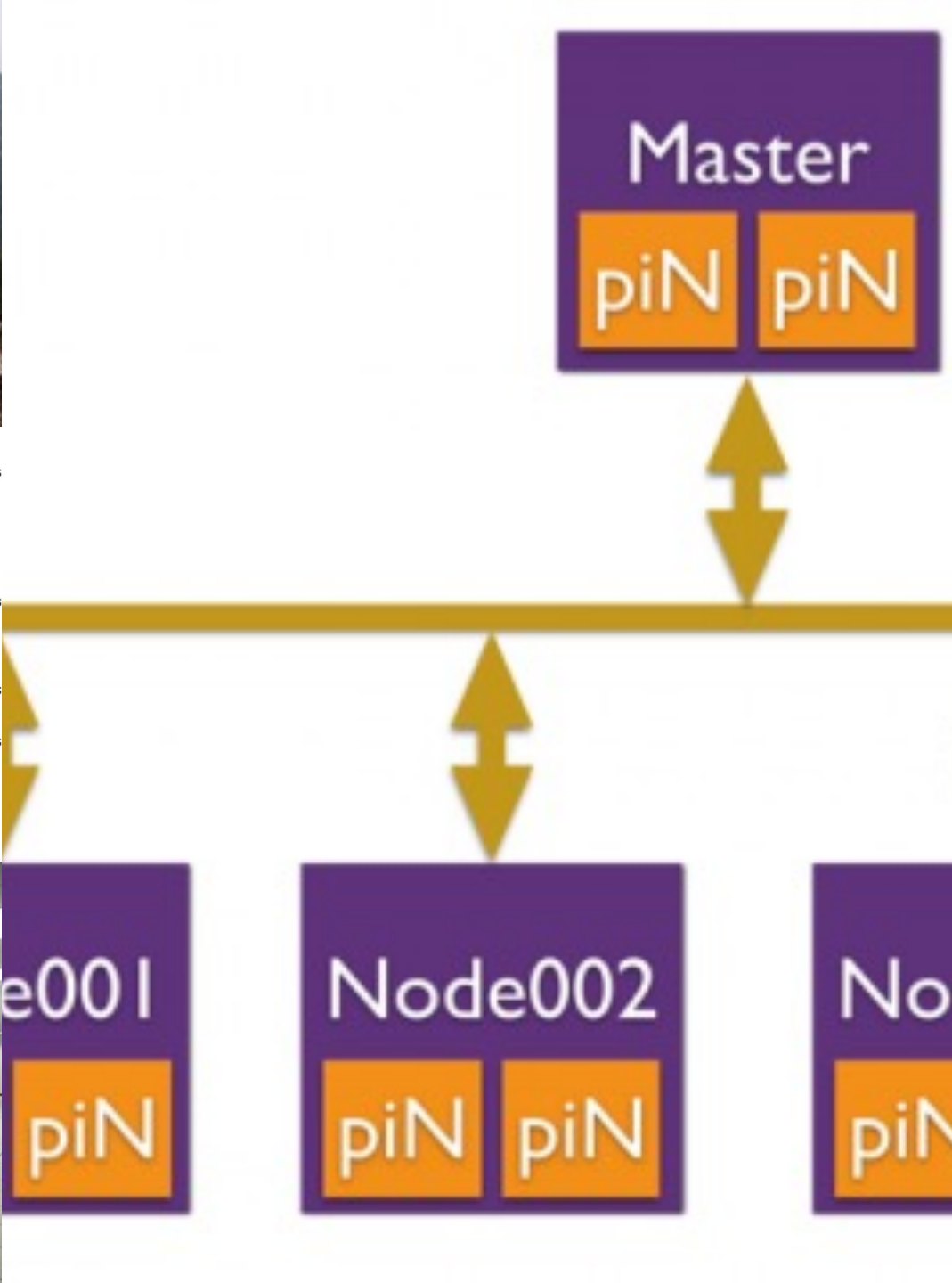
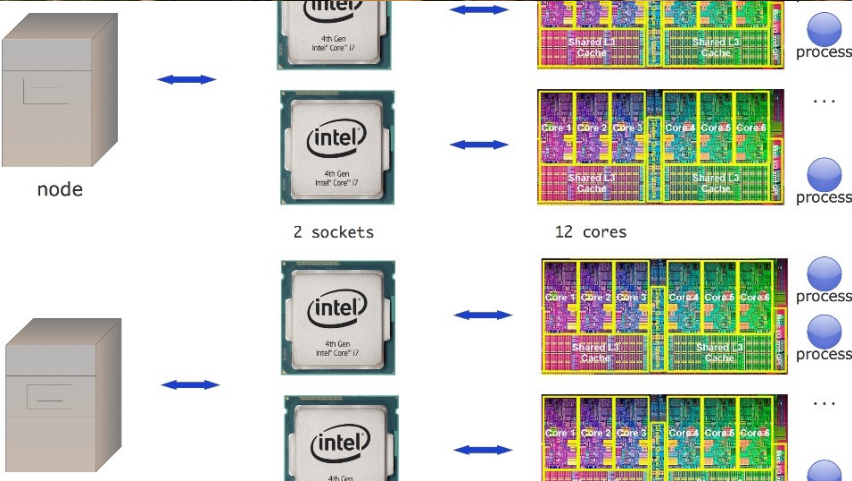


Rust + 2PC

Parallelism at Scale: MPI

cs378



Outline for Today

SOSP
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 what you want to do.

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 rather than just being *planned* 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 significant refinement is needed, I will ask you to hand in a revised proposal in the few weeks after the proposal deadline.

You can work in groups for your project.

- [A very good example](#)

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

I encourage you to come up with your own project idea, but there are suggestions at the end

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

- Provide a detailed timeline of how you plan to build the system. It is really important to
- 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 significant 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](#)

Ideas:

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

The sky is the limit

of this assignment then, is to identify roughly v

ore guidance.

functionality is *completely working* by date X r

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 to

I encourage you to come up with your own project idea, but there are suggestions at the end

You must submit a proposal (1-2 pages long), meeting the guidelines and answering the bas

- Provide a detailed timeline of how you plan to build the system. It is really important to 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 significant 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](#)

Ideas:

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

The sky is the limit

of this assignment then, is to identify roughly v

ore guidance.

functionality is *completely working* by date X r

Questions?

Ownership/Borrowing

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

Ownership/Borrowing

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


Ownership/Borrowing

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

```
fn helper(name: String) {  
    println!("{}", name);  
}
```

Ownership/Borrowing

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

```
fn helper(name: String) {  
    println!("{}", name);  
}
```

Ownership/Borrowing

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

Error: use of moved value: `name`



```
fn helper(name: String) {  
    println!("{}", name);  
}
```

Ownership/Borrowing

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

Error: use of moved value: `name`



```
fn helper(name: String) {  
    println!("{}", name);  
}
```

Take ownership of a String



Ownership/Borrowing

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

Error: use of moved value: `name`

```
fn helper(name: String) {  
    println!("{}", name);  
}
```

Take ownership of a String

```
error[E0382]: use of moved value: `name`  
--> play.rs:28:12  
   |  
24 |     let name = format!(".");  
   |         ---- move occurs because `name` has type `std::string::String`, which does not implement the `Copy` trait  
...  
27 |     helper(name);  
   |         ---- value moved here  
28 |     helper(name);  
   |         ^^^^^ value used here after move
```

Ownership/Borrowing

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

Error: use of moved value: `name`

```
fn helper(name: String) {  
    println!("{}", name);  
}
```


Take ownership of a String

```
error[E0382]: use of moved value: `name`  
--> play.rs:28:12  
24 |     let name = format!(".");  
    |         ---- move occurs because `name` has type `std::string::String`, which does not implement the `Copy` trait  
...  
27 |     helper(name);  
    |         ---- value moved here  
28 |     helper(name);  
    |         ^^^^^ value used here after move
```

What kinds of problems might this prevent?


Ownership/Borrowing

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



Error: use of moved value: `name`

```
fn helper(name: String) {  
    println!("{}", name);  
}
```



Take ownership of a String

```
error[E0382]: use of moved value: `name`  
--> play.rs:28:12  
|  
24 |     let name = format!("...");  
|     ---- move occurs because `name` has type `std::string::String`, which does not implement the `Copy` trait  
...  
27 |     helper(name);  
|     ---- value moved here  
28 |     helper(name);  
|     ^^^^^ value used here after move
```

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

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

Lend the string



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

Shared Borrowing

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

Lend the string



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

Take a reference to a String



Shared Borrowing

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

Lend the string



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

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(||{  
        println!("{}", name);  
    });  
}
```

Shared Borrowing with Concurrency

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

```
fn helper(name: &String) {  
    thread::spawn(||{  
        println!("{}", name);  
    });  
}
```

Lifetime `static` required



Shared Borrowing with Concurrency

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

```
fn helper(name: &String) {  
    thread::spawn(||{  
        println!("{}", name);  
    });  
}
```

Lifetime ``static`` required

```
error[E0621]: explicit lifetime required in the type of `name`  
--> play.rs:11:18  
10 | fn helper(name: &String) -> thread::JoinHandle<()> {  
    |         ----- help: add explicit lifetime ``static` to the type of `name`: `&'static std::string::String`  
11 |     let handle = thread::spawn(move ||{  
    |                               ~~~~~ lifetime ``static` required
```

Does this prevent the exact same class of problems?

Clone, Move

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

```
fn helper(name: String) {  
    thread::spawn(move || {  
        println!("{}", name);  
    });  
}
```


Clone, Move

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

```
fn helper(name: String) {  
    thread::spawn(move || {  
        println!("{}", name);  
    });  
}
```

Explicitly take ownership

Clone, Move

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

Ensure concurrent owners
Work with different copies

```
fn helper(name: String) {  
    thread::spawn(move || {  
        println!("{}", name);  
    });  
}
```

Explicitly take ownership

Clone, Move

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

Ensure concurrent owners
Work with different copies

Is this better?

```
fn helper(name: String) {  
    thread::spawn(move || {  
        println!("{}", name);  
    });  
}
```

Explicitly take ownership

Clone, Move

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

Ensure concurrent owners
Work with different copies

Is this better?

```
fn helper(name: String) {  
    thread::spawn(move || {  
        println!("{}", name);  
    });  
}
```

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

```
struct Structure {  
    id: i32,  
    map: HashMap<String, f32>,  
}  
  
impl Structure {  
    fn mutate(&mut self, name: String, value: f32){  
        self.map.insert(name, value);  
    }  
}
```

Mutability

```
struct Structure {  
    id: i32,  
    map: HashMap<String, f32>,  
}  
  
impl Structure {  
    fn mutate(&mut self, name: String, value: f32){  
        self.map.insert(name, value);  
    }  
}
```

Mutability

```
struct Structure {  
    id: i32,  
    map: HashMap<String, f32>,  
}  
  
impl Structure {  
    fn mutate(&mut self, name: String, value: f32){  
        self.map.insert(name, value);  
    }  
}
```

Key idea:

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

Sharing State: Channels

Sharing State: Channels

```
fn main() {
```

Sharing State: Channels

```
fn main() {  
    let (tx0, rx0) = channel();
```

Sharing State: Channels

```
fn main() {  
    let (tx0, rx0) = channel();  
    thread::spawn(move || {  
        let (tx1, rx1) = channel();  
        tx0.send((format!("yo"), tx1)).unwrap();  
        let response = rx1.recv().unwrap();  
        println!("child got {}", response);  
    });  
}
```

Sharing State: Channels

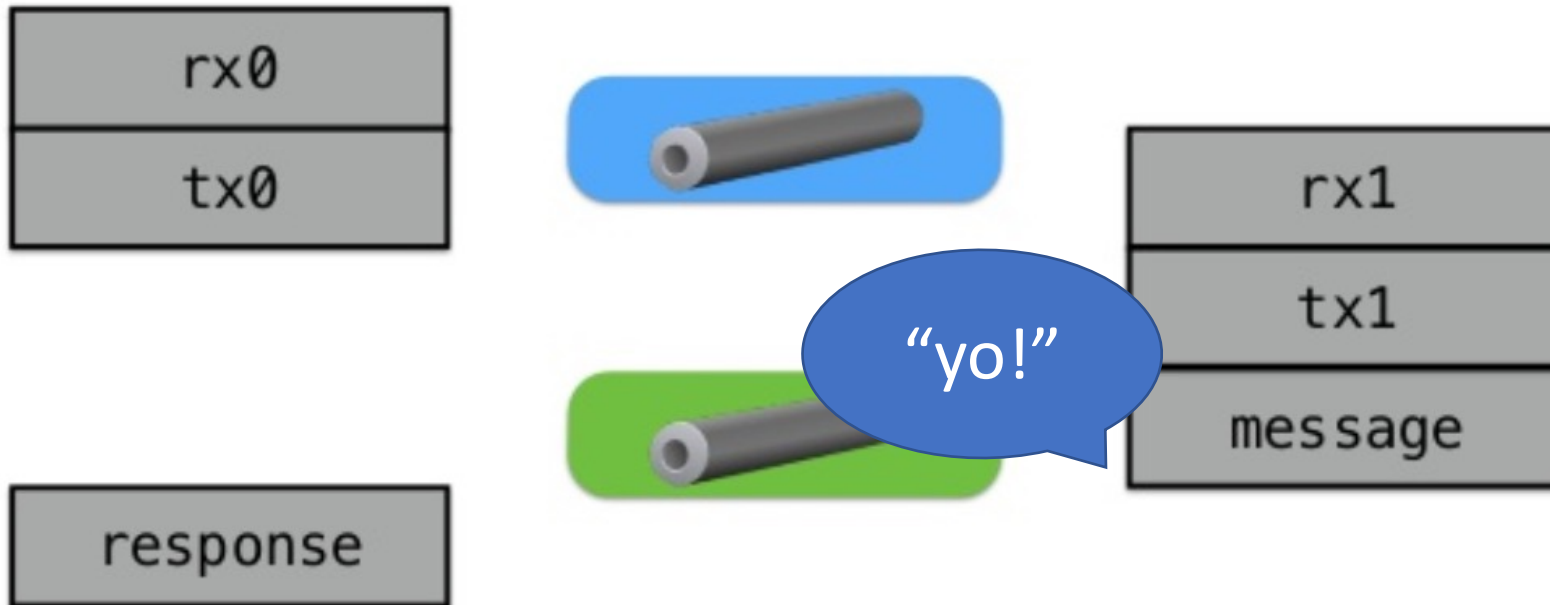
```
fn main() {
    let (tx0, rx0) = channel();
    thread::spawn(move || {
        let (tx1, rx1) = channel();
        tx0.send((format!("yo"), tx1)).unwrap();
        let response = rx1.recv().unwrap();
        println!("child got {}", response);
    });
    let (message, tx1) = rx0.recv().unwrap();
    tx1.send(format!("what up!")).unwrap();
    println("parent received {}", message);
}
```

Sharing State: Channels



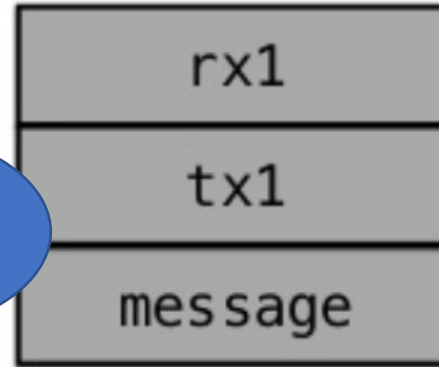
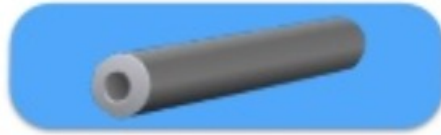
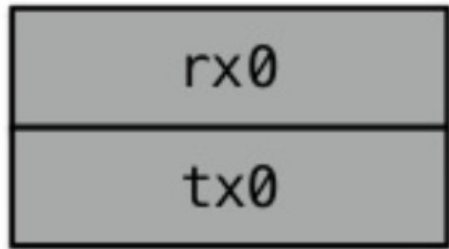
```
let (message, tx1) = rx0.recv().unwrap();
tx1.send(format!("what up!")).unwrap();
println("parent received {}", message);
}
```

Sharing State: Channels



```
let (message, tx1) = rx0.recv().unwrap();  
tx1.send(format!("what up!")).unwrap();  
println("parent received {}", message);  
}
```

Sharing State: Channels



“what up!”

“yo!”

response

```
let (message, tx1) = rx0.recv().unwrap();
tx1.send(format!("what up!")).unwrap();
println("parent received {}", message);
}
```

Sharing State: Channels

```
fn main() {  
    let (tx0, rx0) = channel();  
    thread::spawn(move || {  
        let (tx1, rx1) = channel();  
        tx0.send((format!("yo"), tx1)).unwrap();  
        let response = rx1.recv().unwrap();  
        println!("child got {}", response);  
    });  
    let (message, tx1) = rx0.recv().unwrap();  
    tx1.send(format!("what up!")).unwrap();  
    println("parent received {}", message);  
}
```


Sharing State: Channels

```
fn main() {  
    let (tx0, rx0) = channel();  
    thread::spawn(move || {  
        let (tx1, rx1) = channel();  
        tx0.send((format!("yo"), tx1)).unwrap();  
        let response = rx1.recv().unwrap();  
        println!("child got {}", response);  
    });  
    let (message, tx1) = rx0.recv().unwrap();  
    tx1.send(format!("what up!")).unwrap();  
    println("parent received {}", message);  
}
```

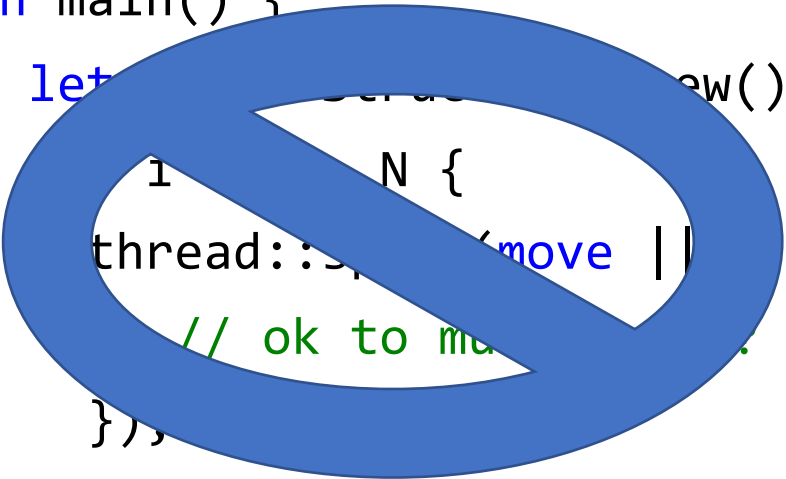
APIs return Option<T>

Sharing State

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

Sharing State

```
fn main() {  
    let server = Server::new();  
    for i in 0..N {  
        thread::spawn(move || {  
            // ok to mu...  
        })  
    }  
}
```



Sharing State: Arc and Mutex

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

Sharing State: Arc and Mutex

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

Sharing State: Arc and Mutex

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

Sharing State: Arc and Mutex

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

Sharing State: Arc and Mutex

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


Sharing State: Arc and Mutex

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

Key ideas:

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

Sharing State: Arc and Mutex

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

Anyone see the error here?

Key ideas:

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

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

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

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

Why doesn't "&" fix it?
(*&var_arc, instead of just var_arc*)

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

Why doesn't "&" fix it?
(*&var_arc, instead of just var_arc*)

Would cloning var_arc fix it?

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


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

Same problem!

```
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(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*

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

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


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

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

Why does this compile?

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

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

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(move || {  
            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?

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(move || {  
            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?

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

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(move || {  
            let ldata = Arc::clone(&var_arc);  
            let vdata = ldata.lock();  
            // 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?

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);
```

Parameters!

