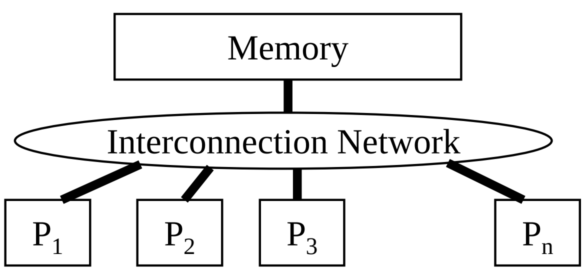
6.189 IAP 2007

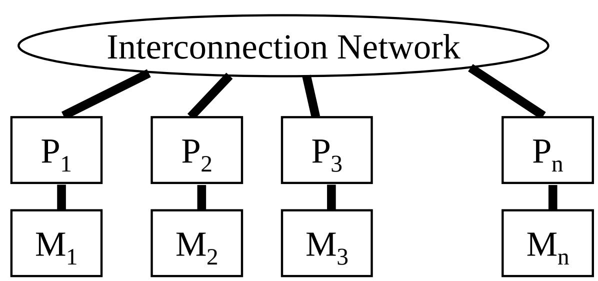
Lecture 5

Parallel Programming Concepts

Recap

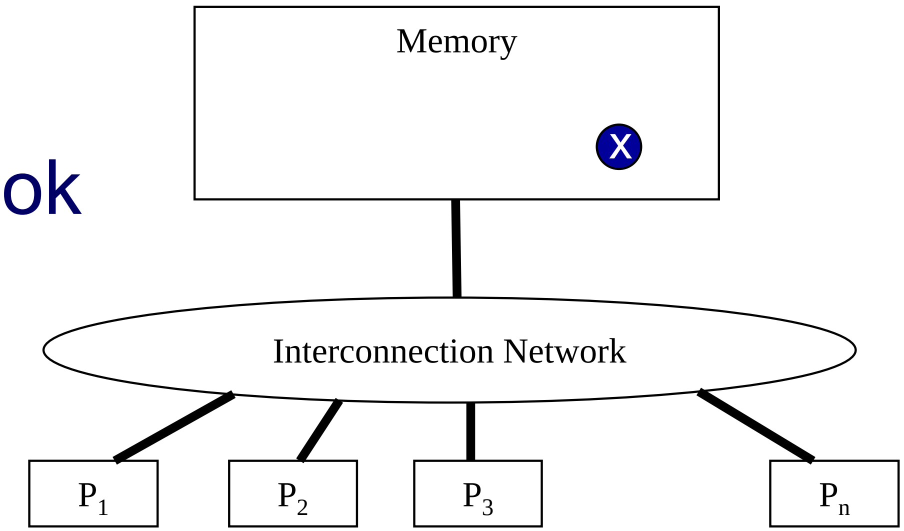
- Two primary patterns of multicore architecture design
  - Shared memory
    - Ex: Intel Core 2 Duo/Quad
    - One copy of data shared among many cores
    - Atomicity, locking and synchronization essential for correctness
    - Many scalability issues
  - Distributed memory
    - Ex: Cell
    - Cores primarily access local memory
    - Explicit data exchange between cores
    - Data distribution and communication orchestration is essential for performance





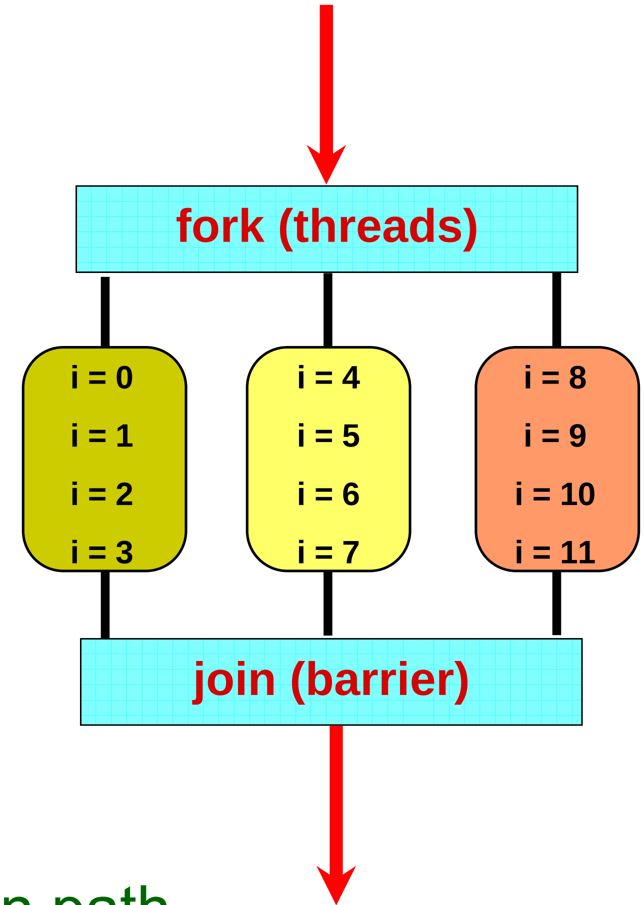
Programming Shared Memory Processors

- Processor 1…n ask for X
- There is only one place to look
- Communication through shared variables
- Race conditions possible
  - Use synchronization to protect from conflicts
  - Change how data is stored to minimize synchronization



Example Parallelization

```
for (i = 0; i < 12; i++)
      C[i] = A[i] + B[i];
```



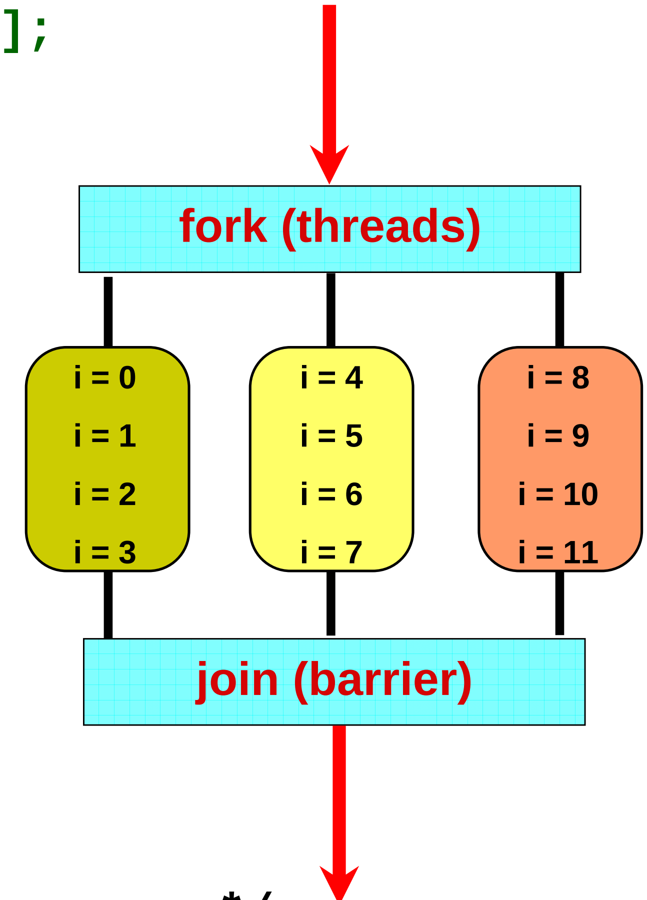
- Data parallel
  - Perform same computation but operate on different data
- A single process can fork multiple concurrent threads
  - Each thread encapsulate its own execution path
  - Each thread has local state and shared resources
  - Threads communicate through shared resources such as global memory

Example Parallelization With Threads

```
int A[12] = {...}; int B[12] = {...}; int C[12];

void add_arrays(int start)
{
   int i;
   for (i = start; i < start + 4; i++)
     C[i] = A[i] + B[i];
}

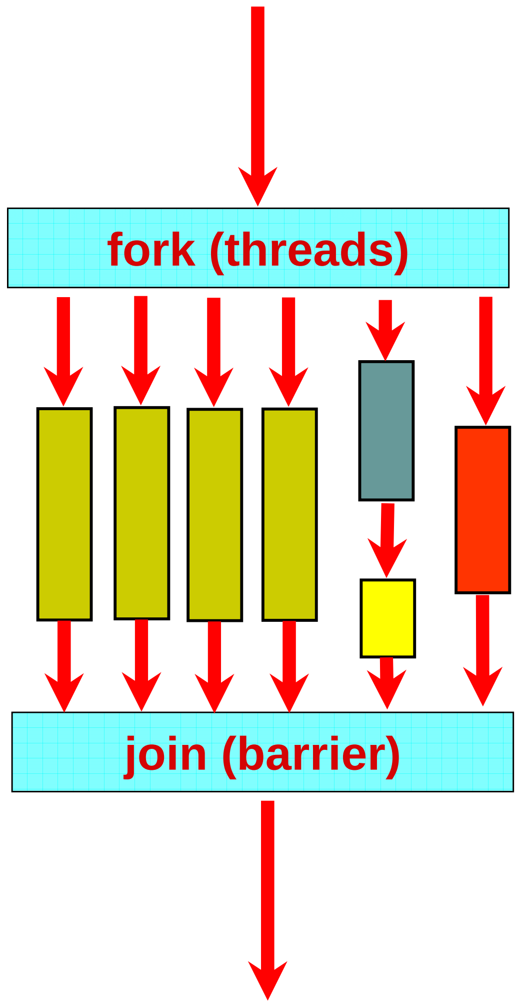
int main (int argc, char *argv[])
{
   pthread_t threads_ids[3];
   int rc, t;
   for(t = 0; t < 4; t++) {
     rc = pthread_create(&thread_ids[t],
                              NULL       /* attributes       */,
                              add_arrays /* function         */,
                              t * 4      /* args to function */);
   }
   pthread_exit(NULL);
}
```



Types of Parallelism

- Data parallelism
  - Perform same computation but operate on different data
- Control parallelism
  - Perform different functions

```
pthread_create(/* thread id         */,
               /* attributes        */,
               /* any function      */,
               /* args to function */);
```

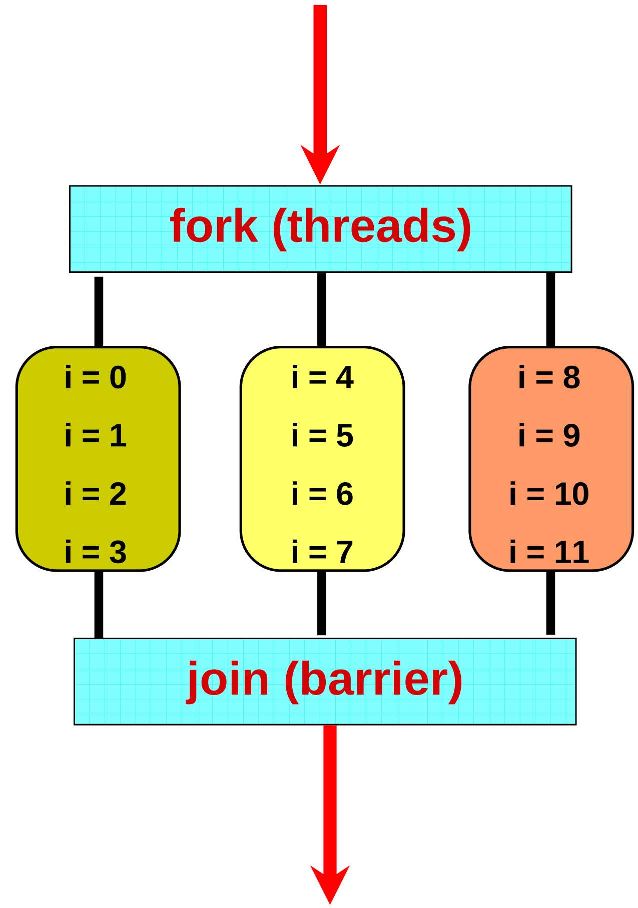


Parallel Programming with OpenMP

- Start with a parallelizable algorithm
  - SPMD model (same program, multiple data)
- Annotate the code with parallelization and synchronization directives (pragmas)
  - Assumes programmers knows what they are doing
  - Code regions marked parallel are considered independent
  - Programmer is responsibility for protection against races
- Test and Debug

Simple OpenMP Example

```
#pragma omp parallel
#pragma omp for
   for(i = 0; i < 12; i++)
      C[i] = A[i] + B[i];
```



