Chapter 5: Thread-Level Parallelism – Part 1

- Introduction
    - What is a parallel or multiprocessor system?
    - Why parallel architecture?
    - Performance potential
    - Flynn classification
- Communication models
- Architectures
- Centralized shared-memory
- Distributed shared-memory
- Parallel programming
- Synchronization
- Memory consistency models

What is a parallel or multiprocessor system?

Multiple processor units working together to solve the same problem

Key architectural issue: Communication model

Why parallel architectures?

Absolute performance

Technology and architecture trends

Dennard scaling, ILP wall, Moore's law

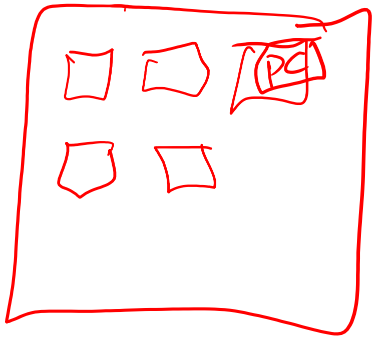
$\Rightarrow$ Multicore chips

Connect multicore together for even more parallelism

$P \propto CV^2$

$\Downarrow$

$V \propto f$



Core

processor

Performance Potential

Amdahl's Law is pessimistic

- Let s be the serial part
- Let p be the part that can be parallelized n ways

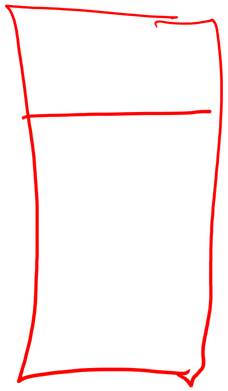
```
Serial:           SSPPPPPP       8
6 processors:     SSP
                    P
                    P
                    P
                    P
                    P
```

Speedup = 8/3 = 2.67

$$T(n) = \frac{1}{s+p/n}$$

As $n \to \infty$, $\boxed{T(n) \to \frac{1}{s}}$

Pessimistic



Performance Potential (Cont.)

Gustafson's Corollary

- Amdahl's law holds if run same problem size on larger machines
- But in practice, we run larger problems and "wait" the same time

Performance Potential (Cont.)

Gustafson's Corollary (Cont.)

- Assume for larger problem sizes
  - Serial time fixed (at s)
  - Parallel time proportional to problem size (truth more complicated)

```
Old Serial:      SSPPPPPP
6 processors:    SSPPPPPP
                   PPPPPP
                   PPPPPP        8
                   PPPPPP
                   PPPPPP
                   PPPPPP
Hypothetical Serial:
   SSPPPPPP PPPPPP PPPPPP PPPPPP PPPPPP PPPPPP
```

- Speedup = (8+5*6)/8 = 4.75
- $T'(n) = s + \boxed{n*p}$; $T'(\infty) \rightarrow \infty$!!!!

How does your algorithm "scale up"?

Flynn classification

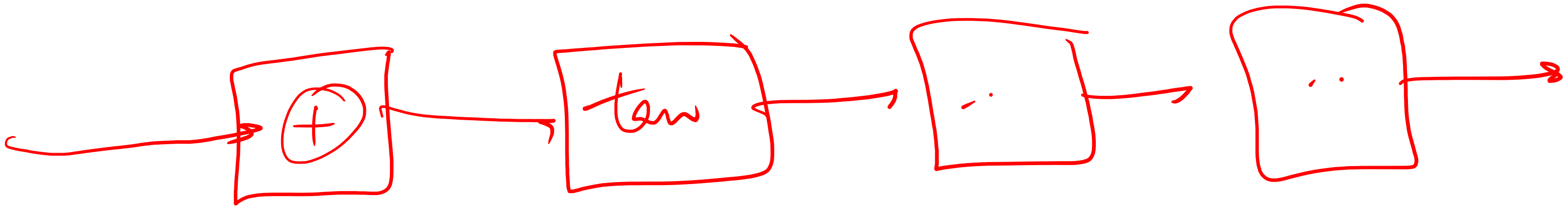
Single-Instruction Single-Data (SISD)

Single-Instruction Multiple-Data (SIMD)

Multiple-Instruction Single-Data (MISD)

Multiple-Instruction Multiple-Data (MIMD)

Systolic



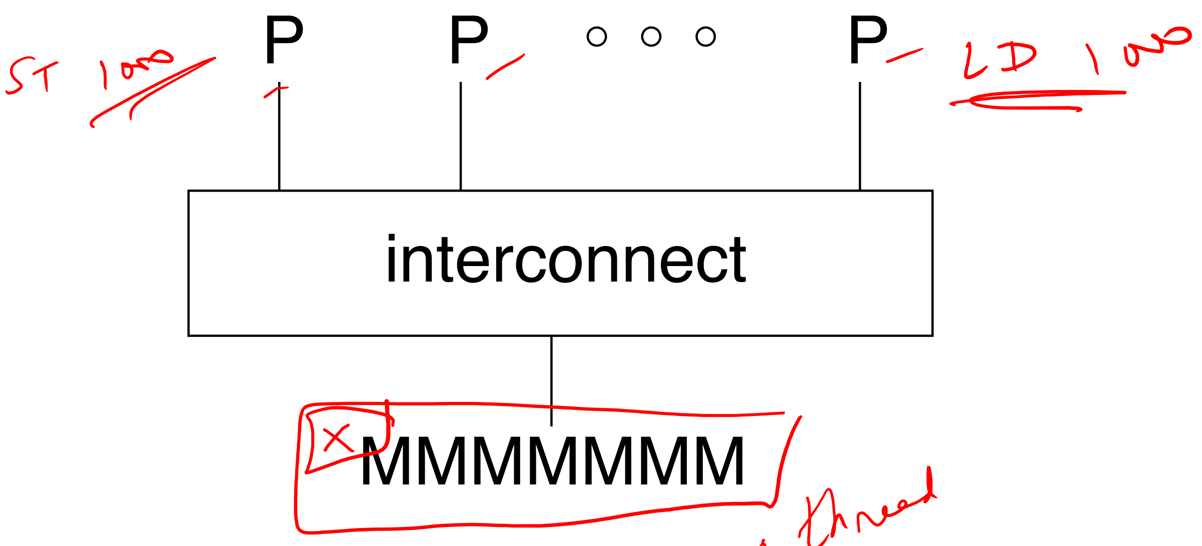
Communication models

Shared-memory

Message passing

Data parallel

Communication Models: Shared-Memory



Each node a processor that runs a process

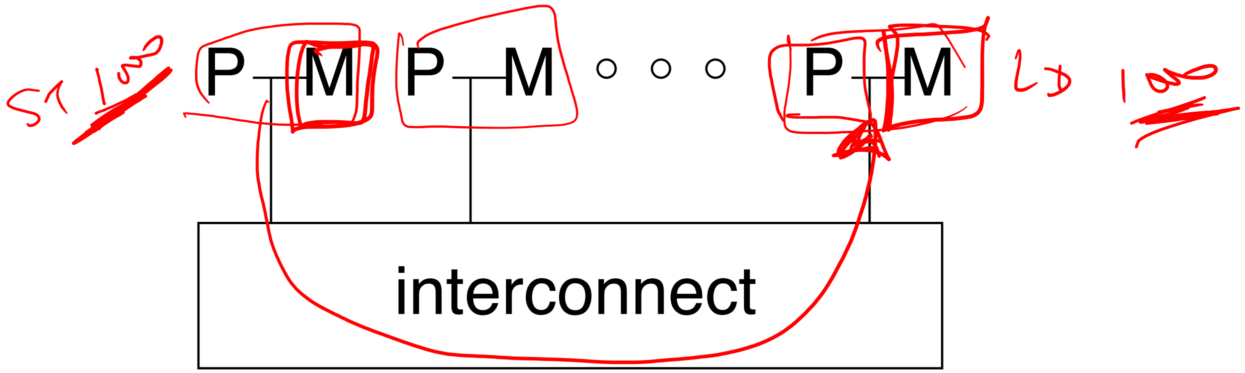
One shared memory

- Accessible by any processor
- The same address on two different processors refers to the same datum

Therefore, write and read memory to

- Store and recall data
- Communicate, Synchronize (coordinate)

Communication Models: Message Passing

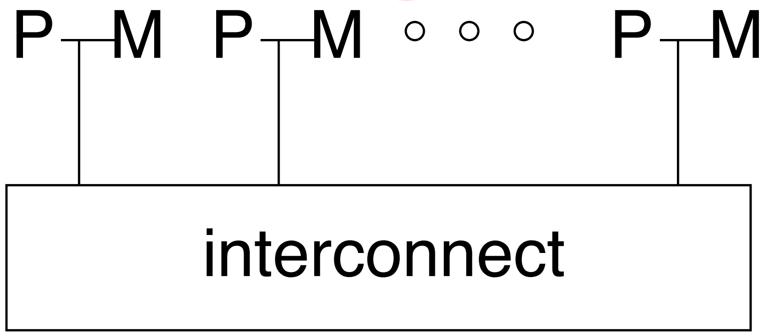


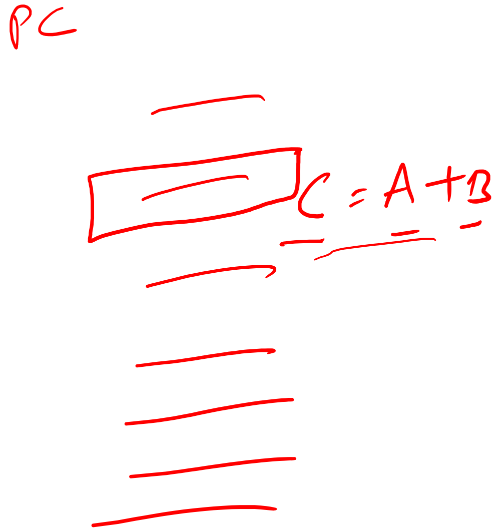
Each node a computer

- Processor – runs its own program (like SM)
- Memory – local to that node, unrelated to other memory

Add messages for internode communication, send and receive like mail

Communication Models: Data Parallel





Virtual processor per datum

Write sequential programs with "conceptual PC" and let parallelism be within the data (e.g., matrices)

C = A + B

Typically SIMD architecture, but MIMD can be as effective

Architectures

All mechanisms can usually be synthesized by all hardware

Key: which communication model does hardware support best?

