# CSE524 Parallel Computation

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## Announcements

- Thanks to everyone who found the UD-scan bugs in the slides and book!
- Approval for MS cluster happened today!
  - Accounts assigned this week
  - Documents up this week
  - Should be developing off-line anyhow (more later)
- Next week is ZPL, but if you're expecting to use it, read text early

There is still time for project revisions

## Tonight's Assignment

- UD-Scan of your choice ... what did you choose?

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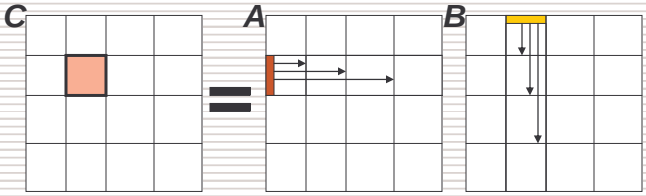
## Multicast Logic

- Recall the question of multicasting in Peril-L in a way that is suitable for SUMMA
- This is the set up: tile rows want column segments and tile columns want row seg.s

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## Memory Allocation

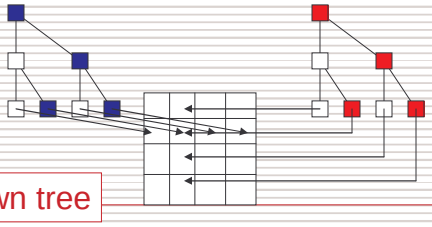
- The problem memory is in global space

```
double A_G[n][n], B_G[n][n], C_G[n][n];
int p=sqrt(P), t=n/p;          Define constants
```

- Allocate materialized memory for row/col for seg.s

```
double Acol_GO[p][p][t],Brow_GO[p][p][t];
```

- Next, induce a tree on the tile rows, columns



**Assume p is a power of 2**

Flow down tree

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## Logical Tree for (a Row) of Tiles

- A node waits on its _GO memory; when it gets it's value, it simply fills out its sibling nodes if any

```
if (v == 0)
  stride=p;
else
  stride = pow(2,loOrdZeroes(v));   No. least sig zeroes
a[0:t-1] = Acol_GO[u][v][0:t-1];    Grab col segment
while (stride > 1) {                Sweep thru siblings
  stride = stride>>1;               Reference next one
  Acol_GO[u][v+stride][0:t-1]=a[0:t-1]; Fill GO mem
}
```

Make it into a procedure: **`mcast()`**

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## Loading _GO Mem As k changes

- Make diagonal tiles responsible

```
for (k=0;k<n;k++){                    For cols of A & rows of B
  if (u==v && u*t<k && k<u*t+t-1){Diag tiles fill first _GO
    for (i=0;i<p;i++){
      Acol_GO[i][0][0:t-1]=A_G[i*t:i*t+t-1][k];
      Brow_GO[0][i][0:t-1]=B_G[k][i*t:i*t+t-1];
    }
  }
  a[0:t-1]=mcast(u,v,Acol);      Do multicast, if needed
  b[0:t-1]=mcast(u,v,Brow);      Do multicast, if needed
  ...
}
```

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## SUMMA Preamble Code

```
double A_G[n][n], B_G[n][n], C_G[n][n];
int p=sqrt(P), t=n/p;                 Define constants
forall u,v in (0..p-1,0..p-1){        Thread in 2D
  double C[t][t]=is_local(C_G)        Ref local tile
  int i,j,k; double a[t], b[t];
  for (i=0;i<t;i++) {
   for (j=0;j<t;j++) {
        C[i][j] = 0.0;                Initialize C
   }
  }
```

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## Inner Loop of SUMMA

```
for (k=0;k<n;k++) {          For cols of A & rows of B
  /* Multicasting code goes here */
for (i=0;i<t;i++) {
   for (j=0;j<t;j++) {
      c[i][j] += a[i]*b[j];   Figure kth terms
   }
  }
 }
}
```

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## Multicast Improvement

- The diagonal tile processors fill all of the _GO memory, so processors wait on them
- Is there a better solution? Issues …
  - A specific tile (diagonal) initializes result
  - All row (col) roots initialized together

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## Revision …

- The first processor in row/col ready, call it a "winner," becomes tree root and tree shifts
  - To shift tree, simply use the u (v) value of winner to offset all node positions, doing all addressing math mod *p*
  - To ensure a uniquely identified winner, use an `exclusive` block (per row/col) & global; if your `k` is higher than the value stored there, you're the winner; update it and fire-up the tree

How much can the computation skew?

