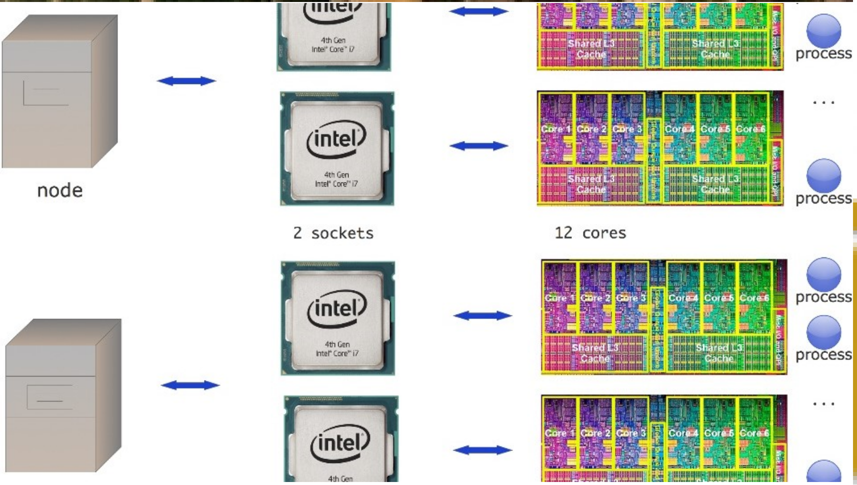
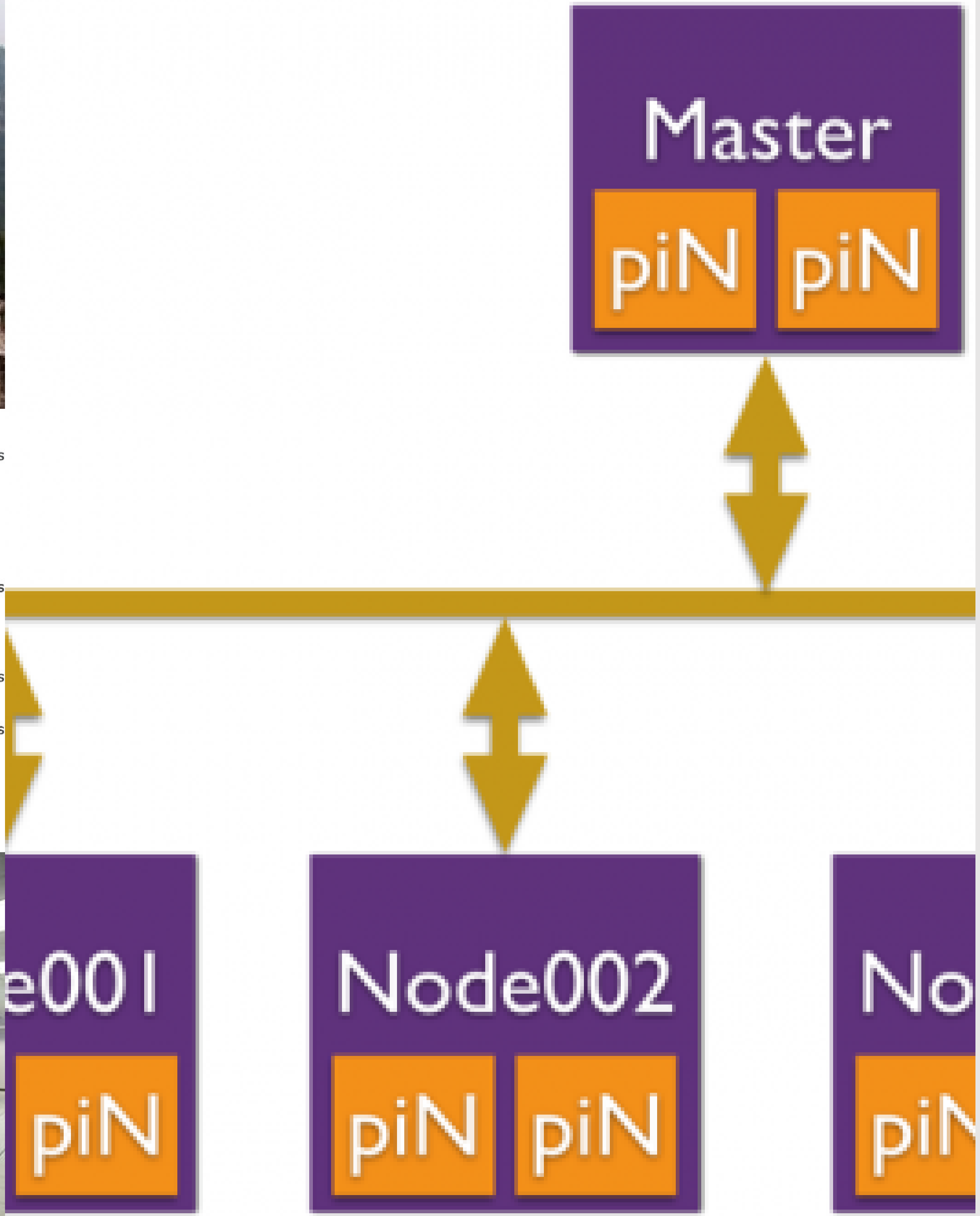
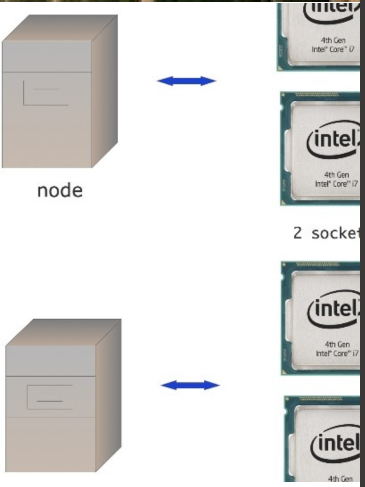
Parallelism at Scale: MPI

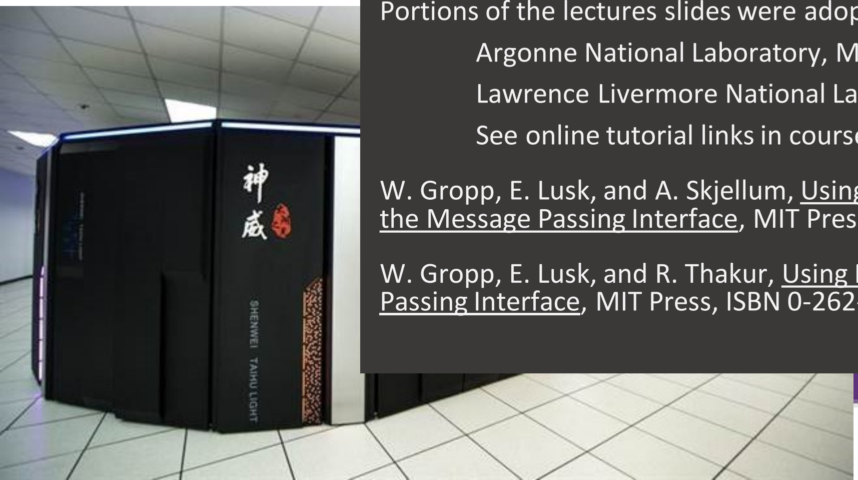
cs378h

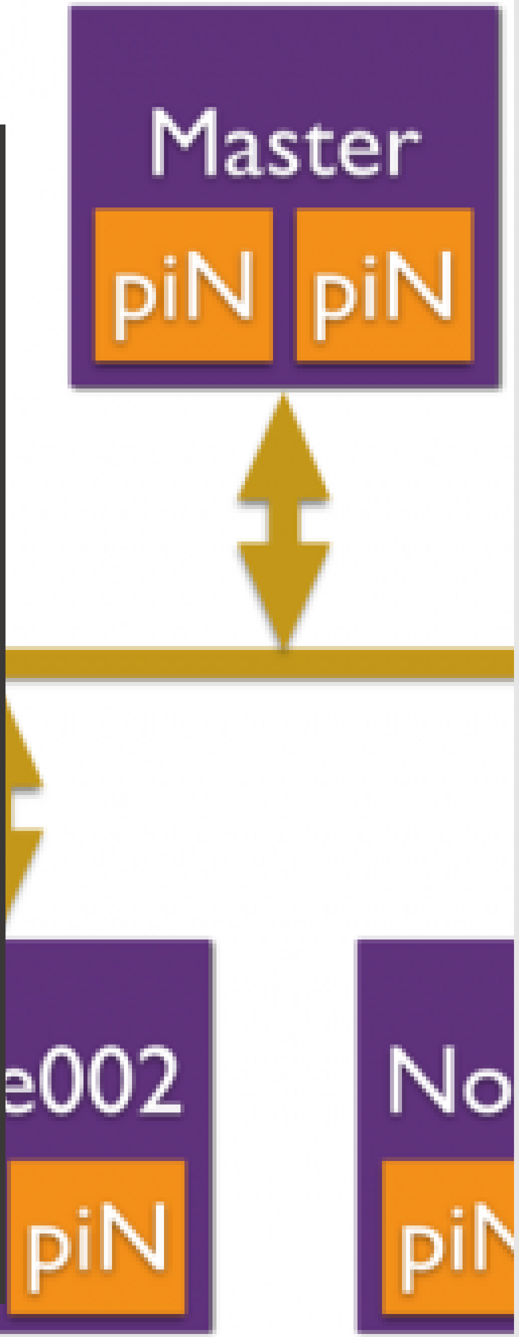

node
2 sockets
12 cores
process
process
process
process


神威


Master
piN piN
Node002
piN piN







Outline for Today

Rust Closures
Project Comments
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.

Sharing State: Arc and Mutex

```rust
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();
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    });
  }
}
```

Sharing State: Arc and Mutex

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```

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*

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

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Would cloning var_arc fix it?

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Same problem!

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    });
```

Same problem!

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

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```

```
[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
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166 |         thread::spawn(|| {
    |                       ^^ may outlive borrowed value `var_arc`
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    |
note: function requires argument type to outlive `'static`
```

Sharing State: Arc and Mutex, *really*

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What's the actual fix?

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Sharing State: Arc and Mutex, *really*

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}
```

Compiles! Yay!
Other fixes?

Sharing State: Arc and Mutex, *really*

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```

Why does this compile?