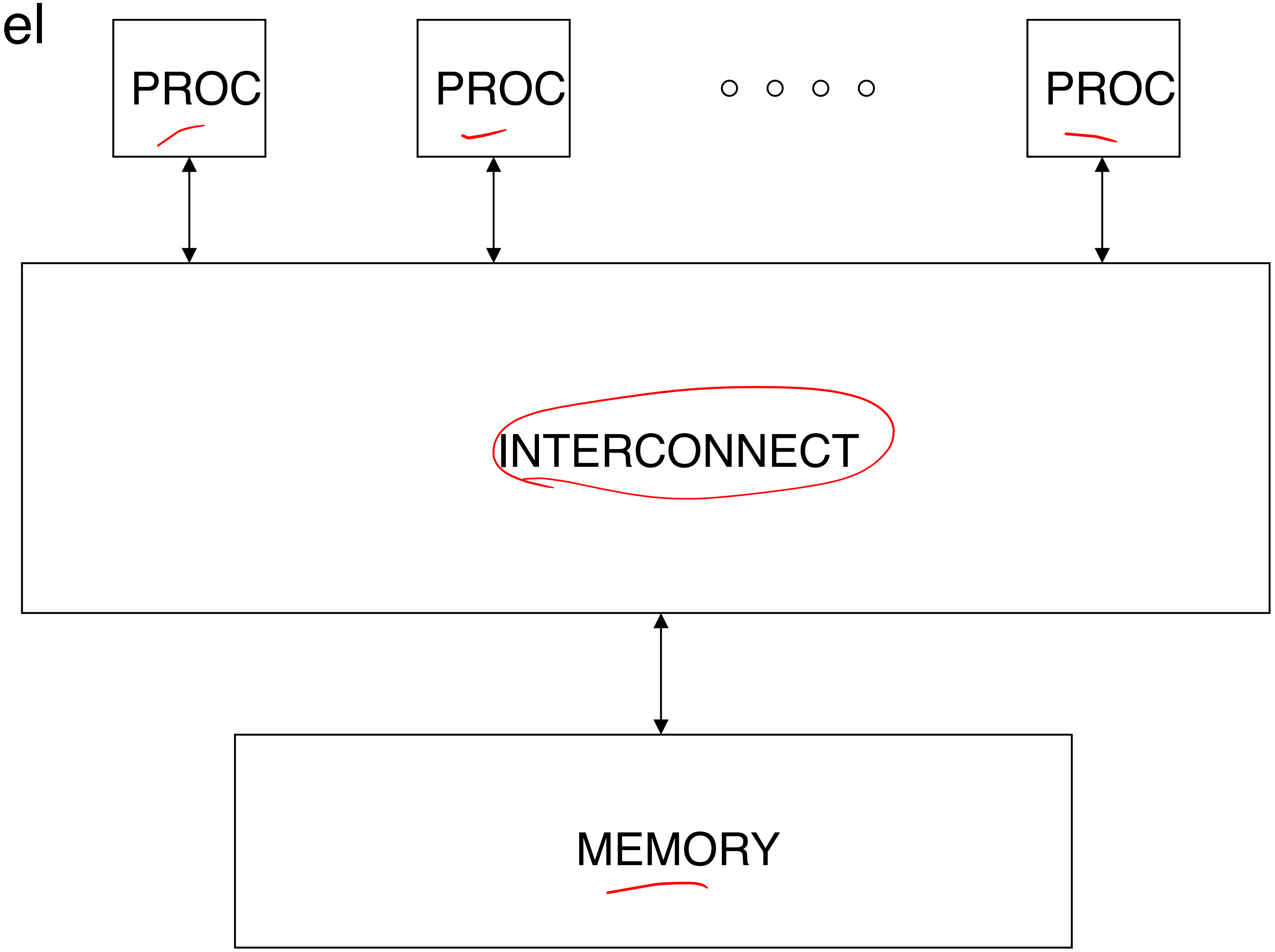
Virtually all small-scale systems, multicores are shared-memory

Which is Best Communication Model to Support?

- Shared-memory
  - Used in small-scale systems
  - Easier to program for dynamic data structures
  - Lower overhead communication for small data
  - Implicit movement of data with caching
  - Hard to build?
- Message-passing
  - Communication explicit harder to program?
  - Larger overheads in communication OS intervention?
  - Easier to build?

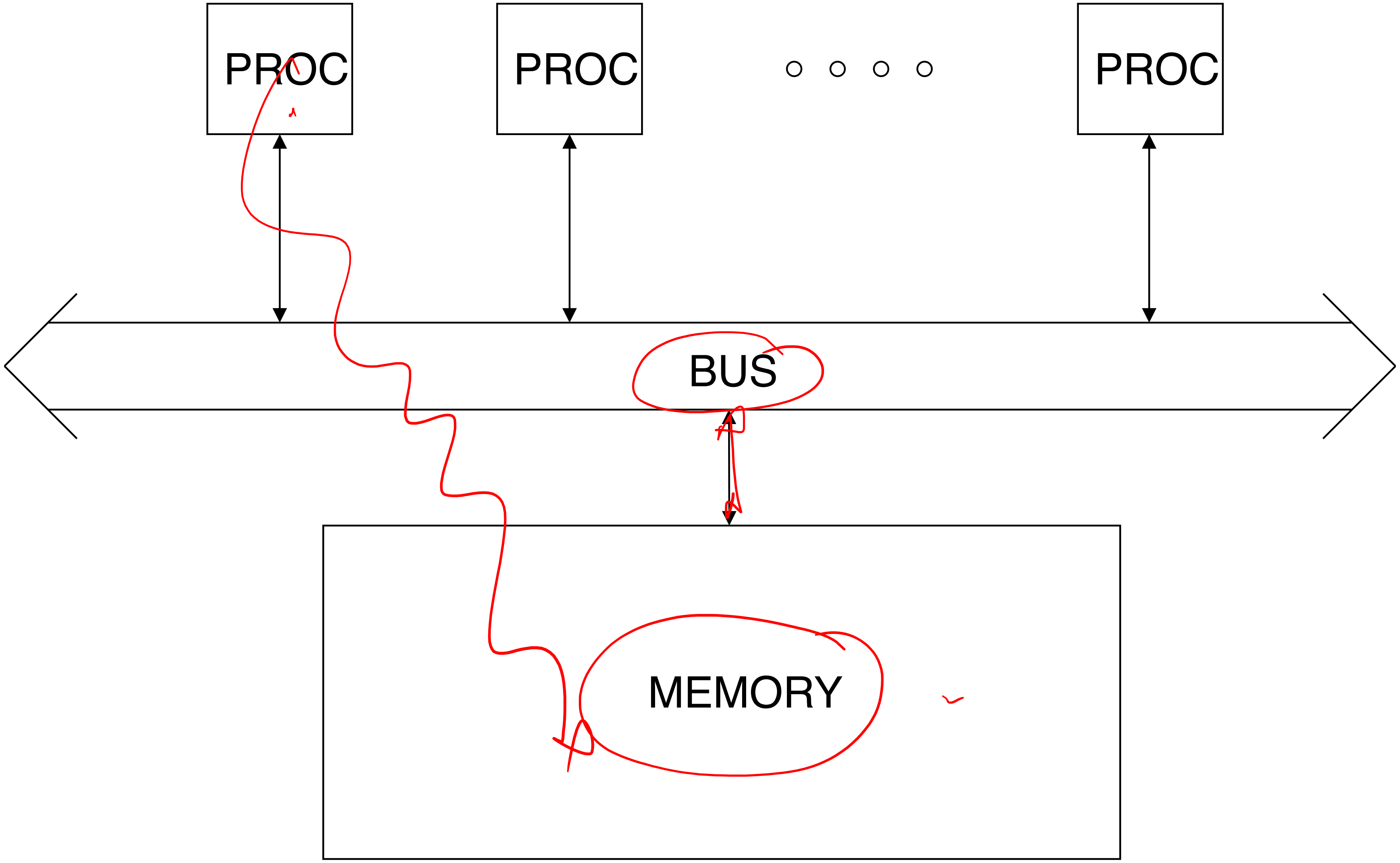
Shared-Memory Architecture

The model



For now, assume interconnect is a bus – *centralized architecture*

Centralized Shared-Memory Architecture



Centralized Shared-Memory Architecture (Cont.)

