CSE 160
Lecture 17

Hypercube algorithm
Gather/Scatter

Announcements

- Quiz #3 return
- Some tips about synchronization bugs

Question 2

(1)	void sweep(int TID, int myMin, int myMax, double ε, double& err){
(2)	for (int s = 0; s < 100; s++) {
(3)	double localErr = 0;
(4)	for (int i = myMin; i < myMax; i++){
(5)	unew[i] = (u[i-1] + u[i+1])/2.0;
(6)	double δ = fabs(u[i] - unew[i]);
(7)	localErr += δ * δ ;
(8)	}
(9a) (9b) (9c)	BEGIN CRITICAL SECTION: err += localErr; END CRITICAL SECTION
(10)	if ((s > 0) && (err < ε))
(11)	break;
(12)	if (!TID){double *t = u; u = unew; unew = t;} // Swap u ↔ unew
(13)	err = 0;
(14)	} // End of s loop
(15)	}

Conservative Synchronization

(1)	void sweep(int TID, int myMin, int myMax, double ε, double& err){
(2-8)	…
(9a) (9b) (9c)	BEGIN CRITICAL SECTION: err += localErr; END CRITICAL SECTION
	BEGIN CRITICAL SECTION:
(10)	if ((s > 0) && (err < ε))
(11)	break;
	END CRITICAL SECTOIN
(12)	if (!TID){double *t = u; u = unew; unew = t;} // Swap u ↔ unew
	BEGIN CRITICAL SECTION:
(13)	err = 0;
	END CRITICAL SECTOIN
(14)	} // End of s loop
(15)	}

Critical sections:
(10)
(13)

Happens Before Relationship?

Thread 1

(1)	for (int s = 0; s < 100; s++) {
(9a) (9b) (9c)	BEGIN CRITICAL SECTION: err += localErr; END CRITICAL SECTION
(10)	if ((s > 0) && (err < ε))
(11)	break;
(12)	if (!TID){ /*u<-->unew*/}
(13)	err = 0;
(14)	}// end of s loop

Thread 2

(1)	for (int s = 0; s < 100; s++) {
(9a) (9b) (9c)	BEGIN CRITICAL SECTION: err += localErr; END CRITICAL SECTION
(10)	if ((s > 0) && (err < ε))
(11)	break;
(12)	if (!TID){ /*u<-->unew*/}
(13)	err = 0;
(14)	} //end of s loop

(9b) ⟷ (10)
(10) ⟷ (13)
(12) i-th iteration ⟷ i+1-th iteration

Minimize Synchronization

(1)	void sweep(int TID, int myMin, int myMax, double ε, double& err){
(2-8)	…
(9a) (9b) (9c)	BEGIN CRITICAL SECTION: err += localErr; END CRITICAL SECTION
	BARRIER()
	~~BEGIN CRITICAL SECTION:~~
(10)	if ((s > 0) && (err < ε))
(11)	break;
	~~END CRITICAL SECTOIN~~
	BARRIER()
(12)	if (!TID){double *t = u; u = unew; unew = t;} // Swap u ↔ unew
	~~BEGIN CRITICAL SECTION:~~
(13)	err = 0;
	~~END CRITICAL SECTOIN~~
	BARRIER()
(14)	} // End of s loop
(15) }	

Some tips about Concurrent bugs

```
//NT is a global vairable
//The function intends to print the number of threads
(1)ThreadFunc(int TID){
(2)    NT++;
(3)    if(TID==0){
(4)        cout<<NT<<endl;
(5)    }
(6)}
```

locks?

barrier()?

Brute force:
try locks and barriers at each global access?

How to do it systematically?