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## Parallel Programming Support

- For decades it's been assumed:

  parallel code = compiler(sequential code)
- Compilers have progressed, but cannot do the conversion in general circumstances
- Two basic solutions
  - Library + serial programming language
    - Main issue: || abstractions limited
  - Legitimate parallel language
    - Main issue: quality of emitted code

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## || Programming Language Topic

- There is much to say about || languages
- Book's Strategy
  - 3 representative approaches (will be 2 more)
  - Give key features, basics; enough to write code but other materials needed for full study
- Course Strategy
  - Discuss several approaches including book's
  - Focus on abstract ideas
  - Summarize and discuss current s-o-t-a

Avoid teaching detail

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## OpenMP

- Nonproprietary extensions (as pragmas) to C, C++, Fortran
- Mainly used to exploit hyper-threading parallelism in a single fetch/execute engine
- Use
  - Programmer inserts pragmas identifying ||ism
  - Compiler recognizing pragmas generates multi-threaded code
  - System in control of most aspects of ||ism

http://www.openmp.org

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## OpenMP Code Examples

- All pragmas begin: `#pragma`
- Convert 32-bit RGB image to 8-bit gray scale

```
#pragma omp parallel for
for (i=0; i < numPixels; i++) {
      pGrayScaleBitmap[i] = (unsigned BYTE)
            (pRGBBitmap[i].red   * 0.299 +
             pRGBBitmap[i].green * 0.587 +
             pRGBBitmap[i].blue  * 0.114);
}
```

- ||ism is “element-wise” … each item independent

Also called “work sharing”

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## Limitations and Semantics

- Not all “element-wise” loops can be ||ised

```
#pragma omp parallel for
for (i=0; i < numPixels; i++) {}
```

  - Loop index: signed integer
  - Termination Test: <,<=,>,=> with loop invariant int
  - Incr/Decr by loop invariant int; change each iteration
  - Count up for <,<=; count down for >,>=
  - Basic block body: no control in/out except at top
- Threads are created and iterations divvied up; requirements ensure iteration count is predictable

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## More OpenMP Code

- Data-dependences require care [wrong code]

```
sum = 0;
#pragma omp parallel for
    for (i=0; i < 100; i++)     {
        sum =+ array[i];
}
```

- A race exists in this code (sum); fix 2 ways:
  - Make sum private by declaring inside loop
  - `#pragma omp parallel for(private sum)`

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## Reduce Abstraction

- OpenMP has reduce

```
sum = 0;
#pragma omp parallel for reduction(+:sum)
    for (i=0; i < 100; i++)     {
        sum += array[i];
}
```

- Reduce ops and init() values:

| | | | | | |
|---|---|---|---|---|---|
| + | 0 | bitwise & | ~0 | logical & | 1 |
| - | 0 | bitwise \| | 0 | logical \| | 0 |
| * | 1 | bitwise ^ | 0 | | |

Even in OpenMP abstracting reduce helps

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## Sections

- Separate tasks can be performed in ||

```
#pragma omp sections {
 #pragma omp section {TaskA();}
 #pragma omp section {TaskB();}
 #pragma omp section {TaskC();}
}
```

- The tasks must not have dependences
  - Each section runs to completion
  - Order not guaranteed
  - Private is allowed

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## Care with Parallel

- Check out this code

```
int i;
#pragma omp parallel for
for (i='a'; i<='z'; i++){printf("%c",i);}
int i;
#pragma omp parallel private (i)
for (i='a'; i<='z'; i++){printf("%c",i);}
```

- Red prints alphabet once; blue unknown #
- The compiler decides on concurrency

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## Treads are created/destroyed

- Threads are created at start of parallel block; destroyed, with implied barrier, at end of || block
- Good advice: Set up threads at start; stay with 'em
- Avoid waiting overhead by using `nowait`

```
#pragma omp for nowait
   for (i=0; i<100; i++)   {arrayA[i]=i; }
#pragma omp for
   for (j=0; j<500; j++)   {arrayB[j]=0; }
```