For higher bandwidth (throughput)

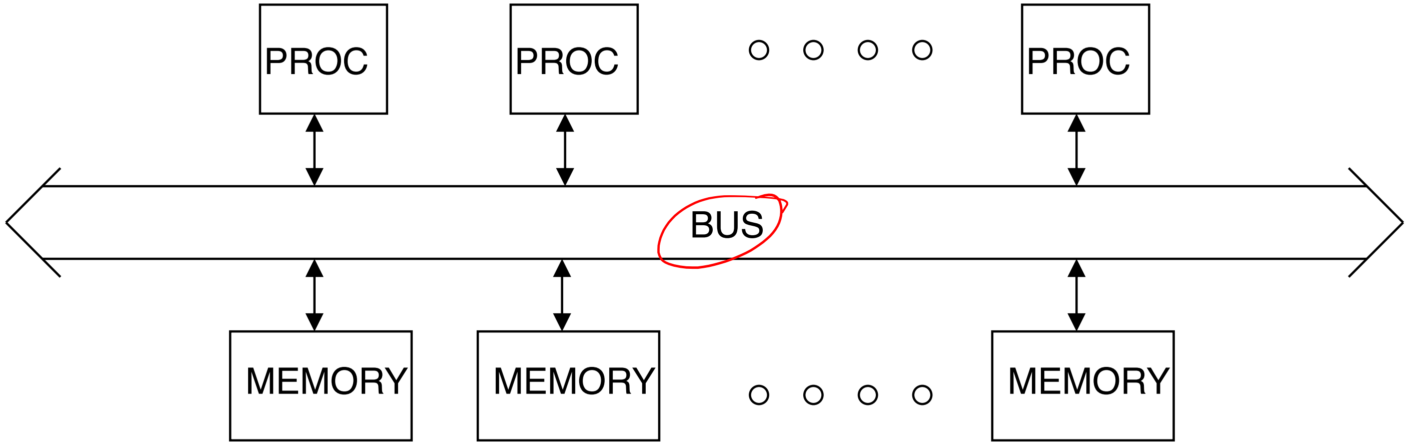
For lower latency

Problem?

▷

Centralized Shared-Memory Architecture (Cont.)**

For higher bandwidth (throughput)

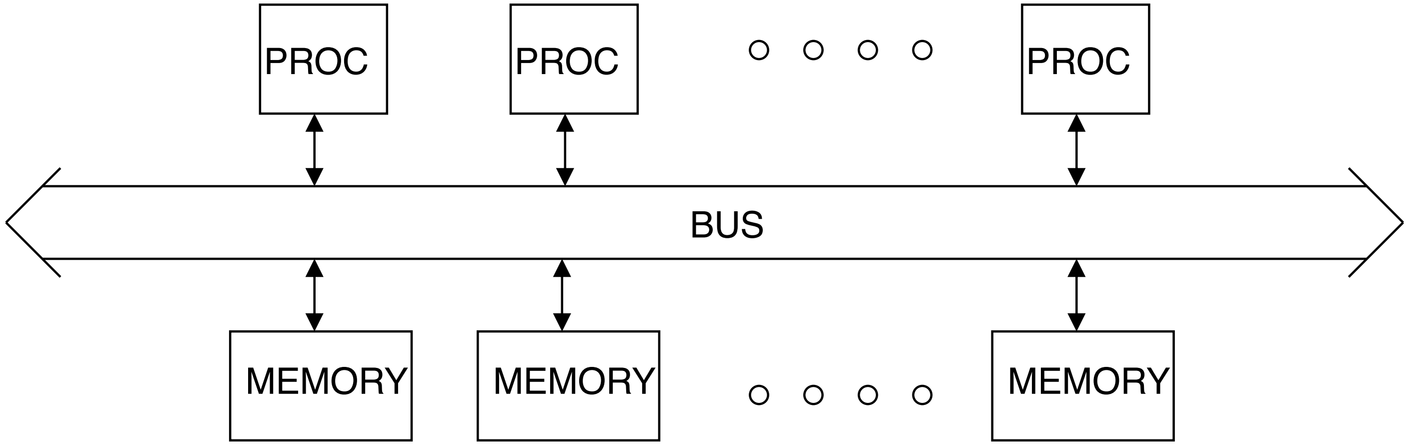


For lower latency

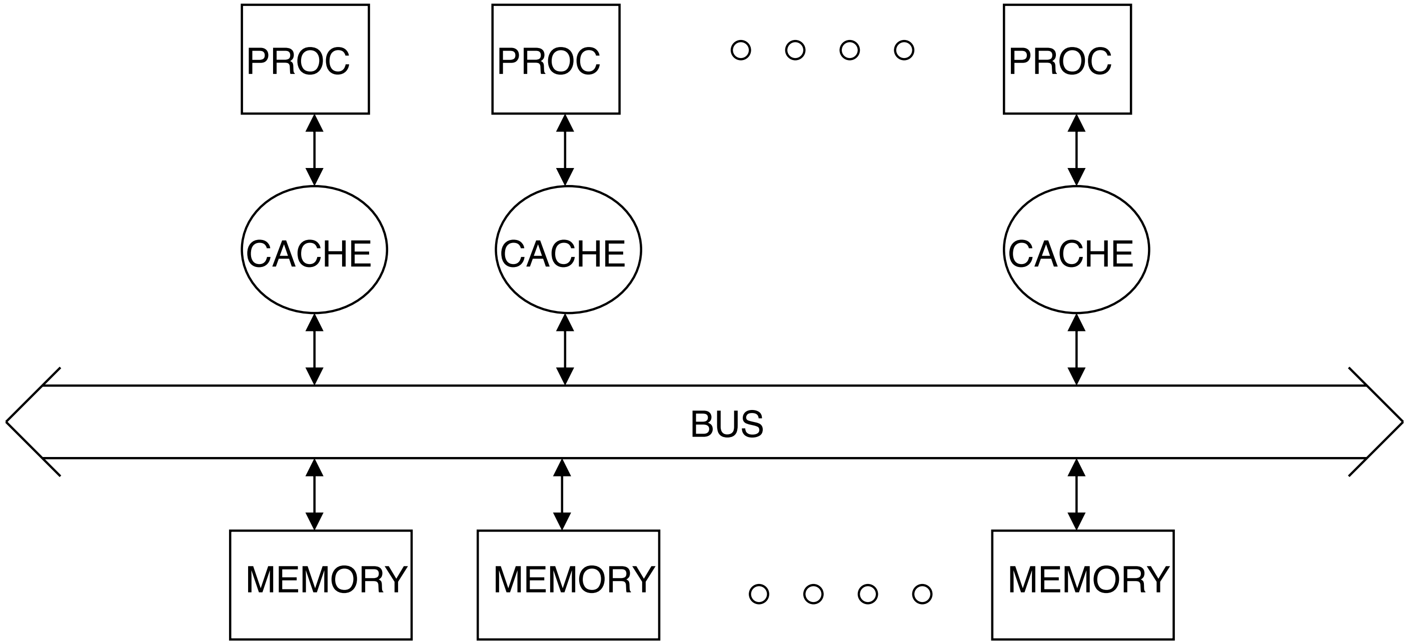
Problem?

