Parallel programming models

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Georgia Tech Summer CRUISE Program
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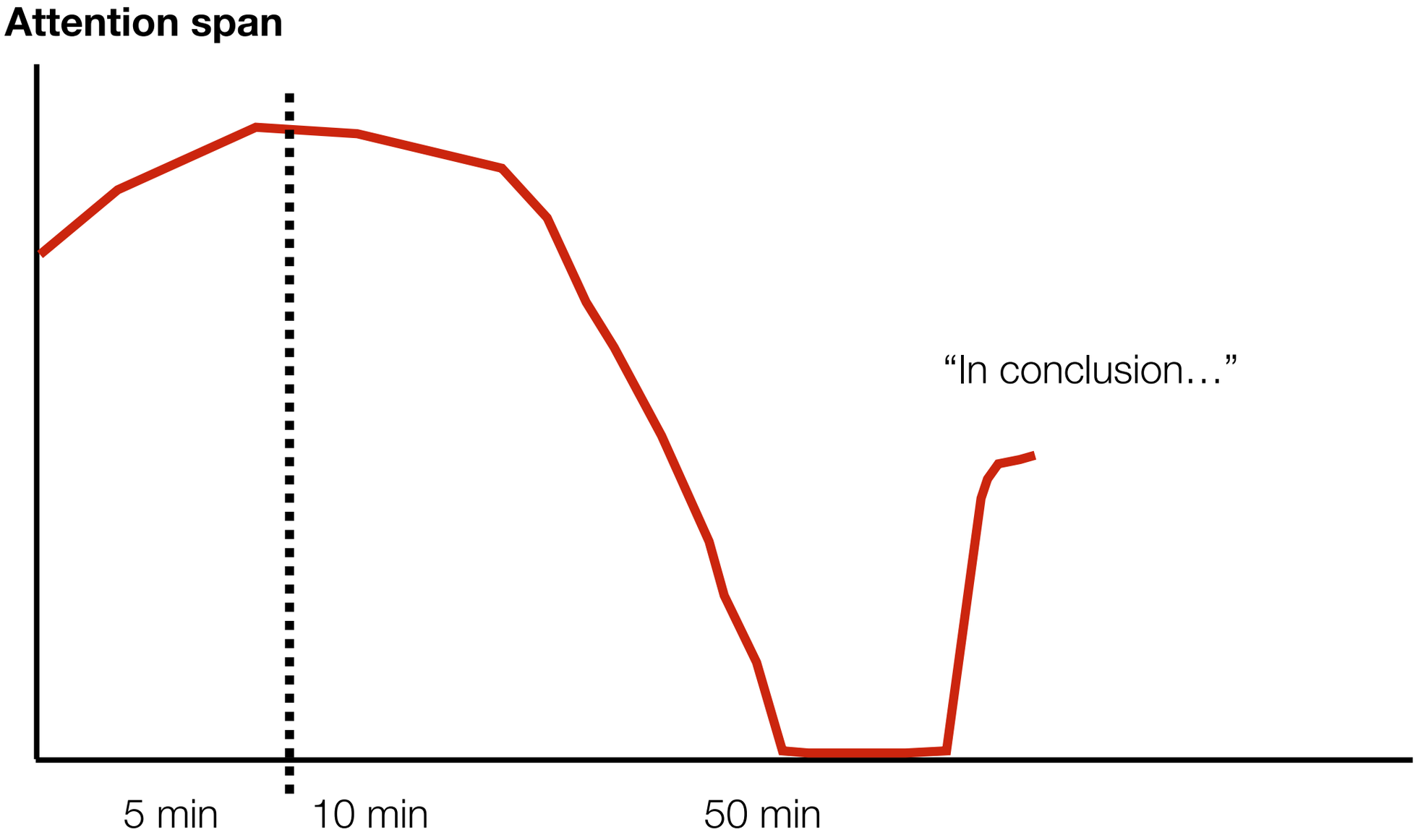
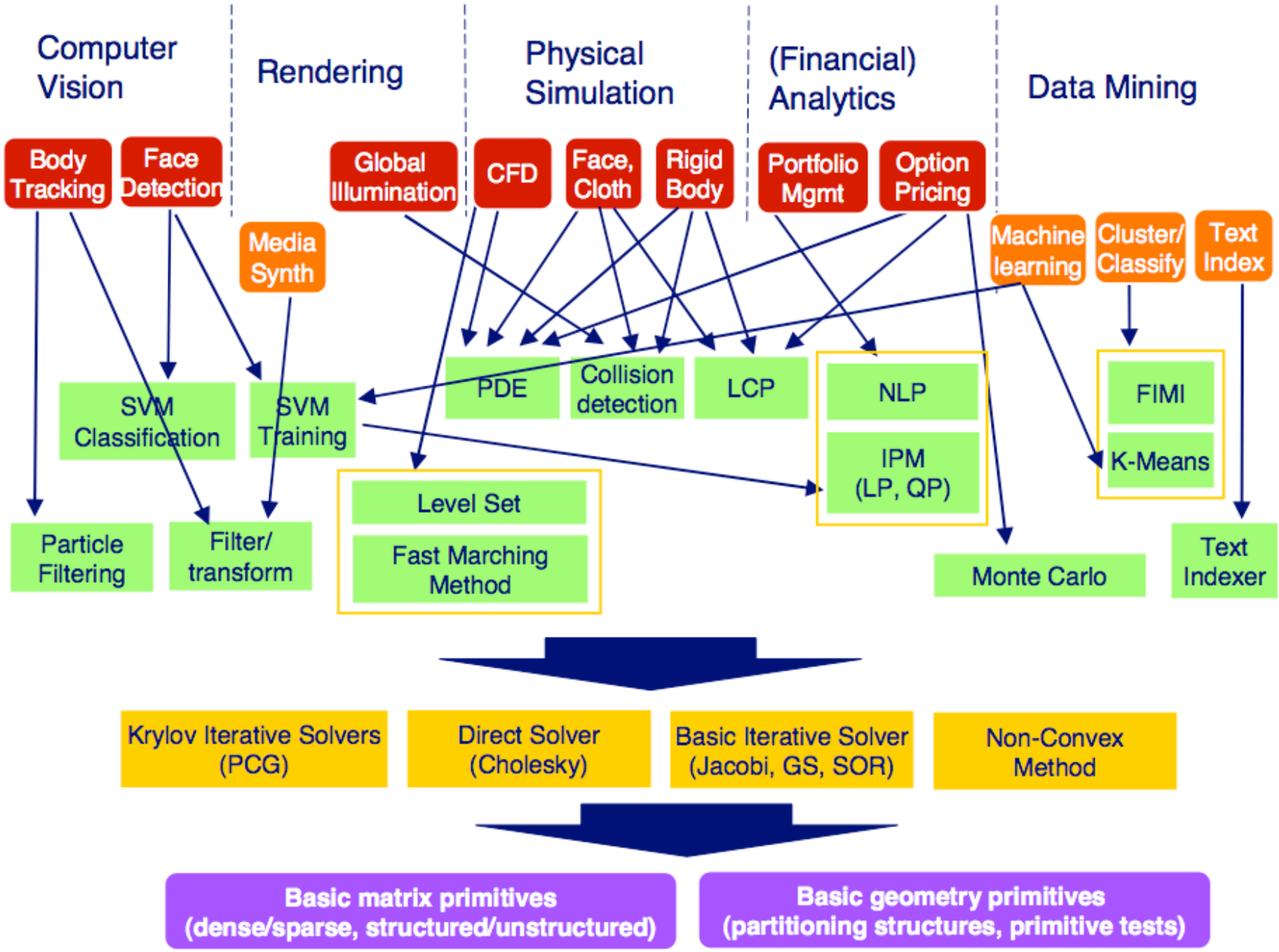


Patterson's Law of Attention Span

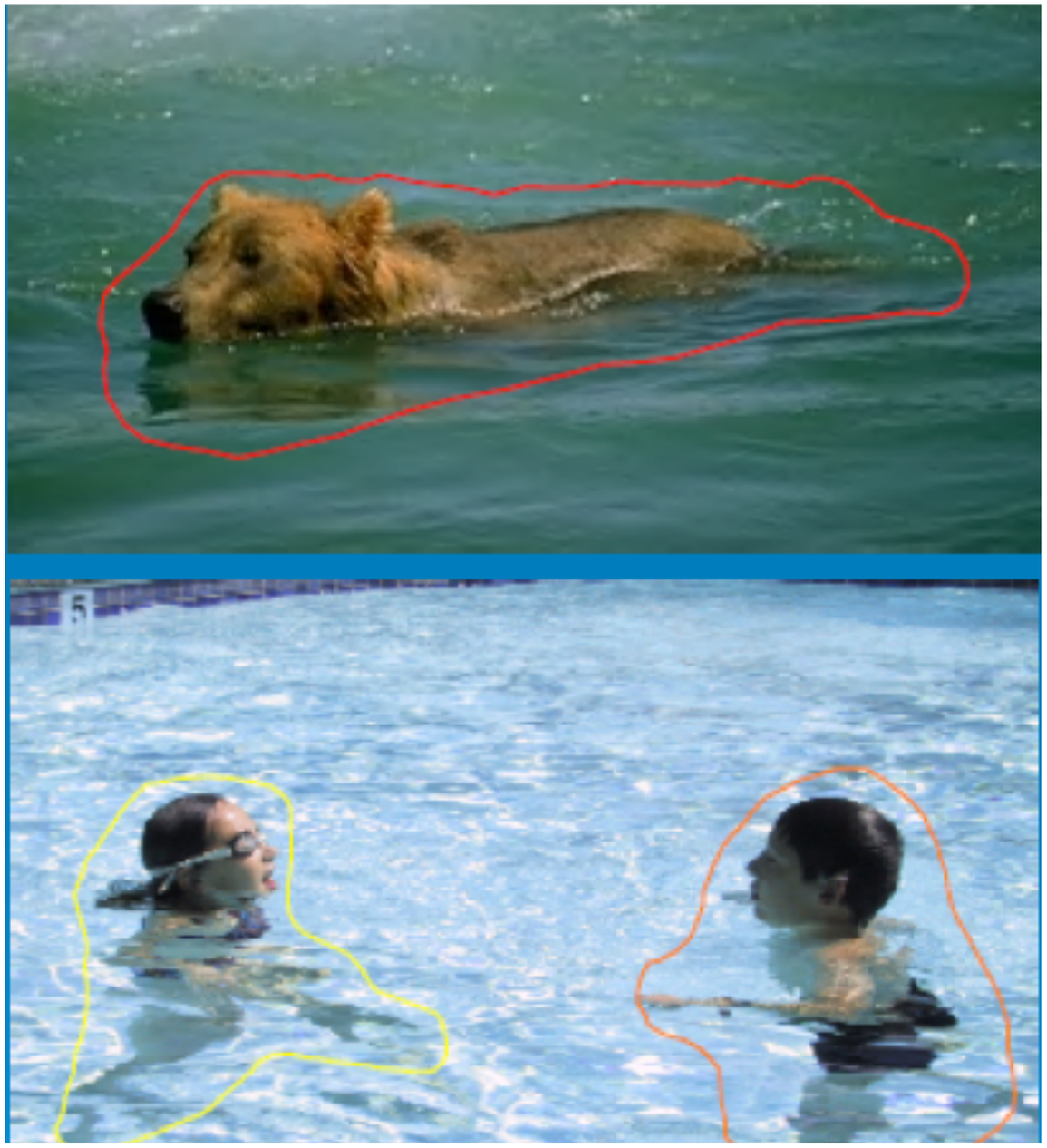
- Problem → parallel algorithm
- Programming models:
  Algorithms → implementation
- Looking forward: DARPA HPCS Languages

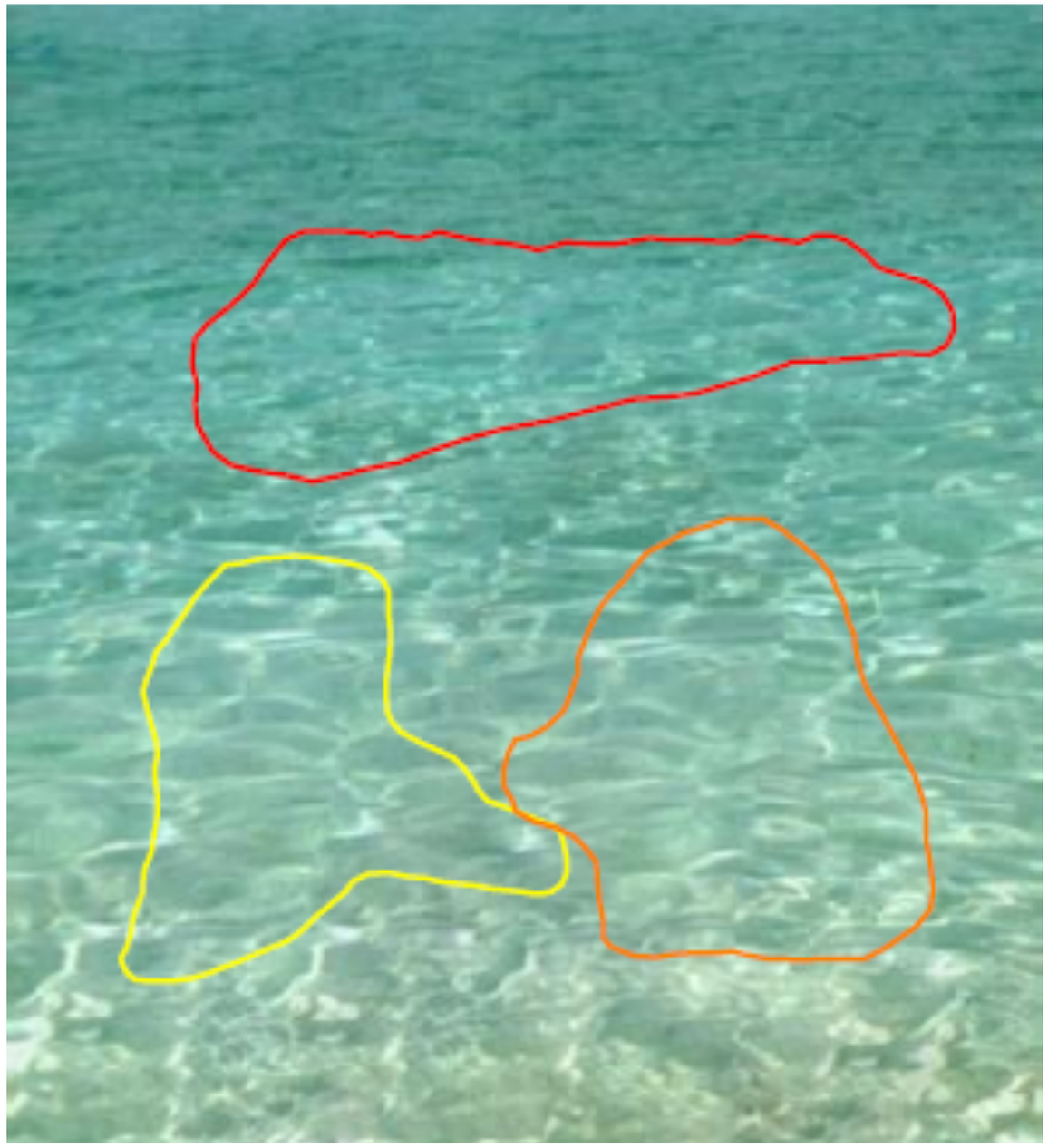
- **Problem → parallel algorithm**
- Programming models:
  Algorithms → implementation
- Looking forward: DARPA HPCS languages



Computationally intensive problems

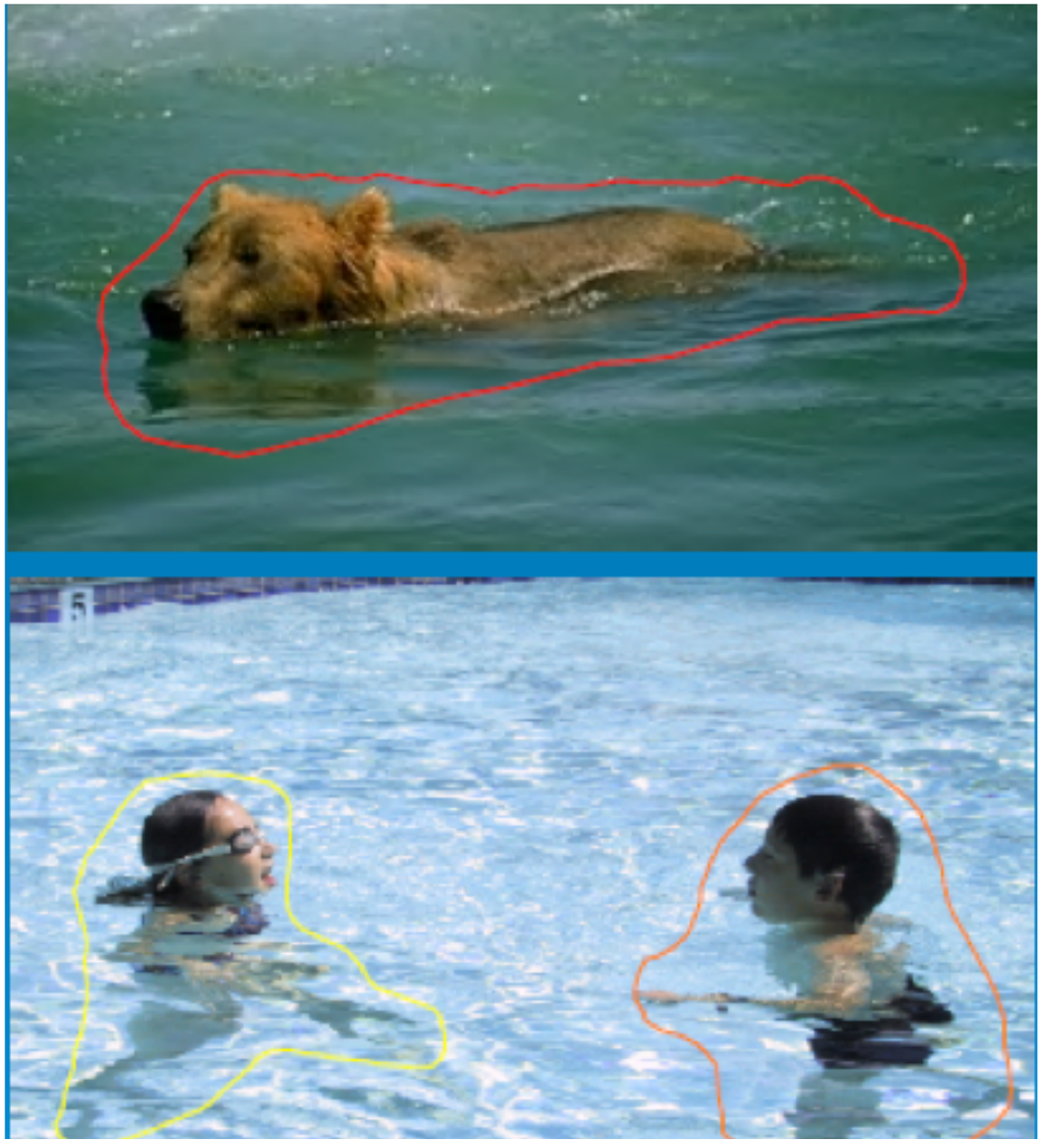
Source: Dubey, *et al.*, Intel (2005)





Problem:
Seamless image cloning

Perez, *et al.*, (SIGGRAPH 2003)