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}
```

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

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    });
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  for i in 0..N { join(); }
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```

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

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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(); }
}
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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?

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]

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Ideas:

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

The sky is the limit

- A very good example

Project Proposal

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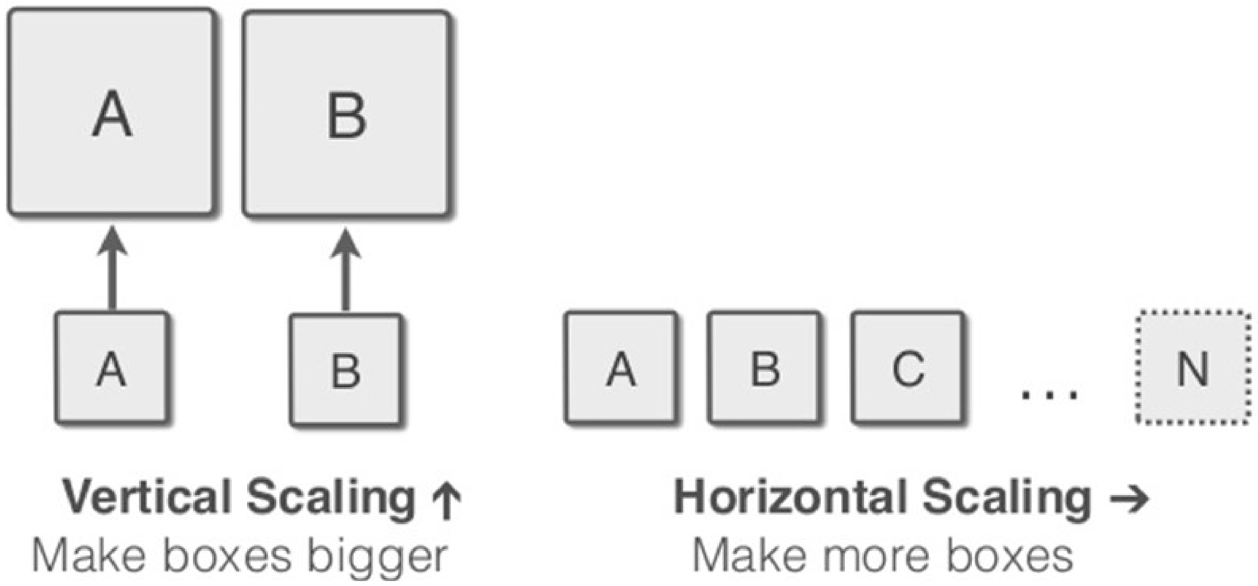
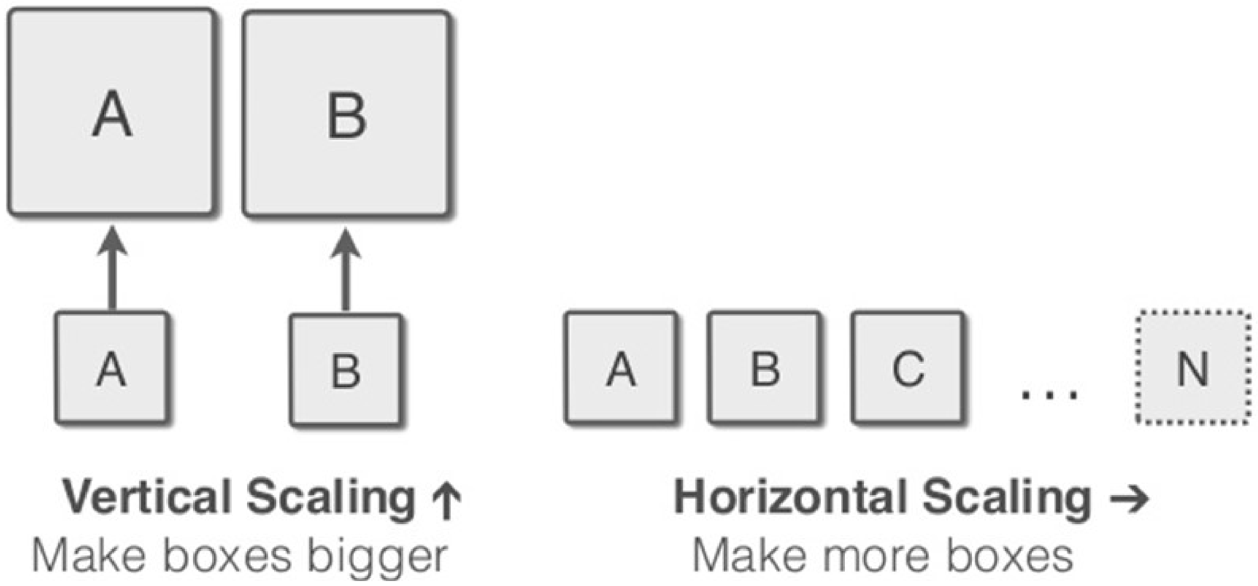
Questions?

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

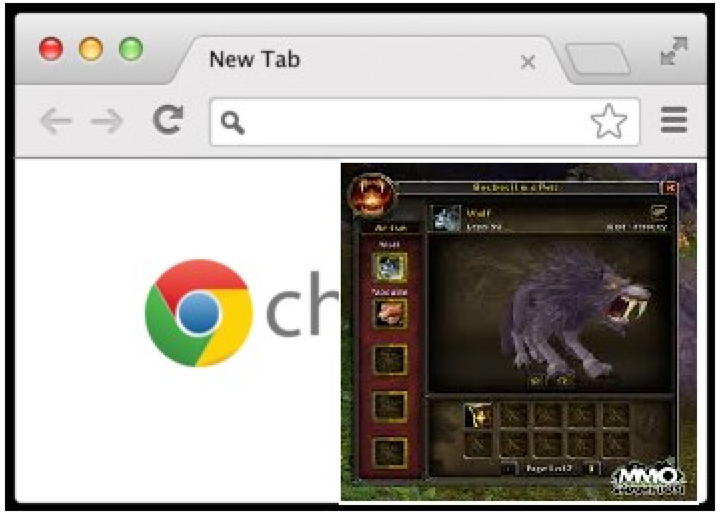
Hot Startup Idea:

www.purchase-a-pooch.biz

Parallel Systems Architects Wanted

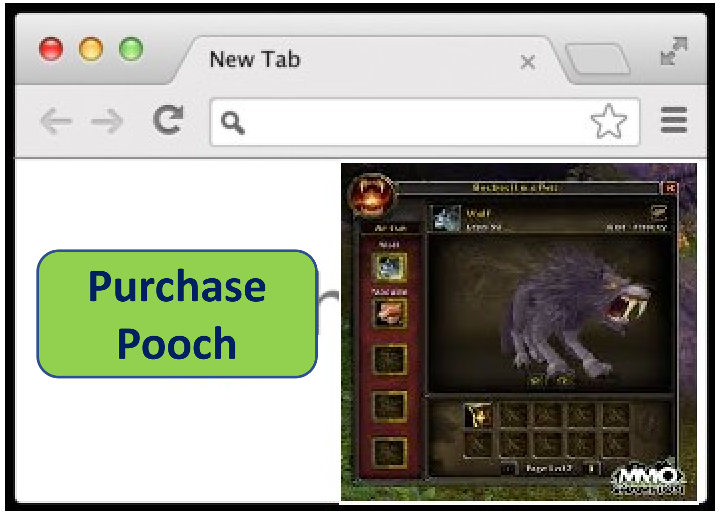
Parallel Systems Architects Wanted

1. User Browses Potential Pets



Parallel Systems Architects Wanted

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



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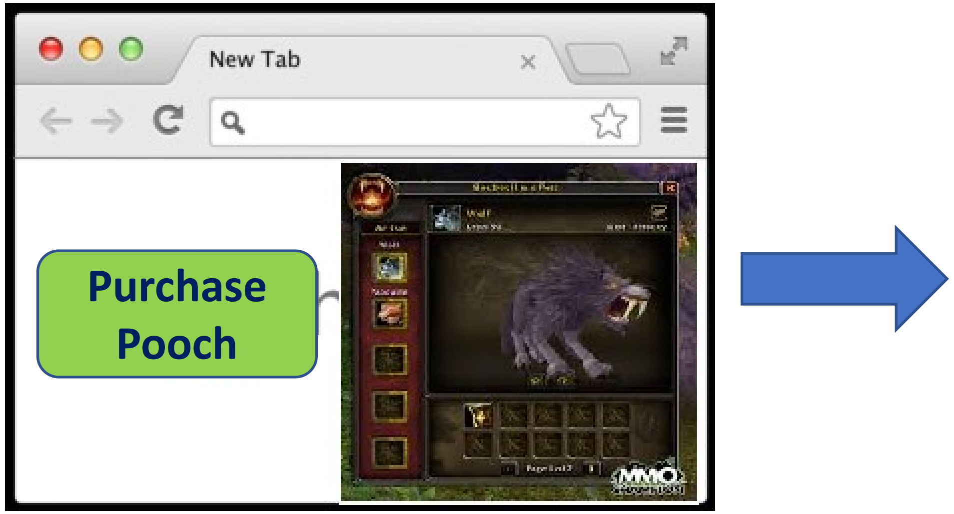

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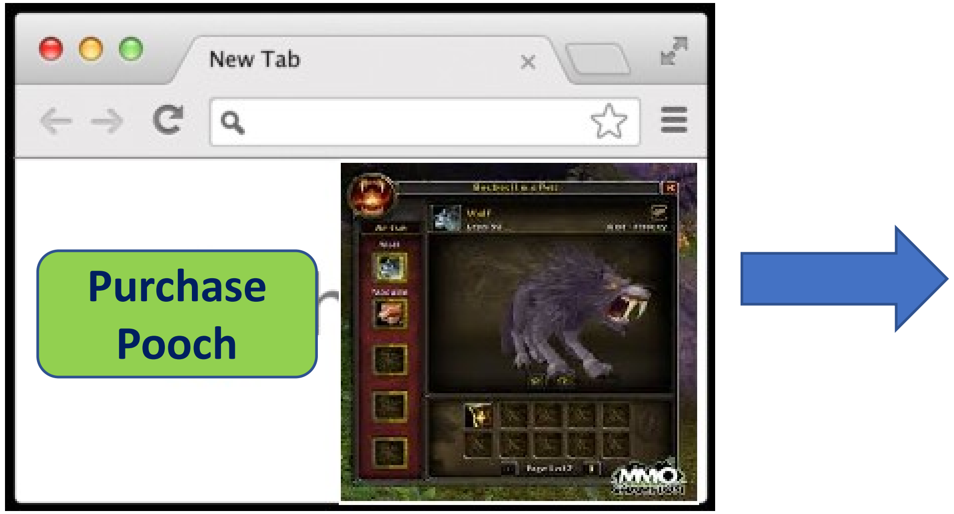

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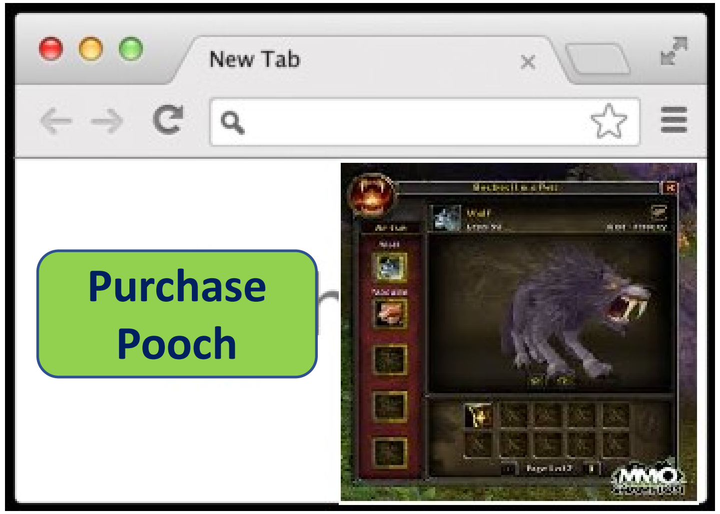
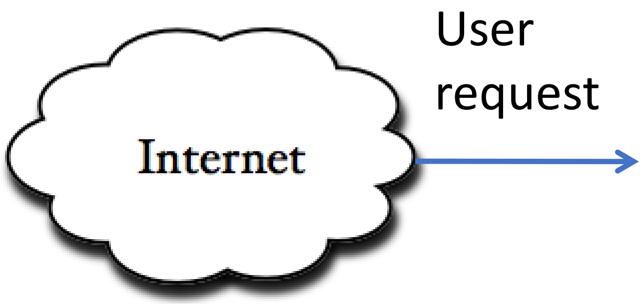
How to handle lots and lots of dogs?



3 Tier architecture



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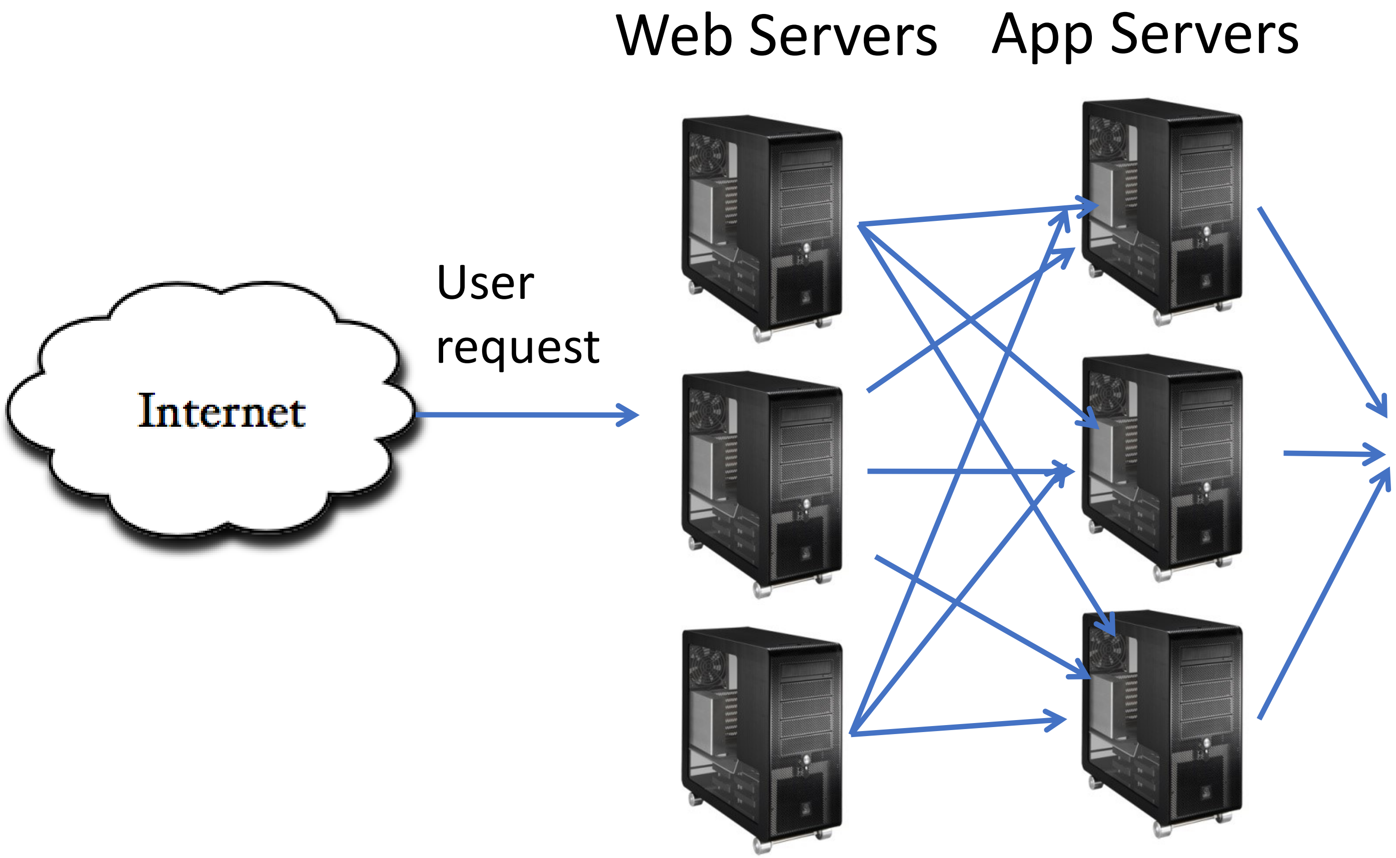
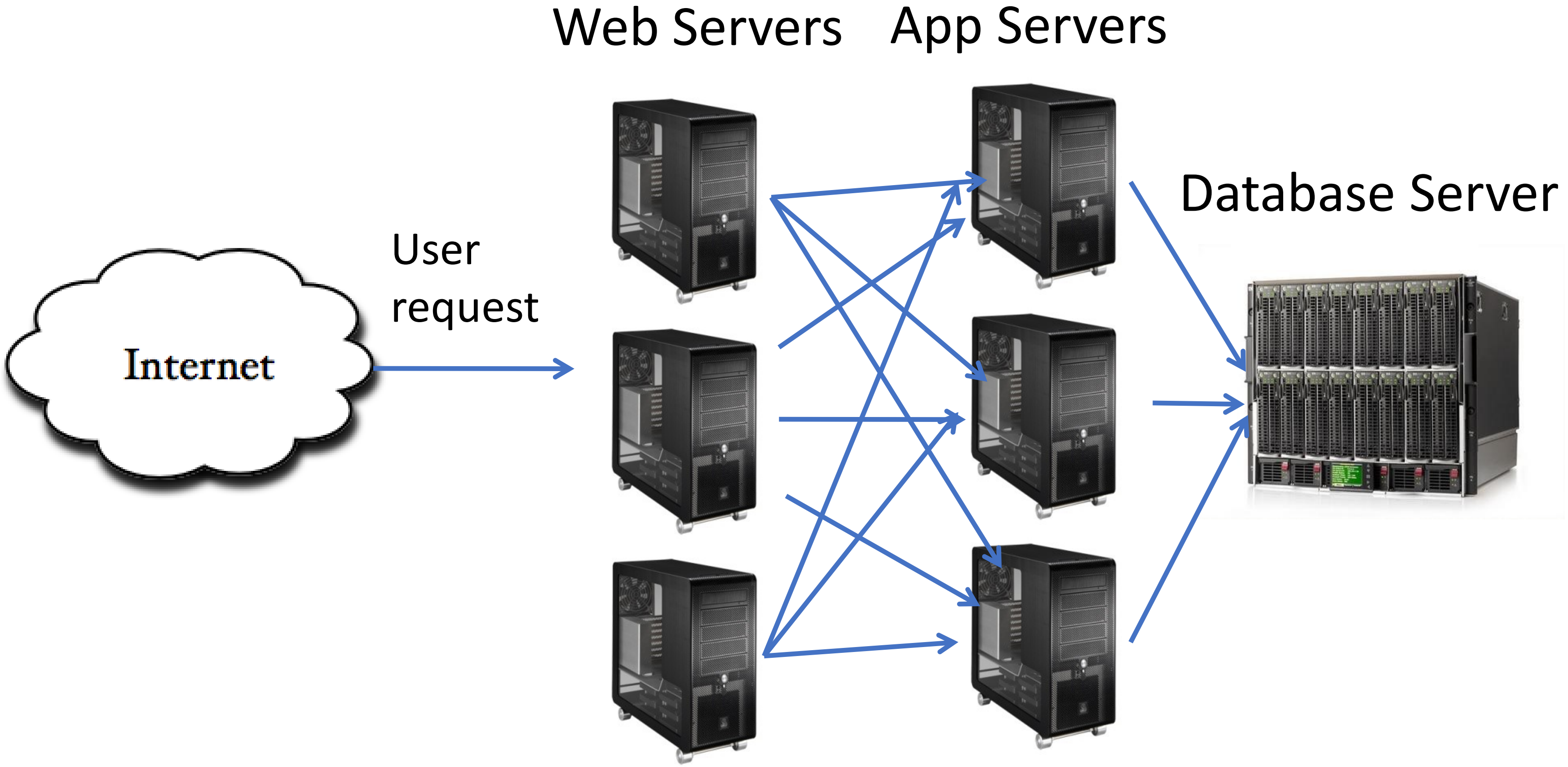


Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*

3 Tier architecture



Web Servers (Presentation Tier) and App servers (Business Tier) scale *horizontally*
Database Server → scales *vertically*

Horizontal Scale → "Shared Nothing"

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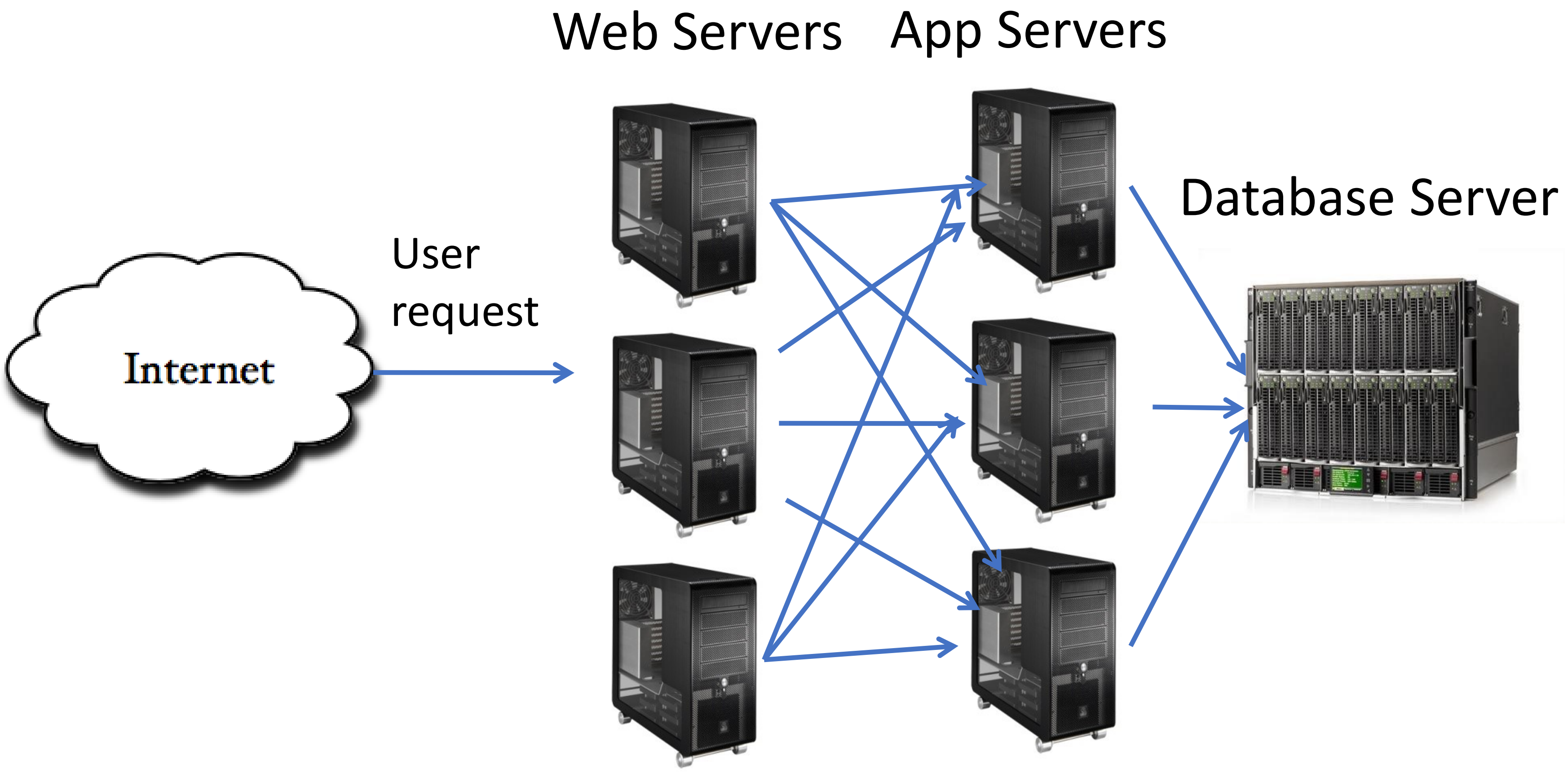

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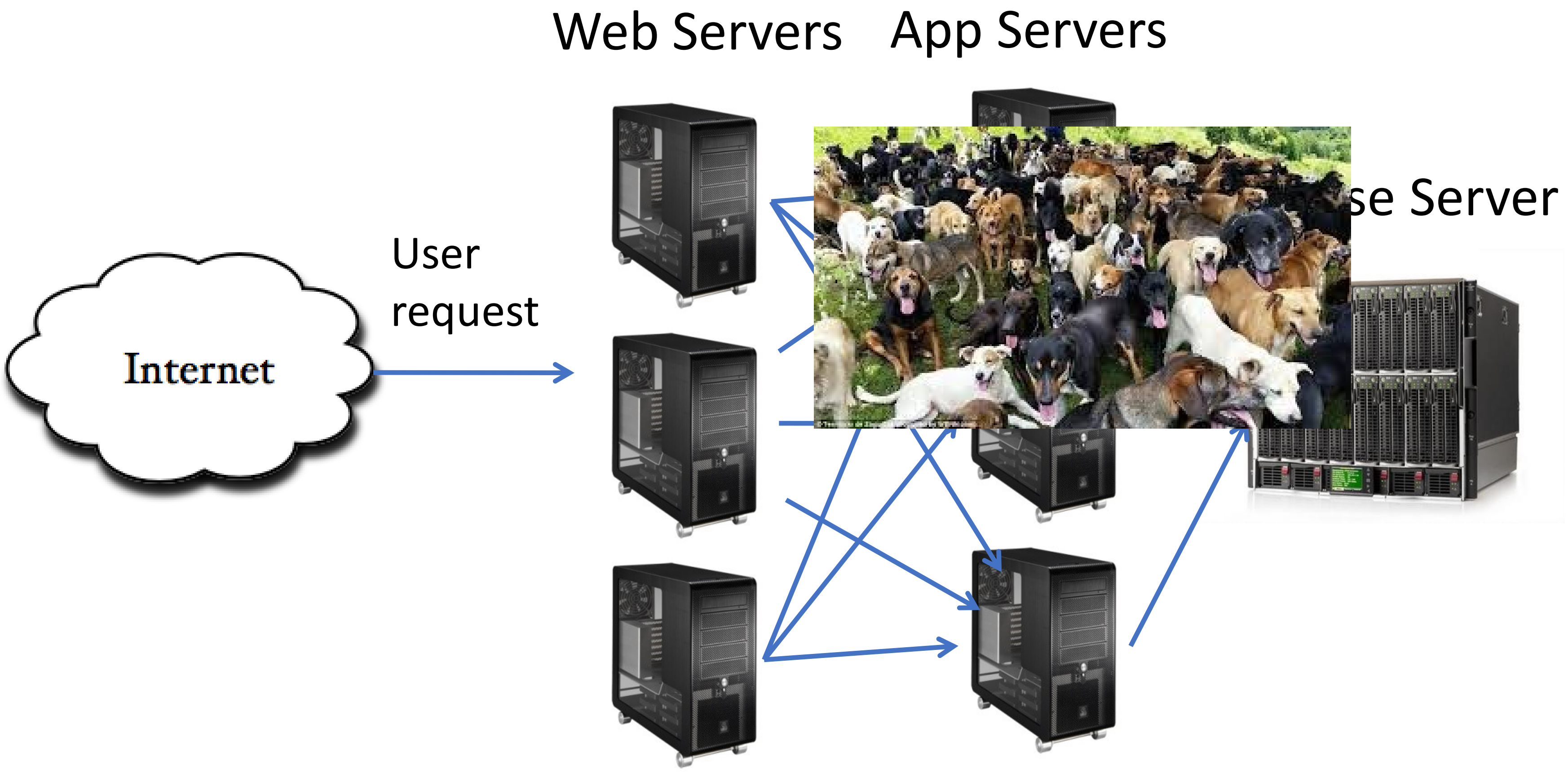

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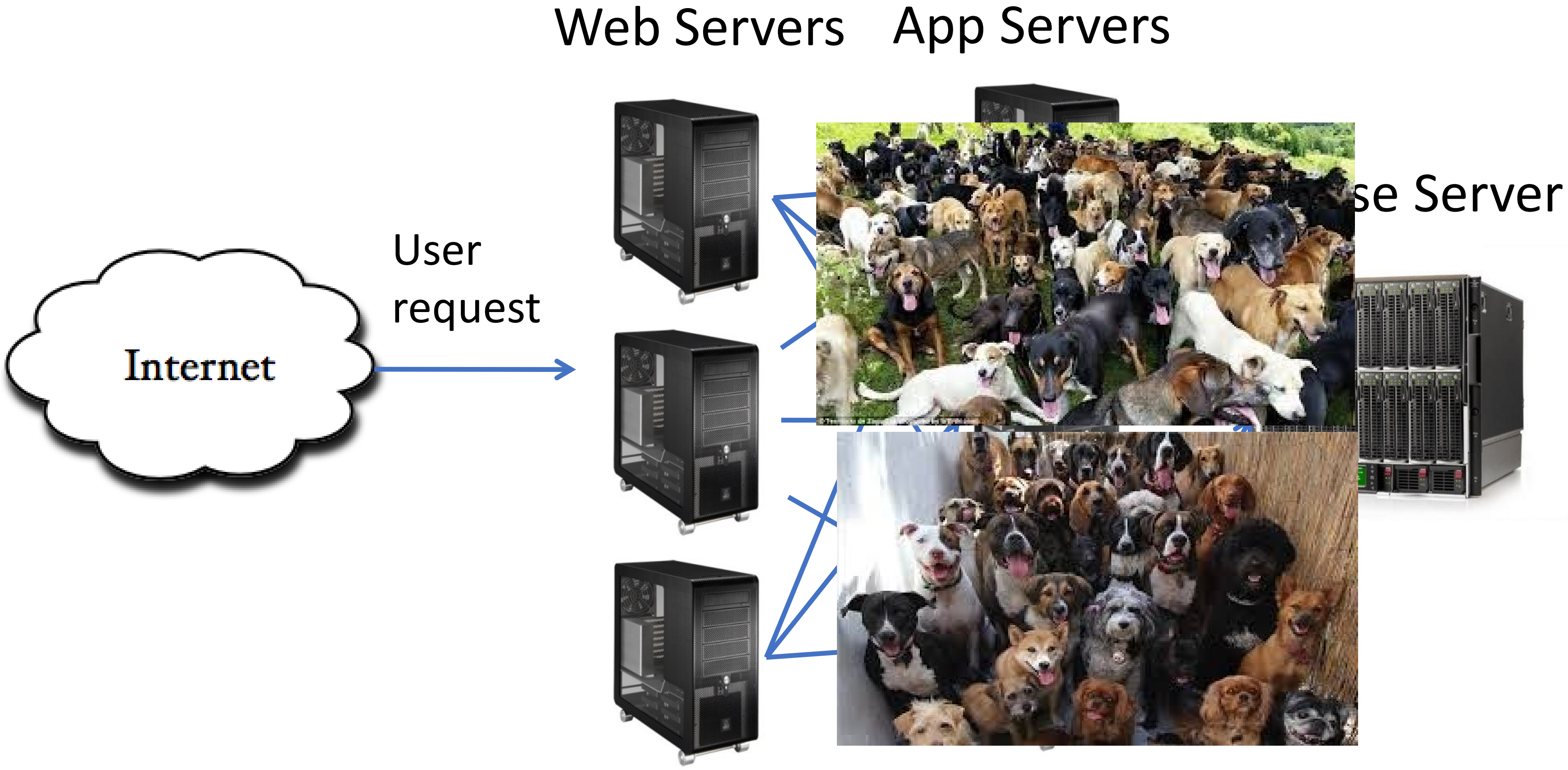

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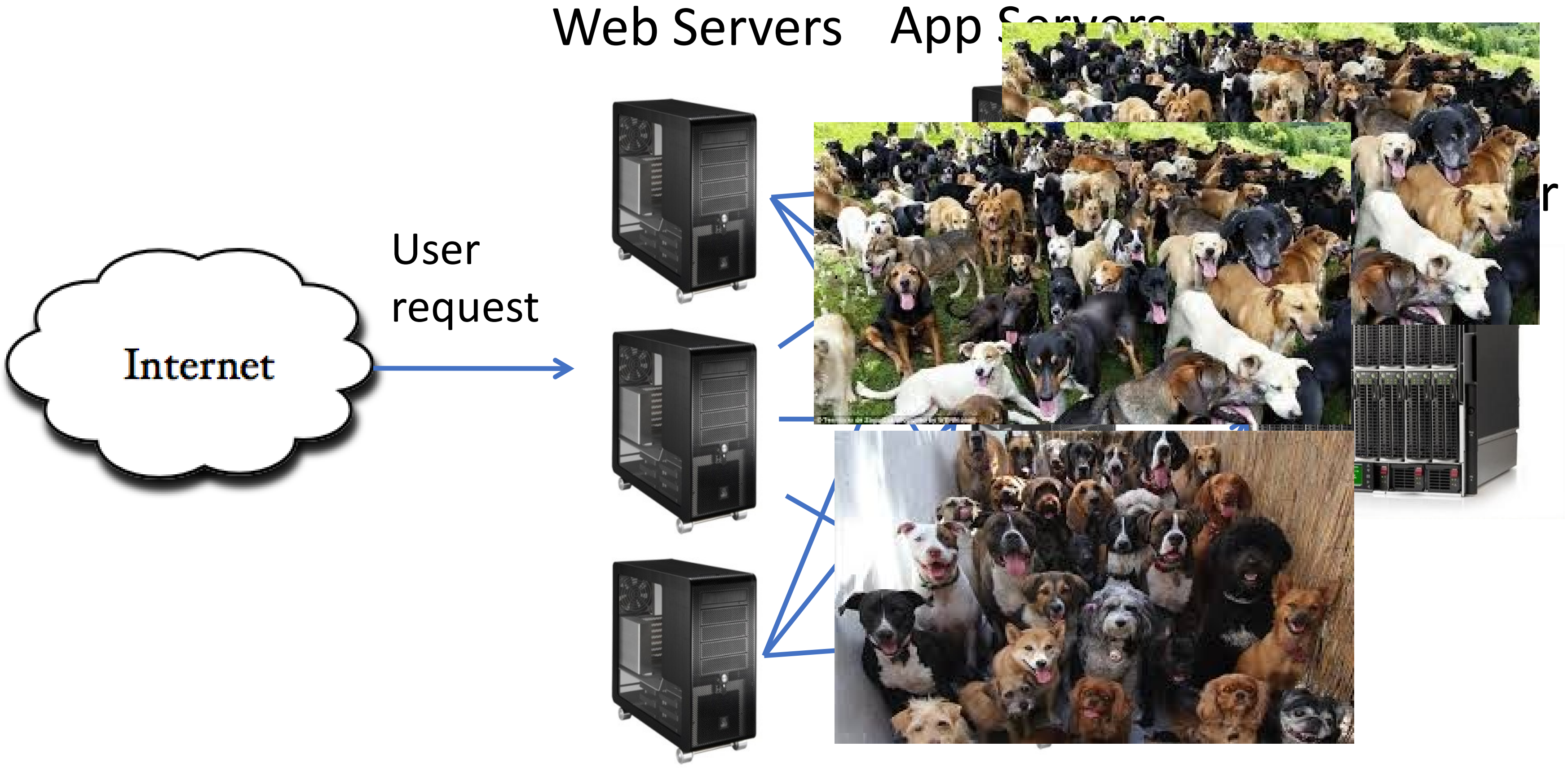

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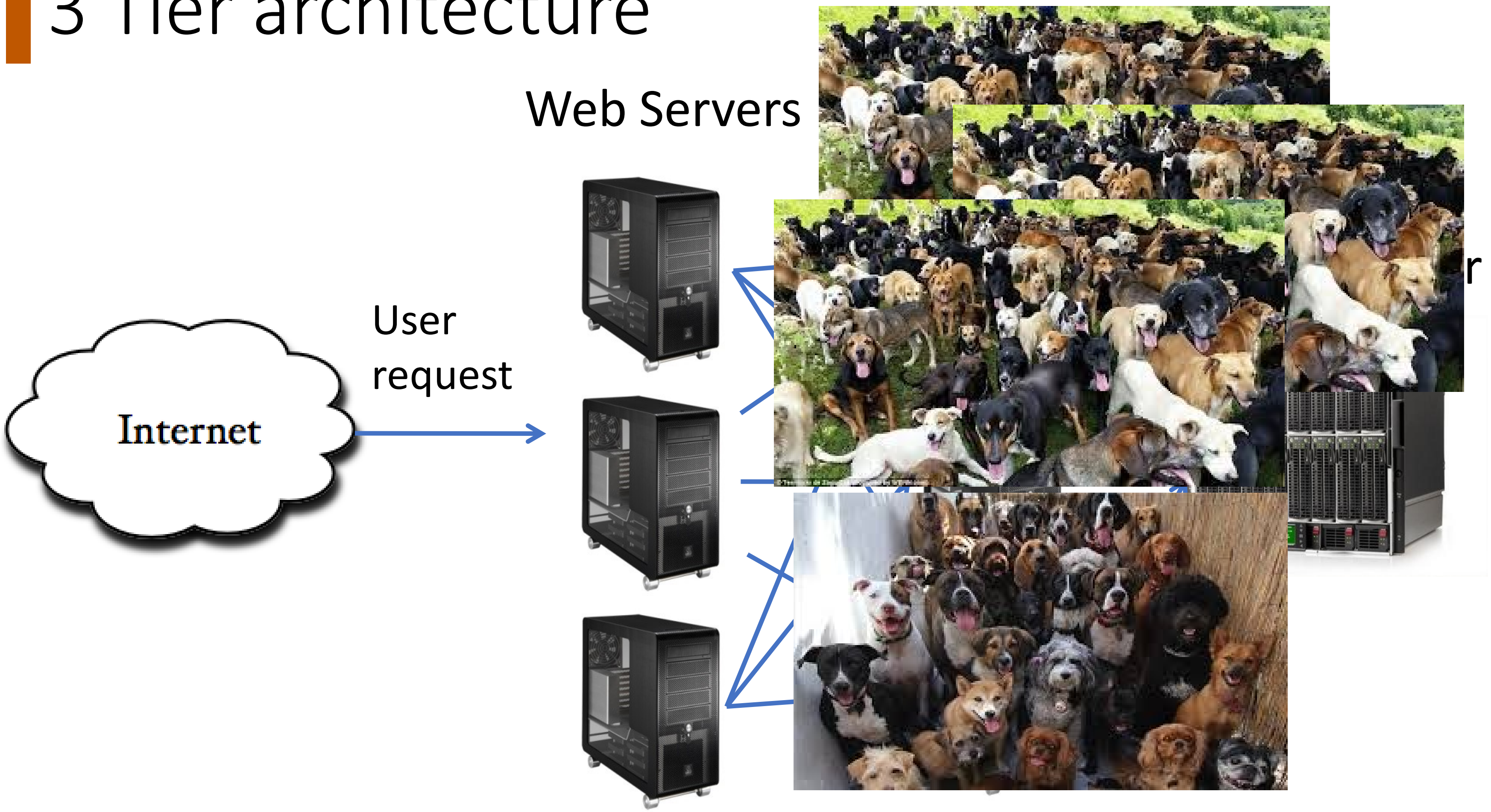

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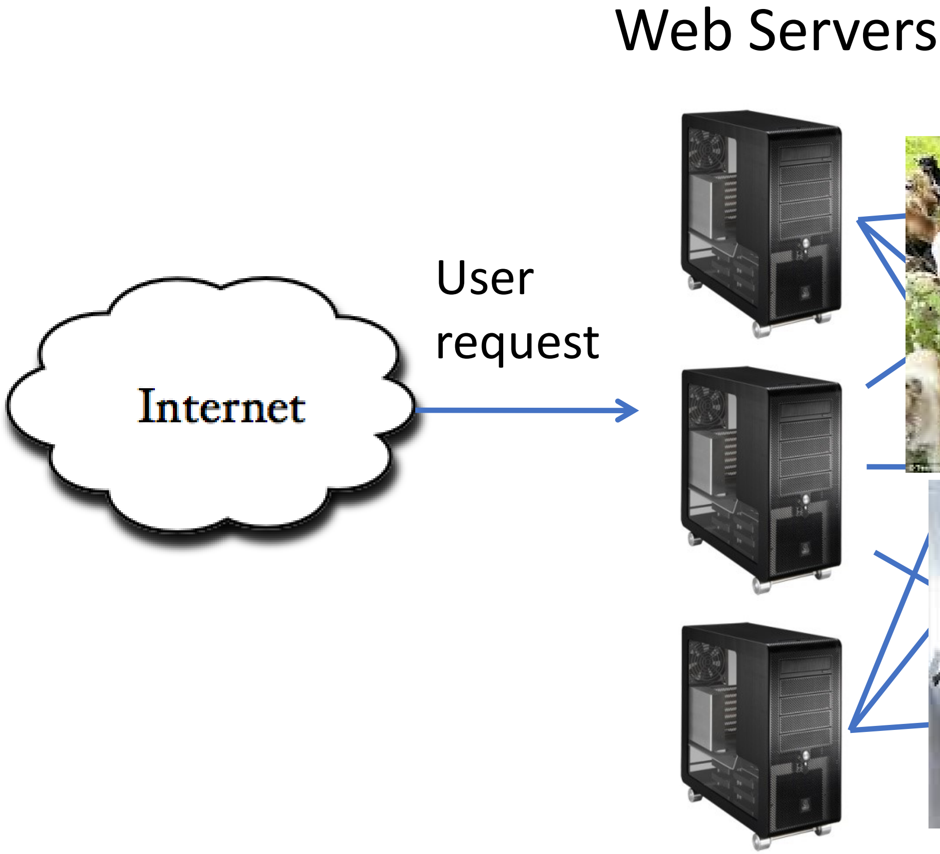

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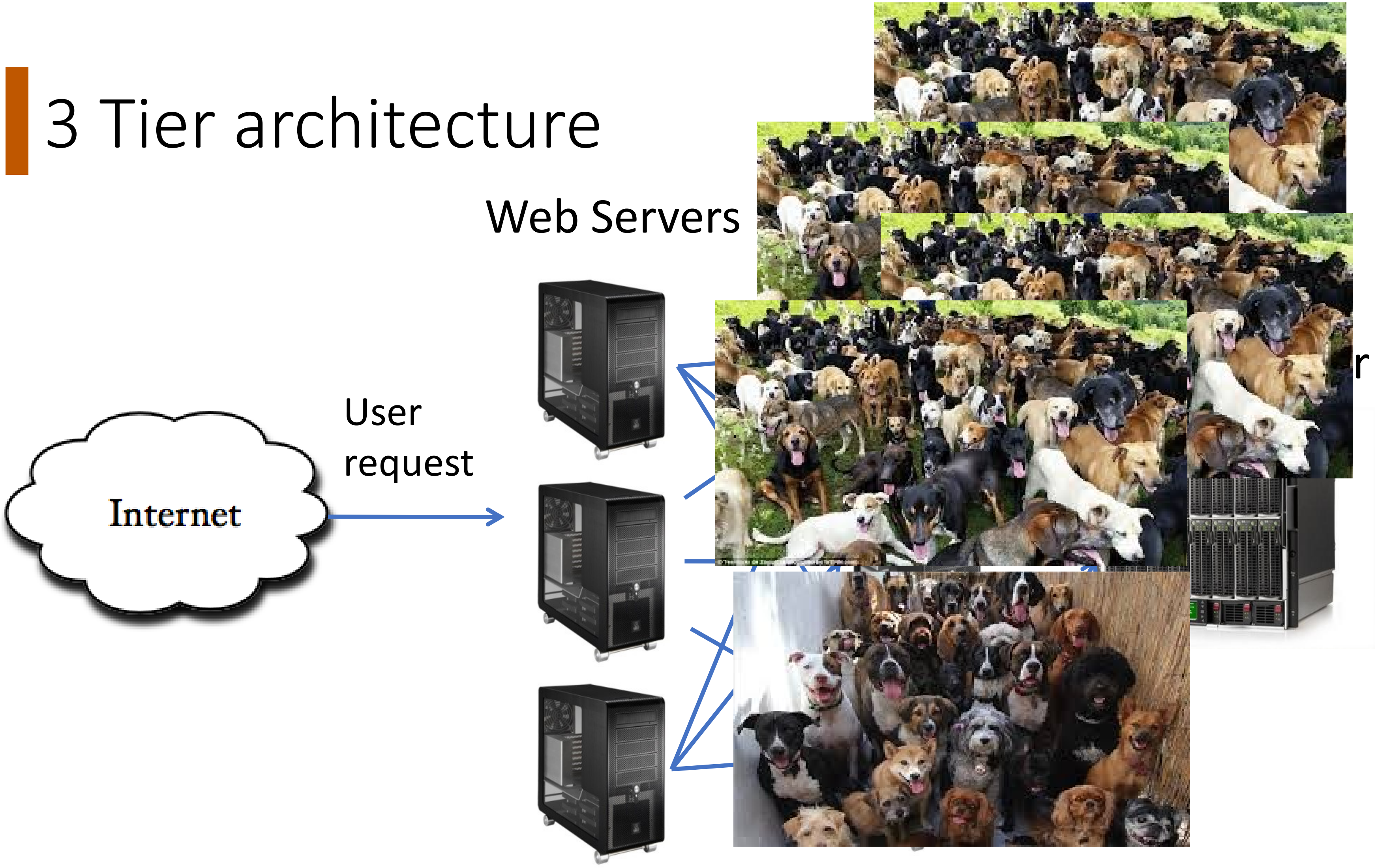

Web Servers (Presentation Tier) and Ap ... *izontally*
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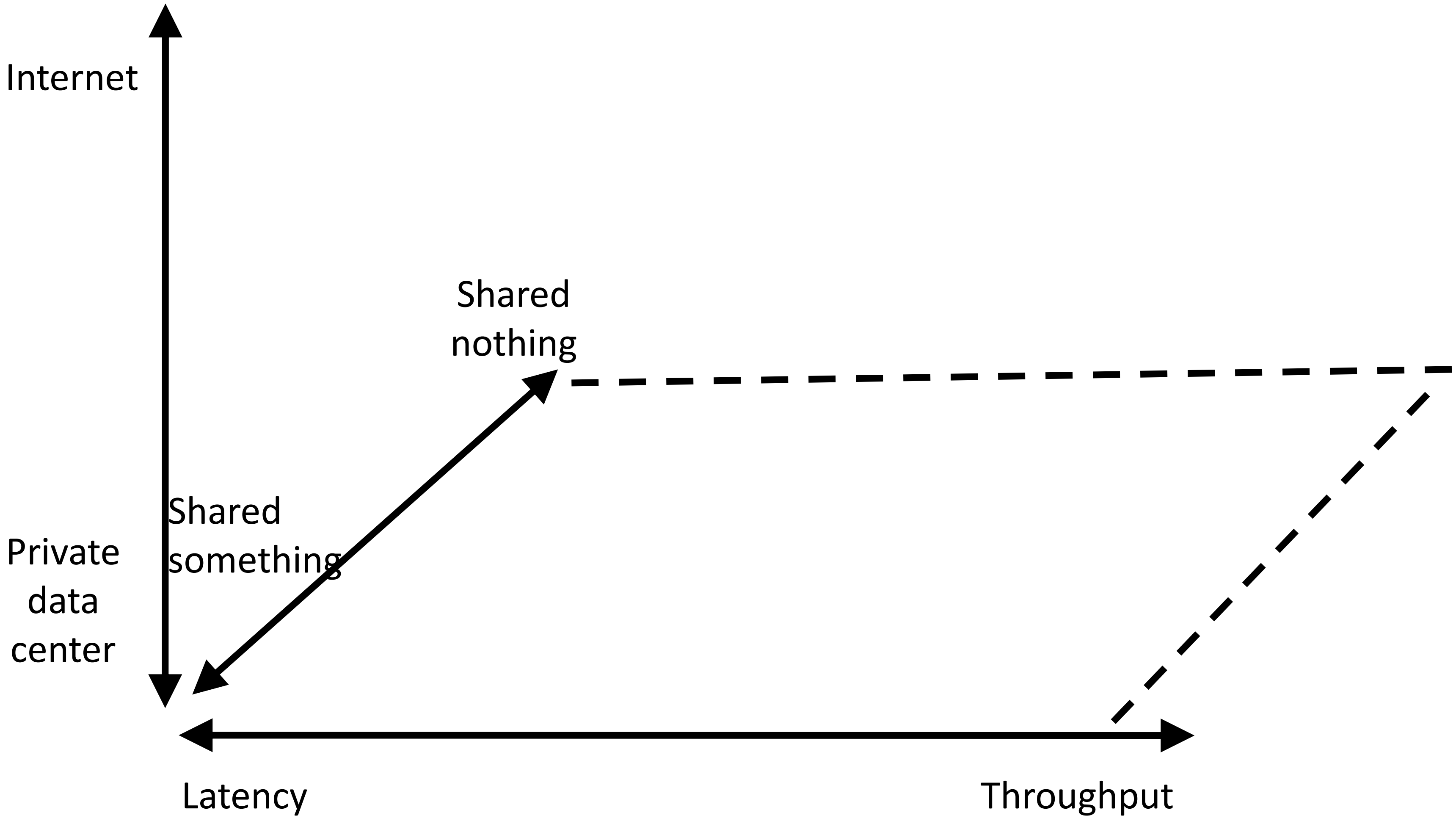
Horizontal Scale → "Shared Nothing"

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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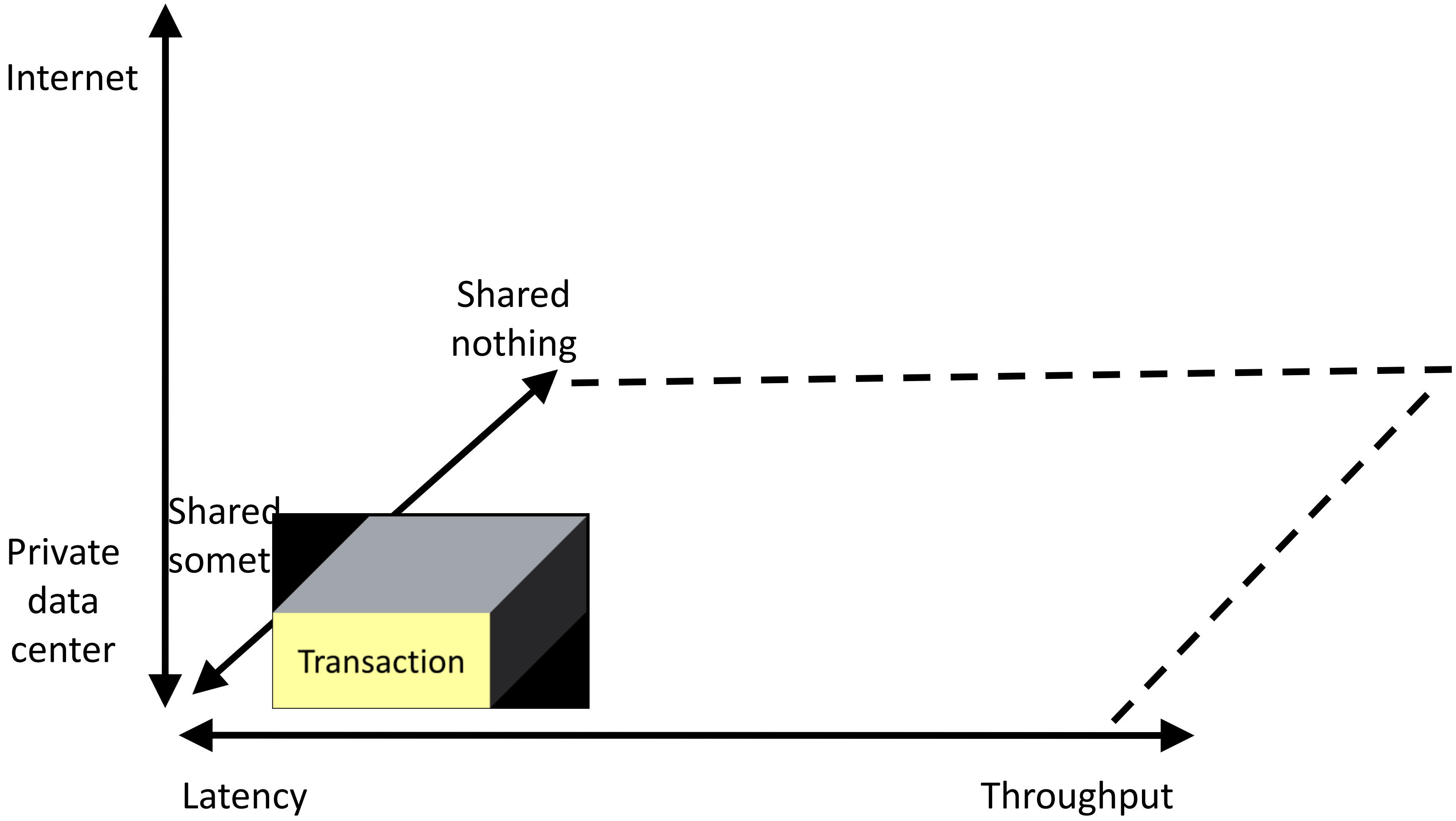

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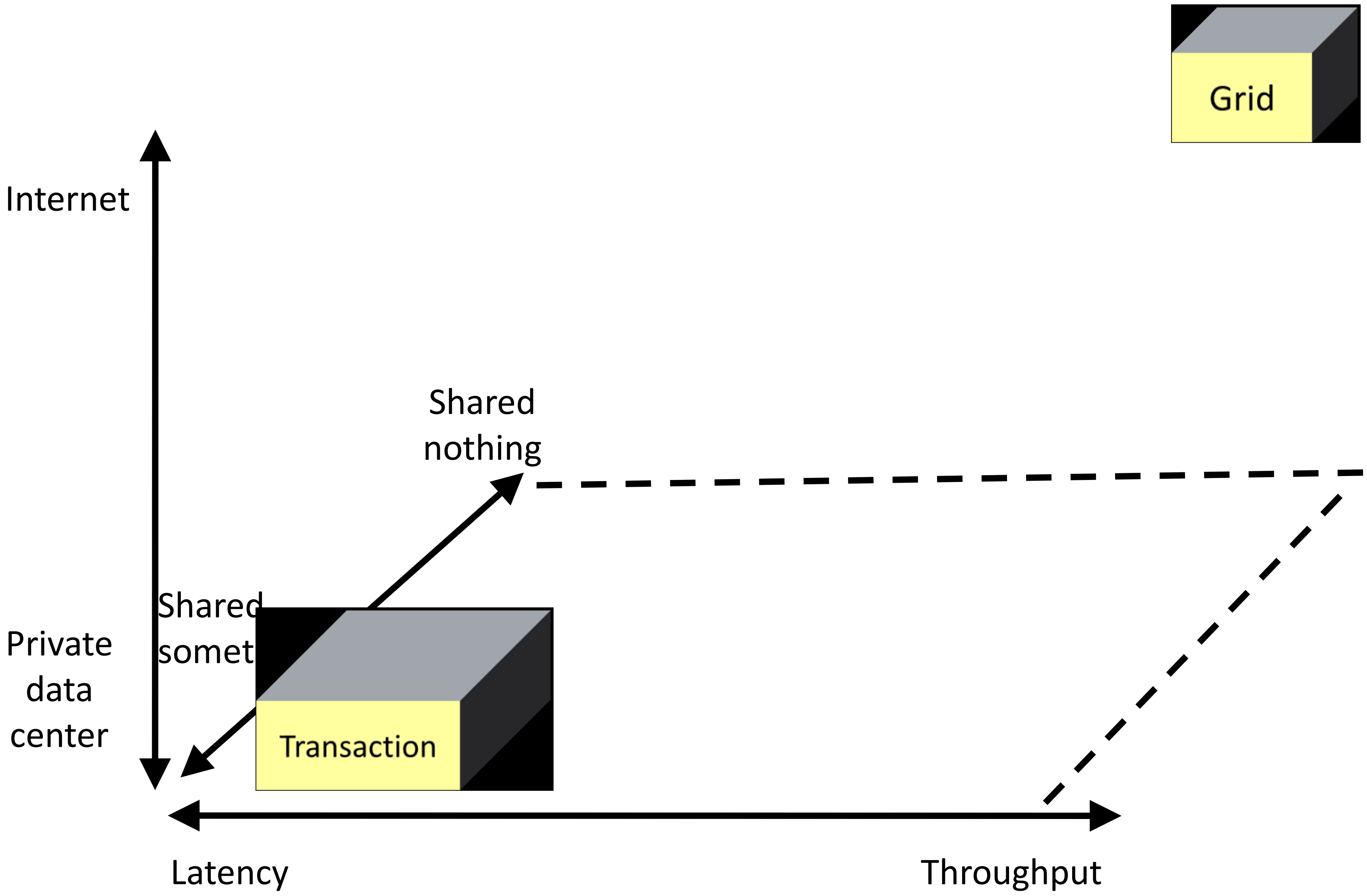

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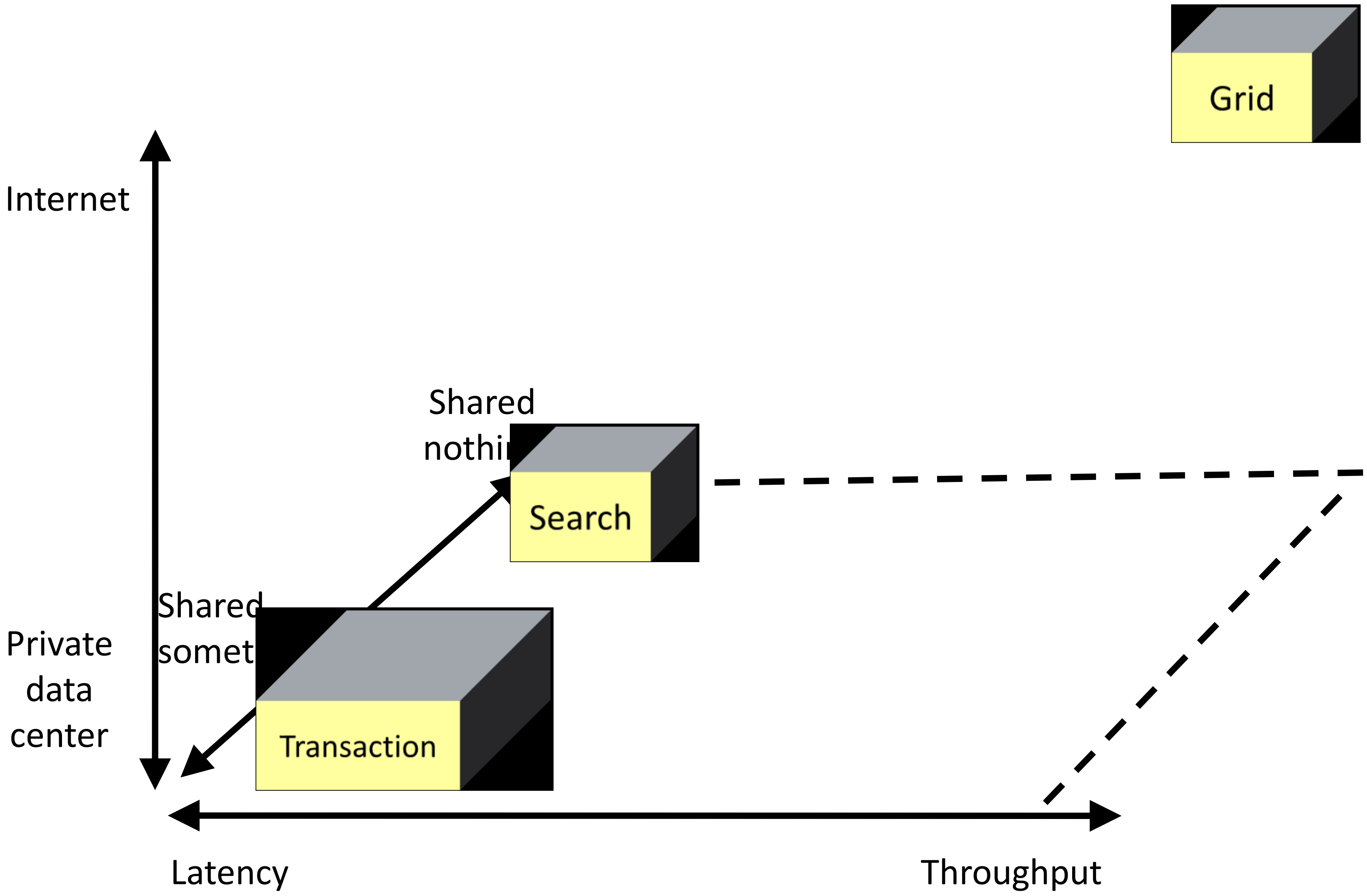

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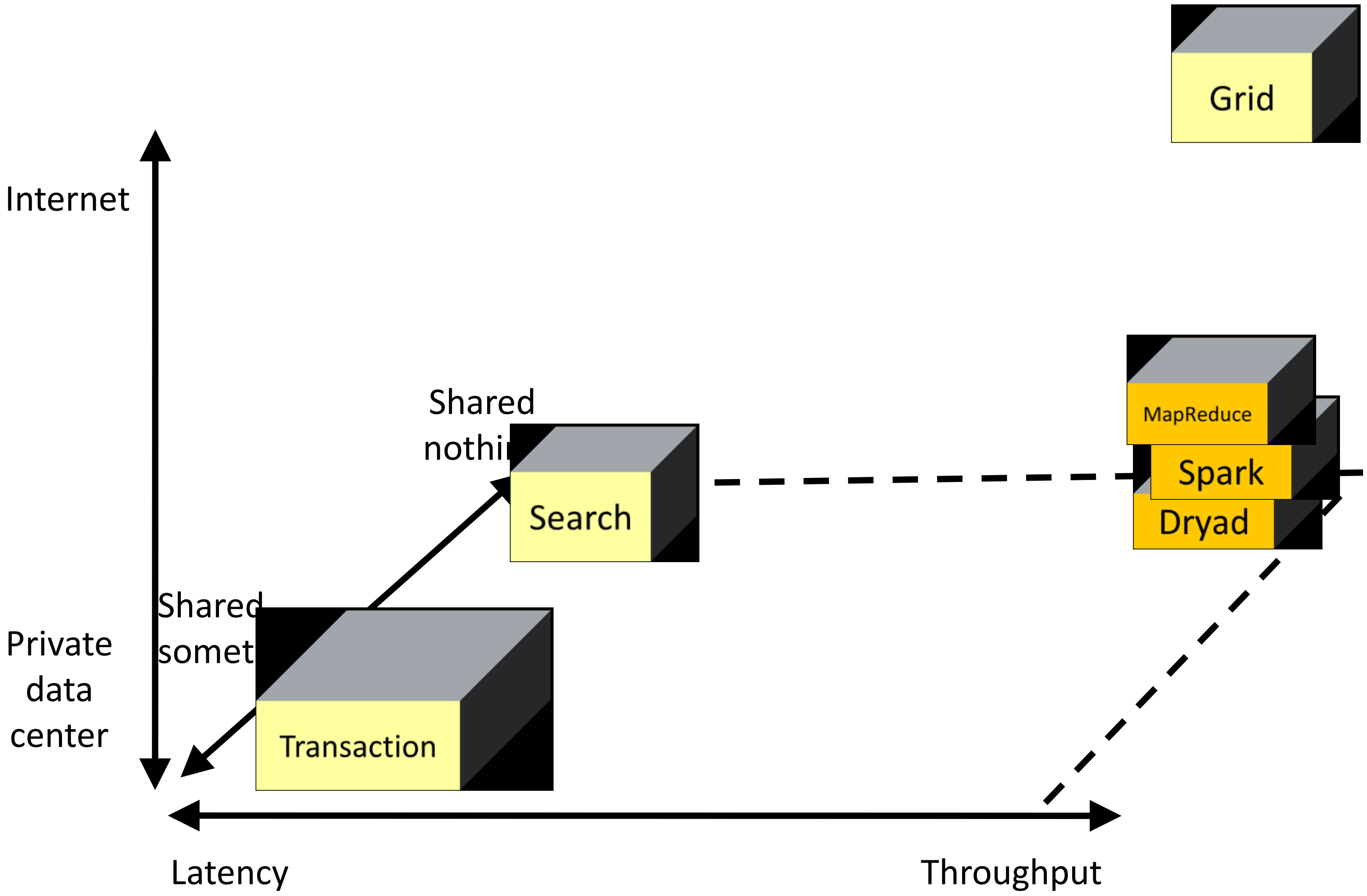

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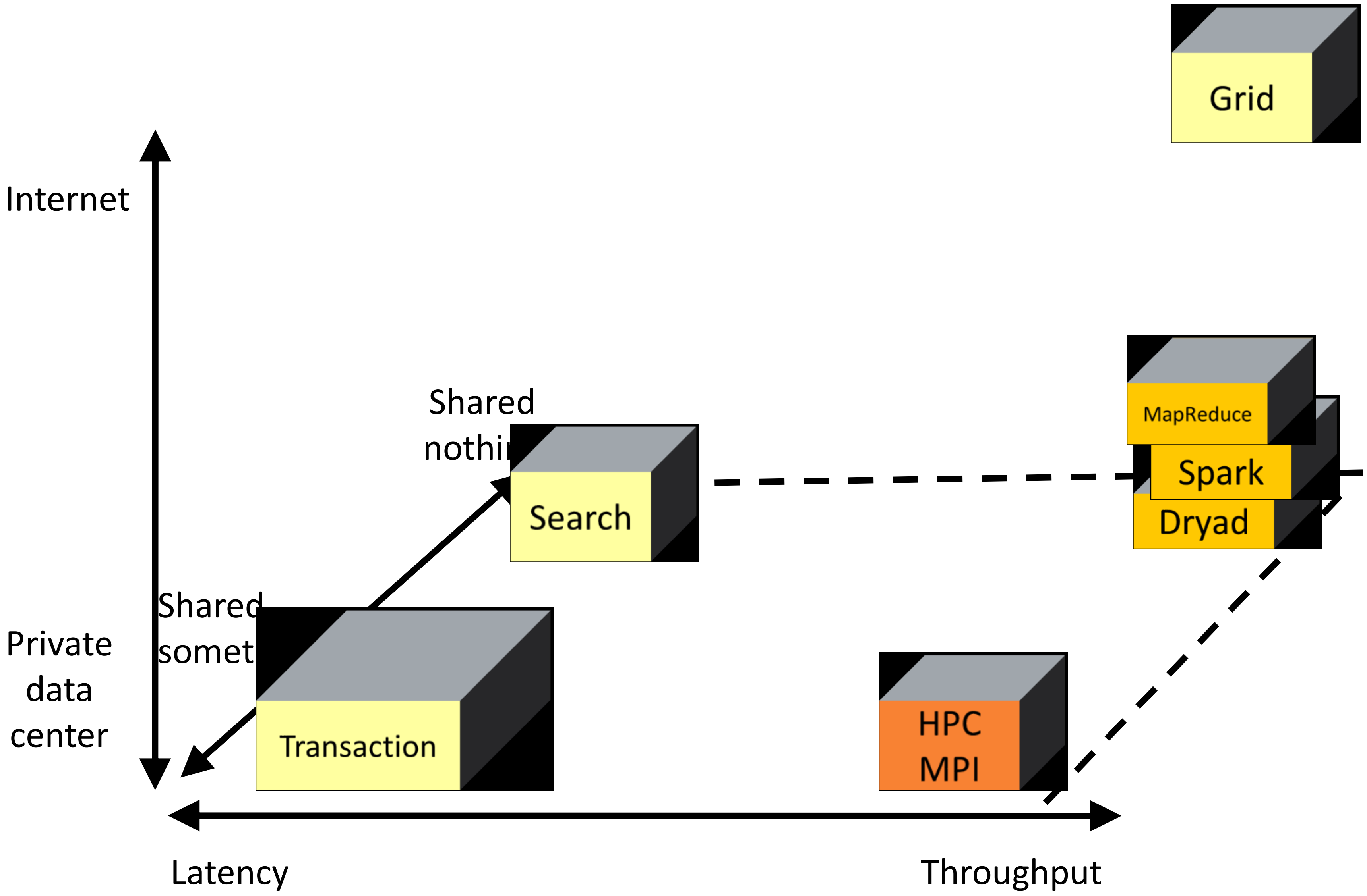

Parallel Architectures and MPI

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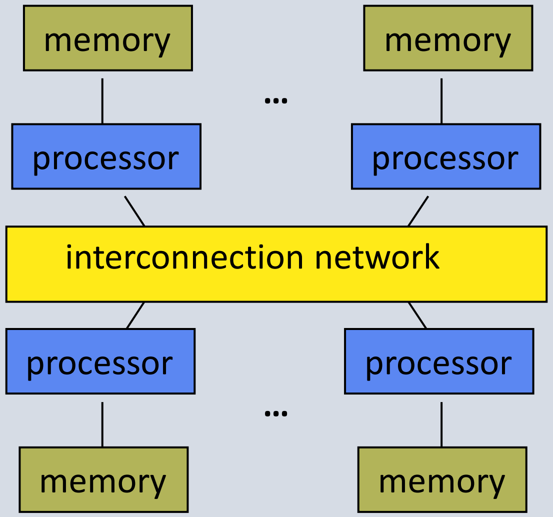
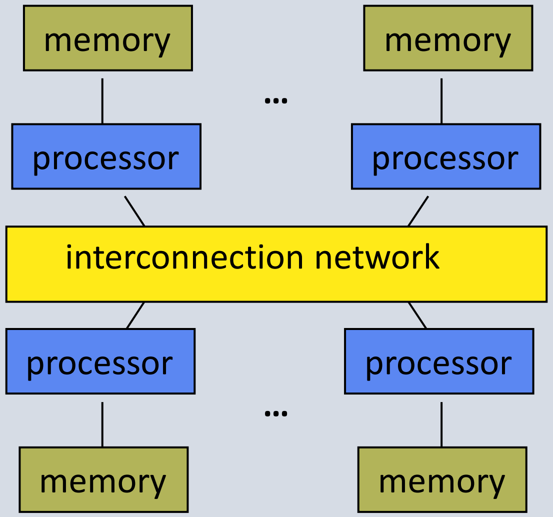


Parallel Architectures and MPI

Distributed Memory Multiprocessor

