CS 181E: Fundamentals of Parallel Programming

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http://www.cs.hmc.edu/courses/2012/fall/cs181e/

Recap of Lecture 10

- Linearizability of Concurrent Executions and Concurrent Objects
- Liveness/progress guarantees
- Optimized Implementations of Isolated

Worksheet #10 solution: Linearizability of method calls on a concurrent object

Is this a linearizable execution?

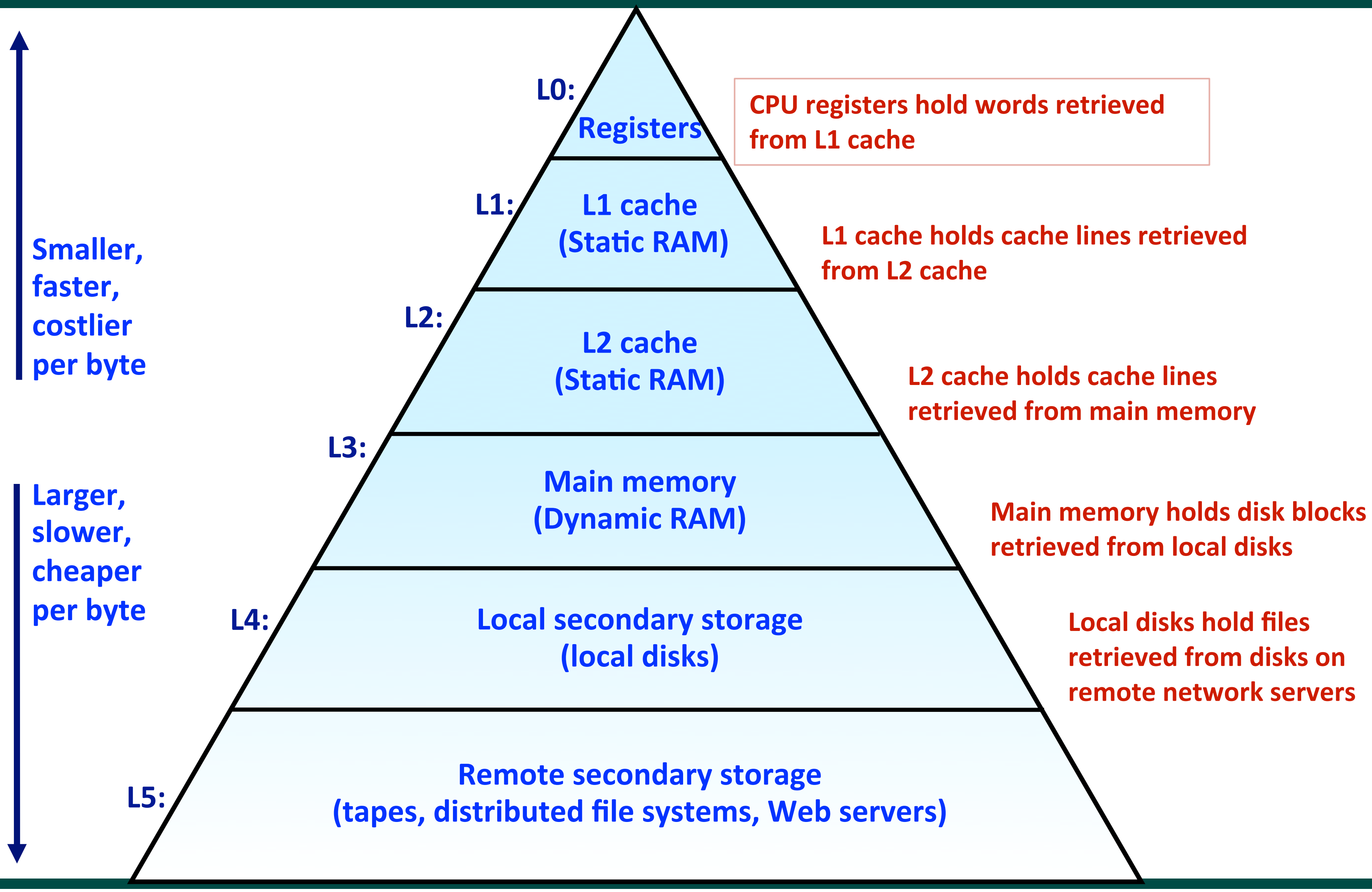
Time	Task *A*	Task *B*
0	Invoke `q.enq(x)`	
1	Return from `q.enq(x)`	
2		Invoke `q.enq(y)`
3	Invoke `q.deq()`	Work on `q.enq(y)`
4	Work on `q.deq()`	Return from `q.enq(y)`
5	Return y from `q.deq()`	

No! q.enq(x) must precede q.enq(y) in all linear sequences of method calls invoked on q. It is illegal for the q.deq() operation to return y.

Outline

- Task Affinity with Places
- Introduction to the Message Passing Interface (MPI)

An example Memory Hierarchy --- what is the cost of a Memory Access?



Smaller, faster, costlier per byte
Larger, slower, cheaper per byte
L0:
Registers
L1:
L1 cache (Static RAM)
L2:
L2 cache (Static RAM)
L3:
Main memory (Dynamic RAM)
L4:
Local secondary storage (local disks)
L5:
Remote secondary storage (tapes, distributed file systems, Web servers)
CPU registers hold words retrieved from L1 cache
L1 cache holds cache lines retrieved from L2 cache
L2 cache holds cache lines retrieved from main memory
Main memory holds disk blocks retrieved from local disks
Local disks hold files retrieved from disks on remote network servers

Source: http://www.cs.cmu.edu/afs/cs/academic/class/15213-f10/www/lectures/09-memory-hierarchy.pptx

Storage Trends

SRAM

Metric	1980	1985	1990	1995	2000	2005	2010	2010:1980
$/MB	19,200	2,900	320	256	100	75	60	320
access (ns)	300	150	35	15	3	2	1.5	200

DRAM

Metric	1980	1985	1990	1995	2000	2005	2010	2010:1980
$/MB	8,000	880	100	30	1	0.1	0.06	130,000
access (ns)	375	200	100	70	60	50	40	9
typical size (MB)	0.064	0.256	4	16	64	2,000	8,000	125,000