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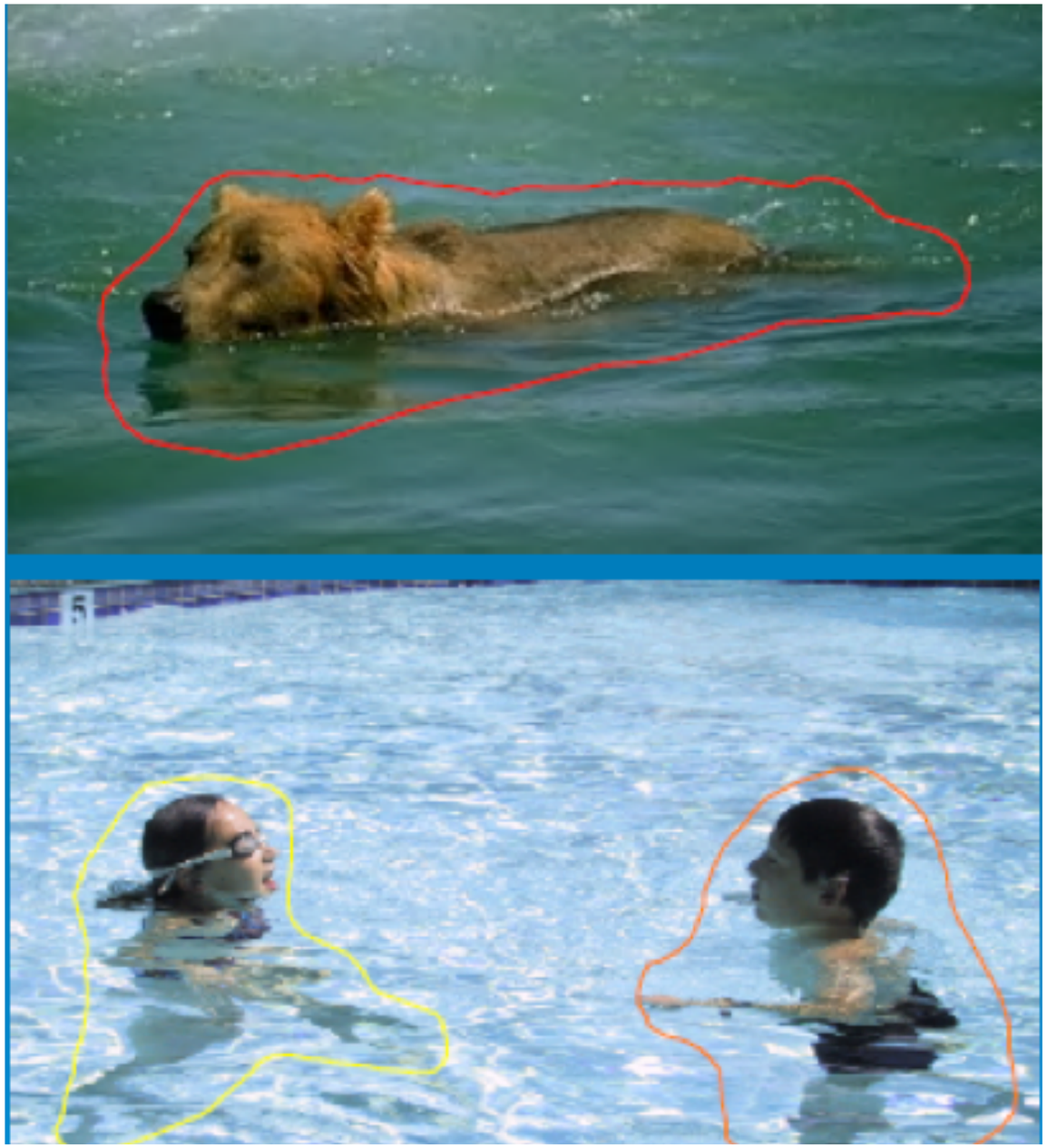
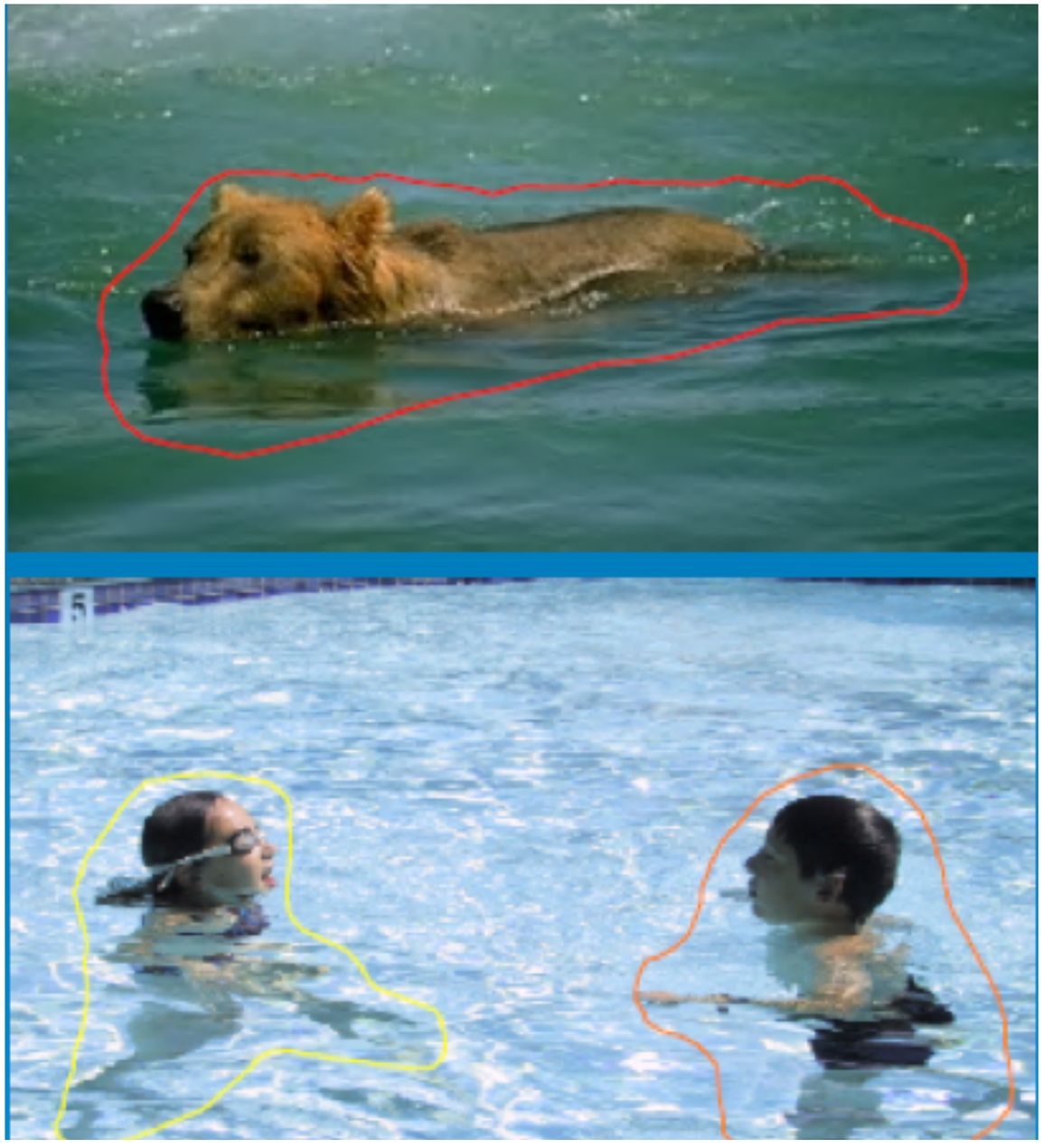


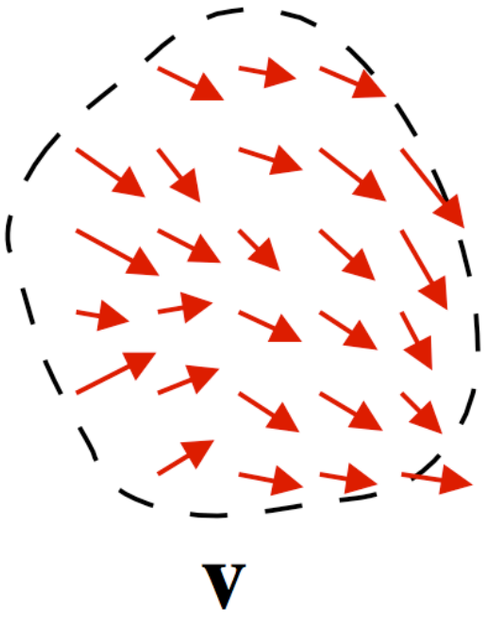
Idea:
Clone the *gradient*...

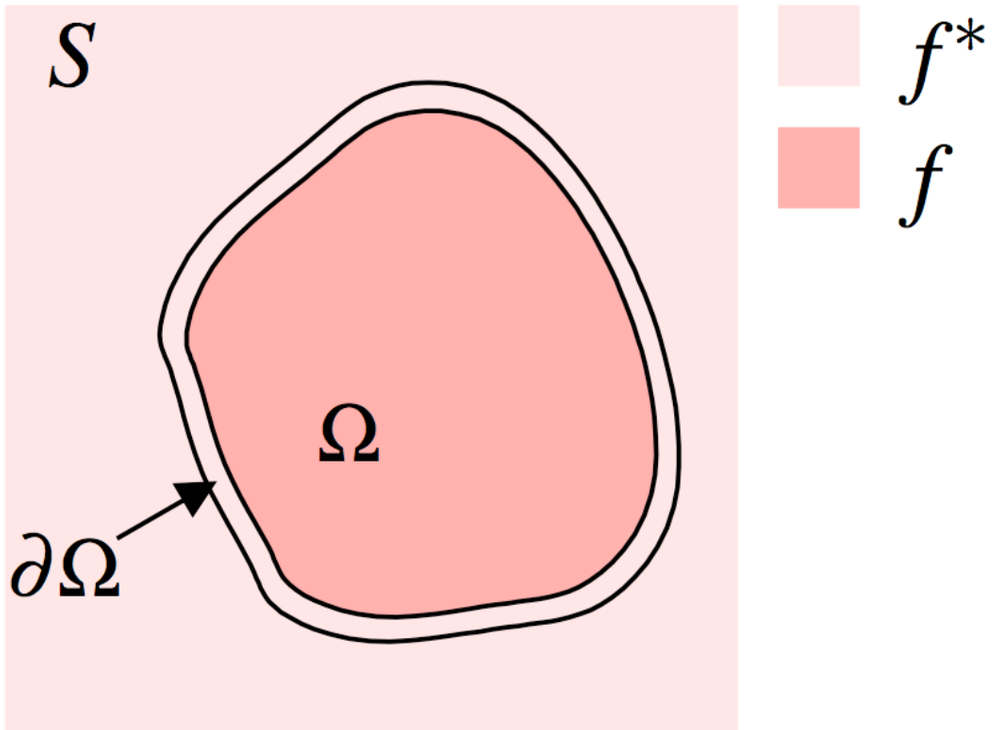
Perez, *et al.*, (SIGGRAPH 2003)



… then *reconstruct.*

Perez, *et al.*, (SIGGRAPH 2003)



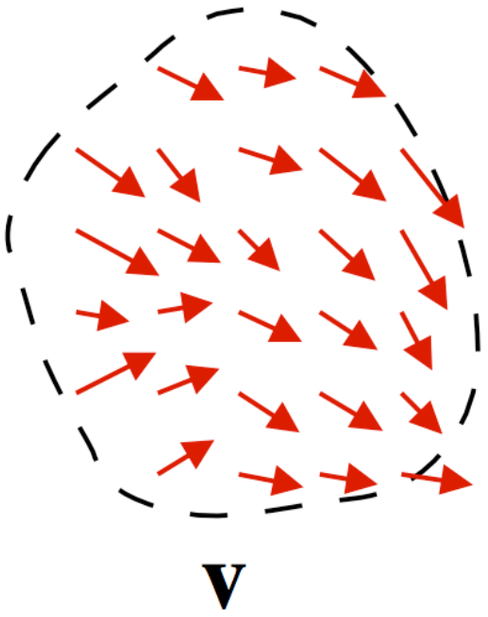


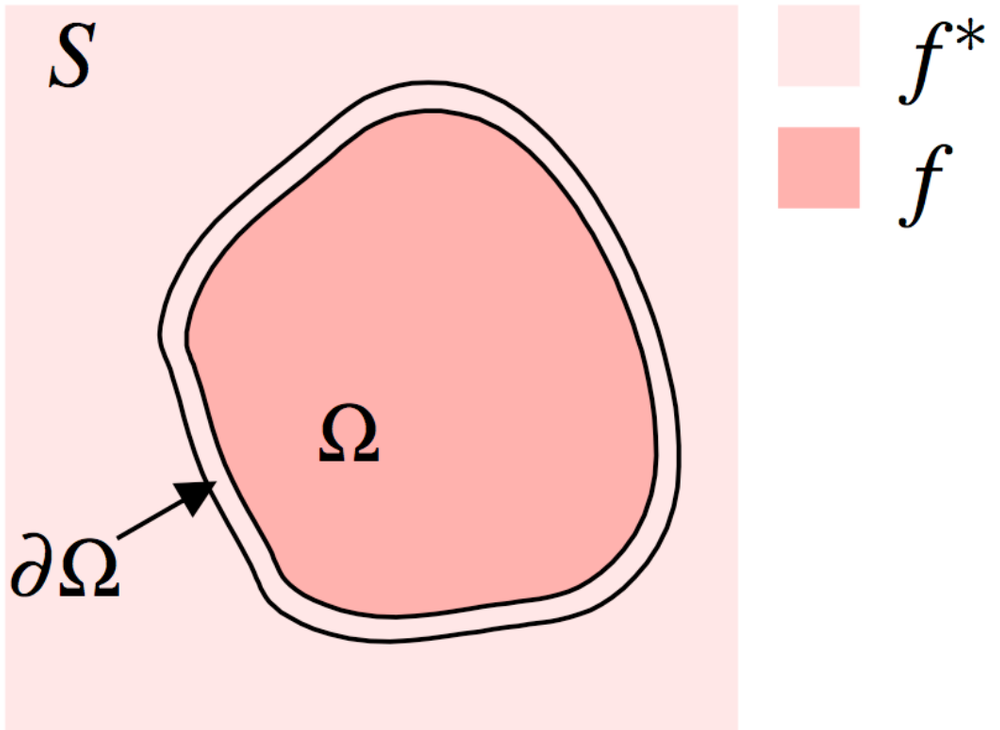
$$\min_f \iint_\Omega |\nabla f - \mathbf{v}|^2 \partial\Omega \quad \text{with} \quad f|_{\partial\Omega} = f^*|_{\partial\Omega}$$

"Guided interpolation"

One possible mathematical formulation:

Find *f(x,y)* given gradient *v(x,y)*



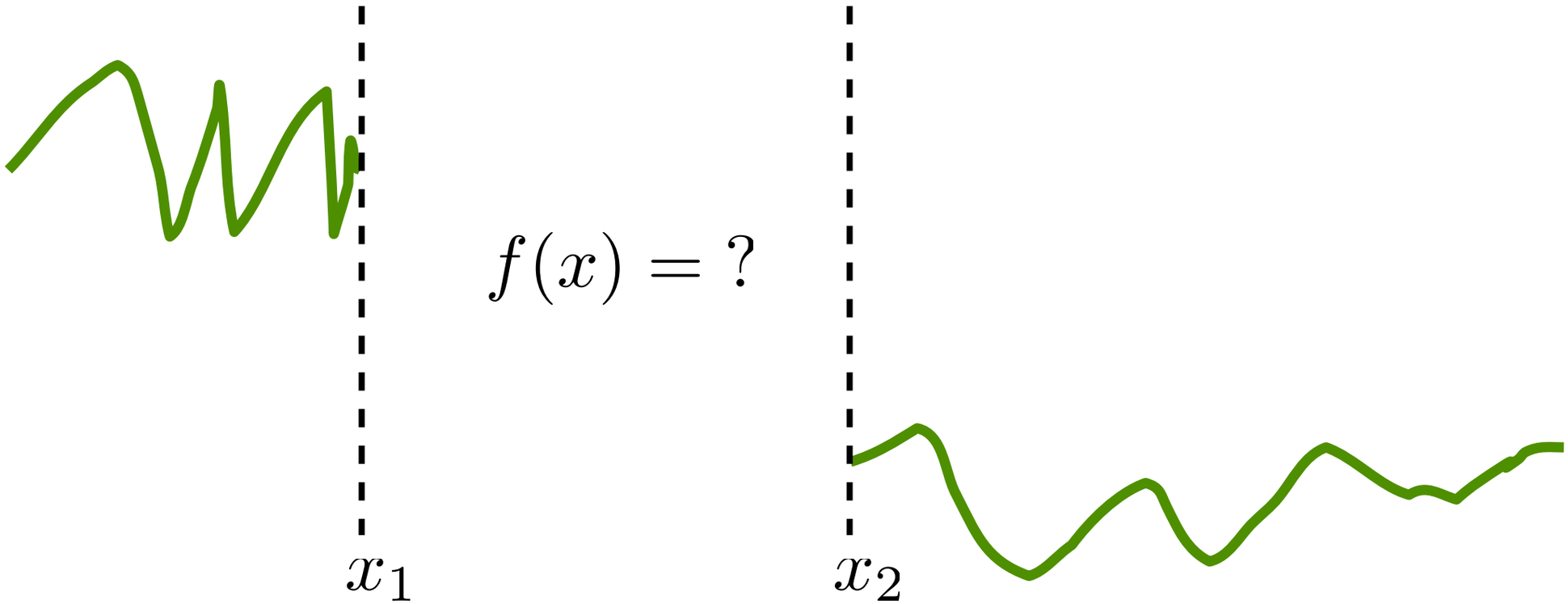


$$\nabla^2 f = \nabla \cdot \mathbf{v} \quad \text{over } \Omega \quad \text{with} \quad f|_{\partial\Omega} = f^*|_{\partial\Omega}$$

Necessary condition:
Poisson's equation.

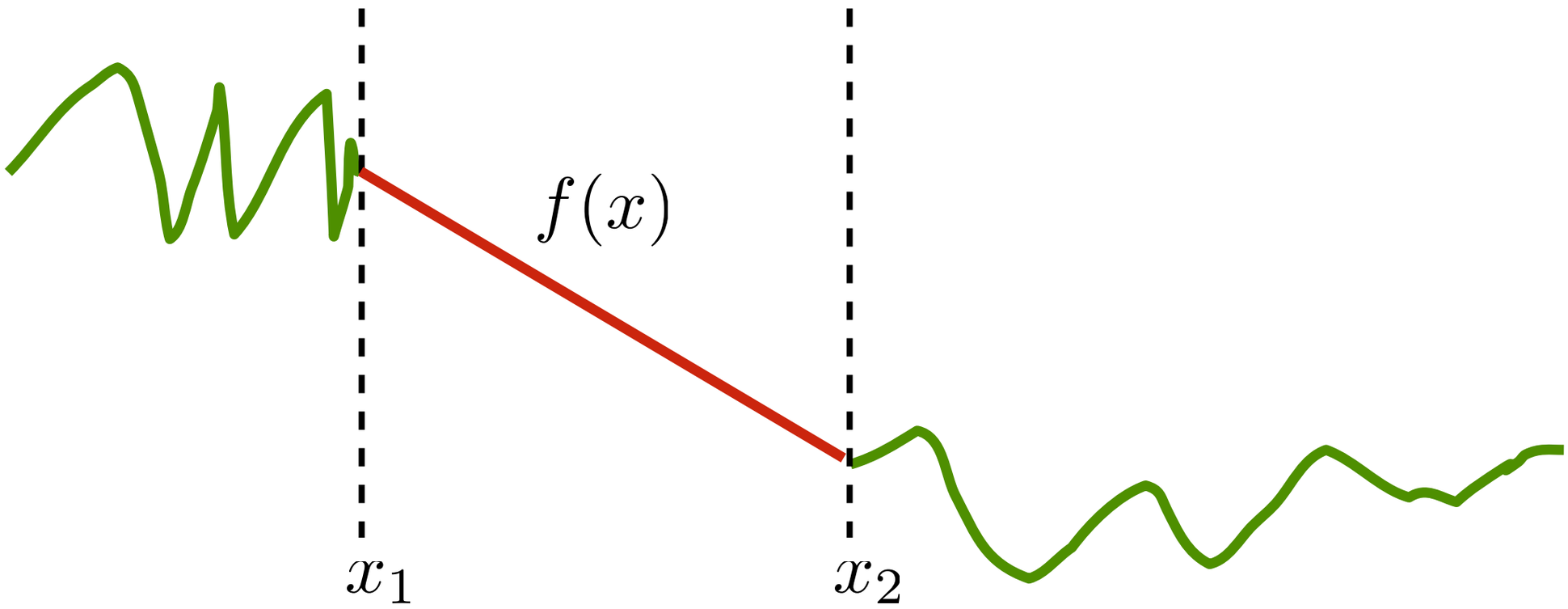
One possible mathematical formulation:

Find *f(x,y)* given gradient *v(x,y)*



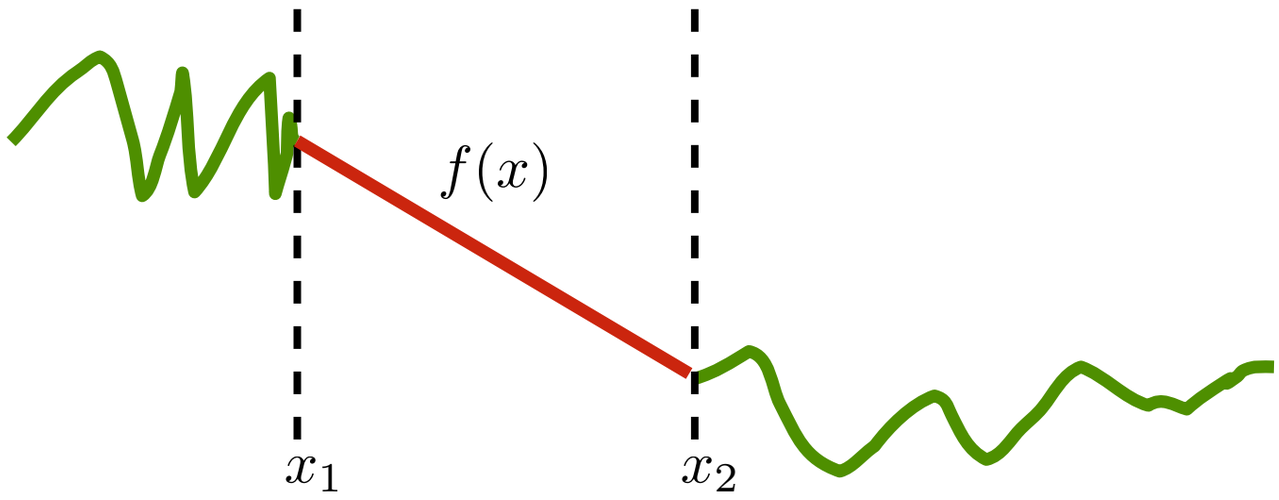
1-D analogue with *v*=0.

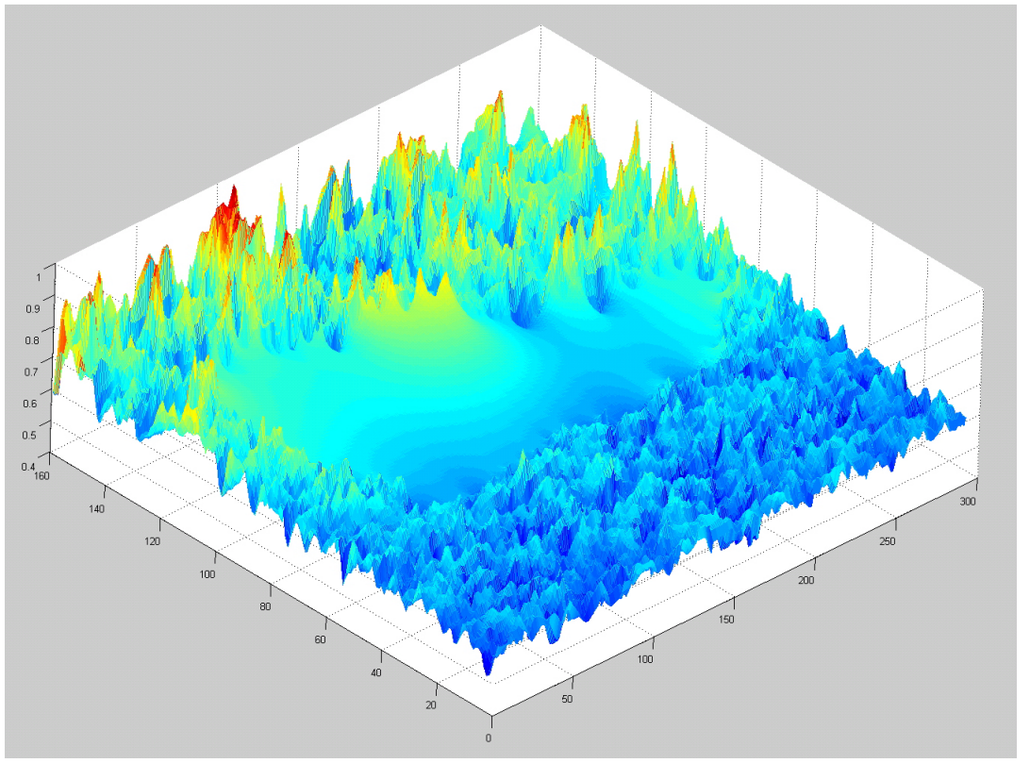
Apply "calculus of variations."