Centralized Shared-Memory Architecture (Cont.)**

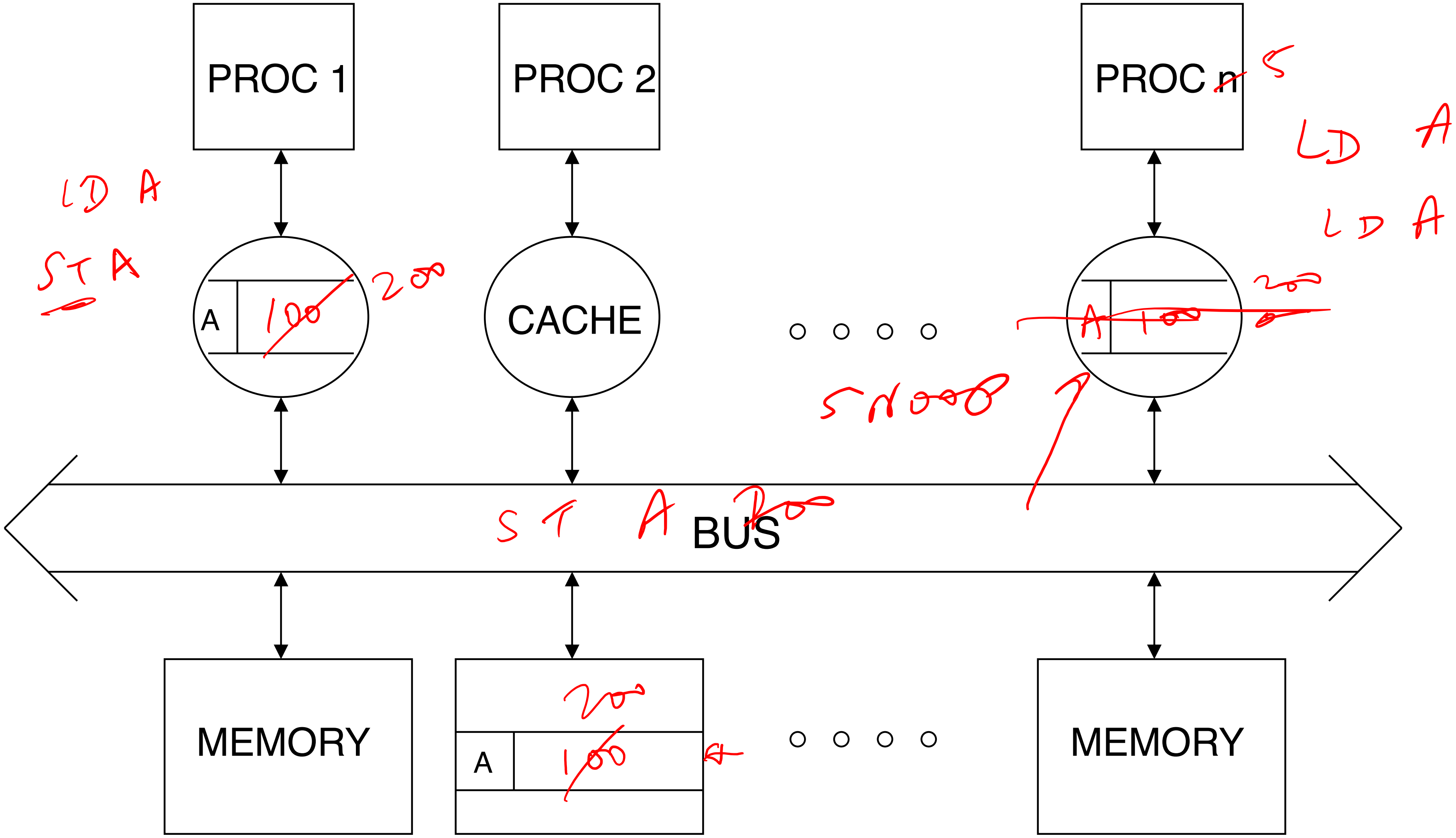
For higher bandwidth (throughput)