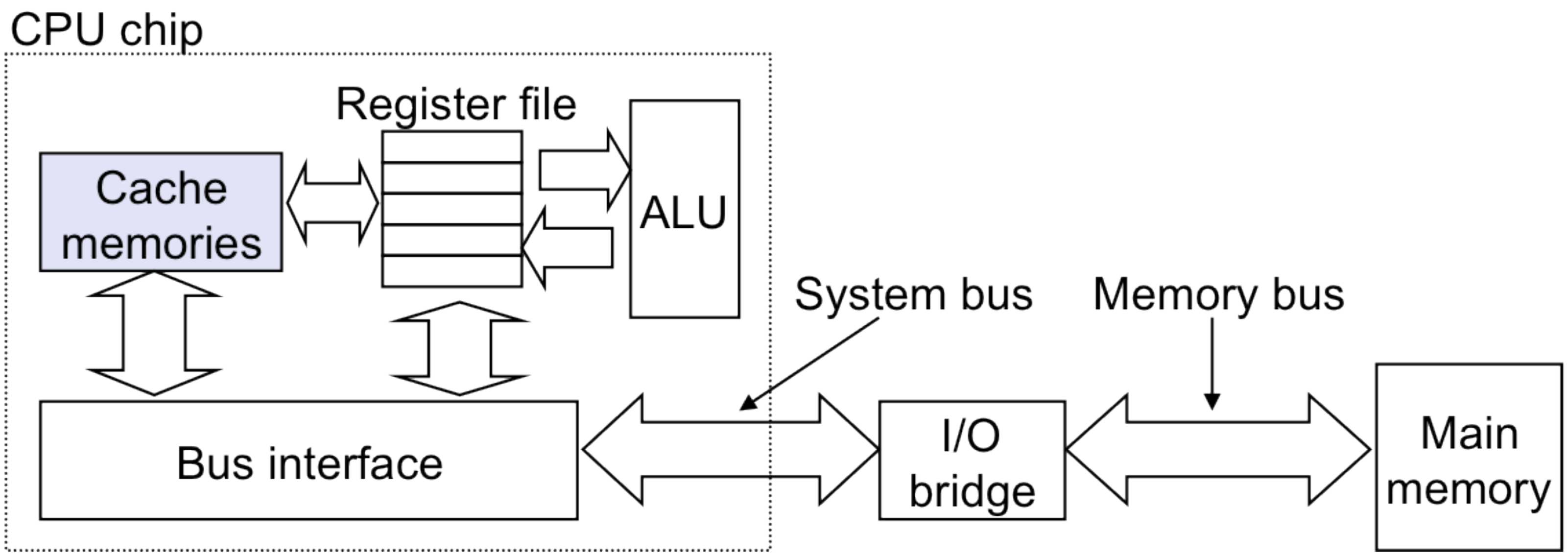
Disk

Metric	1980	1985	1990	1995	2000	2005	2010	2010:1980
$/MB	500	100	8	0.30	0.01	0.005	0.0003	1,600,000
access (ms)	87	75	28	10	8	4	3	29
typical size (MB)	1	10	160	1,000	20,000	160,000	1,500,000	1,500,000

Source: http://www.cs.cmu.edu/afs/cs/academic/class/15213-f10/www/lectures/09-memory-hierarchy.pptx

Cache Memories

- Cache memories are small, fast SRAM-based memories managed automatically in hardware.
  - Hold frequently accessed blocks of main memory
- CPU looks first for data in caches (e.g., L1, L2, and L3), then in main memory.
- Typical system structure:



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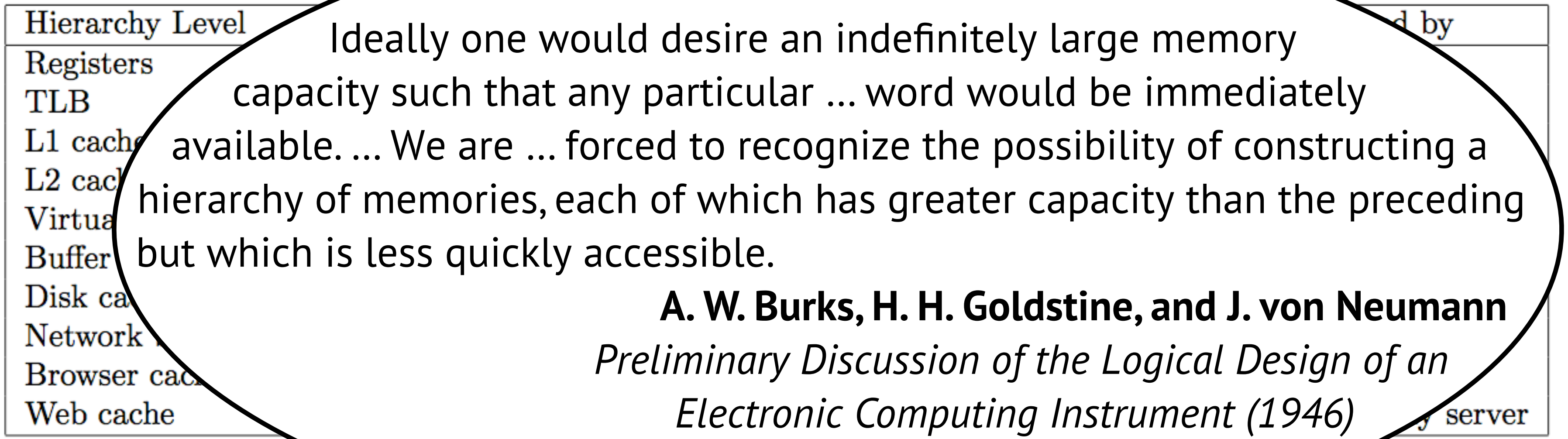
Examples of Caching in the Hierarchy



Hierarchy Level		d by
Registers		
TLB		
L1 cach		
L2 cac		
Virtua		
Buffer		
Disk ca		
Network		
Browser cac		
Web cache		server

> Ideally one would desire an indefinitely large memory capacity such that any particular … word would be immediately available. … We are … forced to recognize the possibility of constructing a hierarchy of memories, each of which has greater capacity than the preceding but which is less quickly accessible.
>
> **A. W. Burks, H. H. Goldstine, and J. von Neumann**
> *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument (1946)*

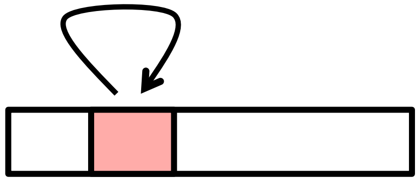
Ultimate goal: create a large pool of storage with average cost per byte that approaches that of the cheap storage near the bottom of the hierarchy, and average latency that approaches that of fast storage near the top of the hierarchy.

Source: http://www.cs.cmu.edu/afs/cs/academic/class/15213-f10/www/lectures/09-memory-hierarchy.pptx

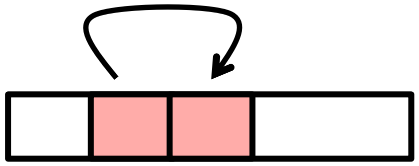
Locality

- **Principle of Locality:**
  - —Empirical observation: Programs tend to use data and instructions with addresses near or equal to those they have used recently

- **Temporal locality:**
  - — Recently referenced items are likely to be referenced again in the near future



- **Spatial locality:**
  - — Items with nearby addresses tend to be referenced close together in time
  - — A Java programmer can only influence spatial locality at the intra-object level
    - – The garbage collector and memory management system determines inter-object placement



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Locality Example

```
sum = 0;
for (i = 0; i < n; i++)
    sum += a[i];
return sum;
```

- Data references
  - Reference array elements in succession (stride-1 reference pattern). Spatial locality
  - Reference variable `sum` each iteration. Temporal locality
- Instruction references
  - Reference instructions in sequence. Spatial locality
  - Cycle through loop repeatedly. Temporal locality