```
// 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(); }
```

```
}
```

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

Potpourri: Rudra

RUDRA: Finding Memory Safety Bugs in Rust at the Ecosystem Scale

Yechan Bae Youngsuk Kim Ammar Askar Jungwon Lim Taesoo Kim
Georgia Institute of Technology

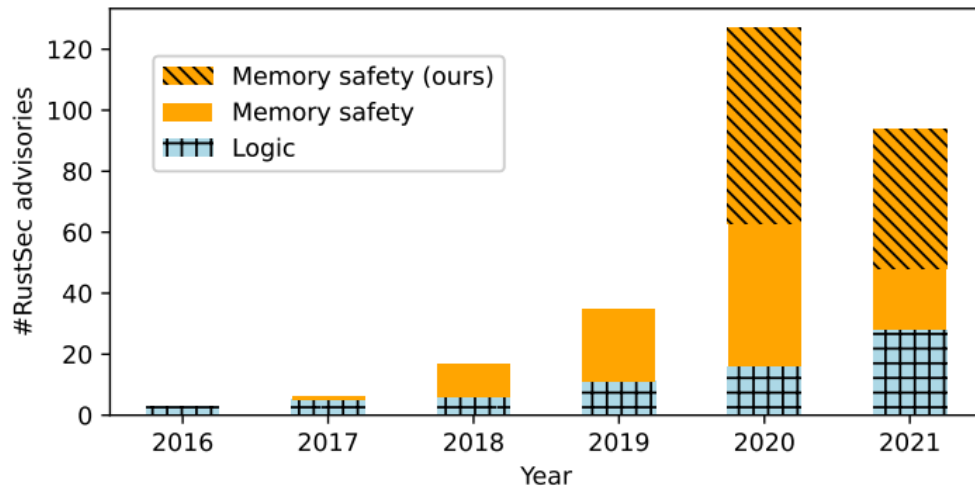


Figure 1. RUDRA found 264 new memory safety bugs in the Rust ecosystem. They received 112 RustSec advisories, which represent 51.6% of the memory safety bugs reported to the official Rust security advisory database, RustSec [39].

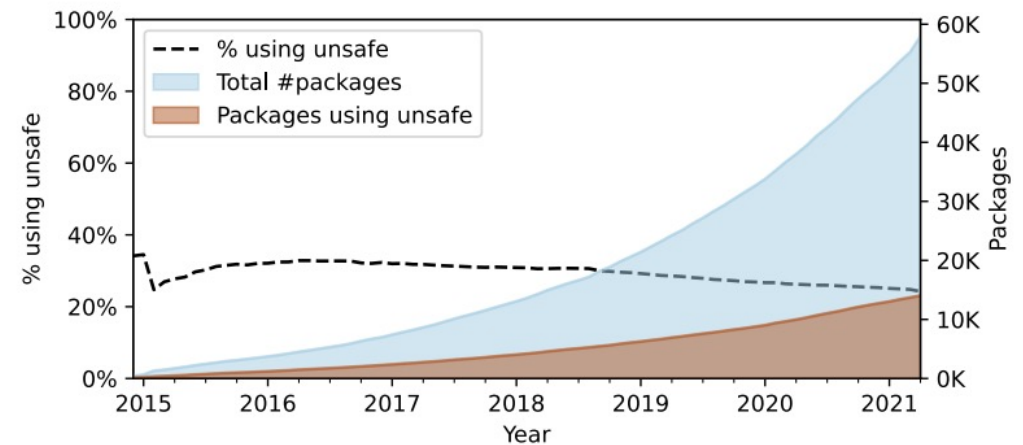


Figure 2. Although the number of packages grows exponentially, the percentage of packages using unsafe code remains consistently around 25-30%, similar to other reports [16, 31].

A hard to find issue

```
1 // CVE-2020-36323: a higher-order invariant bug in join()
2 fn join_generic_copy<B, T, S>(slice: &[S], sep: &[T]) -> Vec<T>
3     where T: Copy, B: AsRef<T> + ?Sized, S: Borrow<B>
4 {
5     let mut iter = slice.iter();
6
7     // `slice` is converted for the first time
8     // during the buffer size calculation.
9     * let len = ...;
10    * let mut result = Vec::with_capacity(len);
11    ...
12    unsafe {
13        let pos = result.len();
14        let target = result.get_unchecked_mut(pos..len);
15
16        // `slice` is converted for the second time in macro
17        // while copying the rest of the components.
18    *   specialize_for_lengths!(sep, target, iter;
19    *       0, 1, 2, 3, 4);
20
21        // Indicate that the vector is initialized
22        result.set_len(len);
23    }
24    result
25 }
26
27 // PoC: a benign join() can trigger a memory safety issue
28 impl Borrow<str> for InconsistentBorrow {
29     fn borrow(&self) -> &str {
30         if self.is_first_time() {
31             "123456"
32         } else {
33             "0"
34         }
35     }
36 }
37
38 let arr: [InconsistentBorrow; 3] = Default::default();
39 arr.join("-");
```

Figure 7. A missing check of the higher-order invariant introduces a time-of-check to time-of-use bug in the Rust standard library (`join()` for `[Borrow<str>]`). RUDRA found this previously unknown bug (CVE-2020-36323 [10]).

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:

```
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)
}
```

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

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)
}
```

Problem: crash in the middle

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

Transactions: Implementation

Transactions: Implementation

- Key idea: turn multiple updates into a single one

Transactions: Implementation

- Key idea: turn multiple updates into a single one
- Many implementation Techniques
 - Two-phase locking
 - Timestamp ordering
 - Optimistic Concurrency Control
 - Journaling
 - 2,3-phase commit
 - Speculation-rollback
 - Single global lock
 - Compensating transactions

Transactions: Implementation

- Key idea: turn multiple updates into a single one
- Many implementation Techniques
 - Two-phase locking
 - Timestamp ordering
 - Optimistic Concurrency Control
 - Journaling
 - 2,3-phase commit
 - Speculation-rollback
 - Single global lock
 - Compensating transactions

Key problems:

- output commit
- synchronization

Transactions: Implementation

- Key idea: turn multiple updates into a single one
- Many implementation Techniques
 - Two-phase locking
 - Timestamp ordering
 - Optimistic Concurrency Control
 - Journaling
 - 2,3-phase commit
 - Speculation-rollback
 - Single global lock
 - Compensating transactions

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)

2PC limitation(s)

- Coordinator crashes at W, never wakes up

2PC limitation(s)

- Coordinator crashes at W, never wakes up
- All nodes block forever!

2PC limitation(s)

- Coordinator crashes at W, never wakes up
- All nodes block forever!
- Can participants ask each other what happened?


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

2PC limitation(s)

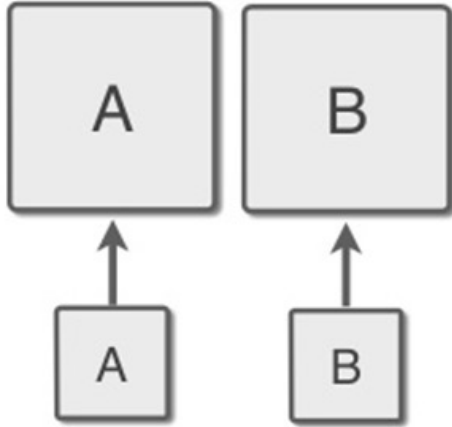
- Coordinator crashes at W, never wakes up
- All nodes block forever!
- Can participants ask each other what happened?
- 2PC: always has risk of indefinite blocking
- Solution: (yes) 3 phase commit!
 - Reliable replacement of crashed “leader”
 - 2PC often good enough in practice

Questions?



Scale Out vs Scale Up

Scale Out vs Scale Up

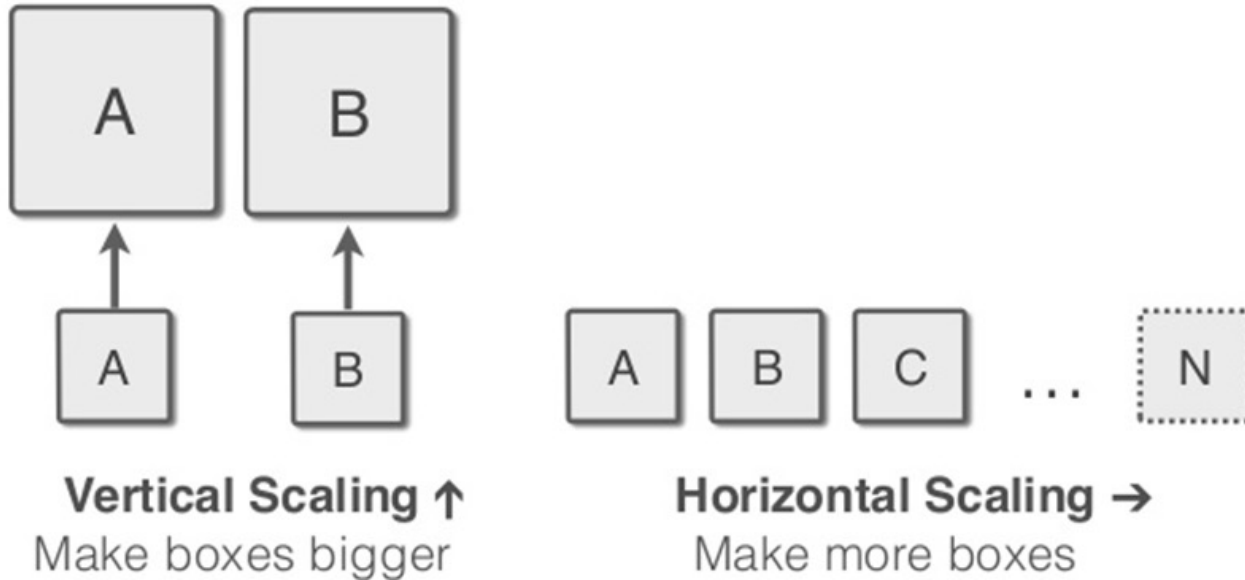


Vertical Scaling ↑
Make boxes bigger



Horizontal Scaling →
Make more boxes

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:

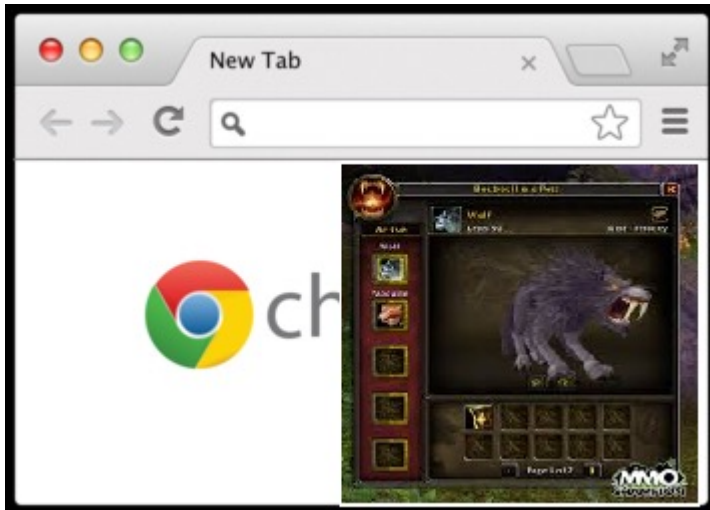
www.purchase-a-pooch.biz



Parallel Systems Architects Wanted

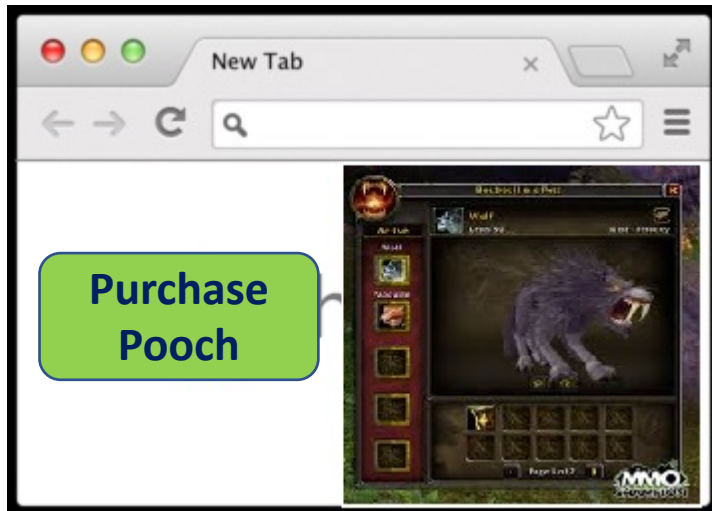
Parallel Systems Architects Wanted

1. User Browses Potential Pets



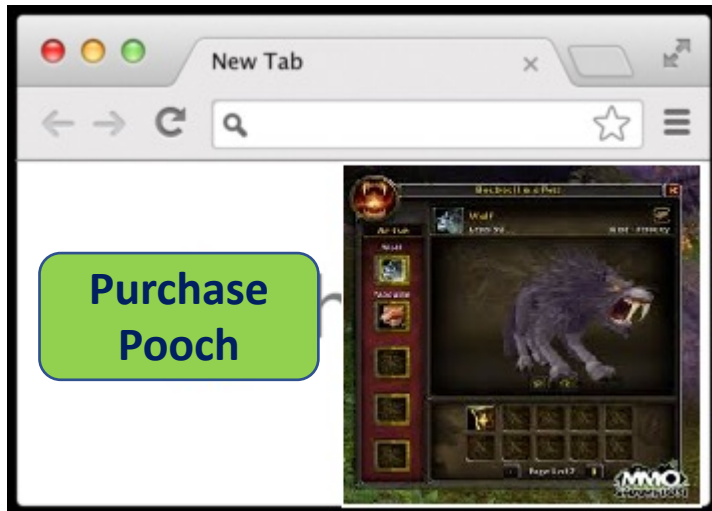
Parallel Systems Architects Wanted

1. User Browses Potential Pets
2. Clicks “Purchase Pooch”



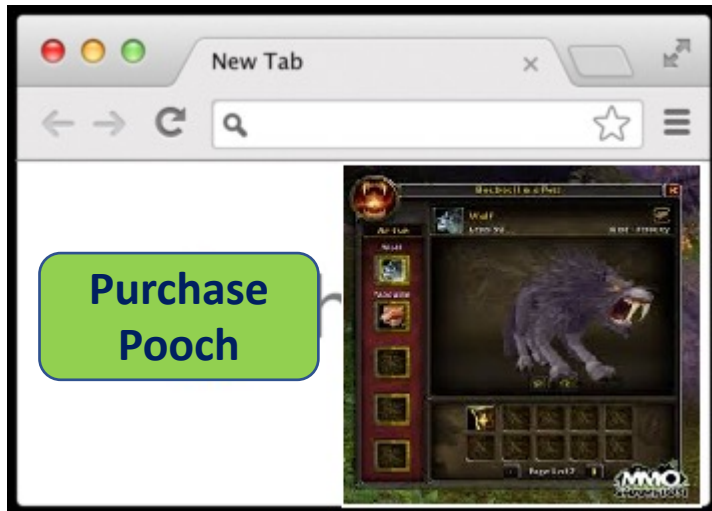
Parallel Systems Architects Wanted

1. User Browses Potential Pets
2. Clicks “Purchase Pooch”
3. Web Server, CGI/EJB + Database complete request



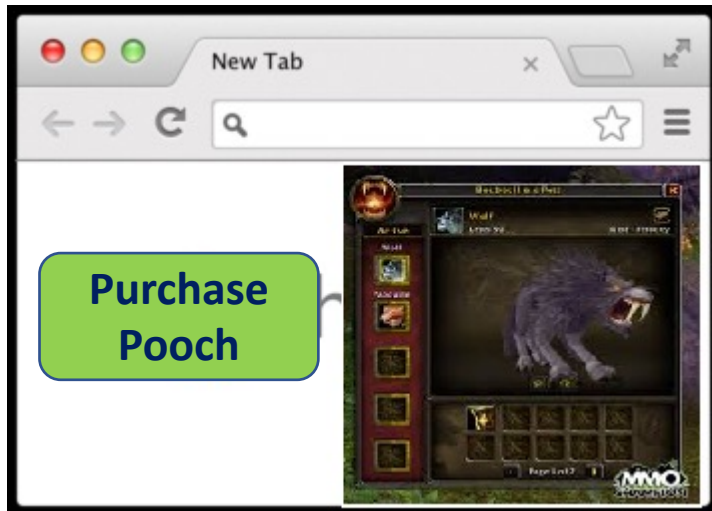
Parallel Systems Architects Wanted

1. User Browses Potential Pets
2. Clicks “Purchase Pooch”
3. Web Server, CGI/EJB + Database complete request
4. Pooch delivered (not shown)

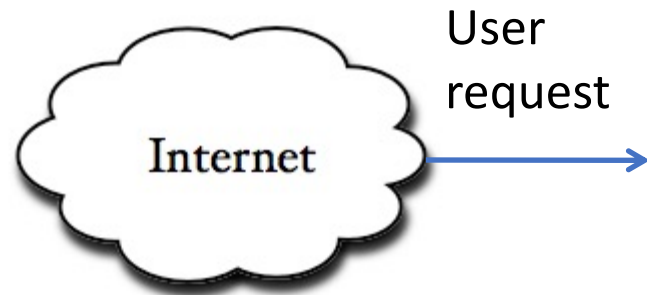


Parallel Systems Architects Wanted

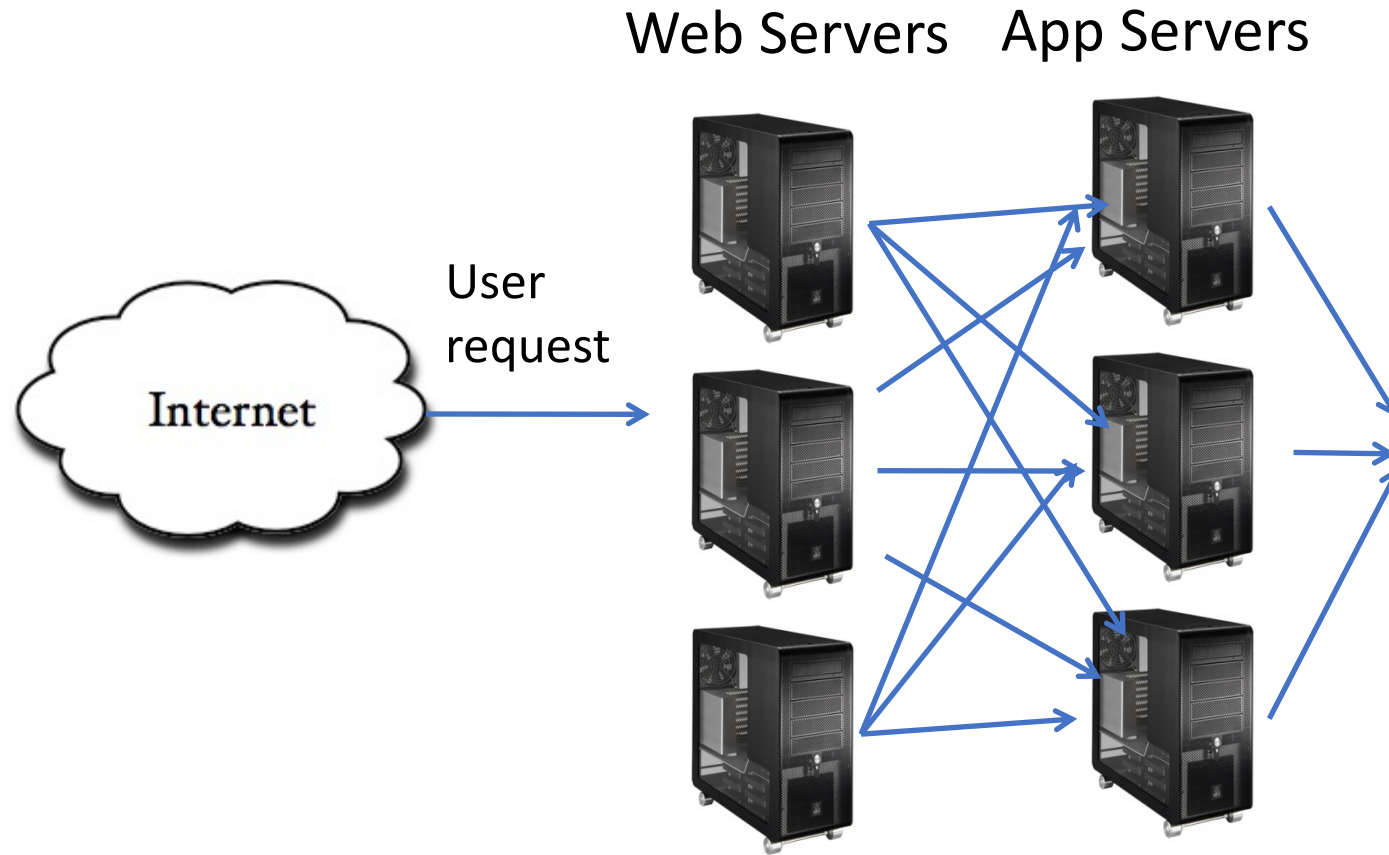
1. User Browses Potential Pets
2. Clicks “Purchase Pooch”
3. Web Server, CGI/EJB + Database complete request
4. Pooch delivered (not shown) How to handle lots and lots of dogs?



