Lecture 4:
Parallel Programming Basics

CMU 15-418: Parallel Computer Architecture and Programming (Spring 2012)

ISPC discussion: sum "reduction"

Compute the sum of all array elements in parallel

```
export uniform float sumall1(
   uniform int N,
   uniform float* x)
{
   uniform float sum = 0.0f;
   foreach (i = 0 ... N)
   {
      sum += x[i];
   }

   return sum;
}
```

```
export uniform float sumall2(
   uniform int N,
   uniform float* x)
{
   uniform float sum;
   float partial = 0.0f;
   foreach (i = 0 ... N)
   {
      partial += x[i];
   }

   // from ISPC math library
   sum = reduceAdd(partial);

   return sum;
}
```

`sum` is of type uniform float (one copy of variable for all program instances)
Undefined behavior: All program instances accumulate into sum in parallel
(read-modify-write operation must be atomic for correctness: it is not)

ISPC discussion: sum "reduction"

Compute the sum of all array elements in parallel

Each instance accumulates a private partial sum (no communication)

Partial sums are added together using the reduceAdd() cross-instance communication primitive. The result is the same for all instances (uniform)

ISPC code at right will execute in a manner similar to handwritten C implementation below.

```
export uniform float sumall2(
   uniform int N,
   uniform float* x)
{
   uniform float sum;
   float partial = 0.0f;
   foreach (i = 0 ... N)
   {
      partial += x[i];
   }

   // from ISPC math library
   sum = reduceAdd(partial);

   return sum;
}
```

```
const int N = 1024;
float* x = new float[N];
__mm256 partial = _mm256_broadcast_ss(0.0f);

// populate x

for (int i=0; i<N; i+=8)
   partial = _mm256_add_ps(partial, _mm256_load_ps(&x[i]));

float sum = 0.f;
for (int i=0; i<8; i++)
   sum += partial[i];
}
```

Parallel programming basics

(CMU 15-418, Spring 2012)

Creating a parallel program

- Thought process:
  - Identify work that can be performed in parallel
  - Partition work (and associated data)
  - Manage data access, communication, and synchronization

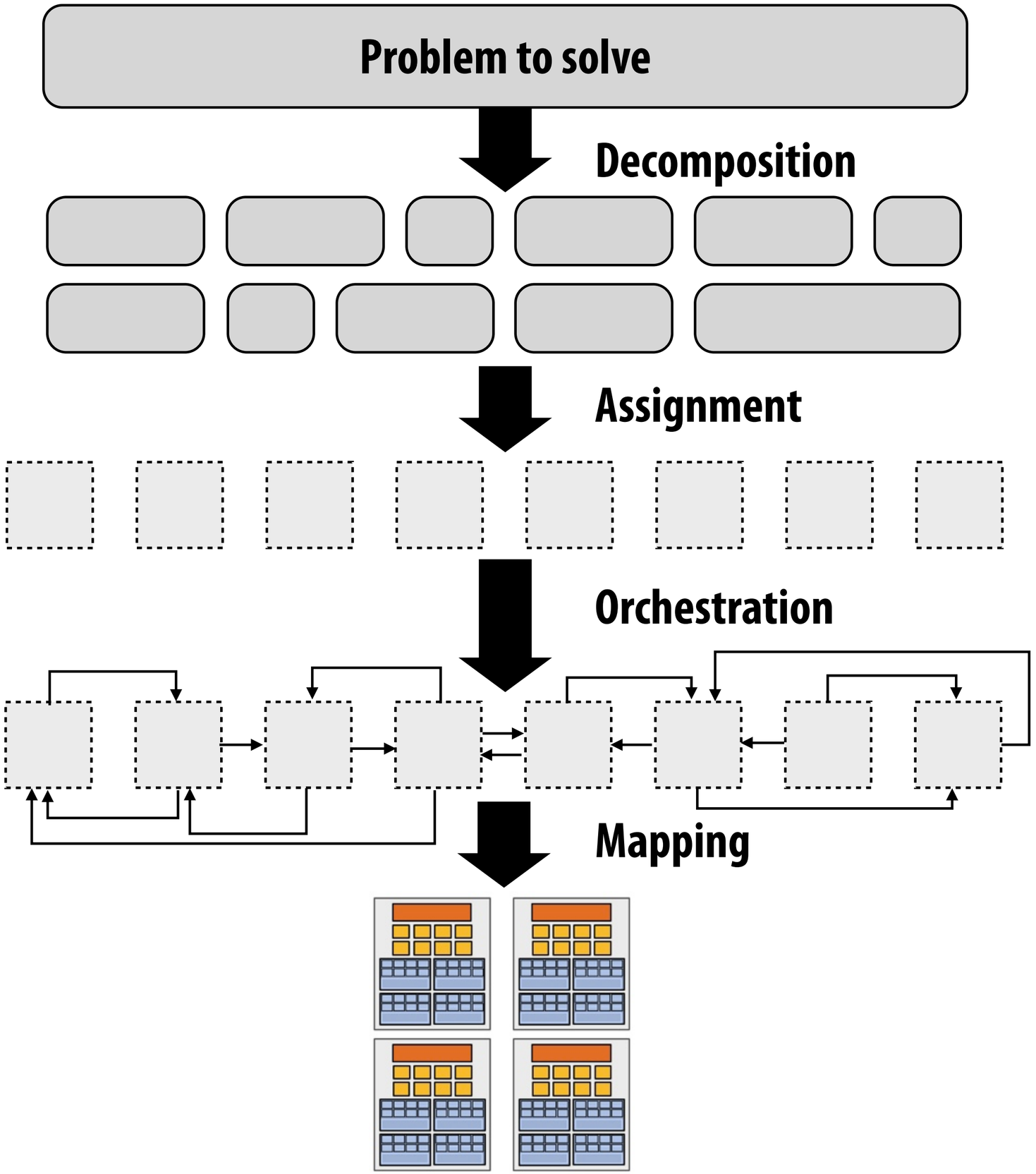
- Recall one** of our main goals is speedup:

  For a fixed problem size:

$$\text{Speedup(P processors)} = \frac{\text{Time (1 processor)}}{\text{Time (P processors)}}$$

** Other goals include efficiency (cost, area, power, etc.), working on bigger problems than on a uniprocessor

Steps in creating a parallel program



These steps are performed by the programmer and/or system (compiler, runtime, hardware)

** textbook uses the term "processes". We're referring to the same concept

Decomposition

- Break up problem into tasks that can be carried out in parallel
  - Need not happen statically
  - Tasks can be identified as program executes

- Want to create enough tasks to keep all execution units on a machine busy.

Key aspect of decomposition: identifying dependencies (a lack of dependencies)

Limited concurrency: Amdahl's law

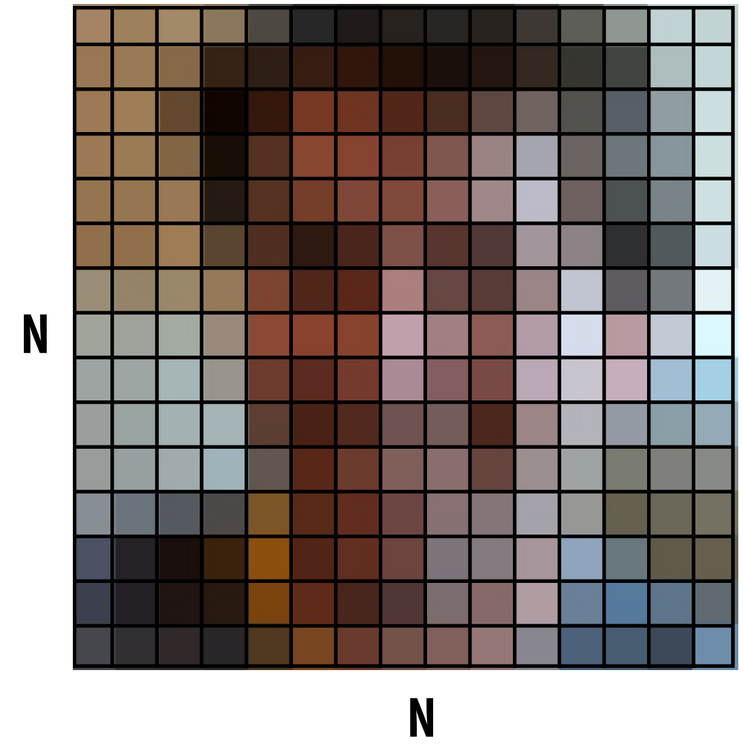
- Say you have a sequential program

- Let $S =$ the fraction of sequential execution that is inherently sequential
  - Dependencies prevent parallel execution

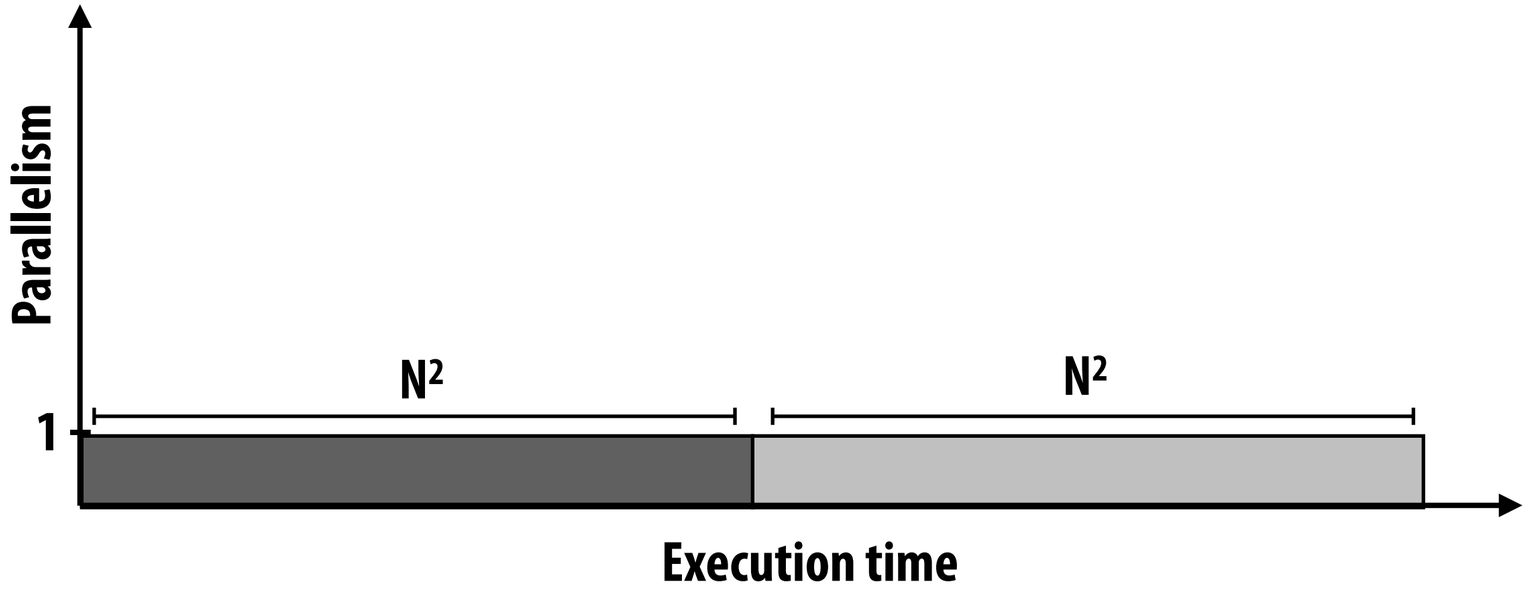
- Then speedup $\leq 1/S$

Amdahl's law example

- 2-phase computation on an N-by-N grid
  - Phase 1: independent computation on each grid element
  - Phase 2: compute sum of all cell values
  - Real-life example: image processing



