Introduction to the Partitioned Global Address Space (PGAS) Programming Model

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Overview

- Module 1: PGAS Fundamentals
- Module 2: UPC
- Module 3: pMATLAB
- Module 4: Asynchronous PGAS and X10

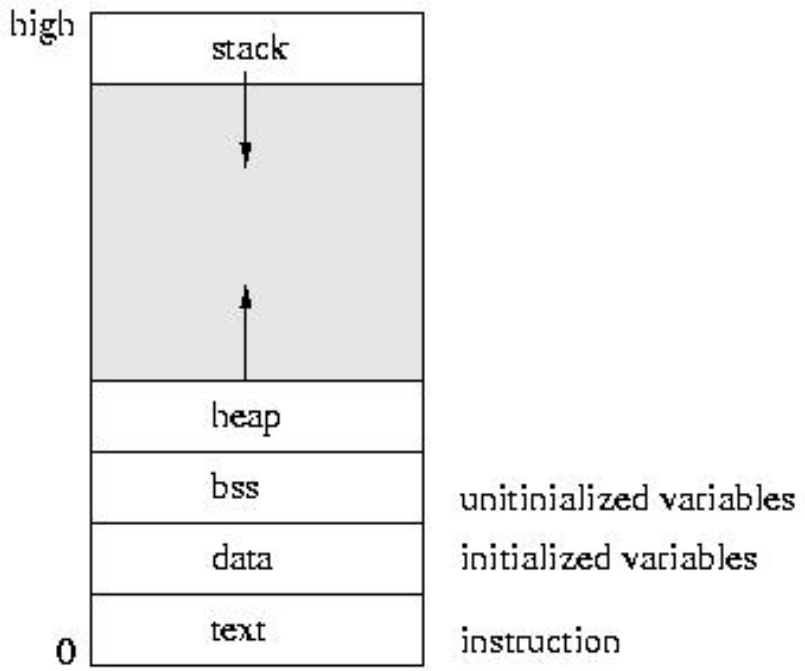
Introduction to PGAS– The Basics

PGAS Model

- Concepts
  - Memories and structures
  - Threads and affinity
  - Local and non-local accesses
- Examples
  - MPI
  - OpenMP
  - UPC
  - X10

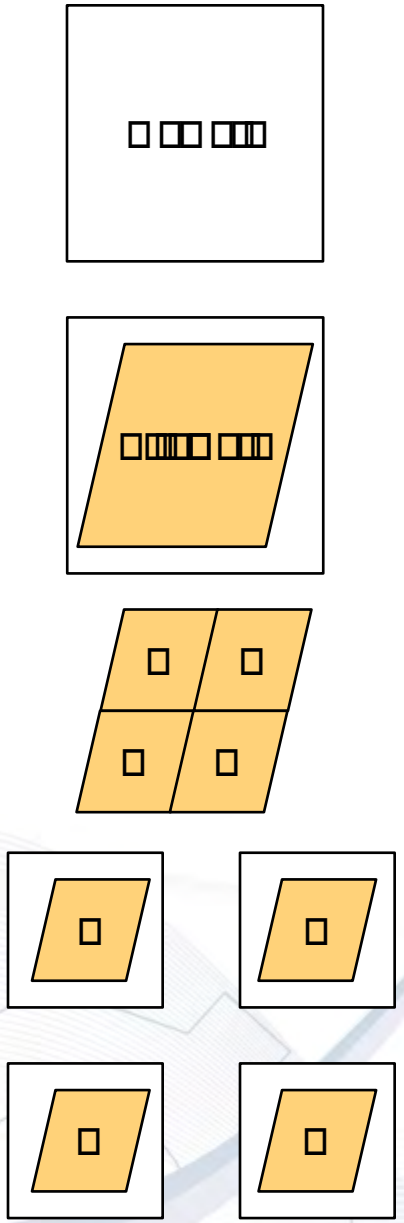
Software Memory Examples

- Executable Image
- Memories
  - Static memory
    - data segment
  - Heap memory
    - Holds allocated structures
    - Grows from bottom of static data region
  - Stack memory
    - Holds function call records
    - Grows from top of stack segment