Thread Synchronization

- Exclusion
  - Critical sections
  - Order not guaranteed
  - Mechanisms(mutex, atomic variables, etc.)
- Synchronization
  - Happen-before relationship
  - Mechanisms(barrier, join, condition variable, spinning loop, etc.)
- Minimal synchronization

Exclusion

- Find all the critical section locations
  - shared variables accessed by different threads
  - at least one access is write

```
//NT is a global vairable
//The function intends to print the //
number of threads
(1)ThreadFunc(int TID){
(2)    NT++;
(3)    if(TID==0){
(4)        cout<<NT<<endl;
(5)    }
(6)}
```

```
(1)ThreadFunc(int TID){
(2)    lock();
(3)    NT++;
(4)    unlock();
(5)    if(TID==0){
(6)        lock();
(7)        cout<<NT<<endl;
(8)        unlock();
(9)    }
(10)}
```

Check for thread synchronization

- Identify happens-before relationship requirements

Thread 1

```
(1)ThreadFunc(int TID){
(2)    lock();
(3)    NT++;
(4)    unlock();
(5)    if(TID==0){
(6)        lock();
(7)        cout<<NT<<endl;
(8)        unlock();
(9)    }
(10)}
```

Happens-before

Thread 2

```
(1)ThreadFunc(int TID){
(2)    lock();
(3)    NT++;
(4)    unlock();
(5)    if(TID==0){
(6)        lock();
(7)        cout<<NT<<endl;
(8)        unlock();
(9)    }
(10)}
```

barrier();

Minimize Synchronization

```
ThreadFunc(int TID){
    lock();
    NT++;
    unlock();
    barrier();
    if(TID==0){
        lock();
        cout<<NT<<endl;
        unlock();
    }
}
```

Three Steps

- Critical section identification
- Happens-before relation
- Minimal synchronization

Today's lecture

- More Collectives
  - Inside MPI
  - Hypercubes and spanning trees
  - Gather/Scatter
- Parallel Print Function

Collective communication

- Basic collectives seen so far
  - Broadcast: distribute data from a designated root process to all the others
  - Reduce: combine data from all processes returning the result to the root process
  - How do we implement them?
- Other Useful collectives
  - Scatter/gather
  - All to all
  - Allgather
- Diverse applications
  - Printing distributed data: “parallel print”
  - Sorting
  - Fast Fourier Transform

Underlying assumptions

- Fast interconnect structure
  - All nodes are equidistant
  - Single-ported, bidirectional links
- Communication time is $\alpha + \beta n$ in the absence of contention
  - Determined by bandwidth β^{-1} for long messages
  - Dominated by latency α for short messages

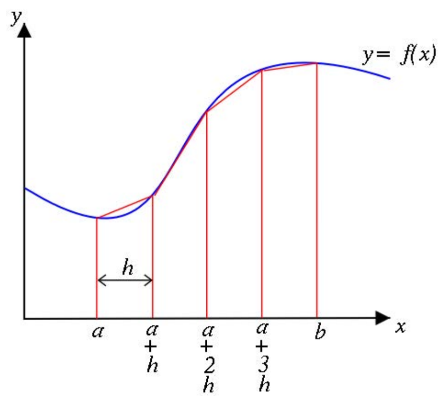
Inside MPI-CH

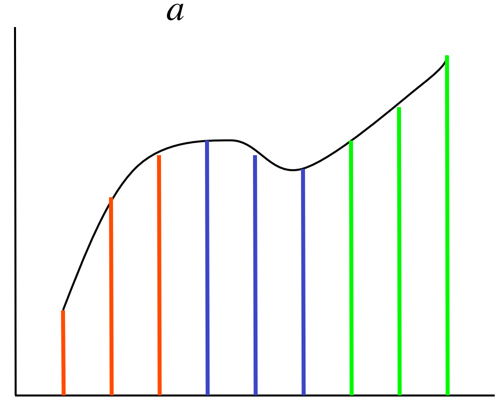
- Tree like algorithm to broadcast the message to blocks of processes, and a linear algorithm to broadcast the message within each block
- Block size may be configured at installation time
- If there is hardware support (e.g. Blue Gene), then it is given responsibility to carry out the broadcast
- Polyalgorithms apply different algorithms to different cases, i.e. long vs. short messages, different machine configurations
- We'll use hypercube algorithms to simplify the special cases when $P=2^k$, k an integer

Recapping the Parallel Implementation of the Trapezoidal Rule

- Decompose the integration interval into sub-intervals
- Each core computes the integral on its subinterval
- All combine their local integrals into a global one
- Use a collective routine to combine the local values

$$\int_a^b f(x)dx$$





Collective communication in MPI

- Collective operations are called by **all** processes within a communicator
- Broadcast: distribute data from a designated "root" process to all the others