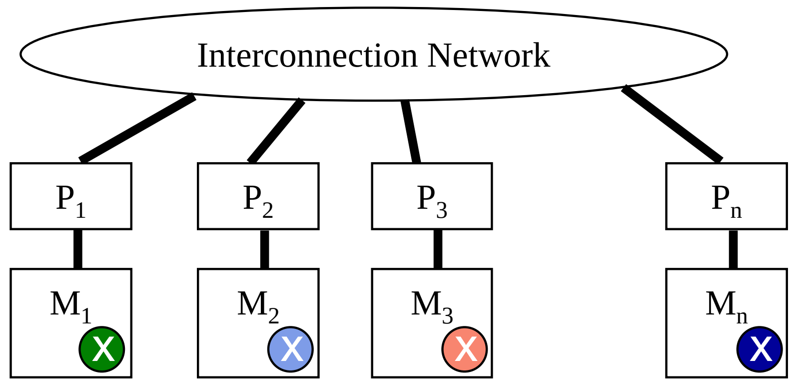
- (data) parallel pragma

  execute as many as there are processors (threads)

- for pragma

  loop is parallel, can divide work (work-sharing)

Programming Distributed Memory Processors

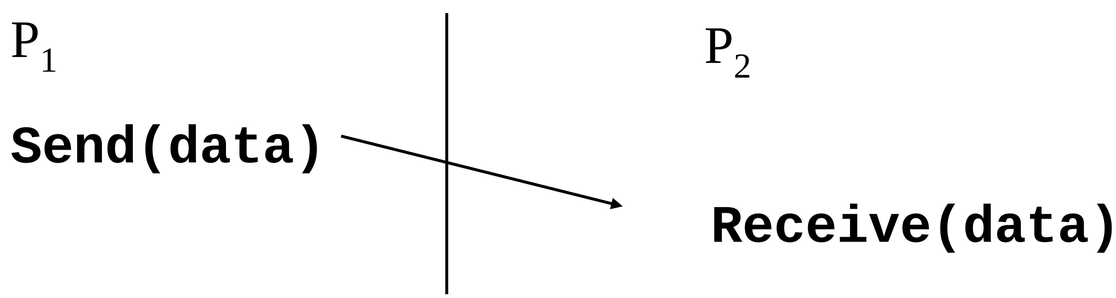


- Processors 1…n ask for X
- There are n places to look
  - Each processor's memory has its own X
  - Xs may vary

- For Processor 1 to look at Processors 2's X
  - Processor 1 has to request X from Processor 2
  - Processor 2 sends a copy of its own X to Processor 1
  - Processor 1 receives the copy
  - Processor 1 stores the copy in its own memory

Message Passing

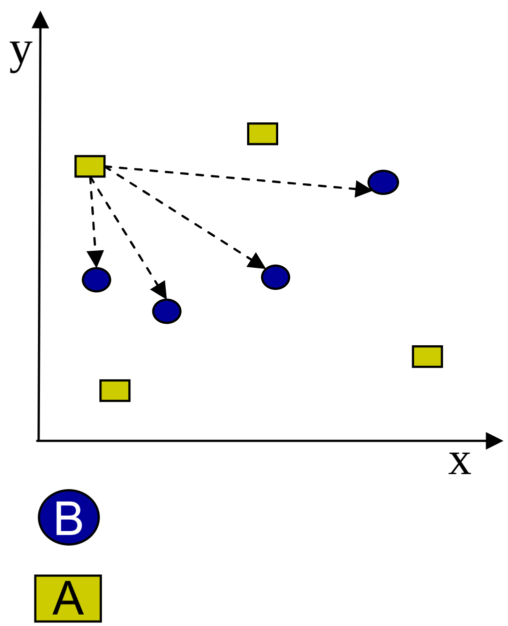
- Architectures with distributed memories use explicit communication to exchange data
  - Data exchange requires synchronization (cooperation) between senders and receivers



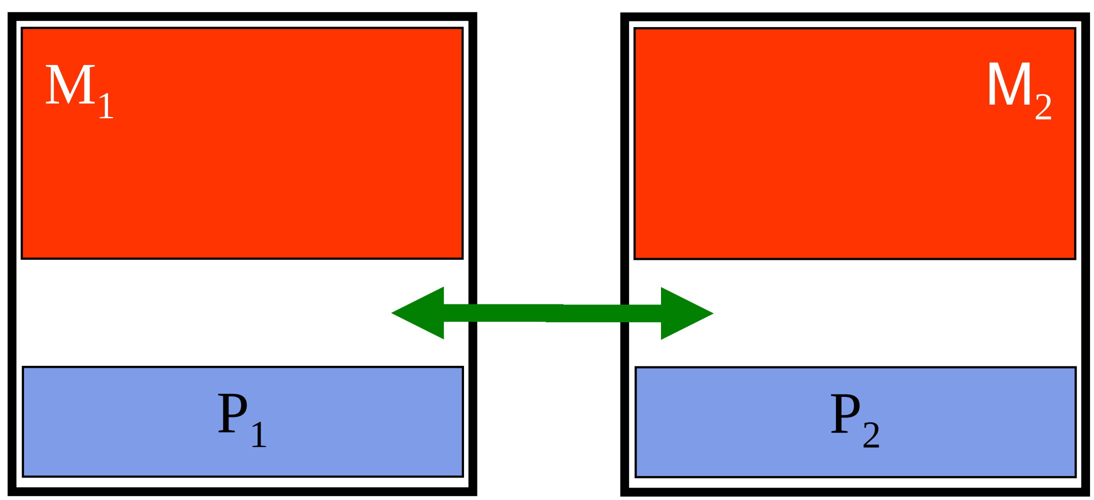
- How is “data” described
- How are processes identified
- Will receiver recognize or screen messages
- What does it mean for a send or receive to complete

Example Message Passing Program

- Calculate the distance from each point in **`A[1..4]`** to every other point in **`B[1..4]`** and store results to **`C[1..4][1..4]`**




```
for (i = 1 to 4)
  for (j = 1 to 4)
    C[i][j] = distance(A[i], B[j])
```



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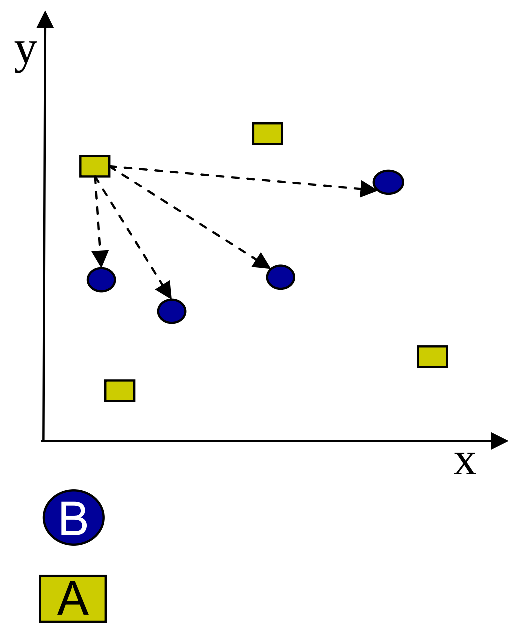

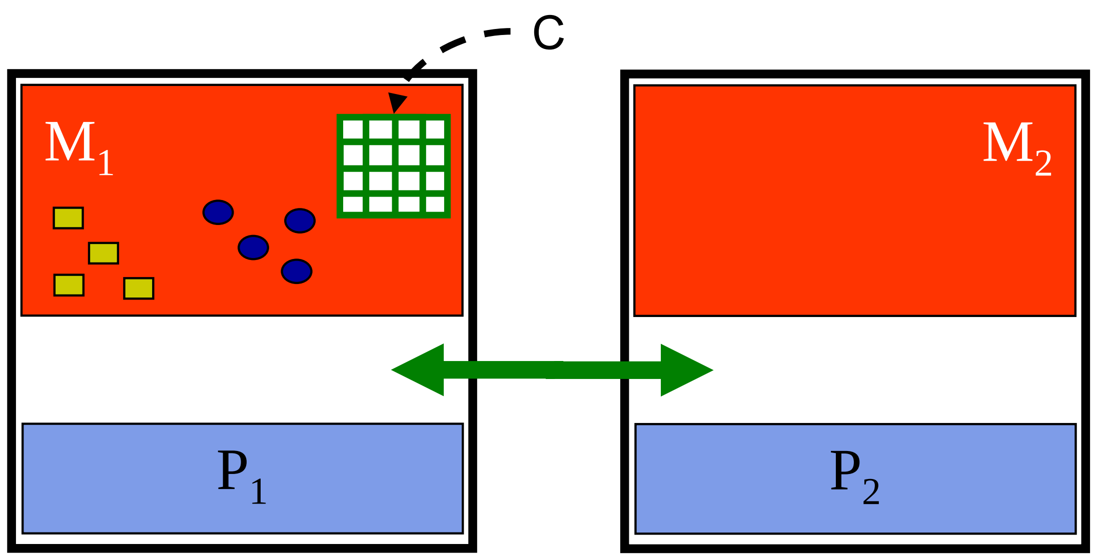

Example Message Passing Program

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```
for (i = 1 to 4)
  for (j = 1 to 4)
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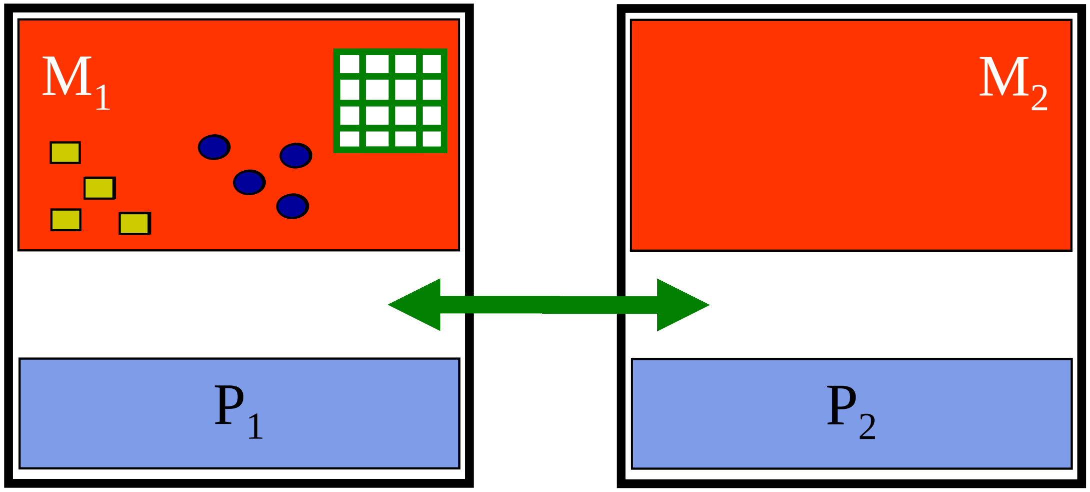
```

- Can break up work between the two processors
  - P_1 sends data to P_2



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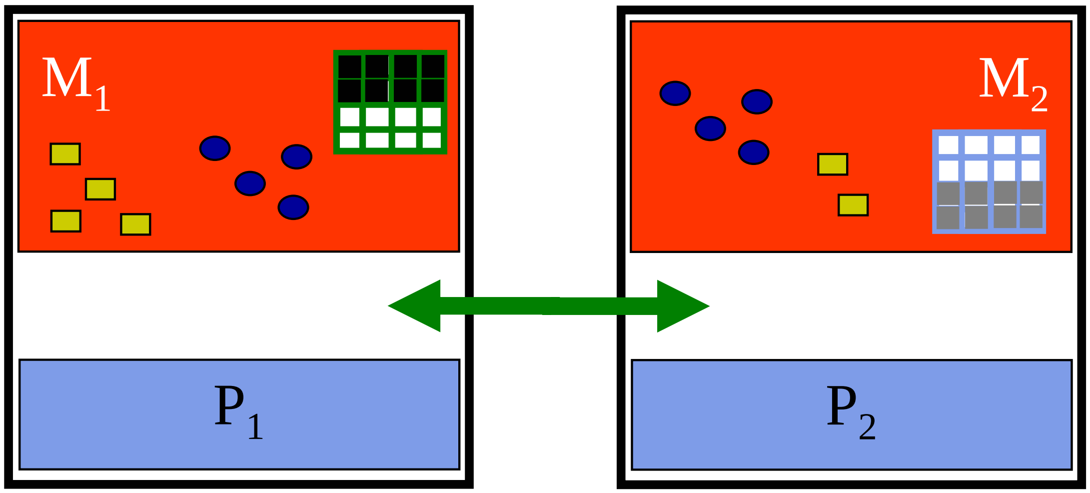
- Can break up work between the two processors
  - P_1 sends data to P_2
  - P_1 and P_2 compute



Example Message Passing Program

- Calculate the distance from each point in **A[1..4]** to every other point in **B[1..4]** and store results to **C[1..4][1..4]**