3 Tier architecture

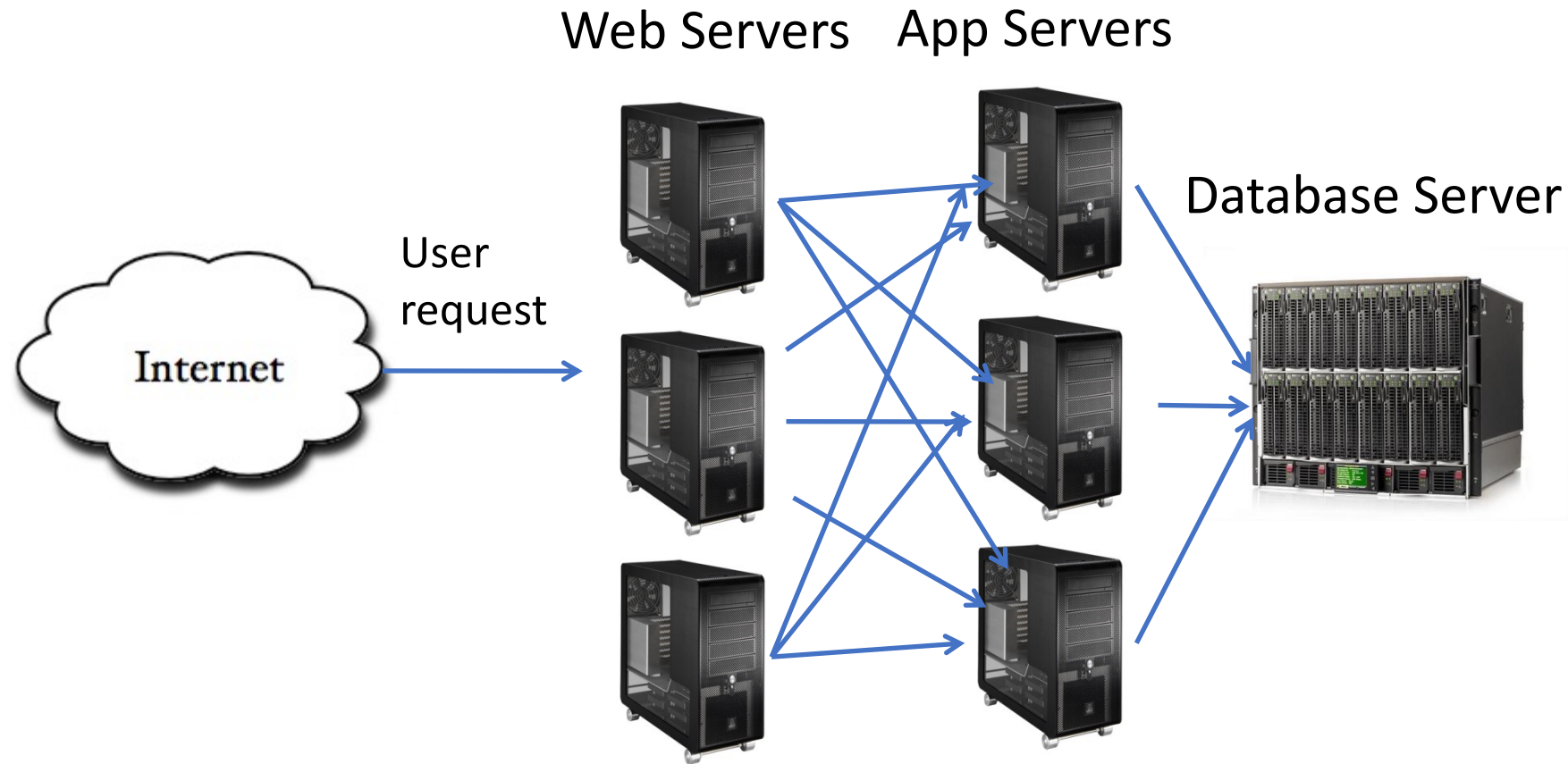


3 Tier architecture



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

3 Tier architecture

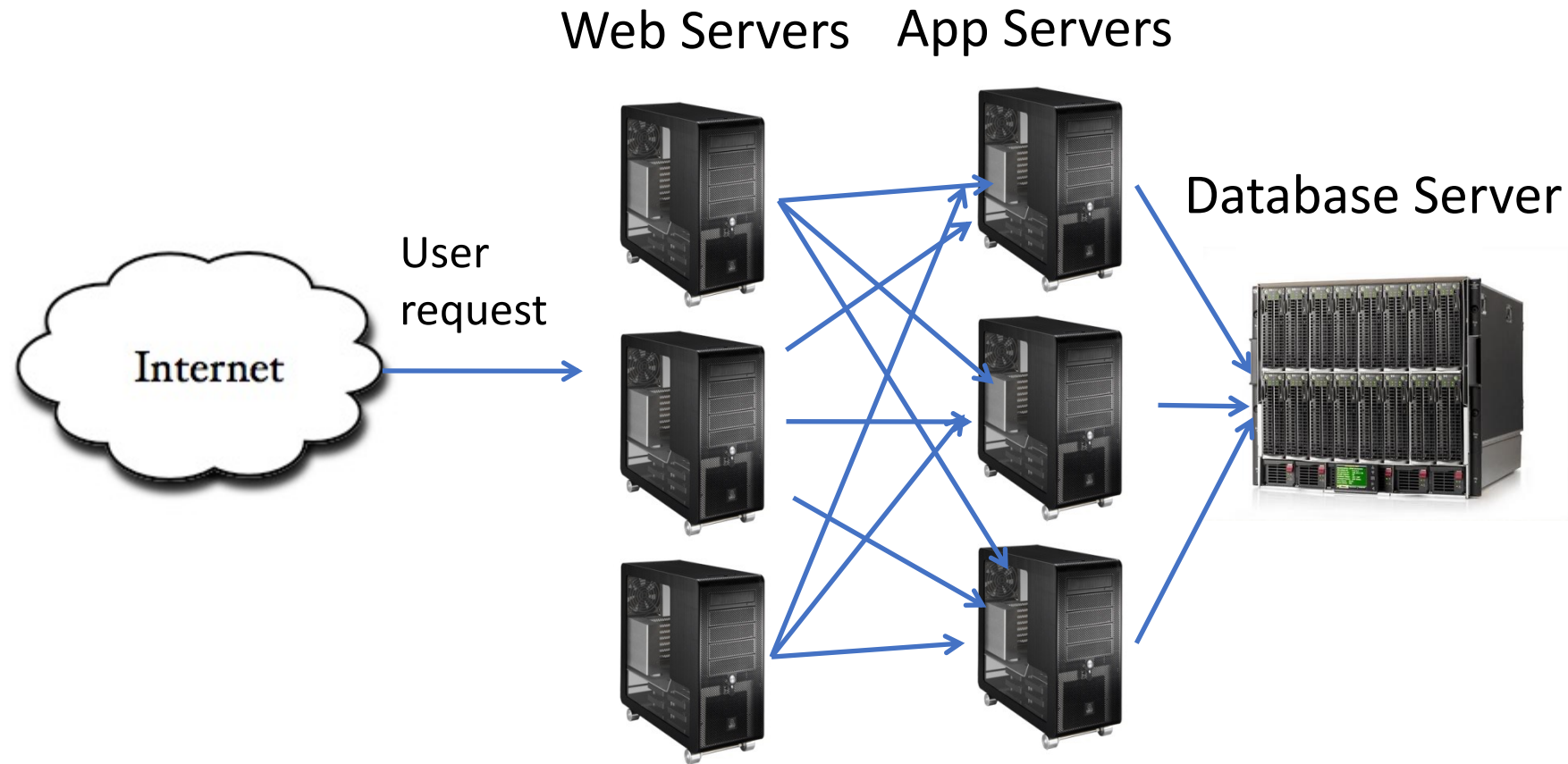


Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

3 Tier architecture



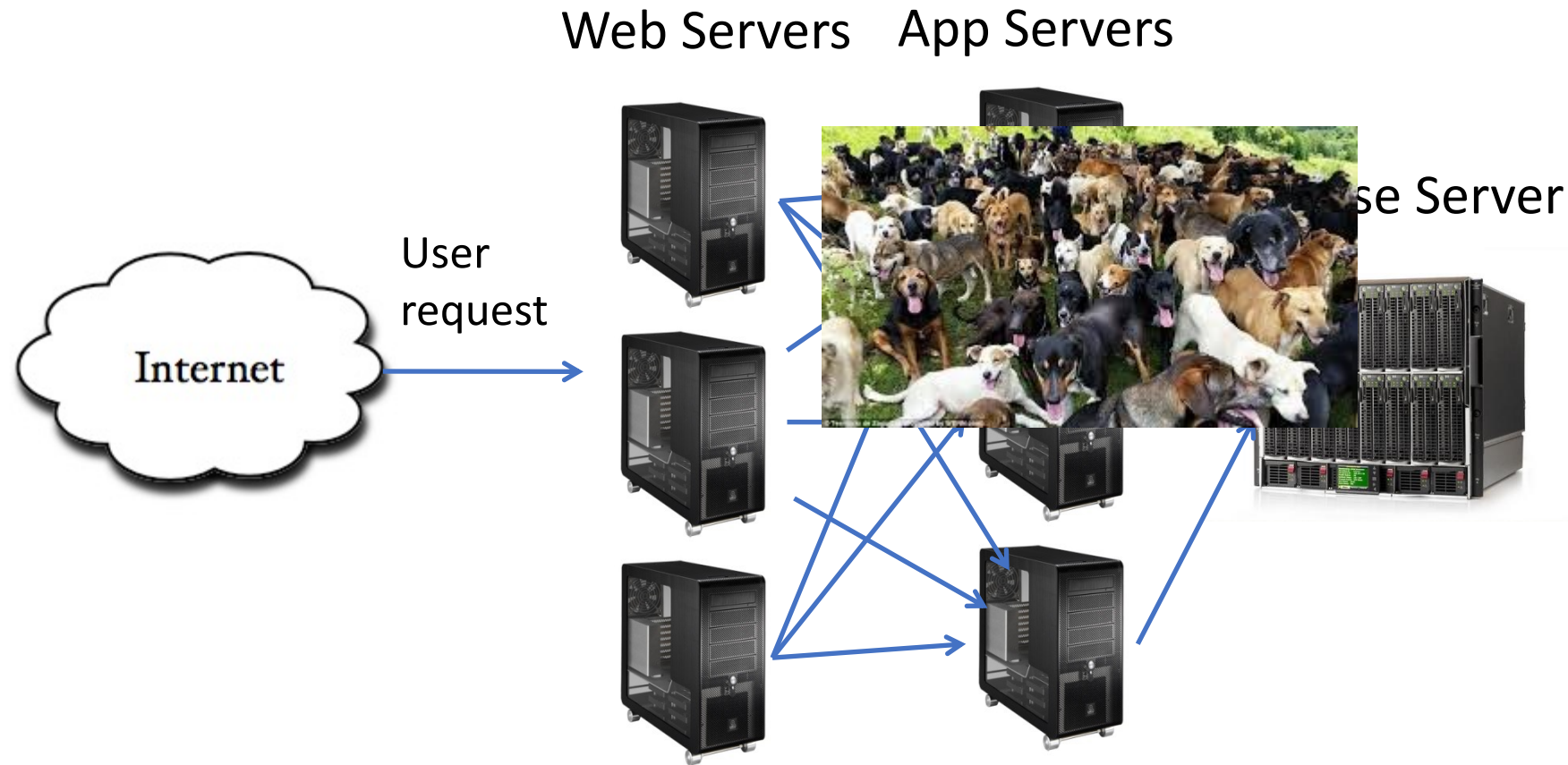
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

Why is this a good arrangement?

3 Tier architecture



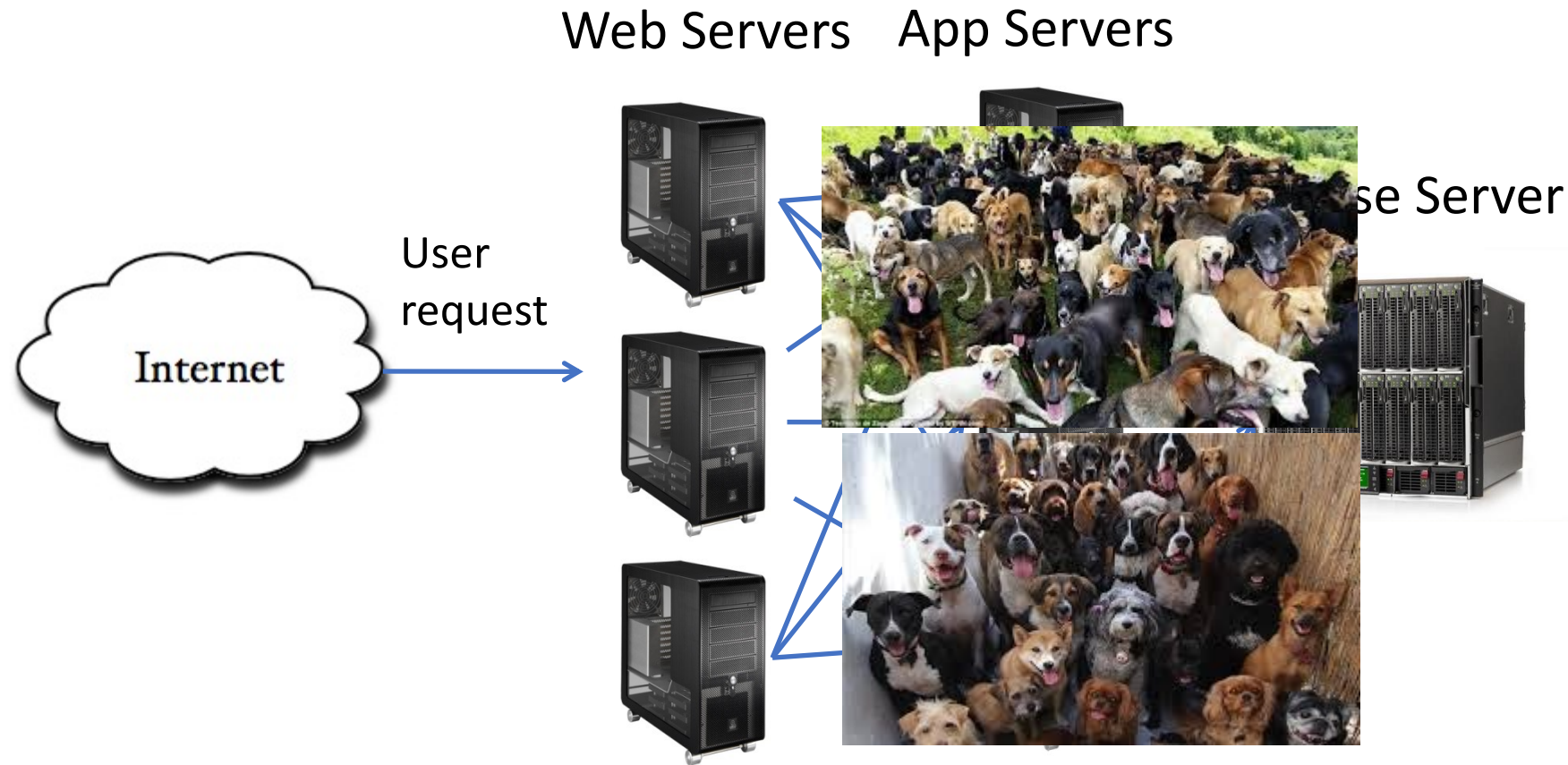
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

Why is this a good arrangement?

3 Tier architecture



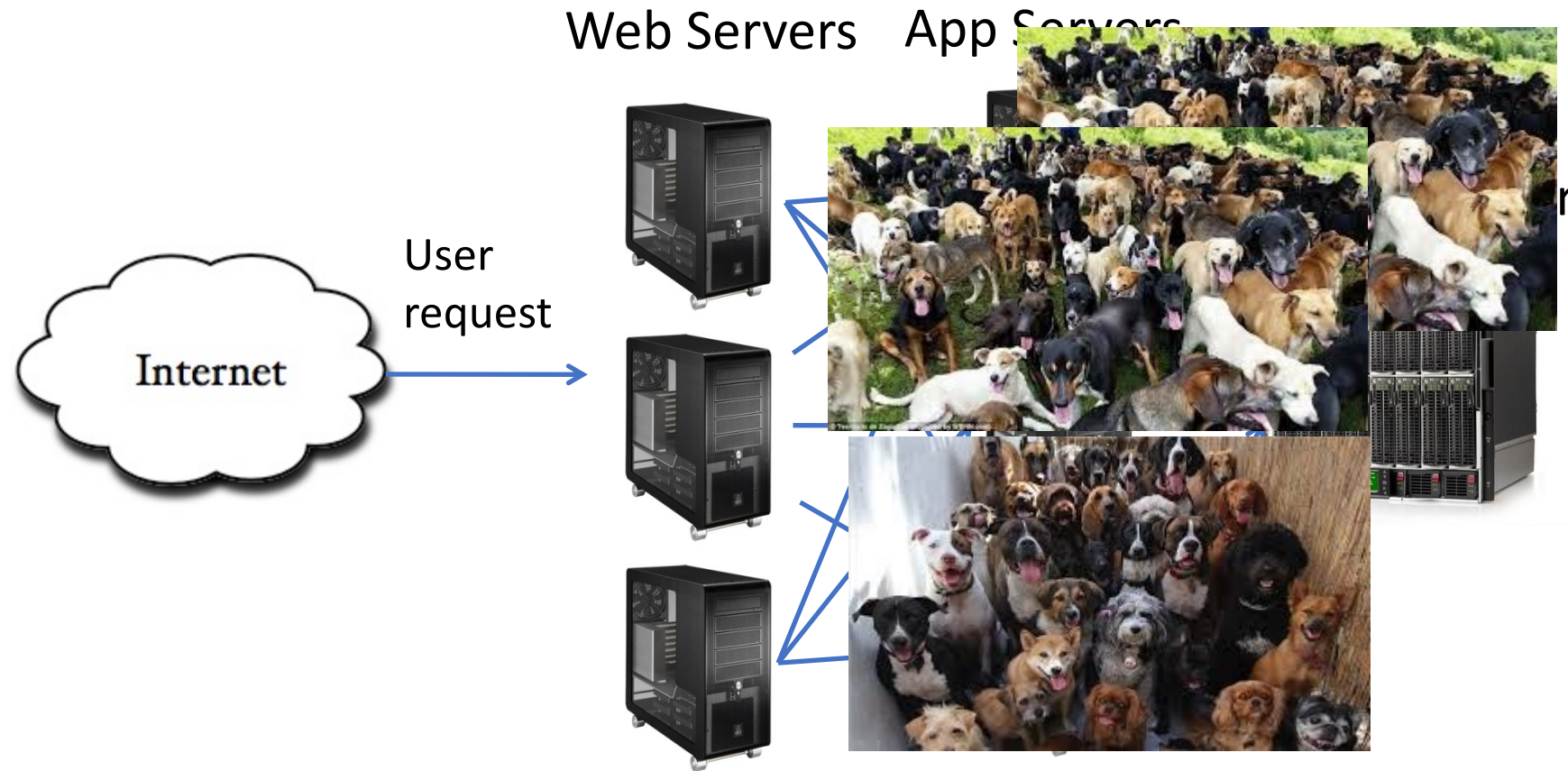
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

Why is this a good arrangement?

3 Tier architecture



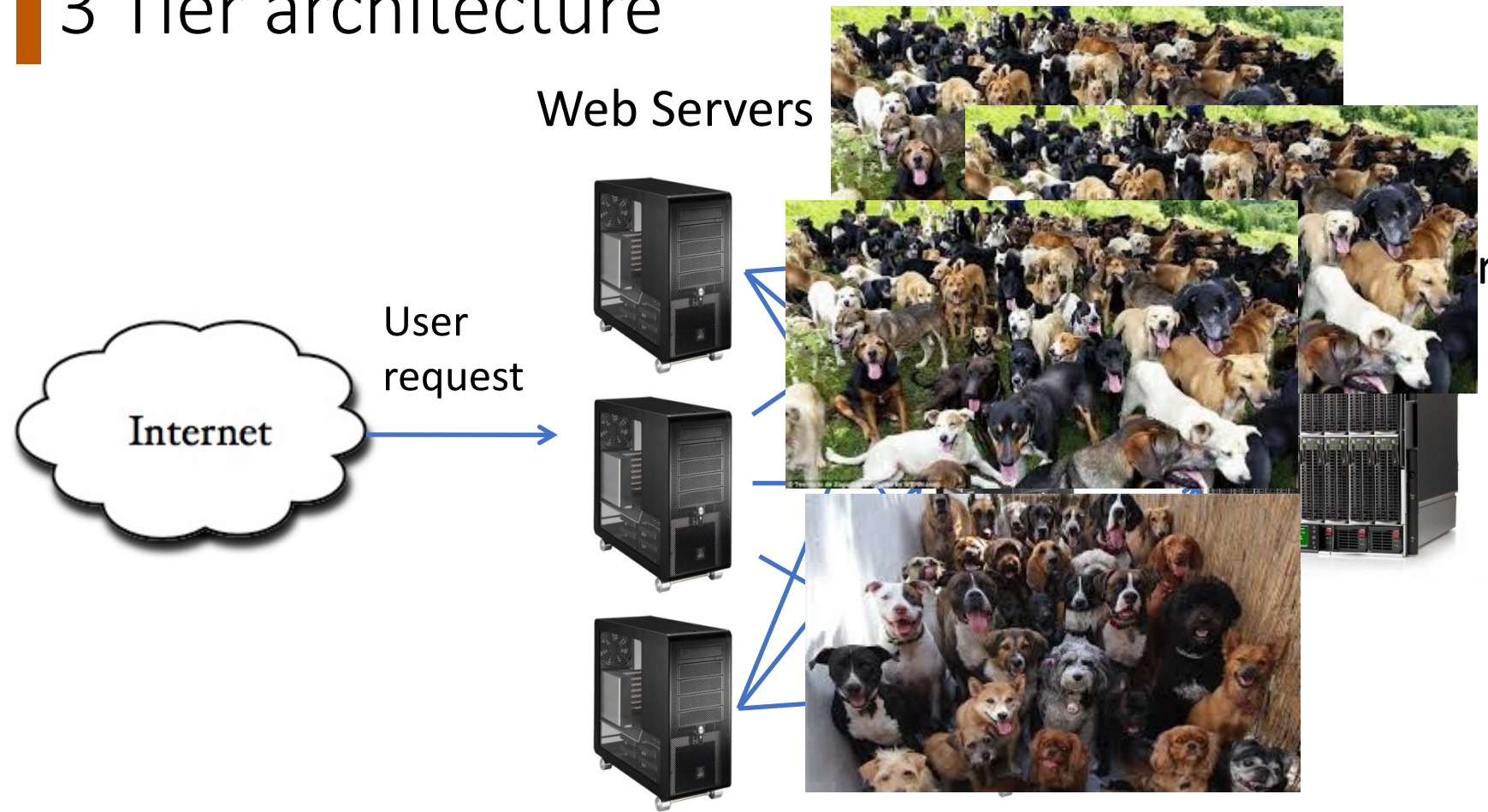
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

Why is this a good arrangement?