  MPI_Bcast(in, count, type, root, comm)
- Reduce: combine data from all processes and return to a deisgated root process

  MPI_Reduce(in, out, count, type, op, root, comm)
- Allreduce: all processes get recuction: **Reduce + Bcast**

Final version

```
int local_n = n/p;

float local_a = a + my_rank*local_n*h,
      local_b = local_a + local_n*h,
      integral = Trap(local_a, local_b, local_n, h);

MPI_Allreduce( &integral, &total, 1,
               MPI_FLOAT, MPI_SUM, WORLD)
```

Broadcast

- The root process transmits of *m* pieces of data to all the *p-1* other processors
- With the linear ring algorithm this processor performs p-1 sends of length m
  - Cost is $(p-1)(\alpha + \beta m)$
- Another approach is to use the *hypercube algorithm,* which has a logarithmic running time

Today's lecture

- More Collectives
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  - Hypercubes and spanning trees
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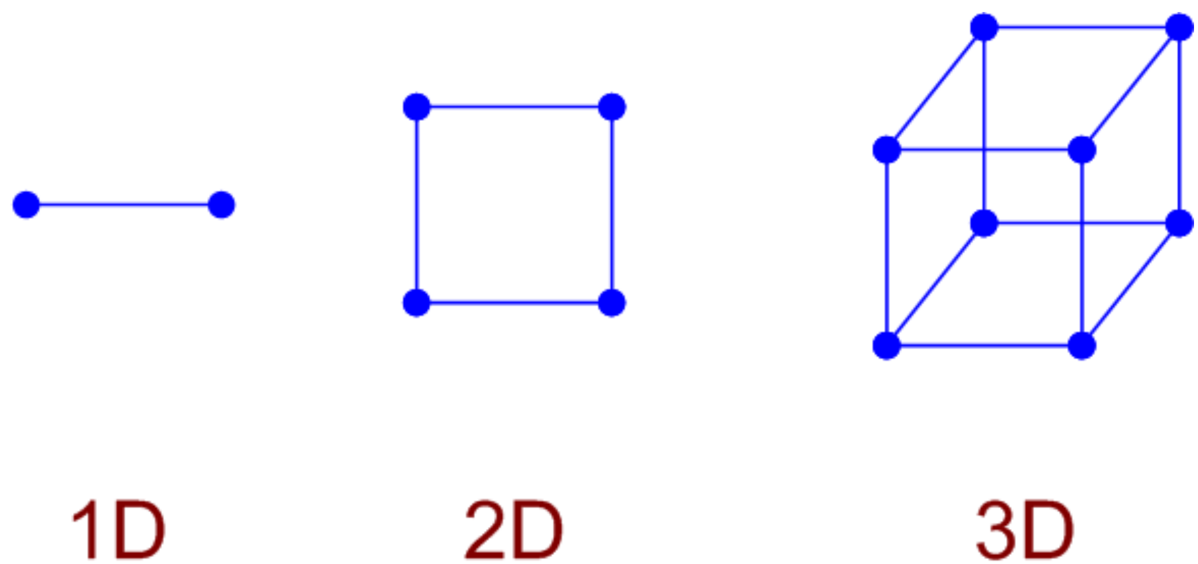
- Parallel Print Function

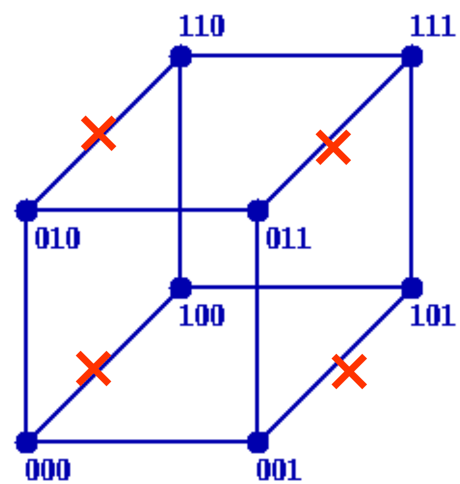
Sidebar: what is a hypercube?