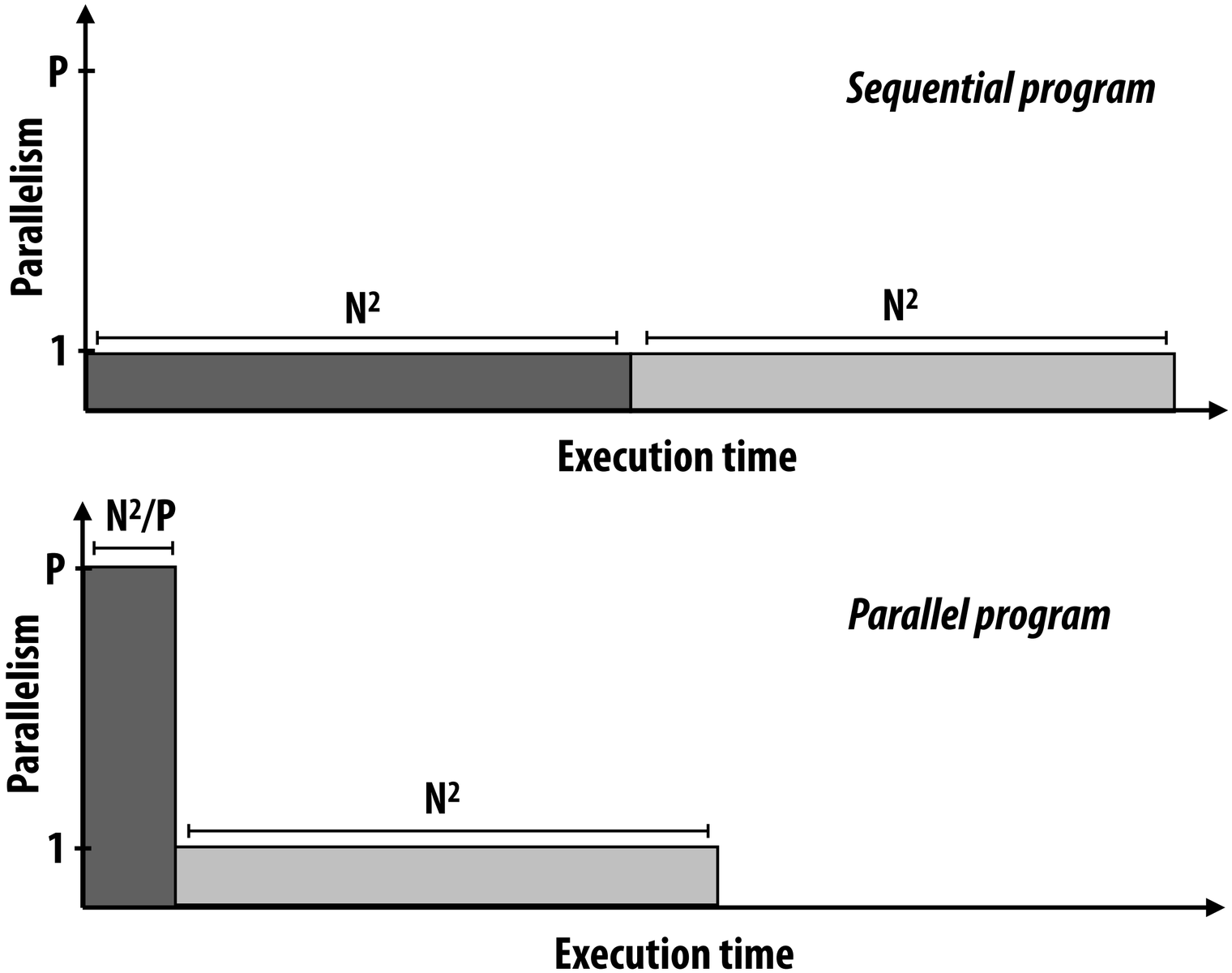
- Sequential implementation
  - Both phases take N^2 time: total is $2N^2$



First attempt at parallelism (P processors)

- **Strategy:**
  - Phase 1: execute in parallel
    - time for phase 1: N^2/P
  - Phase 2: execute serially
    - time for phase 2: N^2

- **Overall performance:**
  - Speedup $\leq \frac{2n^2}{\frac{n^2}{p} + n^2}$
  - Speedup ≤ 2

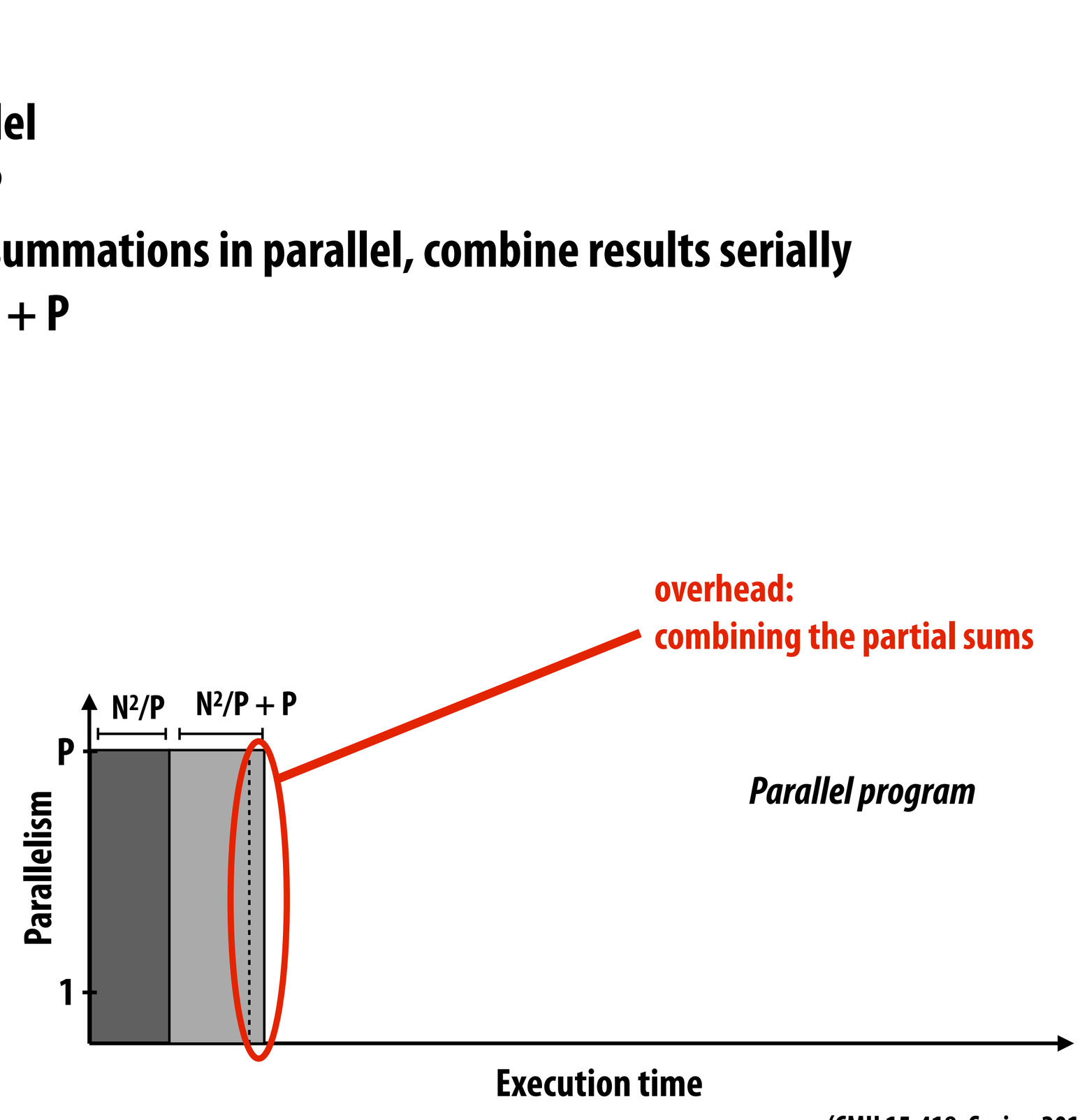


Parallelizing phase 2

- **Strategy:**
  - Phase 1: execute in parallel
    - time for phase 1: N^2/P
  - Phase 2: execute partial summations in parallel, combine results serially
    - time for phase 2: $N^2/P + P$

- **Overall performance:**
  - Speedup $\leq \dfrac{2n^2}{\frac{2n^2}{p} + p}$

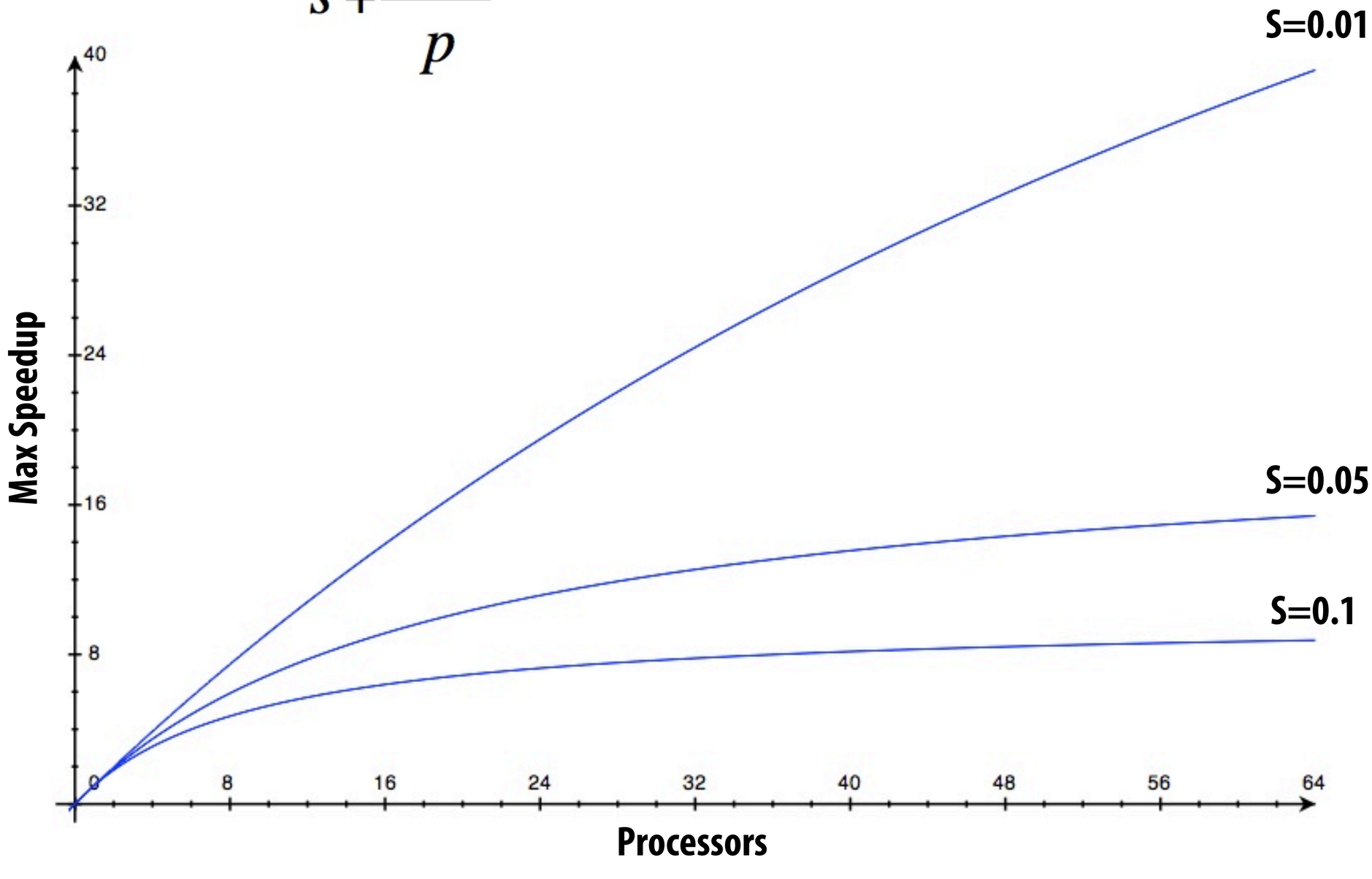
Note: speedup → P when N >> P



Amdahl's law

- Let S = the fraction of sequential execution that is inherently sequential
- Max speedup on P processors given by:

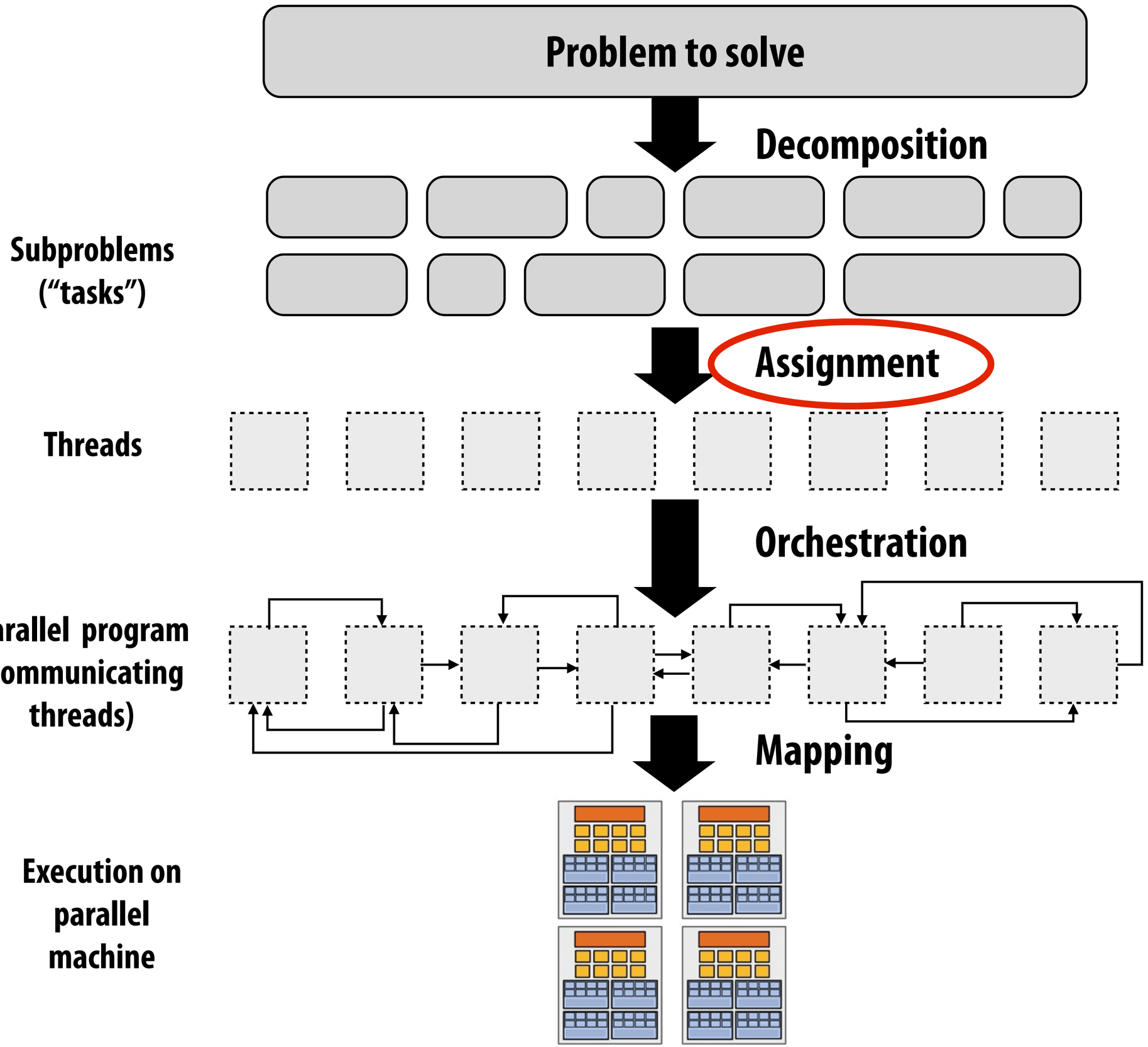
$$\text{speedup} \leq \frac{1}{s + \frac{1-s}{p}}$$



Decomposition

- Who is responsible for performing decomposition?
  - In many cases: the programmer
  - Lots and lots of research on automatic decomposition of sequential programs (very hard in general case)
    - Compiler analyzes program, determines dependencies
      - What if dependencies are data-dependent?
  - Success with simple loops, loop nests
  - The "magic parallelizing compiler" has never materialized

Assignment


Problem to solve
Decomposition
Subproblems ("tasks")
Assignment
Threads
Orchestration
Parallel program (communicating threads)
Mapping
Execution on parallel machine

Assignment

- Assigning tasks to threads
  - Think of the threads as "workers"

- Goals: balance workload, reduce communication costs

- Can be performed statically, or dynamically during execution

- While programmer often responsible for decomposition many languages/runtimes take responsibility for assignment.

Assignment examples in ISPC

```
export void sinx(
    uniform int N,
    uniform int terms,
    uniform float* x,
    uniform float* result)
{
    // assumes N % programCount = 0
    for (uniform int i=0; i<N; i+=programCount)
    {
        int idx = i + programIndex;
        float value = x[idx];
        float numer = x[idx] * x[idx] * x[idx];
        uniform int denom = 6;  // 3!
        uniform int sign = -1;

        for (uniform int j=1; j<=terms; j++)
        {
            value += sign * numer / denom
            numer *= x[idx] * x[idx];
            denom *= (j+3) * (j+4);
            sign *= -1;
        }
        result[i] = value;
    }
}
```

Decomposition by loop iteration

Programmer managed assignment:

- **Static assignment**
- **Assign iterations to instances in interleaved fashion**

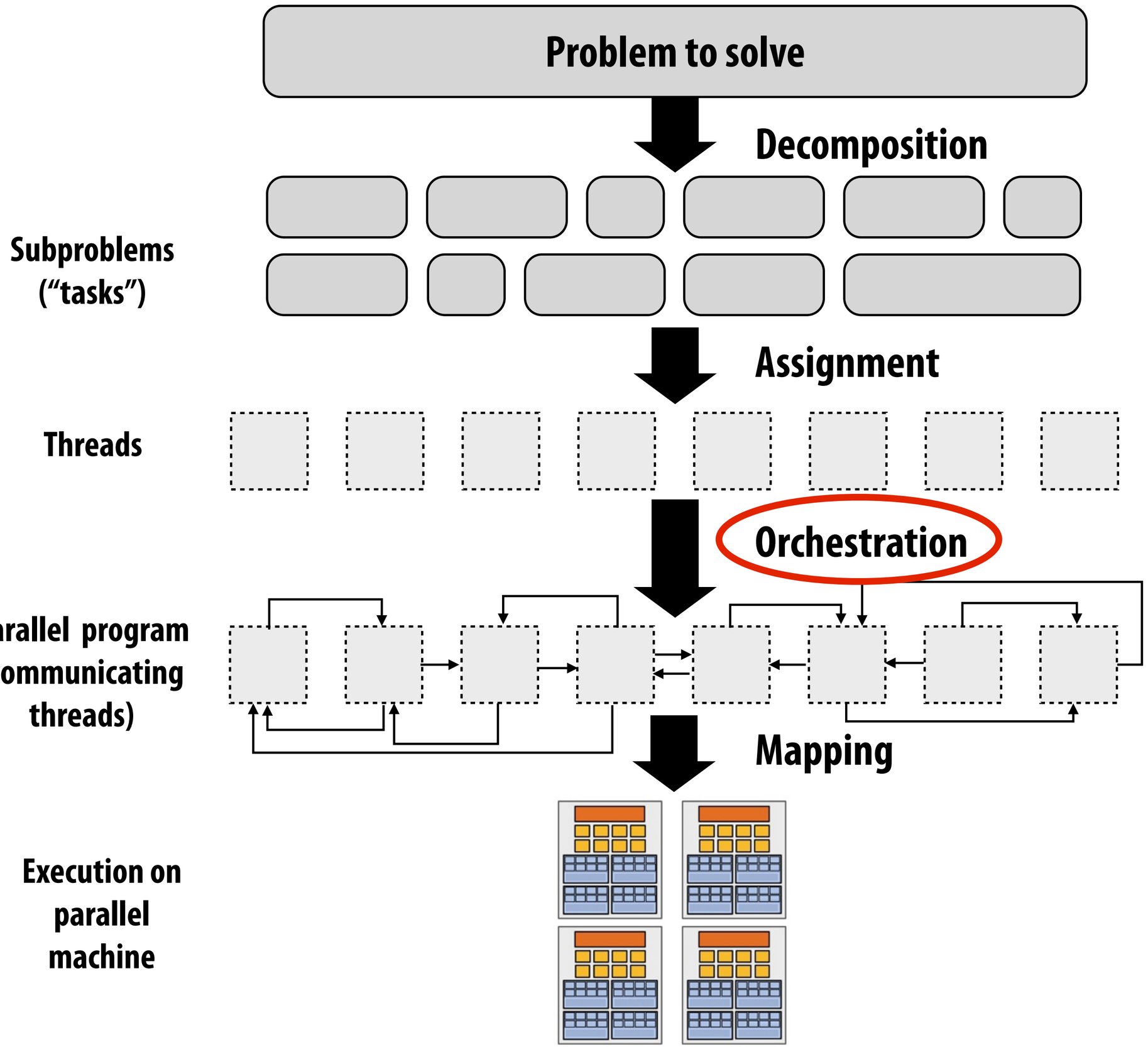
```
export void sinx(
    uniform int N,
    uniform int terms,
    uniform float* x,
    uniform float* result)
{
    foreach (i = 0 ... N)
    {
        float value = x[i];
        float numer = x[i] * x[i] * x[i];
        uniform int denom = 6;  // 3!
        uniform int sign = -1;

        for (uniform int j=1; j<=terms; j++)
        {
            value += sign * numer / denom
            numer *= x[i] * x[i];
            denom *= (j+3) * (j+4);
            sign *= -1;
        }
        result[i] = value;
    }
}
```