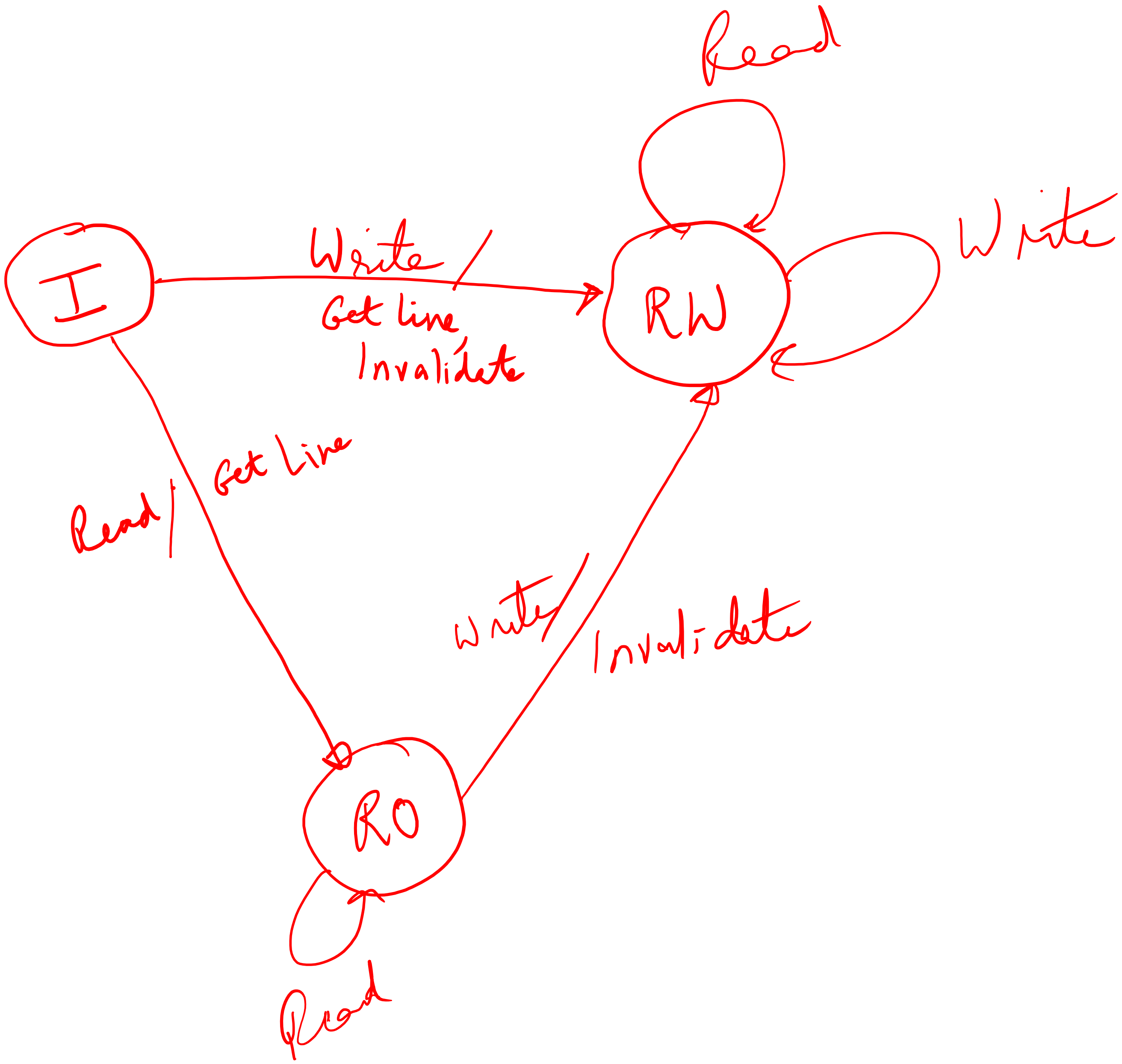
For lower latency



Cache Coherence Problem



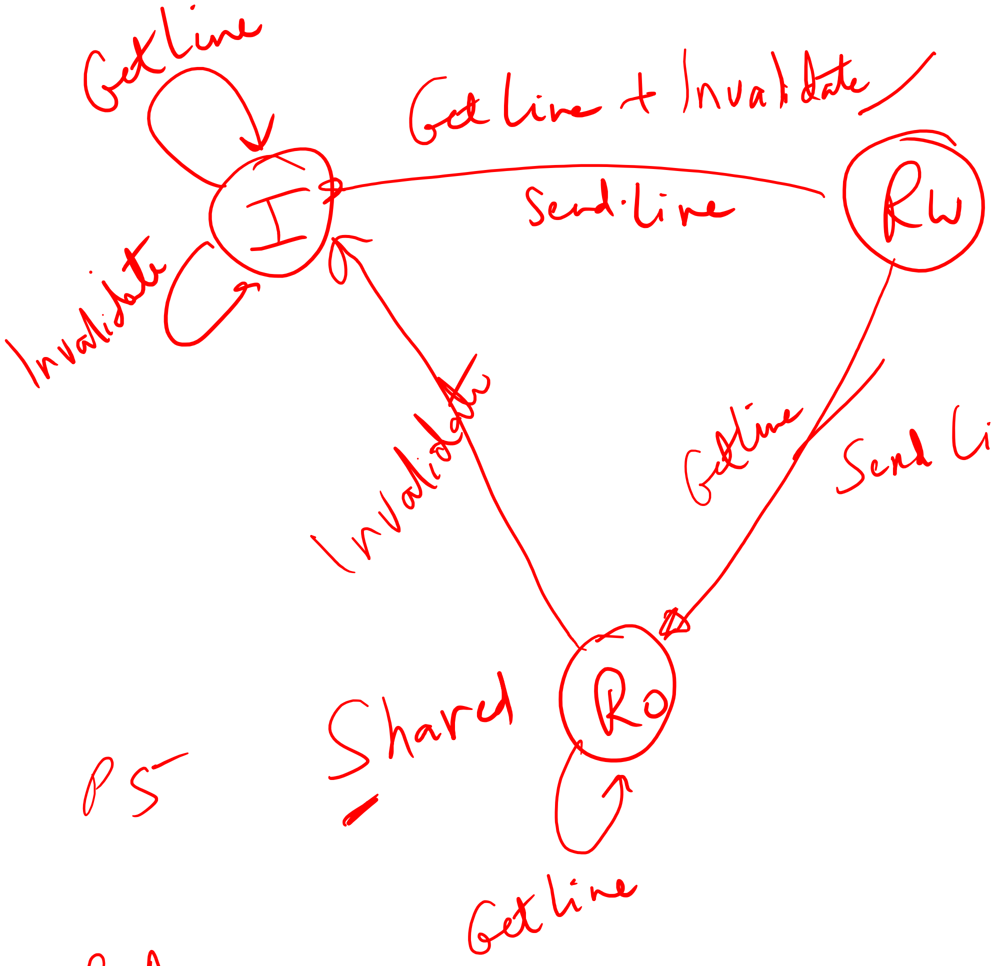
My Own Requests



Snoop Requests

MESI

MOESI



MSI

P1

A:=1

A:=2

P5

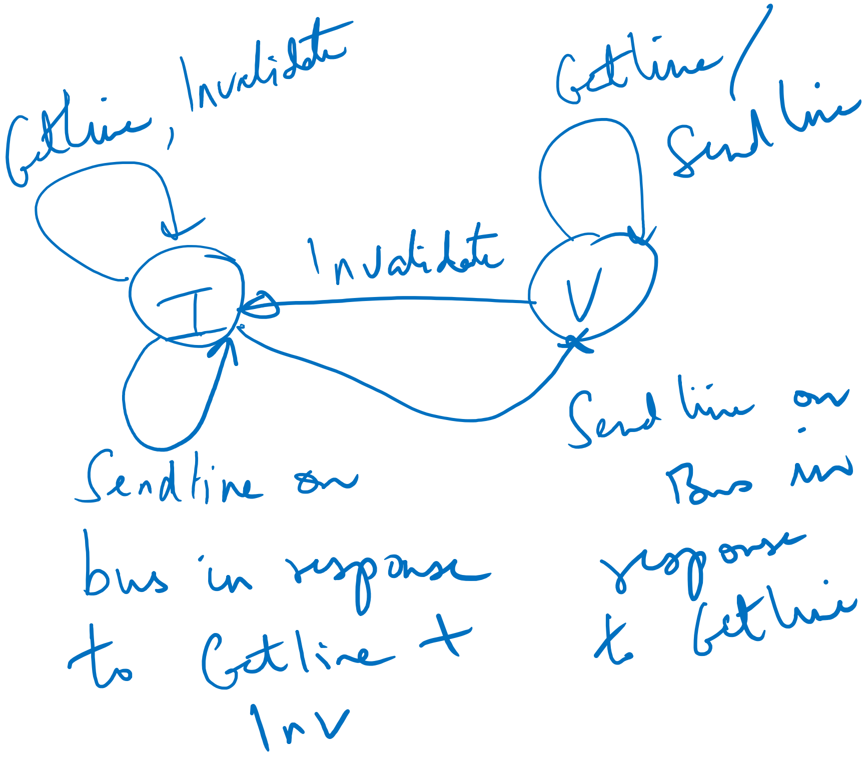
R, A

R, A

R, A

R, A

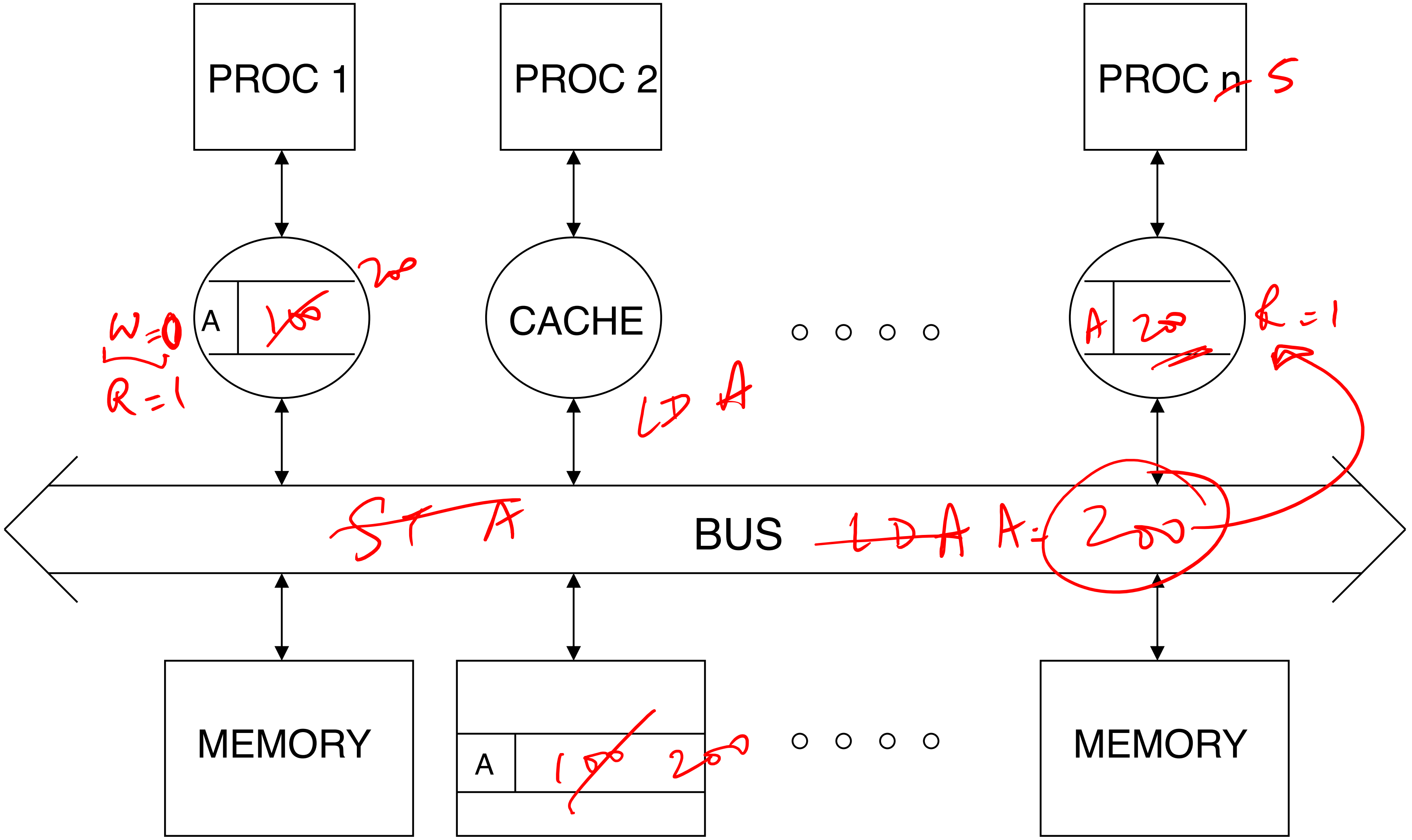
A:=2



Getline, Invalidate
Getline /
Send line
Invalidate
I
V
Send line on bus in response to Getline + Inv
Send line on Bus in response to Getline

Cache Coherence Solutions

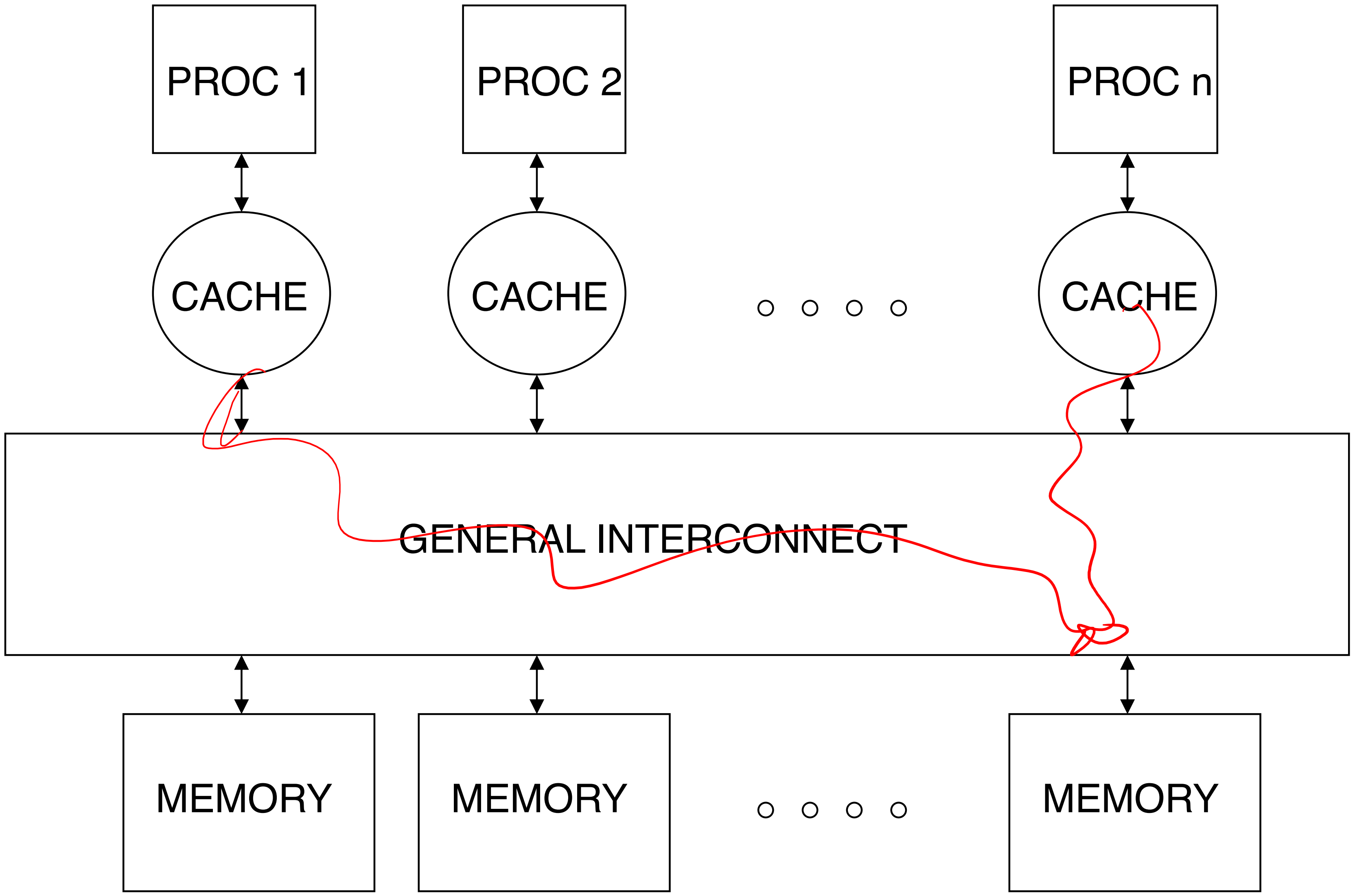
Snooping



Problem with centralized architecture

Distributed Shared-Memory (DSM) Architecture

Use a higher bandwidth interconnection network



Uniform memory access architecture (UMA)

Distributed Shared-Memory (DSM) - Cont.