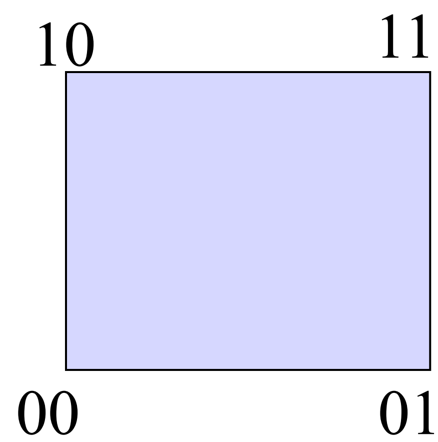
- A hypercube is a d-dimensional graph with 2^d nodes
- A 0-cube is a single node, 1-cube is a line connecting two points, 2-cube is a square, etc
- Each node has d neighbors



Properties of hypercubes

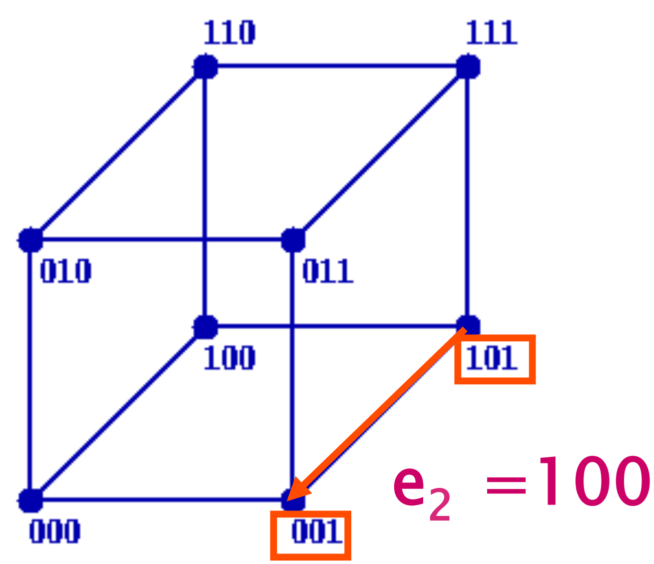
- A hypercube with p nodes has lg(p) dimensions
- *Inductive construction*: we may construct a d-cube from two (d-1) dimensional cubes
- **Diameter:** What is the maximum distance between any 2 nodes?
- **Bisection bandwidth:** How many cut edges (mincut)





