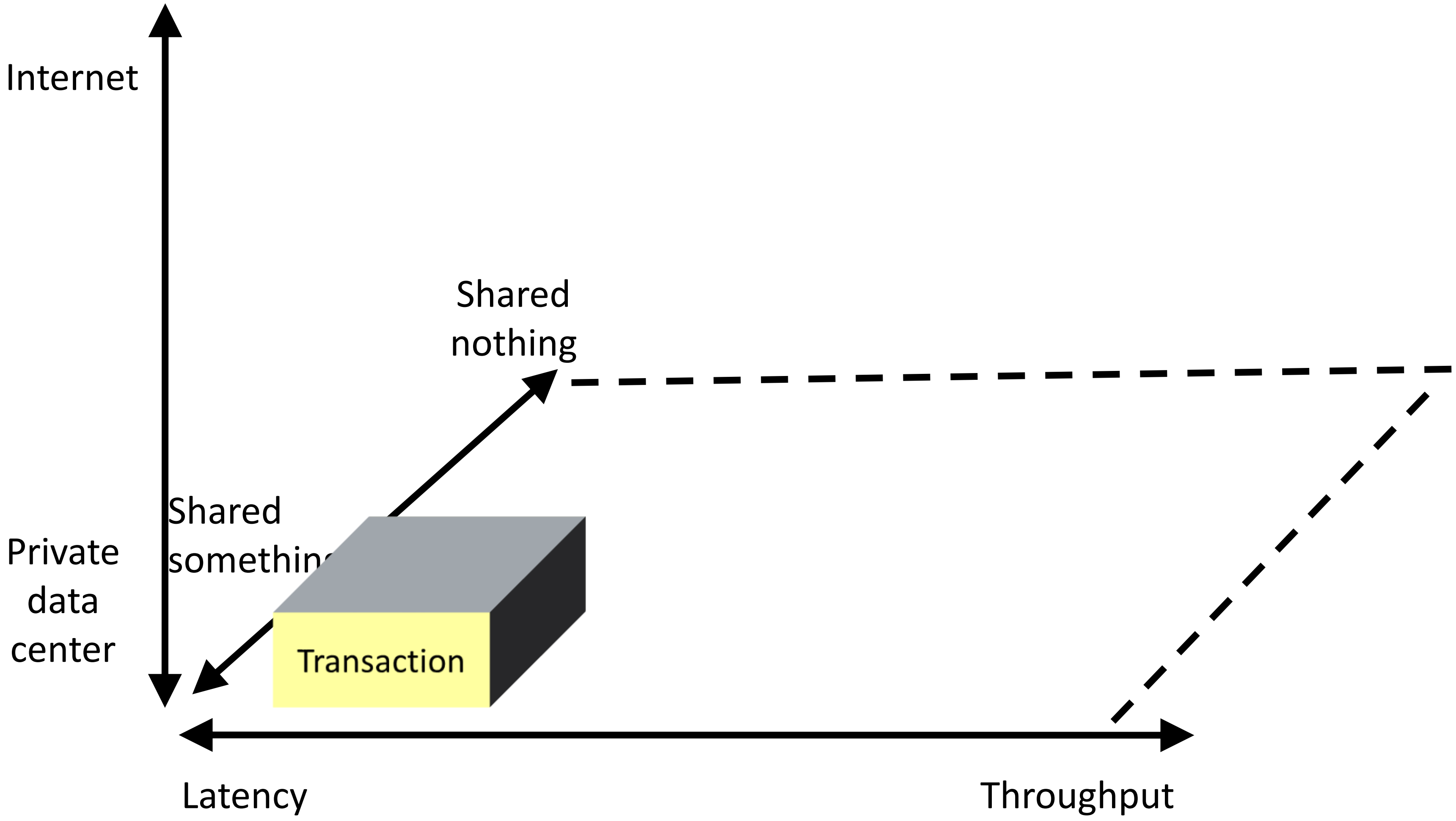

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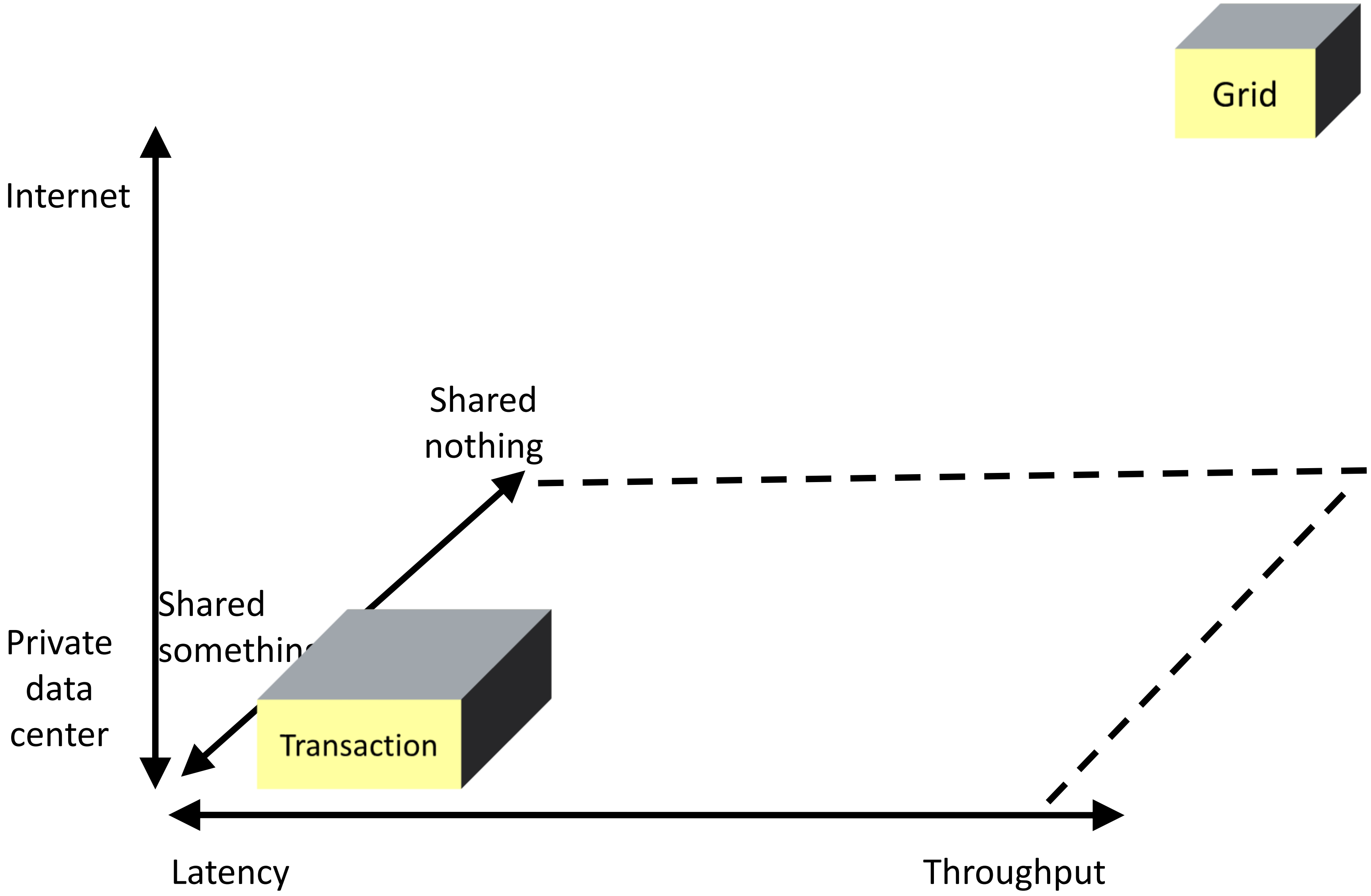

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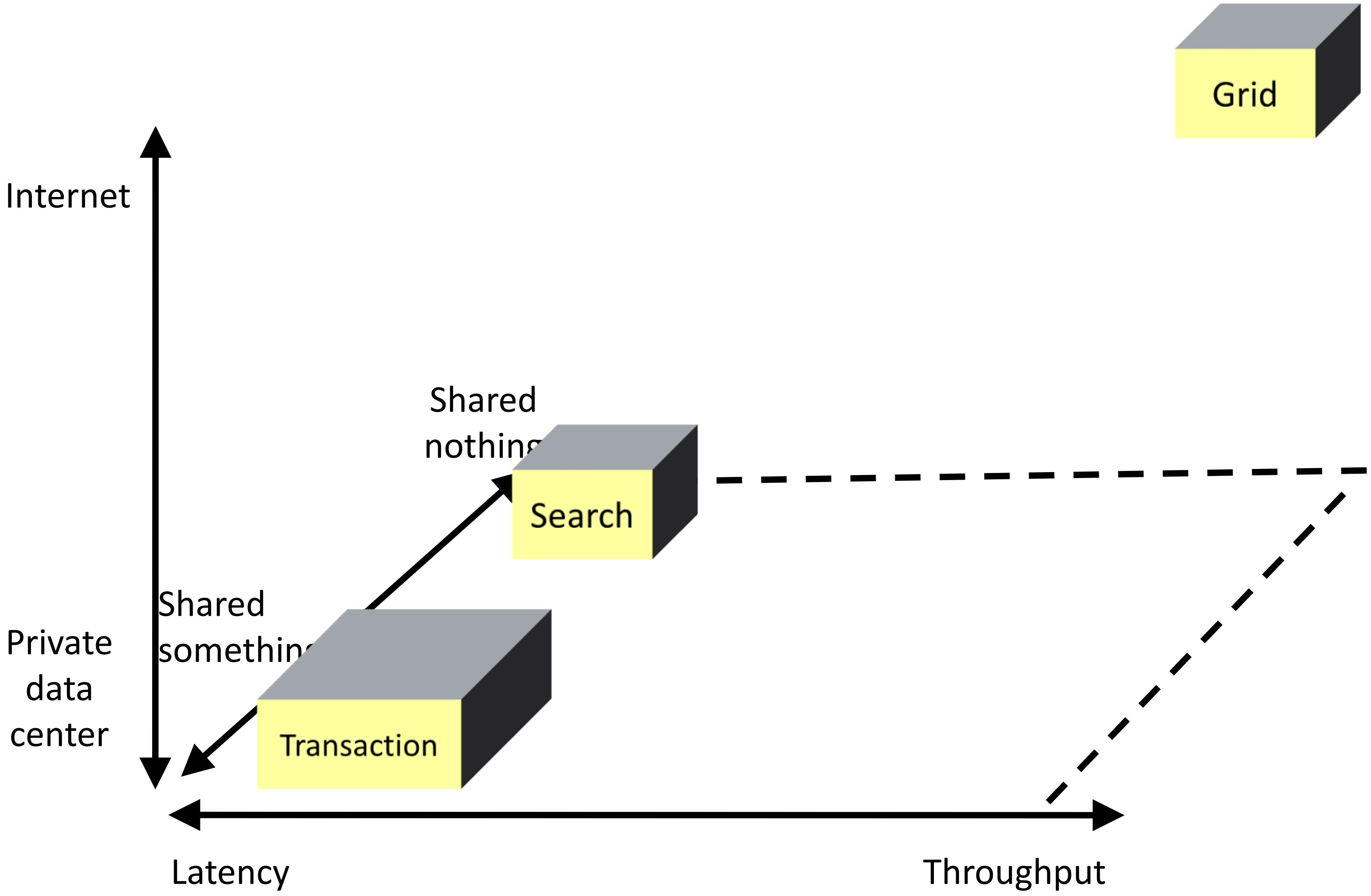