For lower latency: Non-Uniform Memory Access architecture (NUMA)

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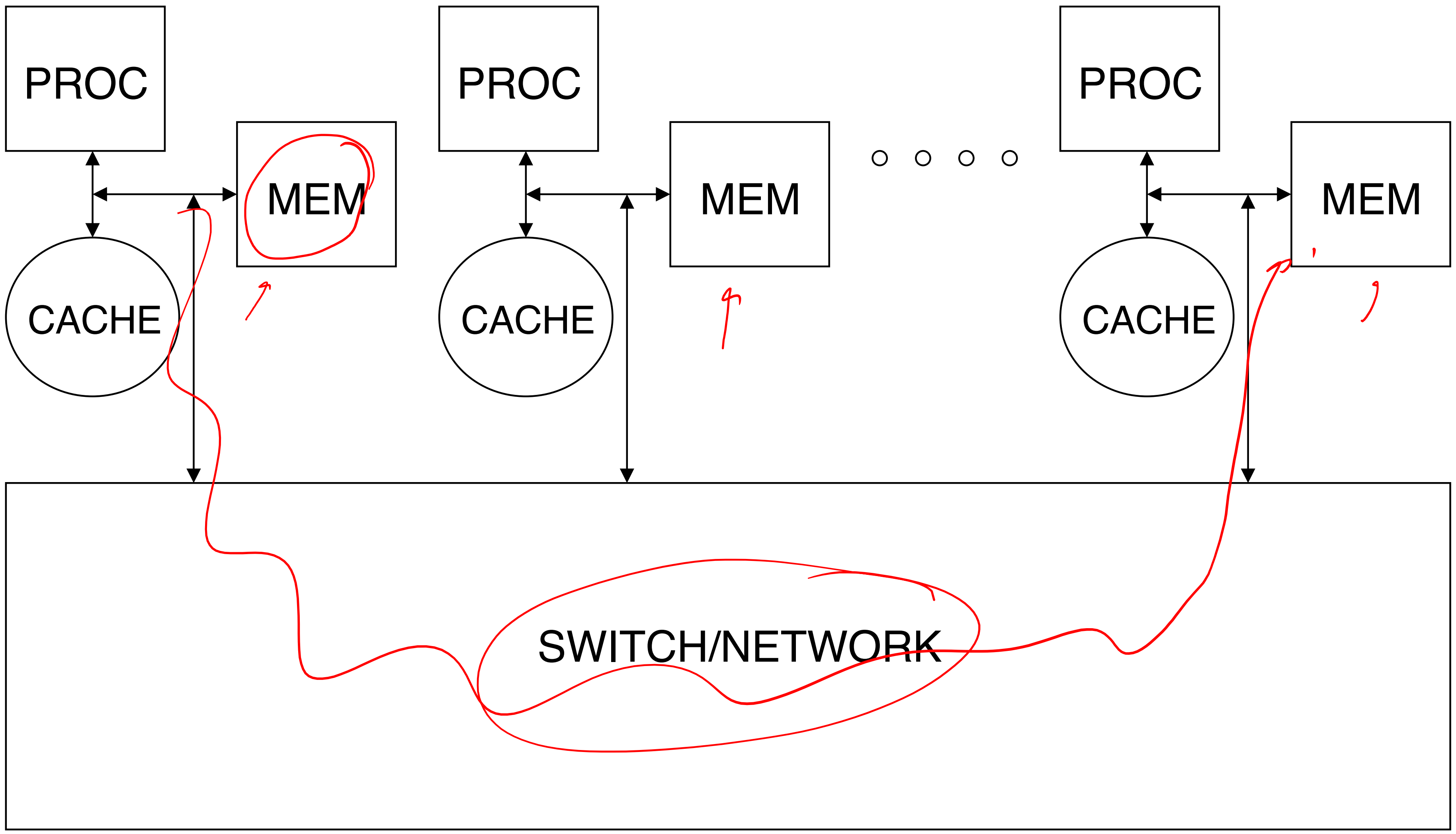
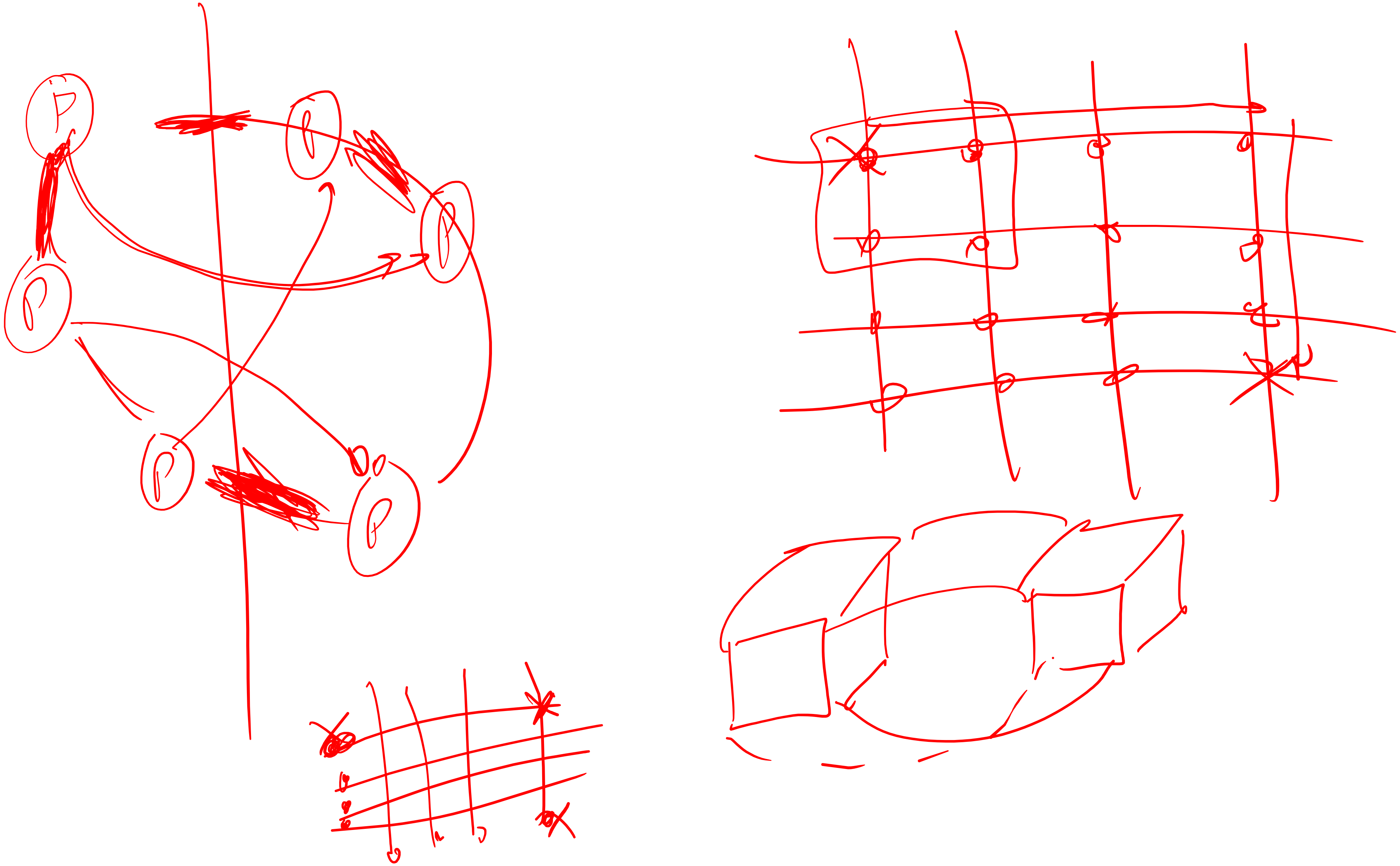
Distributed Shared-Memory (DSM) -- Cont.**