Messaging between nodes



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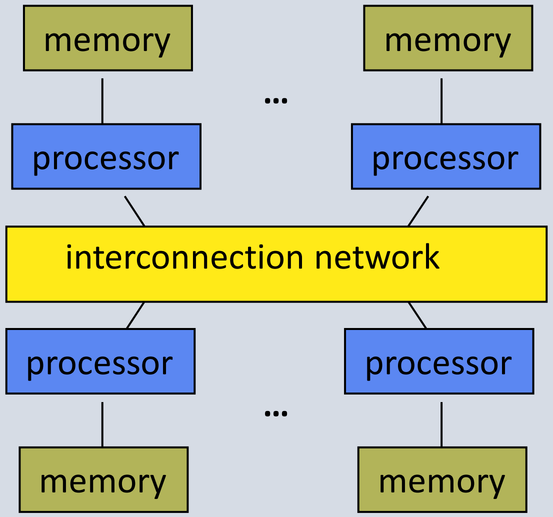

Massively Parallel Processor (MPP)

Many, many processors

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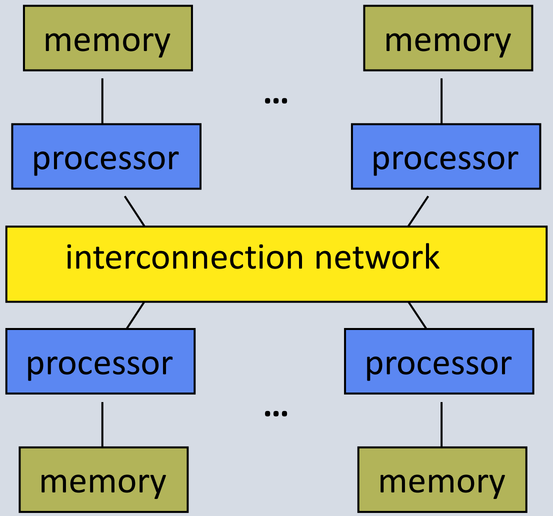

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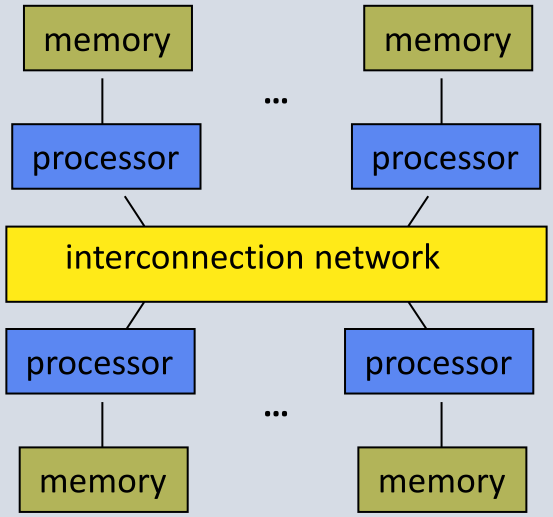

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Cluster of SMPs

- Shared memory in SMP node
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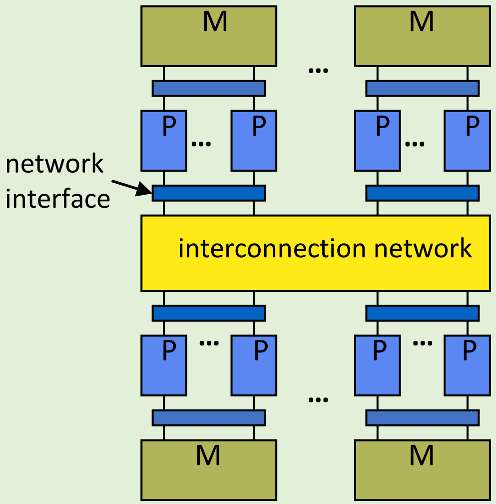

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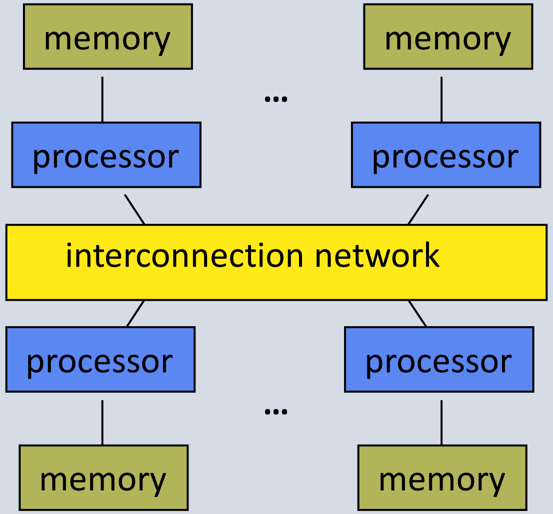

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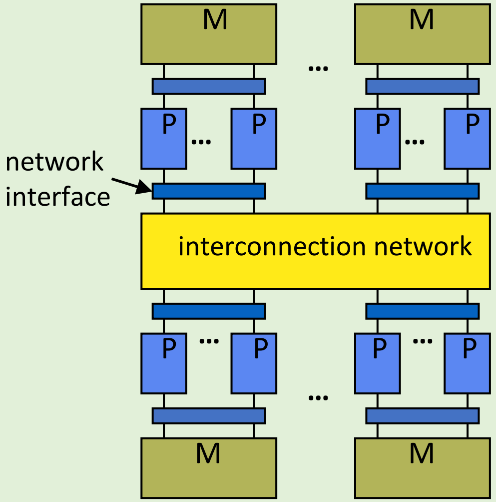

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Multicore SMP+GPU Cluster

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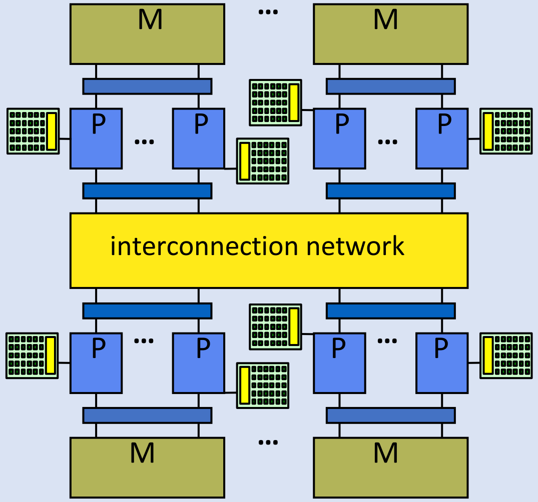

- GPU accelerators attached

Parallel Architectures and MPI

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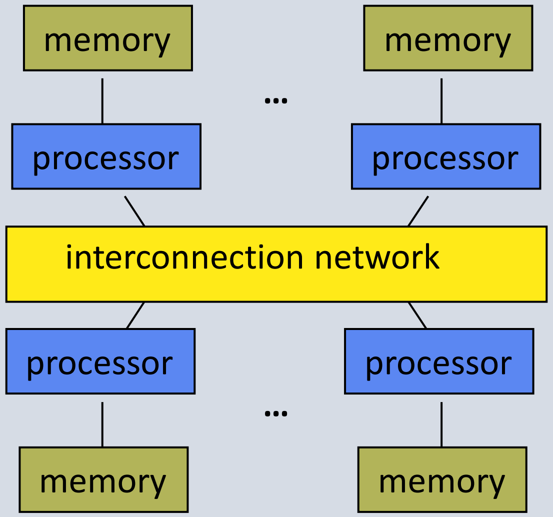

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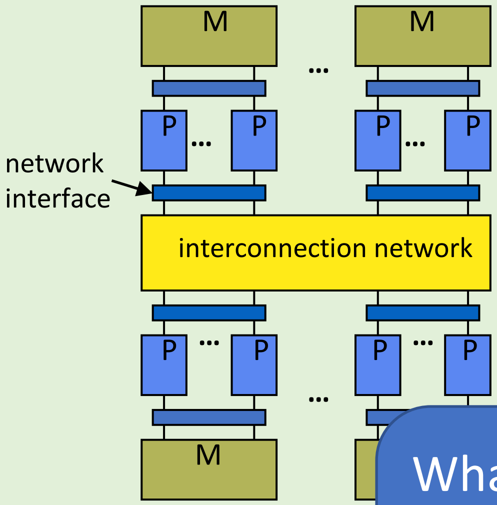

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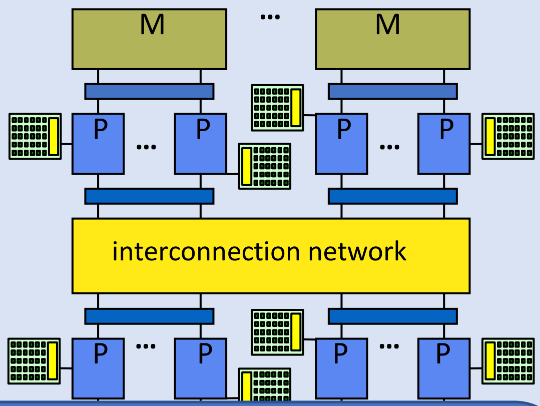

What have we left out?

Parallel Architectures and MPI

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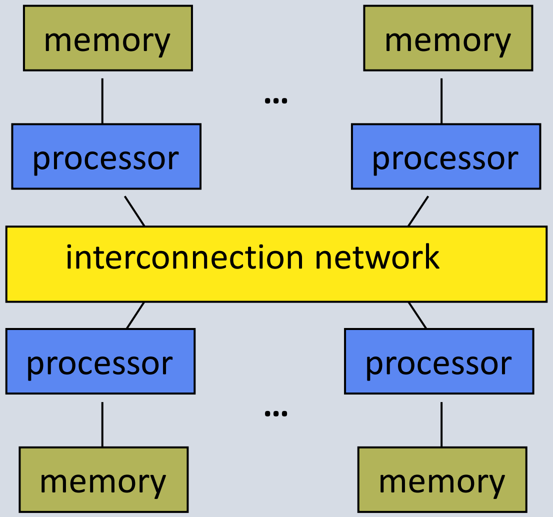

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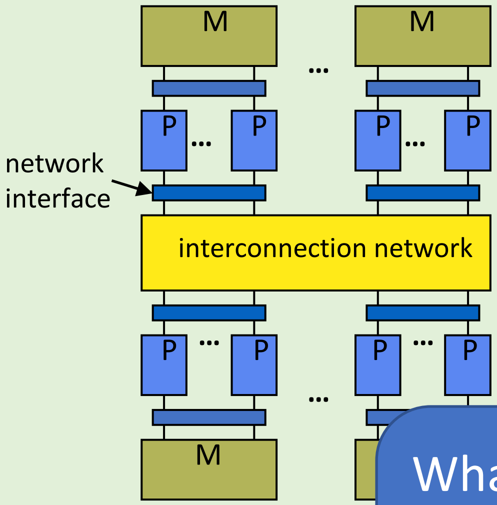

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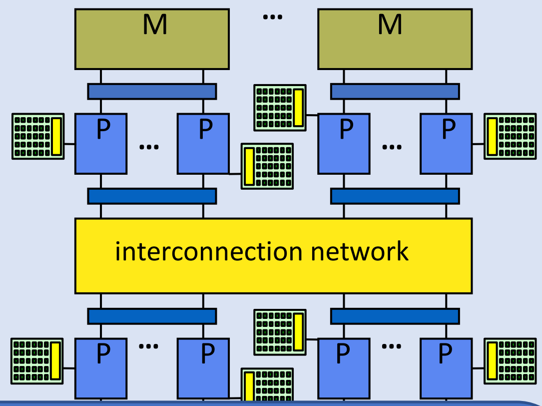

What have we left out?

- DSMs
- CMPs
- Non-GPU Accelerators

What requires extreme scale?

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Simulations—why?

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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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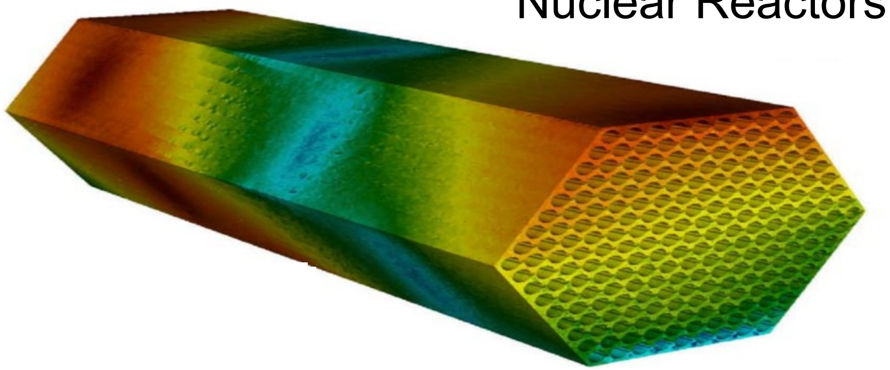