Solution: f(x) = line.

Gradient is zero ⇒ linearly interpolates boundary.

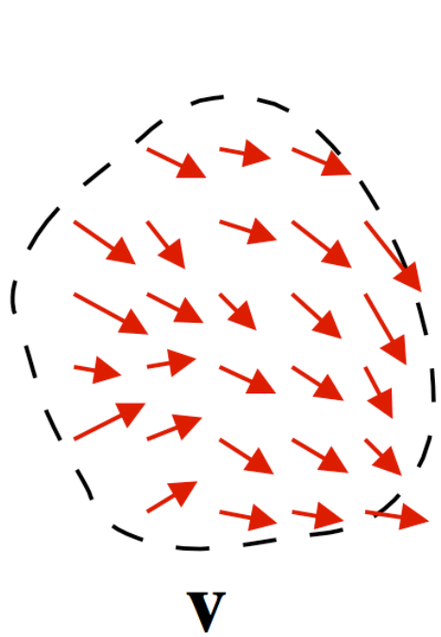

$f(x)$
x_1
x_2

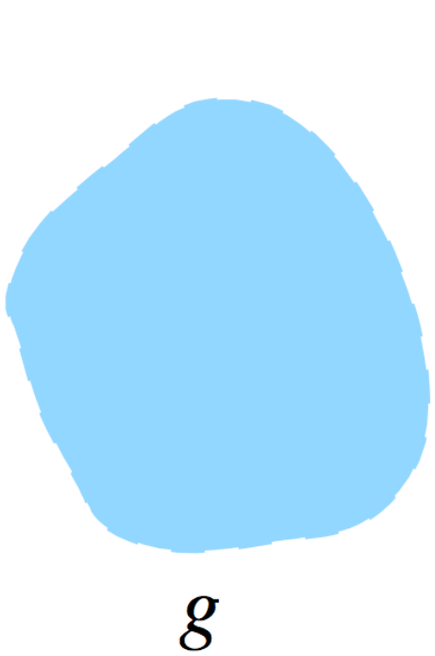

1
0.9
0.8
0.7
0.6
0.5
0.4
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300

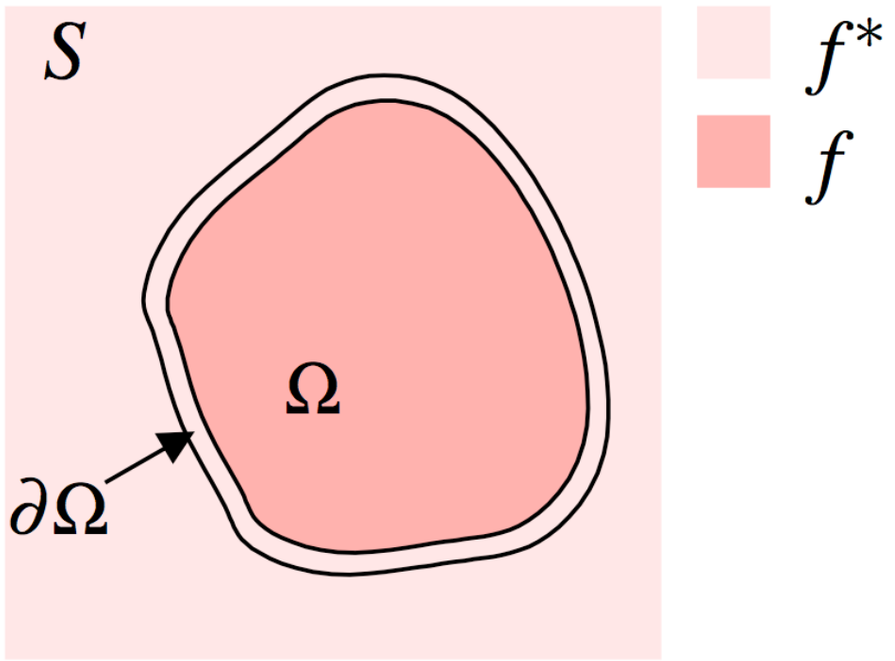
$$\mathbf{v} = \nabla g \quad \Longrightarrow \quad \nabla^2 f = \nabla \cdot \nabla g = \nabla^2 g$$

$$\Longleftrightarrow \quad \nabla^2 (f - g) = 0$$

$$\text{Let } f = g + \hat{f} \quad \Longrightarrow \quad \nabla^2 \hat{f} = 0, \text{ with } \hat{f}|_{\partial\Omega} = (f^* - g)|_{\partial\Omega}$$



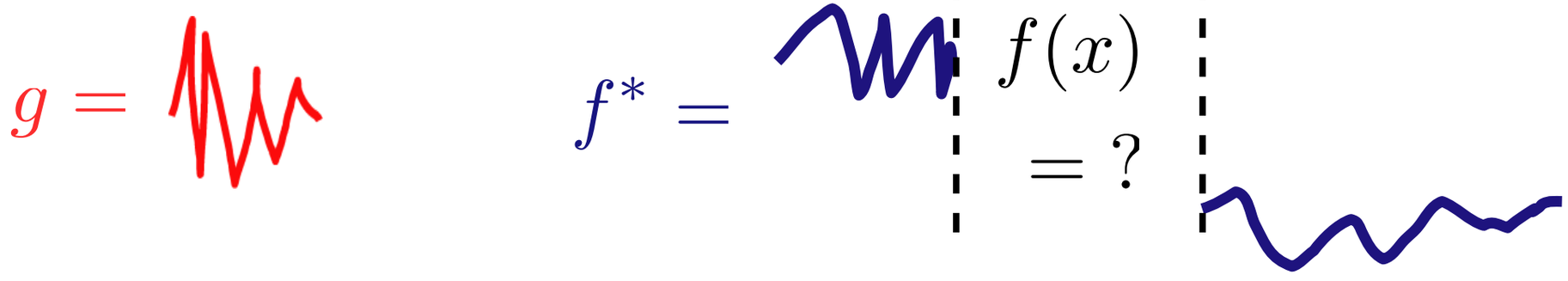




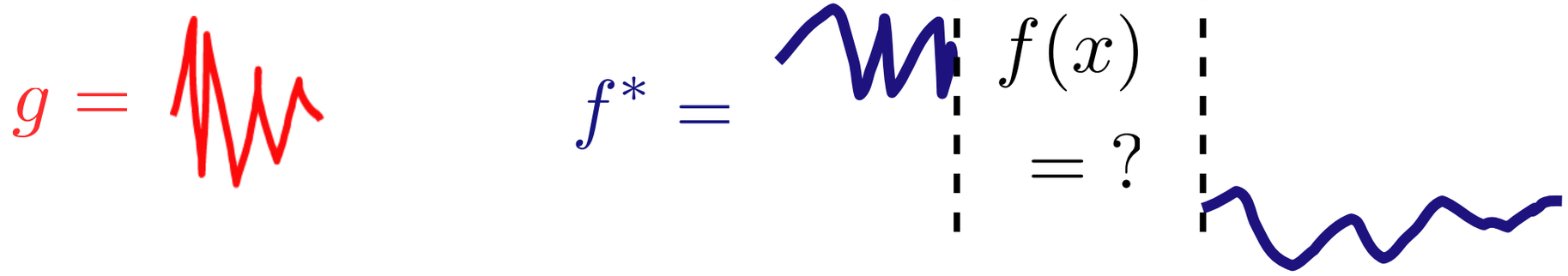
1-D analogue.

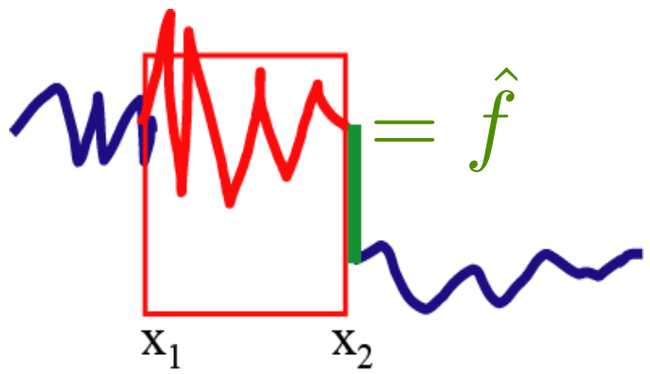
$g =$ 

I-D analogue.

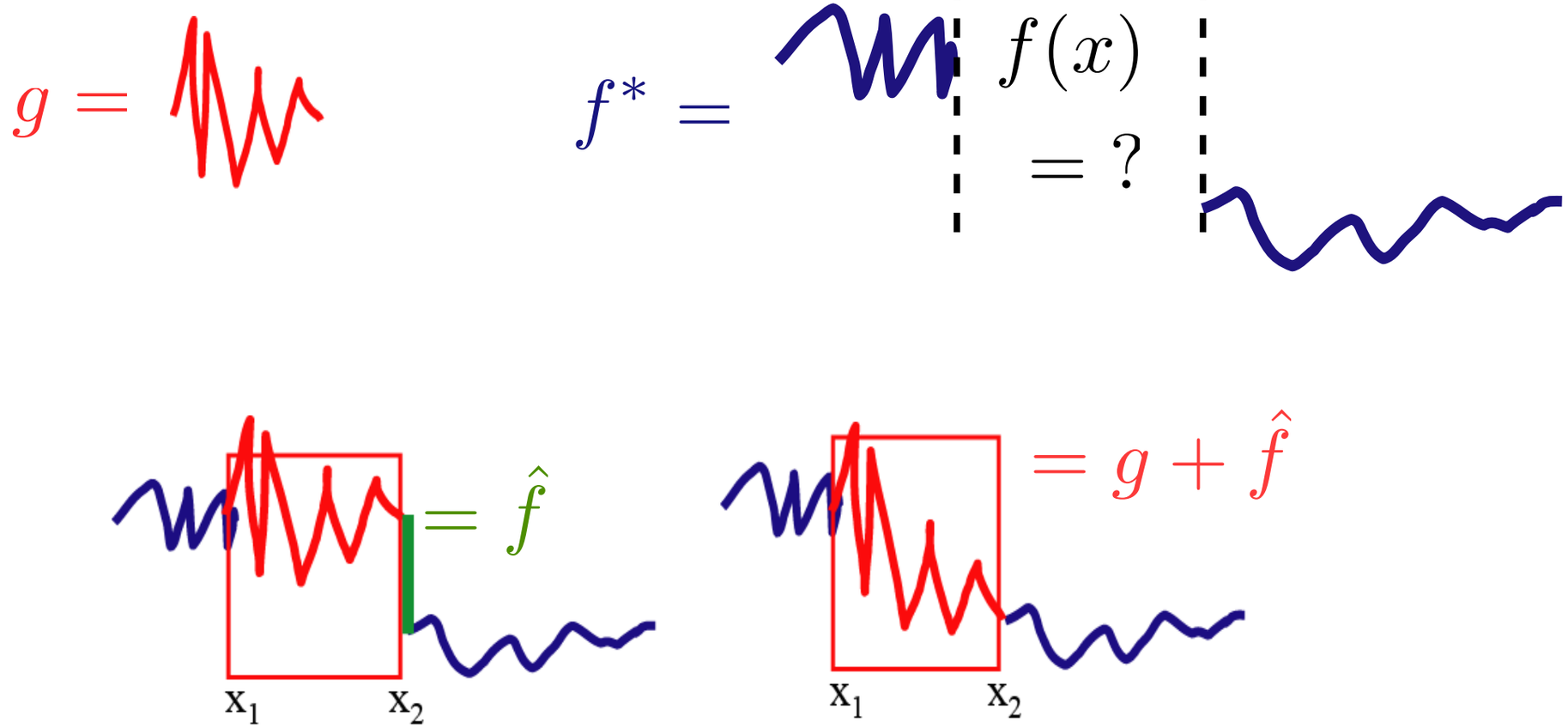


1-D analogue.





1-D analogue.



1-D analogue.

Seamless image cloning: Summary

- Given: Image with a hole, object to "paste in"
- Find: "Seamless" pasting
- A mathematical formulation:
  - Take gradient of image
  - **Solve Poisson's equation**

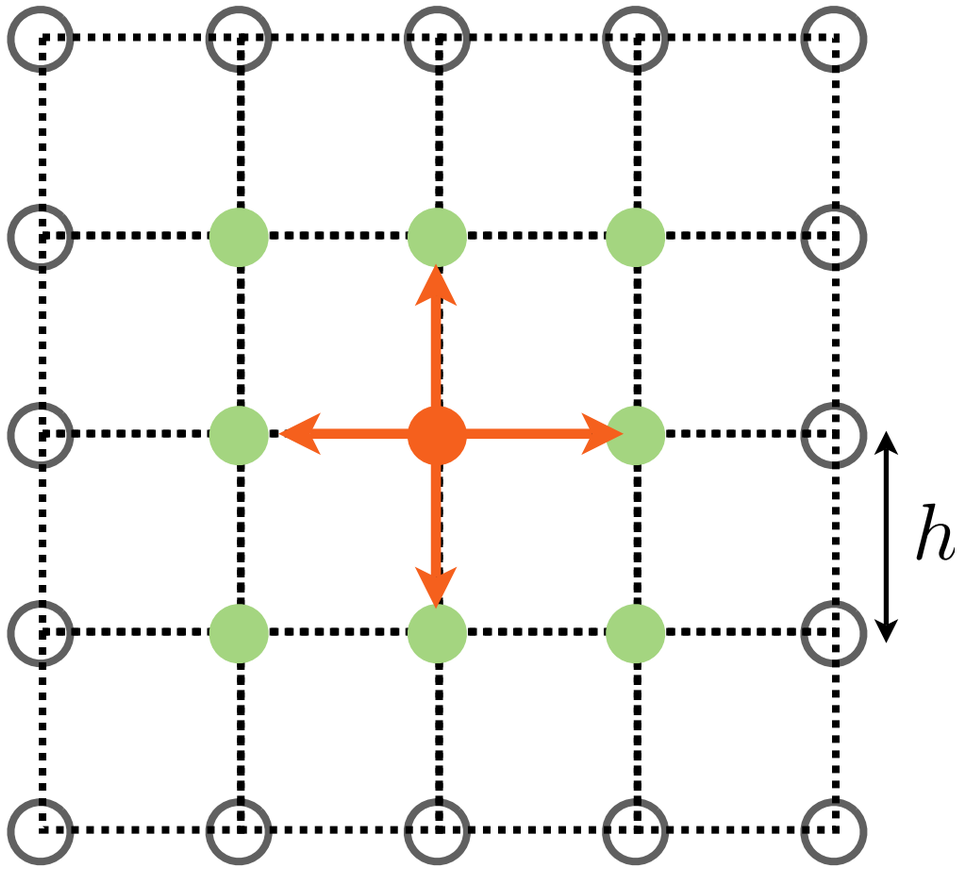
"Traditional" examples of Poisson's equation

- Electrostatics & gravity
- Heat flow
- Diffusion
- Fluid flow
- Elasticity

$$\text{(2-D) Find } f(x,y): \qquad \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = v(x,y)$$

One algorithm for solving Poisson: Jacobi's method

Graph and stencil

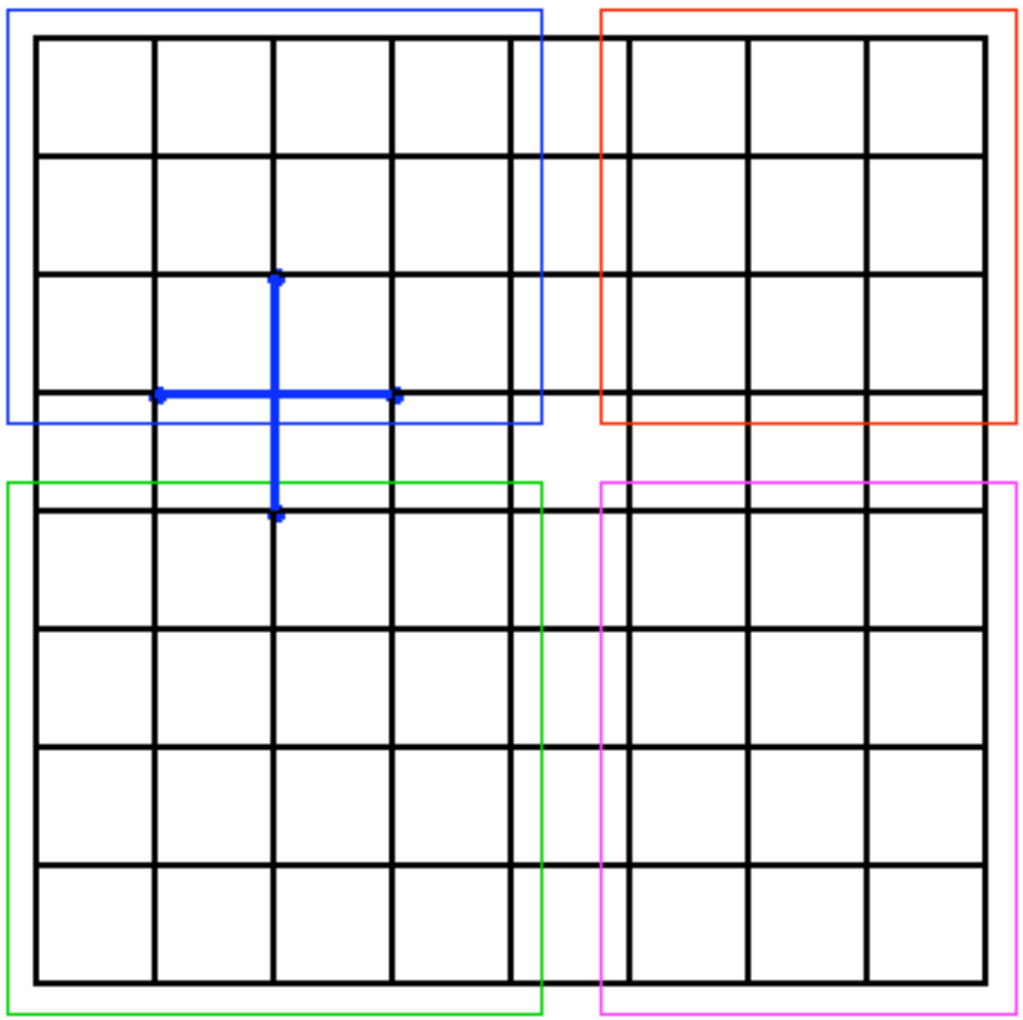


$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0$$

$$\text{For } t \leftarrow 1, 2, 3, \ldots$$

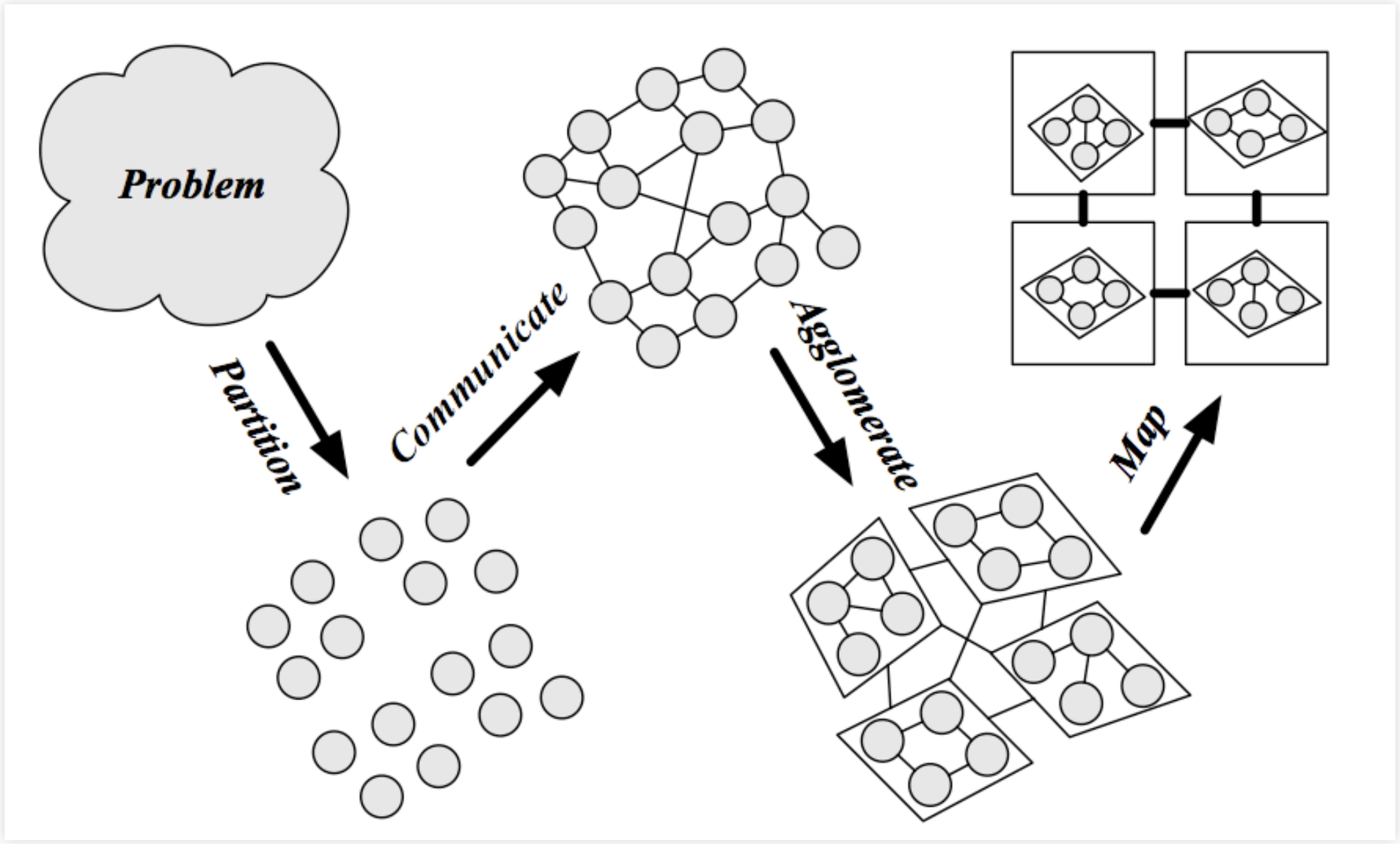
$$f_{i,j}^{t+1} \leftarrow \frac{1}{4}(f_{i+1,j}^{t} + f_{i-1,j}^{t} + f_{i,j+1}^{t} + f_{i,j-1}^{t})$$