Decomposition by loop iteration

Foreach construct exposes independent tasks to system

System-manages assignment of iterations to instances

Orchestration



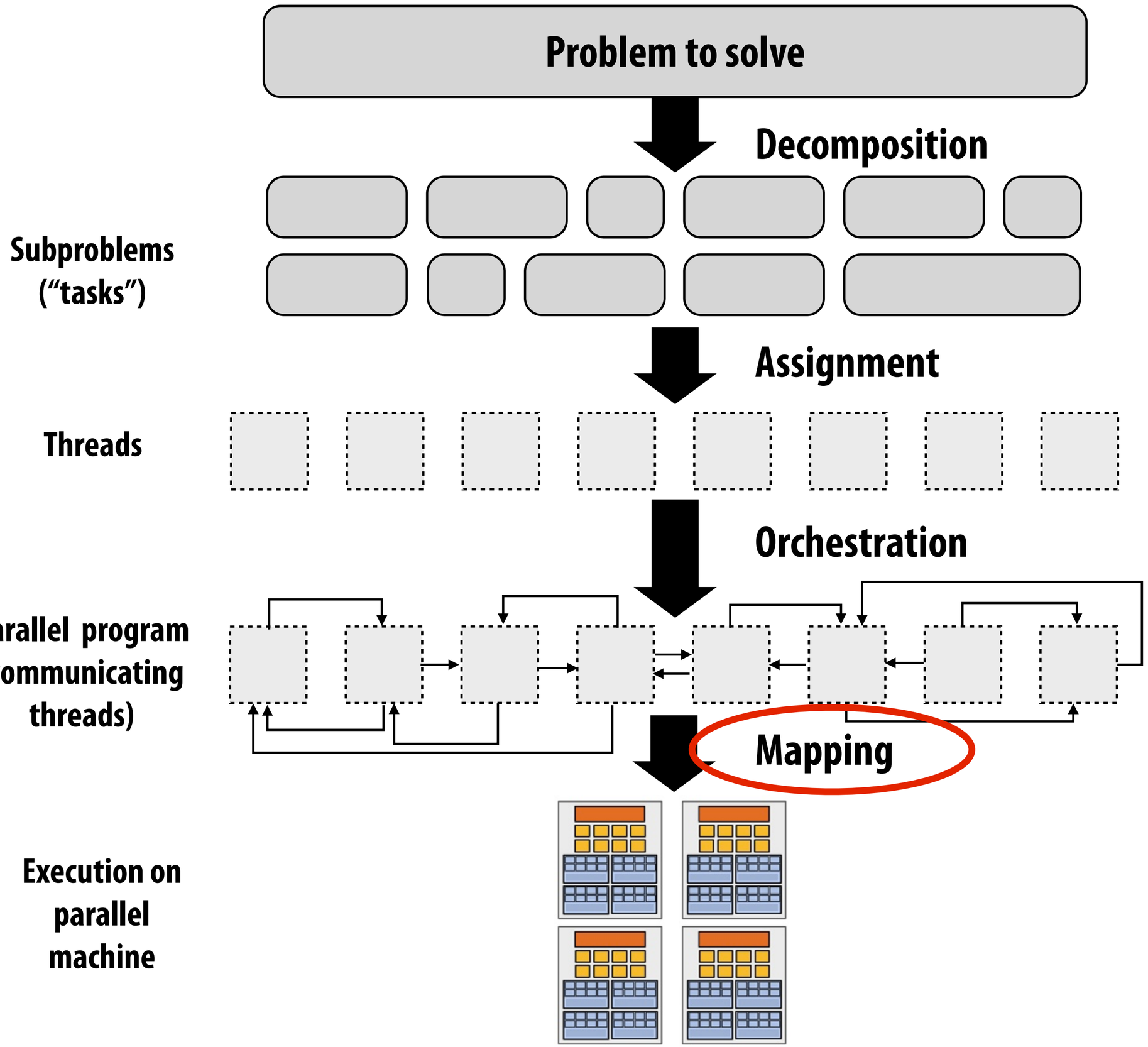
Orchestration

- Involves:
  - Structuring communication
  - Adding synchronization to preserve dependencies
  - Organizing data structures in memory, scheduling tasks

- Goals: reduce costs of communication/sync, preserve locality of data reference, reduce overhead, etc.

- Machine details impact many of these decisions
  - If synchronization is expensive, might use it more sparsely

Mapping

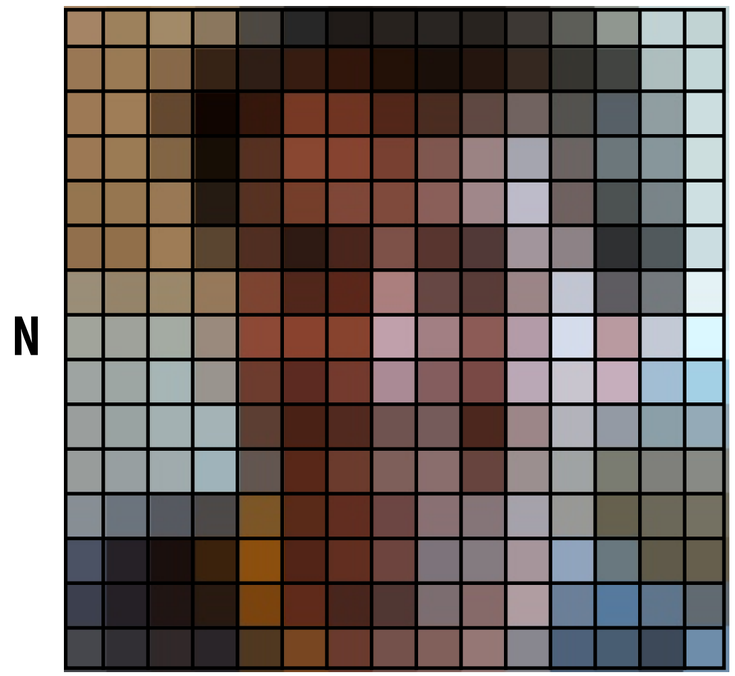

Problem to solve
Decomposition
Subproblems ("tasks")
Assignment
Threads
Orchestration
Parallel program (communicating threads)
Mapping
Execution on parallel machine

Mapping

- Mapping "threads" to execution units
- Usually a job for the OS
- Many mapping decisions are trivial in parallel programs
  - Parallel application uses the entire machine
  - So oversubscribing machine with multiple parallel apps is not common

- More interesting mapping decisions:
  - Place related threads (cooperating threads) on the same processor (maximize locality, data sharing, minimize costs of comm/sync)
  - Mapping of ISPC instances to vector ALUs

Decomposing/assigning computation or data?



Often, the reason a problem requires lots of computation (and needs to be parallelized) is that it involves a lot of data.

I've described the process of parallelizing programs as an act of partitioning computation

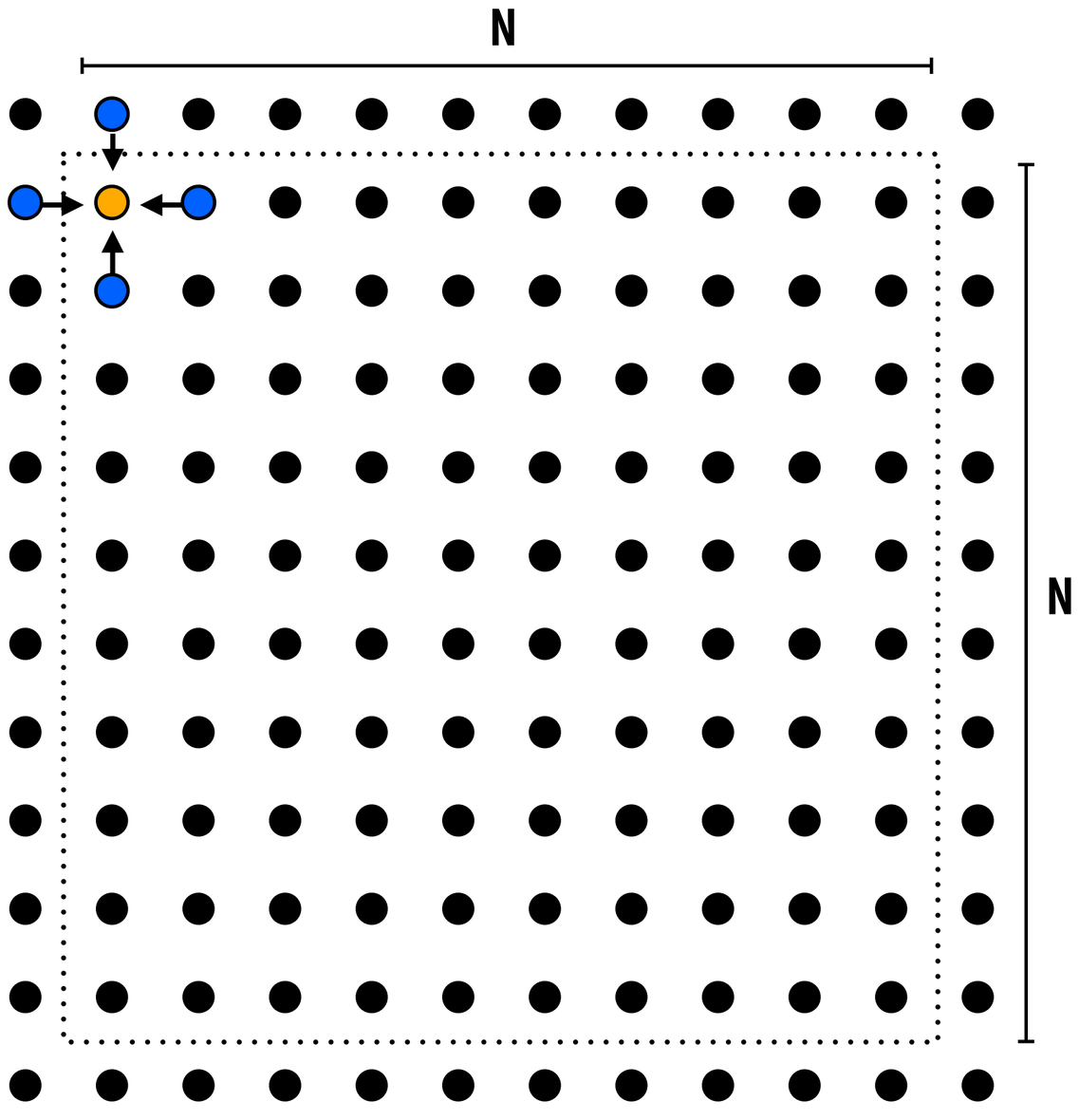
Often equally valid to think of partitioning data. (computations go with the data)

But there are many computations where the correspondence between "tasks" and data is less clear. In these cases it's natural to think of partitioning computation.