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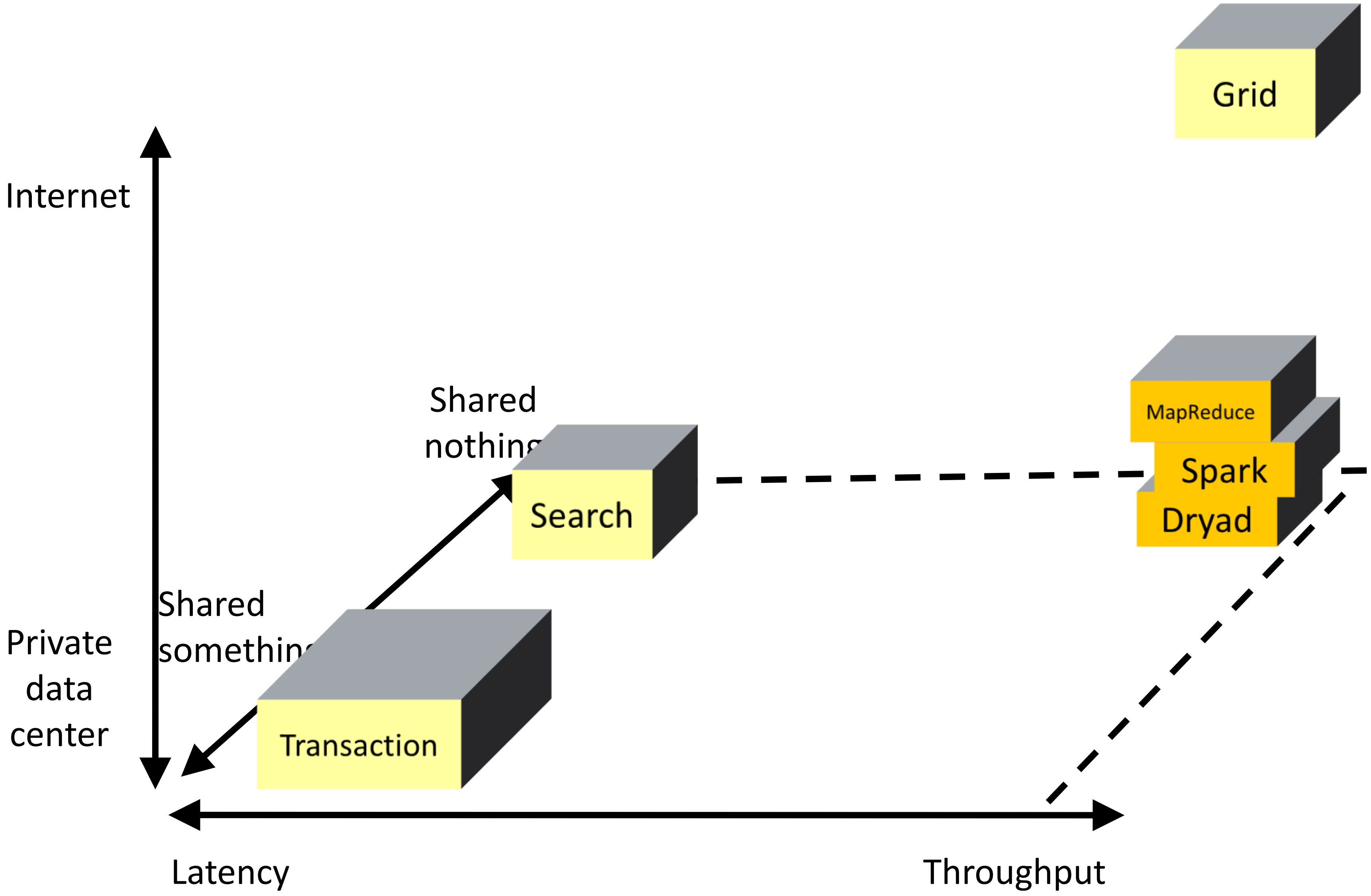

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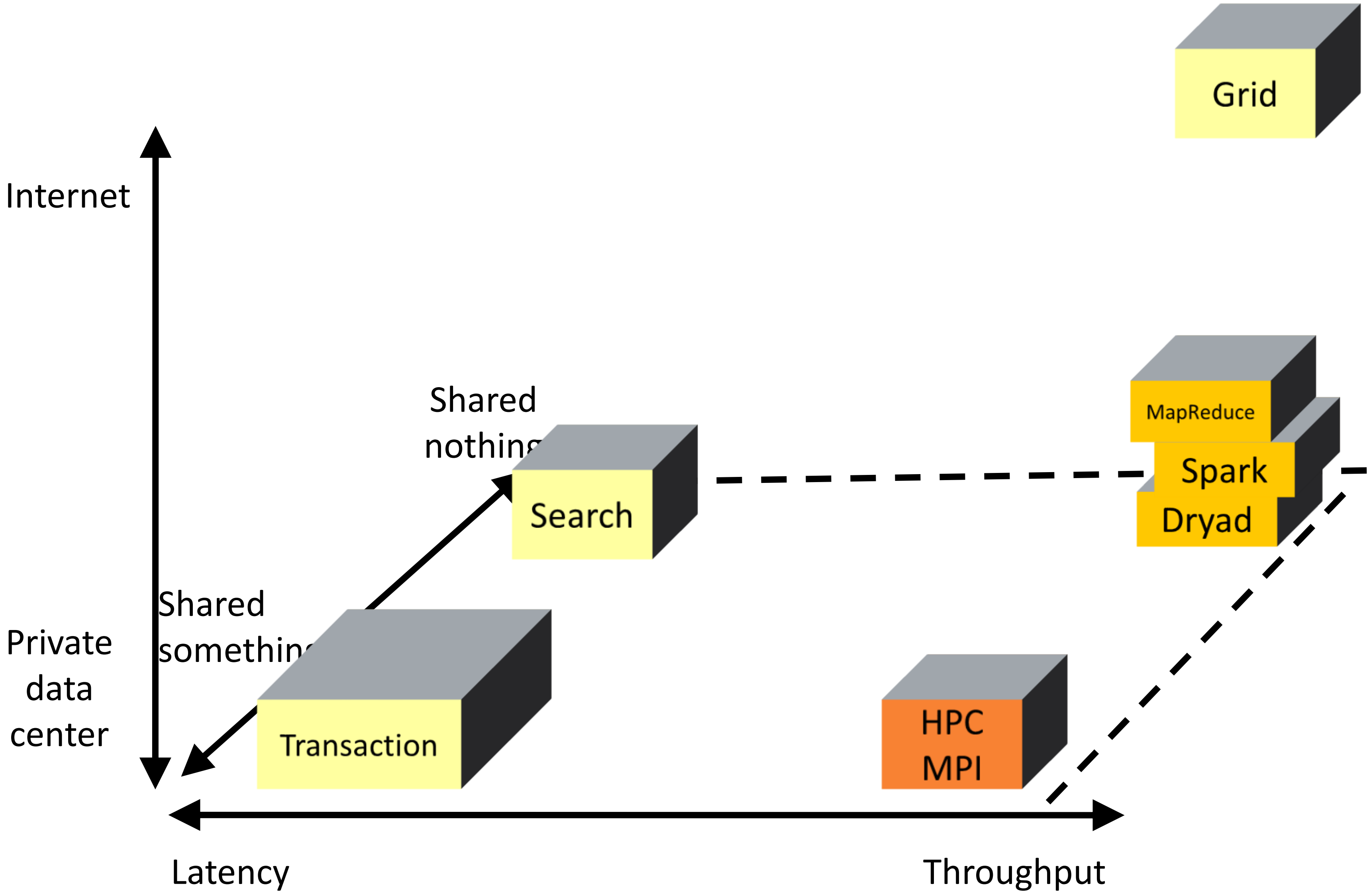