Parallelizing Jacobi



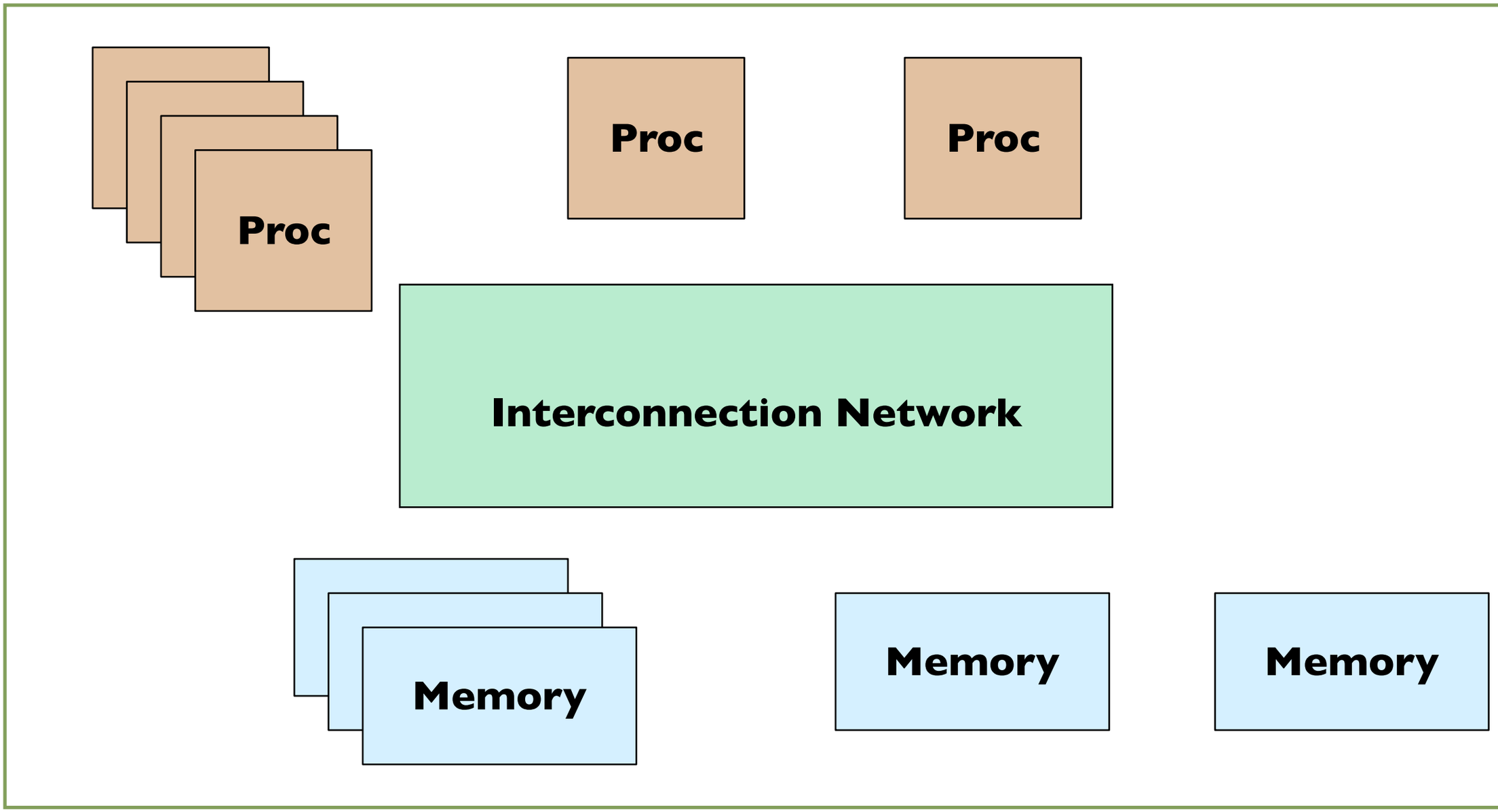
- Update points independently
- Partition?
- Communication?

Summary: Problem → Parallelization



- Problem → parallel algorithm
- **Programming models: Algorithms → implementation**
  - 1. Data parallel
  - 2. Shared memory
  - 3. Message passing
  - Hybrids, e.g., partitioned global address space
- Looking forward: DARPA HPCS languages

Parallel architecture "design space"



Programming models

- Langs + libs composing abstract view of machine
- Major constructs
  - **Control**: Create parallelism? Execution model?
  - **Data**: Private vs. shared?
  - **Synchronization**: Coordinating? Atomicity?
- Variations in models
  - Reflect diversity of machine architectures
  - Imply variations in cost

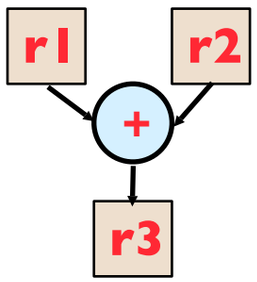
Programming model 1: Data parallel

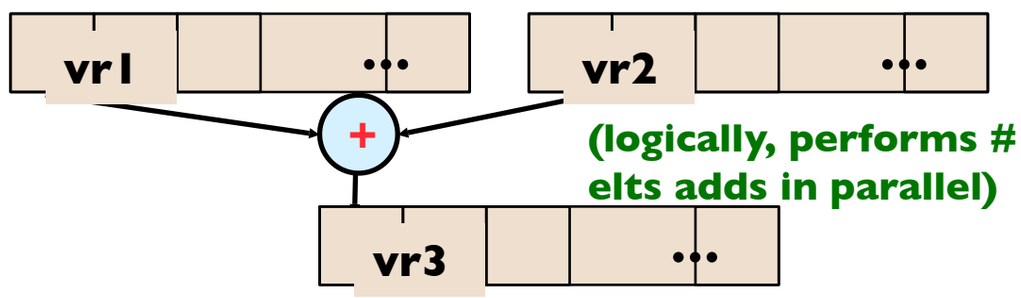
- Program = **1 thread**, **parallel ops** on data
- Communication is implicit
- Drawback: Does not always apply
- Examples: HPF, Matlab, ZPL

```
% Example: Jacobi in MATLAB

I = 2:(n-1);
J = 2:(n-1);
F(I,J) = 0.25*(F(I-1,J) + F(I+1,J) + F(I,J+1) + F(I,J-1));
```

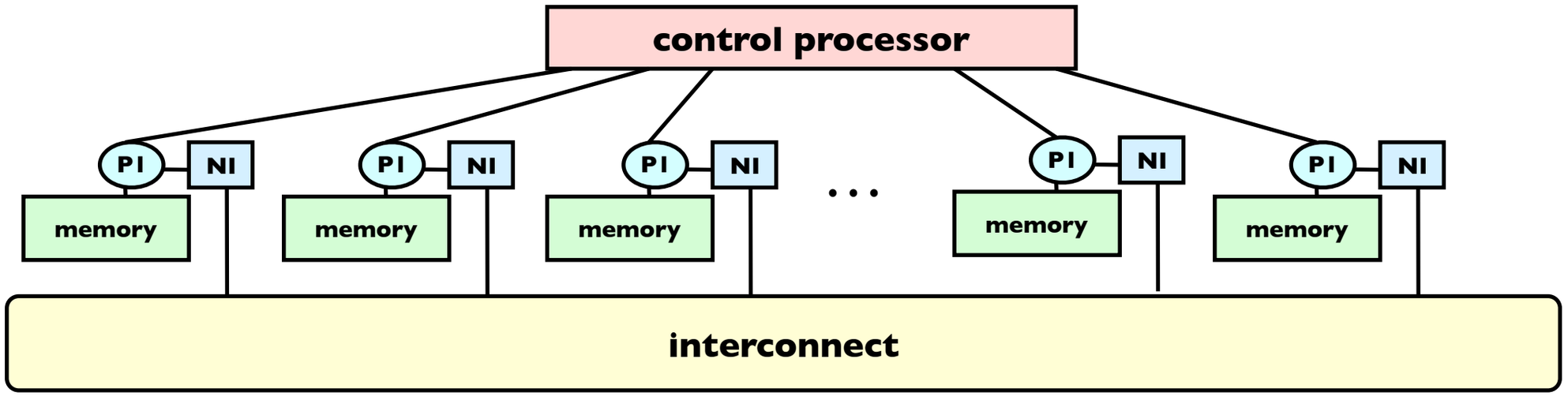
Machine model 1

- Vector processors



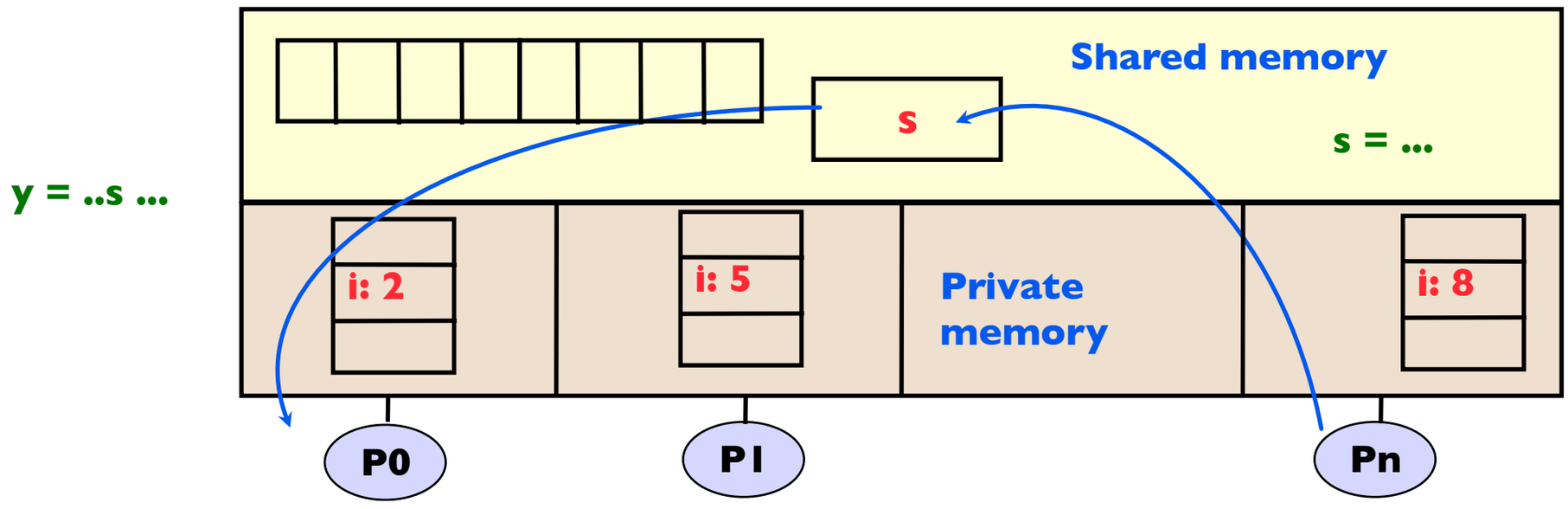


- Single-instruction, multiple-data (SIMD)



Programming model 2: Shared memory

- Program = **multiple threads** of control
- Communicate and synchronize *via* **shared variables**



Race conditions and locks

- **Race condition / data race**:
  Two threads access a variable, with at least one writing and concurrent accesses

shared int s = 0;

Thread 1

```
for i = 0, n/2-1
    s = s + f(A[i])
```

Thread 2

```
for i = n/2, n-1
    s = s + f(A[i])
```

Race conditions and locks

- **Lock** for atomicity, to avoid races

```
shared int s = 0;
shared lock lk;
```

Thread 1

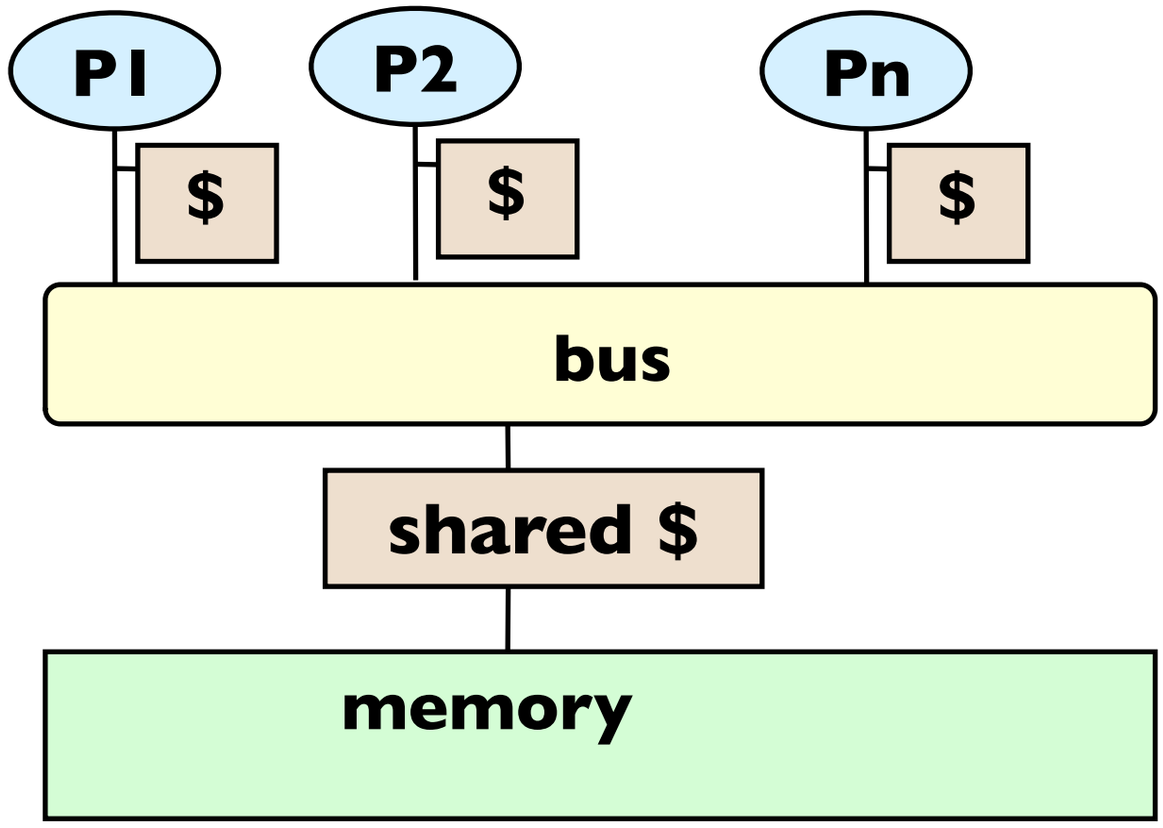
```
local_s1= 0
for i = 0, n/2-1
    local_s1 = local_s1 + f(A[i])
lock(lk);
s = s + local_s1
unlock(lk);
```

Thread 2

```
local_s2 = 0
for i = n/2, n-1
    local_s2= local_s2 + f(A[i])
lock(lk);
s = s +local_s2
unlock(lk);
```

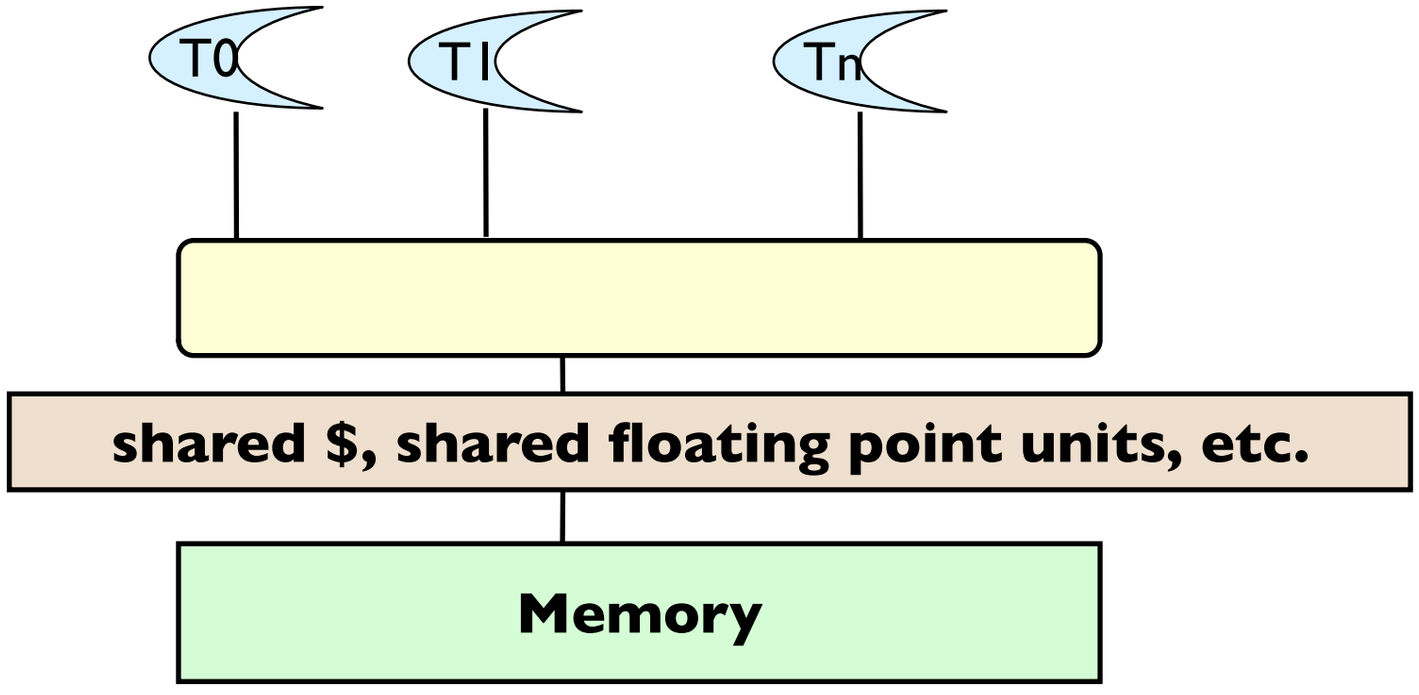
Machine model 2a: SMPs

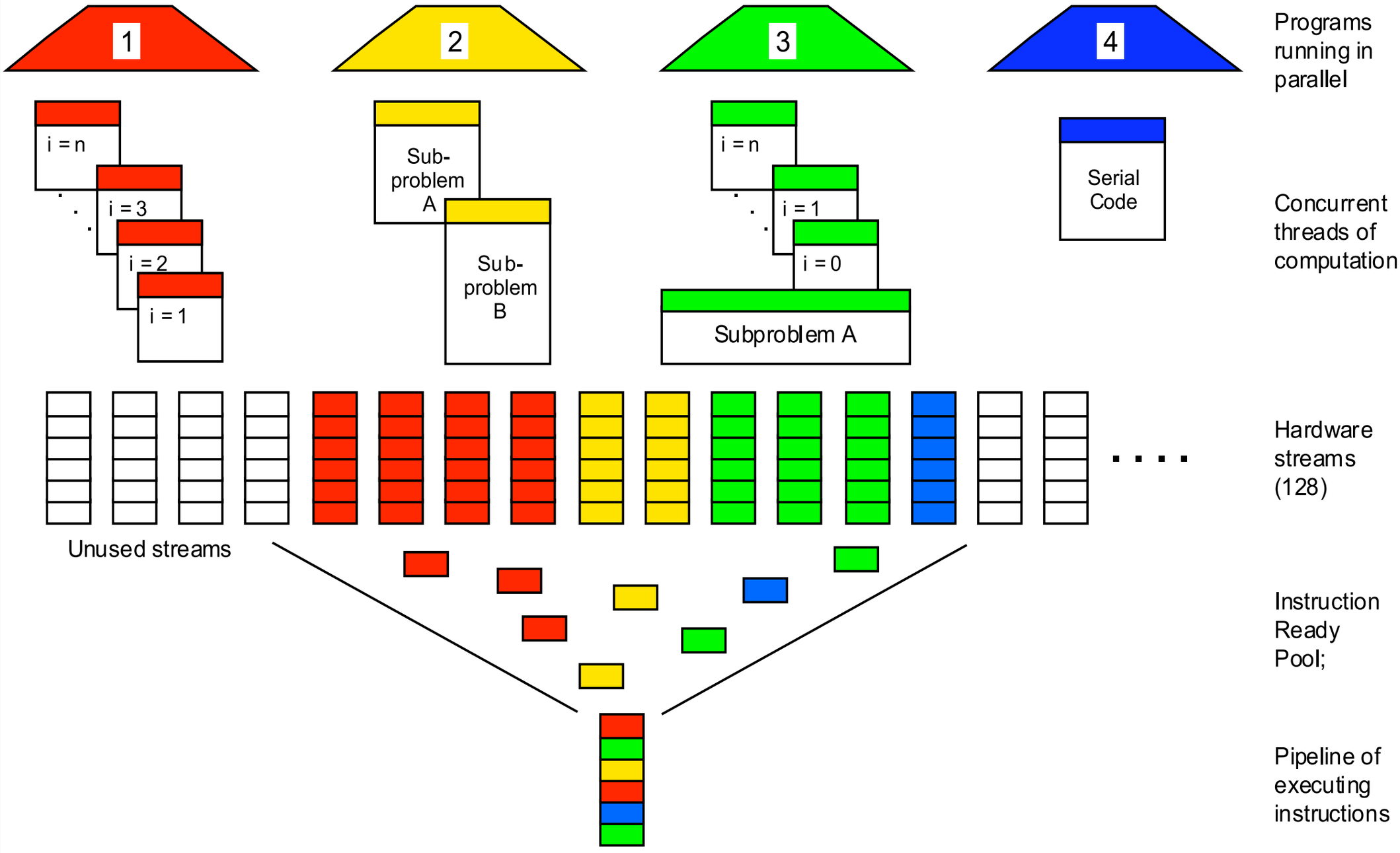
- "Symmetric multiprocessor"
- All processors connect to large shared memory