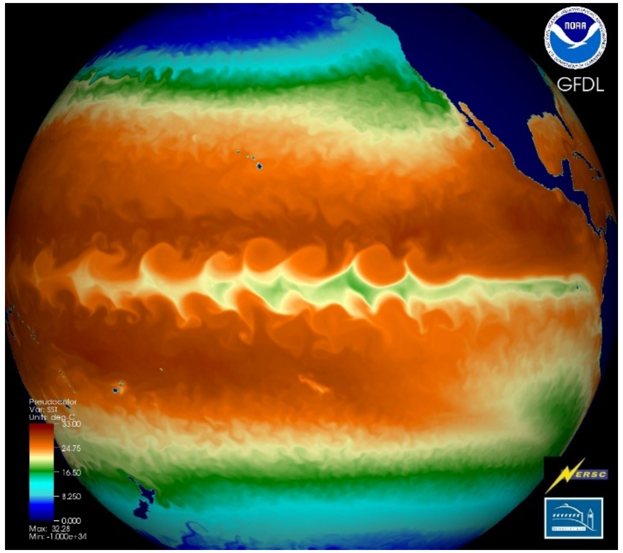
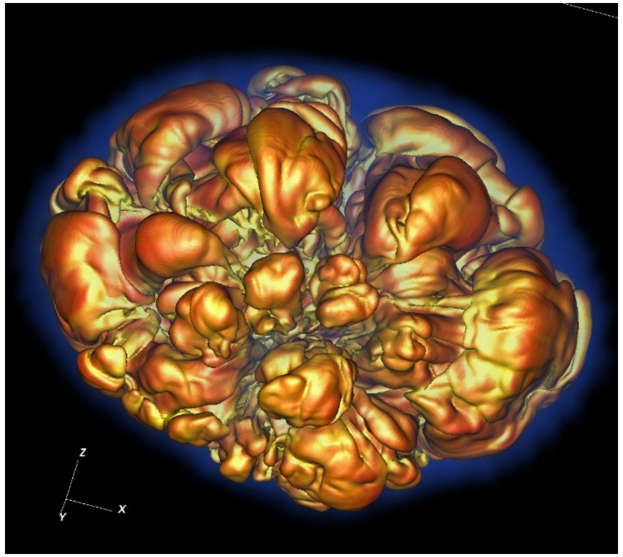
Nuclear Reactors





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)
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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	**Gyoukou** - 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
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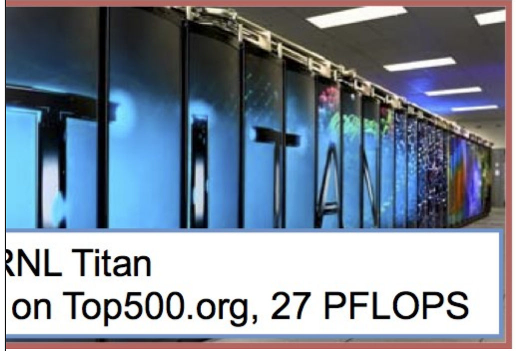

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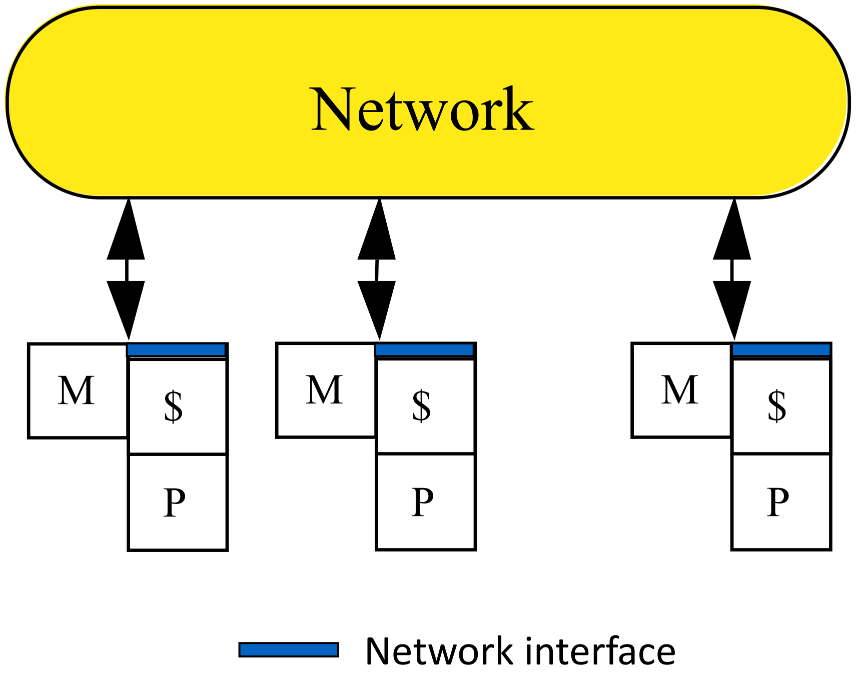

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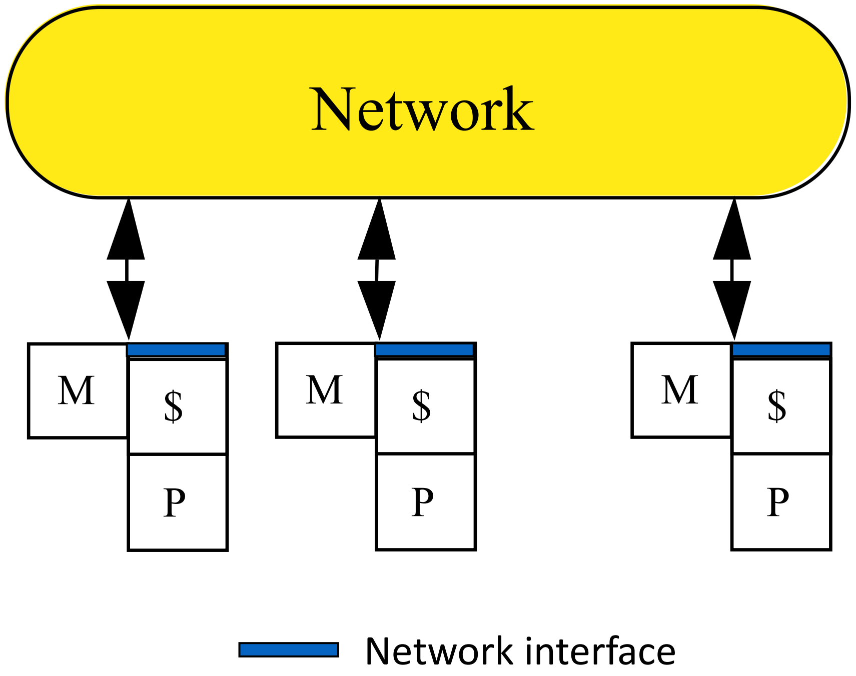

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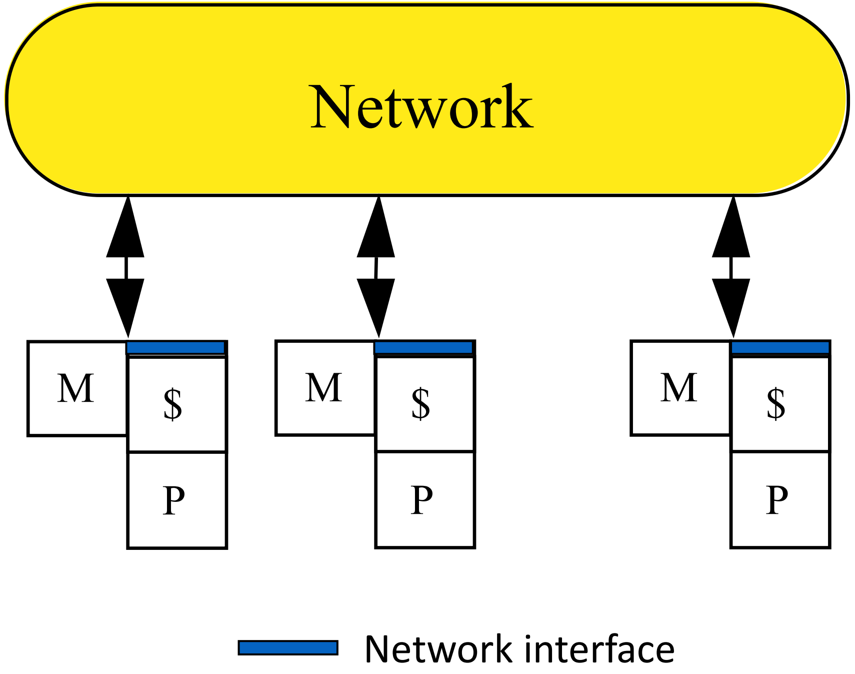
  - Including I/O
- Nodes communicate via network
  - Standard networks (IP)
  - Specialized networks (RDMA, fiber)

Distributed Memory Multiprocessors

Each processor has a local memory

Physically separated address space



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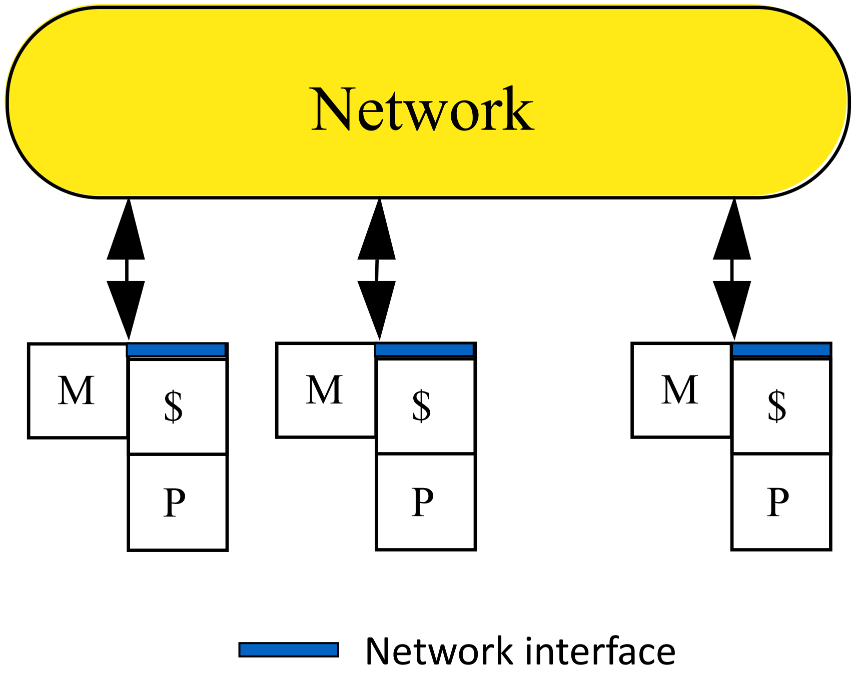
- Message communication
  - *Message passing architecture*
- Processor interconnection network



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Processors: execution units

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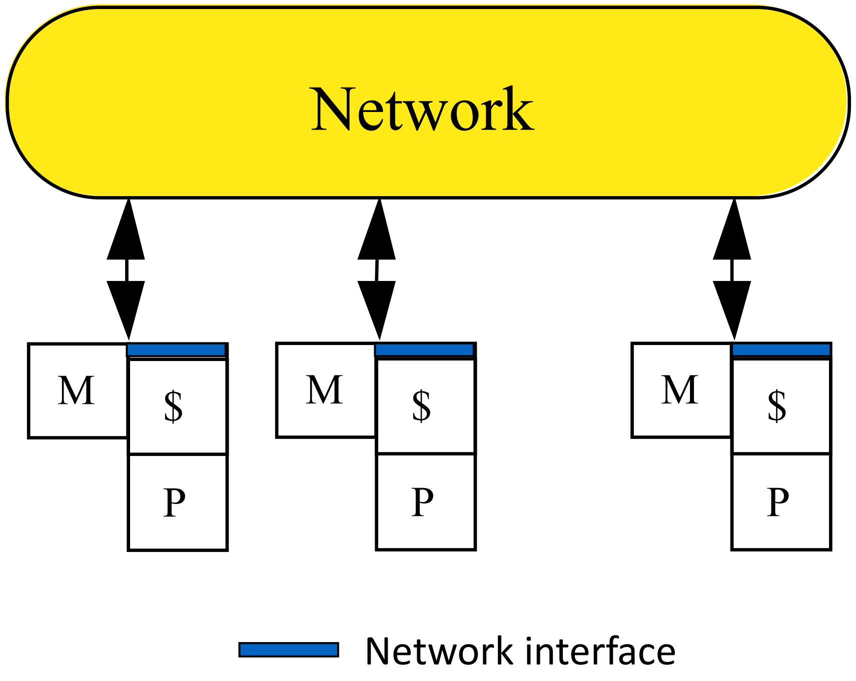

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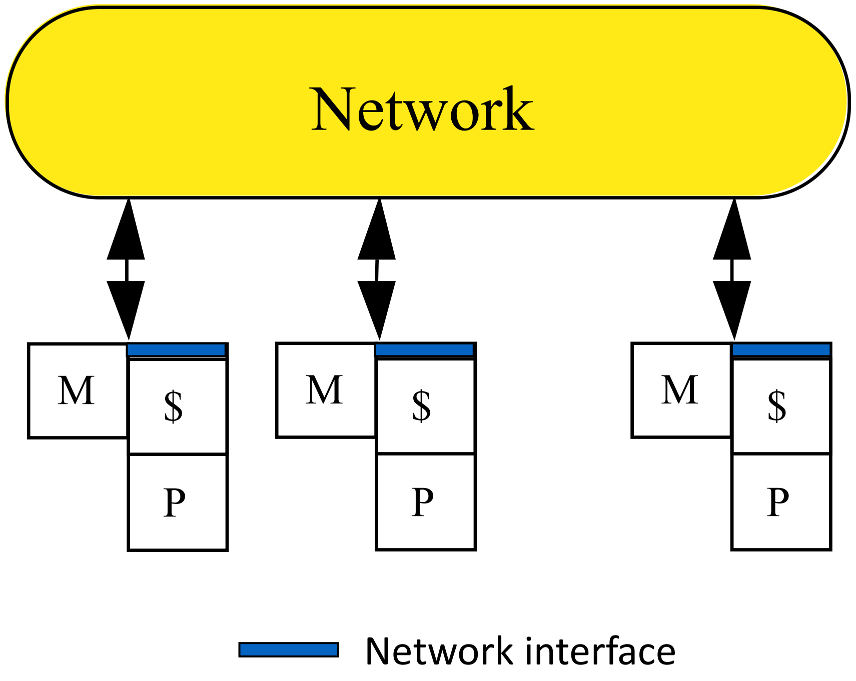
Scalable architecture
- Incremental cost to add hardware (cost of node)



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Bandwidth

- Need high bandwidth in communication
- Match limits in network, memory, and processor
- Network interface speed vs. network bisection bandwidth

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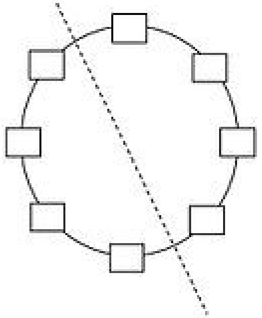