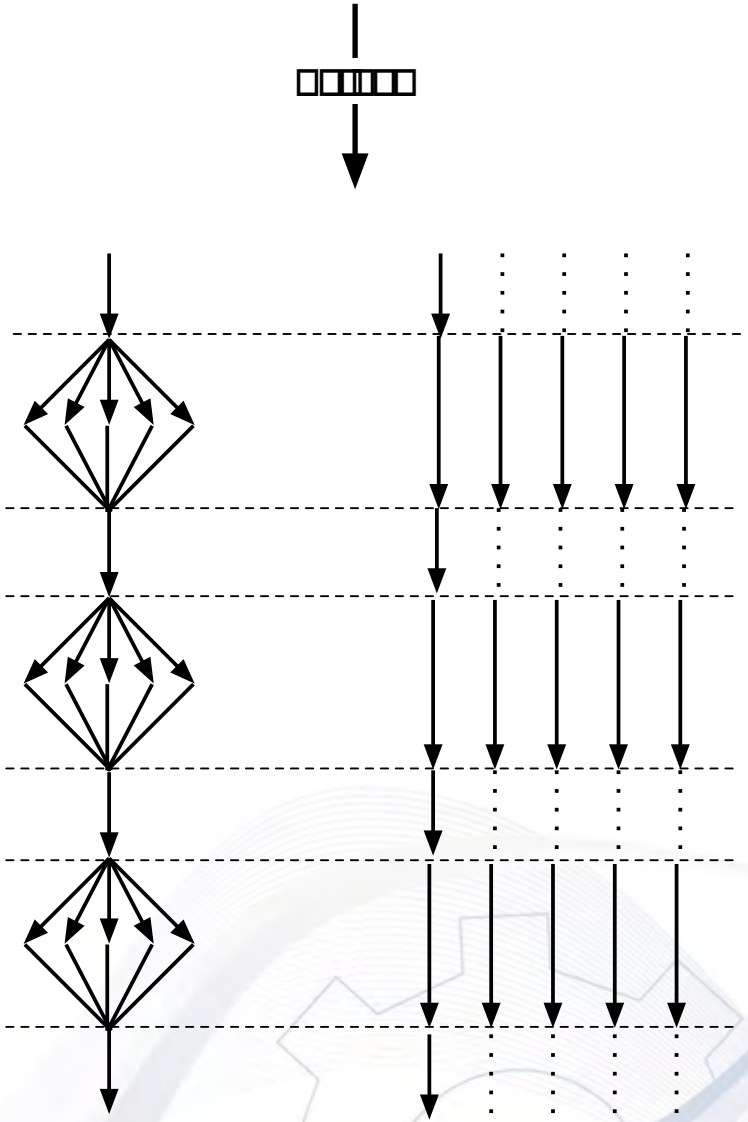
Memories and Structures

- Software Memory
  - Distinct logical storage area in a computer program (e.g., heap or stack)
  - For parallel software, we use multiple memories
- Structure
  - Collection of data created by program execution (arrays, trees, graphs, etc.)
- Partition
  - Division of structure into parts
- Mapping
  - Assignment of structure parts to memories