Machine model 2b: SMTs

- Symmetric multithreaded processors
  - HW threads share memory and functional units
  - Switch threads during long-latency operations



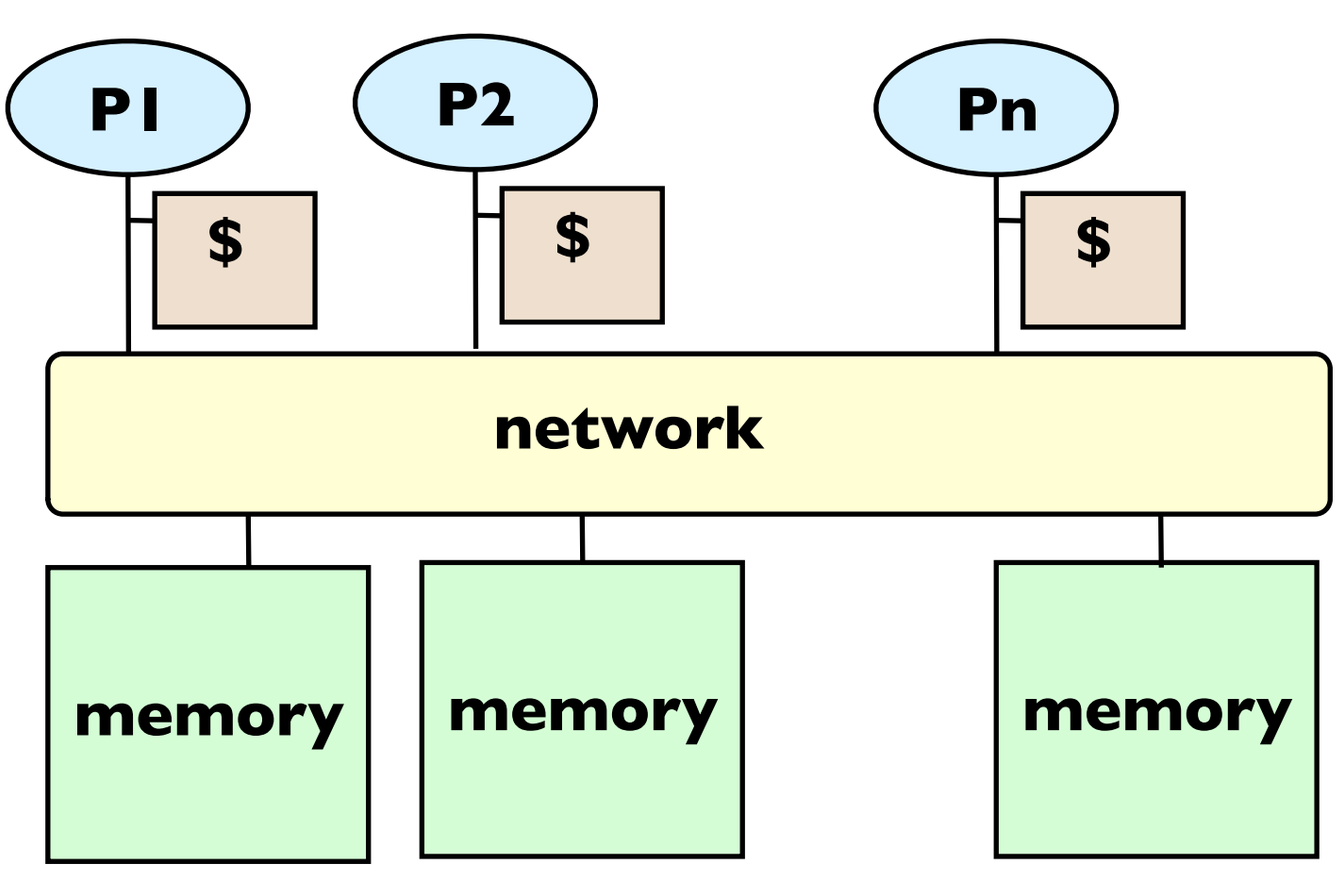


Cray Eldorado processor

Source: John Feo (Cray)

Machine model 2c: Distributed shared mem.

- Memory logically shared, physical distributed
- Challenge to scale cache-coherency

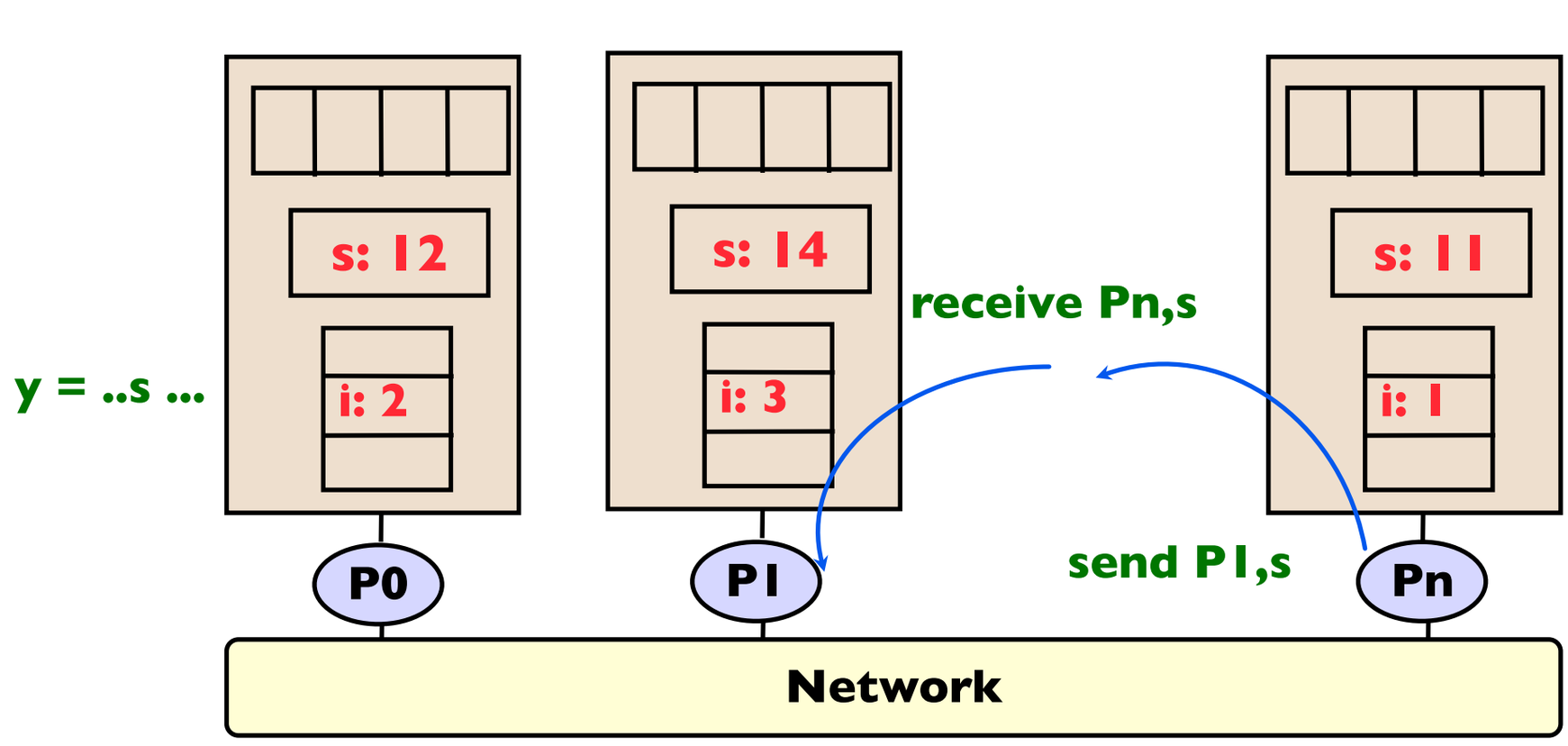


Cache lines (pages) must be large to amortize overhead

⇒ locality is critical to performance

Programming model 3: Message passing

- Program = **named** tasks (processes)
- Tasks communicate via explicit **send/receive** operations



Message passing example

- Example: All-reduce

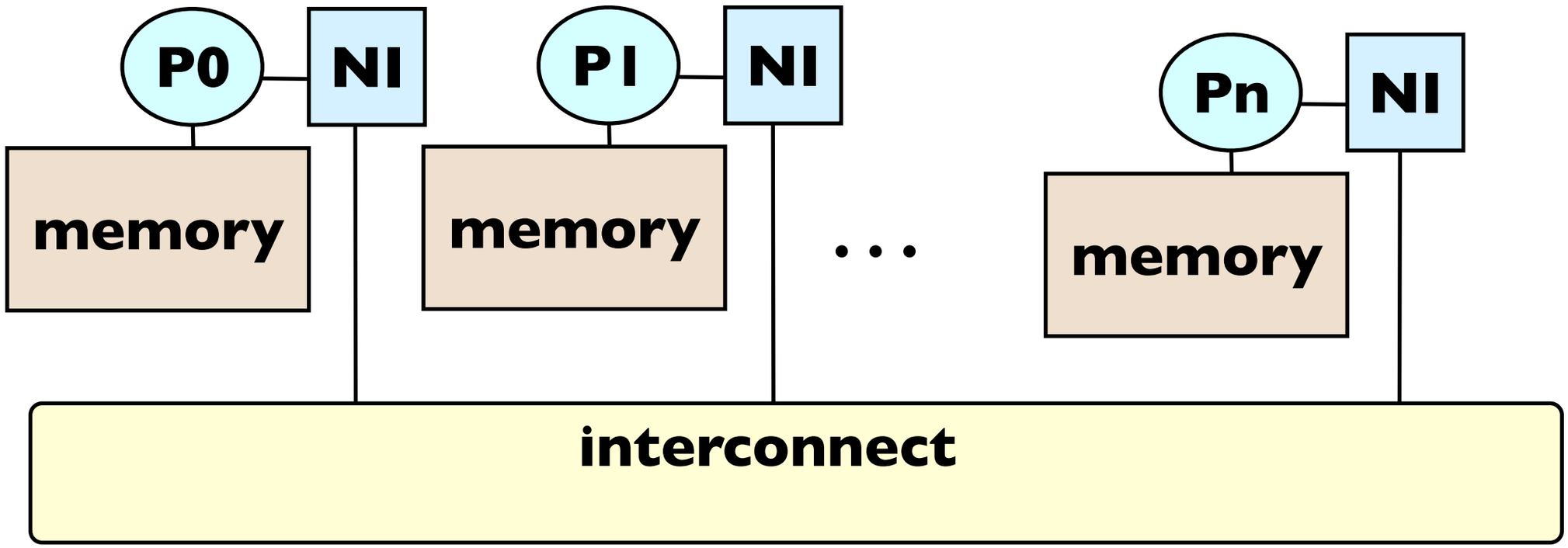
Processor **1**:
x = A[1]
SEND x → Proc. **2**
RECEIVE y ← Proc. **2**
s = x + y

Processor **2**:
x = A[2]
SEND x → Proc. **1**
RECEIVE y ← Proc. **1**
s = x + y

- What could go wrong?

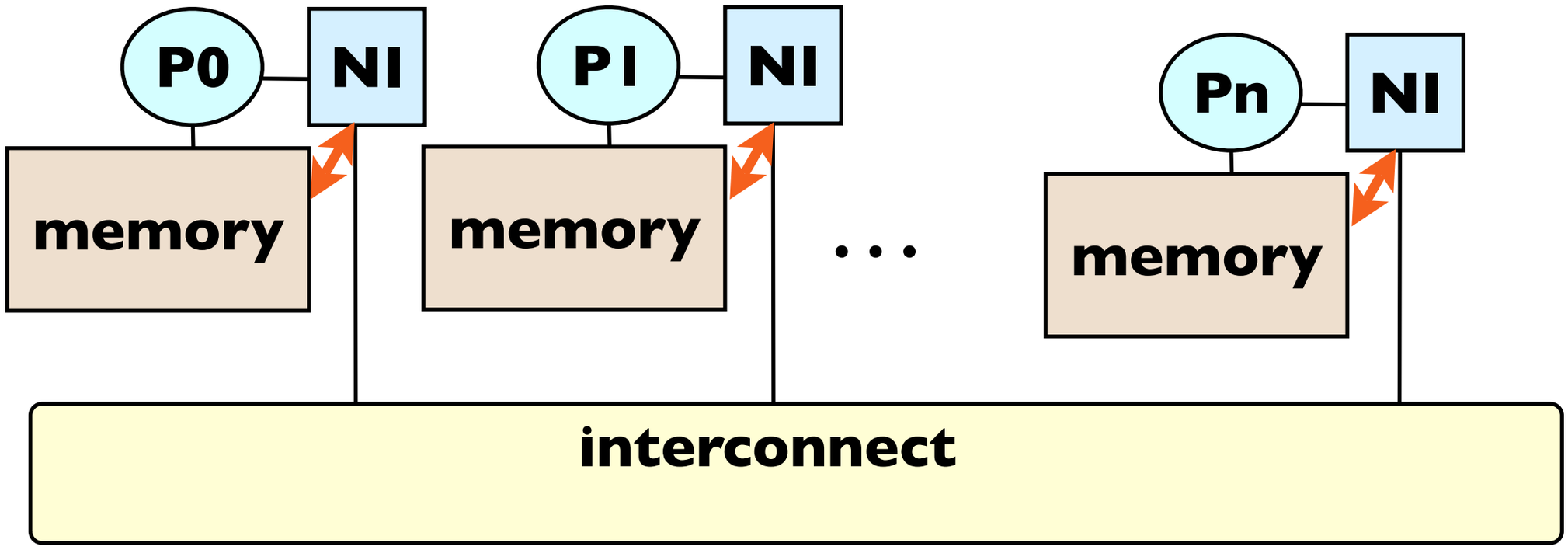
Machine model 3a: Distributed memory

- Separate nodes, memory
- Communicate through network



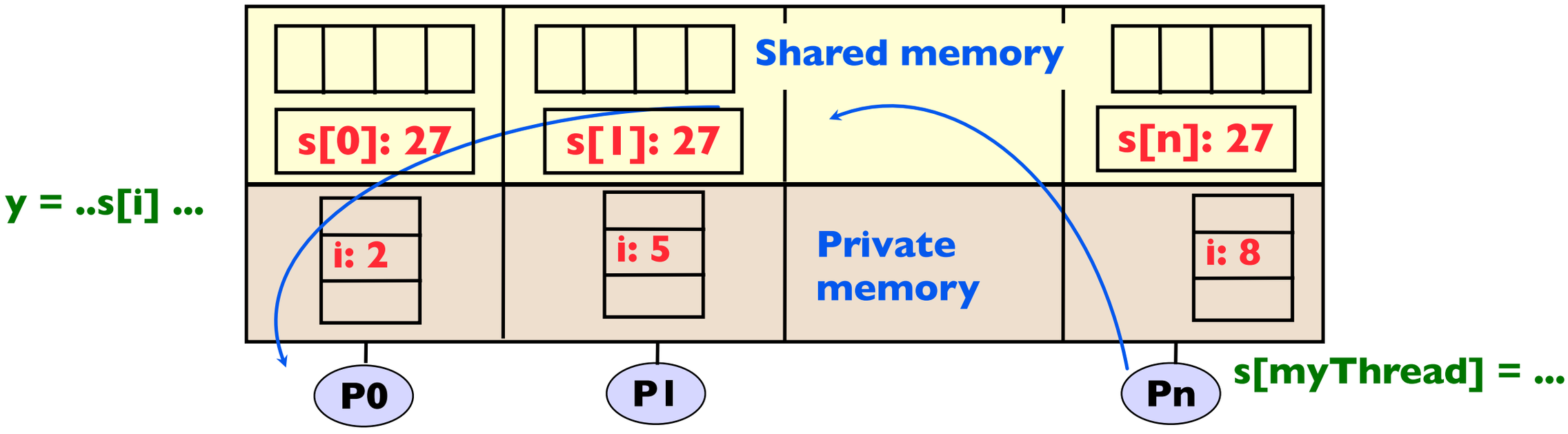
Machine model 3b: Global address space

- Tweak: NI can directly access the processor
- **One-sided** communication; remote direct-memory access (**RDMA**)



Programming model 3b: PGAS

- "Partitioned global address space"
- Data shared **but** partitioned



"Concrete" models

- Data parallel:
  Matlab, HPF
- Shared memory: PThreads / OpenMP / Intel TBB / Cilk
- Message passing:
  Message Passing Interface (MPI)
- PGAS:
  UPC, Co-Array Fortran
- Hybrids:
  CUDA; DARPA HPCS: X10, Chapel, Fortress

- Problem → parallel algorithm
- Programming models:
  Algorithms → implementation
- **Looking forward (?): DARPA HPCS languages**

DARPA HPCS Program

- High-Productivity Computing Systems
- Goal: Create a new generation of economically viable computing systems by 2010
- Funded industrial/academic alliances
  - Architectures
  - Languages / programming models
  - User "productivity"

HPCS language effort

- New languages
  - X10 (IBM)
  - Chapel (Cray)
  - Fortress (Sun)
- Explicit constructs express parallelism & locality
- PGAS + dynamic parallelism (dynamic threads)

Base languages

- X10 (IBM) extends Java
  - Multi-dimensional arrays
  - Value types
  - Parallelism
- Chapel (Cray), Fortress (Sun): New
  - Fortress – Mathematical syntax (unicode)
  - Challenge: Adoption?

Creating parallelism

- Explicitly parallel (no automatic parallelization)
- Designed to encourage expression of as much parallelism as possible
  - Data, loop, task
  - Rely on compiler + run-time to schedule
- Fortress: Loops and argument evaluation parallel by default
- Dynamic parallelism

Locality

- Explicit notions of locality
  - "Places" in X10
  - "Locales" in Chapel
  - "Regions" in Fortress
- Static and dynamic
- Extensive support for data distribution

Synchronization

- Generally believed that locks and barriers are error-prone
- All 3 languages provide "atomic blocks"
  - Syntax forces matching begin/end
  - X10: Place-local atomic blocks
  - Speculation + rollback
- X10 provides "clocks," which are barriers attached to set of tasks
- Support for "futures" (producer-consumer)

Summary

- Ultimate goal is to solve some problem
  - Formalize
  - Develop algorithm (serial or parallel)
- Choice of programming models
  - Abstract model of machine execution
  - Differ in specification of control, data sharing
  - Basic: Data parallel, shared mem., message passing
- Active area of research and debate

- A few concrete programming models
  - PThreads
  - OpenMP
  - MPI
  - Cilk
  - Unified Parallel C (UPC)
  - Co-Array Fortran

POSIX Threads (PThreads)

- Portable system call interface for creating and synchronizing threads
- Threads share all global variables
- Fork/join style

```
errcode = pthread_create (&thread_id,
                          &thread_attribute,
                          &thread_fun,
                          &fun_arg)
   …
errcode = pthread_join (thread_id, NULL);
```

- *Reference*: https://computing.llnl.gov/tutorials/pthreads/

Loop-level parallelism

- May fork threads at any time, *e.g.*, within a loop

```
… A[n];
for (i = 0; i < n; ++i)
   pthread_create (…, &task, &i);
…
```

- Must have sufficient granularity to mask thread-creation overhead

Low-level policy control

- Detached state: Avoid pthread_join calls
- Scheduling parameters: priority, policy (FIFO vs. round-robin)
- Contention scope: With what thread does this thread compete for CPU

Barriers for global synchronization (Optional extension)

- Usage outline

```
pthread_barrier_t b;
pthread_barrier_init (&b, NULL, 3);   // 3 threads
…
pthread_barrier_wait (&b);    // All threads wait
…
pthread_barrier_destroy (&b);
```

Mutual exclusion locks (mutexes)

- Basic usage

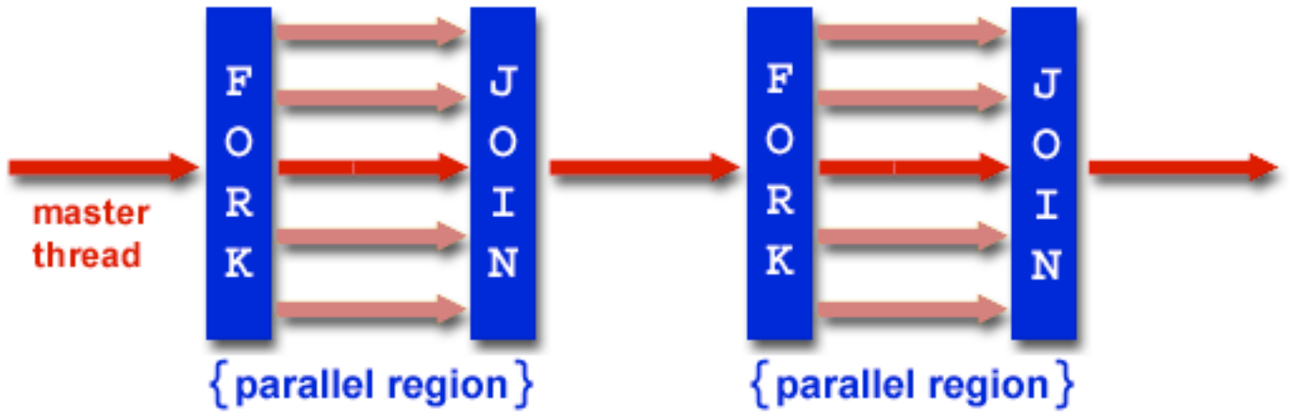
```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_init (&lock, NULL);
…
pthread_mutex_lock (&lock);
    // … do critical work …
pthread_mutex_unlock (&lock);
```