- The explicit barrier has the form

```
#pragma omp barrier
```

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## Dependences

- Handling dependences is entirely up to the programmer
- Tools for protecting code:
  - Privatizing variables -- requires "cleanup code"
  - Reduce
  - Atomic operations
  - Critical sections

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## Synchronizing

- Any statement's execution can in principle be interrupted, so atomicity help would help
- Achieve atomicity using: `atomic`

```
#pragma omp atomic
a[i] += x; // never interrupted
```

- Atomic operations are:

```
expr++, expr--, ++expr, --expr, +=, -=,
*=, /=, <<=, >>=, &=, |=, ^=
```

- Could save cost of using "heavy" protection for some variables

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## Critical Sections

- Guarantee exclusive execution with a critical section

**optional name**

```
#pragma omp critical(maxvalue) {
    if (max < next_value)
        max = next_value;
}
```

- Only 1 thread enters critical section at a time
- Naming avoids all threads but 1 excluded from all critical sections, usually a big win

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## Loop Scheduling

- When loop iterations are not balanced …

```
#pragma omp parallel for schedule(kind [,chunk_size])
```

- The choices for **`kind`** are
  - **`static`** assign chunk size units of work; default is loop_bound/threads; 1 implies interleaving iterations
  - **`dynamic`** work queue with chunk size iterations per thread; default is 1
  - **`guided`** work queue with diminishing chunks down to chunk size
  - **`runtime`** choose 1 of above at run-time w/environ var

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## OpenMP Summary

- Simple facility, low entry cost, potential to exploit parallelism with little pgmming effort
- Simplicity is somewhat deceptive:
  - Programmers are responsible for all potential "gotchas" … still need to think very carefully!
  - Few higher-level abstractions beyond reduce
  - Programming model is threaded von Neumann rather than true parallel
  - *De facto* control over features that give performance are generally ceded to compiler

There is more in the spec

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## Break

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## Threading

- Threading facilities like the POSIX library Pthreads are popular shared-memory parallel programming tools
- Unlike OpenMP, where a compiler takes over to give limited capabilities, threading systems give primitive ops, but little help

  **anything's possible, nothing is easy**
- PRAM-like model tied to shared memory
- Pthreads is a library that's widely available

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## Pthread Standard Structure

- Create threads and wait for their completion

```
#include <pthread.h>
int err;
void main ()
 {
    pthread_t tid[MAX]; /* Thread ID Array */
    for (i=0; i<t; i++) {
       err = pthread_create (&tid[i], NULL,
                             count3s_thread, i);
    }
    for (i=0; i<t; i++) {
       err = pthread_join_(tid[i], &status[i])
    }
 }
```

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## Mutual Exclusion

- Race conditions are avoided using locks

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
void count3s_thread (int id) {
   /* Compute local part of array */
   int length_per_thread = length/t;
   int start = id * length_per_thread;
   for (i=start; i<start+length_per_thread; i++) {
     if (array[i] == 3) {
        pthread_mutex_lock(&lock);
        count++;
        pthread_mutex_unlock(&lock);
     }
   }
 }
```

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## Thread-specific Data

- Mostly Pthreads reference global data
- Pthreads allows for thread-specific data
  - Accessed indirectly via a key
  - Procedural interface makes it somewhat kuldgy
  - Facilities
    - pthread_key_create()
    - pthread_key_delete()
    - pthread_setspecific()
    - pthread_getspecific()

Not suitable for non-trivial data structures

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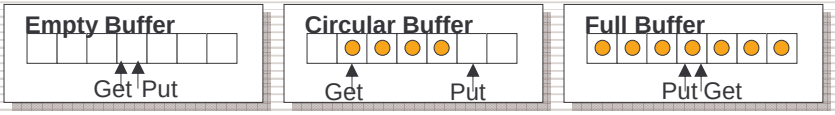
## Condition Variables

- Threads wait on a condition to come true, and then some waiting thread is chosen
  - Non-deterministic and possibly unfair
- Illustrate with a circular buffer