if network is **bisected**, **bisection bandwidth == bandwidth** between the two partitions



Performance: Latency and Bandwidth

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- Need high bandwidth in communication
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Is this different from metrics we've cared about so far?

Ostensible Advantages of Distributed Memory Architectures

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Can you think of any *disadvantages*?

Running on Supercomputers

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- Programmer plans a ***job***; job ==
  - parallel binary program
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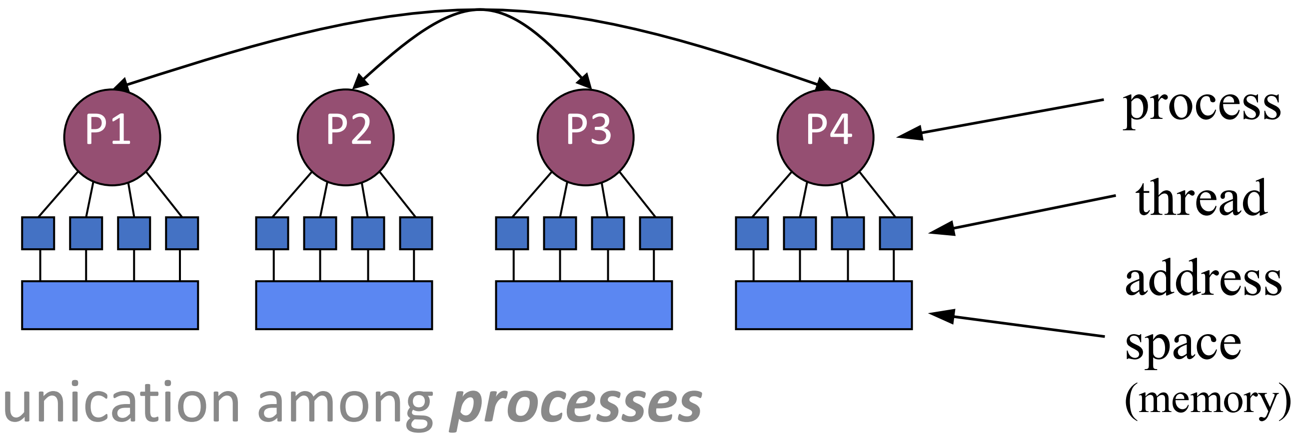
- MPI library interprets this information, hides the details

The Message-Passing Model

Process: a program counter and address space

Processes: multiple threads sharing a single address space



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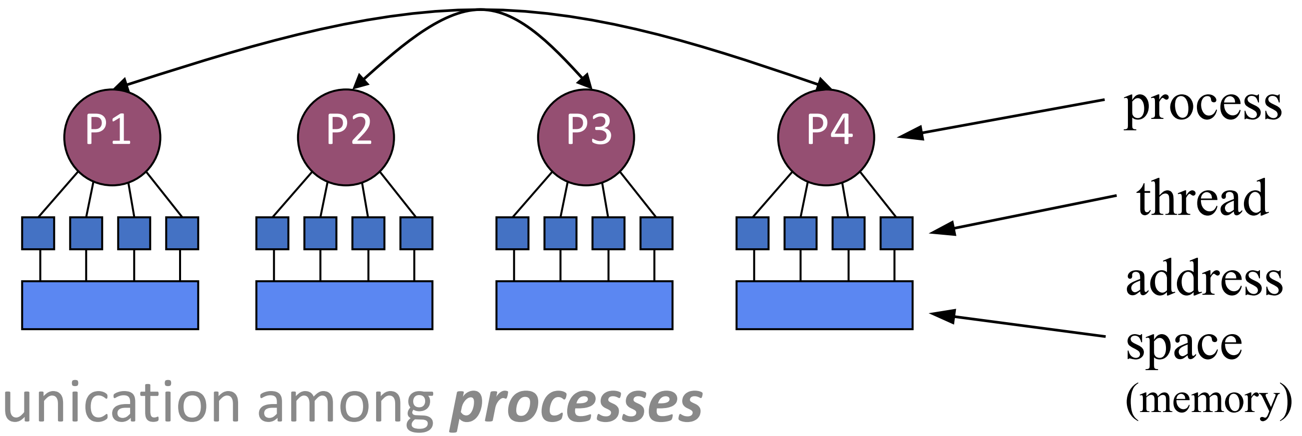

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How does this compare with CSP?

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Proc

MPI

Inte

CSP!

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

Cooperative Operations

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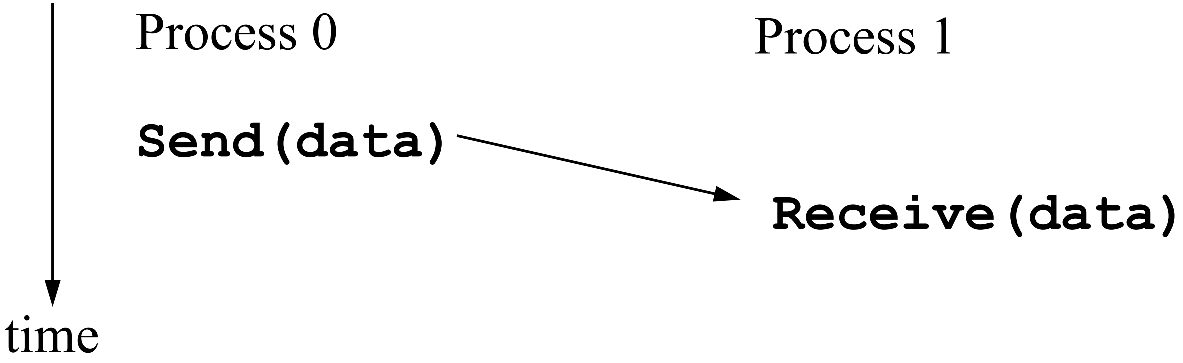

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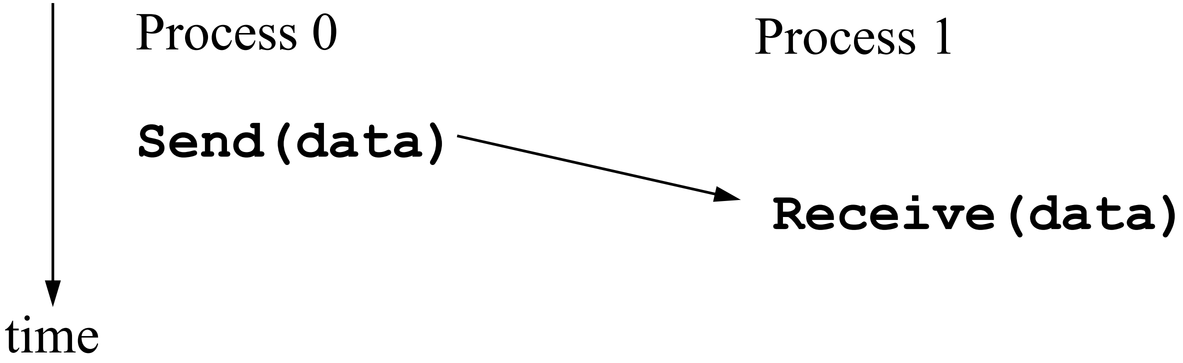

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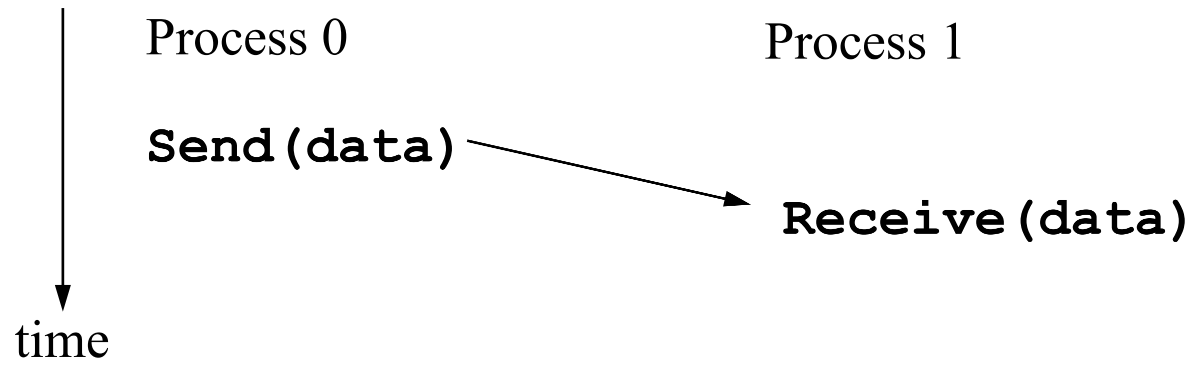

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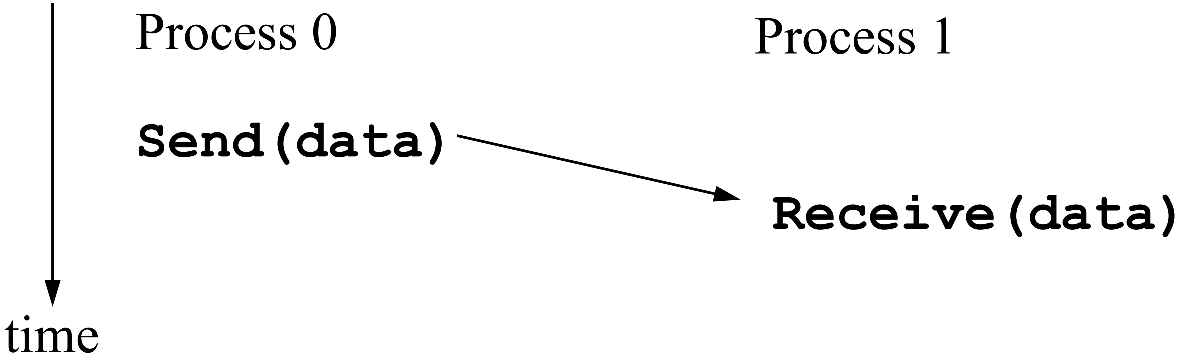

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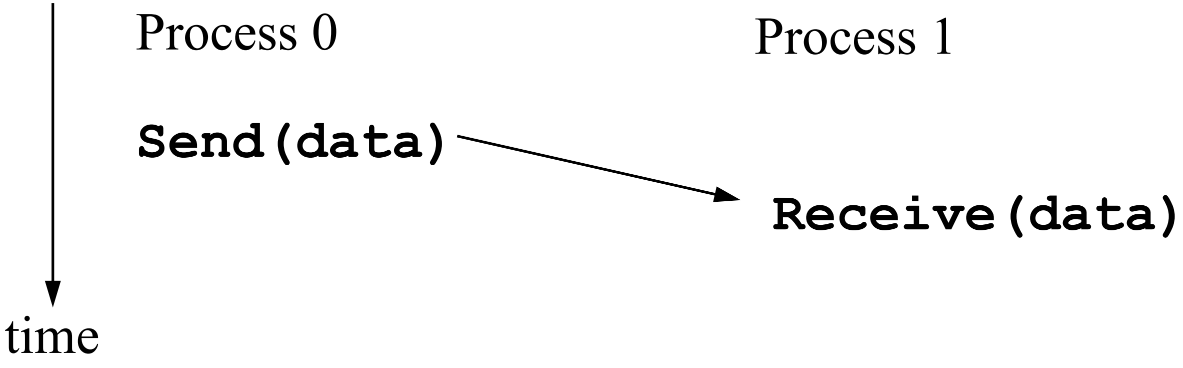

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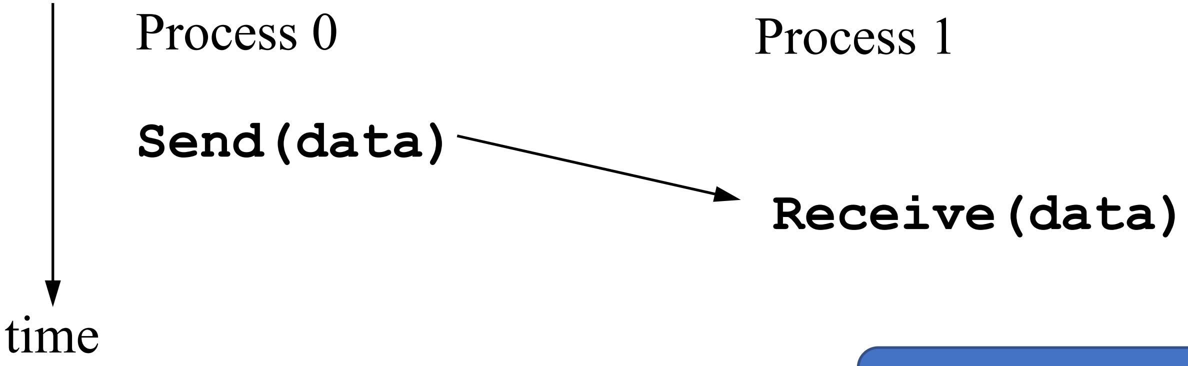
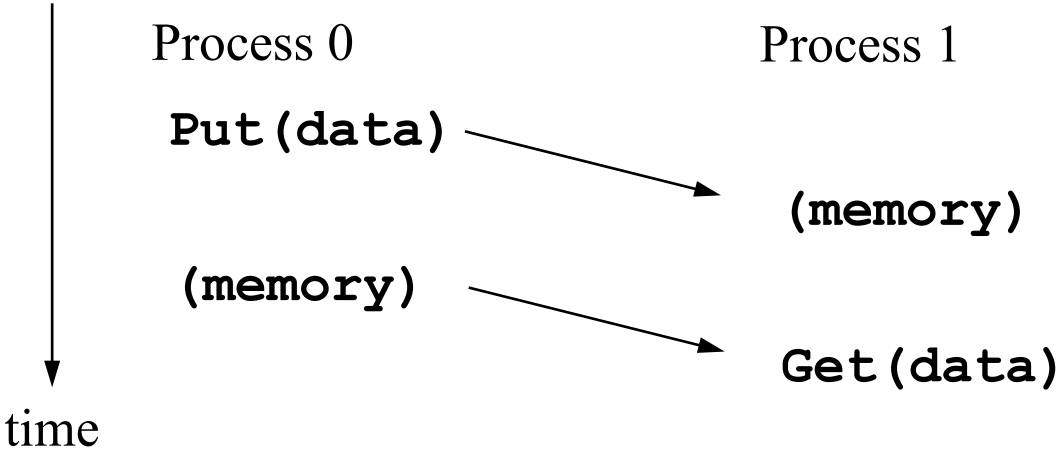