- Beware of **deadlock**

Thread 1	Thread 2
lock (a);	**lock** (b);
lock (b);	**lock** (a);

OpenMP: An API for multithreaded shared-memory programming

- Programmer identifies **serial** and **parallel regions**, not threads



- Library + directives (requires compiler support)
- Official website: http://www.openmp.org
  - Also: https://computing.llnl.gov/tutorials/openMP/

Simple example

```
int main()
{
    printf (“hello, world!\n”); // Execute in parallel

    return 0;
}
```

Simple example

```
int main()
{
   omp_set_num_threads (16);

   #pragma omp parallel
   {
     printf (“hello, world!\n”); // Execute in parallel
   } // Implicit barrier/join
   return 0;
}
```

Concurrent loops

- May parallelize a loop, but **you must check dependencies**

```
s = 0;
for (i = 0; i < n; ++i)
  s += x[i];
```

```
#pragma omp parallel for \
        shared (s)
for (i = 0; i < n; ++i)
  #pragma omp critical
  s += x[i];
```

```
#pragma omp parallel for \
        reduction(+: s)
for (i = 0; i < n; ++i)
  s += x[i];
```

Loop scheduling

- Use “schedule” clause to partition loop iterations
- **Static**: ***k*** iterations per thread, assigned statically

```
#pragma omp parallel for schedule static(k) …
```

- **Dynamic**: ***k*** iterations per thread, using logical work queue

```
#pragma omp parallel for schedule dynamic(k) …
```

- **Guided**: ***k*** iterations per thread initially, reduced with each allocation

```
#pragma omp parallel for schedule guided(k) …
```

- **Run-time**: Use value of environment variable, **OMP_SCHEDULE**

Synchronization primitives

Critical sections	No explicit locks	`#pragma omp critical` `{ … }`
Barriers		`#pragma omp barrier`

Explicit locks	May require flushing	`omp_set_lock (l);`
		`…`
		`omp_unset_lock (l);`

Single-thread regions	Inside parallel regions	`#pragma omp single` `{ /* executed once */ }`

Cilk: C extensions to support dynamic multithreading

Cilk (Leiserson, *et al.*, 1996+)

- **Fork/join-style C extensions** for dynamic multithreaded apps on SMPs

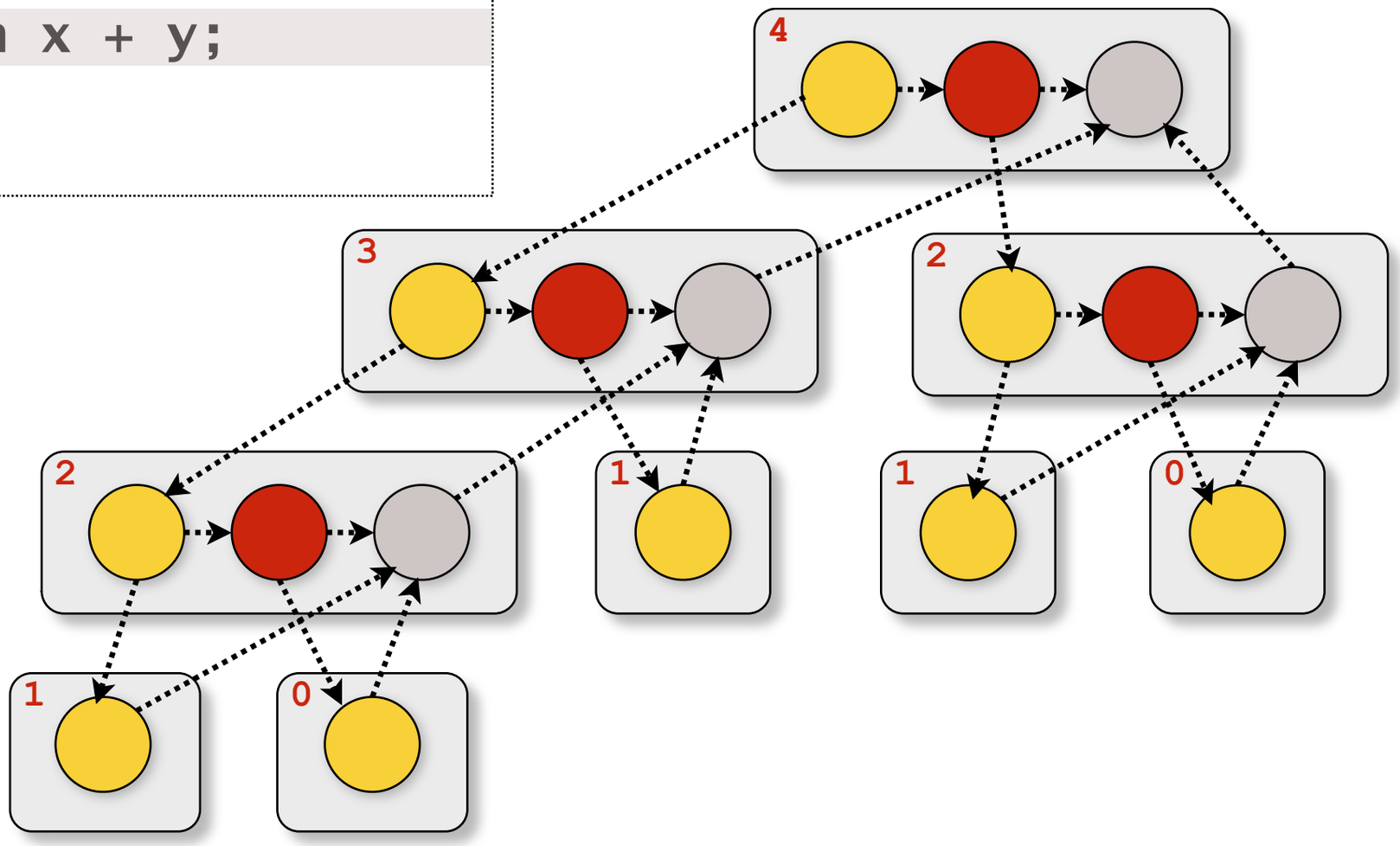
```
int fib (int n) {
  if (n < 2) return 1;
  else {
    int x, y;
    x = fib (n-1);
    y = fib (n-2);

    return x + y;
  }
}
```

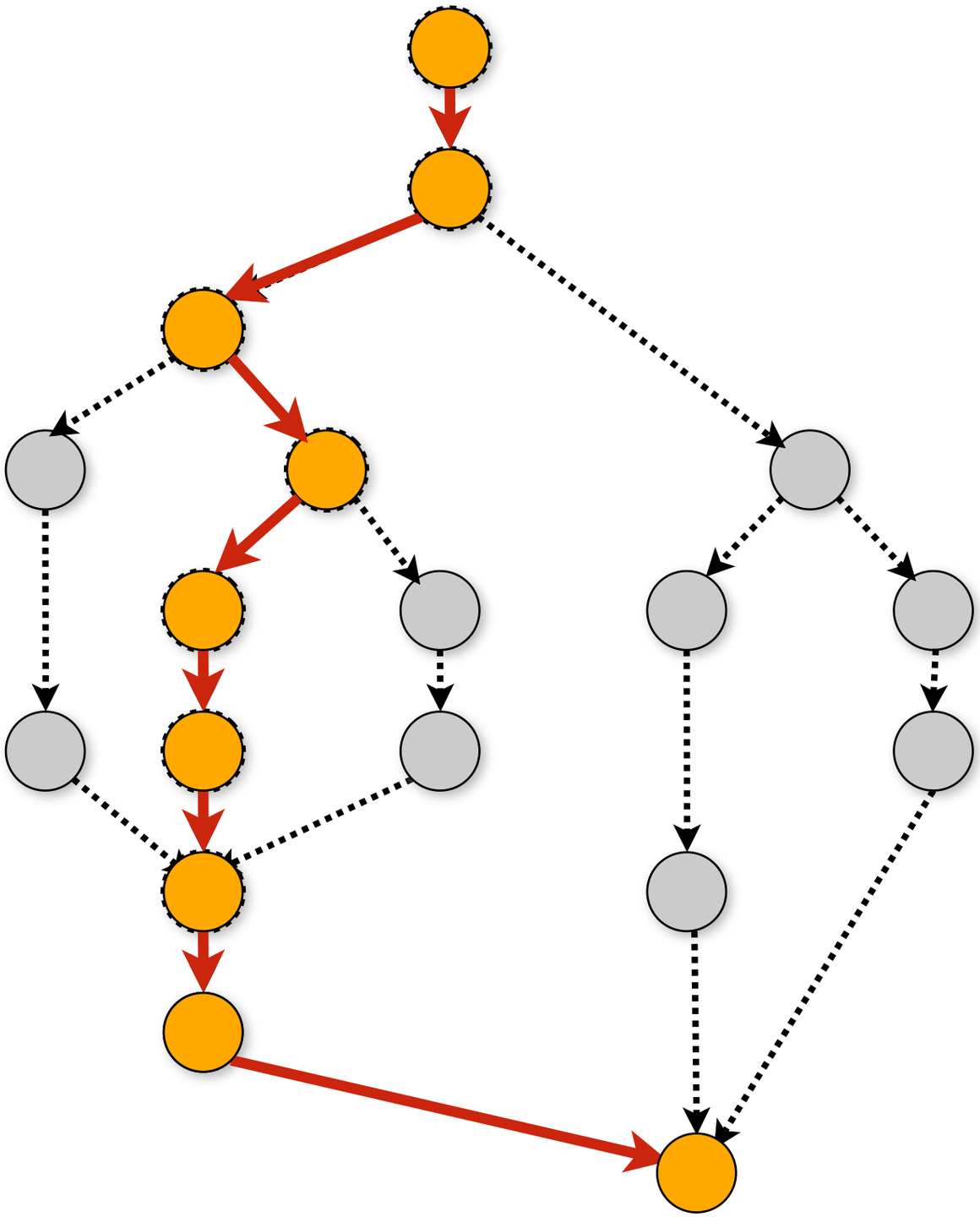
```
cilk int fib (int n) {
  if (n < 2) return 1;
  else {
    int x, y;
    x = spawn fib (n-1);
    y = spawn fib (n-2);
    sync;
    return x + y;
  }
}
```

- **"Faithful" extension**: Omitting parallel keywords = valid serial C program

```
cilk int fib (int n) {
  if (n < 2) return 1;
  else {
    int x, y;
    x = spawn fib (n-1);
    y = spawn fib (n-2);
    sync;
    return x + y;
  }
}
```

Dynamic computation DAG:
fib(4)





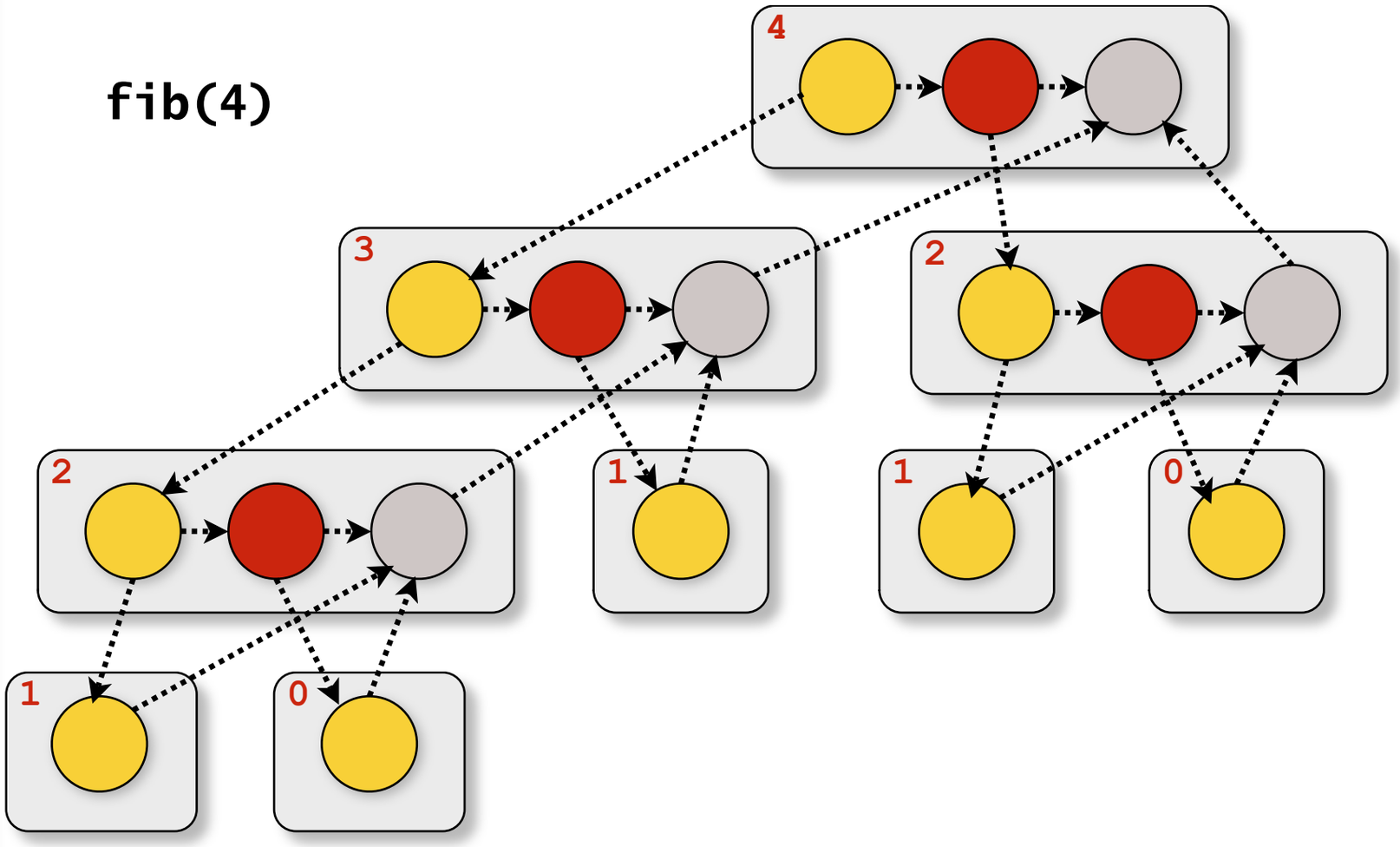
Critical path:

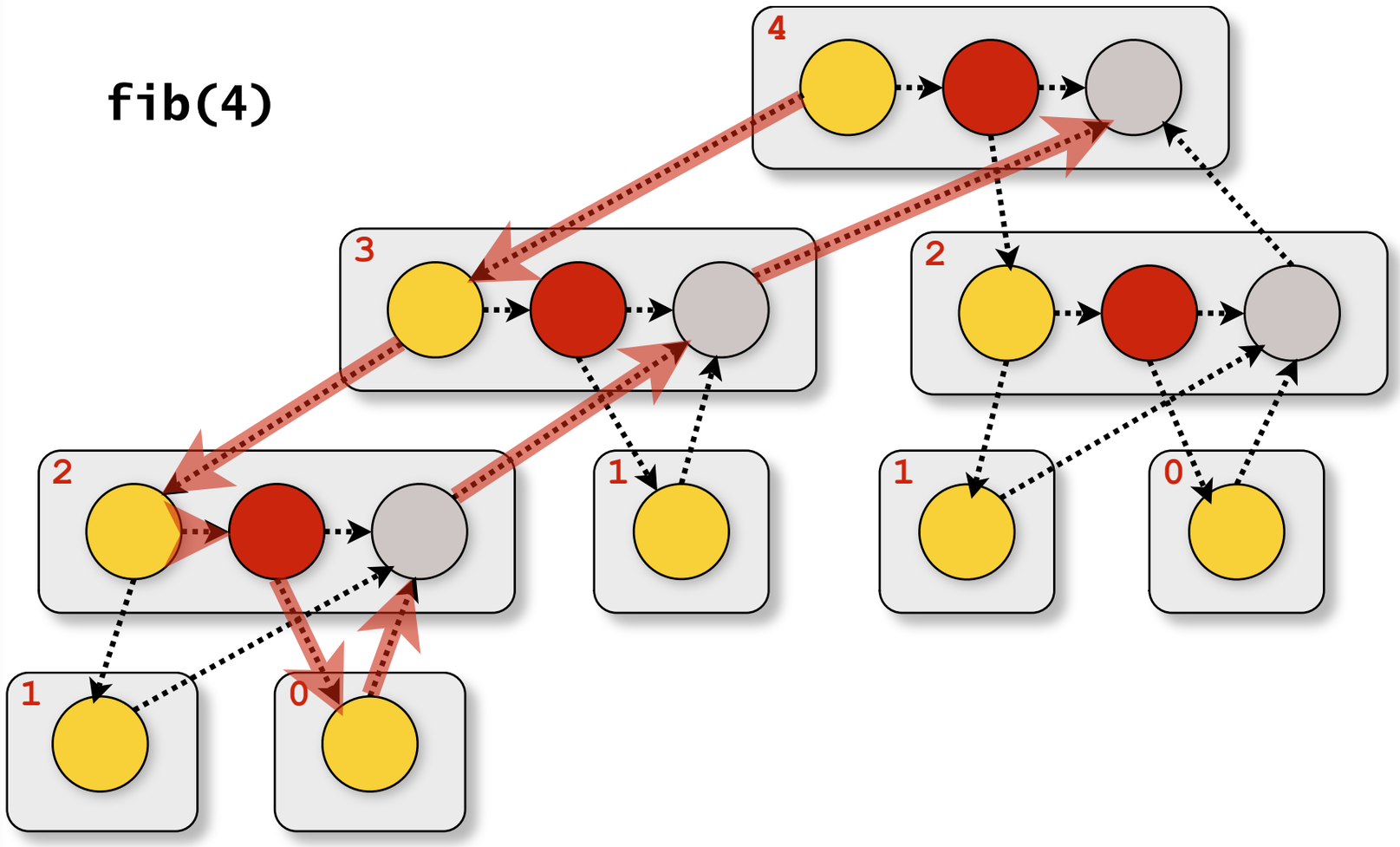
$$T_\infty = \text{“span”}$$

Degree of parallelism:

$$\frac{T_1}{T_\infty}$$

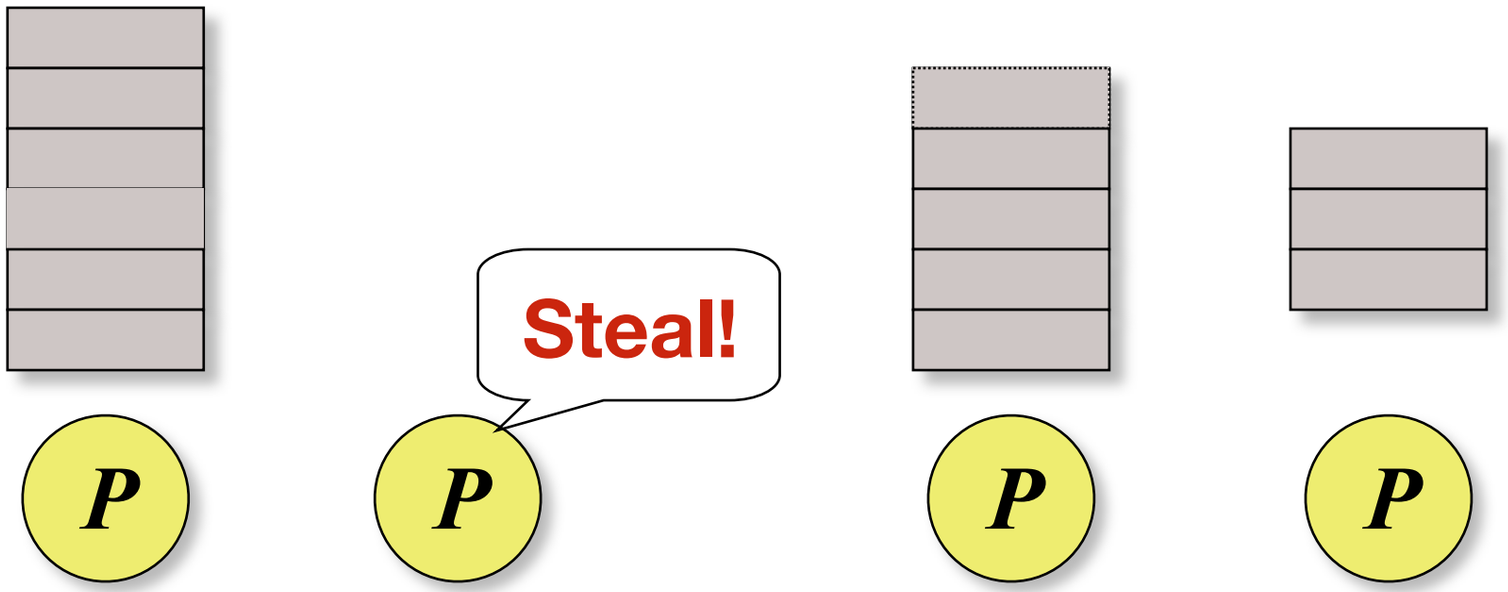
fib(4)





$$T_1 = 17$$
$$T_\infty = 8$$
$$\Longrightarrow \quad \frac{T_1}{T_\infty} \approx 2$$