A parallel programming example

Grid-based solver

- Solve partial differential equation on N+2 x N+2 grid
- Iterative solution
  - Perform Gauss-Seidel sweeps over grid until convergence



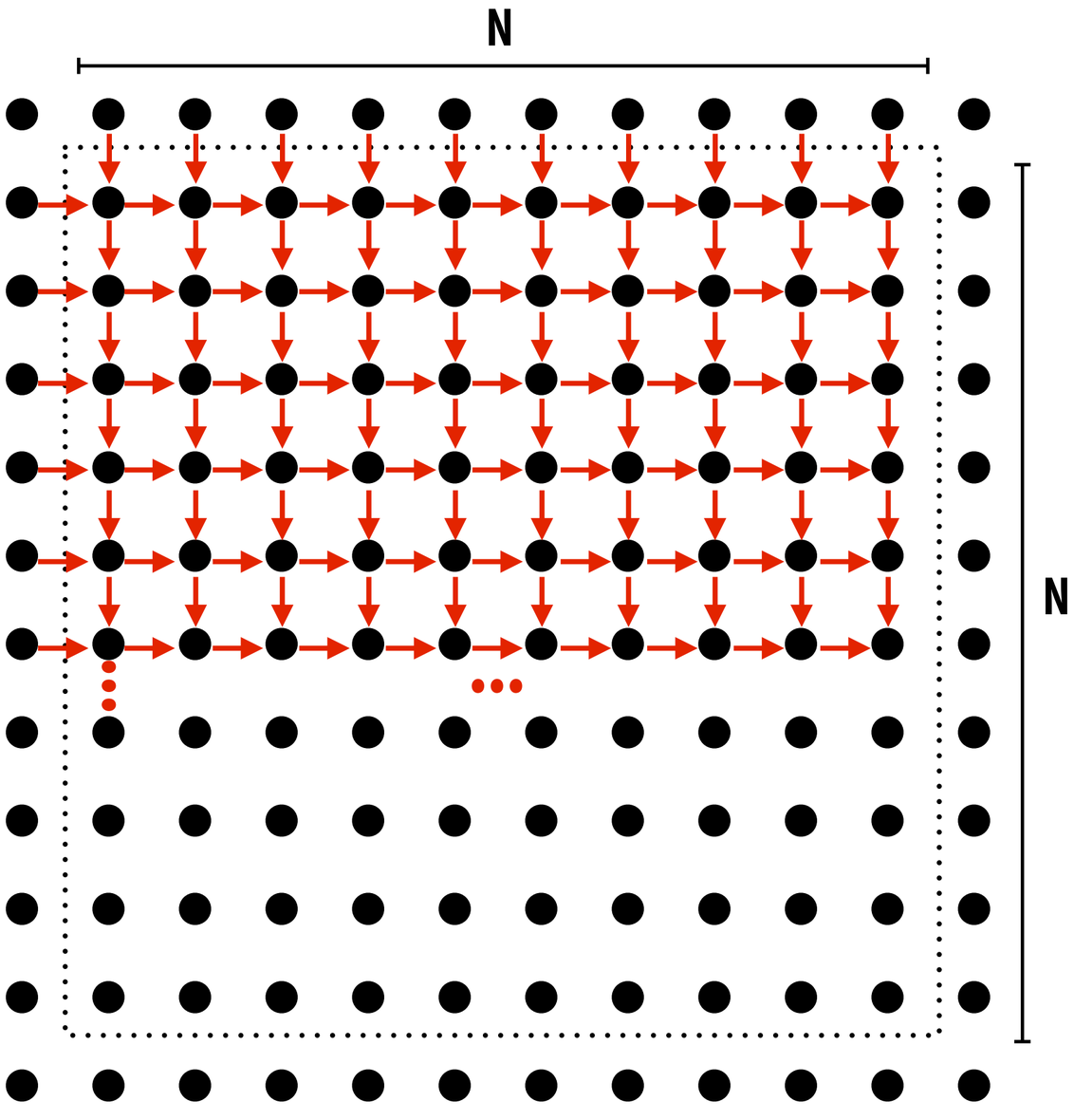

```
A[i,j] = 0.2 * A[i,j] + A[i,j-1] + A[i-1,j]
                      + A[i,j+1] + A[i+1,j];
```

Grid solver algorithm

(generic syntax: to match textbook)

```
1.  int n;                                  /*size of matrix: (n + 2-by-n + 2) elements*/
2.  float **A, diff = 0;

3.  main()
4.  begin
5.     read(n) ;                            /*read input parameter: matrix size*/
6.     A ← malloc (a 2-d array of size n + 2 by n + 2 doubles);
7.     initialize(A);                       /*initialize the matrix A somehow*/
8.     Solve (A);                           /*call the routine to solve equation*/
9.  end main

10. procedure Solve (A)                     /*solve the equation system*/
11.    float **A;                           /*A is an (n + 2)-by-(n + 2) array*/
12. begin
13.    int i, j, done = 0;
14.    float diff = 0, temp;
15.    while (!done) do                     /*outermost loop over sweeps*/
16.       diff = 0;                         /*initialize maximum difference to 0*/
17.       for i ← 1 to n do                 /*sweep over nonborder points of grid*/
18.          for j ← 1 to n do
19.             temp = A[i,j];             /*save old value of element*/
20.             A[i,j] ← 0.2 * (A[i,j] + A[i,j-1] + A[i-1,j] +
21.                A[i,j+1] + A[i+1,j]); /*compute average*/
22.             diff += abs(A[i,j] - temp);
23.          end for
24.       end for
25.       if (diff/(n*n) < TOL) then done = 1;
26.    end while
27. end procedure
```

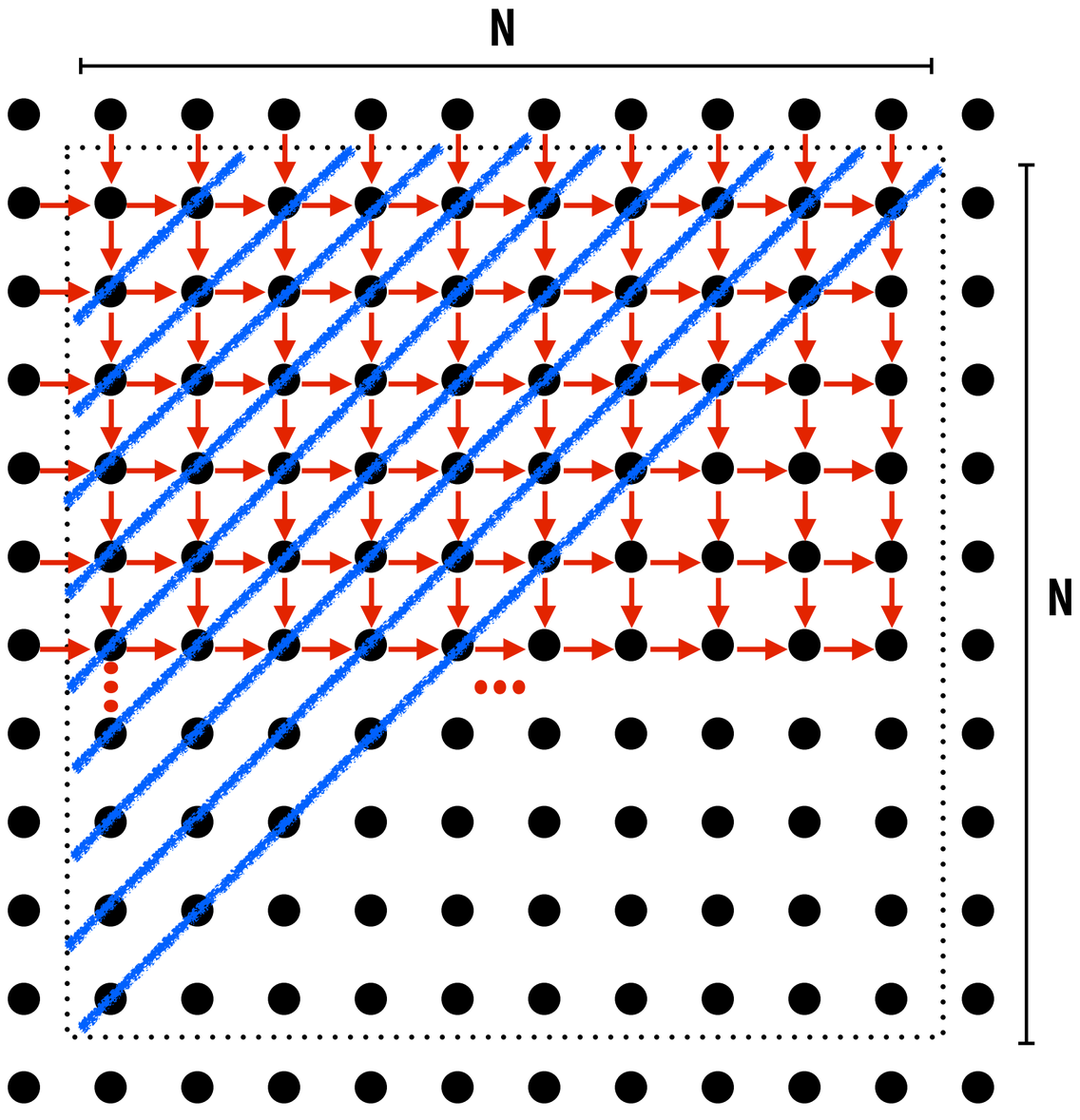
Step 1: identify dependencies (problem decomposition phase)



Each row element depends on element to left.

Each column depends on previous column.

Step 1: identify dependencies (problem decomposition phase)



Parallelism along the diagonals.

Good: parallelism exists!

Possible strategy:

1. **Partition grid cells on a diagonal into tasks**
2. **Update values in parallel**
3. **When complete, move to next diagonal**

Bad: hard to exploit

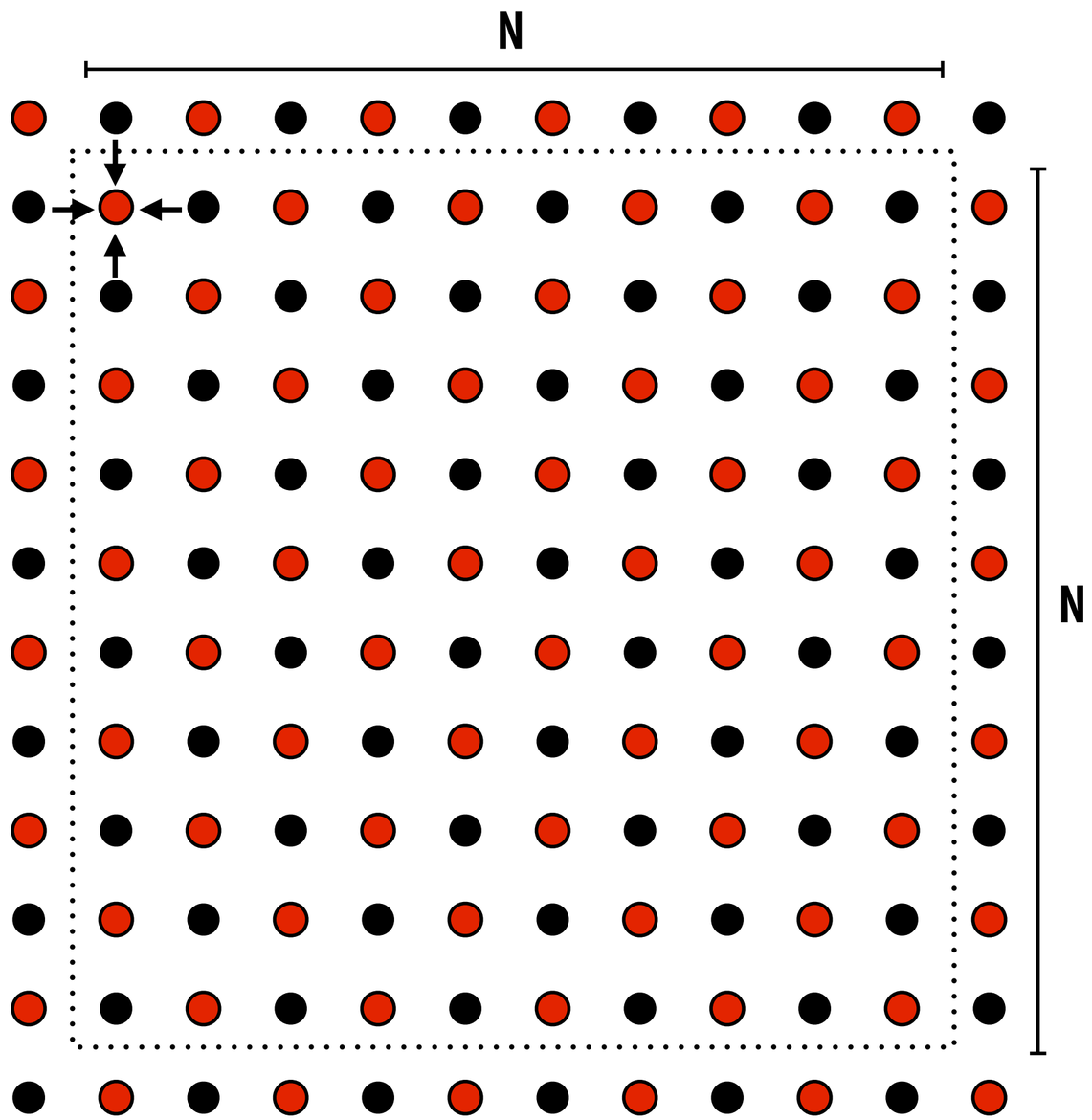
- **Early in computation: not much parallelism**
- **Frequent synchronization (each diagonal)**