Familiar argument?

One-Sided Operations

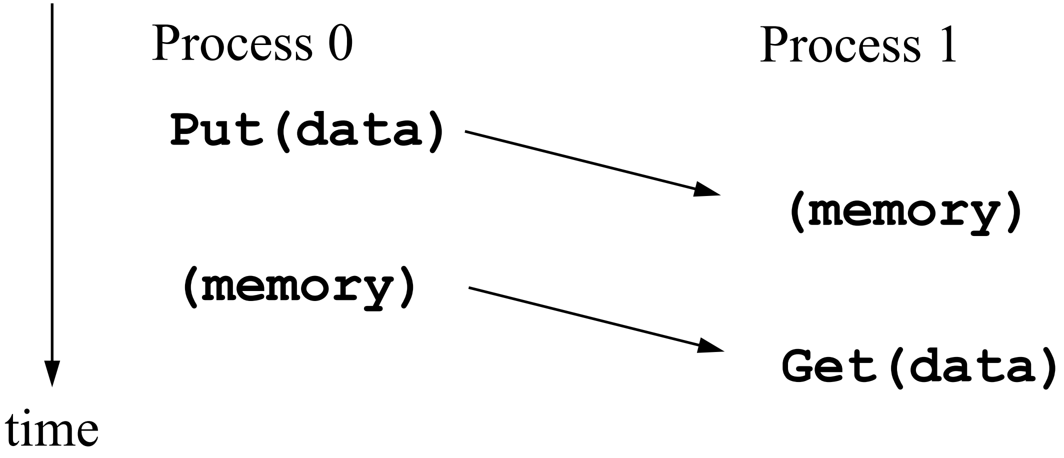
One-Sided Operations



One-Sided Operations

One-sided operations between processes

- Include remote memory reads and writes



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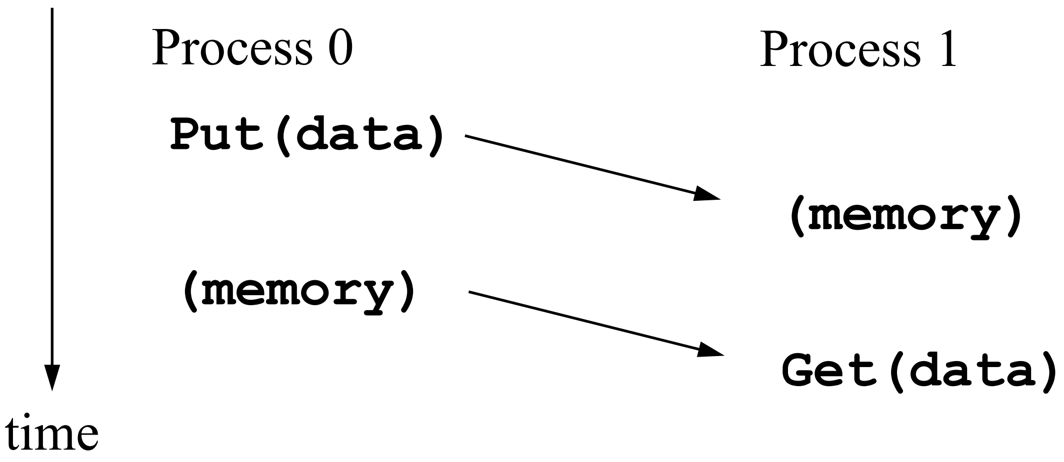

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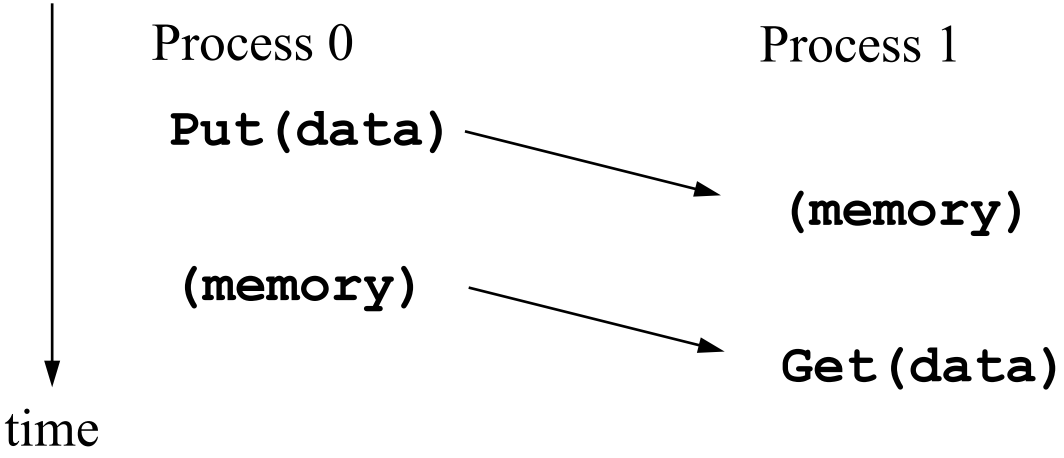

One-Sided Operations

Are 1-sided operations better for performance?

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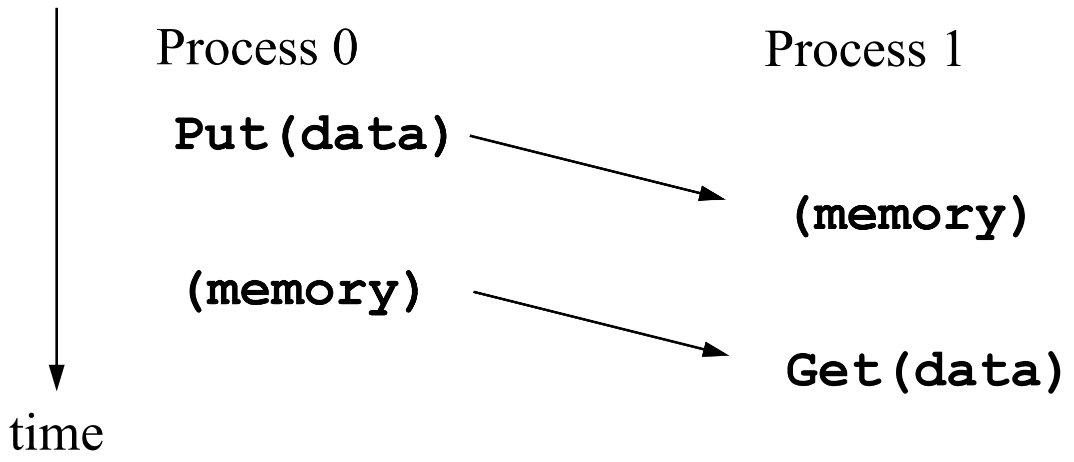

A Simple MPI Program

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

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Running MPI Programs

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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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Two important questions that arise in message passing

- How many processes are being use in computation?
- Which one am I?

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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

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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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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
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  - 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

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Messages are sent with an accompanying user-defined integer *tag*

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  - 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:

MPI_INIT()
MPI_FINALIZE()
MPI_COMM_SIZE()
MPI_COMM_RANK()
MPI_SEND()
MPI_RECV()

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- **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;
    }
}
```