Parallel Architectures and MPI

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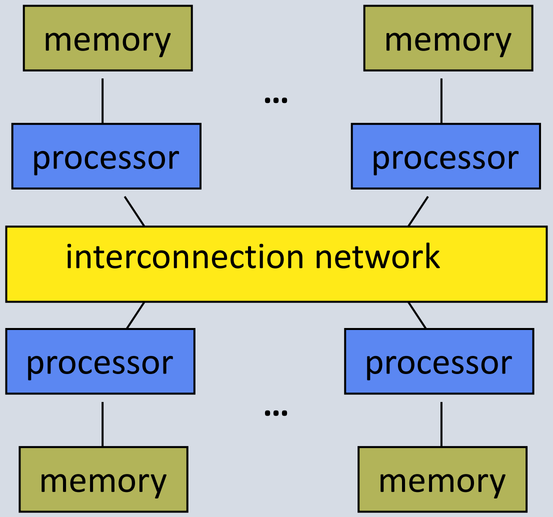
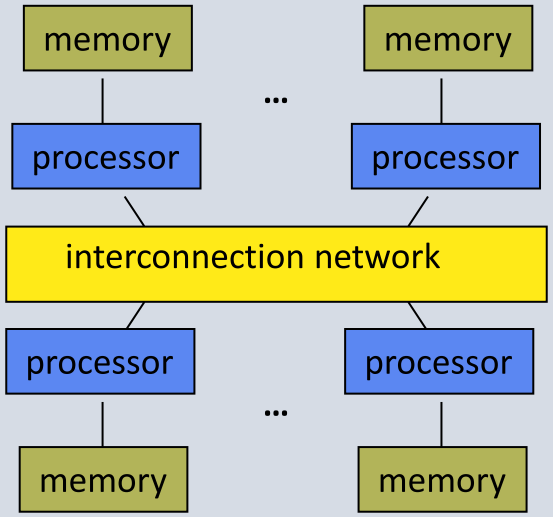


Parallel Architectures and MPI

Distributed Memory
Multiprocessor

Messaging between nodes



Parallel Architectures and MPI

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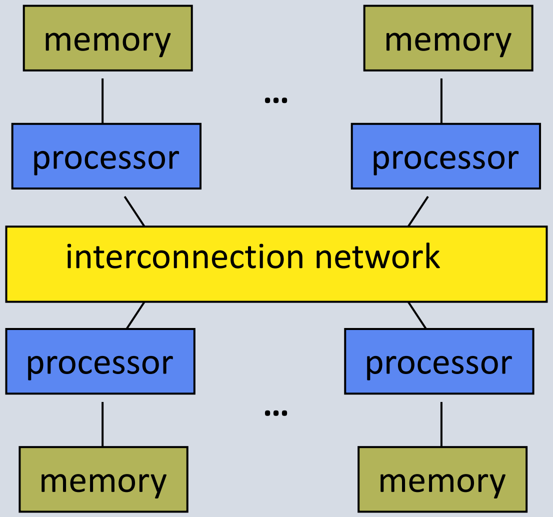


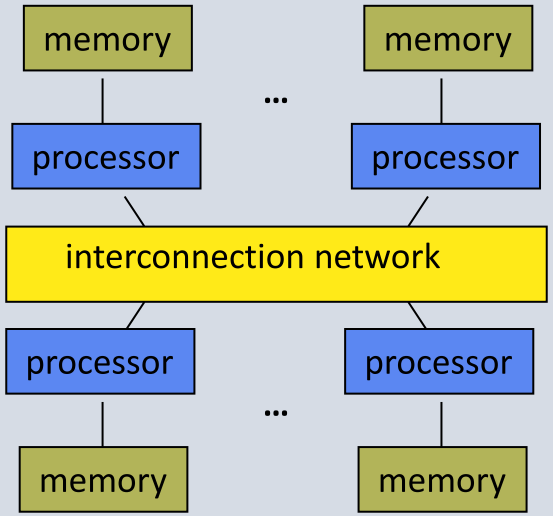
Massively Parallel Processor (MPP)

Many, many processors

Parallel Architectures and MPI

Distributed Memory Multiprocessor

Messaging between nodes



Massively Parallel Processor (MPP)

Many, many processors

Parallel Architectures and MPI

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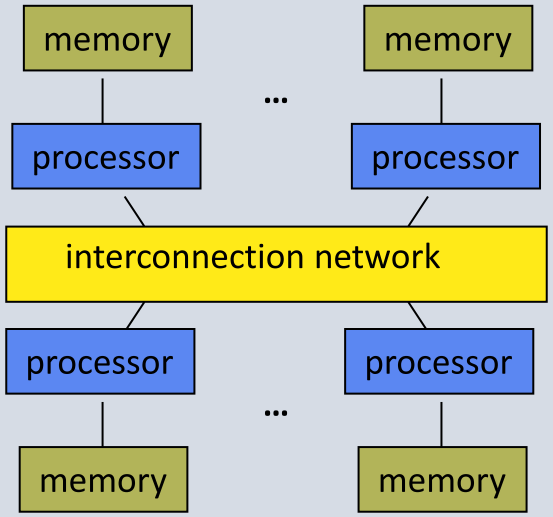

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Cluster of SMPs

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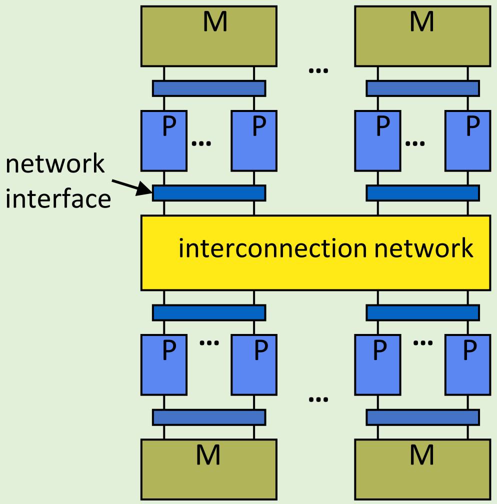

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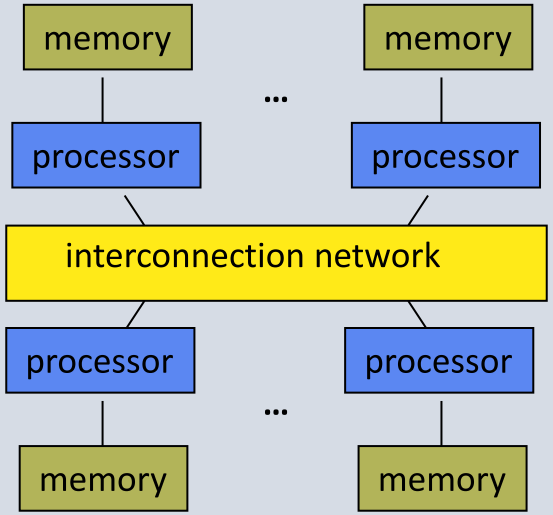

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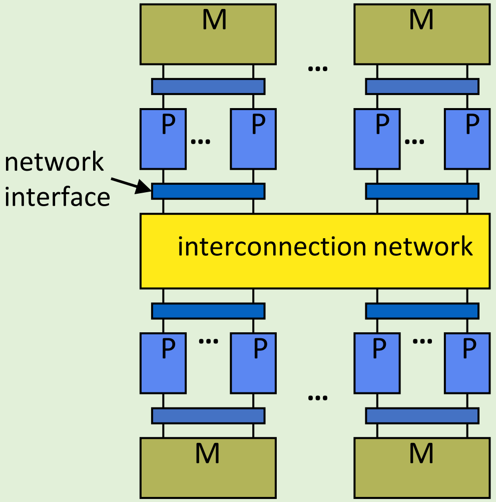

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Multicore SMP+GPU Cluster

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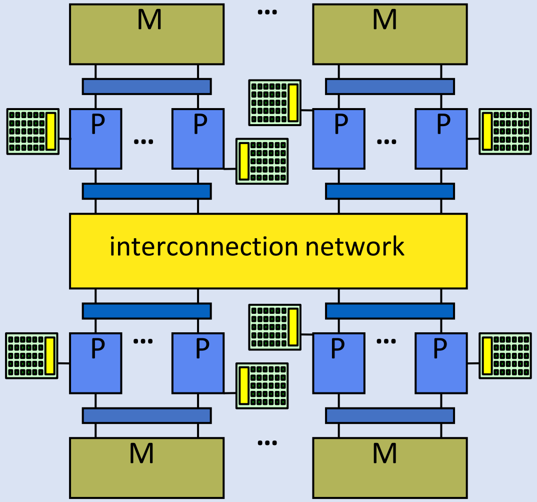

- GPU accelerators attached

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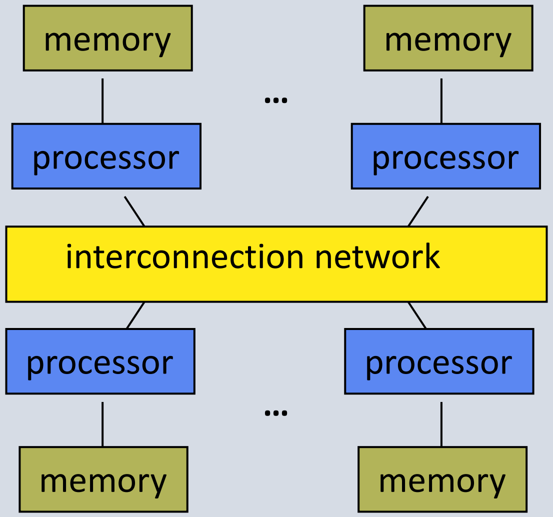

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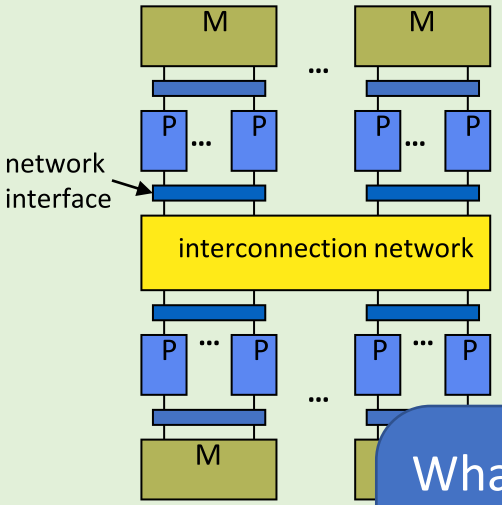

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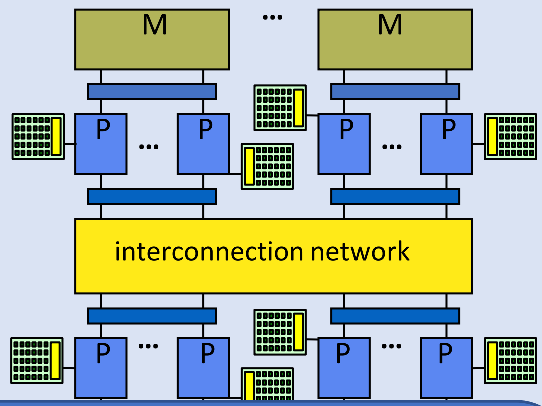

What have we left out?