```
for (i = 1 to 4)
  for (j = 1 to 4)
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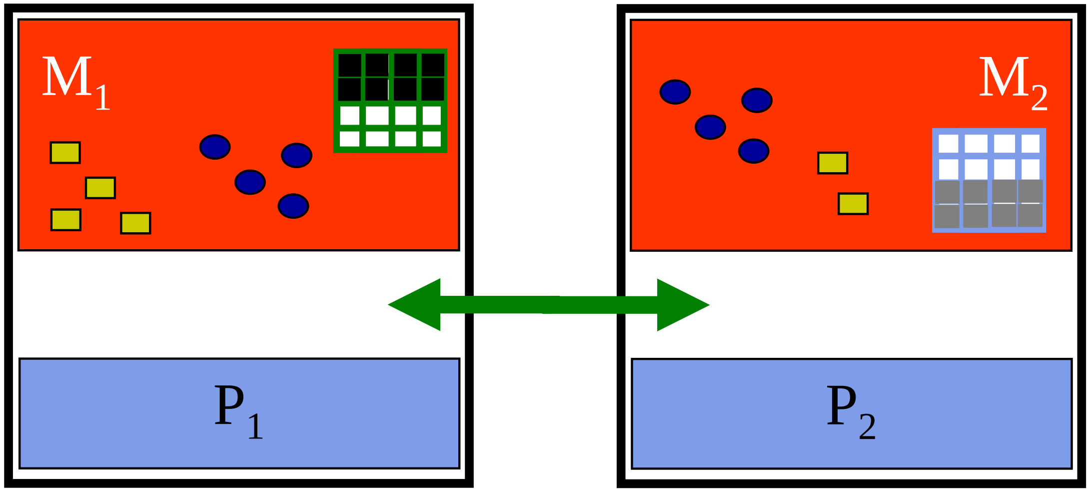
```

- Can break up work between the two processors
  - P_1 sends data to P_2
  - P_1 and P_2 compute
  - P_2 sends output to P_1



Example Message Passing Program

processor 1

```
for (i = 1 to 4)
  for (j = 1 to 4)
    C[i][j] = distance(A[i], B[j])
```

sequential

parallel with messages

processor 1

```
A[n] = {…}
B[n] = {…}

Send (A[n/2+1..n], B[1..n])

for (i = 1 to n/2)
  for (j = 1 to n)
    C[i][j] = distance(A[i], B[j])

Receive(C[n/2+1..n][1..n])
```

processor 2

```
A[n] = {…}
B[n] = {…}

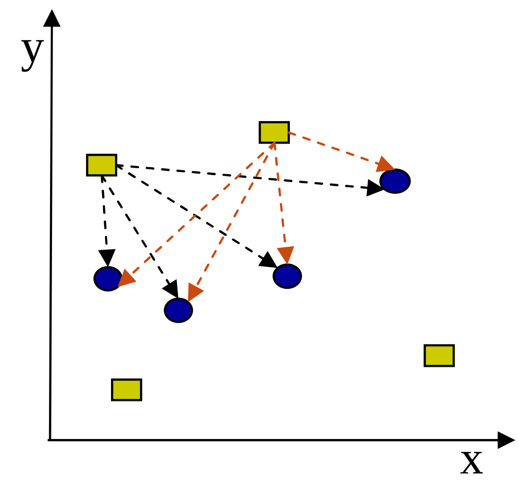
Receive(A[n/2+1..n], B[1..n])

for (i = n/2+1 to n)
  for (j = 1 to n)
    C[i][j] = distance(A[i], B[j])