3 Tier architecture



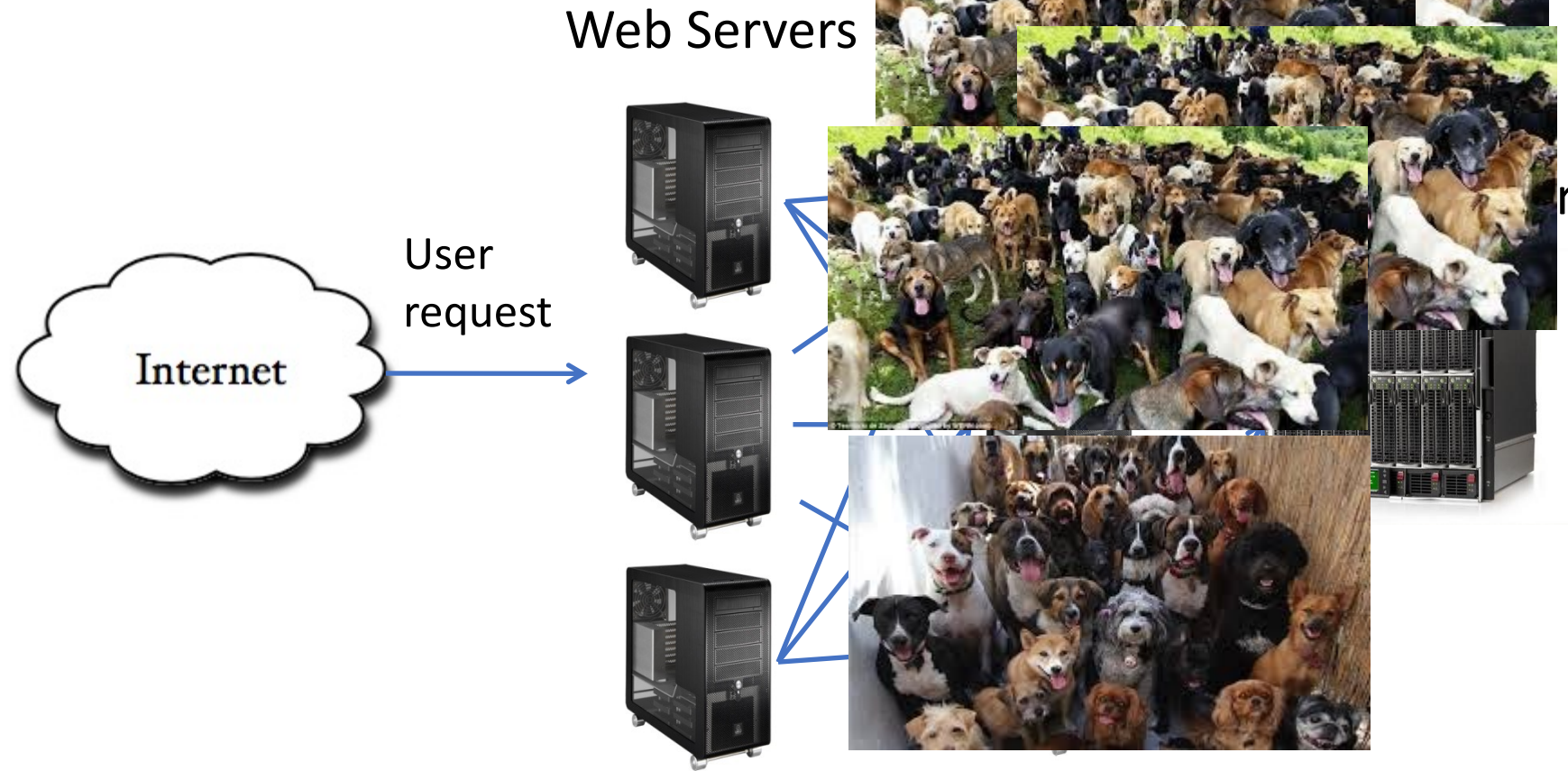
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

Why is this a good arrangement?

3 Tier architecture



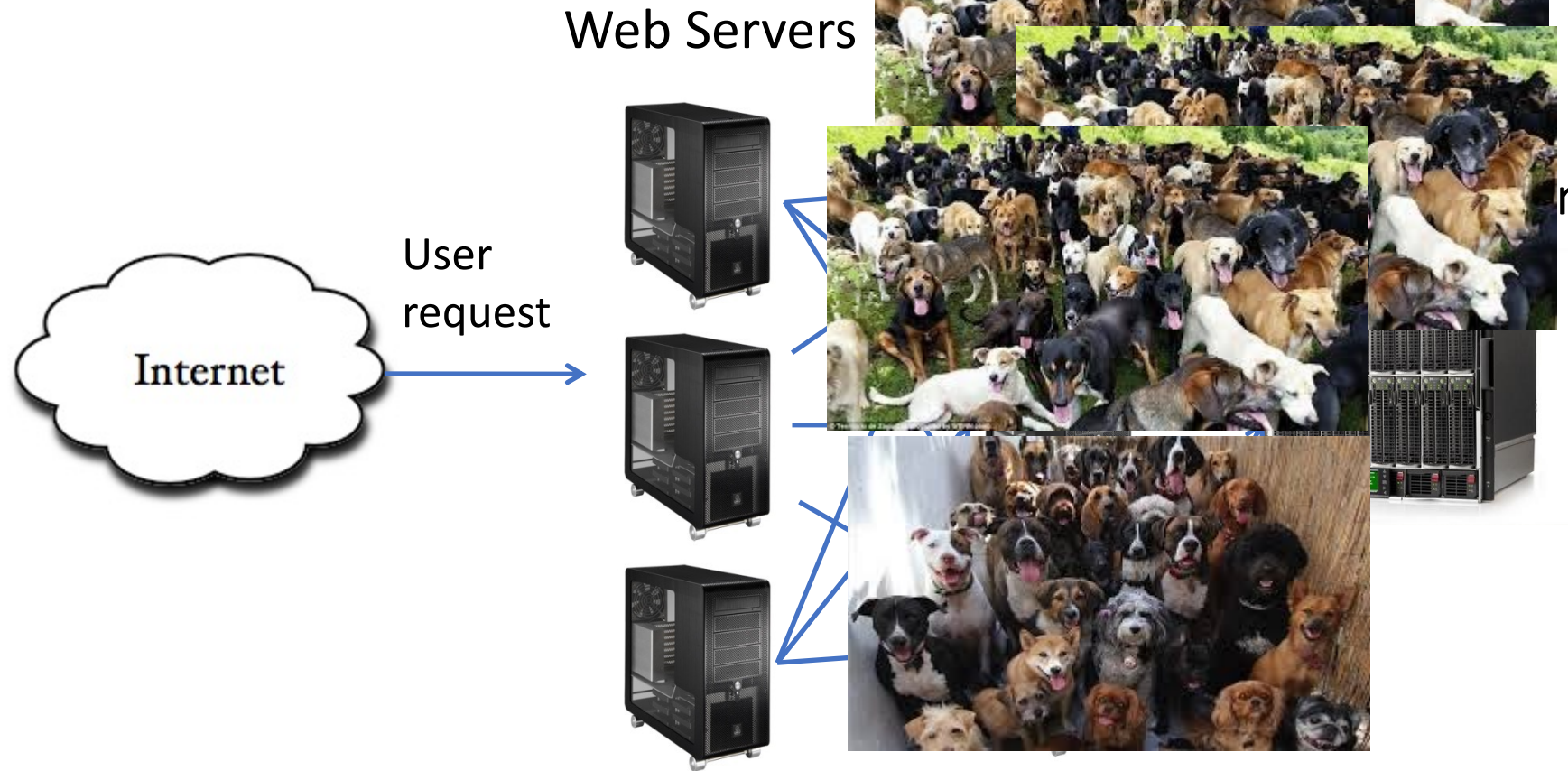
Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

Why is this a good arrangement?

3 Tier architecture



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

Database Server → scales vertically

Horizontal Scale → "Shared Nothing"

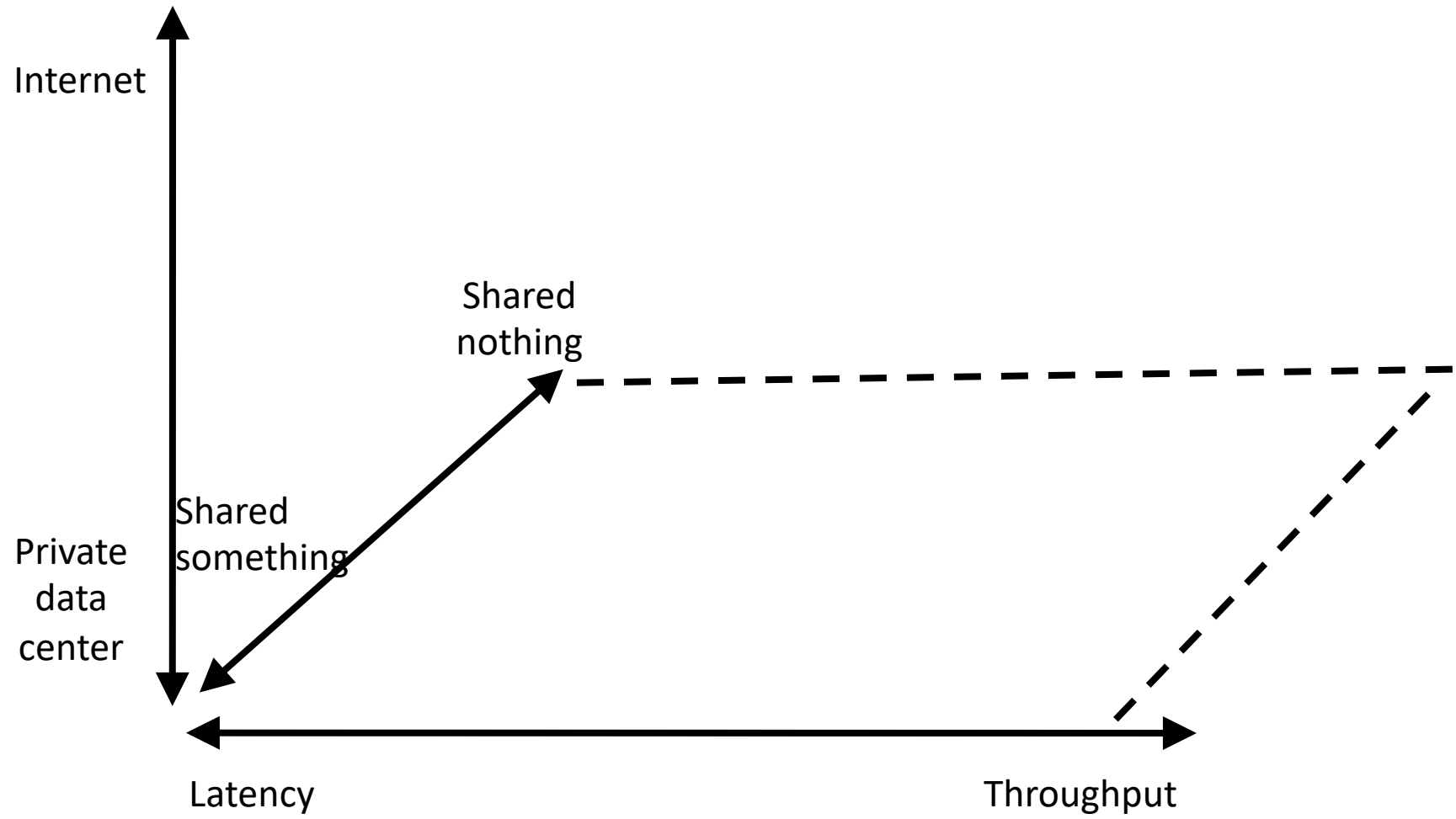
Why is this a good arrangement?