Key idea: change algorithm

- Change order grid cell cells are updated
- Iterates to (approximately) same solution, but converges to solution differently
  - Note: floating point values computed are different, but solution still converges to within error threshold
- Domain knowledge: needed knowledge of Gauss-Seidel iteration to realize this change is okay for application's needs

Exploit application knowledge

Reorder grid traversal: red-black coloring

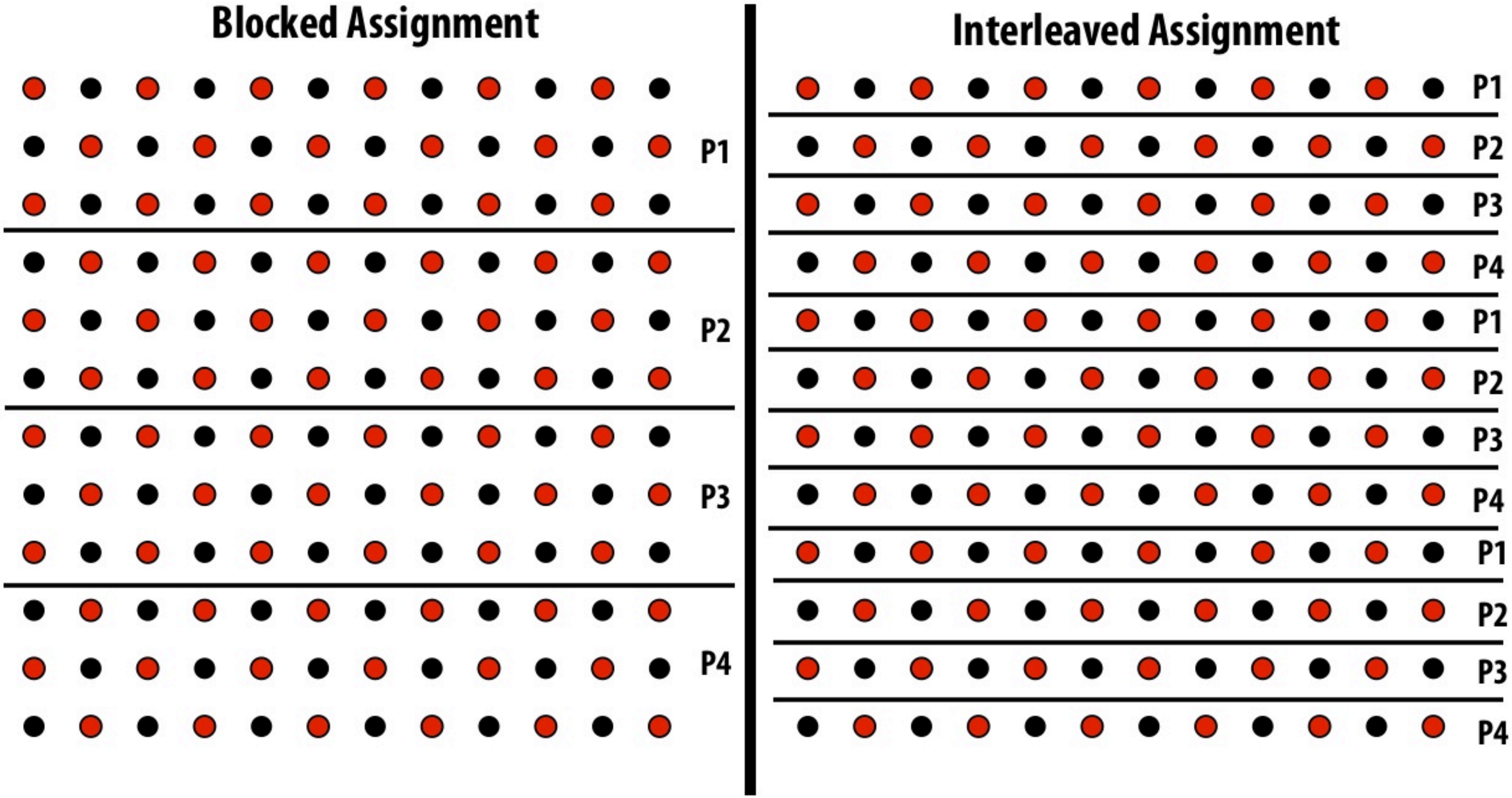


Update all red cells in parallel

When done, update all black cells in parallel
(dependency on red cells)

Repeat until convergence

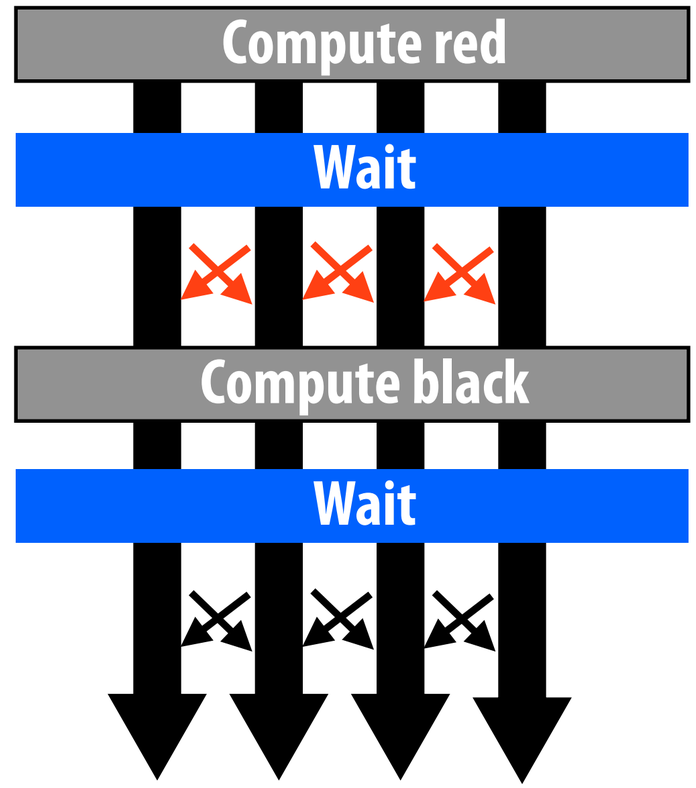
Assignment



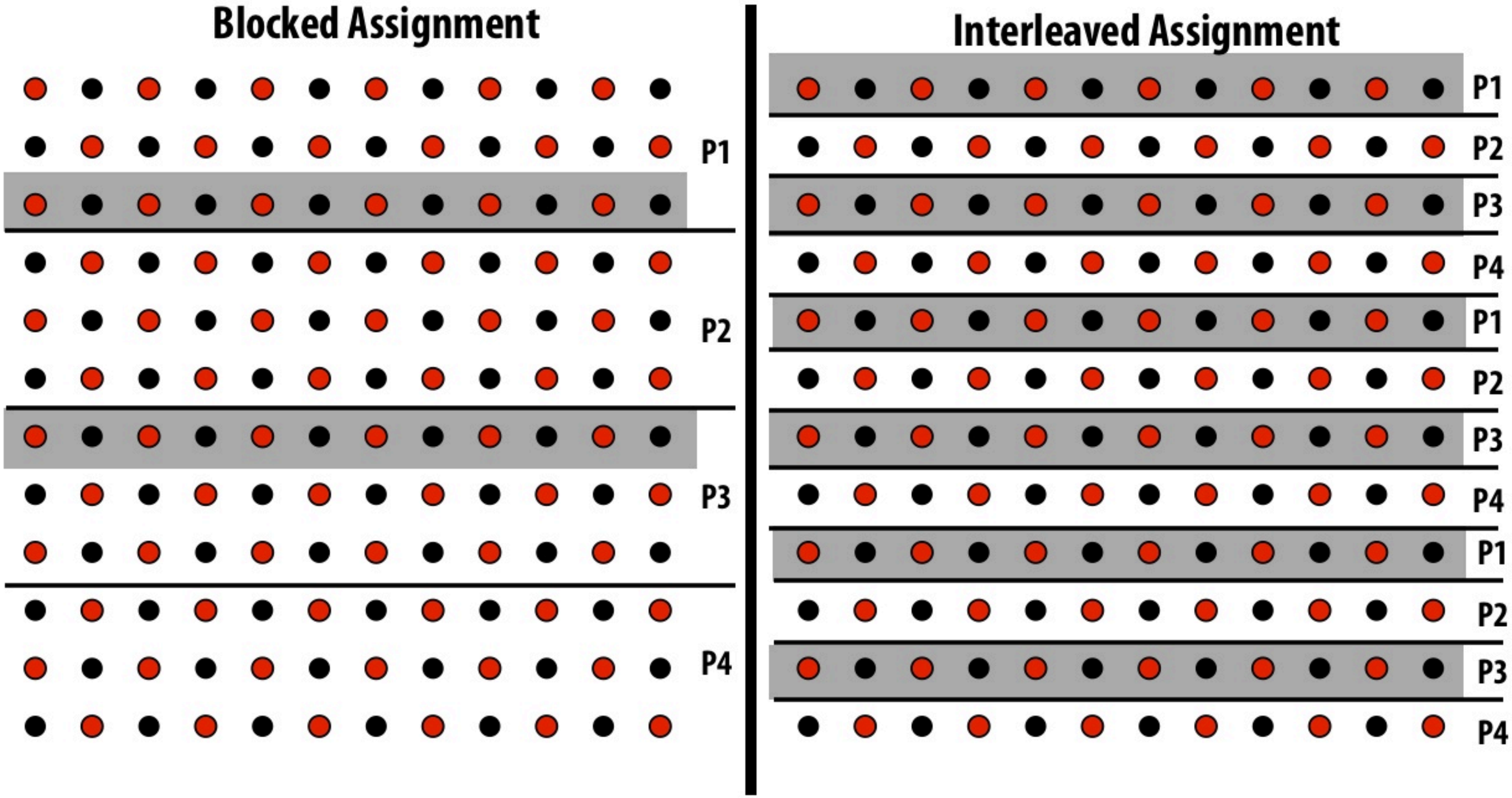
Which is better? Does it matter?