Send (C[n/2+1..n][1..n])
```

Performance Analysis

- Distance calculations between points are independent of each other
  - Dividing the work between two processors → 2x speedup
  - Dividing the work between four processors → 4x speedup



- Communication
  - 1 copy of **`B[]`** sent to each processor
  - 1 copy of **subset** of **`A[]`** to each processor

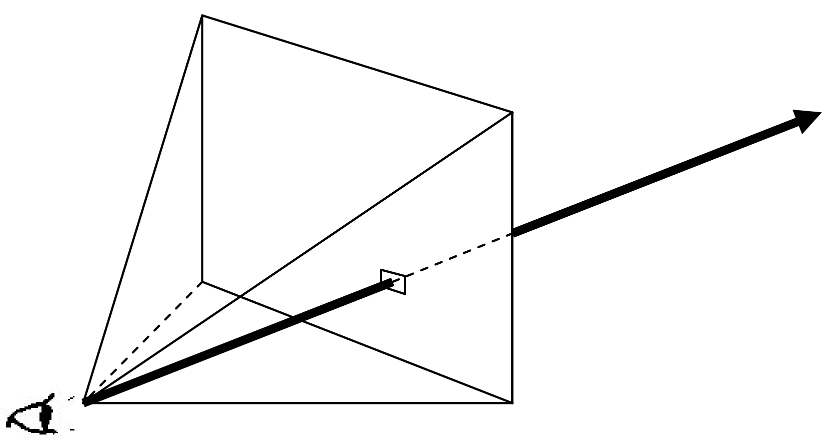
- Granularity of **`A[]`** subsets directly impact communication costs
  - Communication is not free

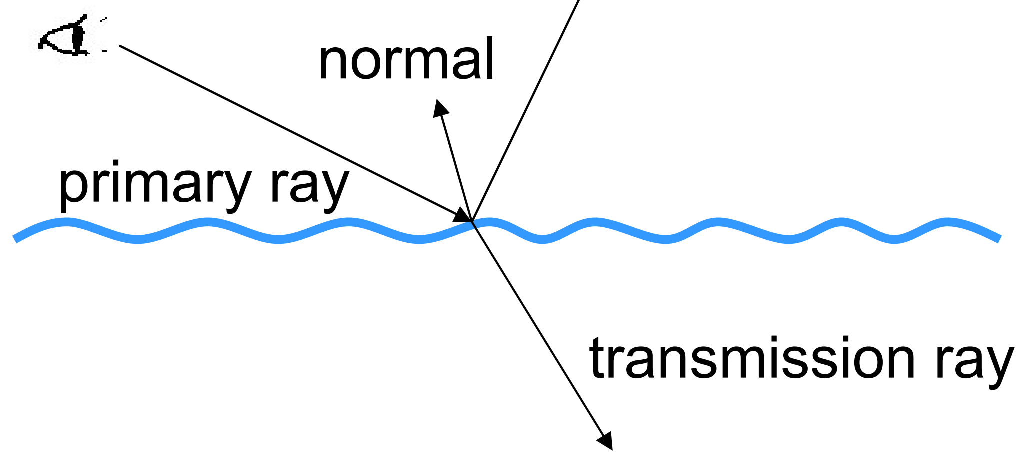
Understanding Performance

- What factors affect performance of parallel programs?
- **Coverage** or extent of parallelism in algorithm
- **Granularity** of partitioning among processors
- **Locality** of computation and communication

Rendering Scenes by Ray Tracing

- Shoot rays into scene through pixels in image plane
- Follow their paths
  - Rays bounce around as they strike objects
  - Rays generate new rays
- Result is color and opacity for that pixel
- Parallelism across rays





Limits to Performance Scalability

- Not all programs are “embarrassingly” parallel

- Programs have sequential parts and parallel parts

Sequential part
(data dependence)

Parallel part
(no data dependence)

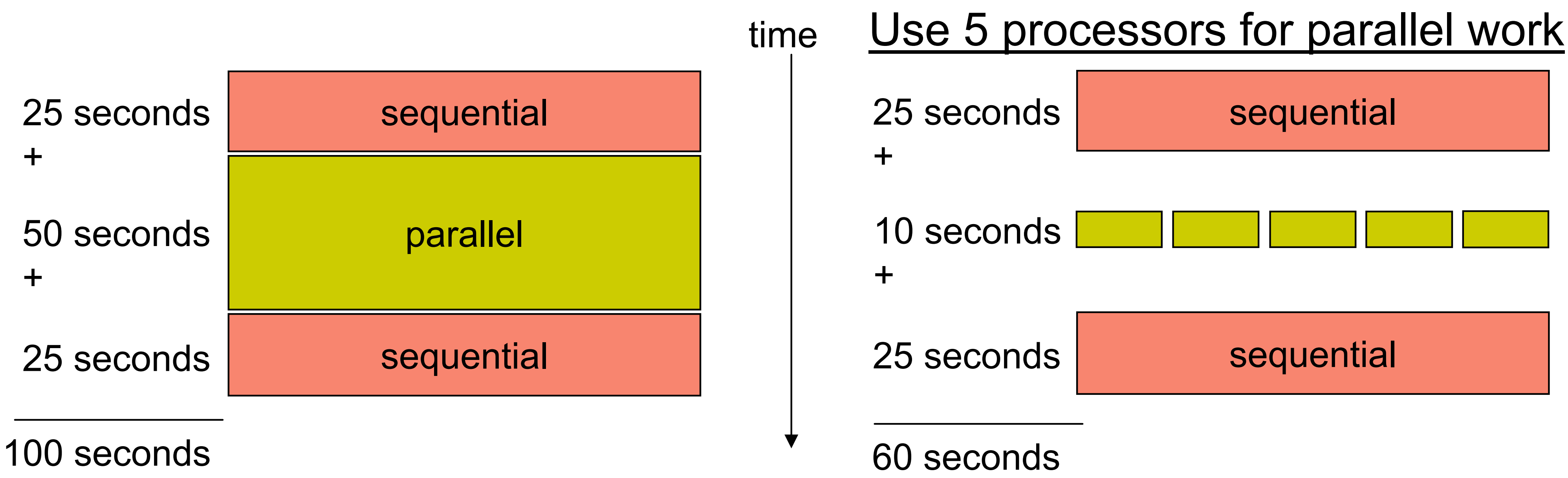
```
a = b + c;
d = a + 1;
e = d + a;
for (i=0; i < e; i++)
    M[i] = 1;
```

Coverage

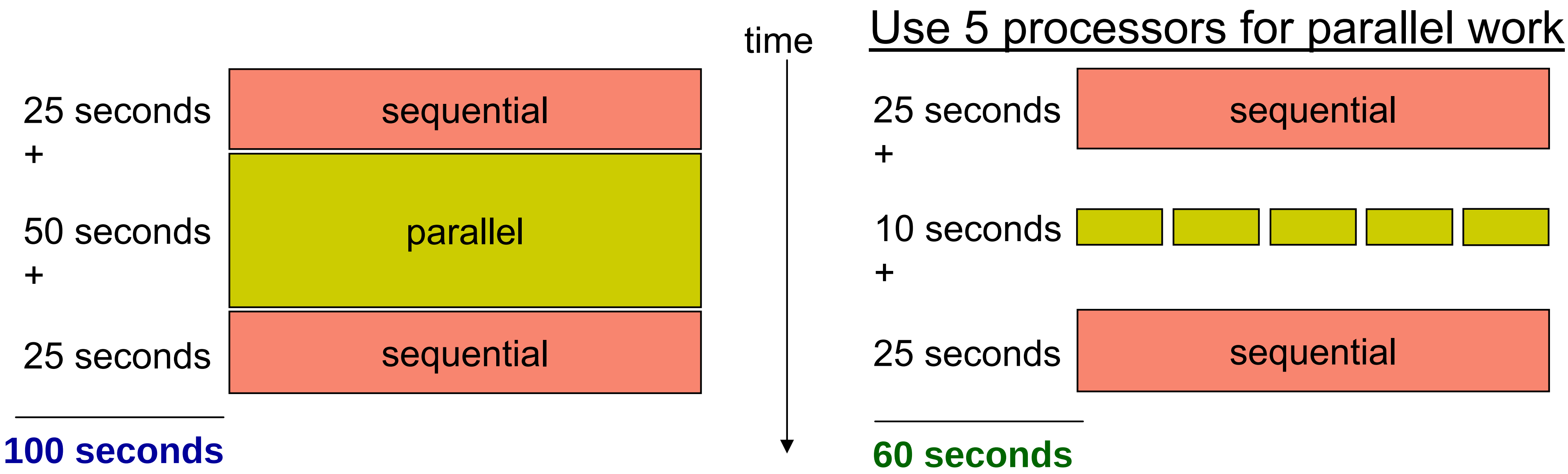
- **Amdahl's Law**: *The performance improvement to be gained from using some faster mode of execution is limited by the fraction of the time the faster mode can be used.*
  - Demonstration of the law of diminishing returns

Amdahl’s Law

- Potential program speedup is defined by the fraction of code that can be parallelized



Amdahl's Law



- Speedup = old running time / new running time
  = 100 seconds / 60 seconds
  = 1.67
  (parallel version is 1.67 times faster)

Amdahl's Law

- p = fraction of work that can be parallelized
- n = the number of processor

$$speedup = \frac{\text{old running time}}{\text{new running time}}$$

$$= \frac{1}{(1-p) + \dfrac{p}{n}}$$

fraction of time to complete sequential work

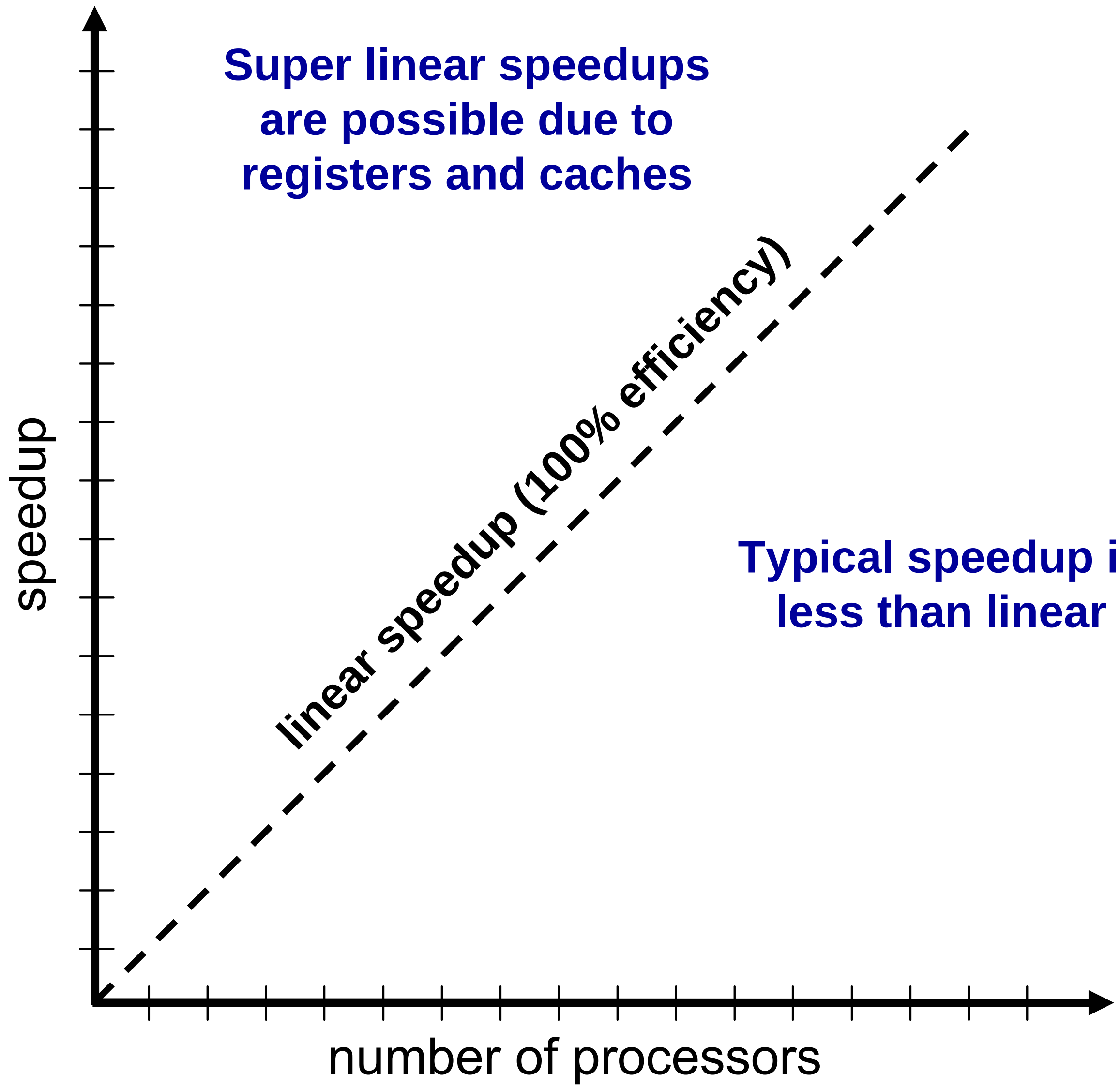
fraction of time to complete parallel work

Implications of Amdahl's Law

- Speedup tends to $\frac{1}{1-p}$ as number of processors tends to infinity

- Parallel programming is worthwhile when programs have a lot of work that is parallel in nature

Performance Scalability



Understanding Performance

- **Coverage** or extent of parallelism in algorithm
- **Granularity** of partitioning among processors
- **Locality** of computation and communication

Granularity

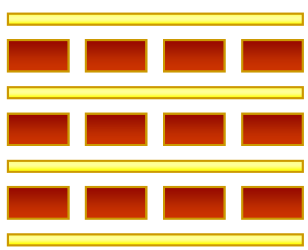
- Granularity is a qualitative measure of the ratio of computation to communication

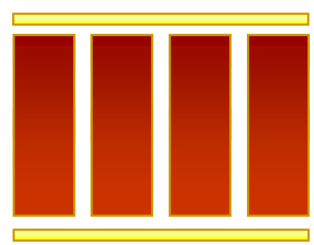
- Computation stages are typically separated from periods of communication by synchronization events

Fine vs. Coarse Granularity

- Fine-grain Parallelism
  - Low computation to communication ratio
  - Small amounts of computational work between communication stages
  - Less opportunity for performance enhancement
  - High communication overhead

- Coarse-grain Parallelism
  - High computation to communication ratio
  - Large amounts of computational work between communication events
  - More opportunity for performance increase
  - Harder to load balance efficiently



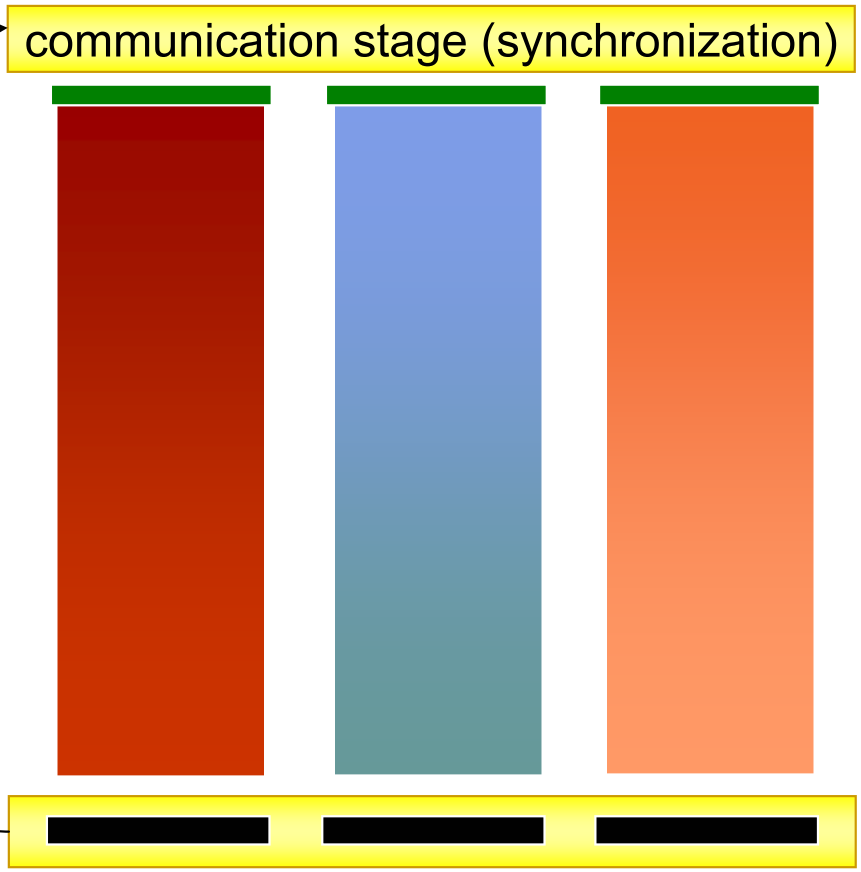


The Load Balancing Problem

- Processors that finish early have to wait for the processor with the largest amount of work to complete
  - Leads to idle time, lowers utilization

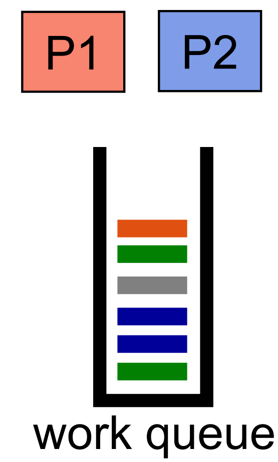
```
// PPU tells all SPEs to start
for (int i = 0; i < n; i++) {
 spe_write_in_mbox(id[i], <message>);
}