For lower latency: Non-Uniform Memory Access architecture (NUMA)



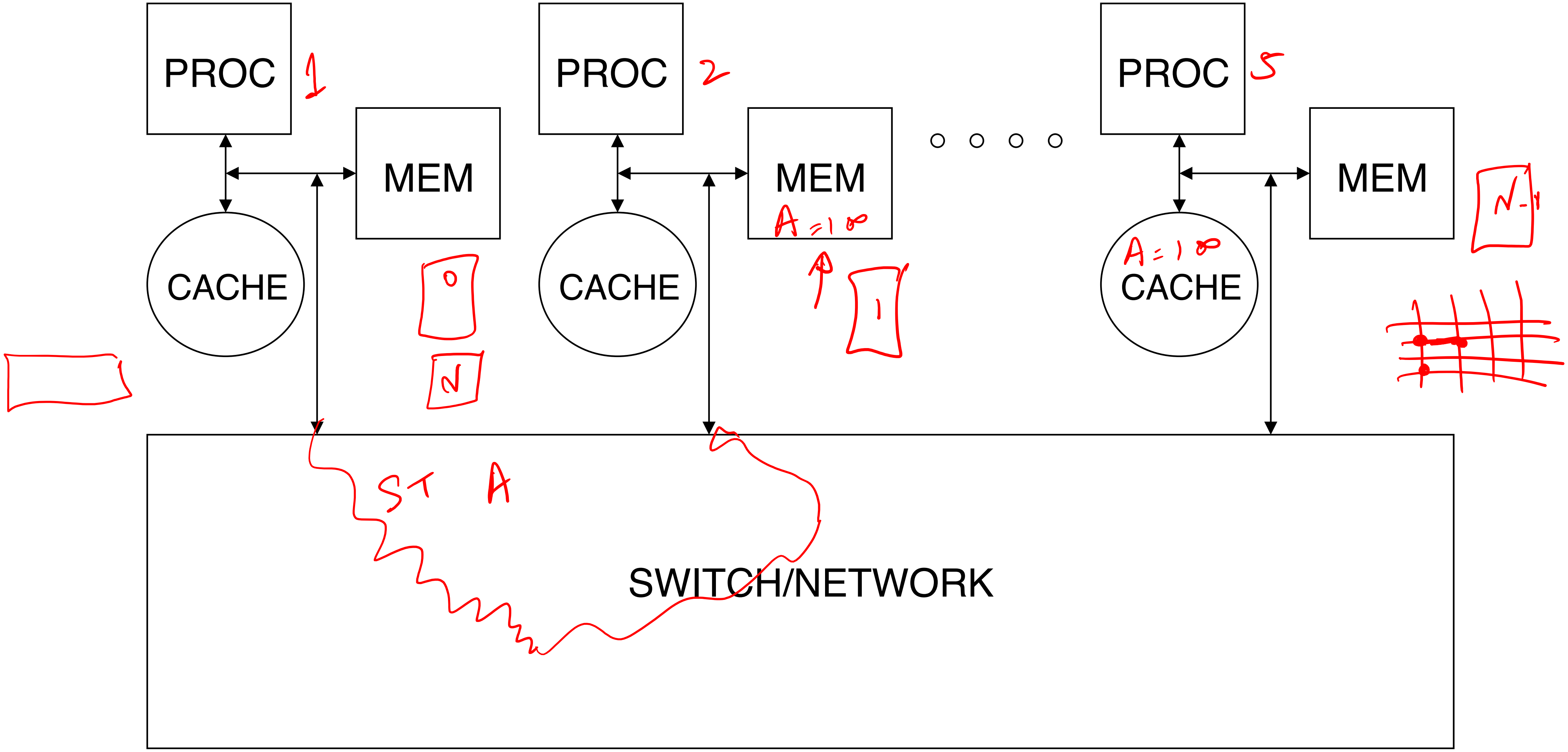
Non-Bus Interconnection Networks

Example interconnection networks



Distributed Shared-Memory - Coherence Problem

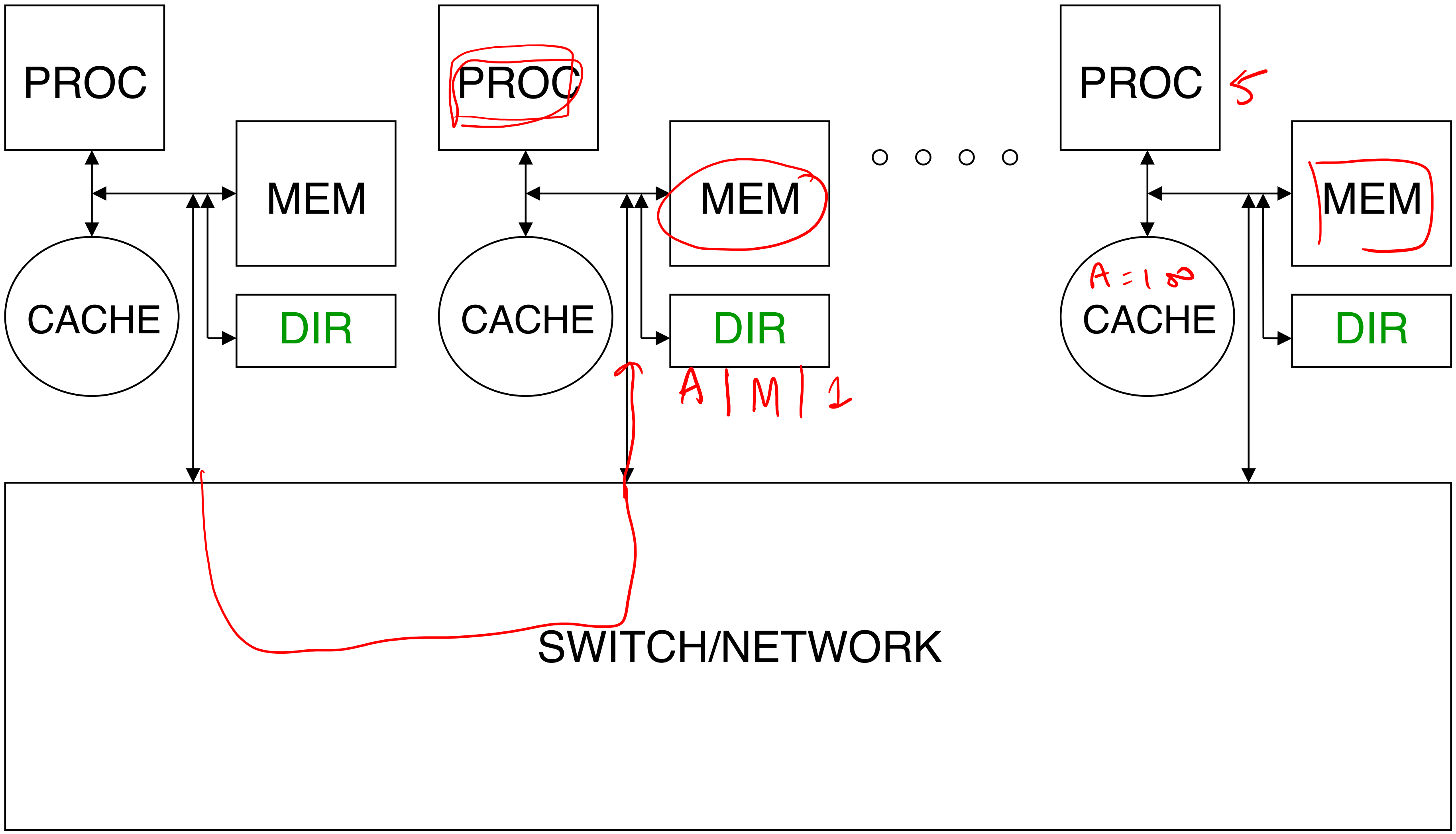
Directory scheme



Level of indirection!

Distributed Shared-Memory - Coherence Problem**

Directory scheme



Level of indirection!

Parallel Programming Example

Add two matrices: C = A + B

Sequential Program

```
main(argc, argv)
int argc; char *argv;
{
   Read(A);
   Read(B);
   for (i = 0; i ! N; i++)
       for (j = 0; j ! N; j++)
              C[i,j] = A[i,j] + B[i,j];
   Print(C);
}
```

Parallel Program Example (Cont.)

Parallel Program Example (Cont.)**

```
main(argc, argv)
int argc; char *argv;
{
  Read(A);
  Read(B);
  for (p = 1; p = number-of-processors; p++)
     create-thread(p, start-procedure);
  start-procedure();
  wait-for-all-threads-to-be-done();
  Print(C);
}

start-procedure()
{
  for (i = my-rows-begin; i != my-rows-end; i++)
     for (j = 0, j ! N, j++)
          C[i,j] = A[i,j] + B[i,j]
  indicate-done();
}
```

The Parallel Programming Process

*The Parallel Programming Process***

Break up computation into tasks ←

Break up data into chunks

- Necessary for message passing machines

Introduce synchronization for correctness ←

Synchronization

- Communication – Exchange data
- Synchronization – Exchange data to order events
    - Mutual exclusion or atomicity
    - Event ordering or Producer/consumer
        - Point to Point
            - Flags
        - Global
            - Barriers

Mutual Exclusion

Example

Each processor needs to occasionally update a counter

L=0

Processor 1

```
while (L!=0) {;}
L=1
Load reg1, Counter
reg1 = reg1 + tmp1
Store Counter, reg1
L=0
```

Processor 2

```
while (L!=0) {;}
L=1
Load reg2, Counter
reg2 = reg2 + tmp2
Store Counter, reg2
L=0
```

Mutual Exclusion Primitives

Hardware instructions

- Test&Set L
    - Atomically tests for 0 and sets to 1
- Unset is simply a store of 0

```
while (Test&Set(L) != 0) {;}
Critical Section
Unset(L)  →  L=0
```

Problem?