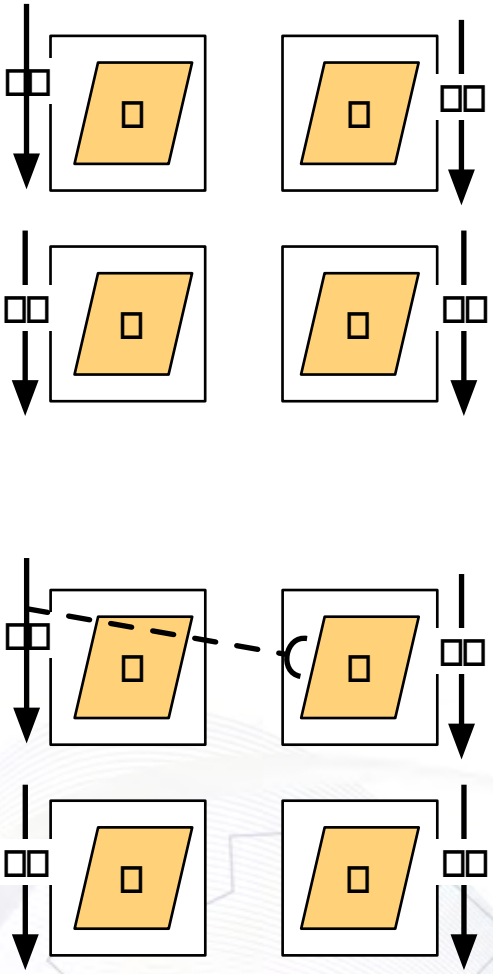
Threads

- Units of execution
- Structured threading
  - Dynamic threads: program creates threads during execution (e.g., OpenMP parallel loop)
  - Static threads: same number of threads running for duration of program
    - Single program, multiple data (SPMD)
- We will defer unstructured threading



Affinity and Nonlocal Access

- Affinity is the association of a thread to a memory
  - If a thread has affinity with a memory, it can access its structures
  - Such a memory is called a local memory
- Nonlocal access
  - Thread 0 wants part B
  - Part B in Memory 1
  - Thread 0 does not have affinity to memory 1



Comparisons

	Thread Count	Memory Count	Nonlocal Access
Traditional	1	1	N/A
OpenMP	Either 1 or p	1	N/A
MPI	p	p	No. Message required.
C+CUDA	1+p	2 (Host/device)	No. DMA required.
UPC, CAF, pMatlab	p	p	Supported.
X10, Asynchronous PGAS	p	q	Supported.

Introduction to PGAS - UPC

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Slides adapted from some by
Tarek El-Ghazawi (GWU)
Kathy Yelick (UC Berkeley)
Adam Leko (U of Florida)

Outline of talk

1. Background
2. UPC memory/execution model
3. Data and pointers
4. Dynamic memory management
5. Work distribution/synchronization

What is UPC?

- UPC - Unified Parallel C
  - An explicitly-parallel extension of ANSI C
  - A distributed shared memory parallel programming language
- Similar to the C language philosophy
  - Programmers are clever and careful, and may need to get close to hardware
    - to get performance, but
    - can get in trouble
- Common and familiar syntax and semantics for parallel C with simple extensions to ANSI C

Players in the UPC field

- UPC consortium of government, academia, HPC vendors, including:
  - ARSC, Compaq, CSC, Cray Inc., Etnus, GWU, HP, IBM, IDA CSC, Intrepid Technologies, LBNL, LLNL, MTU, NSA, UCB, UMCP, UF, US DoD, US DoE, OSU
  - See http://upc.gwu.edu for more details

Hardware support

- Many UPC implementations are available
  - Cray: X1, X1E
  - HP: AlphaServer SC and Linux Itanium (Superdome) systems
  - IBM: BlueGene and AIX
  - Intrepid GCC: SGI IRIX, Cray T3D/E, Linux Itanium and x86/x86-64 SMPs
  - Michigan MuPC: “reference” implementation
  - Berkeley UPC Compiler: just about everything else

General view

A collection of threads operating in a partitioned global address space that is logically distributed among threads. Each thread has affinity with a portion of the globally shared address space. Each thread has also a private space.

Elements in partitioned global space belonging to a thread are said to have affinity to that thread.

First example: sequential vector addition

```
//vect_add.c

#define N 1000
int v1[N], v2[N], v1plusv2[N];
void main()
{
  int i;
  for (i=0; i<N; i++)
       v1plusv2[i]=v1[i]+v2[i];
}
```

First example: parallel vector addition

```
//vect_add.c
#include <upc.h>
#define N 1000
shared int v1[N], v2[N], v1plusv2[N];
void main()
{
  int i;
  upc_forall (i=0; i<N; i++; &v1plusv2[N])
       v1plusv2[i]=v1[i]+v2[i];
}
```