// PPU waits for SPEs to send completion message
for (int i = 0; i < n; i++) {
 while (spe_stat_out_mbox(id[i]) == 0);
 spe_read_out_mbox(id[i]);
}
```



Static Load Balancing

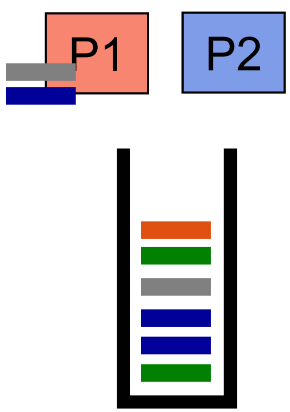
- Programmer make decisions and assigns a fixed amount of work to each processing core a priori



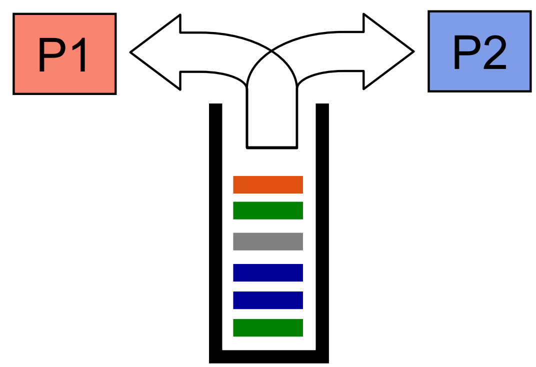
- Works well for homogeneous multicores
  - All core are the same
  - Each core has an equal amount of work
- Not so well for heterogeneous multicores
  - Some cores may be faster than others
  - Work distribution is uneven

Dynamic Load Balancing

- When one core finishes its allocated work, it takes on work from core with the heaviest workload
- Ideal for codes where work is uneven, and in heterogeneous multicore



work queue



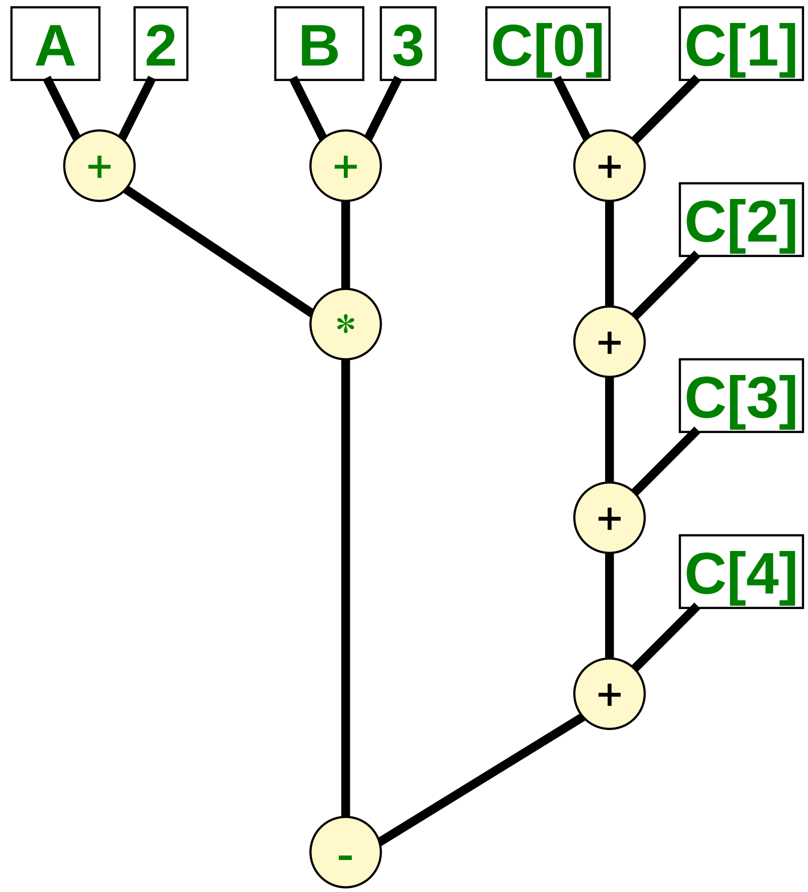
work queue

Granularity and Performance Tradeoffs

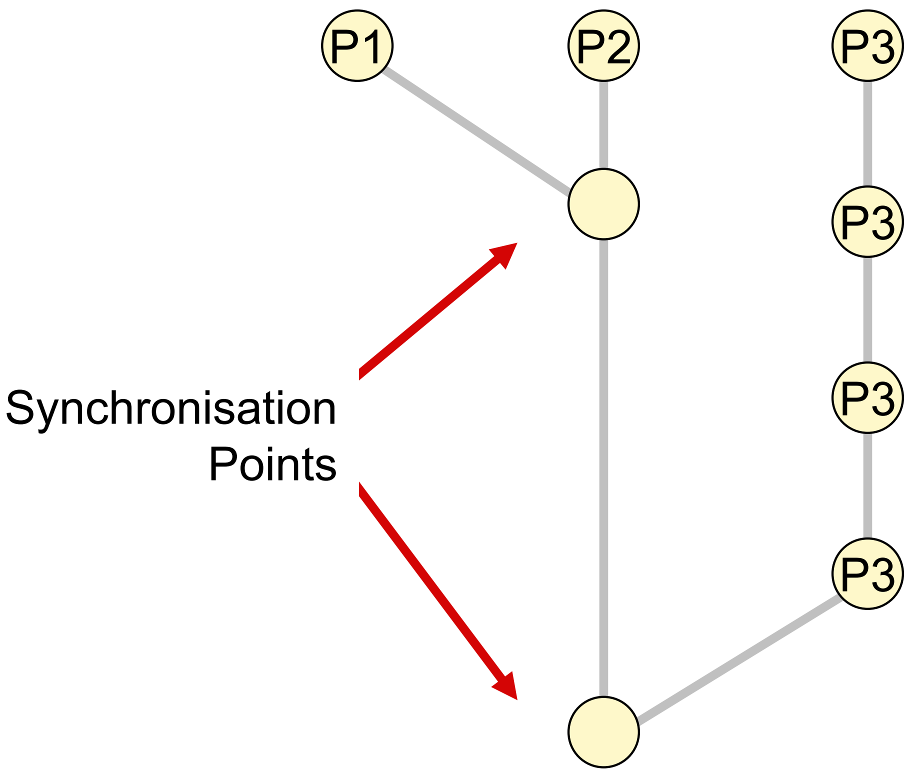
1. Load balancing
   - How well is work distributed among cores?

2. Synchronization
   - Are there ordering constraints on execution?

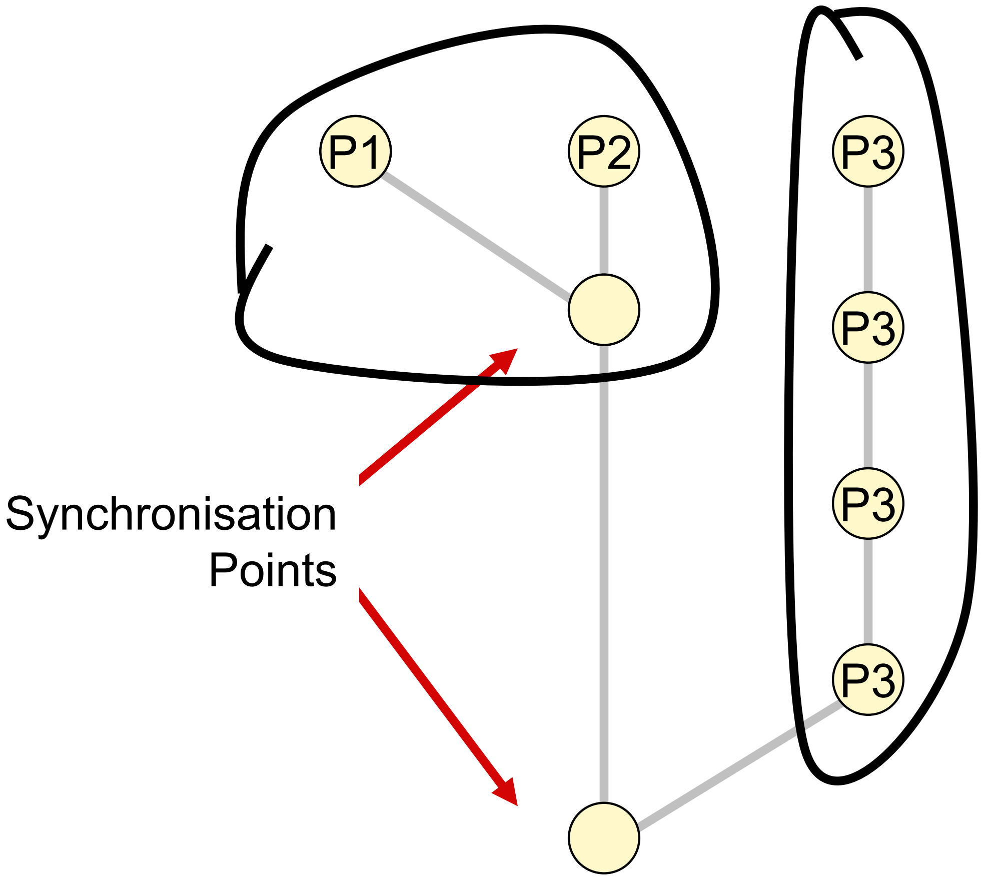
Data Dependence Graph



Dependence and Synchronization



Synchronization Removal



Granularity and Performance Tradeoffs

1. Load balancing
   - How well is work distributed among cores?
2. Synchronization
   - Are there ordering constraints on execution?
3. Communication
   - Communication is not cheap!

Communication Cost Model

total data sent

number of messages

$$C = f * \left(o + l + \frac{n/m}{B} + t - overlap\right)$$

frequency of messages

overhead per message (at both ends)

network delay per message

bandwidth along path (determined by network)

cost induced by contention per message

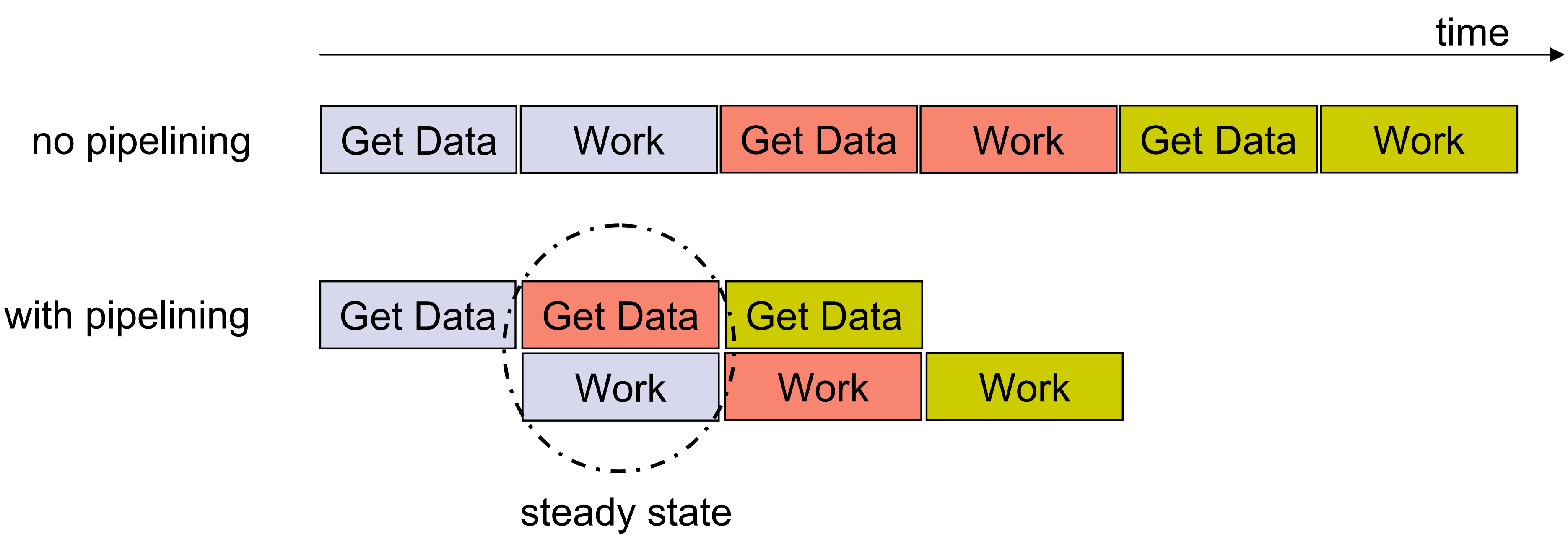
amount of latency hidden by concurrency with computation

Types of Communication

- Cores exchange data or control messages
  - Cell examples: DMA vs. Mailbox
- Control messages are often short
- Data messages are relatively much larger

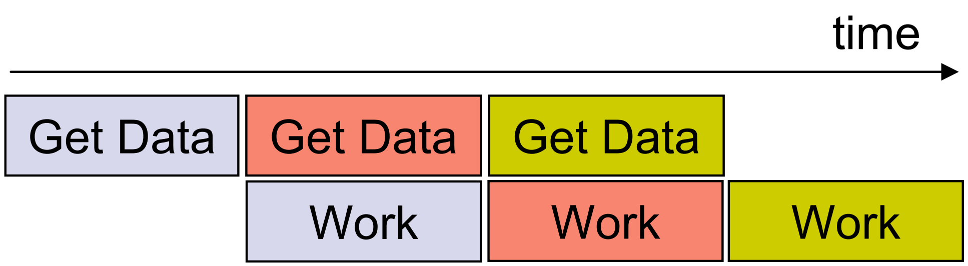
Overlapping Messages and Computation

- Computation and communication concurrency can be achieved with pipelining
  - Think instruction pipelining in superscalars



Overlapping Messages and Computation

- Computation and communication concurrency can be achieved with pipelining
  - Think instruction pipelining in superscalars
- Essential for performance on Cell and similar distributed memory multicores



Cell buffer pipelining example

```
// Start transfer for first buffer
id = 0;
mfc_get(buf[id], addr, BUFFER_SIZE, id, 0, 0);
id ^= 1;

while (!done) {
 // Start transfer for next buffer
 addr += BUFFER_SIZE;
 mfc_get(buf[id], addr, BUFFER_SIZE, id, 0, 0);

 // Wait until previous DMA request finishes
 id ^= 1;
 mfc_write_tag_mask(1 << id);
 mfc_read_tag_status_all();