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

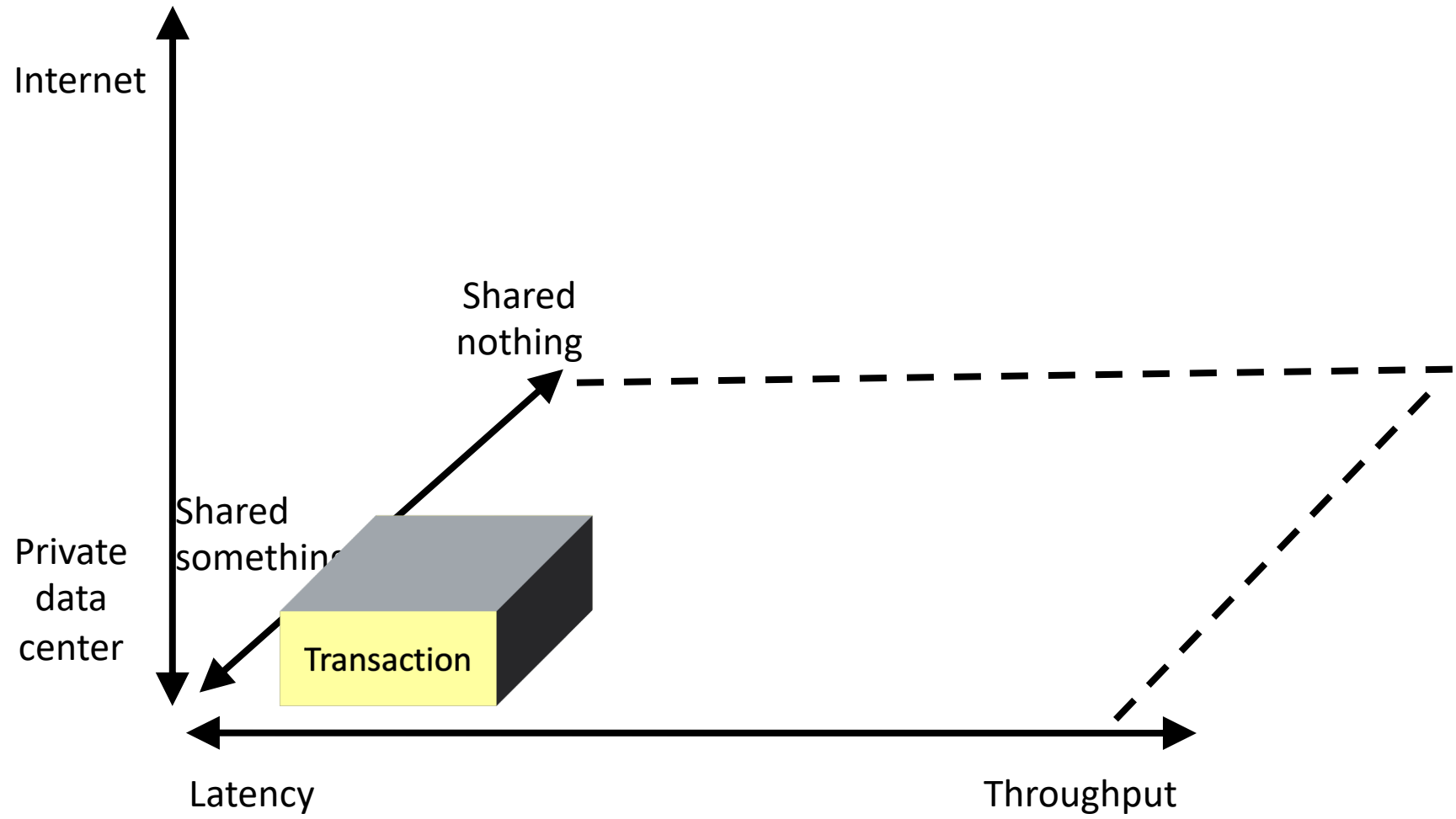
Horizontal Scale: Goal



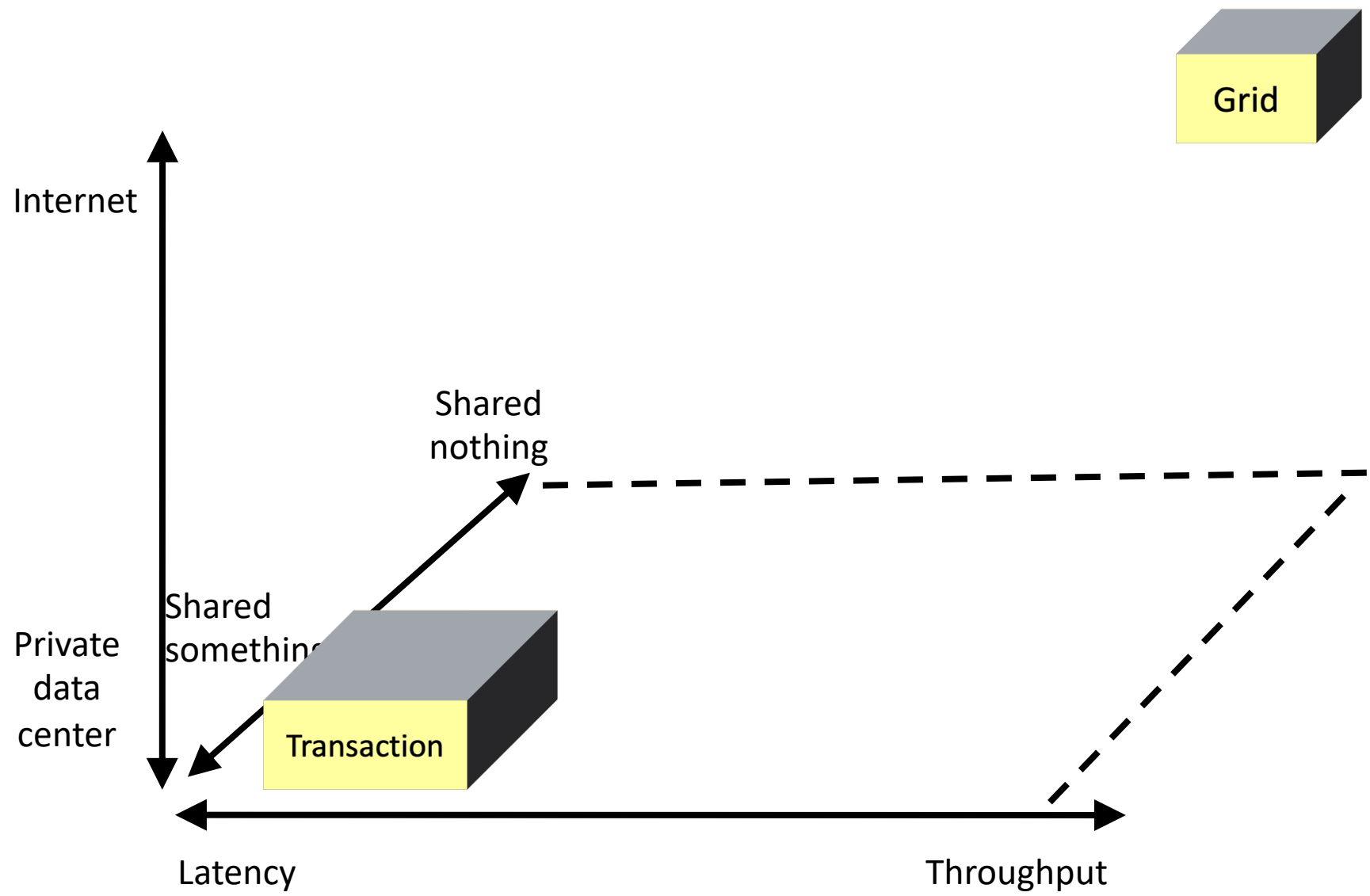
Design Space



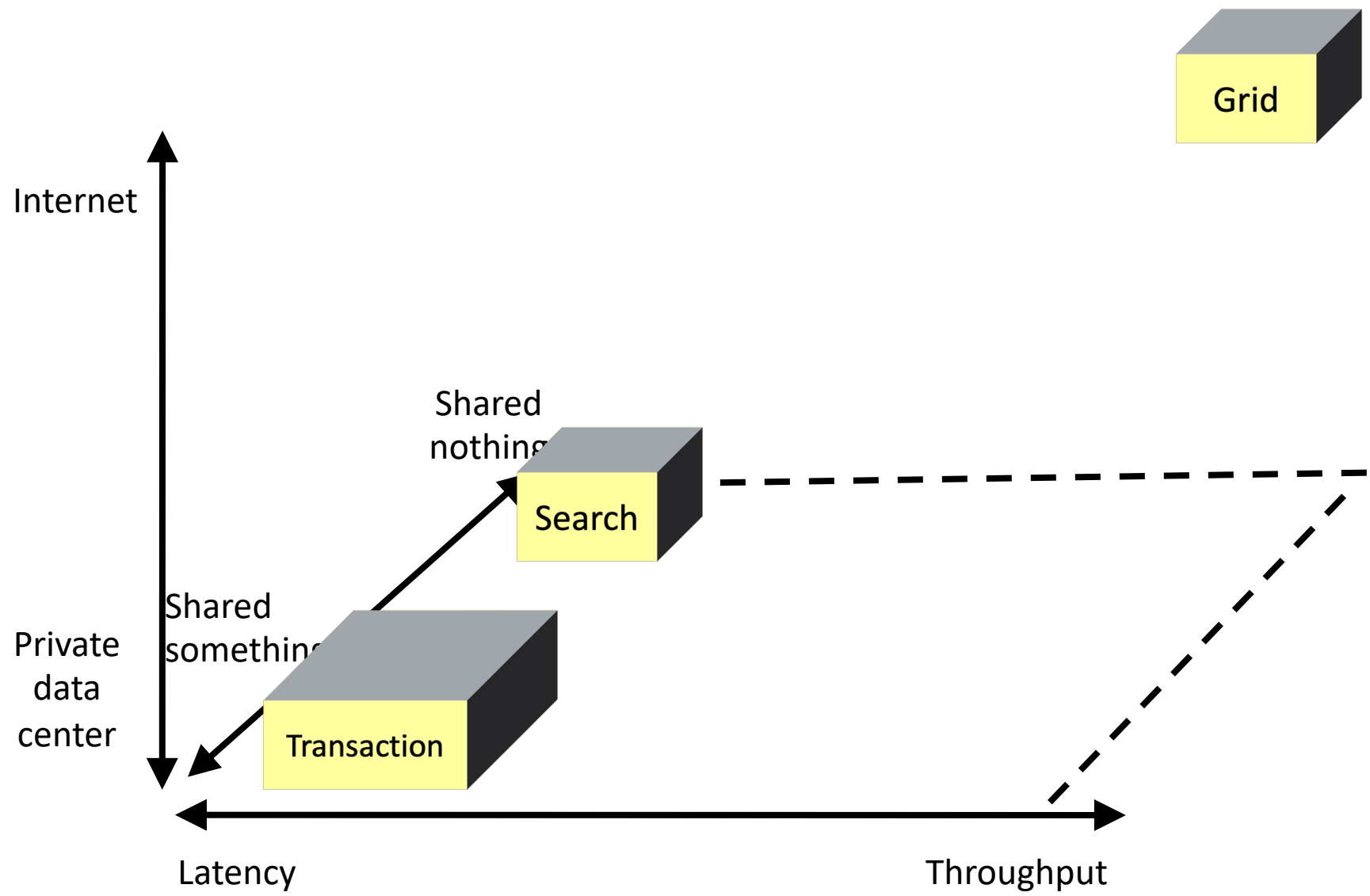
Design Space



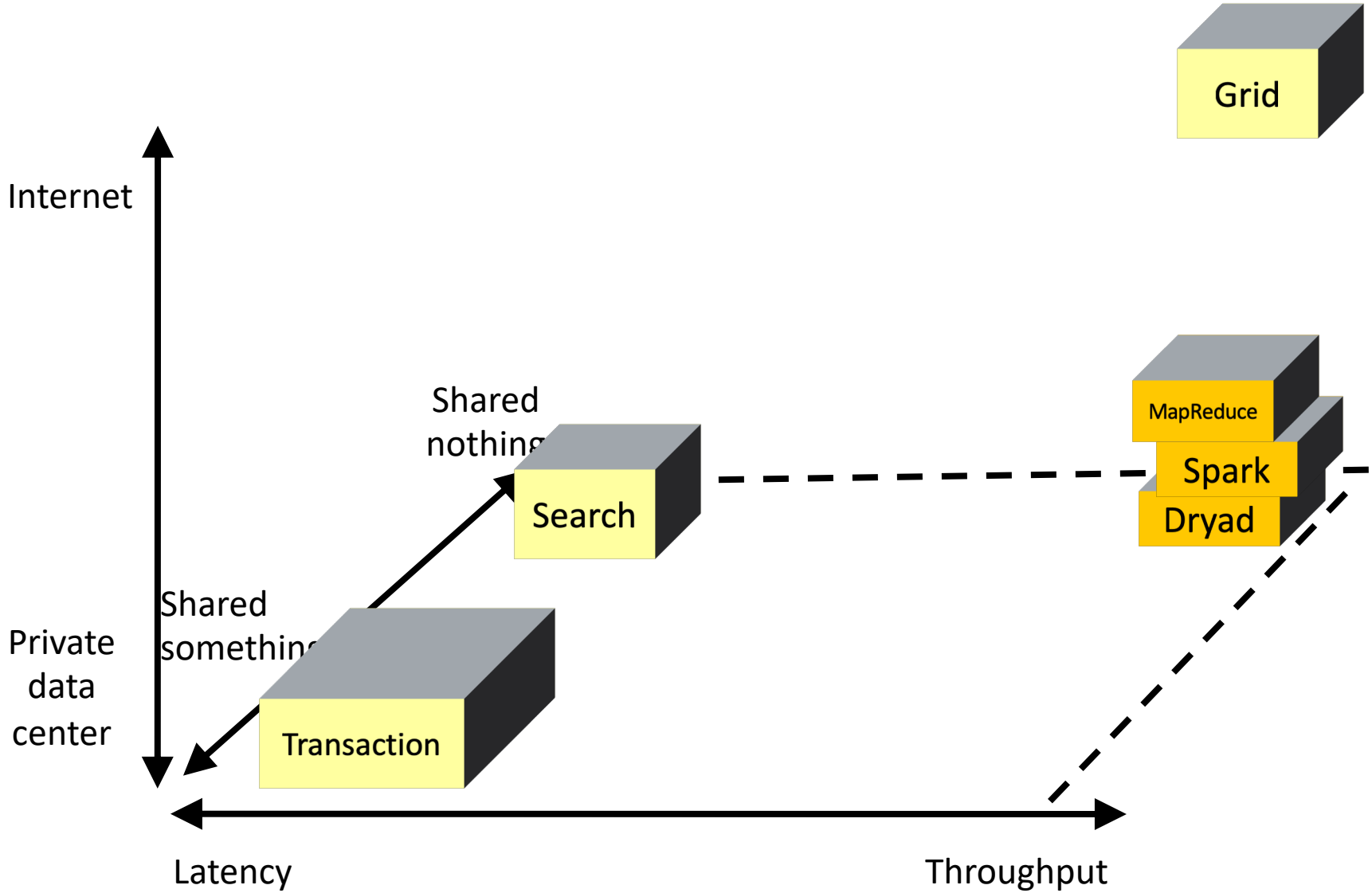
Design Space



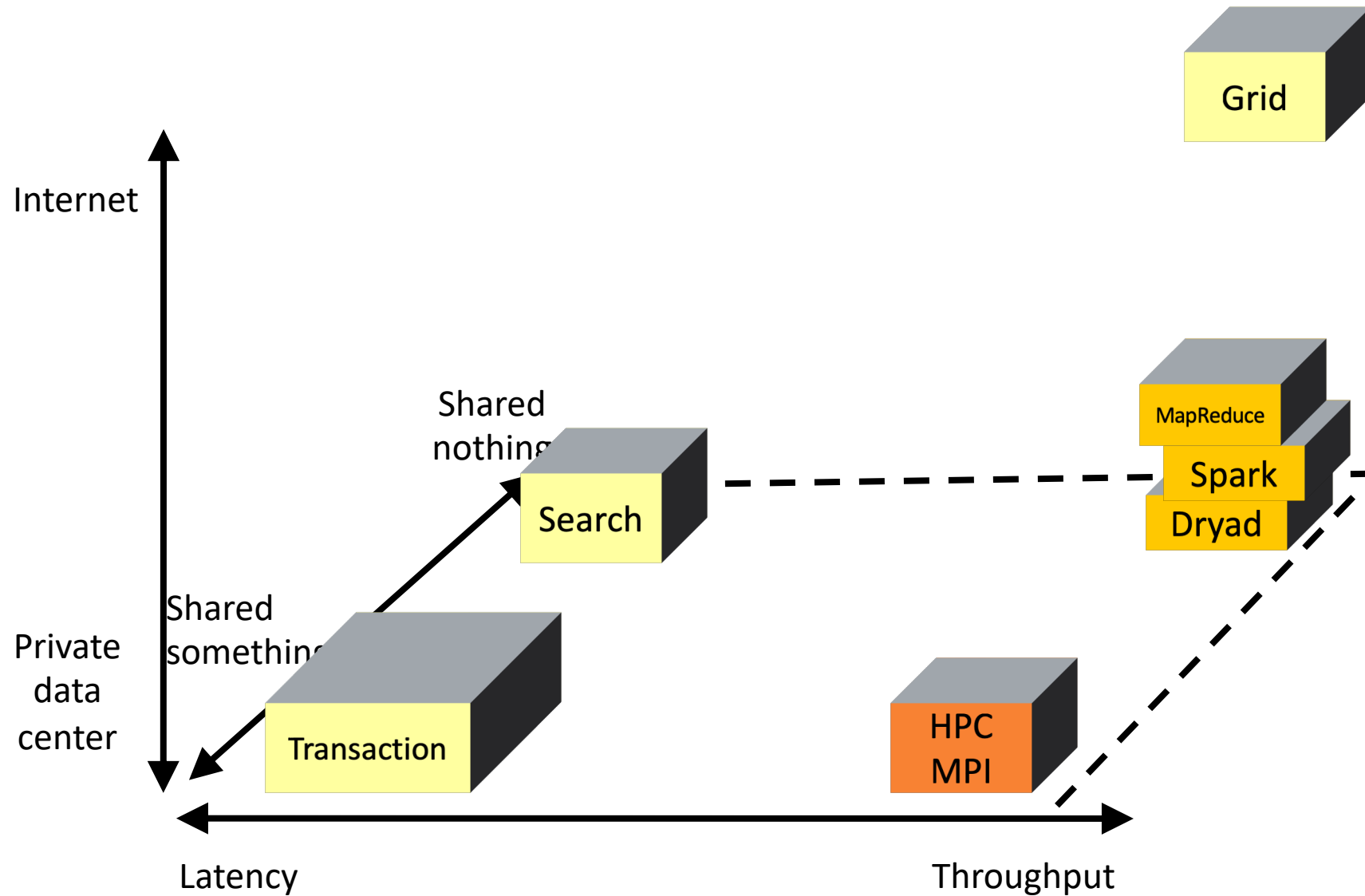
Design Space



Design Space



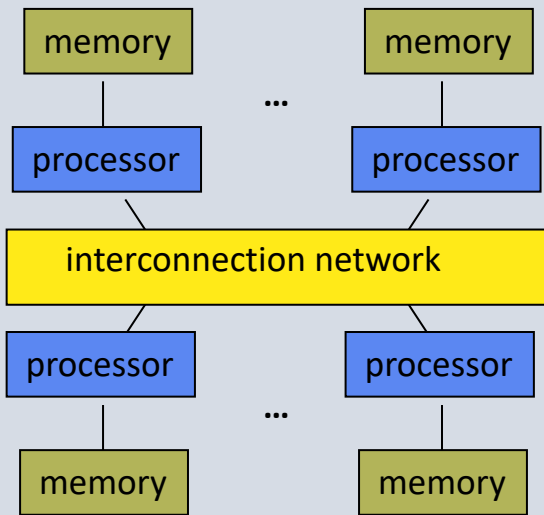
Design Space





Parallel Architectures and MPI

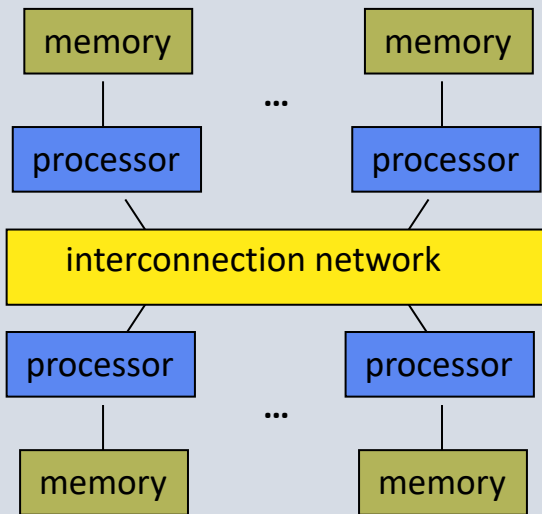
Parallel Architectures and MPI



Parallel Architectures and MPI

Distributed Memory
Multiprocessor

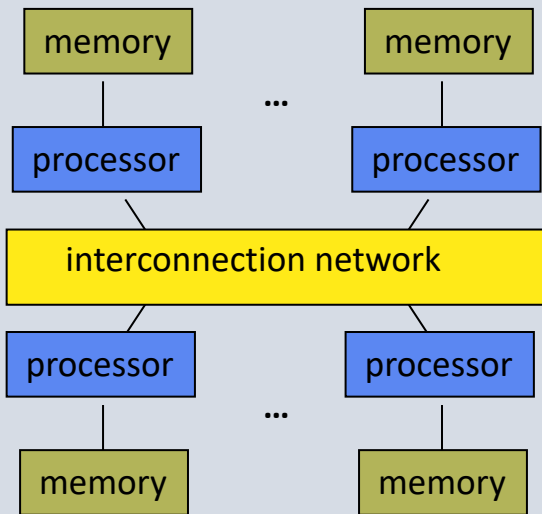
Messaging between nodes



Parallel Architectures and MPI

Distributed Memory
Multiprocessor

Messaging between nodes



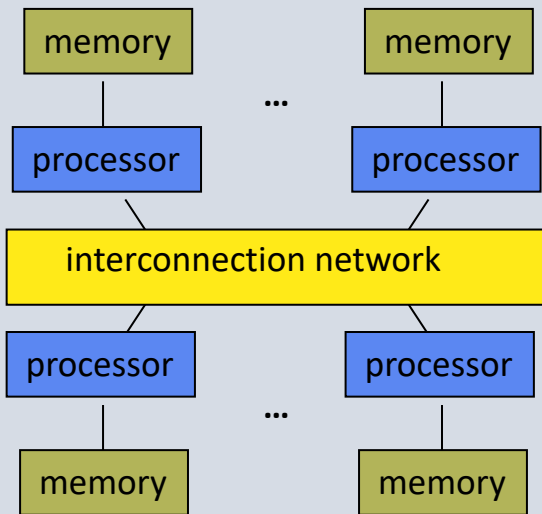
Massively Parallel Processor (MPP)

Many, many processors

Parallel Architectures and MPI

Distributed Memory
Multiprocessor

Messaging between nodes



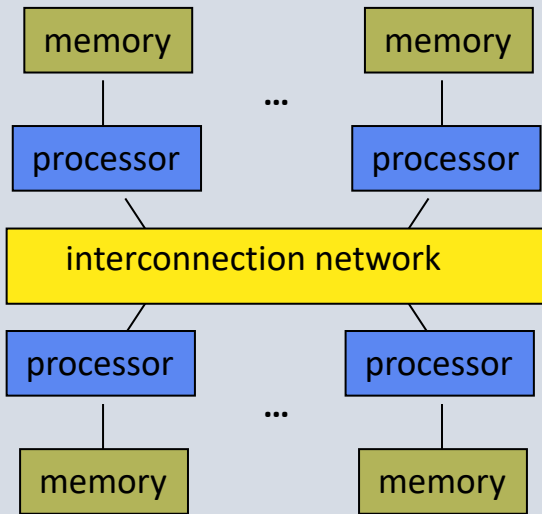
Massively Parallel Processor (MPP)

Many, many processors

Parallel Architectures and MPI

Distributed Memory Multiprocessor

Messaging between nodes

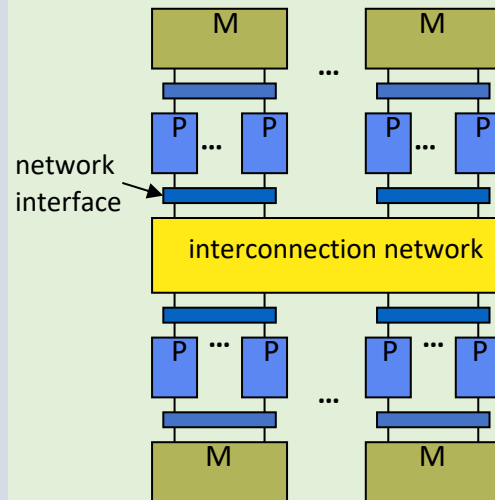


Massively Parallel Processor (MPP)

Many, many processors

Cluster of SMPs

- Shared memory in SMP node
- Messaging \leftrightarrow SMP nodes

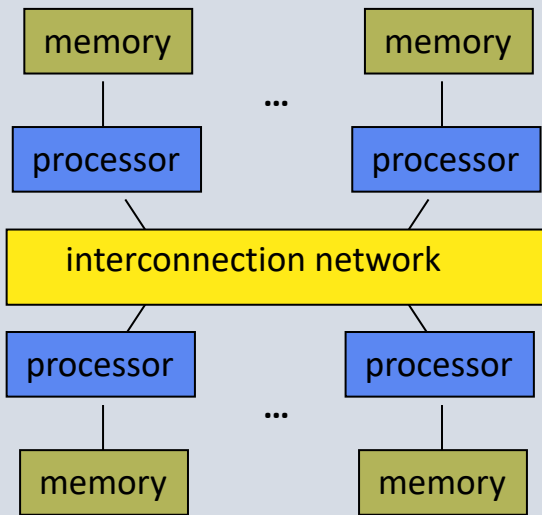


- also regarded as MPP if processor # is large

Parallel Architectures and MPI

Distributed Memory Multiprocessor

Messaging between nodes

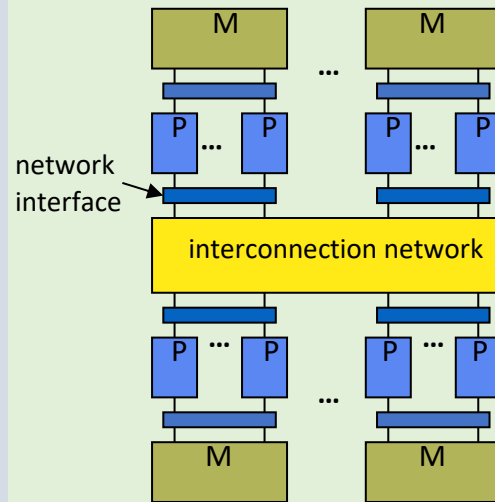


Massively Parallel Processor (MPP)

Many, many processors

Cluster of SMPs

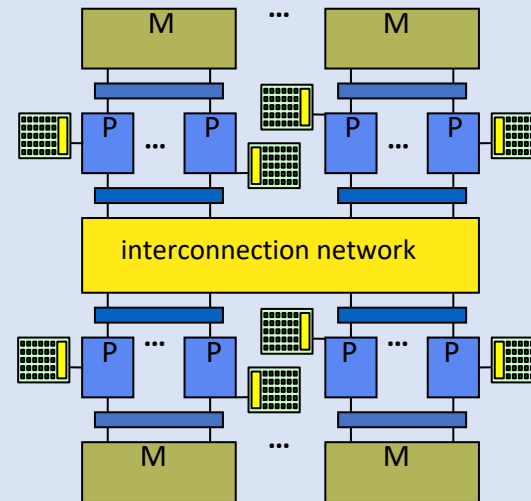
- Shared memory in SMP node
- Messaging \leftrightarrow SMP nodes



- also regarded as MPP if processor # is large

Multicore SMP+GPU Cluster

- Shared mem in SMP node
- Messaging between nodes

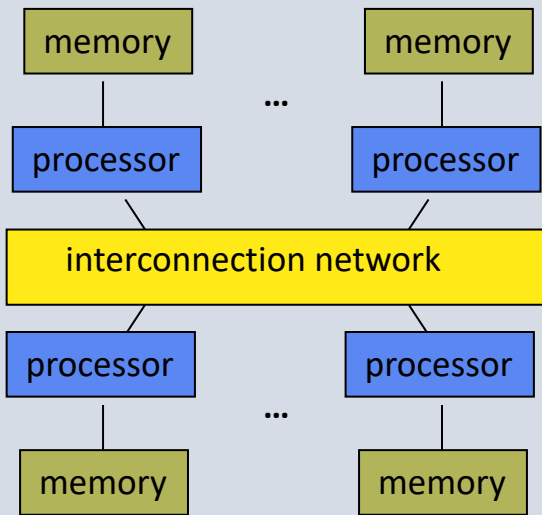


- GPU accelerators attached

Parallel Architectures and MPI

Distributed Memory Multiprocessor

Messaging between nodes

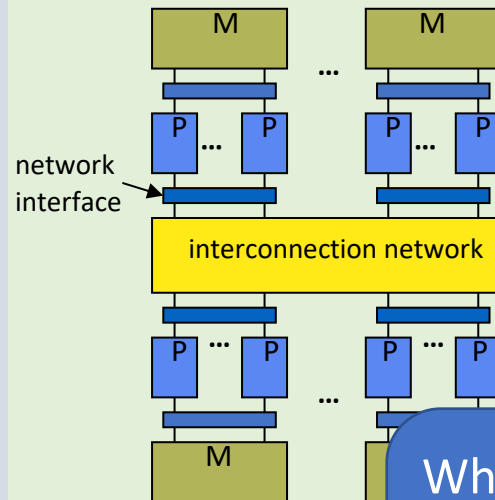


Massively Parallel Processor (MPP)

Many, many processors

Cluster of SMPs

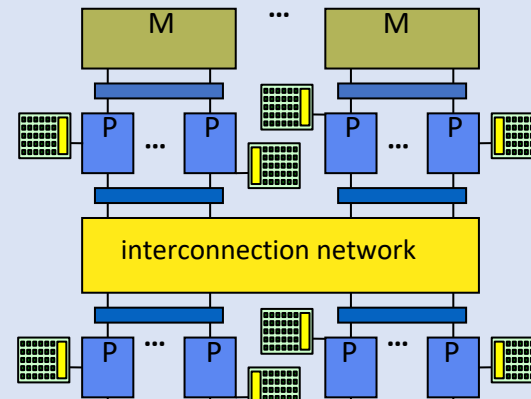
- Shared memory in SMP node
- Messaging \leftrightarrow SMP nodes



- also regarded processor # is

Multicore SMP+GPU Cluster

- Shared mem in SMP node
- Messaging between nodes

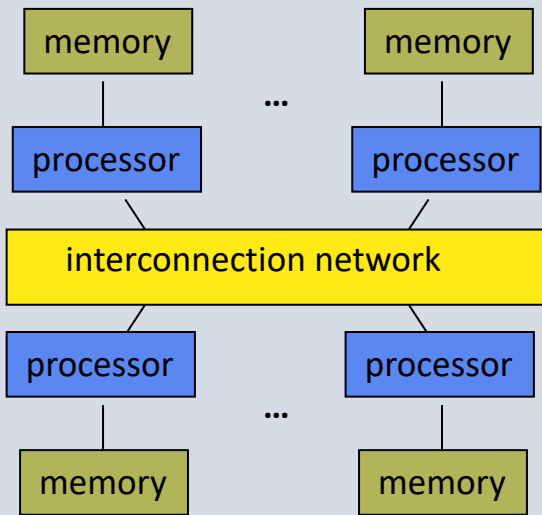


What have we left out?