Parallel Architectures and MPI

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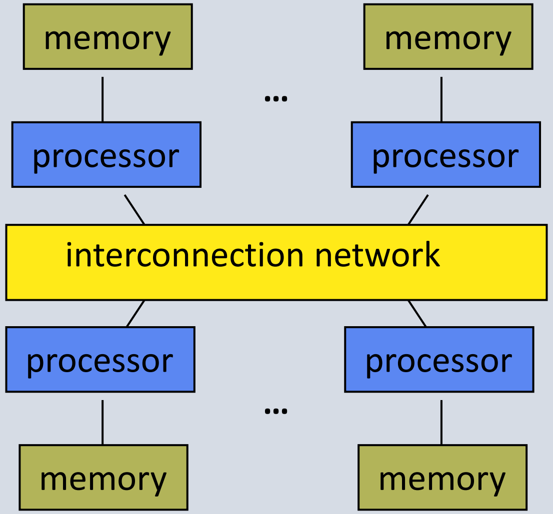

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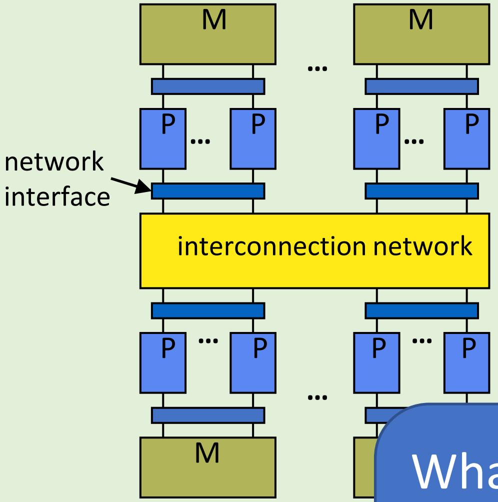

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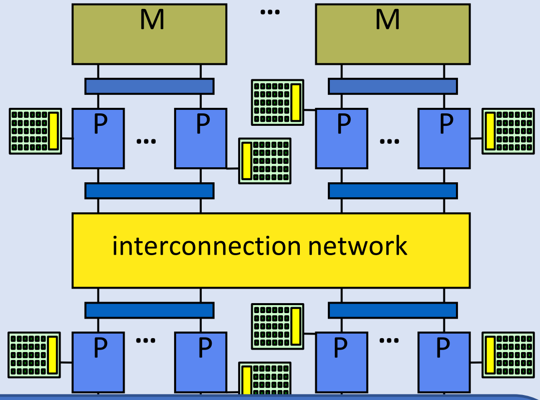

What have we left out?

- DSMs
- CMPs
- Non-GPU Accelerators

What requires extreme scale?

What requires extreme scale?

Simulations—why?

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Simulations—why?

- Simulations are sometimes more cost effective than experiments

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Why extreme scale?

More compute cycles, more memory, etc, lead for faster and/or more accurate simulations

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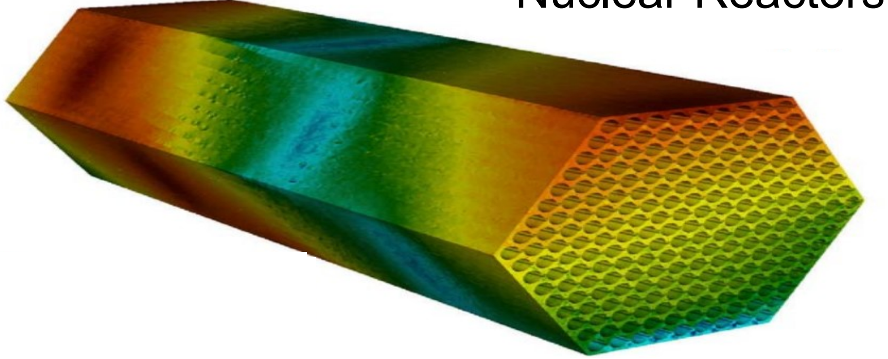
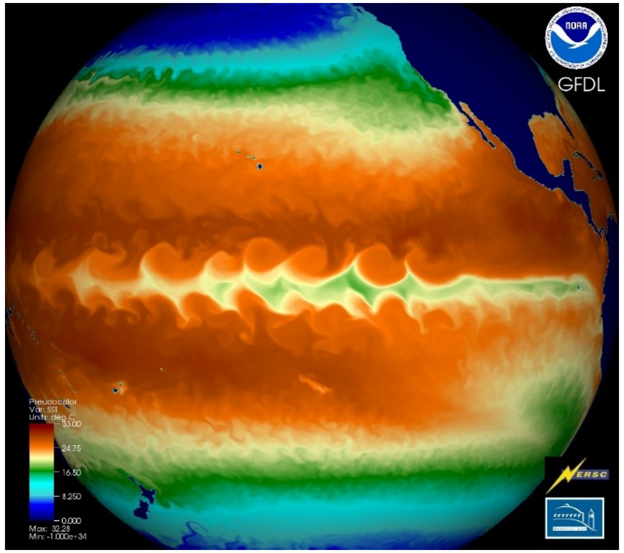
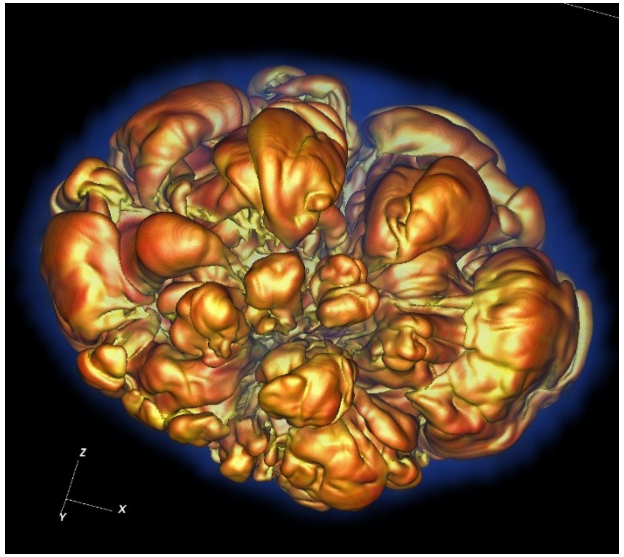
Nuclear Reactors





Climate Change



Astrophysics

Image credit: Prabhat, LBNL

How big is "extreme" scale?

Measured in FLOPs

FLoating point **O**perations **P**er **s**econd

- 1 GigaFLOP = 1 billion FLOPs
- 1 TeraFLOP = 1000 GigaFLOPs
- 1 PetaFLOP = 1000 TeraFLOPs
  - Most current super computers
- 1 ExaFLOP = 1000 PetaFLOPs
  - Arriving in 2018 (supposedly)

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Measured in FLOPs

Floating point **O**perations **P**er second

Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway , NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371
2	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P , NUDT National Super Computer Center in Guangzhou China	3,120,000	33,862.7	54,902.4	17,808
3	**Piz Daint** - Cray XC50, Xeon E5-2690v3 12C 2.6GHz, Aries interconnect , NVIDIA Tesla P100 , Cray Inc. Swiss National Supercomputing Centre (CSCS) Switzerland	361,760	19,590.0	25,326.3	2,272
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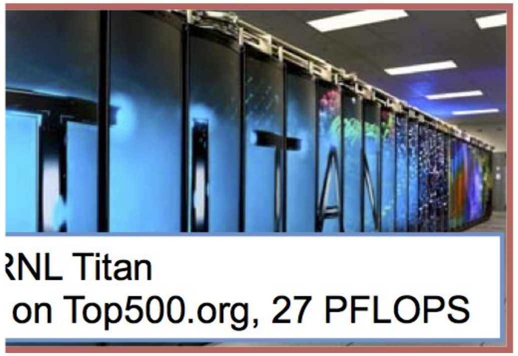

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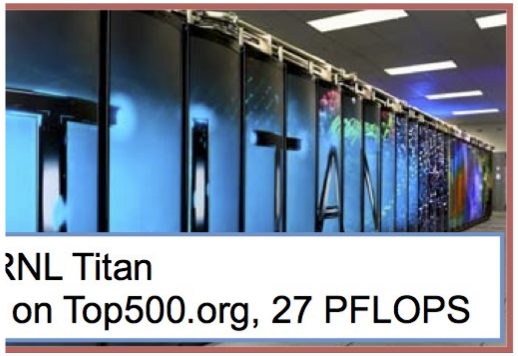