 // Process buffer from previous iteration
 process_data(buf[id]);
}
```

Communication Patterns

- With message passing, programmer has to understand the computation and orchestrate the communication accordingly
  - Point to Point
  - Broadcast (one to all) and Reduce (all to one)
  - All to All (each processor sends its data to all others)
  - Scatter (one to several) and Gather (several to one)

A Message Passing Library Specification

- MPI: specification
  - Not a language or compiler specification
  - Not a specific implementation or product
  - SPMD model (same program, multiple data)
- For parallel computers, clusters, and heterogeneous networks, multicores
- Full-featured
- Multiple communication modes allow precise buffer management
- Extensive collective operations for scalable global communication

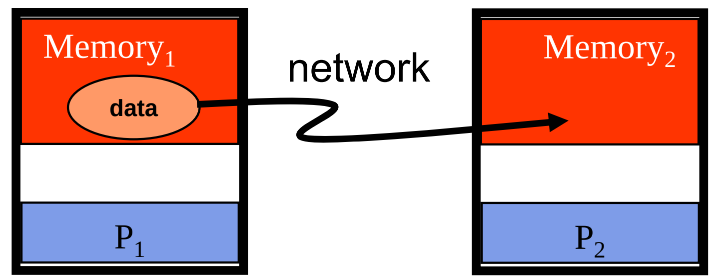
Where Did MPI Come From?

- Early vendor systems (Intel's NX, IBM's EUI, TMC's CMMD) were not portable (or very capable)
- Early portable systems (PVM, p4, TCGMSG, Chameleon) were mainly research efforts
  - Did not address the full spectrum of issues
  - Lacked vendor support
  - Were not implemented at the most efficient level
- The MPI Forum organized in 1992 with broad participation
  - Vendors: IBM, Intel, TMC, SGI, Convex, Meiko
  - Portability library writers: PVM, p4
  - Users: application scientists and library writers
  - Finished in 18 months

Point-to-Point

- Basic method of communication between two processors
  - Originating processor "sends" message to destination processor
  - Destination processor then "receives" the message

- The message commonly includes
  - Data or other information
  - Length of the message
  - Destination address and possibly a tag



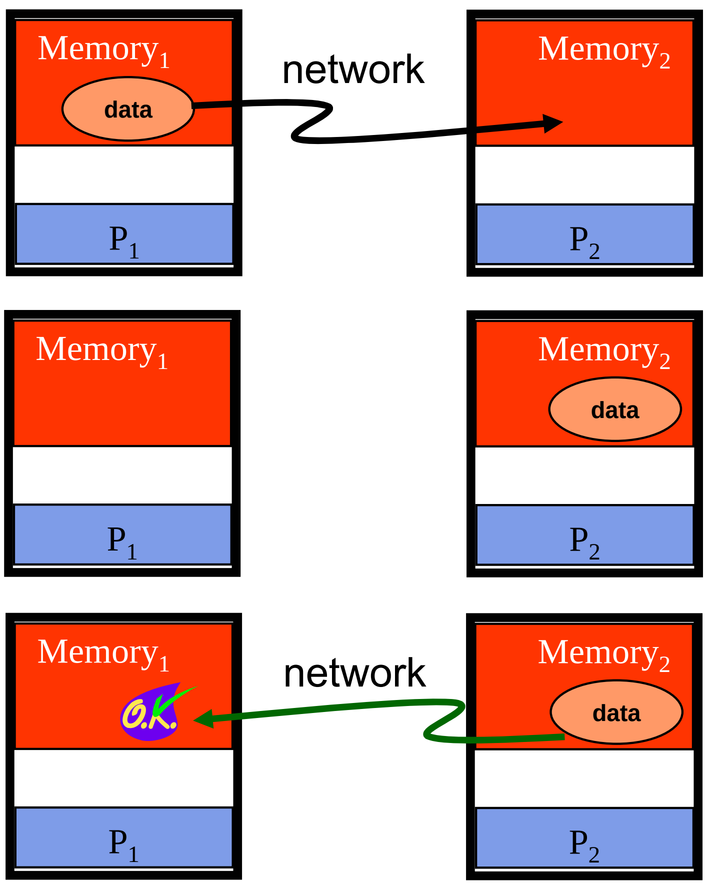
Cell "send" and "receive" commands

```
mfc_get(destination LS addr,
        source memory addr,
        # bytes,
        tag,
        <...>)
```

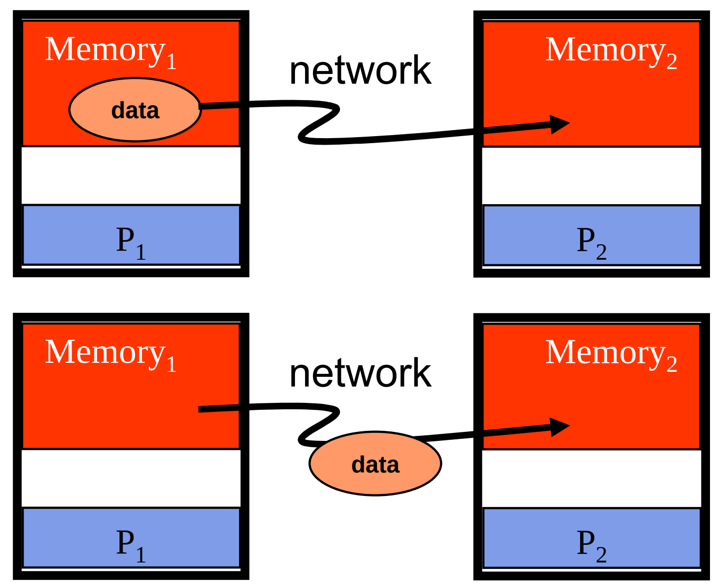
```
mfc_put(source LS addr,
        destination memory addr,
        # bytes,
        tag,
        <...>)
```

Synchronous vs. Asynchronous Messages

- Synchronous send
  - Sender notified when message is received



- Asynchronous send
  - Sender only knows that message is sent



Blocking vs. Non-Blocking Messages

- Blocking messages
  - Sender waits until message is transmitted: **buffer is empty**
  - Receiver waits until message is received: **buffer is full**
  - Potential for deadlock

- Non-blocking
  - Processing continues even if message hasn't been transmitted
  - Avoid idle time and deadlocks

Cell blocking mailbox "send"

```
// SPE does some work
...
// SPE notifies PPU that task has completed
spu_write_out_mbox(<message>);

// SPE does some more work
...
// SPE notifies PPU that task has completed
spu_write_out_mbox(<message>);
```

Cell non-blocking data "send" and "wait"

```
// DMA back results
mfc_put(data, cb.data_addr, data_size, ...);

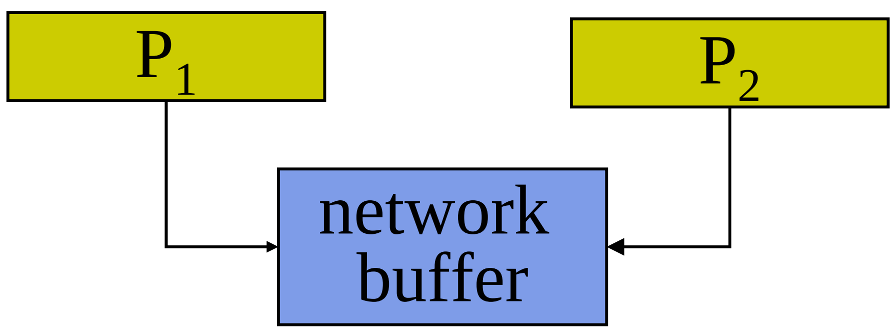
// Wait for DMA completion
mfc_read_tag_status_all();
```

Sources of Deadlocks

- If there is insufficient buffer capacity, sender waits until additional storage is available

- What happens with this code?

P_1	P_2
Send(…)	**Send(…)**
Recv(…)	**Recv(…)**



- Depends on length of message and available buffer

Solutions

- Increasing local or network buffering
- Order the sends and receives more carefully

write message to buffer and block until message is transmitted (buffer becomes empty)

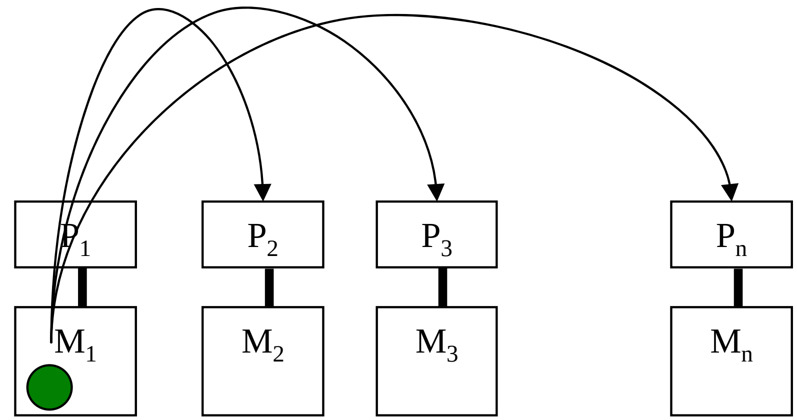
P_1	P_2
Send(…)	**Send(…)**
Recv(…)	**Recv(…)**

blocked since buffer is full (no progress until message can be sent)

P_1	P_2	
Send(…)	**Recv(…)**	matching send-receive pair
Recv(…)	**Send(…)**	matching receive-send pair

Broadcast

- One processor sends the same information to many other processors
  - **`MPI_BCAST`**




```
for (i = 1 to n)
  for (j = 1 to n)
    C[i][j] = distance(A[i], B[j])
```

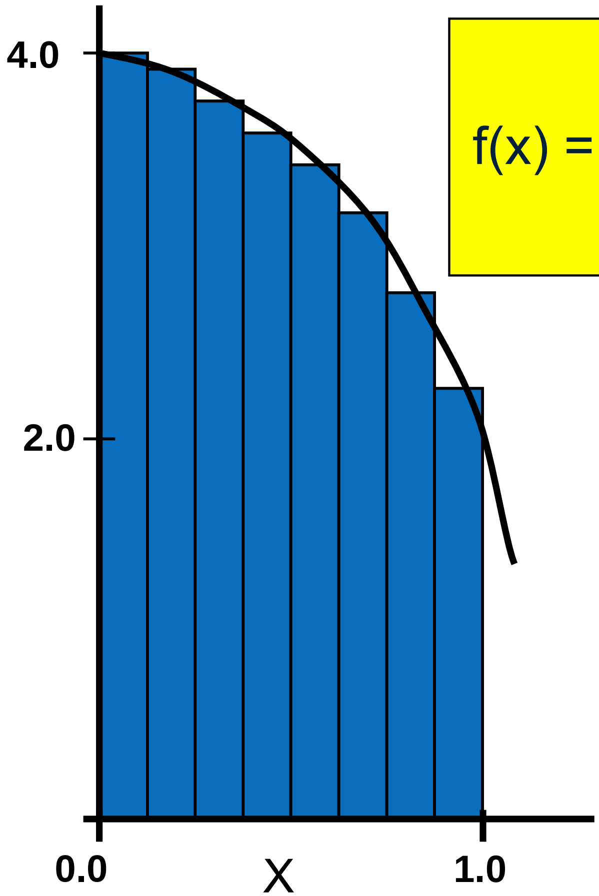
```
A[n] = {…}
B[n] = {…}

Broadcast(B[1..n])
for (i = 1 to n)
  // round robin distribute B
  // to m processors
  Send(A[i % m])
…
```

Reduction

- Example: every processor starts with a value and needs to know the sum of values stored on all processors
- A reduction combines data from all processors and returns it to a single process
  - **`MPI_REDUCE`**
  - Can apply any associative operation on gathered data
    - ADD, OR, AND, MAX, MIN, etc.
  - No processor can finish reduction before each processor has contributed a value
- **`BCAST/REDUCE`** can reduce programming complexity and may be more efficient in some programs

Example: Parallel Numerical Integration



$$f(x) = \frac{4.0}{(1+x^2)}$$

```
static long num_steps = 100000;

void main()
{
    int i;
    double pi, x, step, sum = 0.0;

    step = 1.0 / (double) num_steps;
    for (i = 0; i < num_steps; i++){
        x = (i + 0.5) * step;
        sum = sum + 4.0 / (1.0 + x*x);
    }

    pi = step * sum;
    printf("Pi = %f\n", pi);
}
```

Computing Pi With Integration (OpenMP)

```
static long num_steps = 100000;

void main()
{
   int i;
   double pi, x, step, sum = 0.0;

   step = 1.0 / (double) num_steps;

  #pragma omp parallel for \
      private(x) reduction(+:sum)

   for (i = 0; i < num_steps; i++){
      x = (i + 0.5) * step;
      sum = sum + 4.0 / (1.0 + x*x);
   }

   pi = step * sum;
   printf(“Pi = %f\n”, pi);
}
```

- Which variables are shared?
  - `step`
- Which variables are private?
  - `x`
- Which variables does reduction apply to?
  - `sum`

Computing Pi With Integration (MPI)