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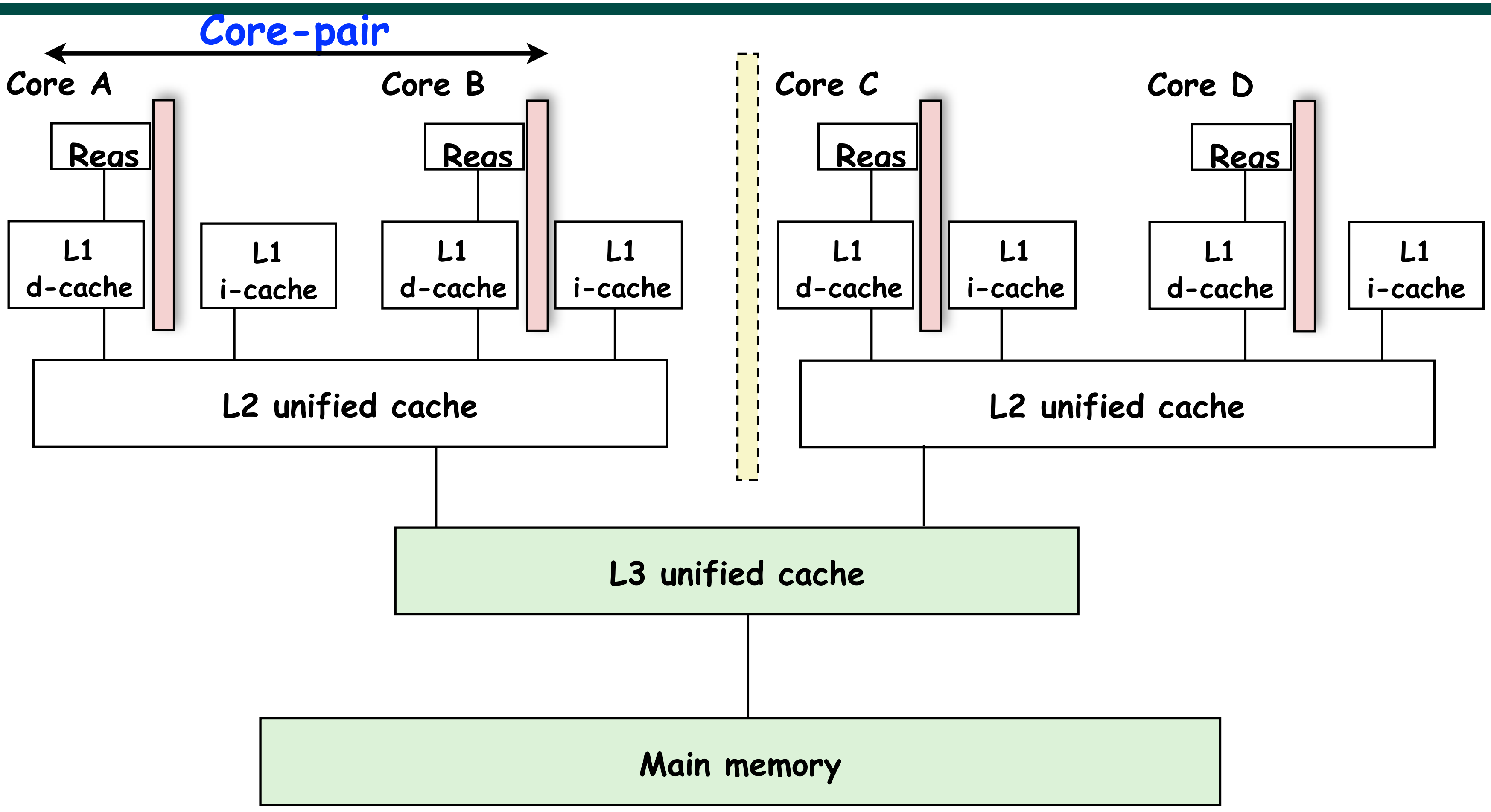
Memory Hierarchy in a Multicore Processor



- Memory hierarchy for a single Intel Xeon Quad-core E5440 HarperTown processor chip

Programmer Control of Task Assignment to Processors

- The parallel programming constructs that we've studied thus far result in tasks that are assigned to processors dynamically by the HJ runtime system
  - Programmer does not worry about task assignment details
- Sometimes, programmer control of task assignment can lead to significant performance advantages due to improved locality
- Motivation for HJ "places"
  - Provide the programmer a mechanism to map each task to a set of processors when the task is created