Distributed Memory Multiprocessors

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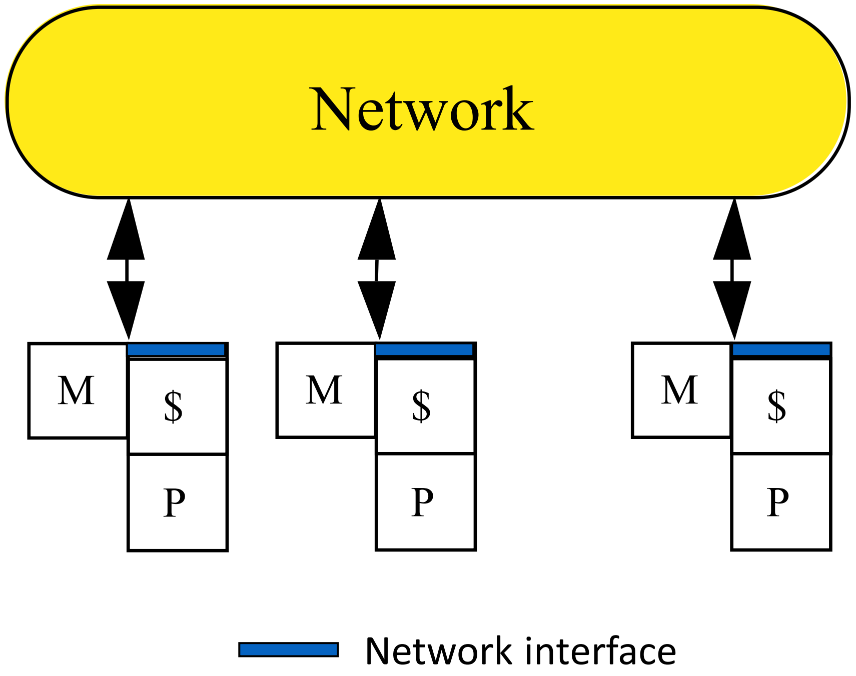

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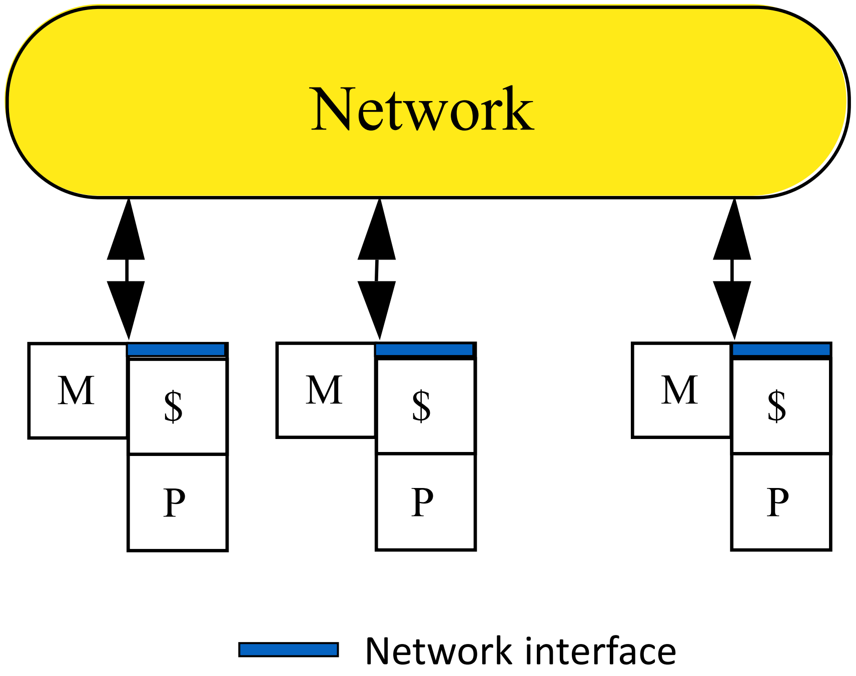
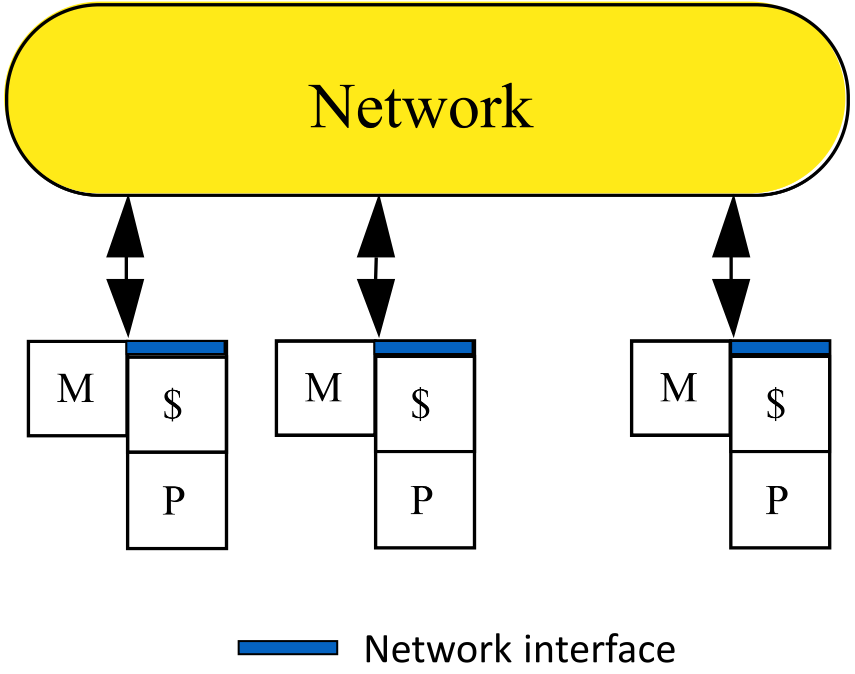


- Nodes: complete computer
  - Including I/O
- Nodes communicate via network
  - Standard networks (IP)
  - Specialized networks (RDMA, fiber)

Distributed Memory Multiprocessors

Each processor has a local memory

Physically separated address space



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- Message communication
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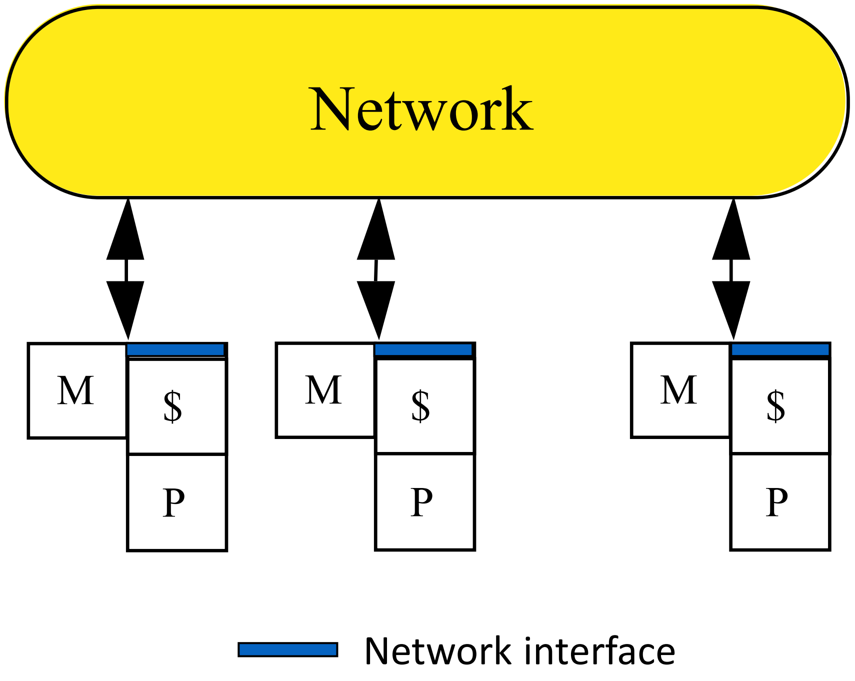

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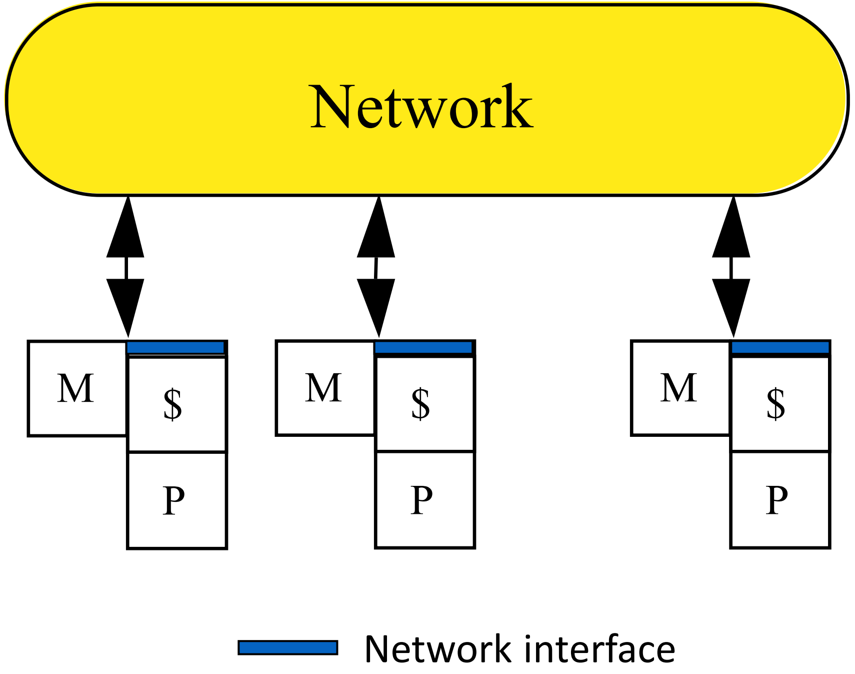
- Memory: data partitioning