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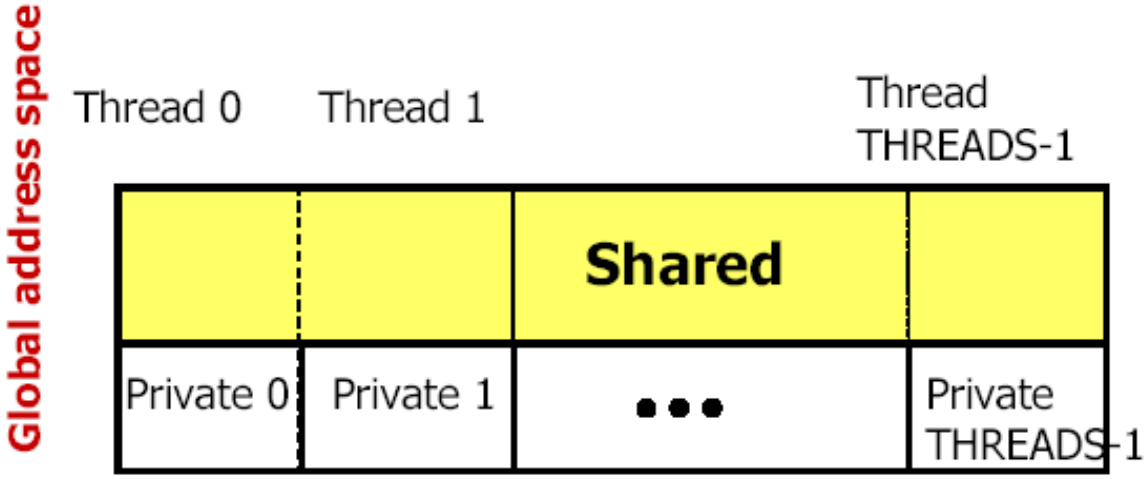
UPC memory model



- A pointer-to-shared can reference all locations in the shared space
- A pointer-to-local ("plain old C pointer") may only reference addresses in its private space or addresses in its portion of the shared space
- Static and dynamic memory allocations are supported for both shared and private memory

UPC execution model

- A number of threads working independently in SPMD fashion
  - Similar to MPI
  - MYTHREAD specifies thread index (0..THREADS-1)
  - Number of threads specified at compile-time or run-time
- Synchronization only when needed
  - Barriers
  - Locks
  - Memory consistency control

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Shared scalar and array data

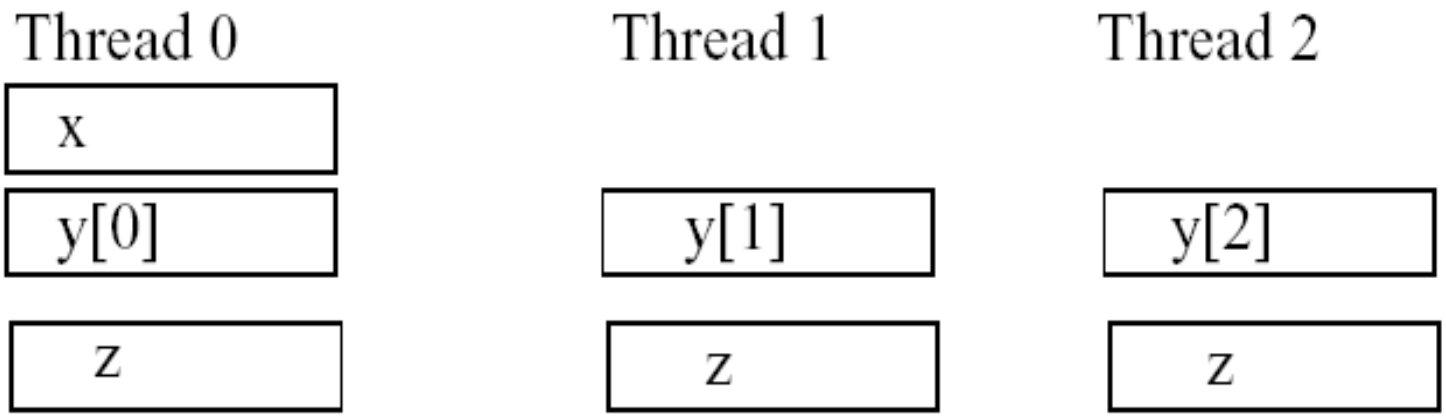
- Shared array elements and blocks can be spread across the threads
  - `shared int x[THREADS]`
    `/* One element per thread */`
  - `shared int y[10][THREADS]`
    `/* 10 elements per thread */`
- Scalar data declarations
  - `shared int a;`
    `/* One item in global space`
    `(affinity to thread 0) */`
  - `int b;`
    `/* one private b at each thread */`