*Mutual Exclusion Primitives***

Hardware instructions

- Test&Set
  - Atomically tests for 0 and sets to 1
- Unset is simply a store of 0

```
while (Test&Set(L) != 0)  {;}
Critical Section
Unset(L)
```

Problem - Traffic

Mutual Exclusion Primitives – Alternative?

Test&Test&Set

*Mutual Exclusion Primitives – Alternative?***

Test&Test&Set

```
A:      while (L != 0)  {;}
        if (Test&Set(L) == 0)  {
                critical Section
        }
        else go to loop A
```

Problem?

Mutual Exclusion Primitives – Alternative?**

Test&Test&Set

```
A:      while (L != 0)  {;}
        if (Test&Set(L) == 0)  {
                critical Section
        }
        else go to loop A
```

Problem

- Traffic on lock release
- What if processor swapped out while holding lock?

Mutual Exclusion Primitives – Fetch&Add

```
Fetch&Add(var, data)
    { /* atomic action */
    temp = var
    var = temp + data
    }
    return temp
```

E.g., let X = 57

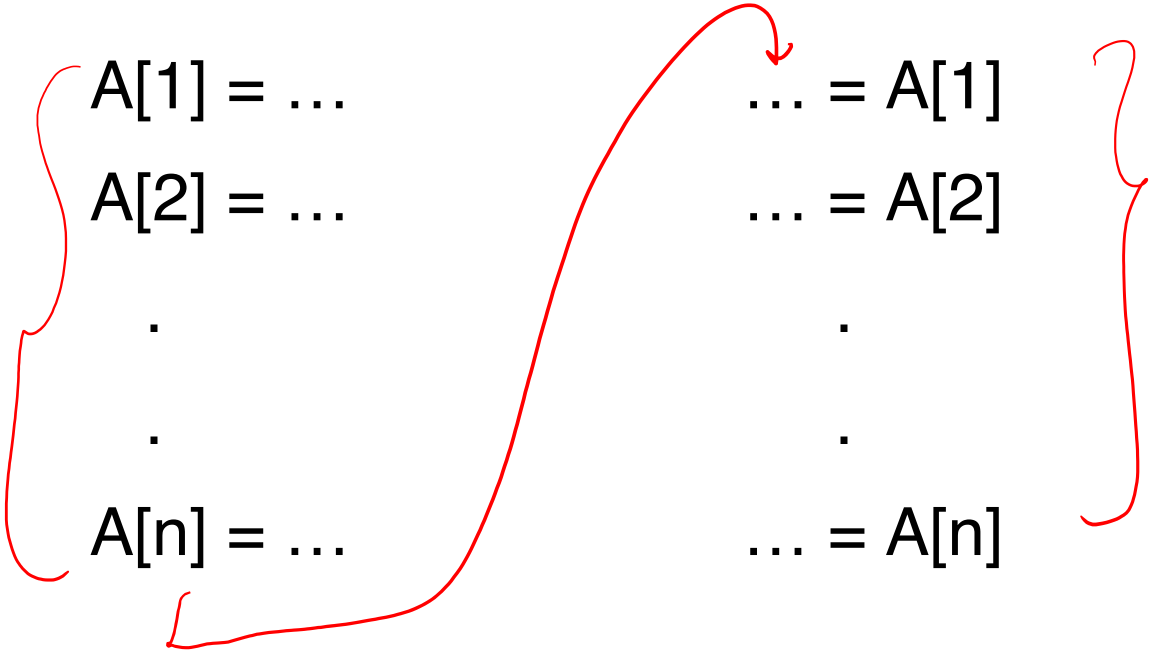
- P1: a = Fetch&Add(X,3)
- P2: b = Fetch&Add(X,5)
  - If P1 before P2, ?
  - If P2 before P1, ?
  - If P1, P2 concurrent ?

x	a	b
~~57~~ 60	57	
$\boxed{65}$		60
62		57
$\boxed{65}$	62	

Point to Point Event Ordering

Example

Producer wants to indicate to consumer that data is ready



Processor 1	Processor 2
A[1] = …	… = A[1]
A[2] = …	… = A[2]
.	.
.	.
A[n] = …	… = A[n]

*Point to Point Event Ordering – Flags***

Example

Producer wants to indicate to consumer that data is ready

```
Processor 1                   Processor 2
                              while (Flag != 1) {;}
A[1] = …                      … = A[1]
A[2] = …                      … = A[2]
   .                              .
   .                              .
A[n] = …                      … = A[n]

Flag = 1
```

Global Event Ordering – Barriers

Example

- All processors produce some data
- Want to tell all processors that it is ready
- In next phase, all processors consume data produced previously

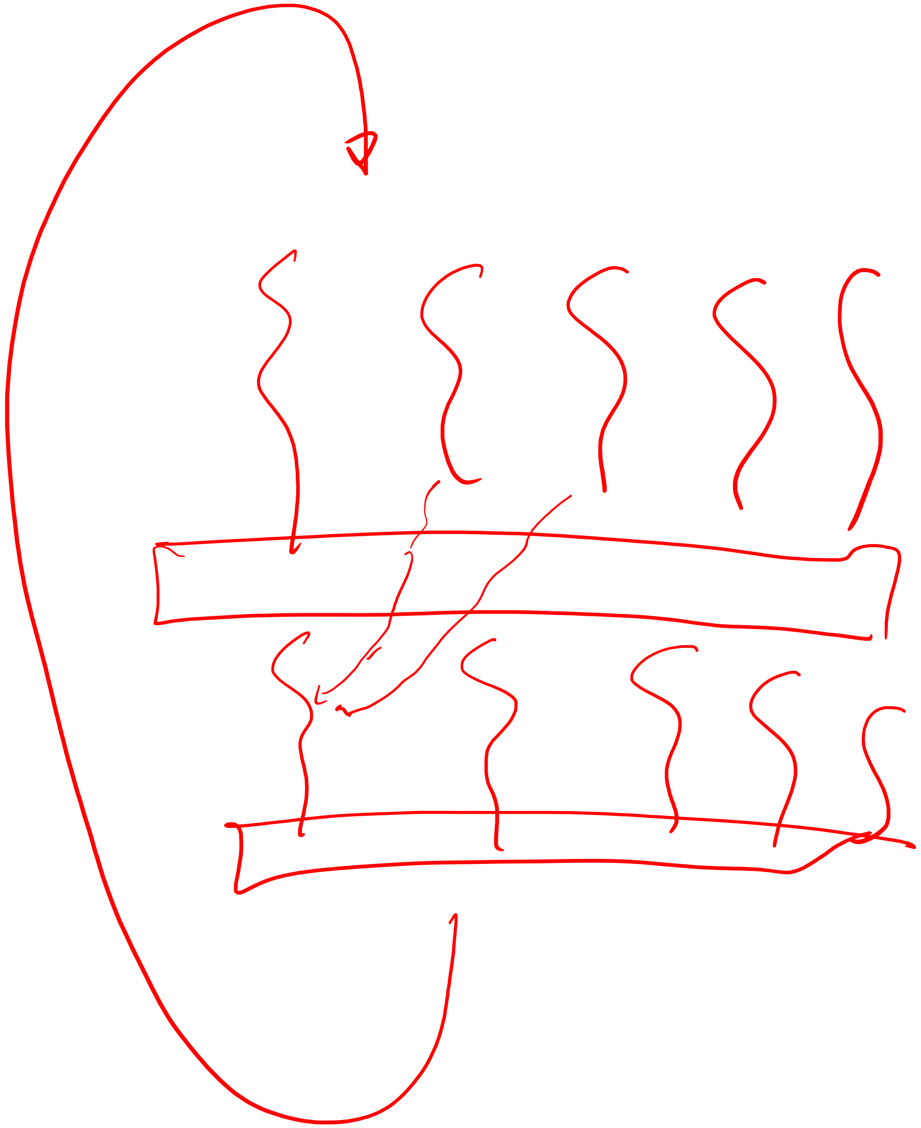
Use barriers

*Implementing Barriers***

Simple barrier

```
temp = Fetch&Inc(count)
while (count != N) {;}
```

Problem:



Implementing Barriers**

Simple barrier

```
temp = Fetch&Inc(count)
while (count != N) {;}
```

Problem: Cannot use it again

*Implementing Barriers***

```
local_flag = !local_flag                 ← 1  0
if Fetch&Inc(count) == N {  ←
      count = 1
      flag = local_flag     ←  1  0
}
                         1  0
while (flag != local_flag) {;}  ←
```