Consider dependencies (data flow)

1. Perform red update in parallel
2. Wait until all processors done
3. Communicate updated red cells to other processors
4. Perform black update in parallel
5. Wait until all processors done
6. Communicate updated black cells to other processors
7. Repeat



Assignment



= data that must be sent to P2 each iteration

Blocked assignment requires less data to be communicated between processors

Grid solver: data-parallel expression

To simplify code: we've dropped red-black separation, now ignoring dependencies (follows textbook section 2.3)

```
1.  int n, nprocs;                          /*grid size (n + 2-by-n + 2) and number of processes*/
2.  float **A, diff = 0;

3.  main()
4.  begin
5.    read(n); read(nprocs);      ;         /*read input grid size and number of processes*/
6.    A ← G_MALLOC (a 2-d array of size n+2 by n+2 doubles);
7.    initialize(A);                        /*initialize the matrix A somehow*/
8.    Solve (A);                            /*call the routine to solve equation*/
9.  end main

10. procedure Solve(A)                      /*solve the equation system*/
11.     float **A;                          /*A is an (n + 2-by-n + 2) array*/
12.   begin
13.   int i, j, done = 0;
14.   float mydiff = 0, temp;
14a.    DECOMP A[BLOCK,*, nprocs];
15.   while (!done) do                      /*outermost loop over sweeps*/
16.     mydiff = 0;                         /*initialize maximum difference to 0*/
17.     for_all i ← 1 to n do               /*sweep over non-border points of grid*/
18.       for all j ← 1 to n do
19.         temp = A[i,j];                  /*save old value of element*/
20.         A[i,j] ← 0.2 * (A[i,j] + A[i,j-1] + A[i-1,j] +
21.           A[i,j+1] + A[i+1,j]);         /*compute average*/
22.         mydiff += abs(A[i,j] - temp);
23.       end for_all
24.     end for_all
24a.      REDUCE (mydiff, diff, ADD);
25.     if (diff/(n*n) < TOL) then done = 1;
26.   end while
27. end procedure
```

assignment: specified explicitly (block assignment)

decomposition: tasks are individual elements

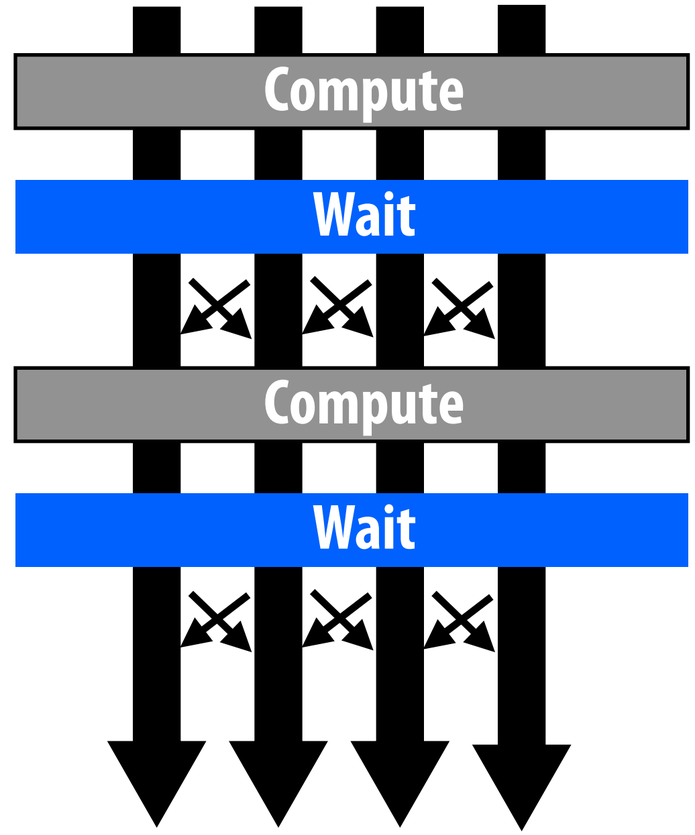
Orchestration: handled by system

(End of for_all block is implicit wait for all workers before returning to sequential control)

Shared address space solver

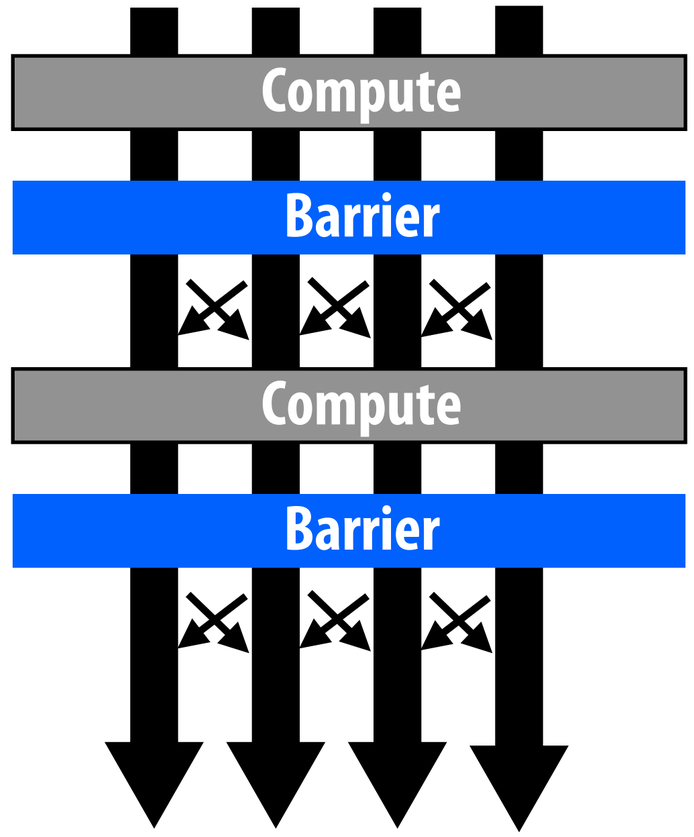
SPMD execution model

- Programmer responsible for synchronization
- Common synchronization primitives:
  - Locks (mutual exclusion): only one thread in the critical region at a time
  - Barriers: wait for threads to reach this point



Barrier

- `Barrier(nthreads)`
- Barriers are a conservative way to express dependencies
- Barriers divide computation into phases
- All computations by all threads before the barrier complete before any computation in any thread after the barrier begins



Shared address space solver (SPMD execution model)

```
LOCKDEC(diff_lock);          /*declaration of lock to enforce mutual exclusion*/
BARDEC (bar1);               /*barrier declaration for global synchronization between
                             sweeps*/

procedure Solve(A)
   float **A;                                  /*A is entire n+2-by-n+2 shared array,
                                               as in the sequential program*/
begin
   int i,j, pid, done = 0;
   float temp, mydiff = 0;                     /*private variables*/
   int mymin = 1 + (pid * n/nprocs);           /*assume that n is exactly divisible by*/
   int mymax = mymin + n/nprocs - 1            /*nprocs for simplicity here*/

   while (!done) do                            /*outer loop over all diagonal elements*/
      mydiff = diff = 0;                       /*set global diff to 0 (okay for all to do it)*/
   BARRIER(bar1, nprocs);
      for i ← mymin to mymax do                /*for each of my rows*/
            for j ← 1 to n do                  /*for all nonborder elements in that row*/
            temp = A[i,j];
            A[i,j] = 0.2 * (A[i,j] + A[i,j-1] + A[i-1,j] +
               A[i,j+1] + A[i+1,j]);
            mydiff += abs(A[i,j] - temp);
         endfor
      endfor
      LOCK(diff_lock);
      diff += mydiff;
      UNLOCK(diff_lock);
      BARRIER(bar1, nprocs);
      if (diff/(n*n) < TOL) then done = 1;     /*check convergence; all get
                                               same answer*/
      BARRIER(bar1, nprocs);
   endwhile
end procedure
```

Value of pid is different for each SPMD instance: use value to compute region of grid to work on

partial sum

Why are there so many barriers?

Need for mutual exclusion

- Each thread executes
  - load the value of diff into register r1
  - add the register r2 to register r1
  - store the value of register r1 into diff
- One possible interleaving: (let starting value of diff=0, r2=1)

T0	T1	
r1 ← diff		T0 reads value 0
	r1 ← diff	T1 reads value 0
r1 ← r1 + r2		T0 sets value of its r1 to 1
	r1 ← r1 + r2	T1 sets value of its r1 to 1
diff ←r1		T0 stores 1 to diff
	diff ←r1	T0 stores 1 to diff

- Need set of three instructions to be atomic

Mechanisms for atomicity

- lock/unlock mutex variable around critical section

```
LOCK(mylock);
// critical section
UNLOCK(mylock);
```

- Some languages have first-class support

```
atomic {
// critical section
}
```

- Intrinsics for hardware-supported atomic rd-modify-write operations

```
atomicAdd(x, 10);
```

- Access to critical section will be serialized across all threads
  - High contention will cause performance problems (recall Amdahl's Law)
  - Note partial accumulation into private `mydiff`

More on specifying dependencies

- Barriers: simple, but conservative (coarse granularity)
  - Everything done up until now must finish, then before next phase
- Specifying specific dependencies can increase performance (by revealing more parallelism)
  - Example: two threads. One produces a result, the other consumes it.