```
static long num_steps = 100000;

void main(int argc, char* argv[])
{
   int i_start, i_end, i, myid, numprocs;
   double pi, mypi, x, step, sum = 0.0;

   MPI_Init(&argc, &argv);
   MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
   MPI_Comm_rank(MPI_COMM_WORLD, &myid);

   MPI_BCAST(&num_steps, 1, MPI_INT, 0, MPI_COMM_WORLD);

   i_start = my_id * (num_steps/numprocs)
   i_end = i_start + (num_steps/numprocs)

   step = 1.0 / (double) num_steps;

   for (i = i_start; i < i_end; i++) {
        x = (i + 0.5) * step
        sum = sum + 4.0 / (1.0 + x*x);
   }
   mypi = step * sum;

   MPI_REDUCE(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);

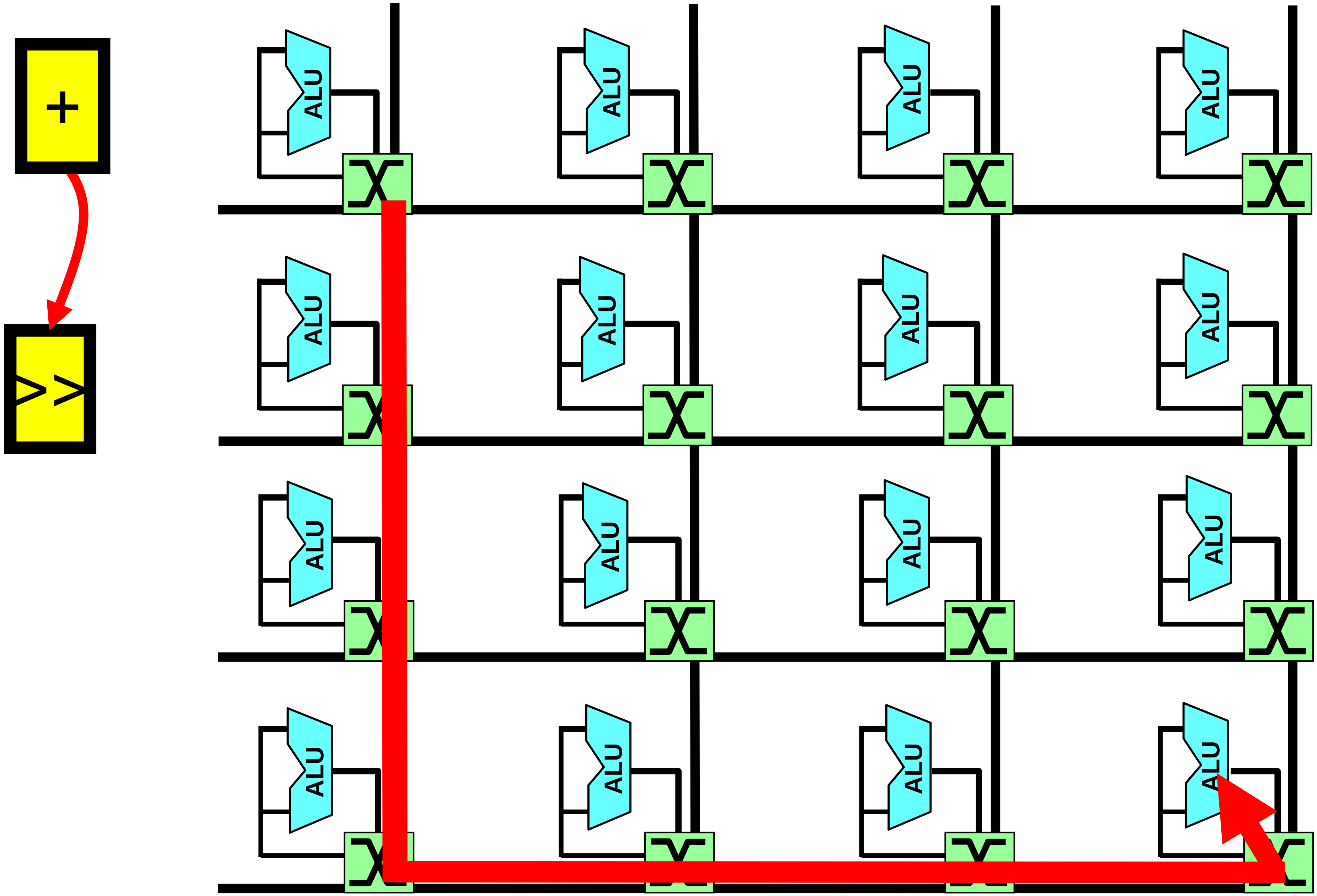
   if (myid == 0)
        printf(“Pi = %f\n”, pi);

   MPI_Finalize();
}
```

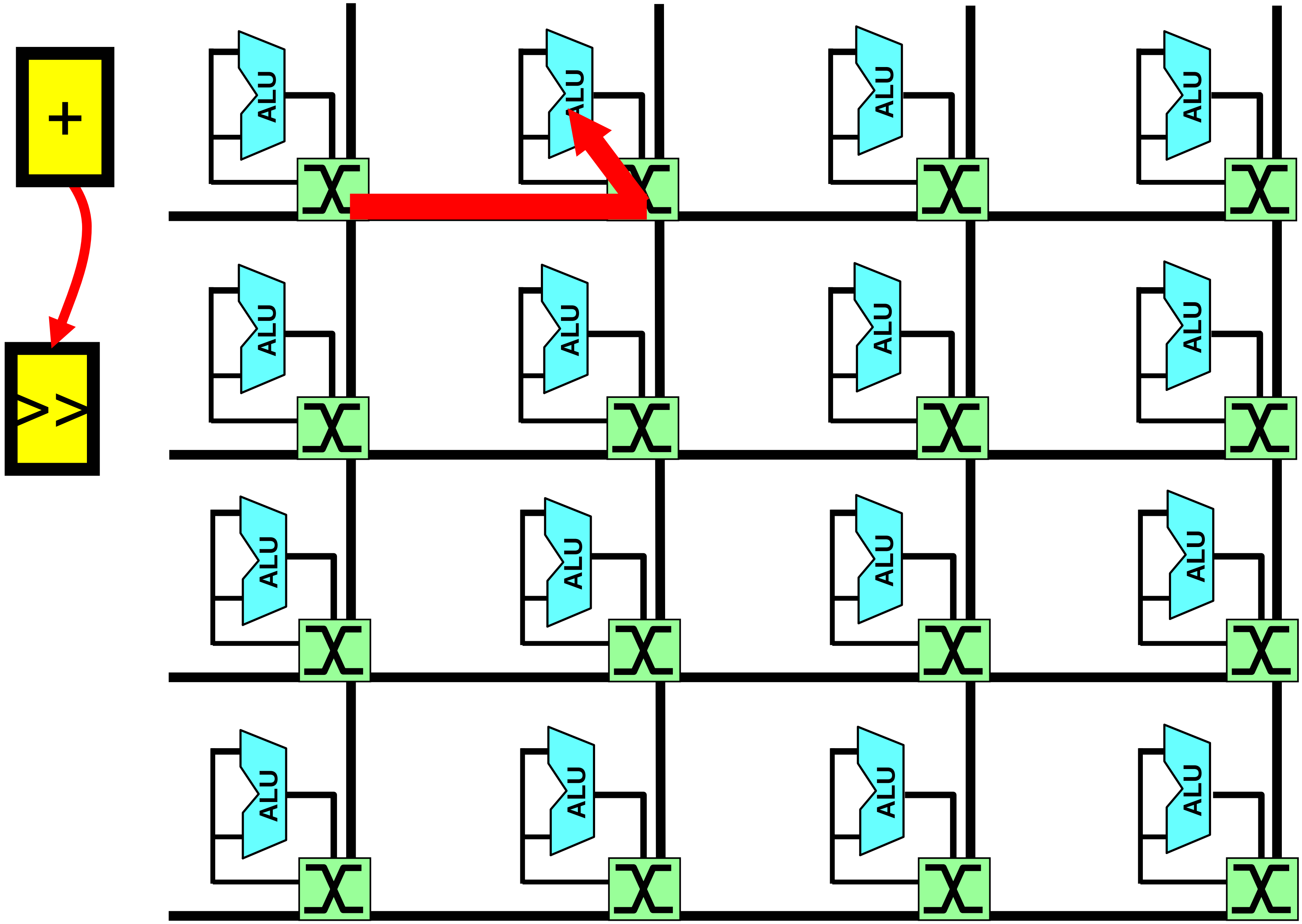
Understanding Performance

- **Coverage** or extent of parallelism in algorithm
- **Granularity** of data partitioning among processors
- **Locality** of computation and communication

Locality in Communication (Message Passing)

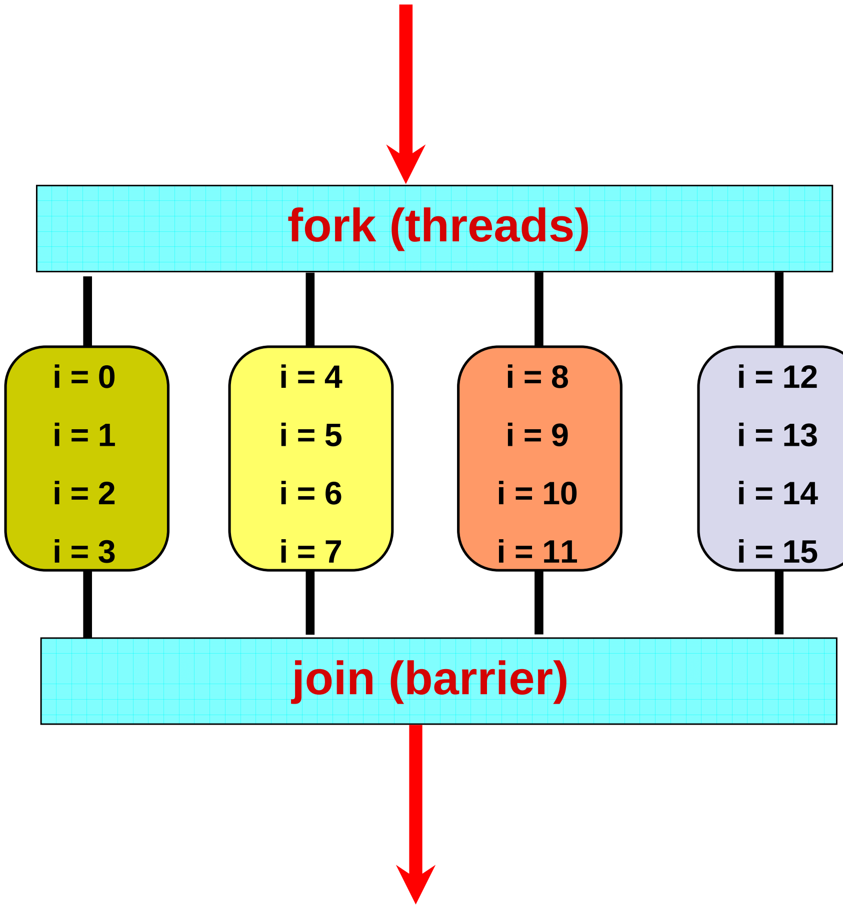


Exploiting Communication Locality



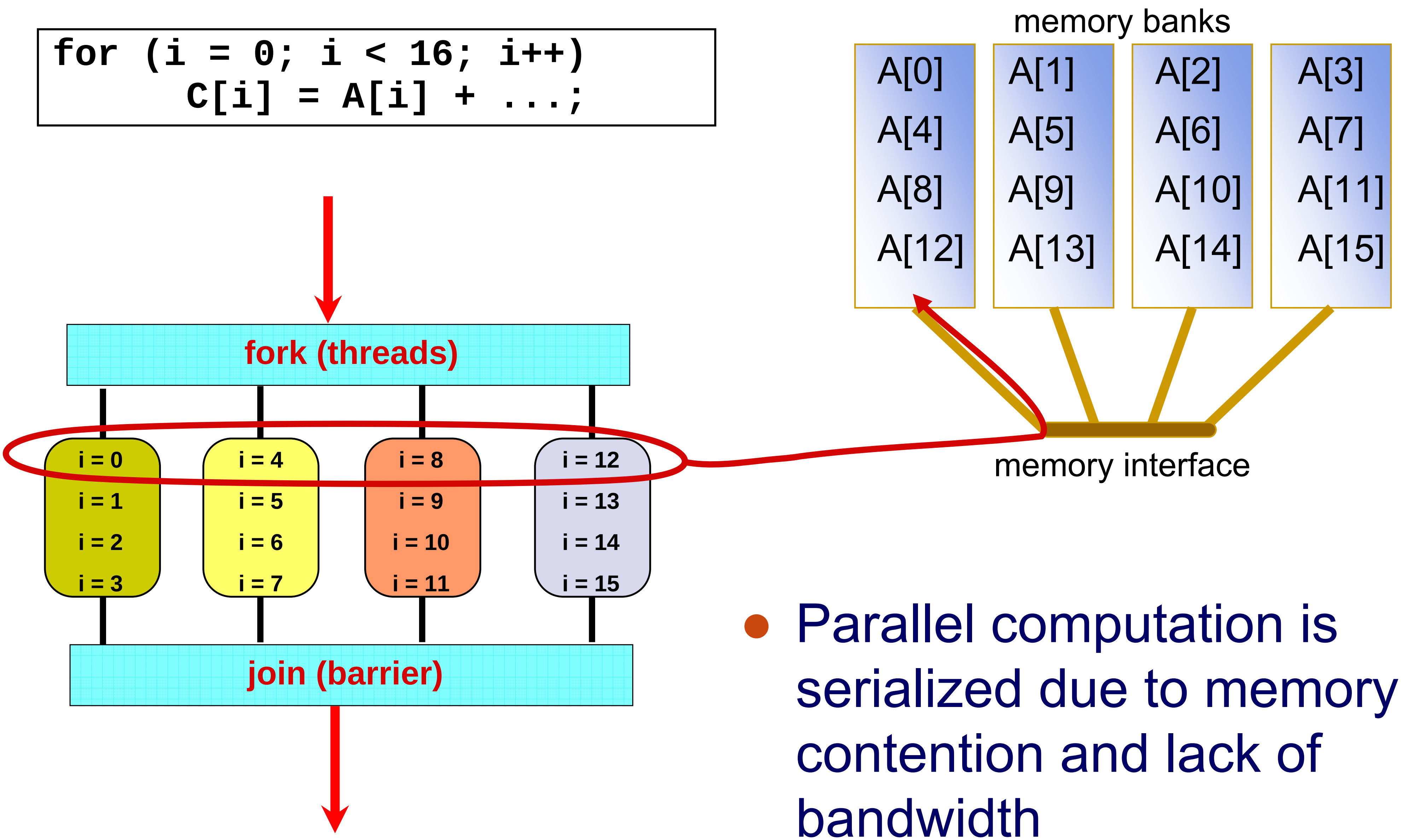
Locality of Memory Accesses (Shared Memory)