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if(i==rank){
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} 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;
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    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;
    }
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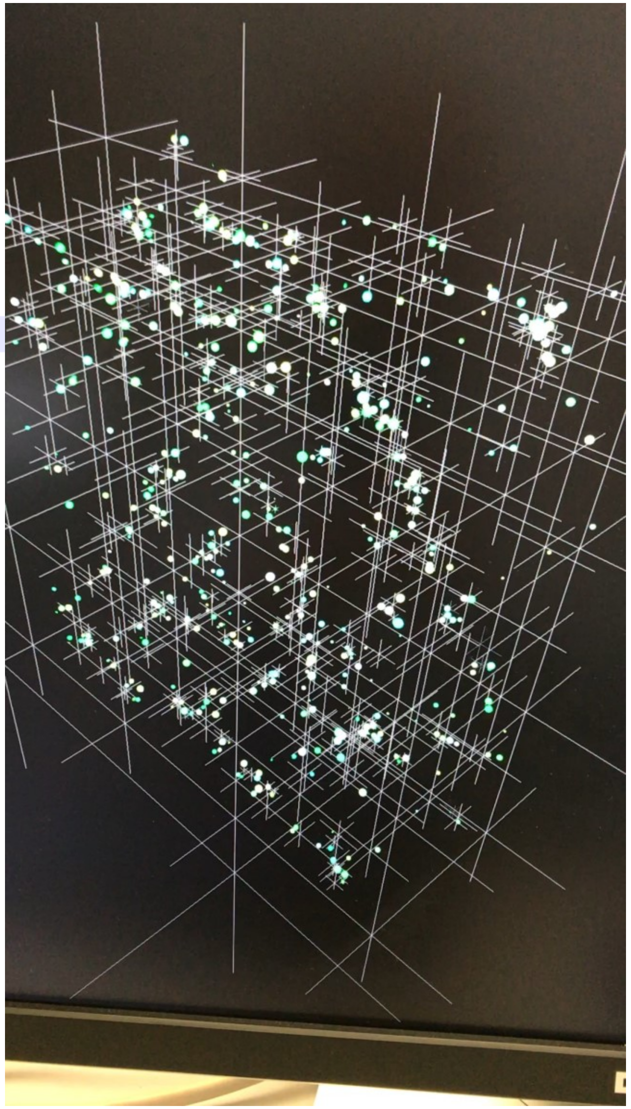
```



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

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- 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