```
pthread_mutex_t lock   = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t nonempty = PTHREAD_COND_INITIALIZER;
pthread_cond_t nonfull  = PTHREAD_COND_INITIALIZER;
Item buffer[SIZE];
int in  = 0;       // Buff index for next insert
int out = 0;       // Buff index for next remove
```

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## Get and Put For Circular Buffer

```
void put (Item x) {              // Producer thread
    pthread_mutex_lock(&lock);
    while (in – out == SIZE)     // While buffer full
      pthread_cond_wait(&nonfull, &lock);
    buffer[in % SIZE] = x; in++;
    pthread_cond_signal(&nonempty);
    pthread_mutex_unlock(&lock);
}
```

```
Item get() {                     // Consumer thread
    Item x;
    pthread_mutex_lock(&lock);
    while (out == in)            // While buffer is empty
       pthread_cond_wait(&nonempty, &lock);
    x = buffer[out % SIZE]; out++;
    pthread_cond_signal(&nonfull);
    pthread_mutex_unlock(&lock);
    return x;
}
```

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## Split-phase Barrier

- Barriers stop threads until everyone's there
- Often wasteful bc barriers are interposed between regions that shouldn't overlap

**earliest place for barrier**
**...**
**computational work**
**...**
**latest place for barrier**

- Sending, receiving also have this feature

Break the coupling between arriving and leaving

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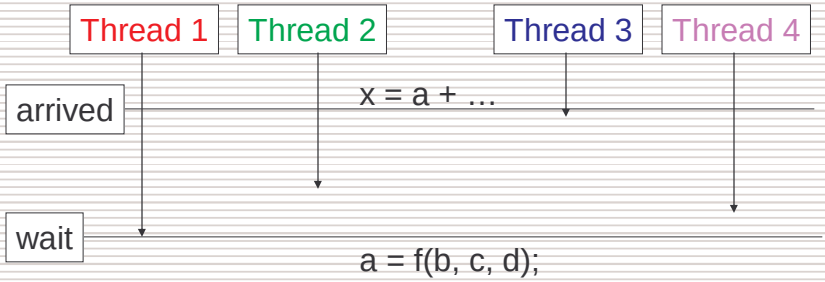
## Arrive and Wait

- Split the barrier into two parts
  - barrier.arrived() -- has reached the first safe pt
  - barrier.wait() -- the last point before overlap




Split phase has many uses

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## Summary on Pthreads

- Pthreads is gives power and flexibility
- It is possible to build gadgets for general concurrent operations
  - Nearly everything is possible
  - Often the complexity can be deceptive
  - Ideas are quite traditional, and newer concepts are available
    - Transactions
    - Shared memory parallel languages like CiLC,SAC
    - Not easy to apply performance (CTA) ideas

There is more in the spec

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## Message Passing

- Message passing is the principle alternative to shared memory parallel programming
  - Based on Single Program, Multiple Data (SPMD) Model with `send()` and `recv()` primitives
  - Message passing is universal, but low-level
  - Parallel Virtual Machine (PVM), Message Passing Interface (MPI) are main libraries, but there've been many
  - More even than threading, message passing is locally focused -- what does each processor do?
  - Isolation of separate address spaces can be a programming asset -- no races--and a pain!

Clear distinction between local, non-local

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## A Typical Process Structure

- SPMD idea => 1 pgm to run on every node

```
int main (argc, argv)
 int argc;
 char **argv;
{
  int myID, size;
  MPI_Status status;
  MPI_Init(&argc, &argv);
  MPI_Comm_size(MPI_COMM_WORLD, &size);
  MPI_Comm_rank(MPI_COMM_WORLD, &myID);
  /* compute stuff in parallel */
  MPI_Finalize()
  return 0;
}
```

**required 1st call**

**MPI_Comm_World is a communicator a set of logically related comm's**

**get count of peers**

**get my index**

**required last call**

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## General Process Structure

- Most computations have two kinds of procs
  - Worker -- performing a share of work
  - Leader -- performing 1-time work needed by all and, perhaps, its share of task
  - Common structure:

```
if (rootproc == myId) {
   ...            /* do stuff for all */
} else {
   ...            /* work on local part */
}
```

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## Sending A Message

- The general form of an MPI send() is:

```
int MPI_Send (              // Blocking Send routine
  void *       buffer,      // Address of data to send
  int          count,       // No. data elements to send
  MPI_Datatype type,        // Type of data elements
  int          dest,        // ID of destination process
  int          tag,         // Tag for this message
  MPI_Comm *   comm         // An MPI communicator
  );
```

```
MPI_Send(&a[offset][0], count, MPI_DOUBLE,
         dest, mtype, MPI_COMM_WORLD);
```

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## Receiving A Message

- The general form of an MPI recv() is:

```
int MPI_Recv (          // Blocking Receive routine
  void *       buffer, // Address receiving data
  int          count,  // No. elements to receive
  MPI_Datatype type,   // Type of each element
  int          source, // ID of sending process
  int          tag,    // Tag for this message
  MPI_Comm     comm,   // MPI communicator
  MPI_Status * status  // Status of this receive
);
```

**MPI_Recv(&a, count, MPI_DOUBLE, source, mtype, MPI_COMM_WORLD, &status);**

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## Marshalling

- MPI assumes data comes from consecutive locations and goes to consecutive locations
- When not true (columns in rmo-allocation)
  - data must be marshalled, copied into buffer, for send
  - data must be demarshalled, copied back, for receive

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# MM in MPI -- 1

A “master--slave” solution

```
MPI_Status status;
main(int argc, char **argv) {
int numtasks,            /* number of tasks in partition */
    taskid,              /* a task identifier */
    numworkers,          /* number of worker tasks */
    source,              /* task id of message source */
    dest,                /* task id of message destination */
    nbytes,              /* number of bytes in message */
    mtype,               /* message type */
    intsize,             /* size of an integer in bytes */
    dbsize,              /* size of a double float in bytes */
    rows,                /* rows of matrix A sent to each worker */
    averow, extra, offset,   /* used to determine rows sent to each worker */
    i, j, k,             /* misc */
    count;
```

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# MM in MPI -- 2

```
double a[NRA][NCA],          /* matrix A to be multiplied */
       b[NCA][NCB],          /* matrix B to be multiplied */
       c[NRA][NCB];          /* result matrix C */
intsize = sizeof(int);
dbsize = sizeof(double);
MPI_Init(&argc, &argv);
MPI_Comm_rank(MPI_COMM_WORLD, &taskid);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
numworkers = numtasks-1;
/****** master task *******/
if (taskid == MASTER) {
for (i=0; i<NRA; i++)
   for (j=0; j<NCA; j++)
     a[i][j]= i+j;
 for (i=0; i<NCA; i++)
   for (j=0; j<NCB; j++)
     b[i][j]= i*j;
```

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# MM in MPI -- 3

```
/* send matrix data to the worker tasks */
  averow = NRA/numworkers;
  extra = NRA%numworkers;
  offset = 0;
  mtype = FROM_MASTER;
  for (dest=1; dest<=numworkers; dest++) {
    rows = (dest <= extra) ? averow+1 : averow;
    MPI_Send(&offset, 1, MPI_INT, dest, mtype, MPI_COMM_WORLD);
    MPI_Send(&rows, 1, MPI_INT, dest, mtype, MPI_COMM_WORLD);
    count = rows*NCA;
    MPI_Send(&a[offset][0], count, MPI_DOUBLE, dest, mtype,
      MPI_COMM_WORLD);
    count = NCA*NCB;
    MPI_Send(&b, count, MPI_DOUBLE, dest, mtype, MPI_COMM_WORLD);

    offset = offset + rows;
    }
```

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# MM in MPI -- 4

```
/* wait for results from all worker tasks */
  mtype = FROM_WORKER;
  for (i=1; i<=numworkers; i++)          {
    source = i;
    MPI_Recv(&offset, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
    MPI_Recv(&rows, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
    count = rows*NCB;
    MPI_Recv(&c[offset][0], count, MPI_DOUBLE, source, mtype,
      MPI_COMM_WORLD,&status);
  }
/**************************** worker task ************************************/
if (taskid > MASTER) {
  mtype = FROM_MASTER;
  source = MASTER;
  MPI_Recv(&offset, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
  MPI_Recv(&rows, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
  count = rows*NCA;
```

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# MM in MPI -- 5