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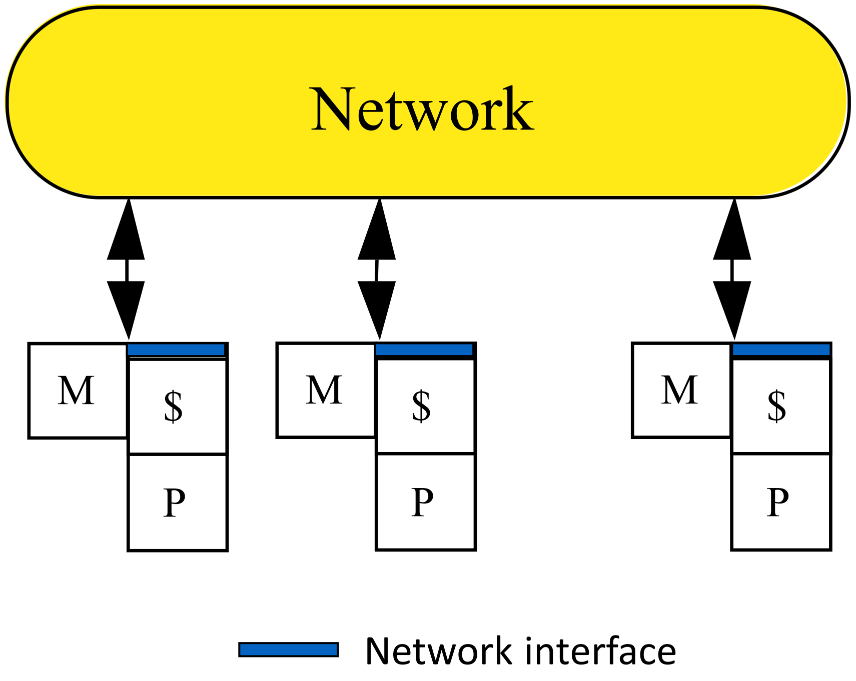
Scalable architecture

- Incremental cost to add hardware (cost of node)



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- Need high bandwidth in communication
- Match limits in network, memory, and processor
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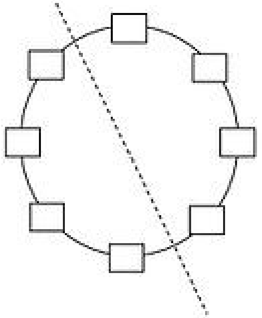

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- Increases programming system burden
- E.g.: communication/computation overlap, prefetch

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Is this different from metrics we've cared about so far?

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Can you think of any *disadvantages*?

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  - parallel binary program
  - "input deck" (specifies input data)
- Submit job to a ***queue***
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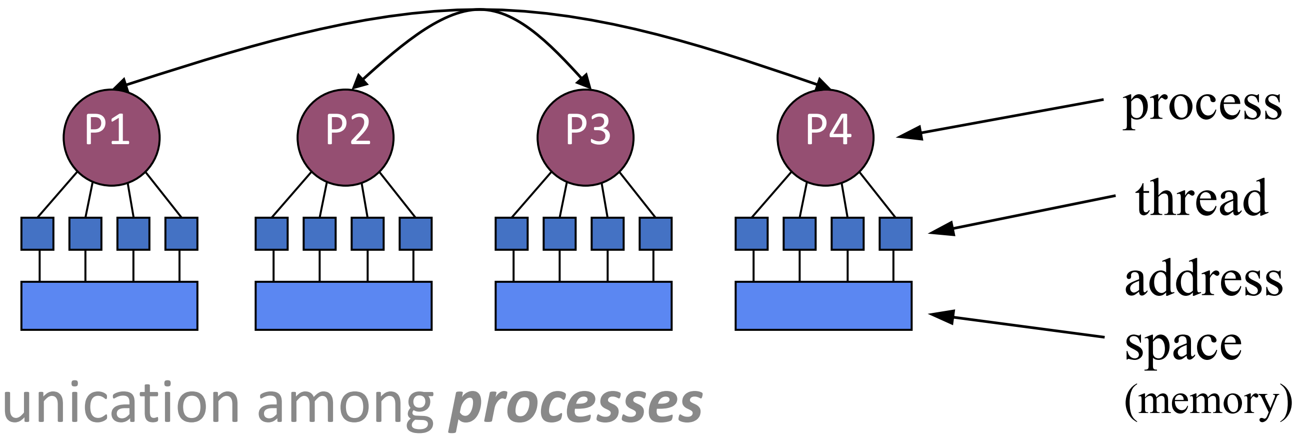
- MPI library interprets this information, hides the details

The Message-Passing Model

Process: a program counter and address space

Processes: multiple threads sharing a single address space



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- Not threads

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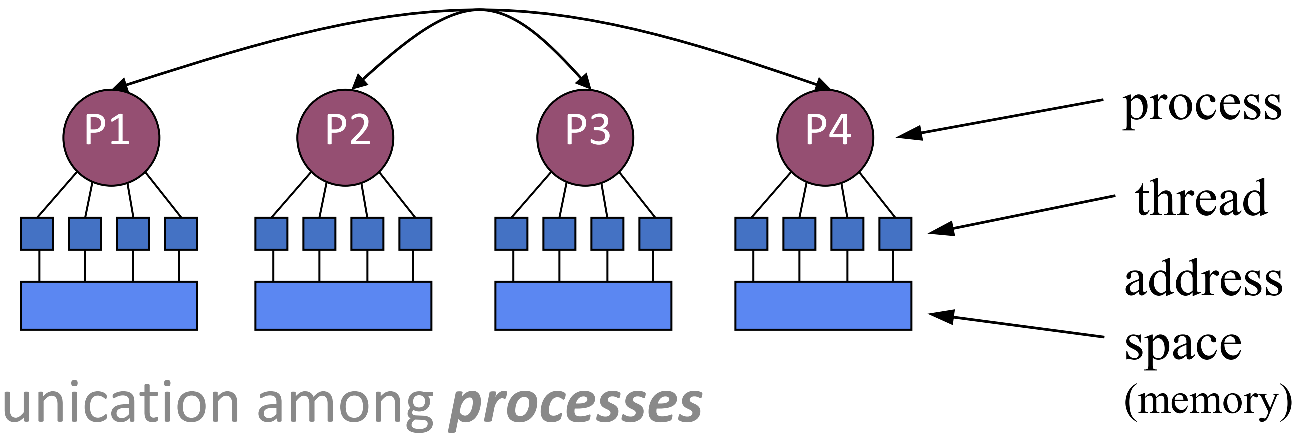

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How does this compare with CSP?

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Proc

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CSP?

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- Two flavors for communication
  - Cooperative operations
  - One-sided operations

Cooperative Operations

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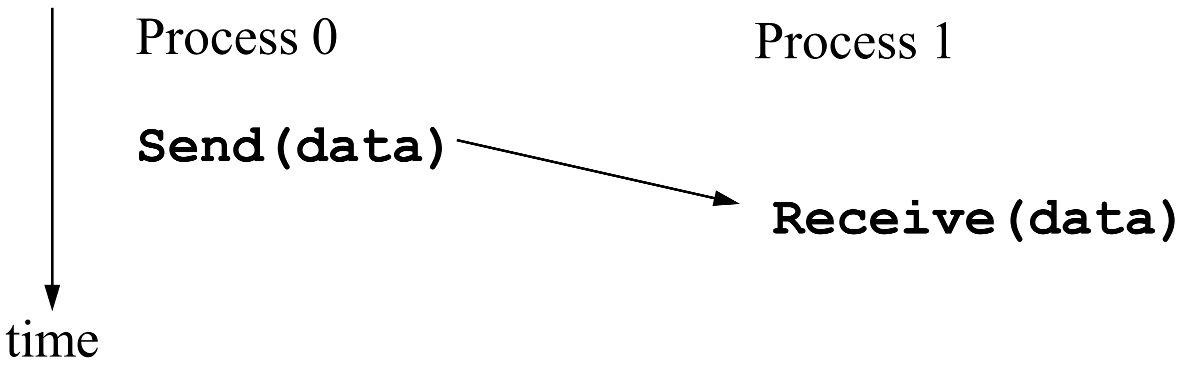
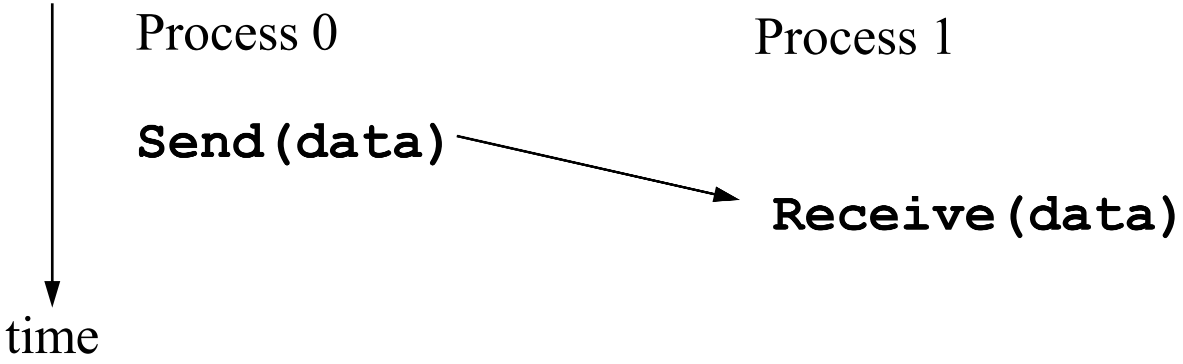