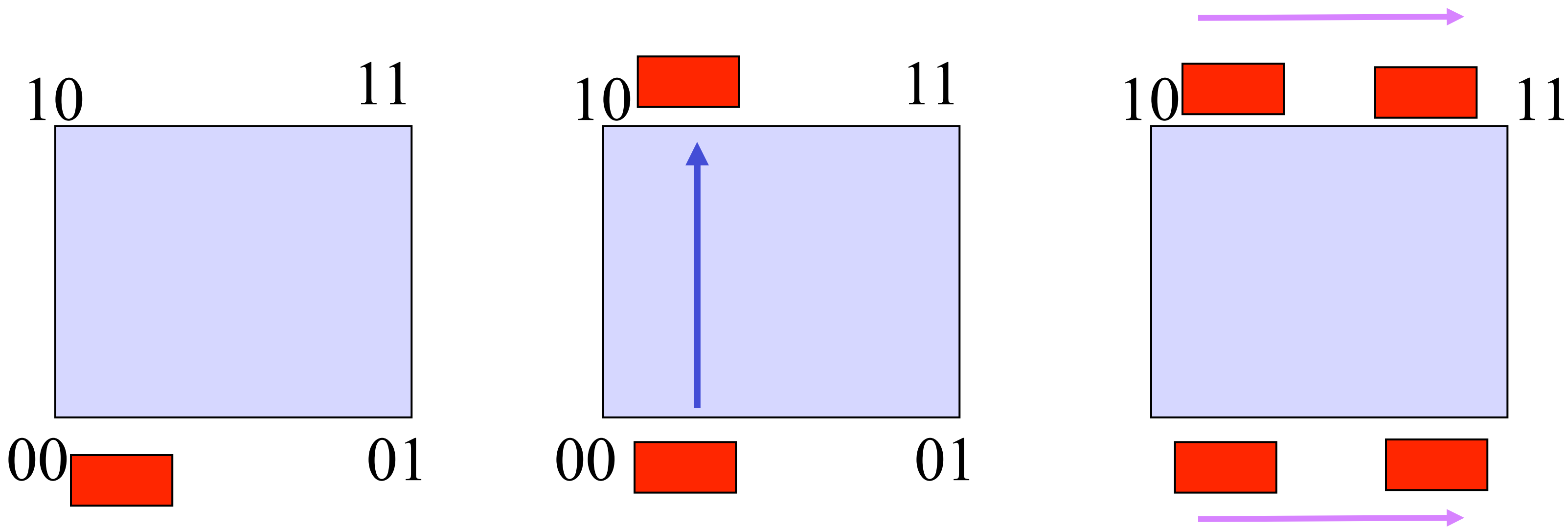
Bookkeeping

- Label nodes with a binary reflected grey code
  http://www.nist.gov/dads/HTML/graycode.html
- Neighboring labels differ in exactly one bit position $001 = 101 \otimes e_2, \quad e_2 = 100$



Hypercube broadcast algorithm with p=4

- Processor 0 is the root, sends its data to its hypercube "buddy" on processor 2 (10)
- Proc 0 & 2 send data to respective buddies



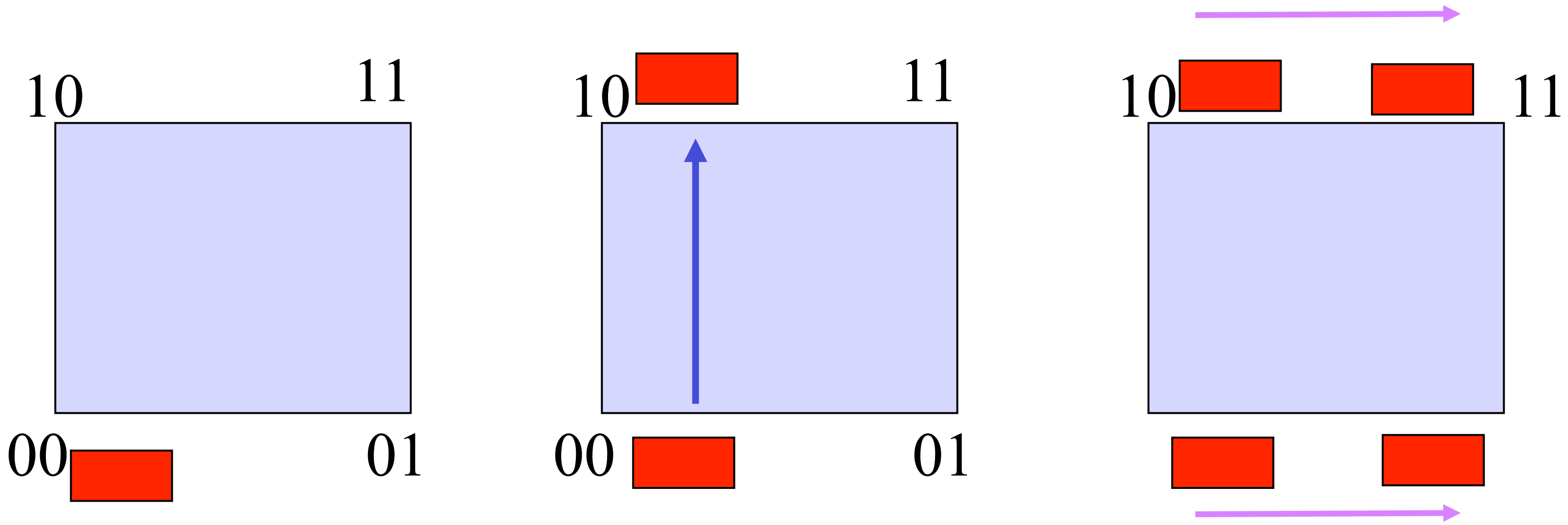
Reduction

- We may use the hypercube algorithm to perform reductions as well as broadcasts
- Another variant of reduction provides all processes with a copy of the reduced result

  Allreduce( )
- Equivalent to a Reduce + Bcast
- A clever algorithm performs an Allreduce in one phase rather than having perform separate reduce and broadcast phases