```
MPI_Recv(&a, count, MPI_DOUBLE, source, mtype, MPI_COMM_WORLD,
   &status); count = NCA*NCB;
MPI_Recv(&b, count, MPI_DOUBLE, source, mtype, MPI_COMM_WORLD,
   &status);

for (k=0; k<NCB; k++)
 for (i=0; i<rows; i++) {
   c[i][k] = 0.0;
   for (j=0; j<NCA; j++)
     c[i][k] = c[i][k] + a[i][j] * b[j][k];
   }
mtype = FROM_WORKER;
MPI_Send(&offset, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD);
MPI_Send(&rows, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD);
MPI_Send(&c, rows*NCB, MPI_DOUBLE, MASTER, mtype,
   MPI_COMM_WORLD);
} /* end of worker */
```

Actual Multiply

91 “Net” Lines

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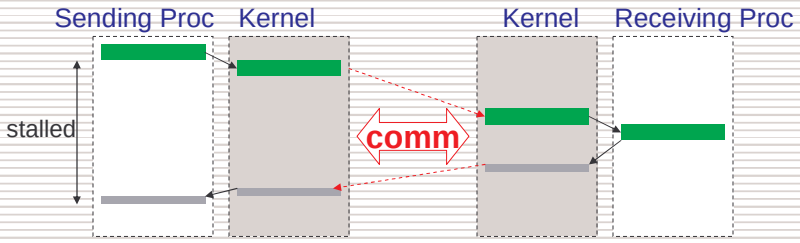
# The Path of a Message

- A blocking send visits 4 address spaces




- Besides being time-consuming, it locks processors together quite tightly

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## Alternative Send/Recvs

- Variants of the operations have other properties:
  - MPI_Rsend() -- assumes sending, receiving processes are synchronized, so no handshaking needed; it's risky
  - MPI_Bsend() -- use a user-space buffer rather than kernel space buffer; resume when buffer loaded
  - MPI_Isend() -- non-blocking send; does not wait for operation to complete; use MPI_Wait()

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## Overlapping Comm and Comp

- Using MPI_Isend()/MPI_Irecv() to overlap communication and computation is smart
- General protocol:
  - Receive "edge" values from neighbors
  - Send "edge" values to neighbors
  - Compute "interior" elements
  - Wait on arrival of edge elements
  - Complete "edge" computations

| | 10 | 20 | 13 | 21 | 7 | 29 | 23 | 20 | 4 | 25 | 1 | 31 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

Shadow buffers assist implementation

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## MPI Has Reduce and Scan

- Reduce and scan apply are ponderous

```
int MPI_Reduce (            // Reduce routine
  void *       sendBuffer,  // Address of local val
  void *       recvBuffer,  // Place to receive into
  int          count,       // No. of elements
  MPI_Datatype datatype,    // Type of each element
  MPI_OP       op,          // MPI operator
  int          root,        // Process to get result
  MPI_Comm     comm         // MPI communicator
  );
```

```
MPI_Reduce (&myCount,&globalCount, 1, MPI_INT, MPI_SUM,
                RootProcess, MPI_COMM_WORLD);
```

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## Message Passing Critique

- Message passing is a very simple model
- Extremely low level; heavy weight
  - Expense comes from λ and lots of local code
  - Communication code is often more than half
  - Tough to make adaptable and flexible
  - Tough to get right and know it
  - Tough to make perform in most cases
- Programming model of choice for scalability

Not as portable as it's claimed to be

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## One-sided Communication

- Intermediate between and shared and message passing is one-sided comm
- Process model w/ global address space
  - get() loads a value from a non-local address
  - put() stores a value into a non-local address
  - No memory consistency: *caveat emptor*
  - Popularized by Cray machines: called shmem
- Libraries are available to implementing

Co-Array Fortran based on concept

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## Working On Project

- Parallel computers of any size are generally tough to use … put it off as long as possible
- Most programming systems allow for development on a workstation
- My recommended steps (not including your personal development techniques):
  - Sketch solution w/diagram + Peril-L
  - Work out logic on sequential platform
  - Consider moving to || platform in parts

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## Homework

- Reading: Chapter 8
  - Read, but do not study …
  - Goal is to conceptualize ZPL's approach
- Project
  - Most projects approved; after reading ZPL, proceed
  - Recommendation: Sketch in Peril-L first
  - Bring **paper** statement of progress to class

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