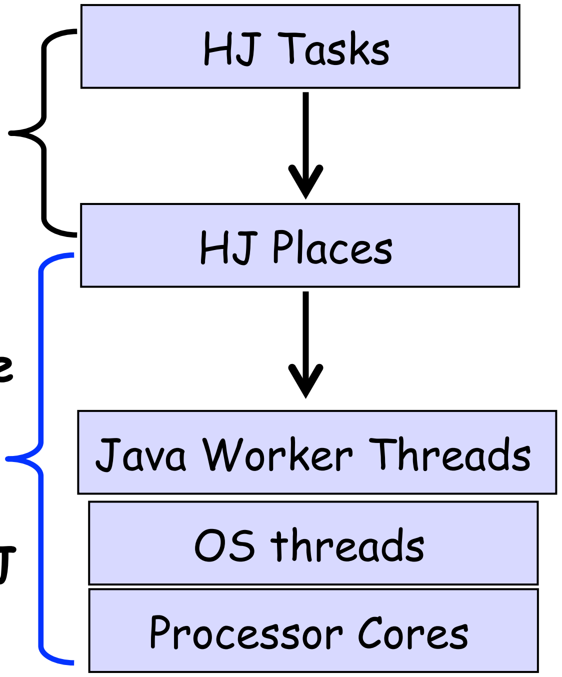
Places in HJ

HJ programmer defines mapping from HJ tasks to set of places

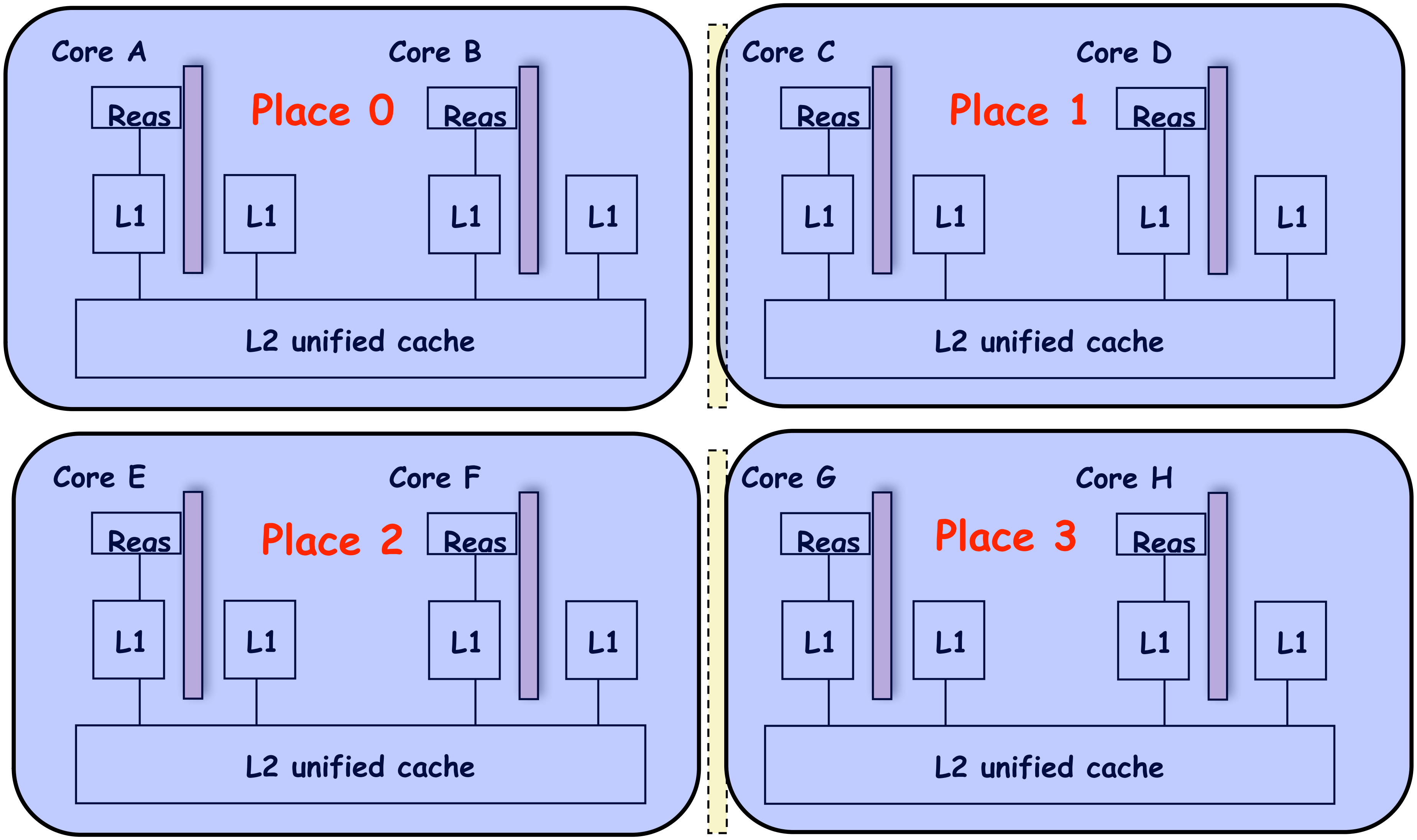
HJ runtime defines mapping from places to one or more worker Java threads per place

The option "-places p:w" when executing an HJ program can be used to specify

- p, the number of places
- w, the number of worker threads per place



Example of –places 4:2 option on an 8-core node (4 places w/ 2 workers per place)



Places in HJ

here = place at which current task is executing

place.MAX_PLACES = total number of places (runtime constant)

Specified by value of `p` in runtime option, `-places p:w`

place.factory.place(i) = place corresponding to index i

<place-expr>.toString() returns a string of the form "place(id=0)"

<place-expr>.id returns the id of the place as an int

async at(P) S

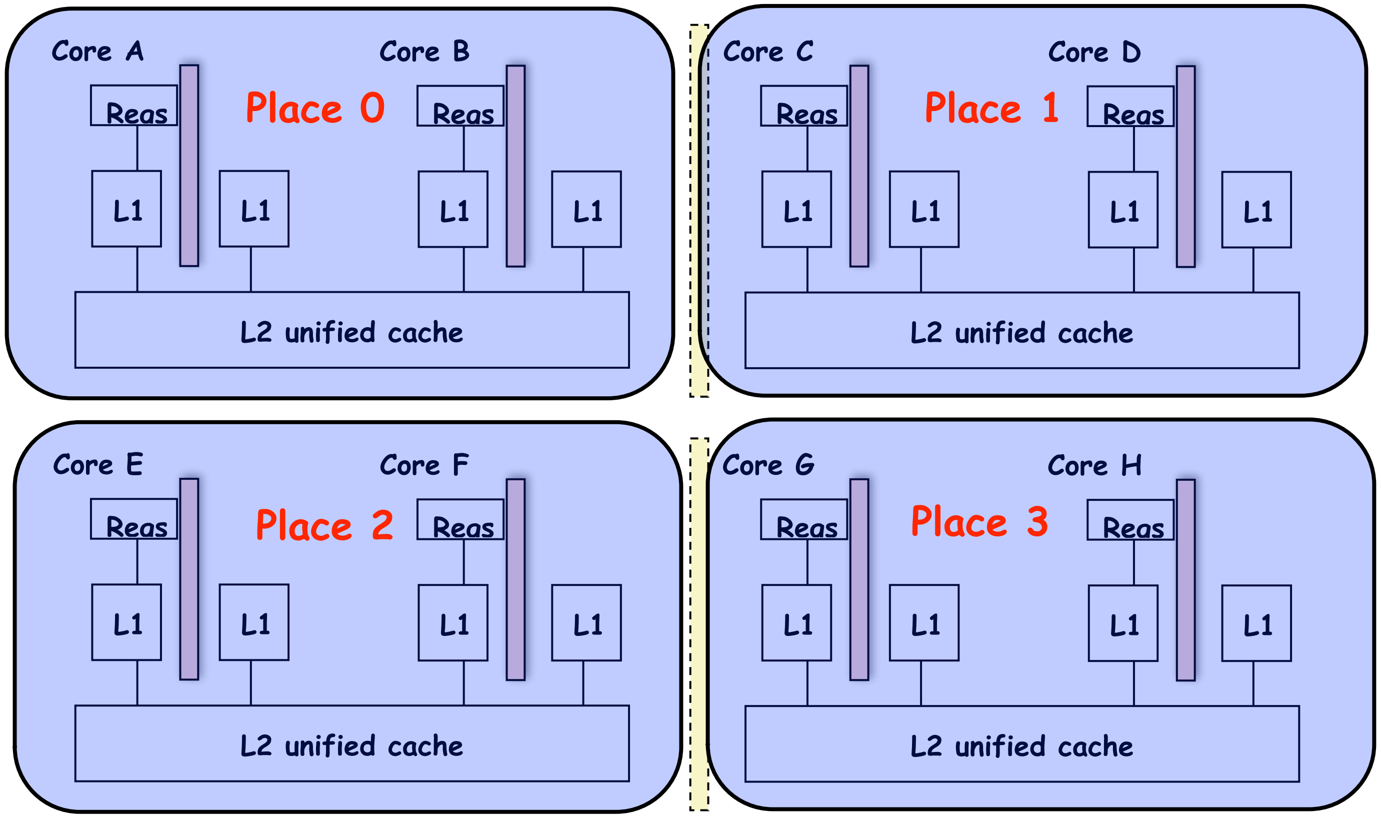
- Creates new task to execute statement S at place P
- **async S** is equivalent to **async at(here) S**
- Main program task starts at **place.factory.place(0)**

Note that **here** in a child task refers to the place P at which the child task is executing, not the place where the parent task is executing