```
for (i = 0; i < 16; i++)
      C[i] = A[i] + ...;
```



Locality of Memory Accesses (Shared Memory)

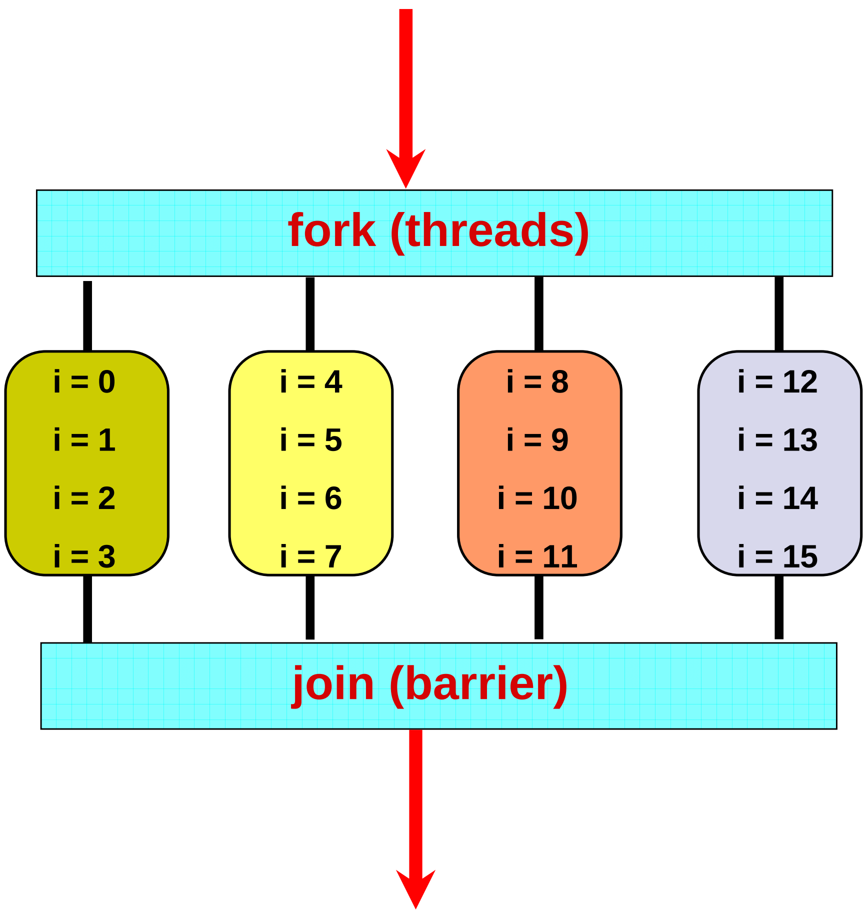
```
for (i = 0; i < 16; i++)
      C[i] = A[i] + ...;
```

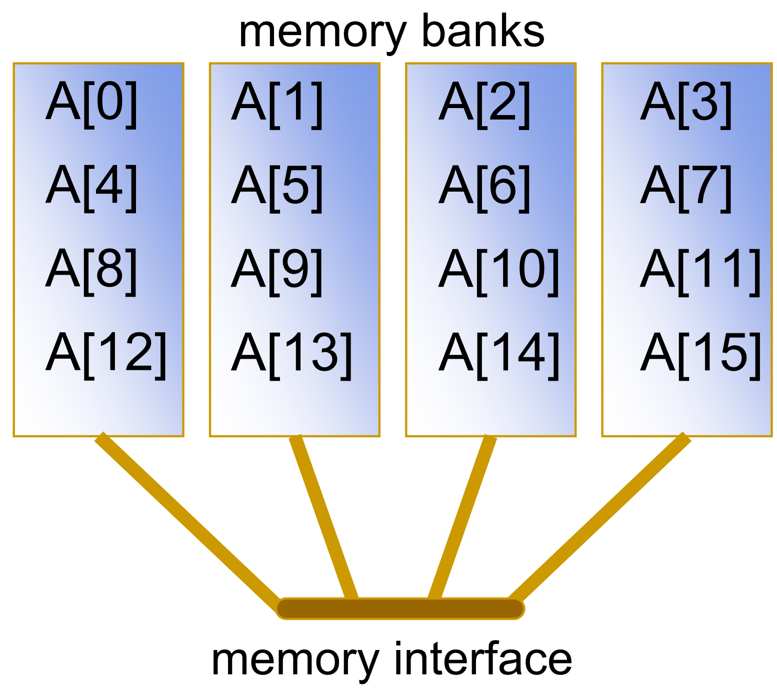


- Parallel computation is serialized due to memory contention and lack of bandwidth

Locality of Memory Accesses (Shared Memory)

```
for (i = 0; i < 16; i++)
      C[i] = A[i] + ...;
```





Locality of Memory Accesses (Shared Memory)

```
for (i = 0; i < 16; i++)
      C[i] = A[i] + ...;
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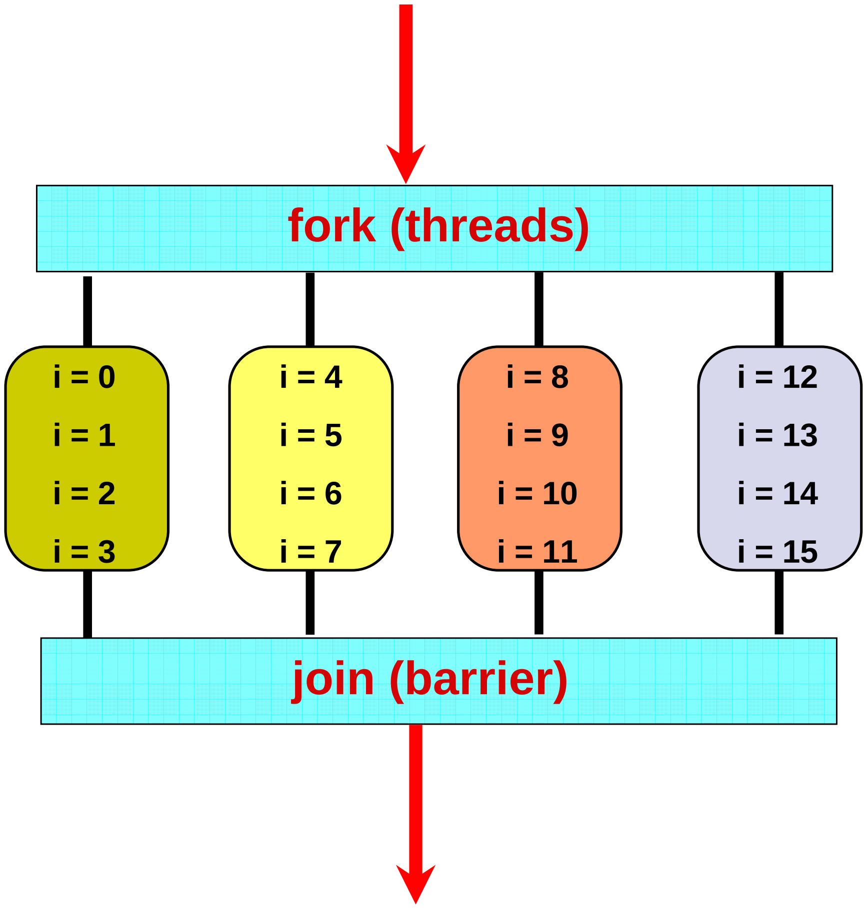

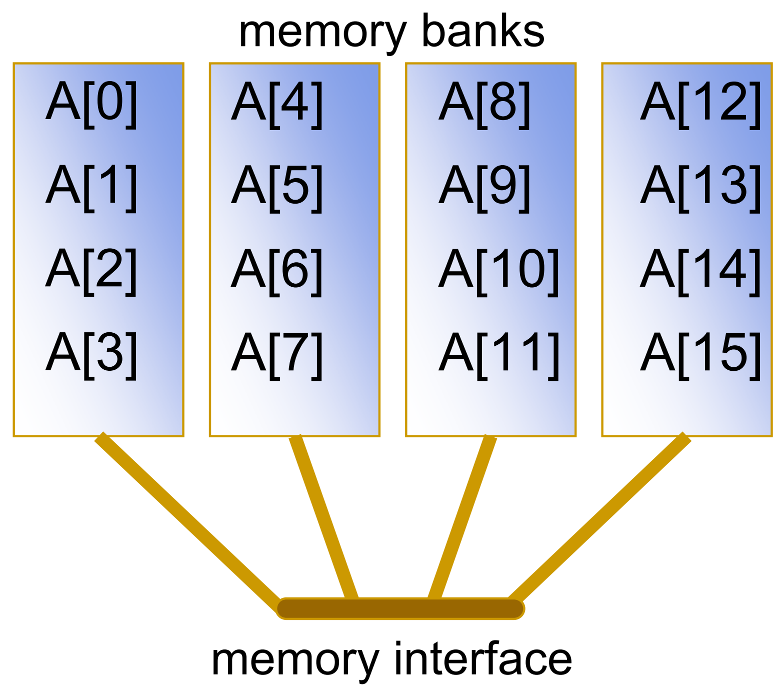

- Distribute data to relieve contention and increase effective bandwidth

Memory Access Latency in Shared Memory Architectures

- Uniform Memory Access (UMA)
  - Centrally located memory
  - All processors are equidistant (access times)
- Non-Uniform Access (NUMA)
  - Physically partitioned but accessible by all
  - Processors have the same address space
  - Placement of data affects performance

Summary of Parallel Performance Factors

- Coverage or extent of parallelism in algorithm
- Granularity of data partitioning among processors
- Locality of computation and communication
- … so how do I parallelize my program?