Shared and private data

- Example (assume THREADS = 3):

```
shared int x; /*x will have affinity to thread 0 */
shared int y[THREADS];
int z;
```

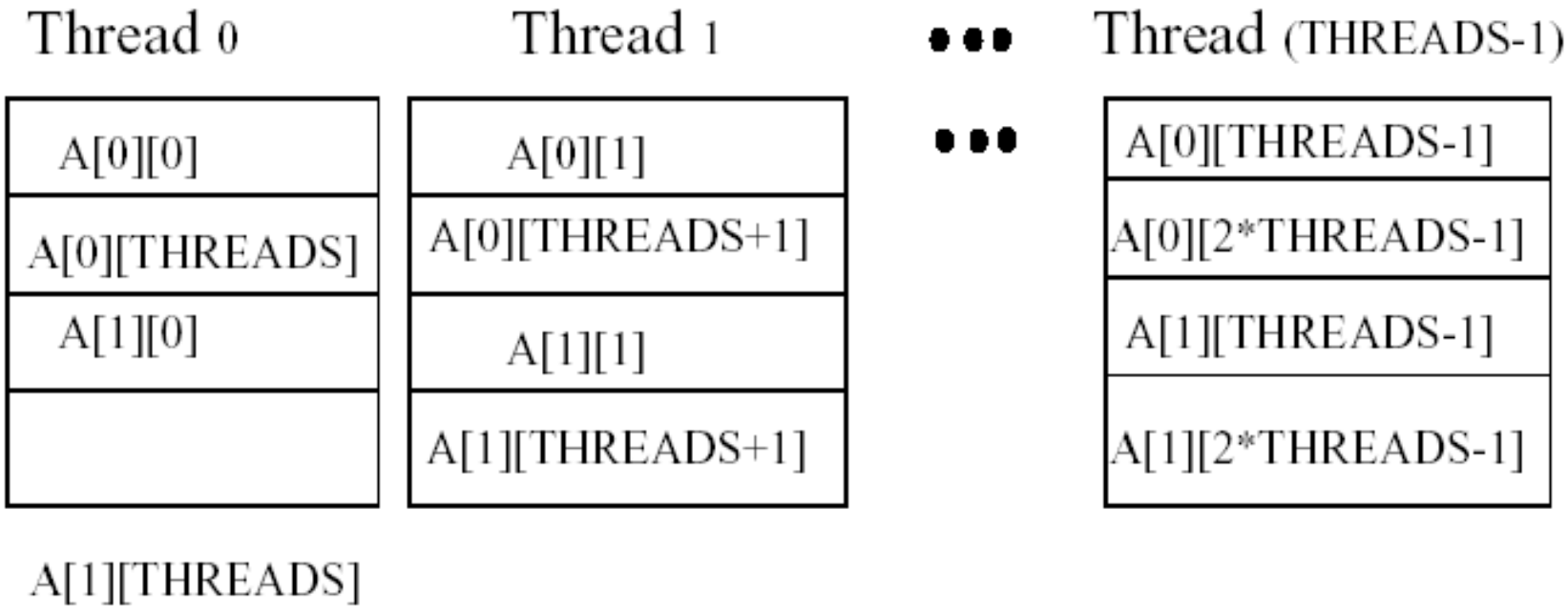
- The resulting layout is:



Shared data

shared int A[2][2*THREADS];

will result in the following data layout:



Remember: C uses row-major ordering

Blocking of shared arrays

- Default block size is 1
- Shared arrays can be distributed on a block per thread basis, round robin, with arbitrary block sizes.
- A block size is specified in the declaration as follows:
  - shared [block-size] array [N];
  - e.g.: shared [4] int a[16];