Cooperative Operations

Data is cooperatively exchanged in message-passing



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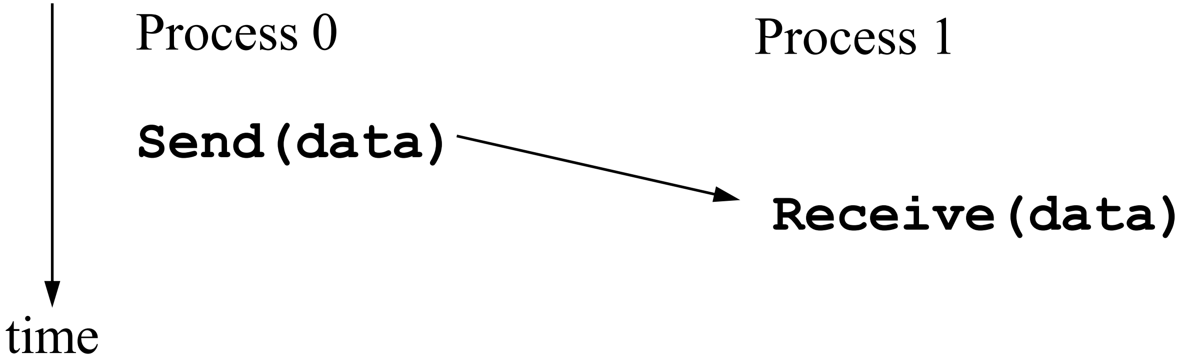

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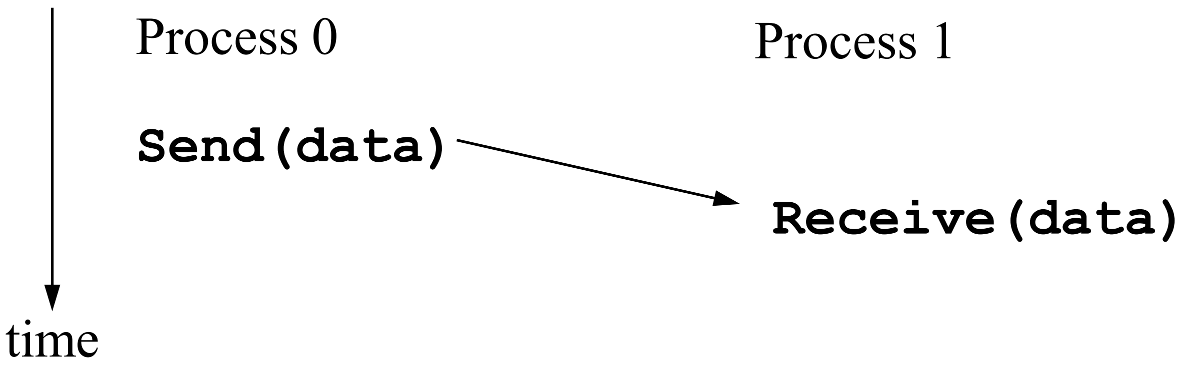

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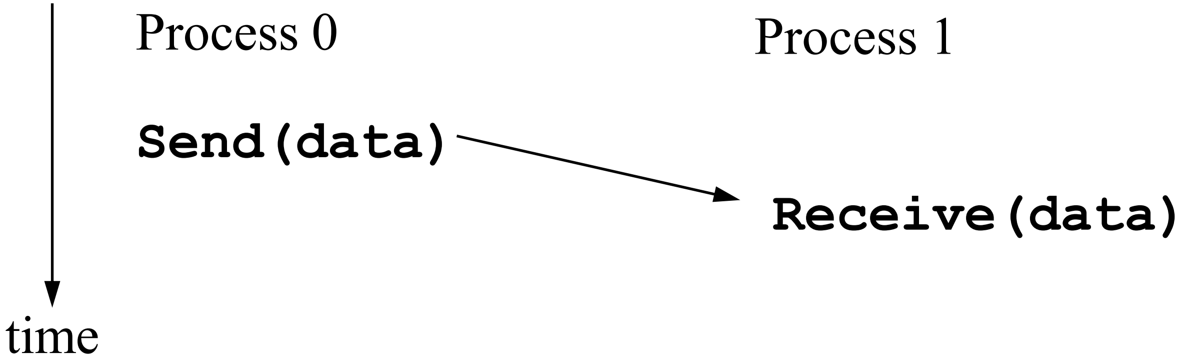

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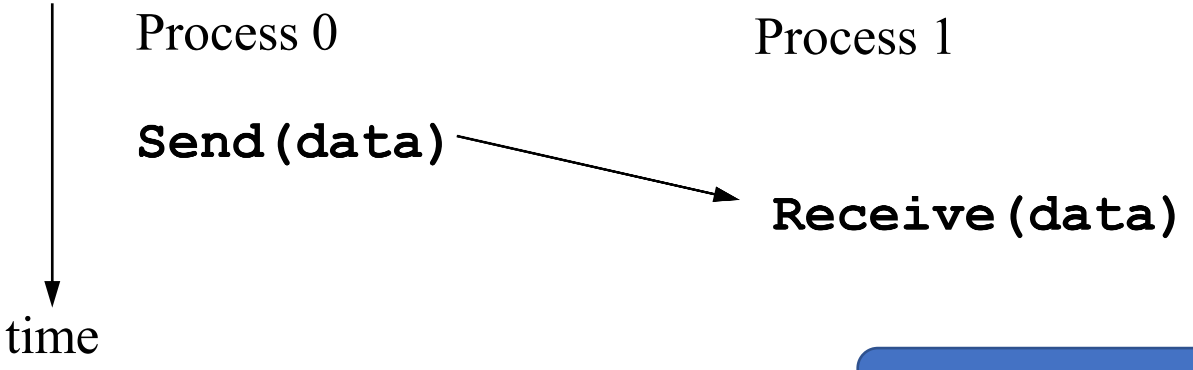

Familiar argument?

One-Sided Operations

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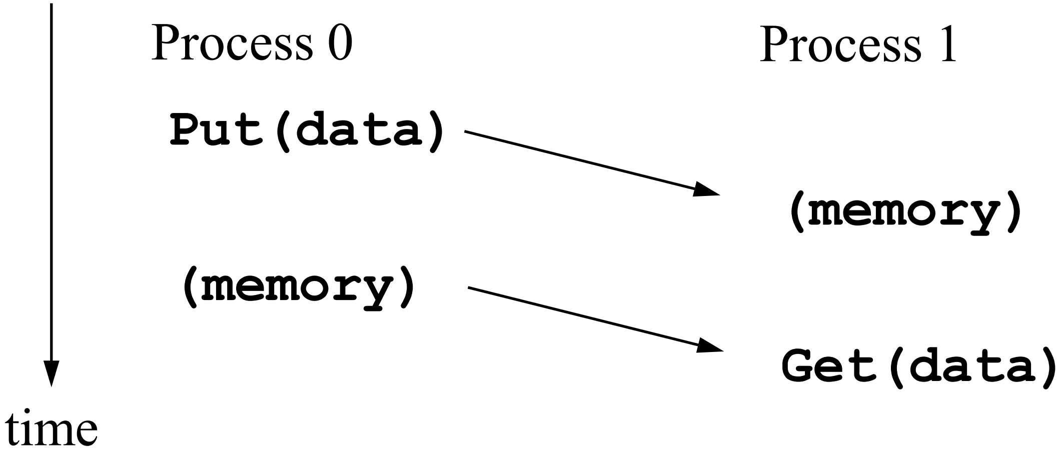

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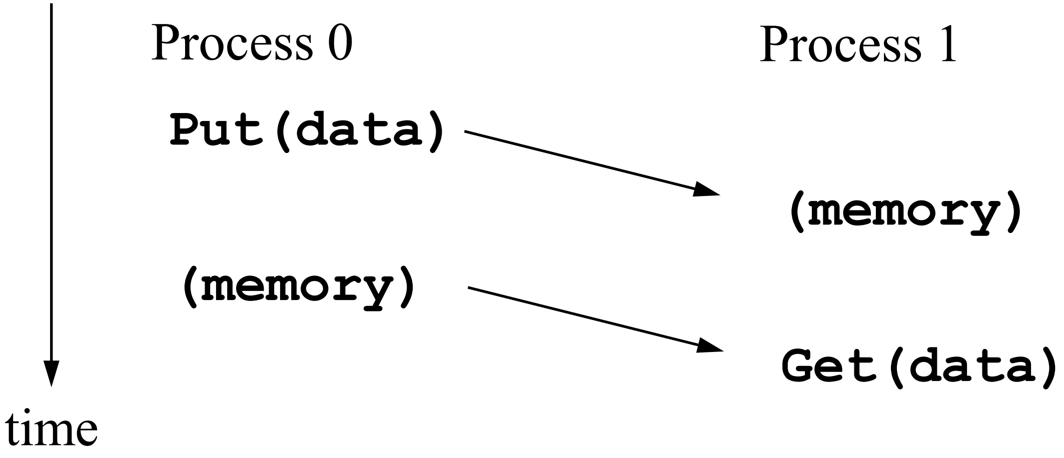
One-sided operations between processes

- Include remote memory reads and writes



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Only one process needs to explicitly participate

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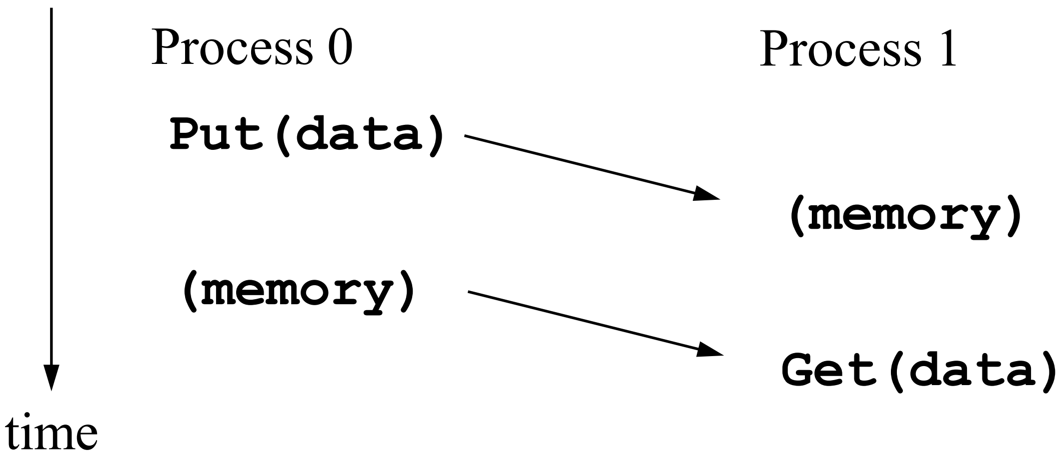