Parallel Architectures and MPI

Distributed Memory Multiprocessor

Messaging between nodes

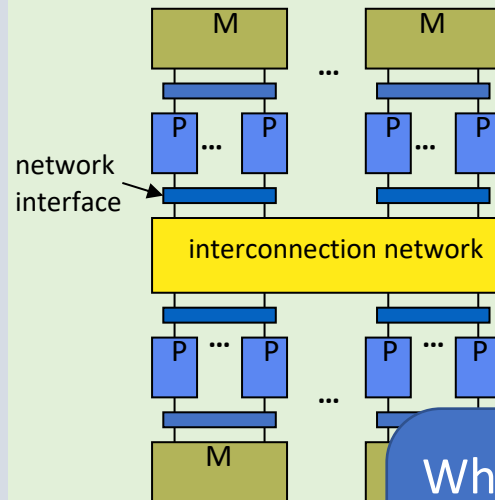


Massively Parallel Processor (MPP)

Many, many processors

Cluster of SMPs

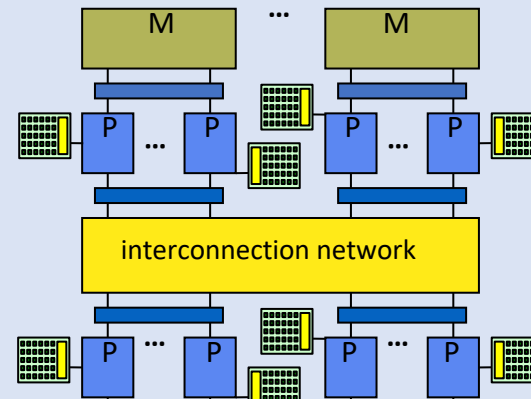
- Shared memory in SMP node
- Messaging \leftrightarrow SMP nodes



- also regarded processor # is

Multicore SMP+GPU Cluster

- Shared mem in SMP node
- Messaging between nodes



What have we left out?

- DSMs
- CMPs
- Non-GPU Accelerators

What requires extreme scale?

What requires extreme scale?

Simulations—why?

What requires extreme scale?

Simulations—why?

Simulations are sometimes more cost effective than experiments

What requires extreme scale?

Simulations—why?

Simulations are sometimes more cost effective than experiments

Why extreme scale?

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

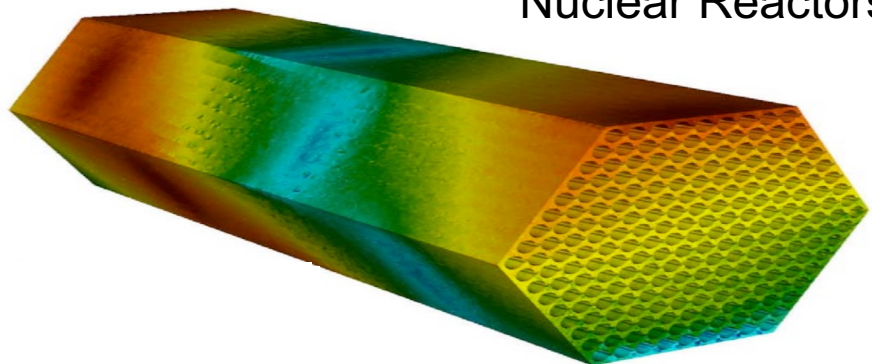
What requires extreme scale?

Simulations—why?

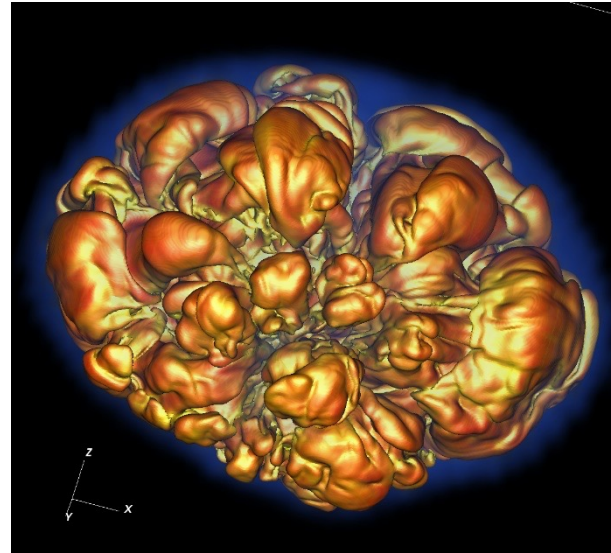
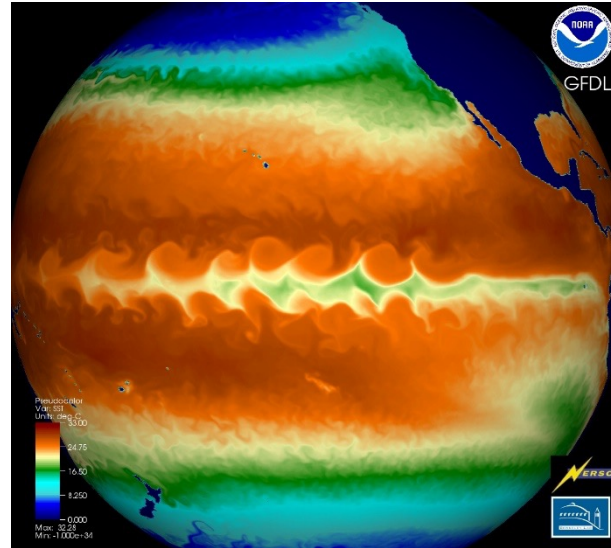
Simulations are sometimes more cost effective than experiments

Why extreme scale?

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



Nuclear Reactors



Astrophysics
Climate Change
Image credit: Prabhat, LBNL

How big is “extreme” scale?

Measured in FLOPs

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

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)



How big is “extreme” scale?

Measured in FLOPs

Floating point Operations Per 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
4	Gyokou - ZettaScaler-2.2 HPC system, Xeon D-1571 16C 1.3GHz, Infiniband EDR, PEZY-SC2 700Mhz , ExaScaler Japan Agency for Marine-Earth Science and Technology Japan	19,860,000	19,135.8	28,192.0	1,350
5	Titan - Cray XK7, Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x , Cray Inc. DOE/SC/Oak Ridge National Laboratory United States	560,640	17,590.0	27,112.5	8,209
6	Sequoia - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom , IBM DOE/NNSA/LLNL	1,572,864	17,173.2	20,132.7	7,890



How big is “extreme” scale?

Measured in FLOPs

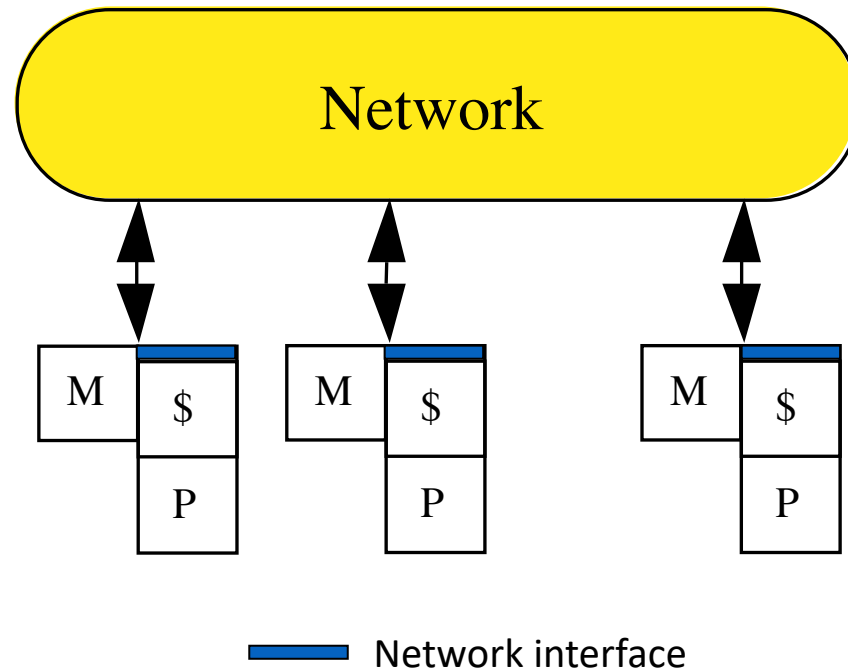
Floating point Operations Per second

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	9,014.6	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
4	Gyokou - ZettaScaler-2.2 HPC system, Xeon D-1571 16C 1.3GHz, Infiniband EDR, PEZY-SC2 700Mhz , ExaScaler Japan Agency for Marine-Earth Science and Technology Japan	19,860,000	19,135.8	28,192.0	1,350
5	Titan - Cray XK7, Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x , Cray Inc. DOE/SC/Oak Ridge National Laboratory United States	560,640	17,590.0	27,112.5	8,209
6	Sequoia - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom , IBM DOE/NNSA/LLNL	1,572,864	17,173.2	20,132.7	7,890

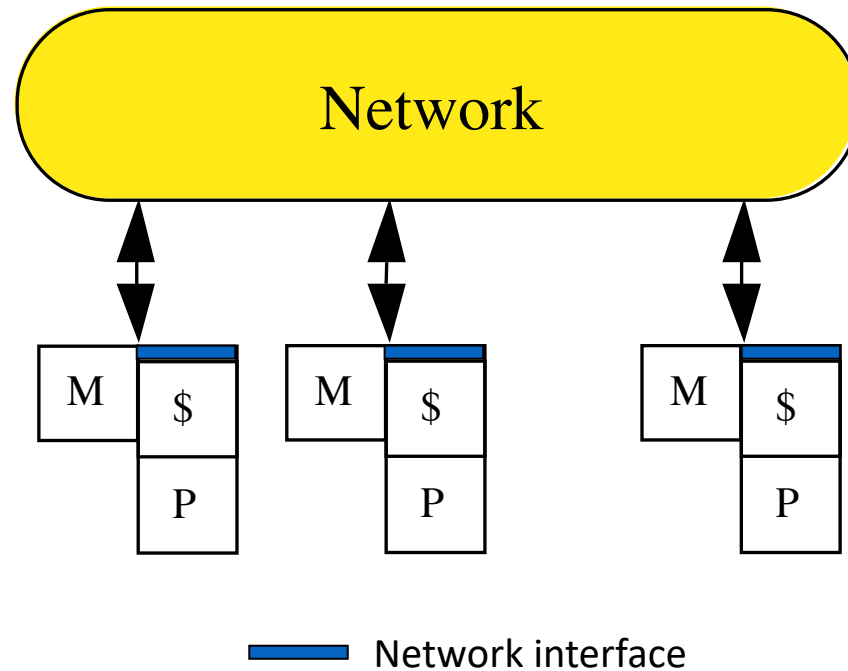


Distributed Memory Multiprocessors

Distributed Memory Multiprocessors



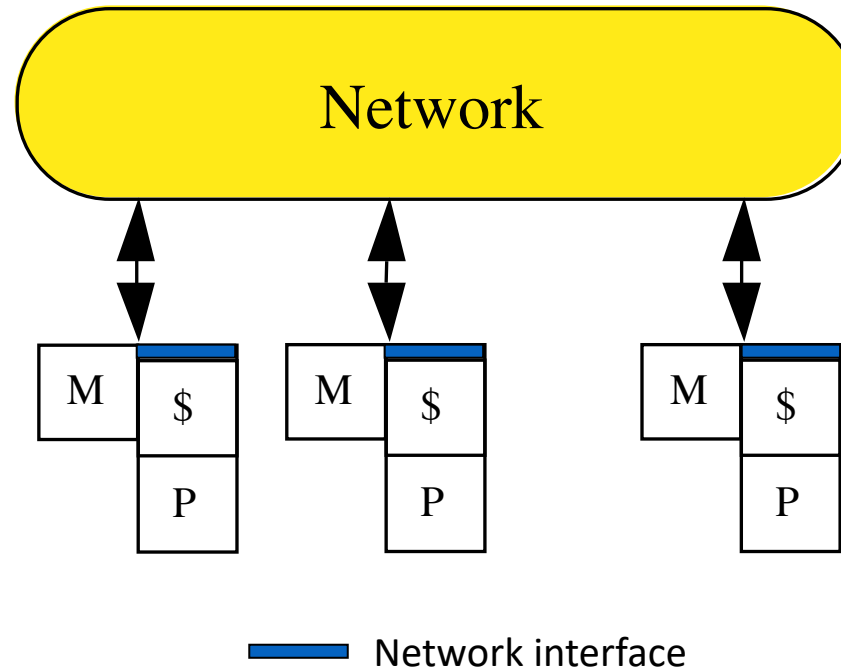
Distributed Memory Multiprocessors



- 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



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

Distributed Memory Multiprocessors

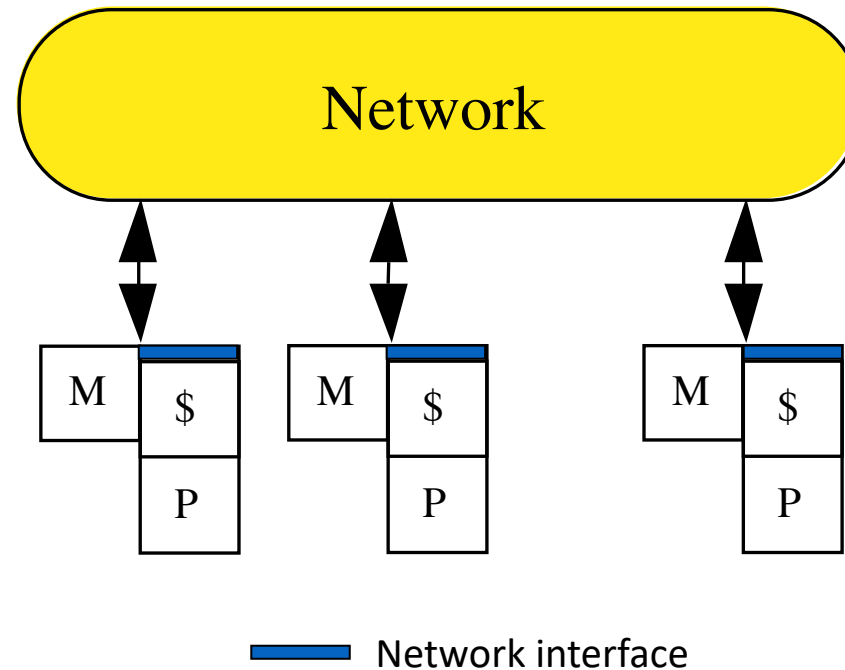
Each processor has a local memory
Physically separated address space

Processors communicate to access
non-local data

Message communication

Message passing architecture

Processor interconnection network



- 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

Processors communicate to access
non-local data

Message communication

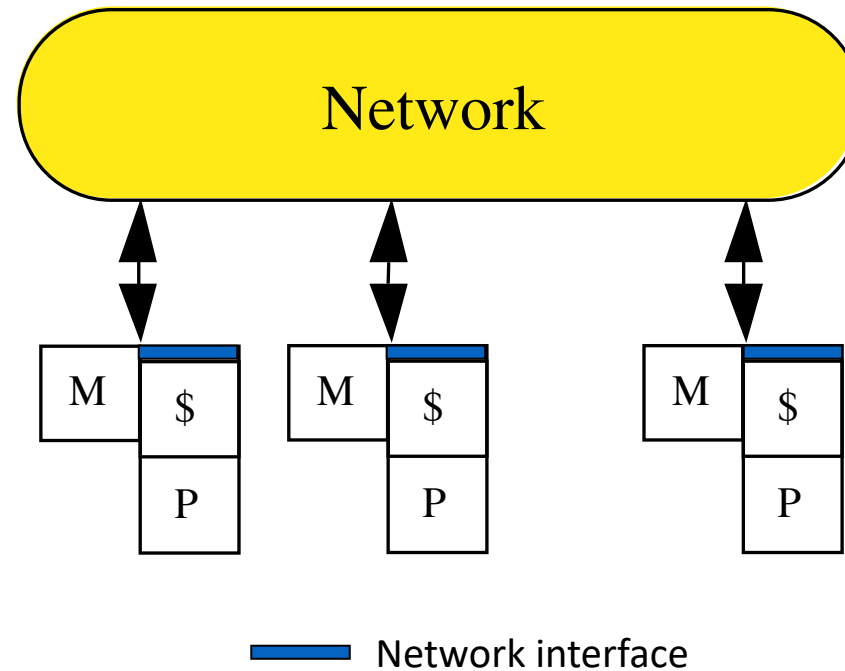
Message passing architecture

Processor interconnection network

Parallel applications partitioned across

Processors: execution units

Memory: data partitioning



- 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

Processors communicate to access
non-local data

Message communication

Message passing architecture

Processor interconnection network

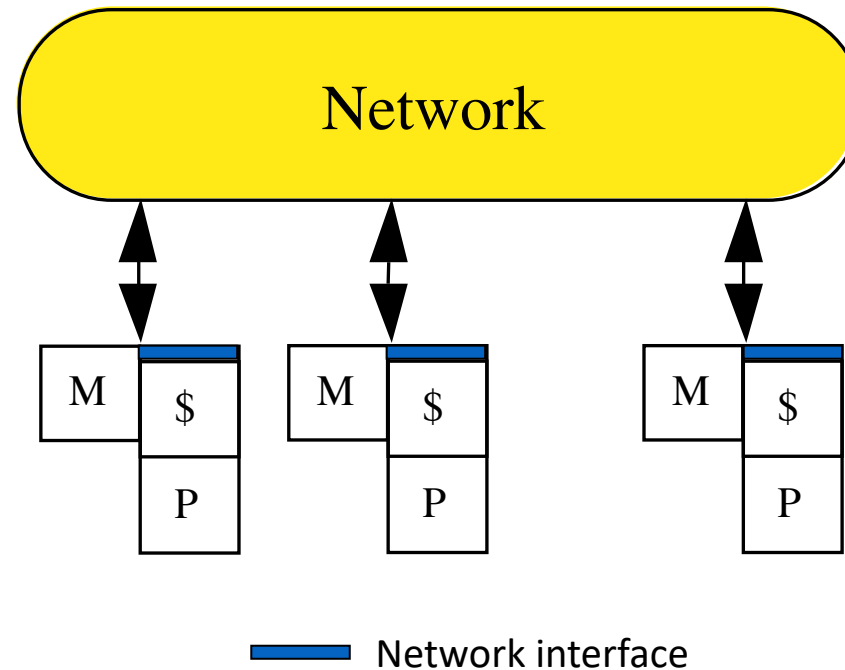
Parallel applications partitioned across

Processors: execution units

Memory: data partitioning

Scalable architecture

Incremental cost to add hardware
(cost of node)



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

Performance: Latency and Bandwidth

Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection
bandwidth

Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection bandwidth

Wait...bisection bandwidth?

Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection bandwidth

Wait...bisection bandwidth?

if network is **bisected**, **bisection bandwidth** == **bandwidth**

Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection bandwidth

Wait...bisection bandwidth?

if network is **bisected**, **bisection bandwidth** == **bandwidth** between the two partitions

Performance: Latency and Bandwidth

Bandwidth

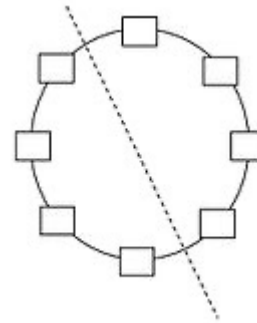
Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection bandwidth

Wait...bisection bandwidth?

if network is **bisected**, **bisection bandwidth** == **bandwidth** between the two partitions



Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection
bandwidth

Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection bandwidth

Latency

Performance affected: processor may have to wait

Hard to overlap communication and computation

Overhead to communicate: a problem in many machines

Performance: Latency and Bandwidth

Bandwidth

- Need high bandwidth in communication

- Match limits in network, memory, and processor

- Network interface speed vs. network bisection bandwidth

Latency

- Performance affected: processor may have to wait

- Hard to overlap communication and computation

- Overhead to communicate: a problem in many machines

Latency hiding

- Increases programming system burden

- E.g.: communication/computation overlap, prefetch

Performance: Latency and Bandwidth

Bandwidth

Need high bandwidth in communication

Match limits in network, memory, and processor

Network interface speed vs. network bisection bandwidth

Latency

Performance affected: processor may have to wait

Hard to overlap communication and computation


Overhead to communicate: a problem in many machines

Latency hiding

Increases programming system burden

E.g.: communication/computation overlap, prefetch

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



Ostensible Advantages of Distributed Memory Architectures

Ostensible Advantages of Distributed Memory Architectures

Hardware simpler (especially versus NUMA), more scalable

Ostensible Advantages of Distributed Memory Architectures

Hardware simpler (especially versus NUMA), more scalable

Communication explicit, simpler to understand

Ostensible Advantages of Distributed Memory Architectures

Hardware simpler (especially versus NUMA), more scalable

Communication explicit, simpler to understand

Explicit communication →

focus attention on costly aspect of parallel computation

Ostensible Advantages of Distributed Memory Architectures

Hardware simpler (especially versus NUMA), more scalable

Communication explicit, simpler to understand

Explicit communication →

focus attention on costly aspect of parallel computation

Synchronization →

naturally associated with sending messages

reduces possibility for errors from incorrect synchronization

Ostensible Advantages of Distributed Memory Architectures

Hardware simpler (especially versus NUMA), more scalable

Communication explicit, simpler to understand

Explicit communication →

focus attention on costly aspect of parallel computation

Synchronization →

naturally associated with sending messages

reduces possibility for errors from incorrect synchronization

Easier to use sender-initiated communication →

some advantages in performance

Ostensible Advantages of Distributed Memory Architectures

Hardware simpler (especially versus NUMA), more scalable

Communication explicit, simpler to understand

Explicit communication →

focus attention on costly aspect of parallel computation

Synchronization →

naturally associated with sending messages

reduces possibility for errors from incorrect synchronization

Easier to use sender-initiated communication →

some advantages in performance

Can you think of any *disadvantages*?



Running on Supercomputers

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine
These are called “hero runs”...

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine

These are called “hero runs”...

Sometimes many smaller jobs

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine

These are called “hero runs”...

Sometimes many smaller jobs

Supercomputers used continuously

Processors: “scarce resource”

jobs are “plentiful”

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine

These are called “hero runs”...

Sometimes many smaller jobs

Supercomputers used continuously

Processors: “scarce resource”

jobs are “plentiful”

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine

These are called “hero runs”...

Sometimes many smaller jobs

Supercomputers used continuously

Processors: “scarce resource”

jobs are “plentiful”

- Scheduler runs scripts that initialize the environment
 - Typically done with environment variables

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine

These are called “hero runs”...

Sometimes many smaller jobs

Supercomputers used continuously

Processors: “scarce resource”

jobs are “plentiful”

- Scheduler runs scripts that initialize the environment
 - Typically done with environment variables
- At the end of initialization, it is possible to infer:
 - What the desired job configuration is (i.e., how many tasks per node)
 - What other nodes are involved
 - How your node’s tasks relates to the overall program

Running on Supercomputers

- Programmer plans a **job**; job ==
 - parallel binary program
 - “input deck” (specifies input data)
- Submit job to a **queue**
- Scheduler allocates resources when
 - resources are available,
 - (or) the job is deemed “high priority”

Sometimes 1 job takes whole machine

These are called “hero runs”...

Sometimes many smaller jobs

Supercomputers used continuously

Processors: “scarce resource”

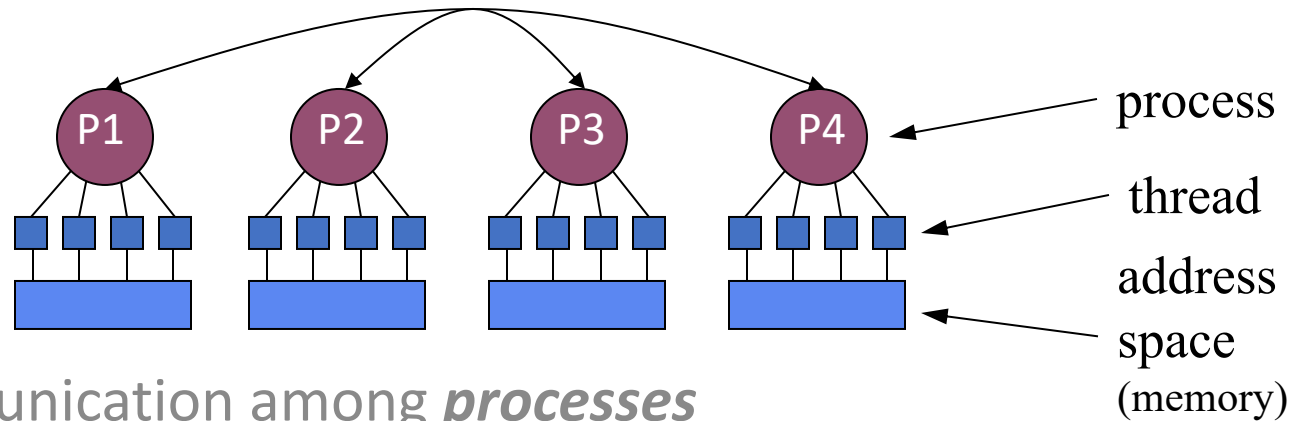
jobs are “plentiful”

- Scheduler runs scripts that initialize the environment
 - Typically done with environment variables
- At the end of initialization, it is possible to infer:
 - What the desired job configuration is (i.e., how many tasks per node)
 - What other nodes are involved
 - How your node’s tasks relates to the overall program
- 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



MPI is for communication among *processes*

Not threads

Inter-process communication consists of

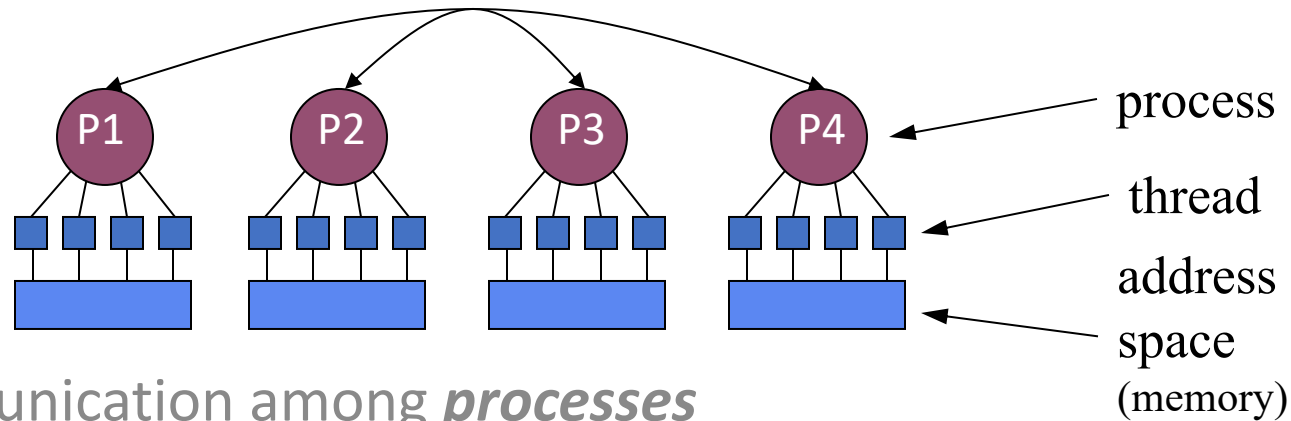
Synchronization

Data movement

The Message-Passing Model

Process: a program counter and address space

Processes: multiple threads sharing a single address space



MPI is for communication among *processes*

Not threads

Inter-process communication consists of

Synchronization

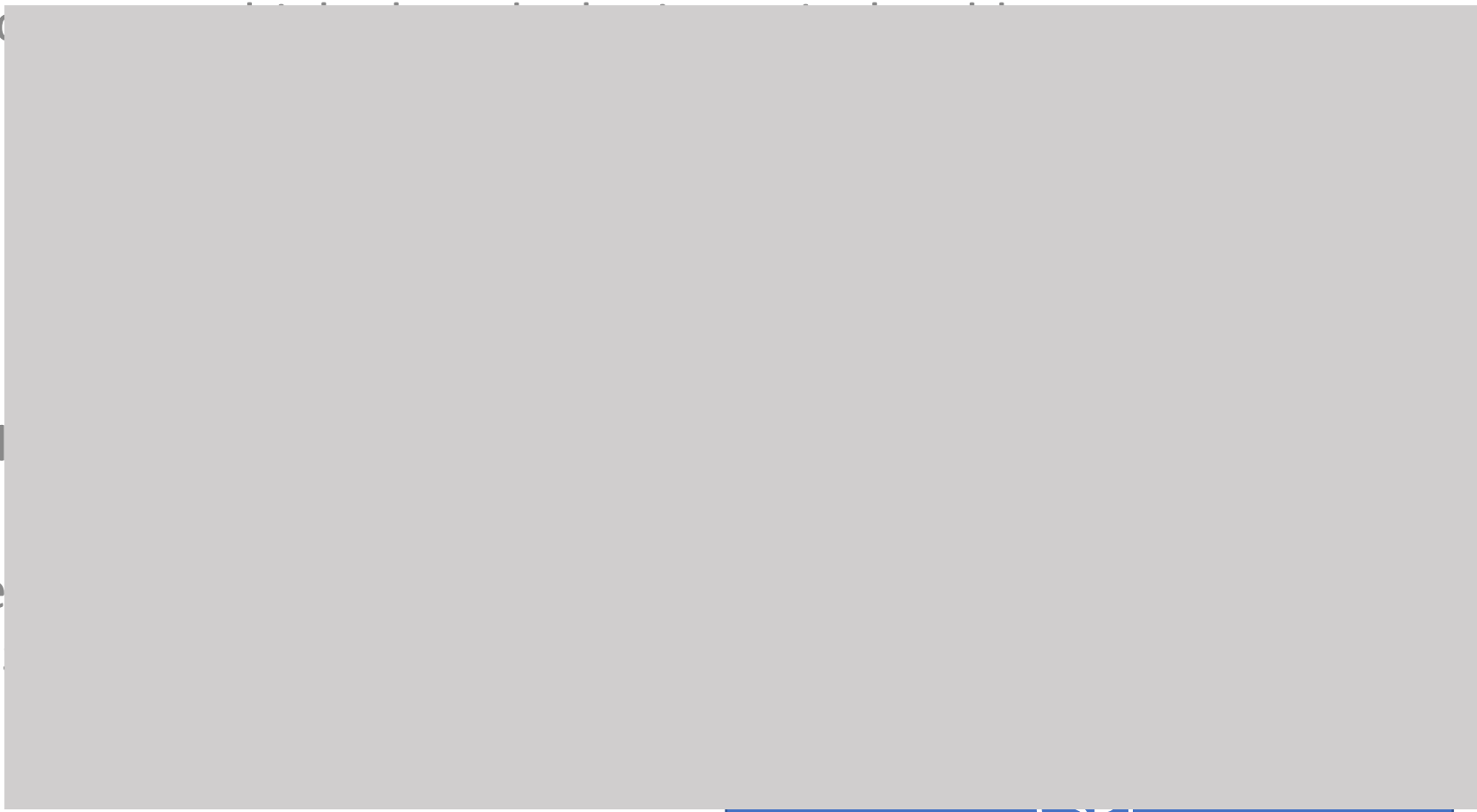
Data movement

How does this compare with
CSP?

The Message-Passing Model

Process: a program counter and address space

Proc



MPI

Inte

The Message-Passing Model

Process: a program counter and address space

- Process
- MPI == ***Message-Passing Interface specification***
 - Extended message-passing model
 - Not a language or compiler specification
 - Not a specific implementation or product

MPI

Inter

The Message-Passing Model

Process: a program counter and address space

- Process
- MPI == ***Message-Passing Interface specification***
 - Extended message-passing model
 - Not a language or compiler specification
 - Not a specific implementation or product
 - Specified in C, C++, Fortran 77, F90

MPI

Inter

The Message-Passing Model

Process: a program counter and address space

Process • MPI == ***Message-Passing Interface specification***

- Extended message-passing model
- Not a language or compiler specification
- Not a specific implementation or product

• Specified in C, C++, Fortran 77, F90

MPI • Message Passing Interface (MPI) Forum

- <http://www.mpi-forum.org/>
- <http://www.mpi-forum.org/docs/docs.html>

Inter

The Message-Passing Model

Process: a program counter and address space

Process

- MPI == ***Message-Passing Interface specification***

- Extended message-passing model
- Not a language or compiler specification
- Not a specific implementation or product

- Specified in C, C++, Fortran 77, F90

MPI

- Message Passing Interface (MPI) Forum

- <http://www.mpi-forum.org/>
- <http://www.mpi-forum.org/docs/docs.html>

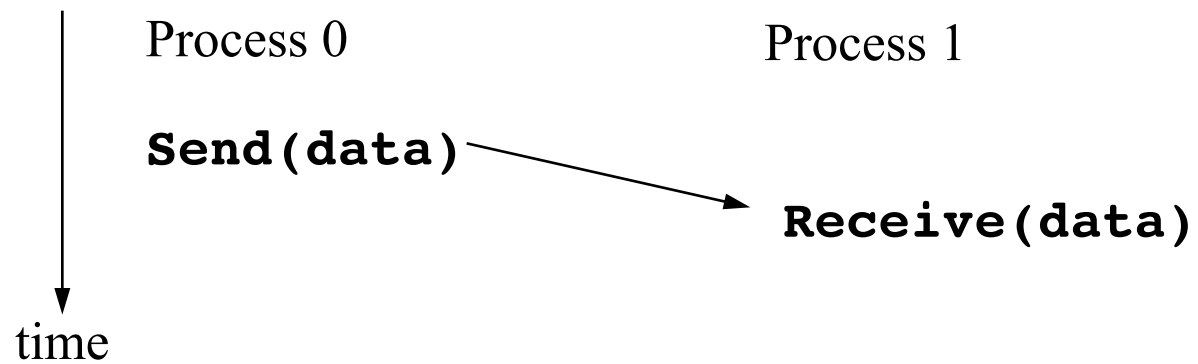
Inter

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



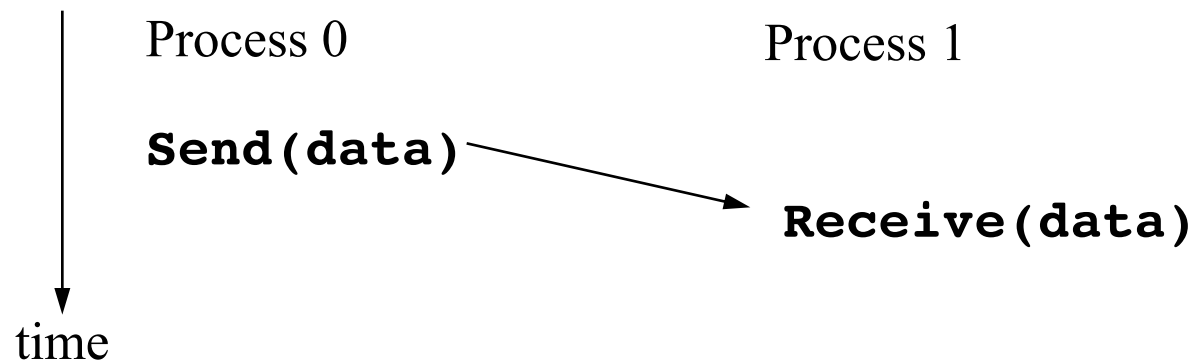
Cooperative Operations

Cooperative Operations



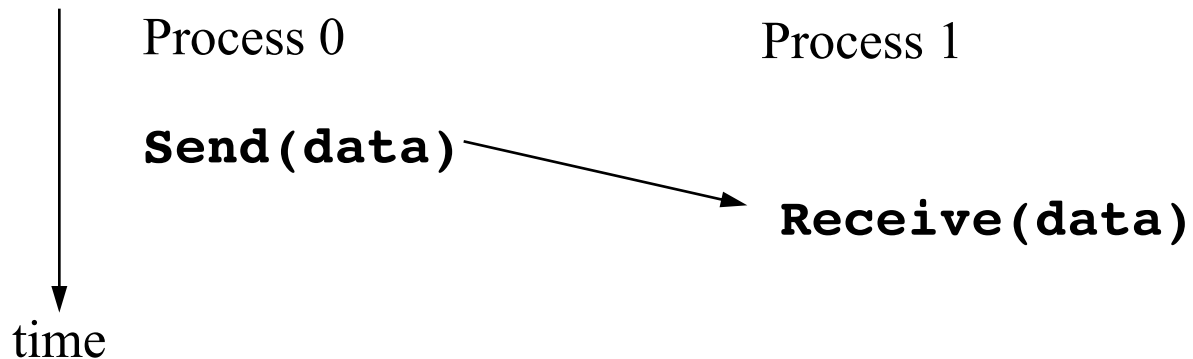
Cooperative Operations

Data is cooperatively exchanged in message-passing



Cooperative Operations

Data is cooperatively exchanged in message-passing
Explicitly sent by one process and received by another



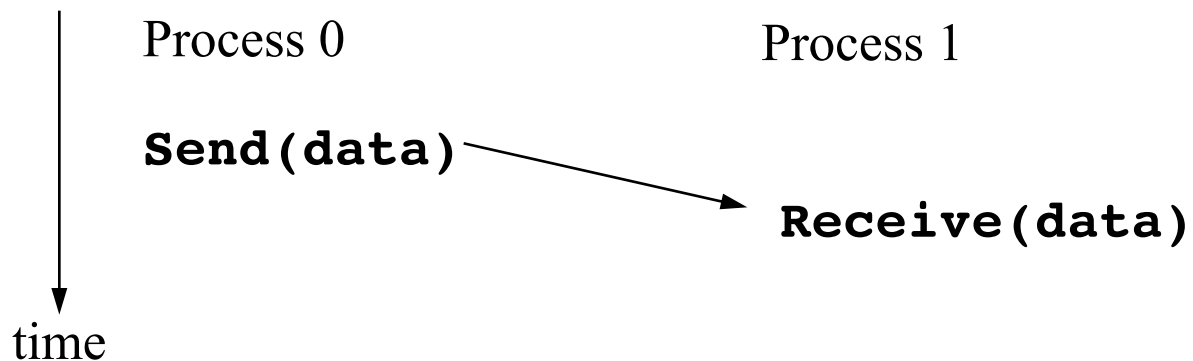
Cooperative Operations

Data is cooperatively exchanged in message-passing

Explicitly sent by one process and received by another

Advantage of local control of memory

Change in the receiving process's memory made with receiver's explicit participation