Example of –places 4:2 option on an 8-core node (4 places w/ 2 workers per place)

```
// Main program starts at place 0
async at(place.factory.place(0)) S1;
async at(place.factory.place(0)) S2;
```

```
async at(place.factory.place(1)) S3;
async at(place.factory.place(1)) S4;
async at(place.factory.place(1)) S5;
```

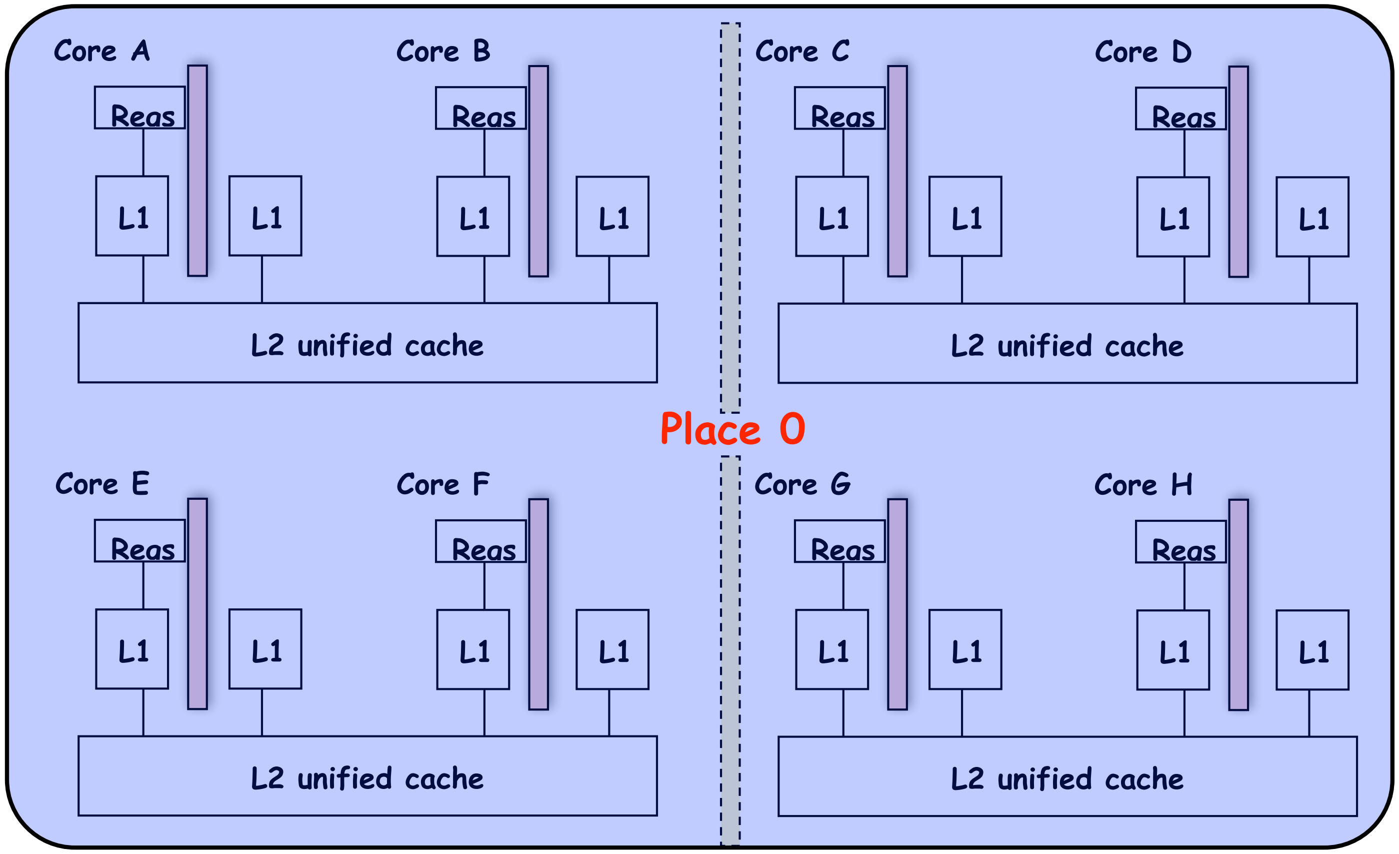


```
async at(place.factory.place(2)) S6;
async at(place.factory.place(2)) S7;
async at(place.factory.place(2)) S8;
```

```
async at(place.factory.place(3)) S9;
async at(place.factory.place(3)) S10;
```

Example of –places 1:8 option (1 place w/ 8 workers per place)

All async's run at place 0 when there's only one place!



Example HJ program with places

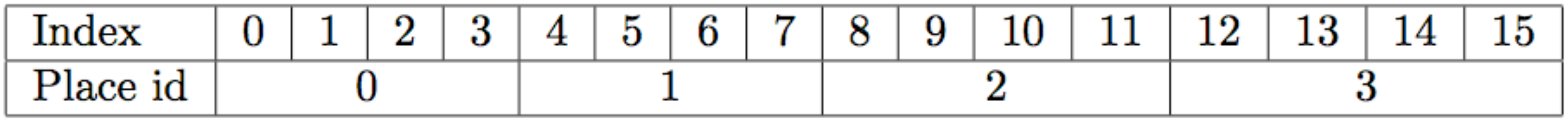
```
class T1 {
  final place affinity;
  . . .
  // T1's constructor sets affinity to place where instance was created
  T1() { affinity = here; ... }
  . . .
}
. . .
finish { // Inter-place parallelism
  System.out.println("Parent place = ", here); // Parent task s place
  for (T1 a = . . .) {
    async at (a.affinity) { // Execute async at place with affinity to a
      a.foo();
      System.out.println("Child place = ", here); // Child task's place
    } // async
  } // for
} // finish
. . .
```

Distributions --- hj.lang.dist

- A distribution maps points in a rectangular index space (region) to places e.g.,
  - i → place.factory.place(i % place.MAX_PLACES-1)
- Programmers are free to create any data structure they choose to store and compute these mappings
- For convenience, the HJ language provides a predefined type, hj.lang.dist, to simplify working with distributions
- Some public members available in an instance d of hj.lang.dist are:
  - d.rank = number of dimensions in the input region for distribution d
  - d.get(p) = place for point p mapped by distribution d. It is an error to call d.get(p) if p.rank != d.rank.
  - d.places() = set of places in the range of distribution d
  - d.restrictToRegion(pl) = region of points mapped to place pl by distribution d

Block Distribution

- dist.factory.block([lo:hi]) creates a block distribution over the one-dimensional region, lo:hi.
- A block distribution splits the region into contiguous subregions, one per place, while trying to keep the subregions as close to equal in size as possible.
- Block distributions can improve the performance of parallel loops that exhibit spatial locality across contiguous iterations.