Cilk's work-stealing scheduler



- Processors maintain **work queues**
- When out of work, processor selects another processor uniformly at **random** and takes work

Performance of Cilk's work-stealing scheduler

- **Theorem**: Expected running time is

$$T_p \leq \frac{T_1}{p} + O(T_\infty)$$

- *Proof sketch*: See Blumofe & Leiserson (FOCS '94)
  - A processor is either **working** or **stealing**.
  - Total time working is $\mathbf{T_1}$.
  - Each steal has **1/p** chance of reducing span by 1, so cost of all steals is $\mathbf{O(p*T_\infty)}$.
  - Expected time: $(T_1 + O(p^* T_\infty)) / p = \mathbf{T_1/p + O(T_\infty)}$

Cilk vs. PThreads

```
for (i = 0; i < N; ++i)
  spawn-or-fork foo (i);
sync-or-join;
```

- What happens if one instance of **foo** waits on another?
- Liveness property
  - Cilk: Lazy ("**may**") parallelism
  - PThreads: Eager ("**must**") parallelism

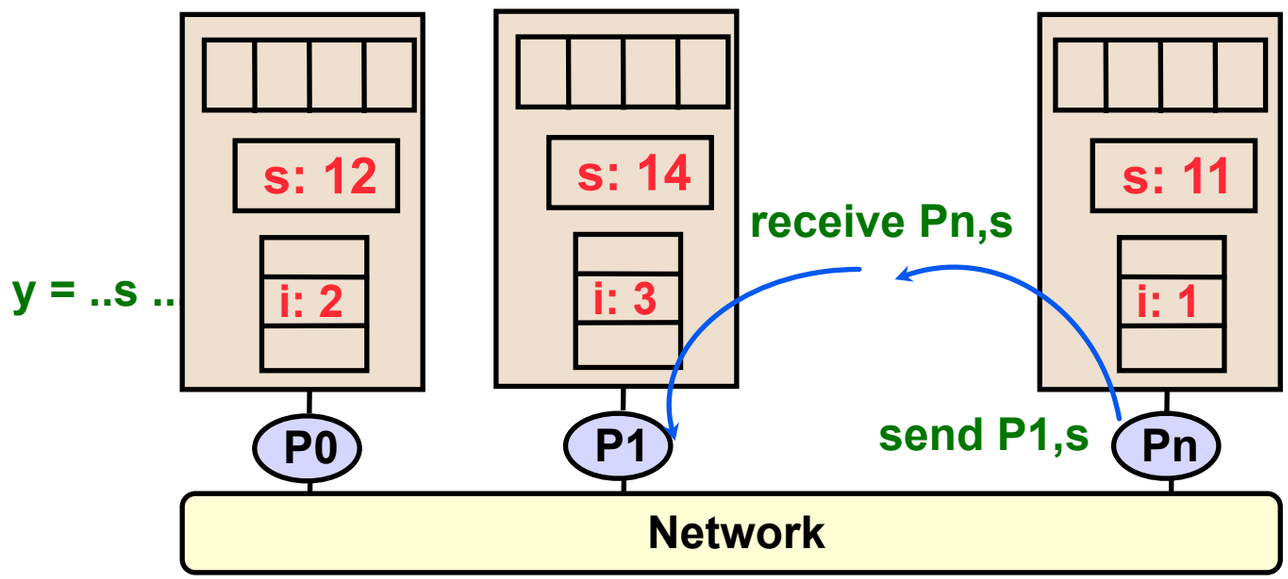
Additional features and caveats

- Provides
  - Fence (Cilk_fence)
  - Locking (Cilk_lock)
  - Automatic clean-up for local dynamic allocation (Cilk_alloca)
  - Aborts
- “Inlets” support use of spawned results in arbitrary expressions
- Run-time scheduler uses work-stealing
- Beware sharing through pointer-passing, deadlocks

Message Passing Interface (MPI)

Recall the message passing model

- Program = **named** processes
- **No shared** address space
- Processes communicate *via* **explicit send/receive** operations



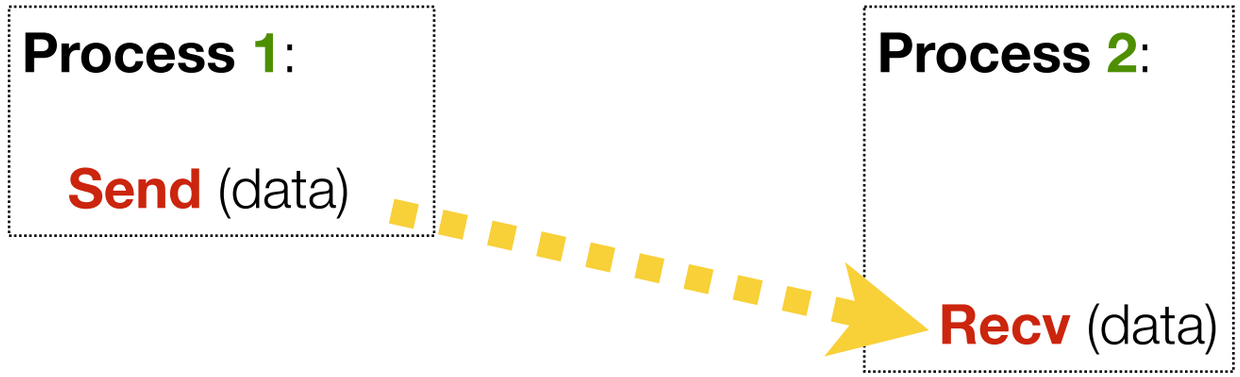
Message Passing Interface (MPI)

- Logical processes/tasks with distinct address spaces
- Communication primitives
  - Pairwise, or "**point-to-point**," send & recieve
  - **Collectives** on subsets of processes: broadcast, scatter/gather, reduce
- **Barrier** synchronization
- Advanced interface: **topology**, **one-sided**, **I/O**
- **Profiling** interface
- See: http://www.mpi-forum.org ; https://computing.llnl.gov/tutorials/mpi/

Hello, world in MPI

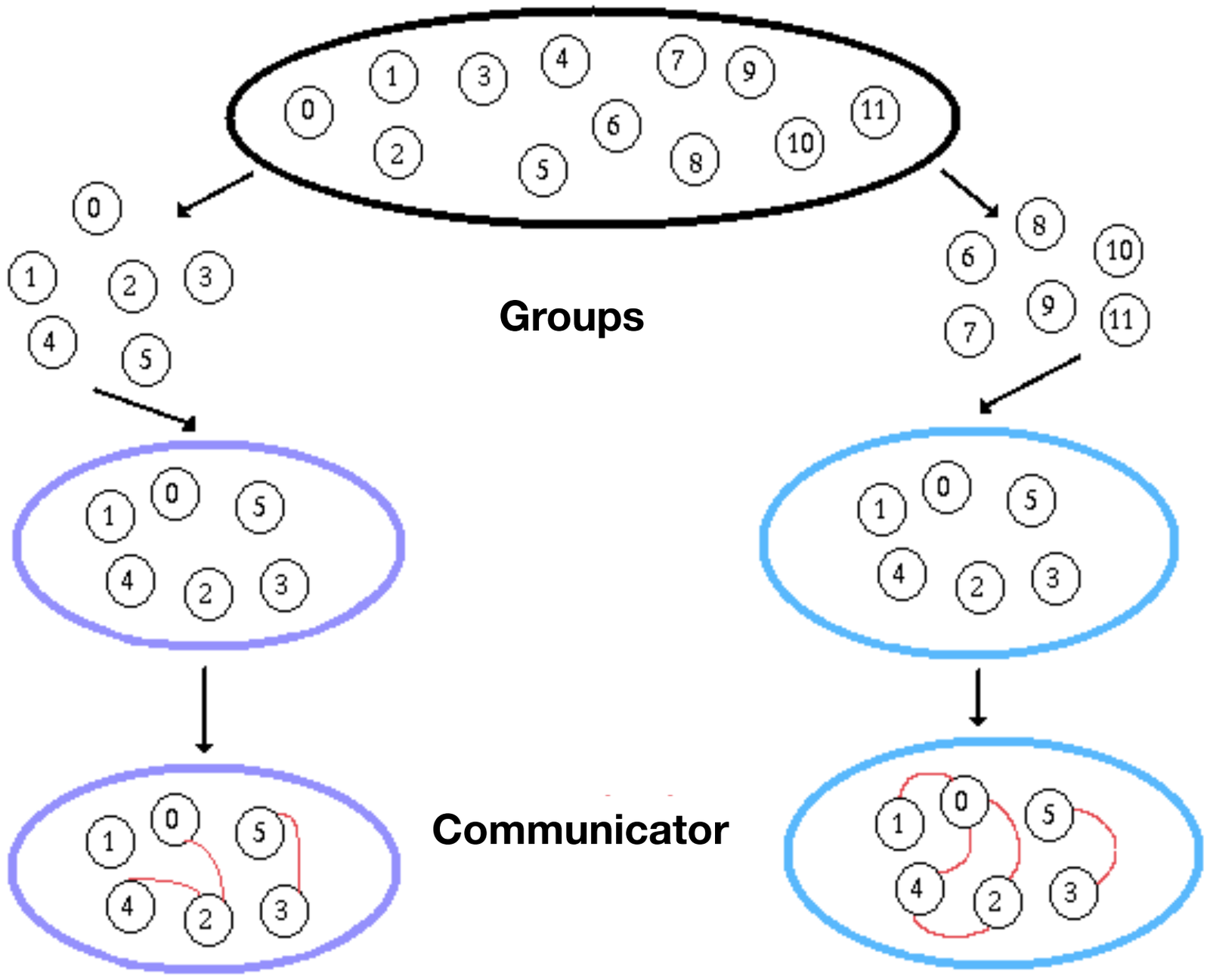
```
#include "mpi.h"
#include <stdio.h>

int main (int argc, char *argv[] )
{
    int rank, size;
    MPI_Init (&argc, &argv);
    MPI_Comm_rank (MPI_COMM_WORLD, &rank);
    MPI_Comm_size (MPI_COMM_WORLD, &size);
    printf ("I am %d of %d\n", rank, size);
    MPI_Finalize ();
    return 0;
}
```

Basic concepts: Send and receive



- How to **describe "data?"**
- How to **identify** processes?
- How will **receiver** recognize and screen messages?
- What does it mean for operations to **complete**?

MPI_COMM_WORLD



Basic concepts: Communicators

- **Group** = subset of processes
- **Communicator** = Group + attributes (*e.g.*, topology)
- **Rank** = process ID in its communicator
- **MPI_COMM_WORLD** = Group consisting of all processes
- **MPI_ANY_RANK** = Wildcard rank

Basic concepts: Data types

- In MPI call, “data” = (**address**, **count**, **type**)
- Data type = (recursively defined)
  - “Standard” scalar types: **MPI_INT**, **MPI_DOUBLE**, **MPI_CHAR**, …
  - An array of data types
  - A strided block of data types
  - An indexed array of blocks of data types
  - An arbitrary structure of data types

Basic concepts: Message tags and status objects

- **Message tags**
  - Every message has a user-defined integer ID
  - Wildcard: **MPI_ANY_TAG**

- **Status objects**: Opaque structures for querying error and other conditions

MPI blocking send:

MPI_Send (buffer-start, count, **type**, **dest-rank**, **tag**, **communicator**)

Process 1:

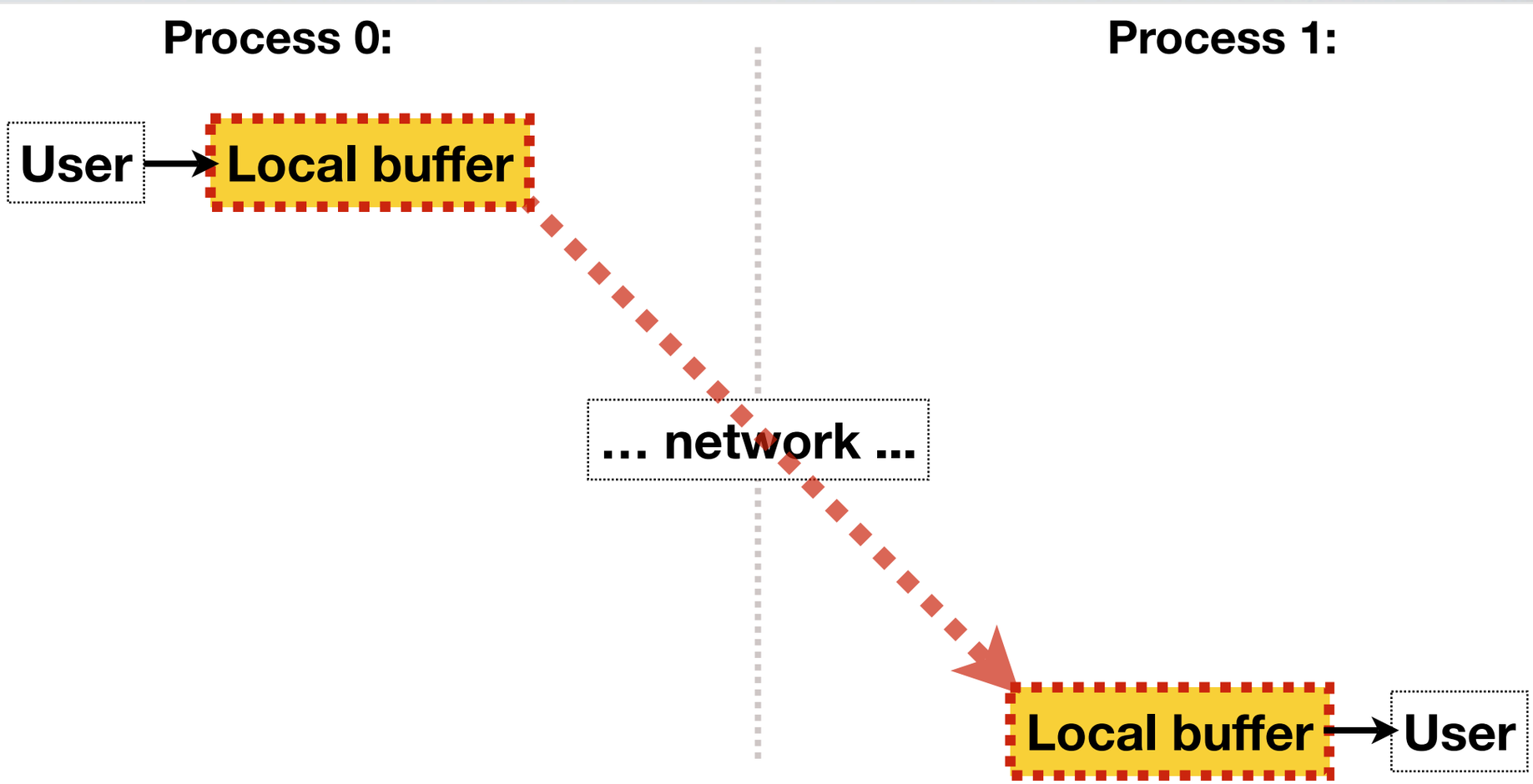
```
MPI_Send (data, n, MPI_INT, 2, tag, comm);
```

Process 2:

```
MPI_Recv (data, n, MPI_INT, 1, tag, comm, &stat);
```

- **Buffer** = (buffer-start, count, type) ; **Target** = (dest-rank, tag, comm)
- On return:
  - Data delivered to “the system”
  - May **reuse** buffer
  - Semantic note: Target may **not yet** have received message

What happens to data on “send”?



MPI blocking receive:

MPI_Recv (buffer-start, count, **type**, **source-rank**, **tag**, **comm, status**)

Process 1:
```
MPI_Send (data, n, MPI_INT, 2, tag, comm);
```

Process 2:
```
MPI_Recv (data, n, MPI_INT, 1, tag, comm, &stat);
```

- **Buffer** = (buffer-start, count, type) ; **Source** = (source-rank, tag, comm)
- Returns when **matching message** received
  - Match on source triplet; wildcards OK
  - Receiving fewer than *n* items is OK, but more is an error
  - May query “status” for more information (*e.g.*, size of message)

(Potentially) Avoid copies with non-blocking communication

- Non-blocking operations **return immediately** with handles
- **Wait** on handles

```
MPI_Request req;
MPI_Status stat;

MPI_Isend (buf, n, MPI_INT, dest, tag, comm, &req);

// … do not use “buf” …

MPI_Wait (&req, &stat);
```

- May poll instead of wait (“test”), or poll or wait on multiple requests

Other communication modes

- **Synchronous** sends (**MPI_Ssend**): Send completes when receive begins
- **Buffered** mode (**MPI_Bsend**): Use user-supplied buffer
- **Ready** mode (**MPI_Rsend**): User guarantees matching receive has posted
- Non-blocking versions of above
- **MPI_Recv** accepts messages sent in any mode
- **MPI_Sendrecv** initiates simultaneous send and receive

Beware of deadlock

- **"Unsafe" orderings** of send/receive

(a)

Process 1:
Recv (data → **2**)
Send (data ← **2**)

Process 2:
Recv (data → **1**)
Send (data ← **1**)

(b)

Process 1:
Send (data → **2**)
Recv (data ← **2**)

Process 2:
Send (data → **1**)
Recv (data ← **1**)

- How to avoid?

Ways to avoid deadlock

- Use **safe orderings**

Process 1:
Send (data → **2**)
Recv (data ← **2**)

Process 2:
Recv (data → **1**)
Send (data ← **1**)

- Use **simultaneous** send/receive

Process 1:
Sendrecv (data → **2**)

Process 2:
Sendrecv (data → **1**)

More ways to avoid deadlock

- **Supply** buffer space

Process 1:
Bsend (data → **2**)
Recv (data ← **2**)

Process 2:
Bsend (data → **1**)
Recv (data ← **1**)

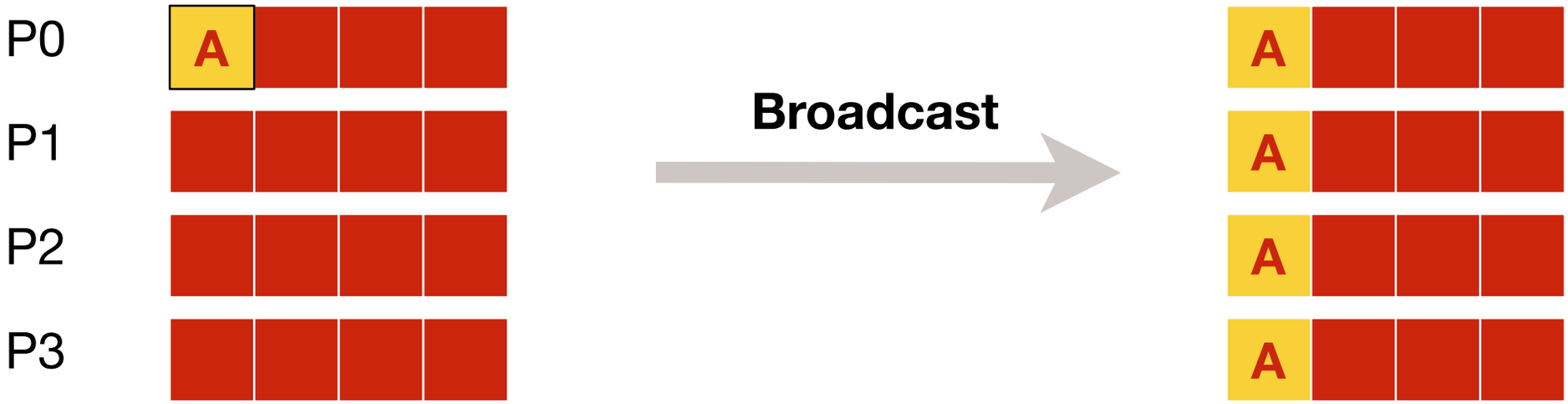
- Use **non-blocking** send/receive

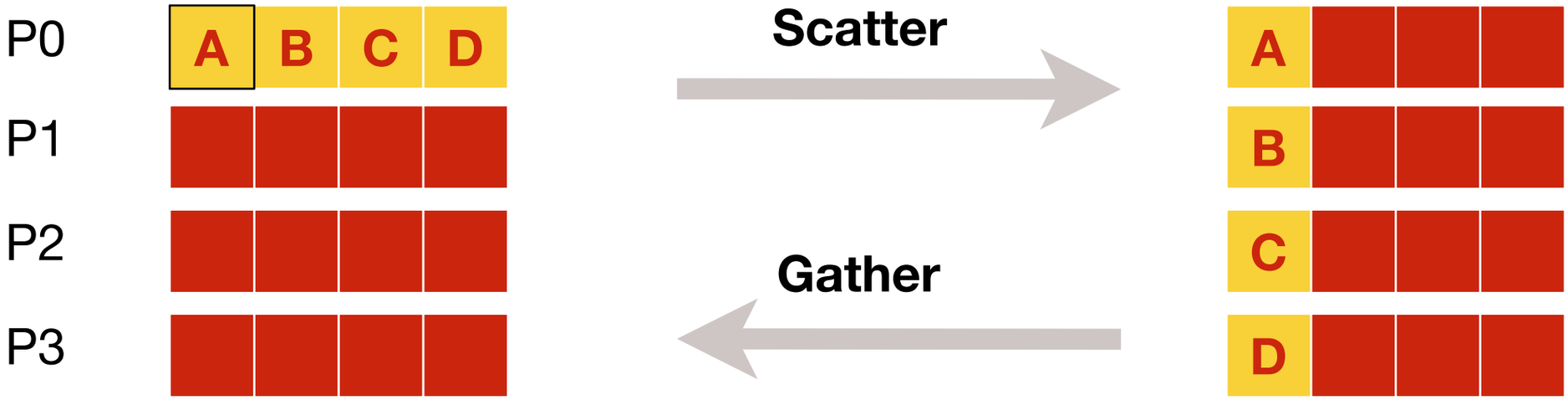
Process 1:
Isend (data1 → **2**)
Irecv (data2 ← **2**)
Waitall