Allreduce

- Can take advantage of duplex connections



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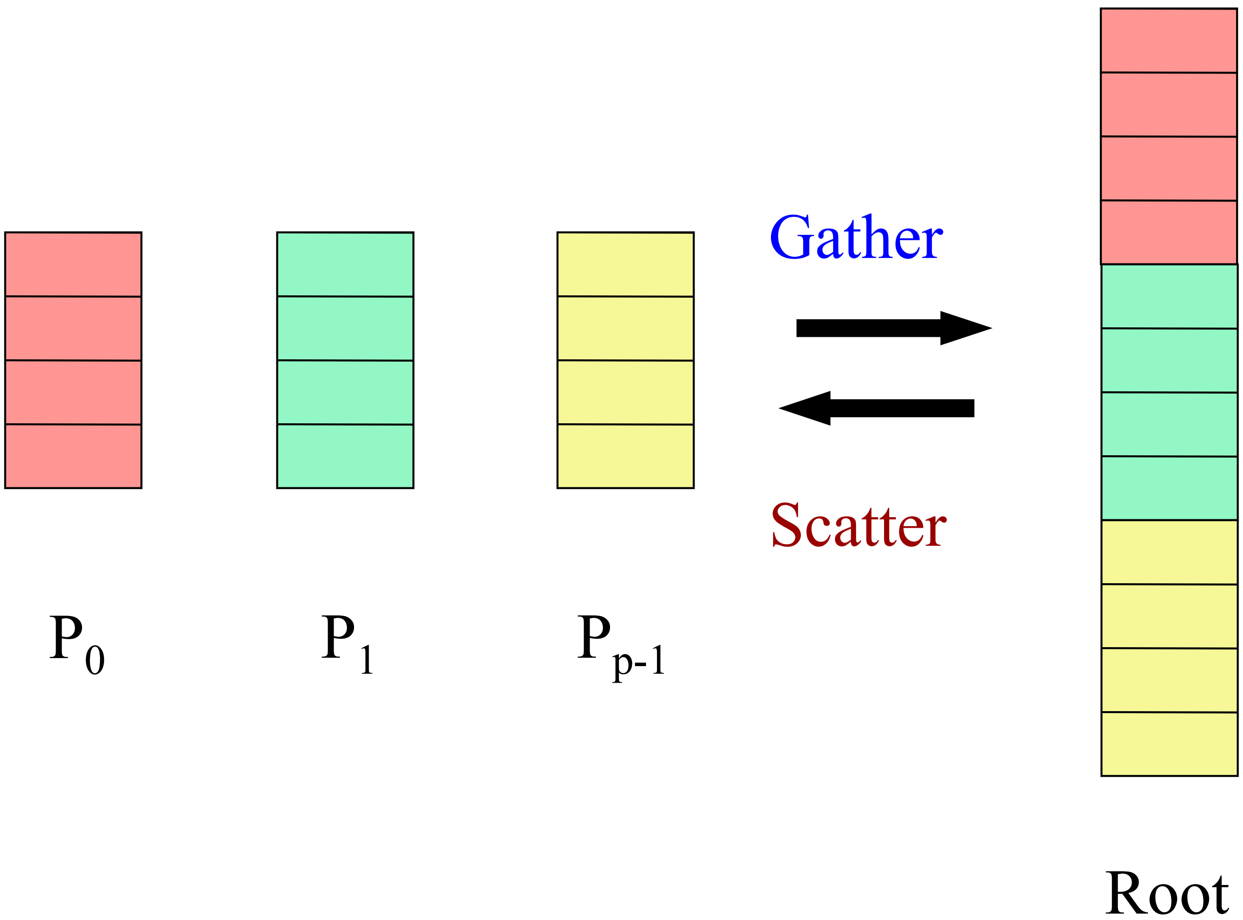
Scatter/Gather



Scatter

- Simple linear algorithm
  - Root processor sends a chunk of data to all others
  - Reasonable for long messages