Index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Place id	0				1				2				3			

Block Distribution (contd)

- If the input region is multidimensional, then a block distribution is computed over the linearized one-dimensional version of the multidimensional region
- Example in Table 2: dist.factory.block([0:7,0:1]) for 4 places

Index	[0,0]	[0,1]	[1,0]	[1,1]	[2,0]	[2,1]	[3,0]	[3,1]	[4,0]	[4,1]	[5,0]	[5,1]	[6,0]	[6,1]	[7,0]	[7,1]
Place id	0				1				2				3			

Distributed Parallel Loops

- Listing 2 shows the typical pattern used to iterate over an input region r, while creating one async task for each iteration p at the place dictated by distribution d i.e., at place d.get(p).
- This pattern works correctly regardless of the rank and contents of input region r and input distribution d i.e., it is not constrained to block distributions

```
finish {
  region r = ... ; // e.g., [0:15] or [0:7,0:1]
  dist d = dist.factory.block(r);
  for (point p:r)
    async at(d.get(p)) {
      // Execute iteration p at place specified by distribution d
      . . .
    }
} // finish
. . .
```

Cyclic Distribution

- dist.factory.cyclic([lo:hi]) creates a cyclic distribution over the one-dimensional region, lo:hi.
- A cyclic distribution "cycles" through places 0 … place.MAX PLACES – 1 when spanning the input region
- Cyclic distributions can improve the performance of parallel loops that exhibit load imbalance
- Example in Table 3: dist.factory.cyclic([0:15]) for 4 places

Index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Place id	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3

- Example in Table 4: dist.factory.cyclic([0:7,0:1]) for 4 places

Index	[0,0]	[0,1]	[1,0]	[1,1]	[2,0]	[2,1]	[3,0]	[3,1]	[4,0]	[4,1]	[5,0]	[5,1]	[6,0]	[6,1]	[7,0]	[7,1]
Place id	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3

Chunked Fork-Join Iterative Averaging Example with Places

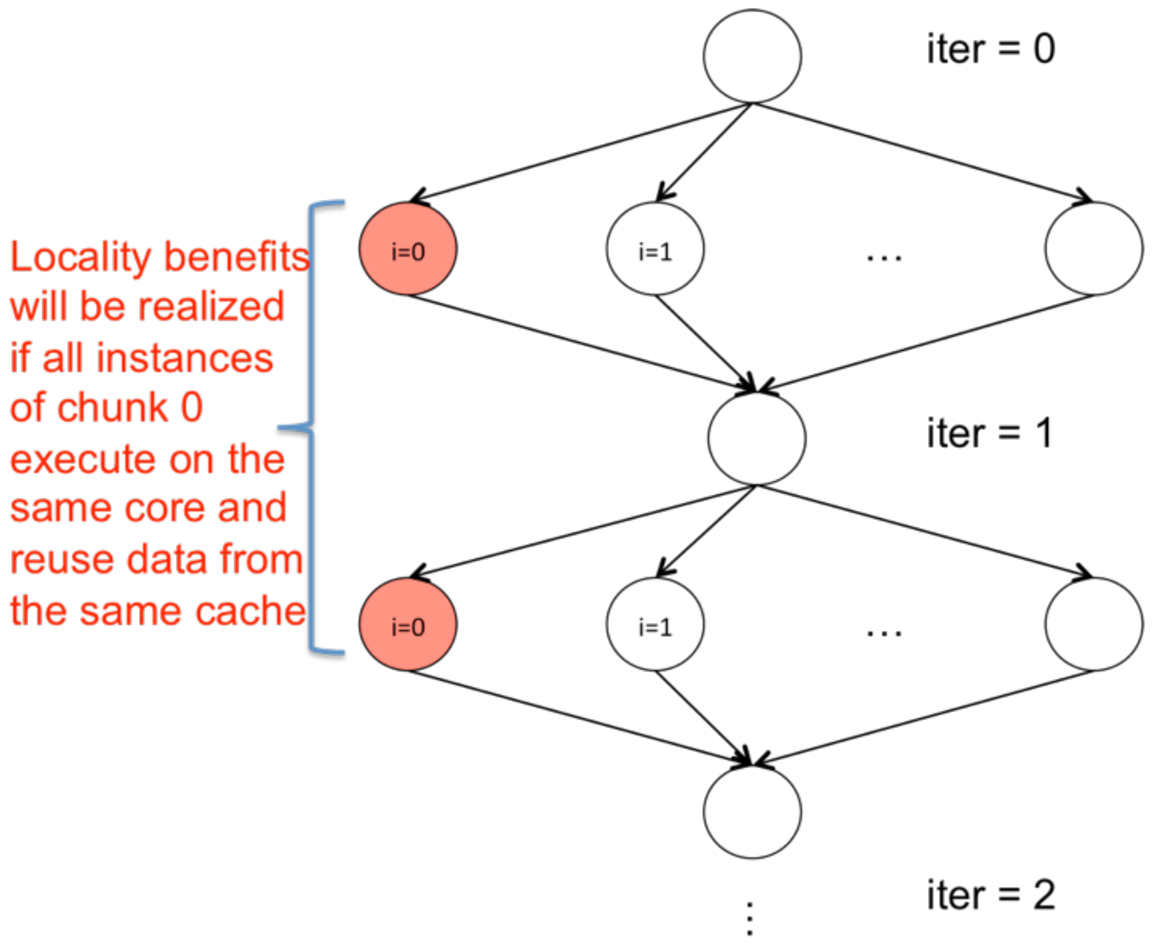
```
public void runDistChunkedForkJoin(int iterations,
                                   int numChunks, dist d) {
  for (int iter = 0; iter < iterations; iter++) {
    finish for (point [jj] : [0:numChunks-1])
      async at(d.get(jj)) {
        for (point [j] : getChunk([1:n],numChunks,jj))
          myNew[j] = (myVal[j-1] + myVal[j+1]) / 2.0;
    } // finish-for-async
    double[] temp = myNew; myNew = myVal; myVal = temp;
  } // for iter
} // runDistChunkedForkJoin
```

Chunk jj is always executed in the same place for each iteration,

alues

Let's try another example of a distributed parallel loop in Worksheet 11!

Analyzing Locality of Fork-Join Iterative Averaging Example with Places



iter = 0
Locality benefits will be realized if all instances of chunk 0 execute on the same core and reuse data from the same cache
i=0
i=1
…
iter = 1
i=0
i=1
…
iter = 2

Index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Place id	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3

Block-Cyclic Distribution

- dist.factory.blockCyclic([lo:hi],b) creates a block-cyclic distribution over the one-dimensional region, lo:hi.
- A block-cyclic distribution combines the locality benefits of the block distribution with the load-balancing benefits of the cyclic distribution by introducing a block size parameter, b.
- The linearized region is first decomposed into contiguous blocks of size b, and then the blocks are distributed in a cyclic manner across the places.
- Example in Table 5: dist.factory.blockCyclic([0:15],2) for 4 place with block size b = 2

Index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Place id	0	0	1	1	2	2	3	3	0	0	1	1	2	2	3	3

Outline

- Task Affinity with Places
- Introduction to the Message Passing Interface (MPI)