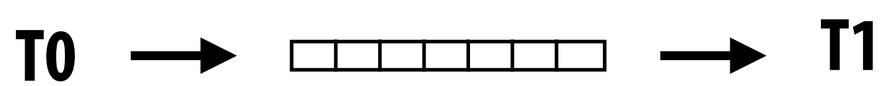
T0

```
// produce x, then let T1 know
X = 1;
flag = 1;
```

T1

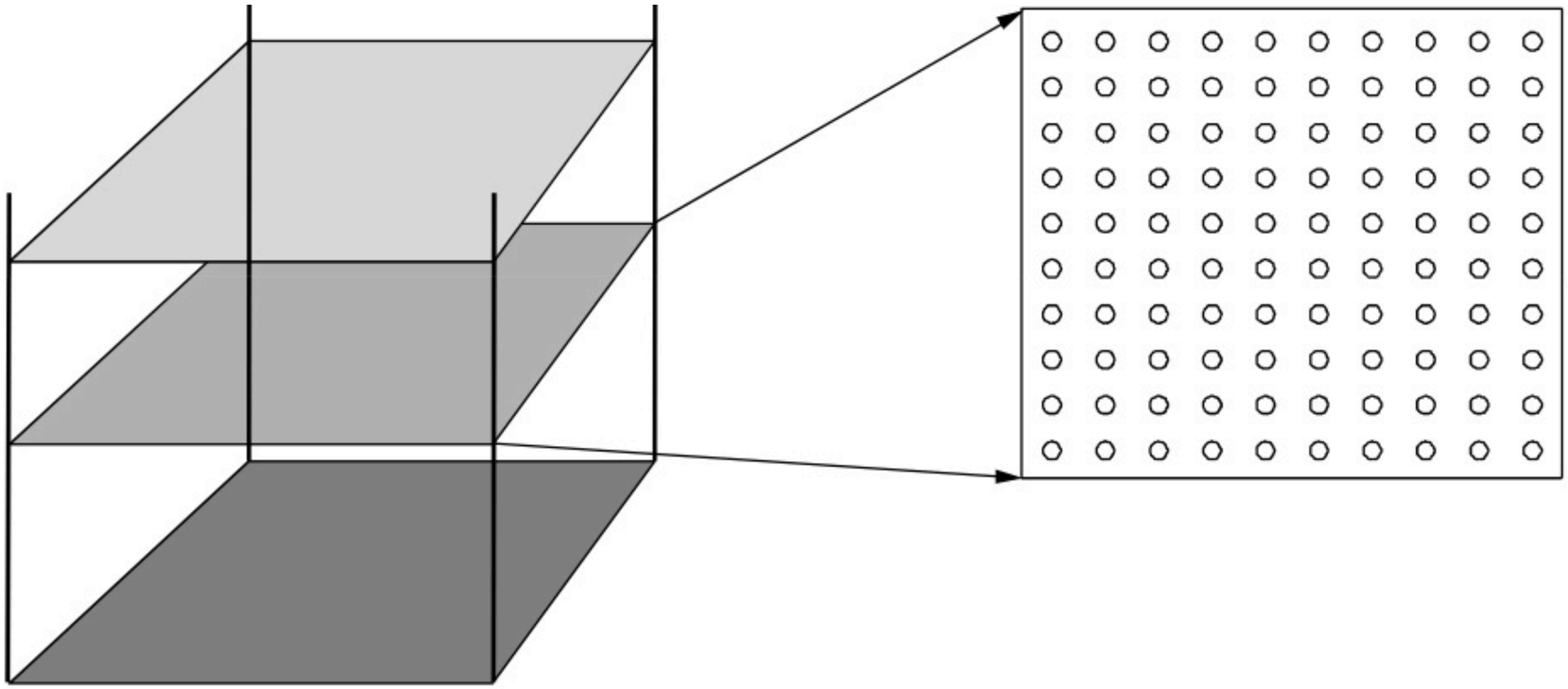
```
while (flag == 0);
print X;
```

- We just implemented a message queue



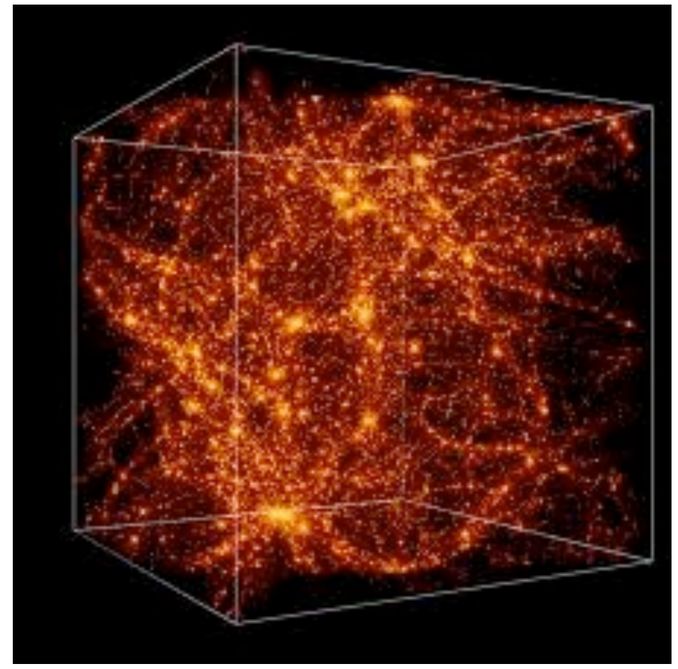
Next time: message passing version

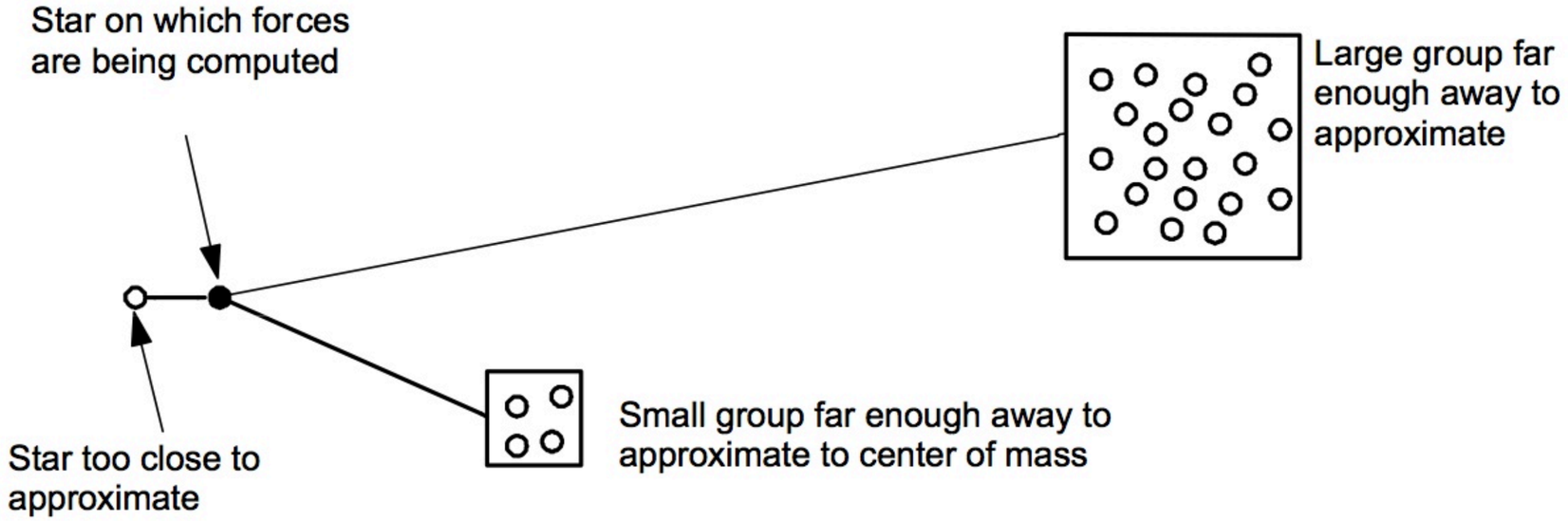
Example application 1: Modeling ocean currents



- Discretize ocean into slices represented as 2D grids
  - Toy example today (grid solver) was taken from this case study
- Discretize time evolution: Δt
- High accuracy simulation = small Δt and high resolution grids

Example application 2: Galaxy evolution





- Represent galaxy as a bunch of particles (think: particle = star)
- Compute forces due to gravity
  - Gravity has infinite extent: $O(N^2)$
  - But falls off with distance, so algorithm groups far away stars into aggregates
- N-body simulation: commonly used way to simulate fluids, molecular dynamics

Example application 3: Ray tracing

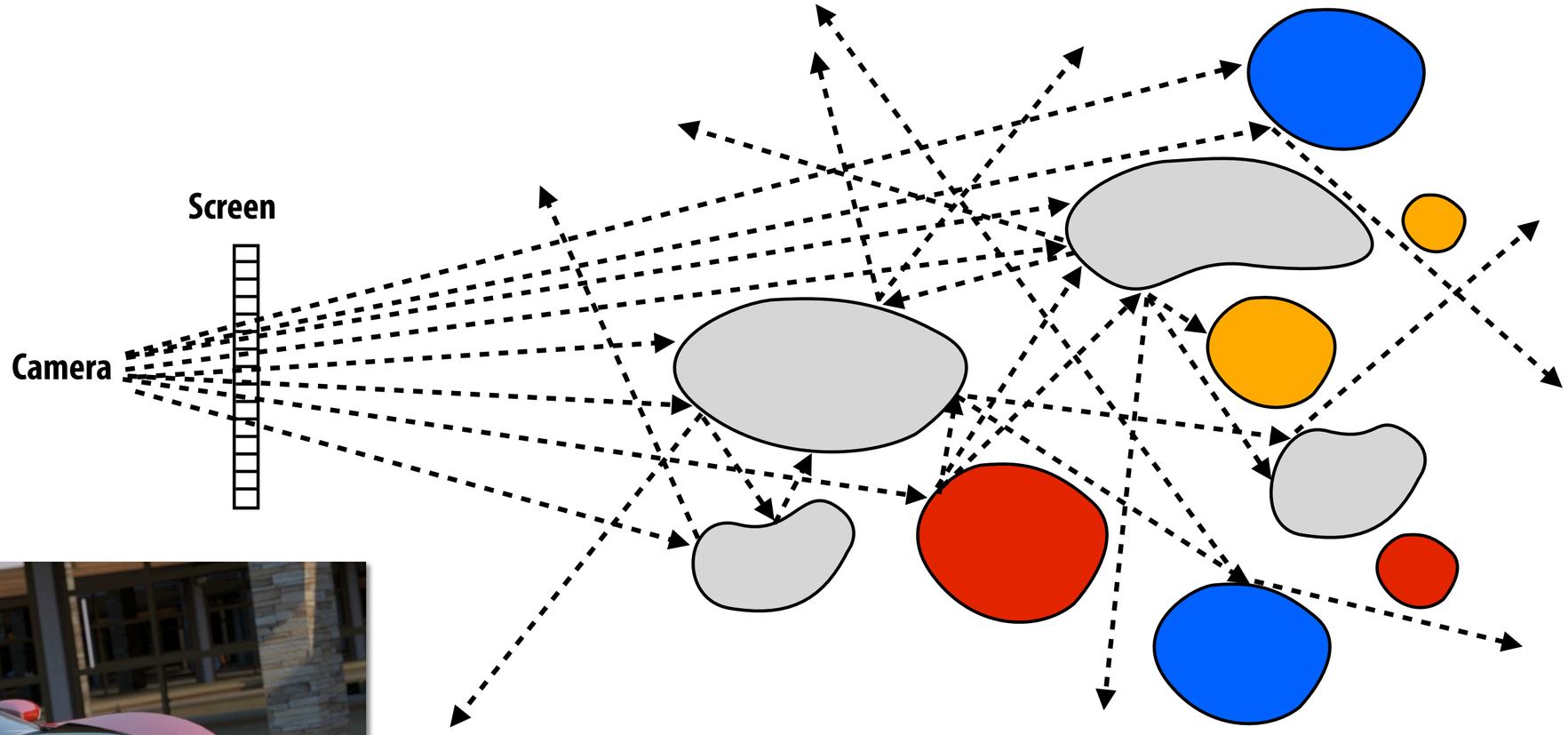


Image credit: NVIDIA
(this image can be rendered at "interactive rates" but not real-time yet)

Image Credit: Sony
(Cloudy With a Chance of Meatballs)

- Simulate propagation of light through scene to synthesize realistic images
- Compute amount of light traveling along rays

Summary

- **Amdahl's Law**
  - Overall speedup limited by amount of serial execution in code

- **Steps in creating a parallel program**
  - Decomposition, assignment, orchestrating, mapping
  - We'll talk a lot about making good decisions in each of these phases in coming lectures (in practice, very inter-related)

- **Focus today: identifying dependencies**
- **Focus soon: identifying locality**