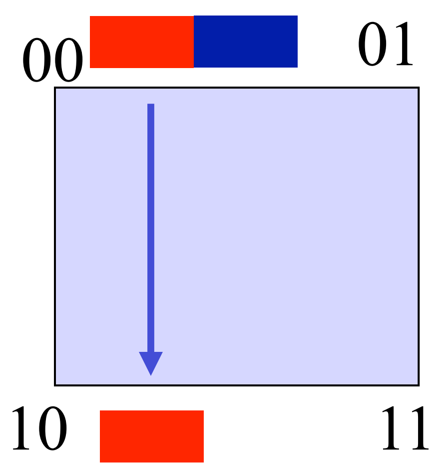
$$(p-1)\alpha + \frac{p-1}{p} n\beta$$

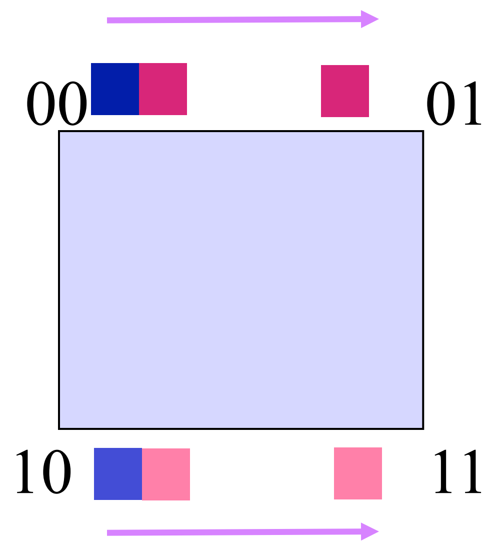
- Similar approach taken for Reduce and Gather
- For short messages, we need to reduce the complexity of the latency (α) term

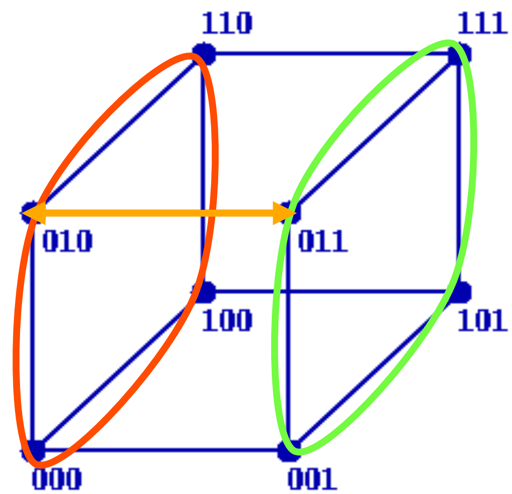
Minimum spanning tree algorithm

- Recursive hypercube-like algorithm with ⌈log P⌉ steps
  - Root sends half its data to process (root + p/2) **mod** p
  - Each receiver acts as a root for corresponding half of the processes
  - MST: organize communication along edges of a minimum-spanning tree covering the nodes
- Requires O(n/2) temp buffer space on intermediate nodes
- Running time:

$$\lceil \lg P \rceil \alpha + \frac{p-1}{p} n\beta$$







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Parallel print function

- Application of Gather
- Problem: how to sort out all the output on the screen
- Many messages say the same thing

```
Process 0 is alive!
Process 1 is alive!
        …
Process 15 is alive!
```

- Compare with

```
Processes[0-15] are  alive!
```

- Parallel print facility
  http://www.llnl.gov/CASC/ppf

Summary of capabilities

- Compact format list sets of nodes with common output

```
PPF_Print( MPI_COMM_WORLD, "Hello world" );
```

```
0-3: Hello world
```

- %N specifier generates process ID information

```
PPF_Print( MPI_COMM_WORLD, "Message from %N\n" );
```

```
Message from 0-3
```

- Lists of nodes

```
PPF_Print(MPI_COMM_WORLD,
          (myrank % 2)
           ? "[%N] Hello from the odd numbered nodes!\n"
           : "[%N] Hello from the even numbered nodes!\n")
```

```
[0,2] Hello from the even numbered nodes!
[1,3] Hello from the odd numbered nodes!
```

Practical matters

- Installed in $(PUB)/lib/PPF
- Specify ppf=1 and mpi=1 on the "make" line
  - Defined in arch.gnu-4.7_c++11.generic
  - Each module that uses the facility must

    #include "ptools_ppf.h"

- Look in $(PUB)/Examples/MPI/PPF for example programs ppfexample_cpp.C and test_print.c
- Uses MPI_Gather()