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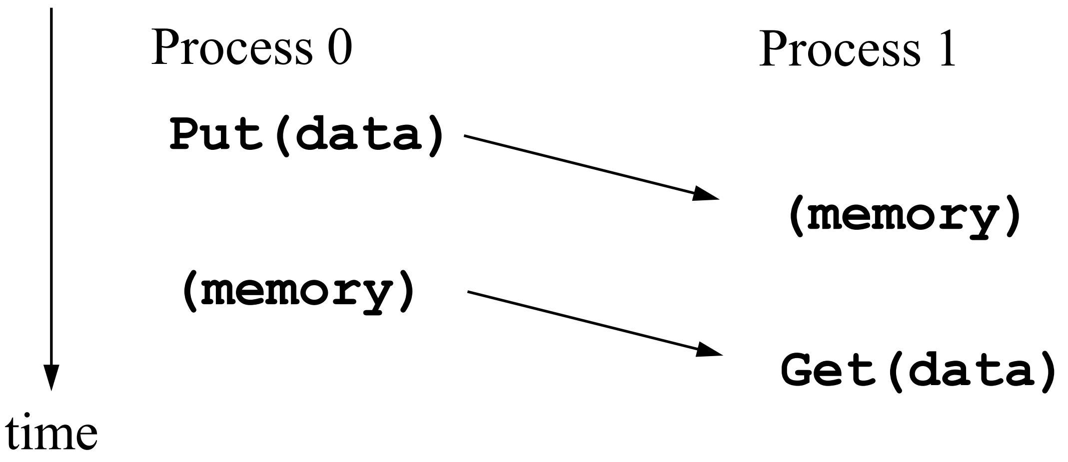

One-Sided Operations

Are 1-sided operations better for performance?

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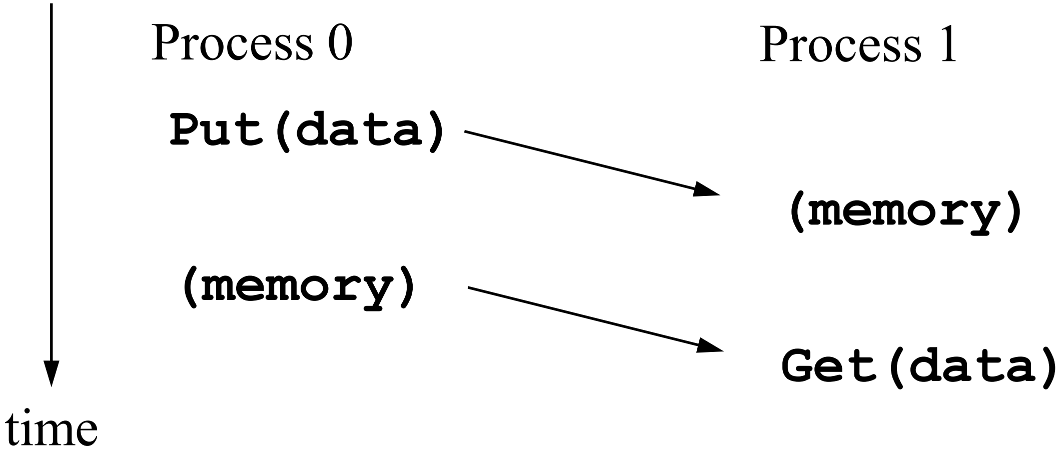

A Simple MPI Program

```
#include "mpi.h"
#include <stdio.h>

int main( int argc, char *argv[] )
{
    MPI_Init( &argc, &argv );
    printf( "Hello, world!\n" );
    MPI_Finalize();
    return 0;
}
```

MPI_Init

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Hardware resources allocated

- MPI-managed ones anyway…

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Start processes on different nodes

- Where does their executable program come from?

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- Undo all of init
- Be able to do it on success or failure exit

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  - In C++, exceptions are thrown (MPI-2)
- A user can also write and install custom error handlers
- Libraries may handle errors differently from applications

Running MPI Programs

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% mpirun -np <procs> a.out

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% mpirun -np <procs> a.out

- **For MPICH under Linux**

mpiexec <args>

- Recommended part of MPI-2, as a recommendation
- **mpiexec** for MPICH (distribution from ANL)
- **mpirun** for SGI's MPI

Finding Out About the Environment

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- How many processes are being use in computation?
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MPI provides functions to answer these questions

- **MPI_Comm_size** reports the number of processes
- **MPI_Comm_rank** reports the rank
  - number between 0 and size-1
  - identifies the calling process

Hello World Revisited

```
#include "mpi.h"
#include <stdio.h>

int main( int argc, char *argv[] )
{
    int rank, size;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &rank );
    MPI_Comm_size( MPI_COMM_WORLD, &size );
    printf( "I am %d of %d\n", rank, size );
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    return 0;
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Comm?
"Communicator"

Basic Concepts

- Processes can be collected into *groups*
- Each message is sent in a *context*
  - Must be received in the same context!
- A group and context together form a *communicator*
- A process is identified by its *rank*
  - With respect to the group associated with a communicator
- There is a default communicator MPI_COMM_WORLD
  - Contains all initial processes

MPI Datatypes

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- Predefined data type from the language
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There are MPI functions to construct custom datatypes

- Array of (int, float) pairs
- Row of a matrix stored columnwise

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  - Support communication between processes on machines with different memory representations and lengths of elementary datatypes
  - MPI provides the representation translation if necessary
- Allows application-oriented layout of data in memory
  - Reduces memory-to-memory copies in implementation
  - Allows use of special hardware (scatter/gather)

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- Messages are sent with an accompanying user-defined integer *tag*
  - Assist the receiving process in identifying the message
- Messages can be screened at receiving end by specifying specific tag
  - **MPI_ANY_TAG** matches any tag in a receive
- Tags are sometimes called "message types"
  - MPI calls them "tags" to avoid confusion with datatypes

MPI Basic (Blocking) Send

```
MPI_SEND (start, count, datatype, dest, tag, comm)
```

- The message buffer is described by:
  - `start`, `count`, `datatype`
- The target process is specified by `dest`
  - Rank of the target process in the communicator specified by `comm`
- Process blocks until:
  - Data has been delivered to the system
  - Buffer can then be reused
- Message may not have been received by target process!

MPI with Only Six Functions

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Many parallel programs can be written using:

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Why have any other APIs (e.g. broadcast, reduce, etc.)?

Point-to-point (send/recv) isn’t always the most efficient...

- Add more support for communication

Excerpt: Barnes-Hut

```
int ctr=nLocalOriginal;
int offset=nLocalOriginal-nLocal;
for(i=0;i<worldSize;i++){
if(i==rank){
    MPI_Bcast(s_particles,N_POS_ELEMS*nLocalMax+1,MPI_DOUBLE,i,MPI_COMM_WORLD);
} else {
    MPI_Bcast(l_particles,N_POS_ELEMS*nLocalMax+1,MPI_DOUBLE,i,MPI_COMM_WORLD);
    for(k=0;k<l_particles[0];k++, ctr++){
    if(l_particles[MASS(k)]<0){
        offset++;
        _nparticles--;
    } else {
        s_particles[PX(ctr)]=l_particles[PX(k)];
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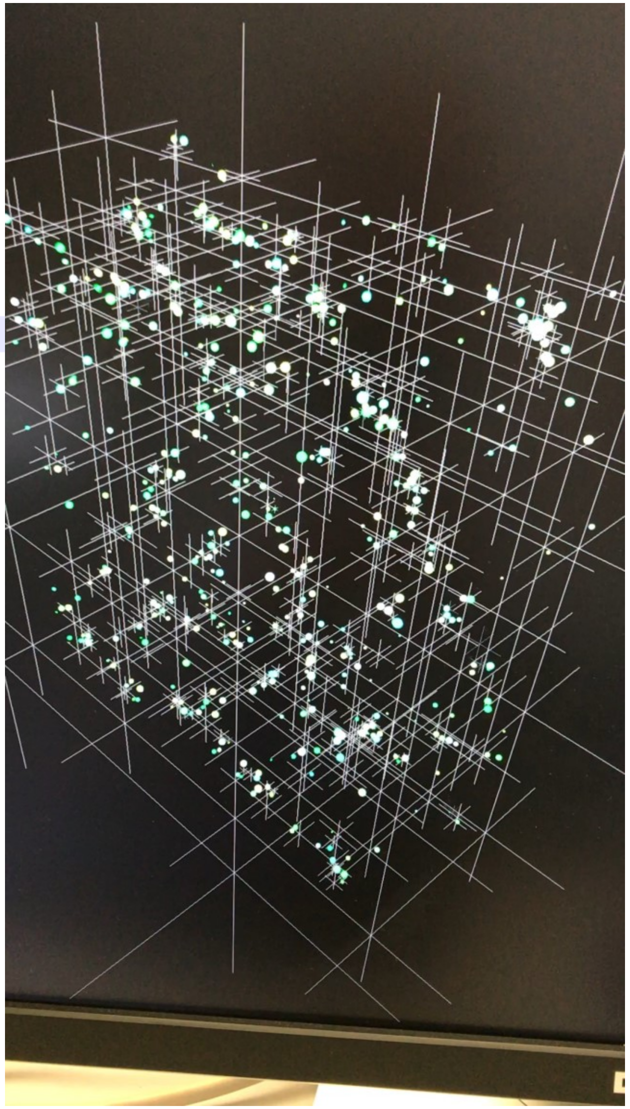

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  - You need a portable parallel program
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  - You care about performance
- NOT USE
  - You don’t need parallelism at all
  - You can use libraries (which may be written in MPI) or other tools
  - You can use multi-threading in a concurrent environment
    - You don’t need extreme scale