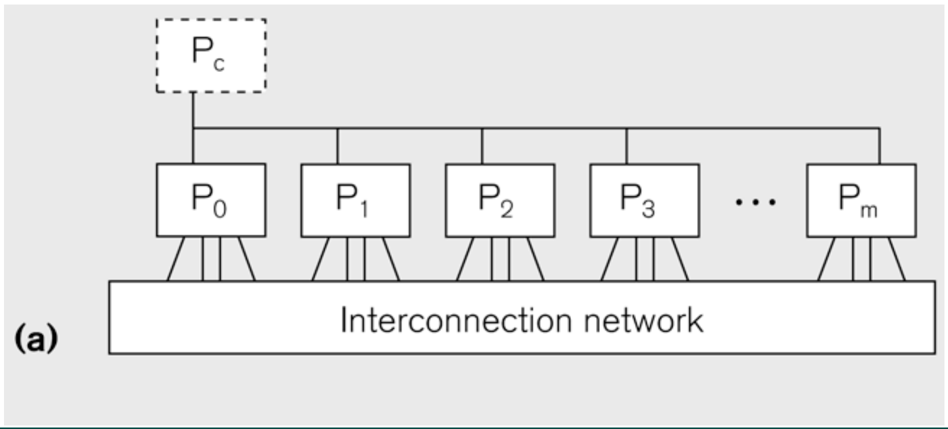
Organization of a Distributed-Memory Multiprocessor

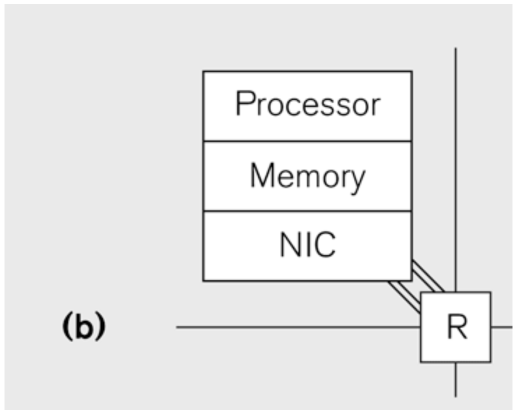
Figure (a)

- Host node (Pc) connected to a cluster of processor nodes (P_0 … P_m)
- Processors P_0 … P_m communicate via a dedicated high-performance interconnection network (e.g., Infiniband)
  - — Supports much lower latencies and higher bandwidth than standard TCP/IP networks

Figure (b)

- Each processor node consists of a processor, memory, and a Network Interface Card (NIC) connected to a router node (R) in the interconnect





Principles of Message-Passing Programming

- The logical view of a machine supporting the message-passing paradigm consists of p processes, each with its own exclusive address space.
  1. Each data element must belong to one of the partitions of the space; hence, data must be explicitly partitioned and placed.
  2. All interactions (read-only or read/write) require cooperation of two processes - the process that has the data and the process that wants to access the data.
- These two constraints, while onerous, make underlying costs very explicit to the programmer.
- In this loosely synchronous model, processes synchronize infrequently to perform interactions. Between these interactions, they execute completely asynchronously.
- Most message-passing programs are written using the single program multiple data (SPMD) model.

SPMD Pattern

- SPMD: Single Program Multiple Data
- Run the same program on P processing elements (PEs)
- Use the "rank" … an ID ranging from 0 to (P-1) … to determine what computation is performed on what data by a given PE
- Different PEs can follow different paths through the same code
- Convenient pattern for hardware platforms that are not amenable to efficient forms of dynamic task parallelism
  - General-Purpose Graphics Processing Units (GPGPUs)
  - Distributed-memory parallel machines
- Key design decisions --- how should data and computation be distributed across PEs?

Using the SPMD model with a Global View of Data: Iterative Averaging (Slide 9, Lecture 13)

```
double[] gVal=new double[n+2]; double[] gNew=new double[n+2];
gVal[n+1] = 1; // Boundary condition
int Cj = Runtime.getNumOfWorkers();
forall (point [jj]:[0:Cj-1]) { // SPMD computation with "id" = jj
  double[] myVal = gVal; double[] myNew = gNew; // Local copy
  for (point [iter] : [0:numIters-1]) {
    // Compute MyNew as function of input array MyVal
    for (point [j]:getChunk([1:n],[Cj],[jj]))
      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
    next; // Barrier before executing next iteration of iter loop
    // Swap myVal and myNew (replicated computation)
     double[] temp=myVal; myVal=myNew; myNew=temp;
    // myNew becomes input array for next iter
  } // for
} // forall
```

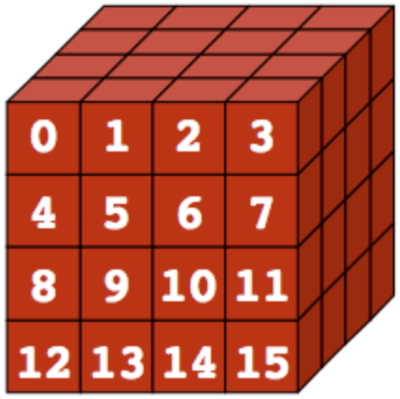
Data Distribution: Local View in Distributed-Memory Systems

Distributed memory

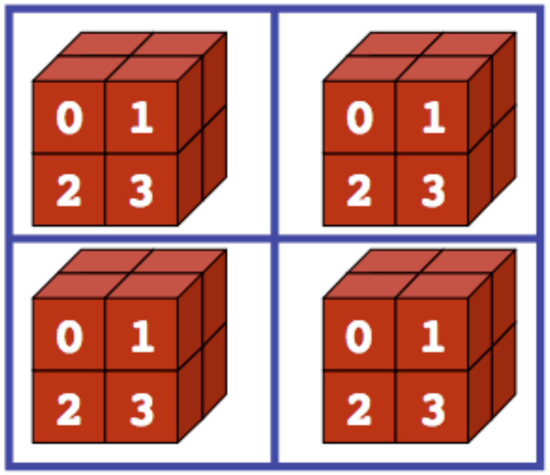
- Each process sees a local address space
- Processes send messages to communicate with other processes

Data structures

- Presents a Local View instead of Global View
- Programmer must make the mapping



Global View

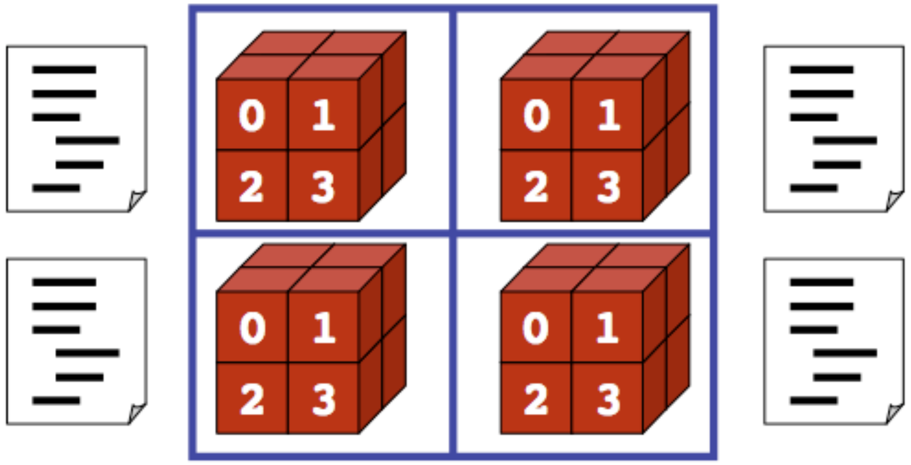


Local View (4 processes)