Blocking of shared arrays

- Block size and THREADS determine affinity
- The term affinity means in which thread's local shared-memory space, a shared data item will reside
- Element i of a blocked array has affinity to thread:

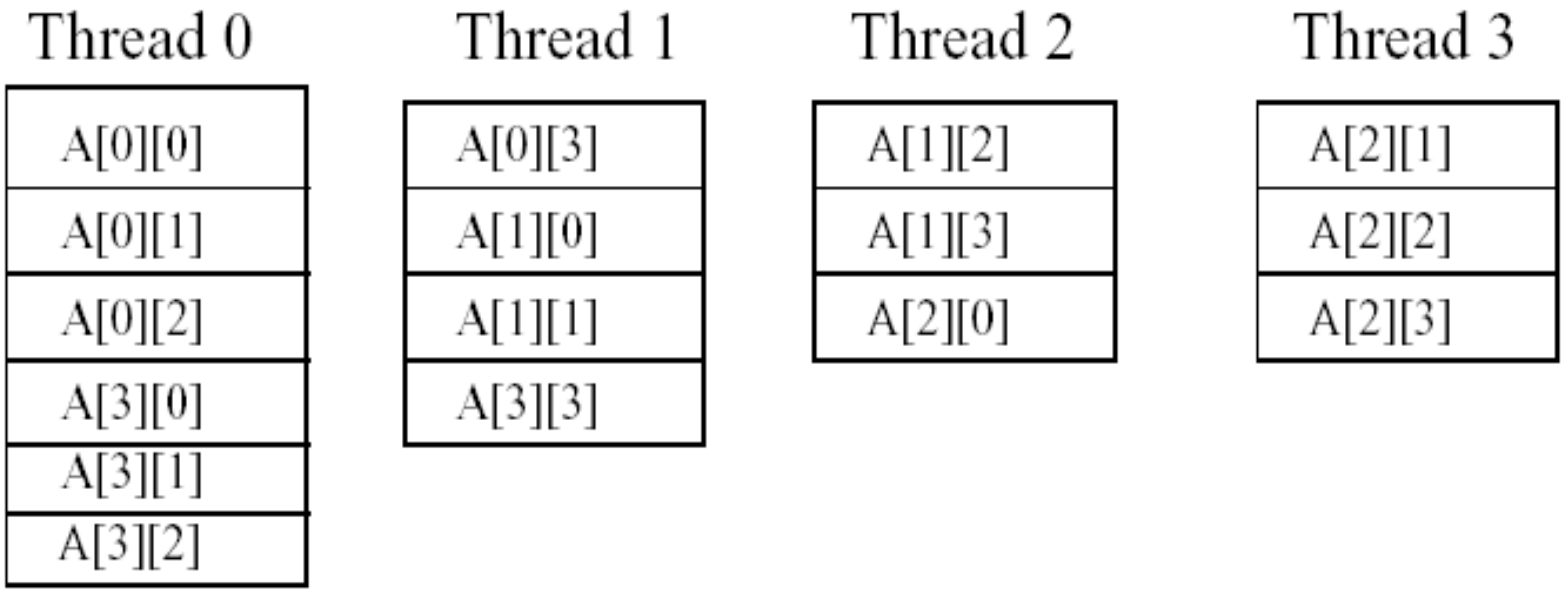
$$\left\lfloor \frac{i}{blocksize} \right\rfloor \bmod THREADS$$

Shared and private data

- Assuming THREADS = 4

  shared [3] int A[4][THREADS];

  will result in the following data layout:



Shared and private data summary

- Shared objects placed in memory based on affinity
- Affinity can be also defined based on the ability of a thread to refer to an object by a private pointer
- All non-array scalar shared qualified objects have affinity with thread 0
- Threads may access shared and private data

UPC pointers

- Pointer declaration:
  - `shared int *p;`
- p is a pointer to an integer residing in the shared memory space
- p is called a pointer to shared
- Other pointer declared same as in C
  - `int *ptr;`
  - "pointer-to-local" or "plain old C pointer," can be used to access private data and shared data with affinity to MYTHREAD

Pointers in UPC

Where does the pointer reside?