Process 2:
Isend (data1 → **1**)
Irecv (data2 ← **1**)
Waitall

Collective communication

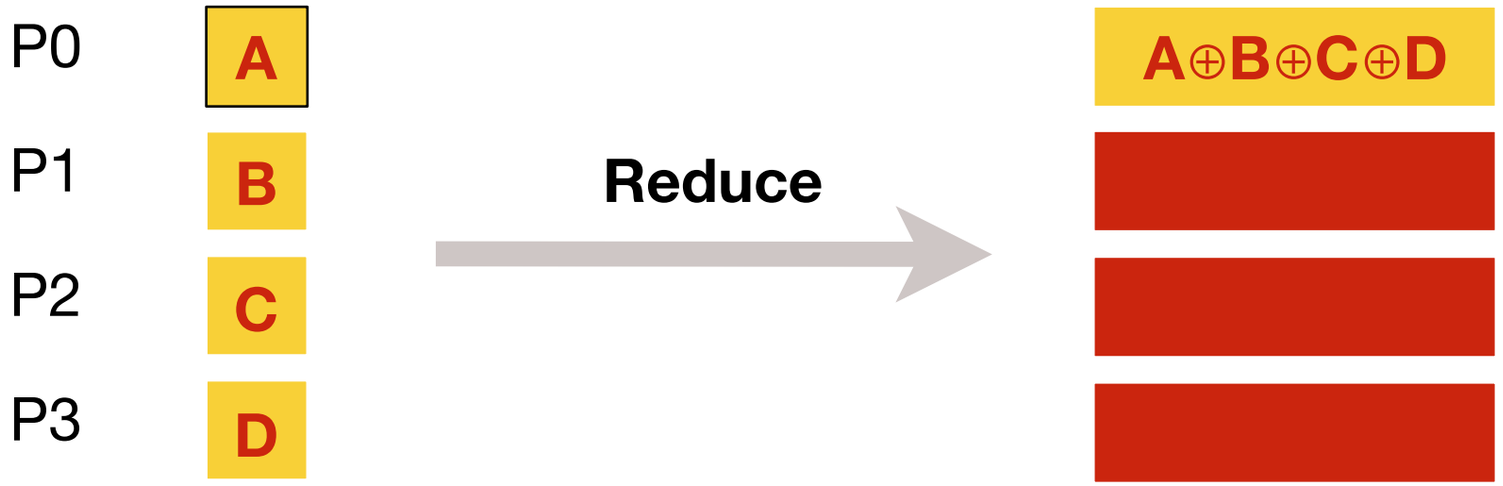
- Higher-level communication primitives
  - **MPI_Bcast**: Broadcast data to all processes
  - **MPI_Reduce**: Combine data from all processes to one process
  - **MPI_Barrier**
- Each process executes same operation
- Presumably optimized/tuned for hardware, but …

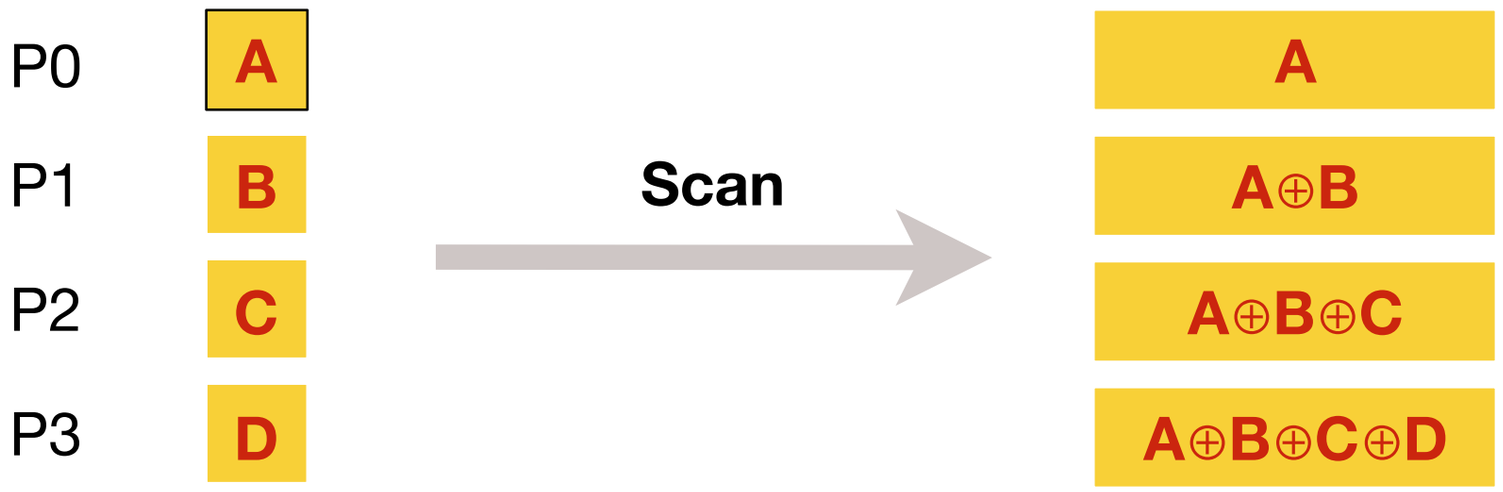

P0
P1
P2
P3
A
Broadcast
A
A
A
A


P0
P1
P2
P3
A B C D
Scatter
A
B
C
D
Gather


P0
P1
P2
P3
A
B
C
D
All gather
A B C D
A B C D
A B C D
A B C D


P0
P1
P2
P3
A0 B0 C0 D0
A1 B1 C1 D1
A2 B2 C2 D2
A3 B3 C3 D3
All-to-all
A0 A1 A2 A3
B0 B1 B2 B3
C0 C1 C2 C3
D0 D1 D2 D3


P0
A
P1
B
P2
C
P3
D
Reduce
A⊕B⊕C⊕D


P0
A
P1
B
P2
C
P3
D
Scan
A
A⊕B
A⊕B⊕C
A⊕B⊕C⊕D

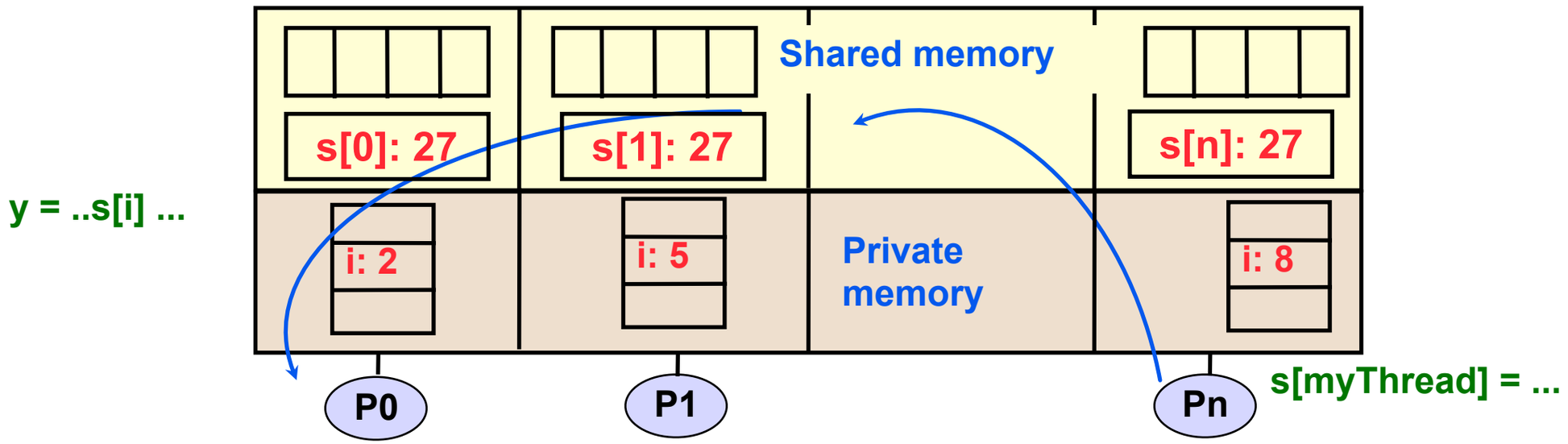
Summary: MPI

- Most commonly used MPI primitives
  - Init, Comm_size, Comm_rank, Send, Recv, Finalize
  - Non-blocking primitives for correctness and performance
- “Advanced” MPI features
  - Custom communicators
  - I/O
  - one-sided communication

Unified Parallel C (UPC)

Recall the partitioned global address space (PGAS) model

- Program = **named** threads
- Shared data, but **partitioned** over local processes
- Implied cost model: **remote accesses cost more**



Unified Parallel C (UPC)

- Implements PGAS model using concise, explicit parallel extensions to C
- Aimed at “low-level” performance programmers
- Precursors: Split-C, AC, PCP
- Other PGAS languages: Co-Array Fortran, Titanium (Java)

UPC execution model: Threads running in SPMD fashion

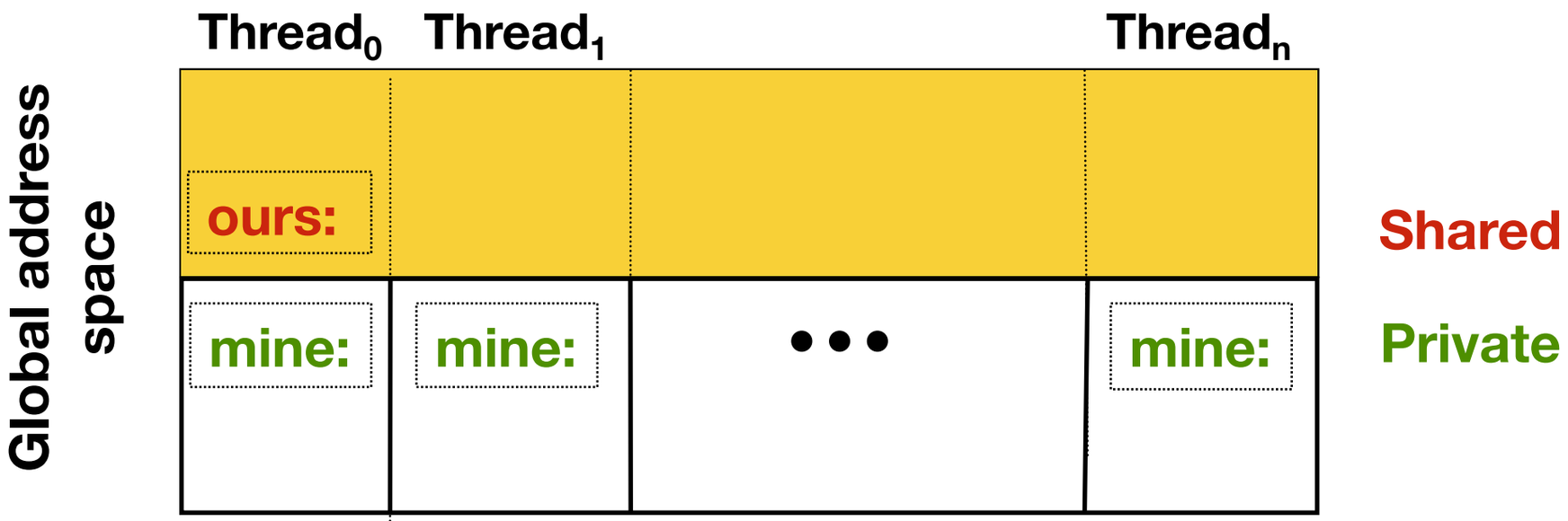
- **THREADS** = no. of threads, specified at compile- or run-time
- **MYTHREAD** = current thread's index (0 … **THREADS**-1)
- **upc_barrier**: All wait (global sync)

“Hello, world” in UPC

```
#include <upc.h>
#include <stdio.h>

int main ()
{
    printf (“[Thread %d of %d] Hello, world!\n”,
             MYTHREAD, THREADS);
    return 0;
}
```

Private vs. shared variables in UPC

```
int mine;          /* thread-private */
shared int ours; /* thread 0 */
```



Shared arrays distributed cyclically by default

```
shared int x[THREADS];     /* 1 elt per thread */
shared int y[3][THREADS]; /* 3 elt per thread */
shared int z[3][3];        /* 2 or 3 per thread */
```

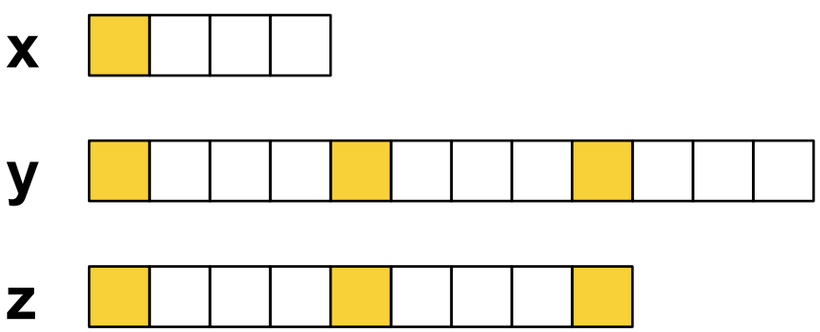
Example:

THREADS = 4

■ = “lives” on thread 0

Distribution rule:

1. Linearize
2. Distribute round-robin



Synchronization

- "Traditional" all-threads block barrier: **upc_barrier** [LABEL];
- Split-phase barrier

```
upc_notify;    /* Ready */
… do computation …
upc_wait;      /* Wait */
```

- Locks

```
upc_lock_t* l = upc_all_lock_alloc ();
   …
upc_lock (l);
   … critical code …
upc_unlock (l);
```

UPC collectives

- Usual suspects, **untyped**: broadcast, scatter, gather, reduce, prefix, …
- Interface has synchronization modes
  - Avoid over-synchronizing (barrier before/after is simplest, but may be unnecessary)
  - Data collected may be read/written by any thread
- Simple interface for collecting scalar values (*i.e.*, **typed**)
  - Berkeley UPC value-based collectives
  - Reference: http://upc.lbl.gov/docs/user/README-collectivev.txt

Example: Compute sum of an array

```
shared double data[N][THREADS];

…

{
   double s_local = 0; /* local sum */
   double s;  /* global sum */

   for (i = 0; i < N; ++i)
     s_local += data[i][MYTHREAD];

   /* Reduce to sum on thread 0 */
   s = bupc_allv_reduce (double, s_local, 0, UPC_ADD);
       /* Implicit barrier */

   if (MYTHREAD == 0)
     printf (“Sum = %g\n”, s);
   …
}
```

Common idiom: Owner computes

Example: Vector addition

```
shared double A[N], B[N], Sum[N];  /* laid out cyclically */
…
{
   int i;
   for (i = 0; i < N; ++i)
     if (i % THREADS == MYTHREAD)  /* owner computes */
        Sum[i] = A[i] + B[i];
   …
}
```

Work sharing with `upc_forall`

- Special type of loop for preceding idiom

```
upc_forall (init; test; inc; affinity)
  statement;
```

- Programmer asserts iterations are independent
- "Affinity" field
  - Integer: affinity % **`THREADS`** == **`MYTHREAD`**
  - Pointer: **`upc_threadof`** (affinity) == **`MYTHREAD`**
- Compiler may do better than iterate N times

Common idiom: Owner computes

Example: Vector addition using **upc_forall**

```
int i;
upc_forall (i = 0; i < N; ++i; i)  /* Note affinity */
    Sum[i] = A[i] + B[i];
```

Recall: Shared arrays in UPC

```
shared int x[THREADS];      /* 1 elt per thread */
shared int y[3][THREADS]; /* 3 elt per thread */
shared int z[3][3];         /* 2 or 3 per thread */
```

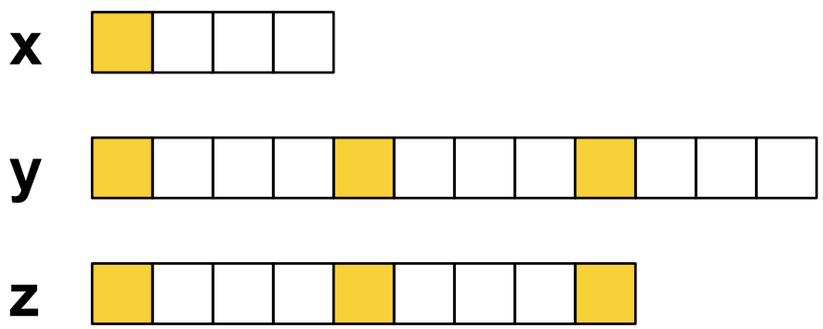
Example:

THREADS = 4

= "lives" on thread 0

Distribution rule:

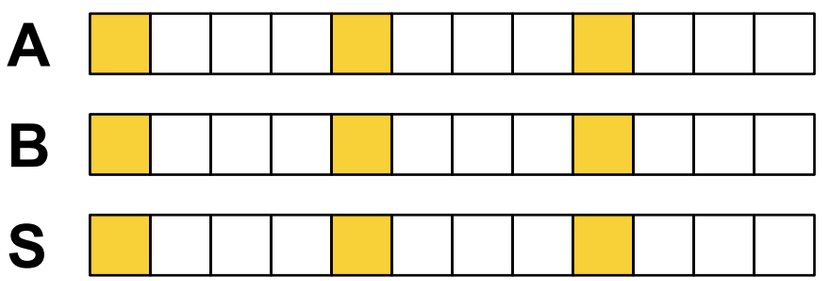
1. Linearize
2. Distribute cyclically



Recall: Shared arrays in UPC

Example: Vector addition using **upc_forall**

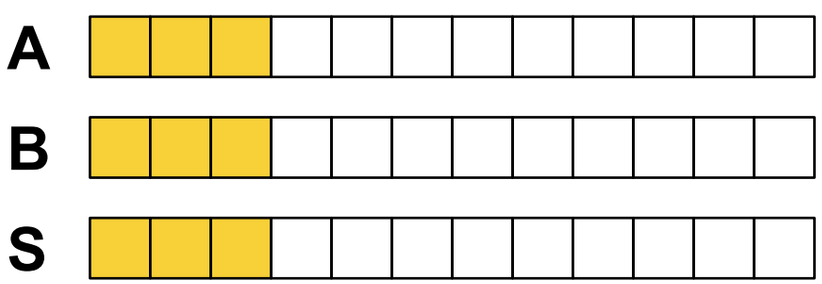
```
shared int A[N], B[N], C[N]; /* distributed cyclically */
… {
   int i;
   upc_forall (i = 0; i < N; ++i; i)  /* Note affinity */
      C[i] = A[i] + B[i];
… }
```



Blocked arrays in UPC

Example: Vector addition using **upc_forall**

```
shared int [*] A[N], B[N], C[N]; /* distributed by blocks */
… {
   int i;
   upc_forall (i = 0; i < N; ++i; &C[i]) /* Note affinity */
      C[i] = A[i] + B[i];
… }
```

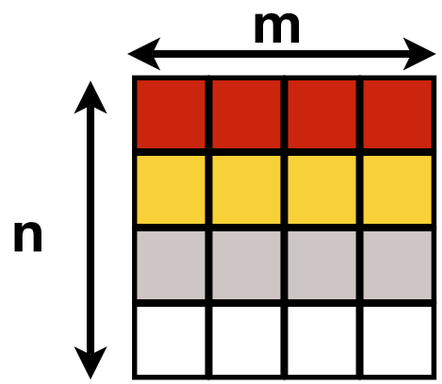


Data layout in UPC

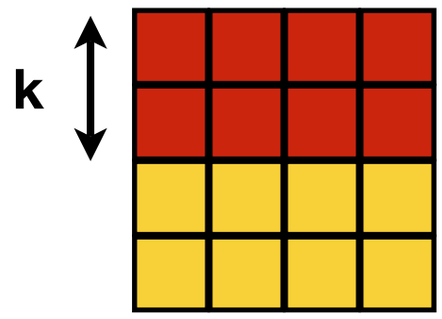
- All non-arrays bound to thread 0
- Variety of layout specifiers exist
  - No specifier (default): **Cyclic**
  - **[*]**: **Blocked**
  - **[0]** or **[ ]**: **Indefinite**, all on 1 thread
  - **[b]** or **[b1][b2]…[bn]** = **[b1*b2*…*bn]**: **Fixed** block size
- **Affinity** of element i = *floor*(i / block-size) % **THREADS**
- Dynamic allocation also possible (**upc_alloc**)

2-D array layouts in UPC

Example: n x m array




```
shared int [m] a1[n][m];
```




```
shared int [k][m] a2[n][m];
```

Co-Array Fortran (CAF)

Co-Array Fortran (CAF)

- Extends Fortran 95 to support PGAS programming model
  - Program == collection of **images** (*i.e.*, threads)
  - Array **“co-dimension”** type extension to specify data distribution
- References:
  - http://www.co-array.org
  - http://www.hipersoft.rice.edu/caf/index.html

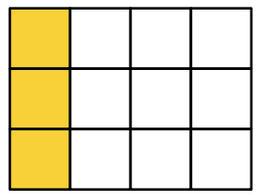
Co-array data type

- Declare real array, locally of length n, globally distributed

Example: n = 3, **num_images**( ) = 4

```
real :: A(n)[*]
```

A



- Compare to UPC

```
shared float [*] A_upc[n*THREADS];
```

```
shared float [3] A_upc[THREADS][3];
```

Communication in CAF

- Example: Every image copies from an image, p

```
real :: A(n)[*]
…
A(:) = A(:)[p]
```

- Syntax “**[p]**” is a visual flag to user

More CAF examples

```
real :: s  ! Scalar
real :: z[*]  ! “co-scalar”
real, dimension(n)[*] :: X, Y  ! Co-arrays
integer :: p, list(m)  ! Image IDs
   …
X       = Y[p]    ! 1. get
Y[p]    = X       ! 2. put
Y[:]    = X       ! 3. broadcast
Y[list] = X       ! 4. broadcast over subset
X(list) = z[list] ! 5. gather
s = minval(Y[:])  ! 6. min (reduce) all Y
X(:)[:] = s       ! 7. initialize whole co-array
```

Multiple co-dimensions

```
real :: x(n)[p,q,*]
```

- Organizes images in logical 3-D grid
- Grid size: p x q x k, where p*q*k == **num_images**( )