Cooperative Operations

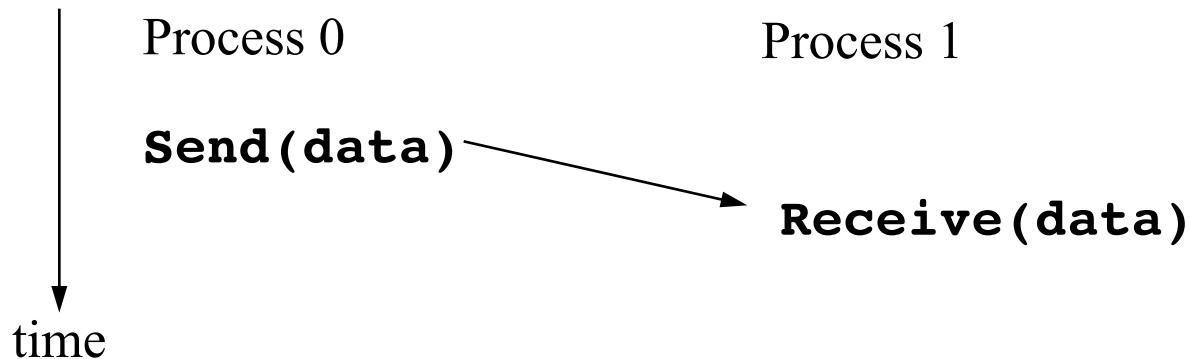
Data is cooperatively exchanged in message-passing

Explicitly sent by one process and received by another

Advantage of local control of memory

Change in the receiving process's memory made with receiver's explicit participation

Communication and synchronization are combined



Cooperative Operations

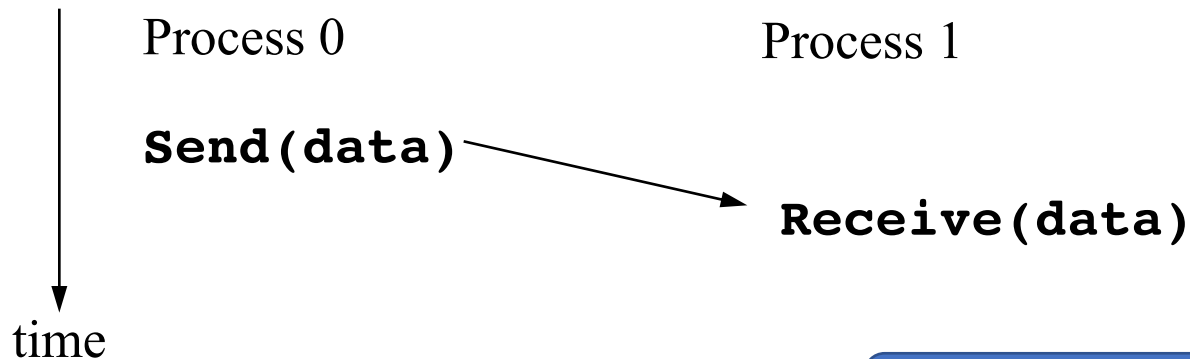
Data is cooperatively exchanged in message-passing

Explicitly sent by one process and received by another

Advantage of local control of memory

Change in the receiving process's memory made with receiver's explicit participation

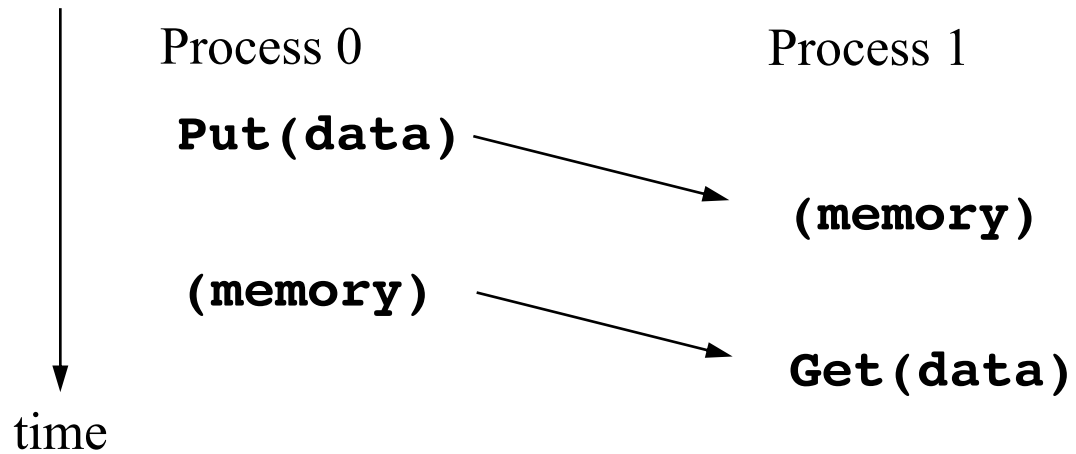
Communication and synchronization are combined



Familiar argument?

One-Sided Operations

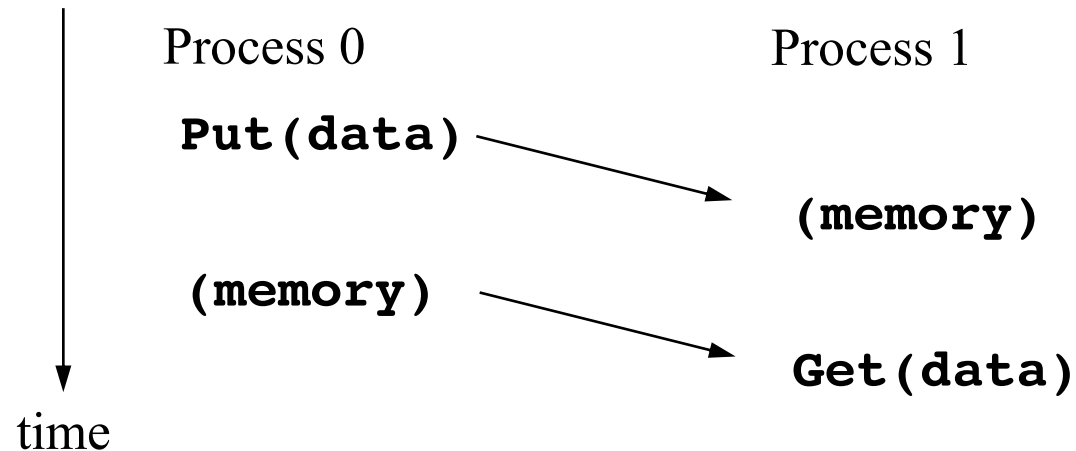
One-Sided Operations



One-Sided Operations

One-sided operations between processes

Include remote memory reads and writes



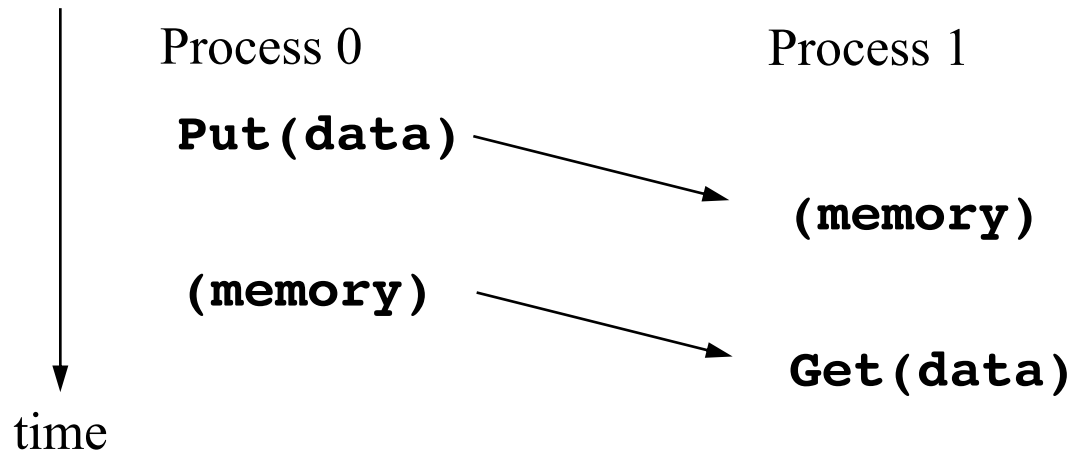
One-Sided Operations

One-sided operations between processes

Include remote memory reads and writes

Only one process needs to explicitly participate

There is still agreement implicit in the SPMD program



One-Sided Operations

One-sided operations between processes

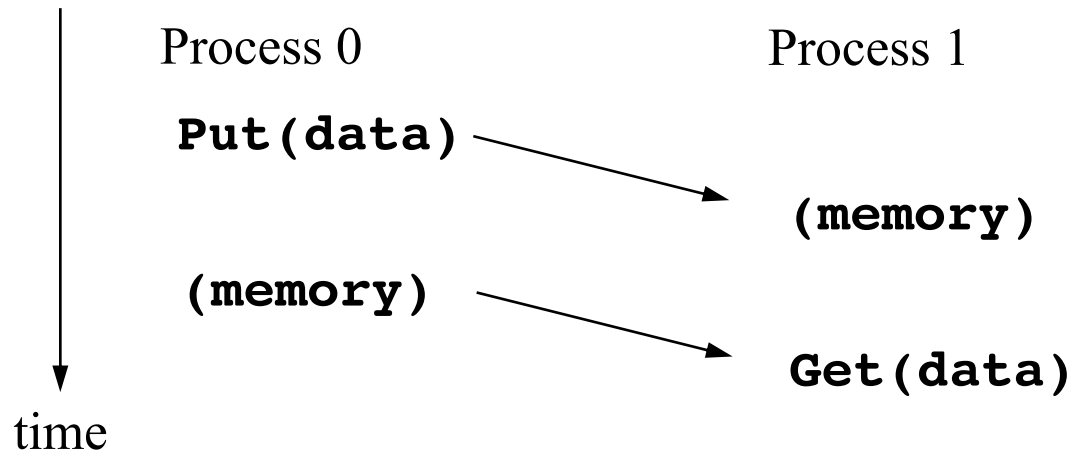
Include remote memory reads and writes

Only one process needs to explicitly participate

There is still agreement implicit in the SPMD program

Implication:

Communication and synchronization are decoupled



Are 1-sided operations better for performance?

One-Sided Operations

One-sided operations between processes

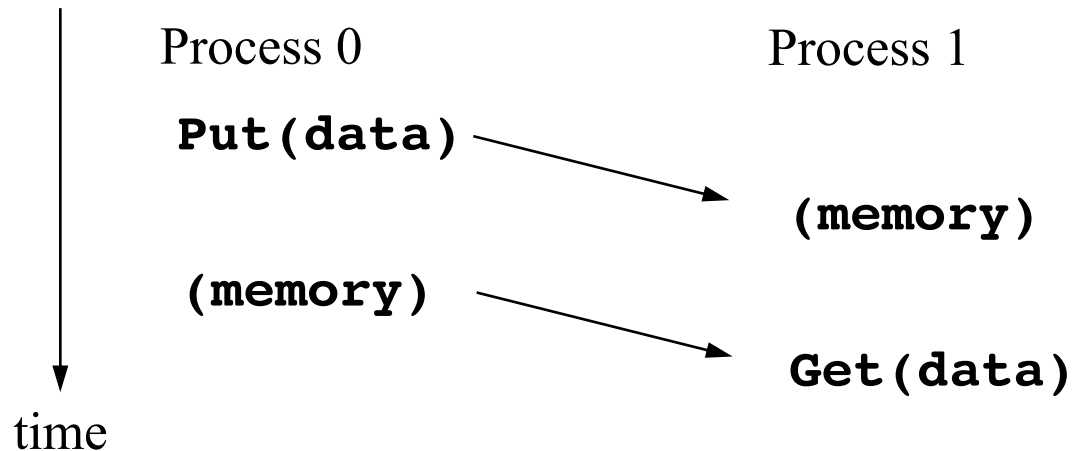
Include remote memory reads and writes

Only one process needs to explicitly participate

There is still agreement implicit in the SPMD program

Implication:

Communication and synchronization are decoupled



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

MPI_Init

Hardware resources allocated
MPI-managed ones anyway...

MPI_Init

Hardware resources allocated

MPI-managed ones anyway...

Start processes on different nodes

Where does their executable program come from?

MPI_Init

Hardware resources allocated

MPI-managed ones anyway...

Start processes on different nodes

Where does their executable program come from?

Give processes what they need to know

Wait...what do they need to know?

MPI_Init

Hardware resources allocated

MPI-managed ones anyway...

Start processes on different nodes

Where does their executable program come from?

Give processes what they need to know

Wait...what do they need to know?

Configure OS-level resources

MPI_Init

Hardware resources allocated

MPI-managed ones anyway...

Start processes on different nodes

Where does their executable program come from?

Give processes what they need to know

Wait...what do they need to know?

Configure OS-level resources

Configure tools that are running with MPI

MPI_Init

Hardware resources allocated

MPI-managed ones anyway...

Start processes on different nodes

Where does their executable program come from?

Give processes what they need to know

Wait...what do they need to know?

Configure OS-level resources

Configure tools that are running with MPI

...

MPI_Finalize

MPI_Finalize

Why do we need to finalize MPI?

MPI_Finalize

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

MPI_Finalize

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

MPI_Finalize

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

MPI_Finalize

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

What type of exit protocol might be used?

MPI_Finalize

Executive Summary

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

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

What type of exit protocol might be used?

MPI_Finalize

Executive Summary

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

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

What type of exit protocol might be used?

- By default, an error causes all processes to abort

MPI_Finalize

Executive Summary

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

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

What type of exit protocol might be used?

- By default, an error causes all processes to abort
- The user can cause routines to return (with an error code)
 - In C++, exceptions are thrown (MPI-2)

MPI_Finalize

Executive Summary

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

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

What type of exit protocol might be used?

- By default, an error causes all processes to abort
- The user can cause routines to return (with an error code)
 - In C++, exceptions are thrown (MPI-2)
- A user can also write and install custom error handlers

MPI_Finalize

Executive Summary

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

Why do we need to finalize MPI?

What is necessary for a “graceful” MPI exit?

Can bad things happen otherwise?

Suppose one process exits...

How do resources get de-allocated?

How to shut down communication?

What type of exit protocol might be used?

- By default, an error causes all processes to abort
- The user can cause routines to return (with an error code)
 - 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

Running MPI Programs

MPI-1 does not specify how to run an MPI program

Running MPI Programs

MPI-1 does not specify how to run an MPI program

Starting an MPI program is dependent on implementation

Scripts, program arguments, and/or environment variables

Running MPI Programs

MPI-1 does not specify how to run an MPI program

Starting an MPI program is dependent on implementation

Scripts, program arguments, and/or environment variables

```
% mpirun -np <procs> a.out
```

For MPICH under Linux

Running MPI Programs

MPI-1 does not specify how to run an MPI program

Starting an MPI program is dependent on implementation

Scripts, program arguments, and/or environment variables

% 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

Finding Out About the Environment

Two important questions that arise in message passing

How many processes are being use in computation?

Which one am I?

Finding Out About the Environment

Two important questions that arise in message passing

How many processes are being use in computation?

Which one am I?

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 );
    MPI_Finalize();
    return 0;
}
```

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 );
    MPI_Finalize();
    return 0;
}
```

□ What does this program do?

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 );
    MPI_Finalize();
    return 0;
}
```

□ What does this program do?

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

MPI Datatypes

Message data (sent or received) is described by a triple
address, count, datatype

MPI Datatypes

Message data (sent or received) is described by a triple
address, count, datatype

An MPI *datatype* is recursively defined as:

- Predefined data type from the language

- A contiguous array of MPI datatypes

- A strided block of datatypes

- An indexed array of blocks of datatypes

- An arbitrary structure of datatypes

MPI Datatypes

Message data (sent or received) is described by a triple
address, count, datatype

An MPI *datatype* is recursively defined as:

- Predefined data type from the language

- A contiguous array of MPI datatypes

- A strided block of datatypes

- An indexed array of blocks of datatypes

- An arbitrary structure of datatypes

There are MPI functions to construct custom datatypes

- Array of (int, float) pairs

- Row of a matrix stored columnwise

MPI Datatypes

Message data (sent or received) is described by a triple
address, count, datatype

An MPI *datatype* is recursively defined as:

- Predefined data type from the language

- A contiguous array of MPI datatypes

- A strided block of datatypes

- An indexed array of blocks of datatypes

MPI Datatypes

Message data (sent or received) is described by a triple
address, count, datatype

An MPI *datatype* is recursively defined as:

Predefined data type from the language

A contiguous array of MPI datatypes

A strided block of datatypes

An indexed array of blocks of datatypes

- Enables heterogeneous communication
 - Support communication between processes on machines with different memory representations and lengths of elementary datatypes
 - MPI provides the representation translation if necessary

MPI Datatypes

Message data (sent or received) is described by a triple
address, count, datatype

An MPI *datatype* is recursively defined as:

Predefined data type from the language

A contiguous array of MPI datatypes

A strided block of datatypes

An indexed array of blocks of datatypes

- Enables heterogeneous communication
 - 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)

■ MPI Tags

■ MPI Tags

Messages are sent with an accompanying user-defined integer *tag*
Assist the receiving process in identifying the message

MPI Tags

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

MPI Tags

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

MPI with Only Six Functions

Many parallel programs can be written using:

`MPI_INIT()`

`MPI_FINALIZE()`

`MPI_COMM_SIZE()`

`MPI_COMM_RANK()`

`MPI_SEND()`

`MPI_RECV()`

MPI with Only Six Functions

Many parallel programs can be written using:

`MPI_INIT()`

`MPI_FINALIZE()`

`MPI_COMM_SIZE()`

`MPI_COMM_RANK()`

`MPI_SEND()`

`MPI_RECV()`

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

MPI with Only Six Functions

Many parallel programs can be written using:

`MPI_INIT()`

`MPI_FINALIZE()`

`MPI_COMM_SIZE()`

`MPI_COMM_RANK()`

`MPI_SEND()`

`MPI_RECV()`

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

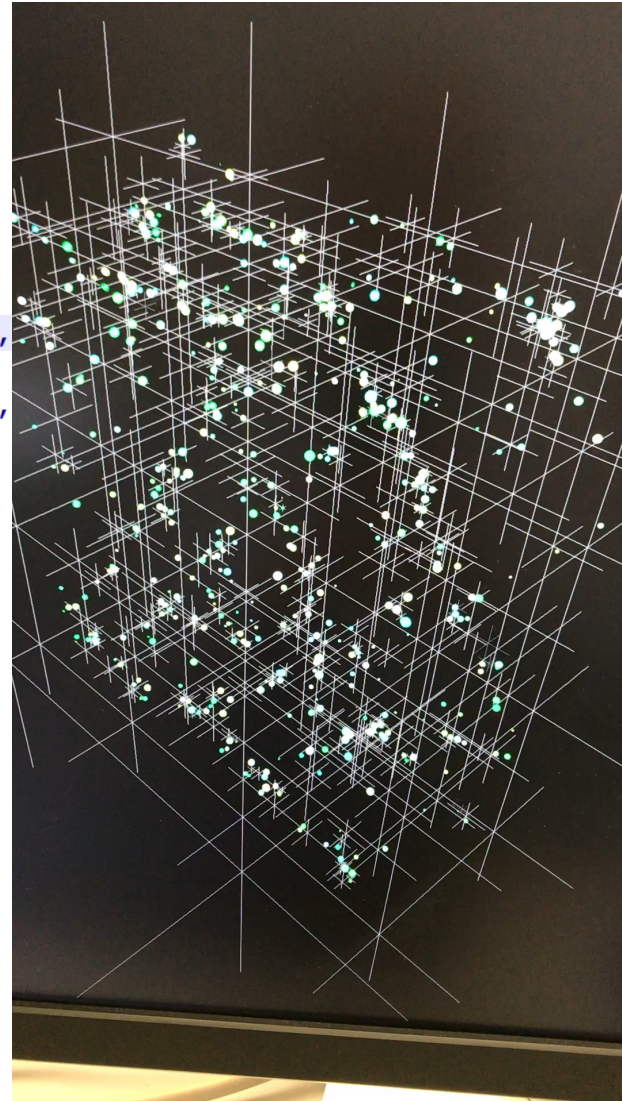
```
int ctr=nLocalOriginal;
int offset=nLocalOriginal-nLocal;
for(i=0;i<worldSize;i++){
if(i==rank){
MPI_Bcast(s_particles,N_POS_ELEMS*nLocalMax+1,MPI_DOUBLE,i,MPI_COMM_WORLD);
} else {
MPI_Bcast(l_particles,N_POS_ELEMS*nLocalMax+1,MPI_DOUBLE,i,MPI_COMM_WORLD);
for(k=0;k<l_particles[0];k++, ctr++){
if(l_particles[MASS(k)]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

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)];
s_particles[PY(ctr)]=l_particles[PY(k)];
s_particles[PZ(ctr)]=l_particles[PZ(k)];
s_particles[MASS(ctr)]=l_particles[MASS(k)];
indexes[ctr-offset]=ctr;
}
}
}
```

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,
} else {
MPI_Bcast(l_particles,N_POS_ELEMS*nLocalMax+1,MPI_DOUBLE,
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)];
s_particles[PY(ctr)]=l_particles[PY(k)];
s_particles[PZ(ctr)]=l_particles[PZ(k)];
s_particles[MASS(ctr)]=l_particles[MASS(k)];
indexes[ctr-offset]=ctr;
}
}
}
```



To use or not use MPI?

To use or not use MPI?

- USE
 - You need a portable parallel program
 - You are writing a parallel library
 - You have irregular or dynamic data relationships
 - You care about performance

To use or not use MPI?

- USE

- You need a portable parallel program
- You are writing a parallel library
- You have irregular or dynamic data relationships
- 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