Where does it point?	Private	Shared
Private	PP	PS
Shared	SP	SS

Pointers in UPC

- How to declare them?
  - `int *p1; /* private pointer pointing locally */`
  - `shared int *p2; /* private pointer pointing into the shared space */`
  - `int *shared p3; /* shared pointer pointing locally */`
  - `shared int *shared p4; /* shared pointer pointing into the shared space */`

Pointers in UPC

- What are the common usages?
  - `int *p1; /* access to private data or to local shared data */`
  - `shared int *p2; /* independent access of threads to data in shared space */`
  - `int *shared p3; /* not recommended*/`
  - `shared int *shared p4; /* common access of all threads to data in the shared space*/`

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Dynamic memory allocation

- Dynamic memory allocation of shared memory is available in UPC
- Functions can be collective or not
- A collective function has to be called by every thread and will return the same value to all of them

Global memory allocation

```
shared void *upc_global_alloc(size_t nblocks,
  size_t nbytes);
```

nblocks : number of blocks

nbytes : block size

- Non collective, expected to be called by one thread
- The calling thread allocates a contiguous memory space in the shared space
- If called by more than one thread, multiple regions are allocated and each thread which makes the call gets a different pointer
- Space allocated per calling thread is equivalent to :

  shared [nbytes] char[nblocks * nbytes]

Collective global memory allocation

```
shared void *upc_all_alloc(size_t nblocks,
  size_t nbytes);
```

nblocks: number of blocks

nbytes: block size

- This function has the same result as upc_global_alloc. But this is a collective function, which is expected to be called by all threads
- All the threads will get the same pointer
- Equivalent to :

  shared [nbytes] char[nblocks * nbytes]

Freeing memory

```
void upc_free(shared void *ptr);
```

- The upc_free function frees the dynamically allocated shared memory pointed to by ptr
- upc_free is not collective

Some memory functions in UPC

- Equivalent of memcpy :
  - `upc_memcpy(dst, src, size)`
    `/* copy from shared to shared */`
  - `upc_memput(dst, src, size)`
    `/* copy from private to shared */`
  - `upc_memget(dst, src, size)`
    `/* copy from shared to private */`
- Equivalent of memset:
  - `upc_memset(dst, char, size)`
    `/* initialize shared memory with a character */`

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Work sharing with upc_forall()

- Distributes independent iterations
- Each thread gets a bunch of iterations
- Affinity (expression) field determines how to distribute work
- Simple C-like syntax and semantics

```
upc_forall (init; test; loop; expression)
  statement;
```

- Function of note:

```
upc_threadof(shared void *ptr)
```

returns the thread number that has affinity to the pointer-to-shared

Synchronization

- No implicit synchronization among the threads
- UPC provides the following synchronization mechanisms:
  - Barriers
  - Locks
  - Fence
  - Spinlocks (using memory consistency model)

Synchronization: barriers

- UPC provides the following barrier synchronization constructs:
  - Barriers (Blocking)
    - upc_barrier {expr};
  - Split-Phase Barriers (Non-blocking)
    - upc_notify {expr};
    - upc_wait {expr};
    - Note: upc_notify is not blocking, upc_wait is

Synchronization: fence

- UPC provides a fence construct
  - Equivalent to a null strict reference, and has the syntax
    - `upc_fence;`
  - Null strict reference:
    - `{static shared strict int x; x=x;}`
- Ensures that all shared references issued before the upc_fence are complete

Synchronization: locks

- In UPC, shared data can be protected against multiple writers :
  - `void upc_lock(upc_lock_t *l)`
  - `int upc_lock_attempt(upc_lock_t *l) // returns 1 on success and 0 on failure`
  - `void upc_unlock(upc_lock_t *l)`
- Locks can be allocated dynamically. Dynamically allocated locks can be freed
- Dynamic locks are properly initialized and static locks need initialization