Using the SPMD model with a Local View

SPMD code

– Write one piece of code that executes on each processor



Local View (4 processes)

Processors must communicate via messages for non-local data accesses

- Similar to communication constraint for actors (except that we allowed hybrid combinations of global task parallelism and local actor parallelism in HJ)

MPI: The Message Passing Interface

- Sockets and Remote Method Invocation (RMI) are communication primitives used for distributed Java programs.
  - —Designed for standard TCP/IP networks rather than high-performance interconnects
- The Message Passing Interface (MPI) standard was designed to exploit high-performance interconnects
  - —MPI was standardized in the early 1990s by the MPI Forum—a substantial consortium of vendors and researchers
    - http://www-unix.mcs.anl.gov/mpi
  - —It is an API for communication between nodes of a distributed memory parallel computer
  - —The original standard defines bindings to C and Fortran (later C++)
    - Java support is available from a research project, mpiJava, developed at Indiana University 10+ years ago

      http://www.hpjava.org/mpiJava.html

Features of MPI

- MPI is a platform for Single Program Multiple Data (SPMD) parallel computing on distributed memory architectures, with an API for sending and receiving messages
- It includes the abstraction of a "communicator", which is like an N-way communication channel that connects a set of N cooperating processes (analogous to a phaser)
- It also includes explicit datatypes in the API, that are used to describe the contents of communication buffers.

The Minimal Set of MPI Routines (mpiJava)

- MPI.Init(args)
  - initialize MPI in each process
- MPI.Finalize()
  - terminate MPI
- MPI.COMM_WORLD.Size()
  - number of processes in COMM_WORLD communicator
- MPI.COMM_WORLD.Rank()
  - rank of this process in COMM_WORLD communicator
- Note:
  - In this subset, processes act independently with no information communicated among the processes.
  - "embarrassingly parallel", Cleve Moler.

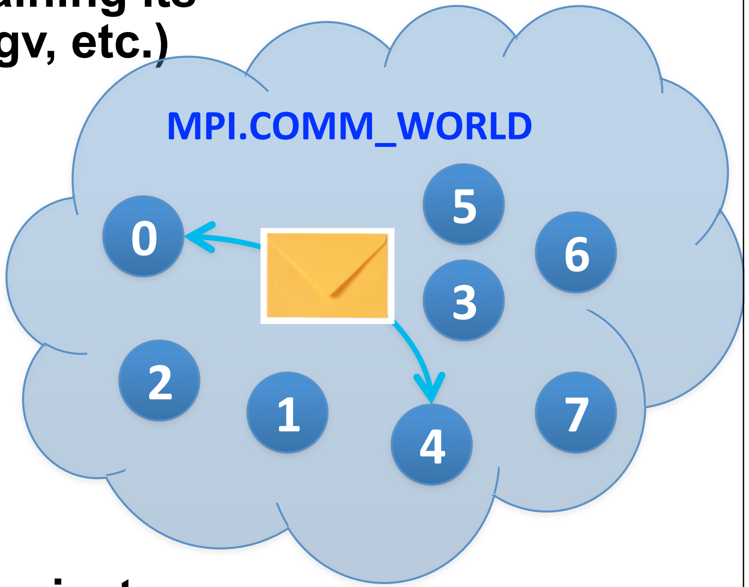
Our First MPI Program (mpiJava version)

main() is enclosed in an implicit "forall" --- each process runs a separate instance of main() with "index variable" = myrank

```
import mpi.*;
class Hello {
    static public void main(String[] args) {
        // Init() be called before other MPI calls
        MPI.Init(args); /
        int npes = MPI.COMM_WORLD.Size()
        int myrank = MPI.COMM_WORLD.Rank() ;
        System.out.println("My process number is " + myrank);
        MPI.Finalize(); // Shutdown and clean-up
    }
}
```

MPI Communicators

- Communicator is an internal object
  - —*Communicator registration is like phaser registration, except that MPI does not support dynamic parallelism*
- MPI programs are made up of communicating processes
- Each process has its own address space containing its own attributes such as rank, size (and argc, argv, etc.)
- MPI provides functions to interact with it
- Default communicator is MPI.COMM_WORLD
  - —All processes are its members
  - —It has a size (the number of processes)
  - —Each process has a rank within it
  - —Can think of it as an ordered list of processes
- Additional communicator(s) can co-exist
- A process can belong to more than one communicator
- Within a communicator, each process has a unique rank



Adding Send() and Recv() to the Minimal Set of MPI Routines (mpiJava)

- MPI.Init(args)
  - initialize MPI in each process
- MPI.Finalize()
  - terminate MPI
- MPI.COMM_WORLD.Size()
  - number of processes in COMM_WORLD communicator
- MPI.COMM_WORLD.Rank()
  - rank of this process in COMM_WORLD communicator
- MPI.COMM_WORLD.Send()
  - send message using COMM_WORLD communicator
- MPI.COMM_WORLD.Recv()
  - receive message using COMM_WORLD communicator

$\updownarrow$ Point-to-point commn

Example with Send() and Recv() calls

```
import mpi.*;

class myProg {
  public static void main( String[] args ) {
    int tag0 = 0;
    MPI.Init( args );                      // Start MPI computation
    if ( MPI.COMM_WORLD.rank() == 0 ) { // rank 0 = sender
      int loop[] = new int[1]; loop[0] = 3;
      MPI.COMM_WORLD.Send( "Hello World!", 0, 12, MPI.CHAR, 1, tag0 );
      MPI.COMM_WORLD.Send( loop, 0, 1, MPI.INT, 1, tag0 );
    } else {                                  // rank 1 = receiver
      int loop[] = new int[1]; char msg[] = new char[12];
      MPI.COMM_WORLD.Recv( msg, 0, 12, MPI.CHAR, 0, tag0 );
      MPI.COMM_WORLD.Recv( loop, 0, 1, MPI.INT, 0, tag0 );
      for ( int i = 0; i < loop[0]; i++ ) System.out.println( msg );
    }
    MPI.Finalize( );                       // Finish MPI computation
  }
}
```

Send() and Recv() calls are blocking operations by default

Worksheet #11 (to be done individually or in pairs): impact of distribution on parallel completion time

Name 1: ______________________   Name 2: ______________________

```
public void sampleKernel(int iterations,
                         int numChunks, dist d) {
  for (int iter = 0; iter < iterations; iter++) {
    finish for (point [jj] : [0:numChunks-1])
      async at(d.get(jj)) {
        perf.addLocalOps(jj);
        // Assume that time to process chunk jj is O(jj)
    } // finish-for-async
    double[] temp = myNew; myNew = myVal; myVal = temp;
  } // for iter
} // sample kernel
```

- Assume an execution with n places using the option, -places n:1
- Will a block or cyclic distribution for d have a smaller parallel completion time, assuming that all tasks on the same place are serialized?