Introduction to PGAS - pMatlab

Credit: Slides based on some from Jeremey Kepner
http://www.ll.mit.edu/mission/isr/pmatlab/pmatlab.html

Agenda

- Overview
- pMatlab Execution (SPMD)
  - Replicated arrays
- Distributed arrays
  - Maps
  - Local components

Not real PGAS

- PGAS – Partitioned Global Address Space
- MATLAB doesn't expose address space
  - Uses implicit memory management
  - User creates arrays
  - MATLAB interpreter allocates/frees the memory
- So, when I say PGAS in MATLAB, I mean
  - Running multiple copies of the interpreter
  - Distributed arrays: allocating a single (logical) array as a collection of local (physical) array components
- Multiple implementations
  - Open source: MIT Lincoln Labs' pMatlab + OSC bcMPI
  - Commercial: Mathworks' Parallel Computing Toolbox, Interactive Supercomputing (now Microsoft) Star-P

http://www.osc.edu/bluecollarcomputing/applications/bcMPI/index.shtml

Serial Program

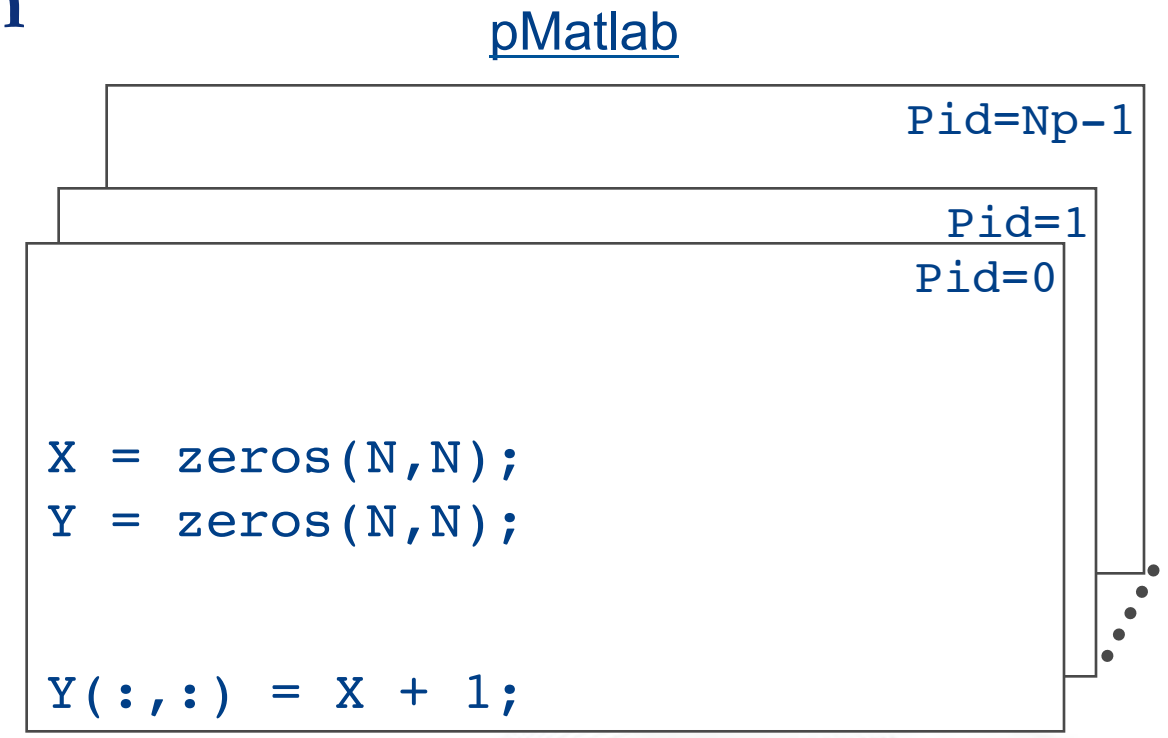
Matlab

```
X = zeros(N,N);
Y = zeros(N,N);

Y(:,:) = X + 1;
```

- Matlab is a high level language
- Allows mathematical expressions to be written concisely
- Multi-dimensional arrays are *fundamental* to Matlab

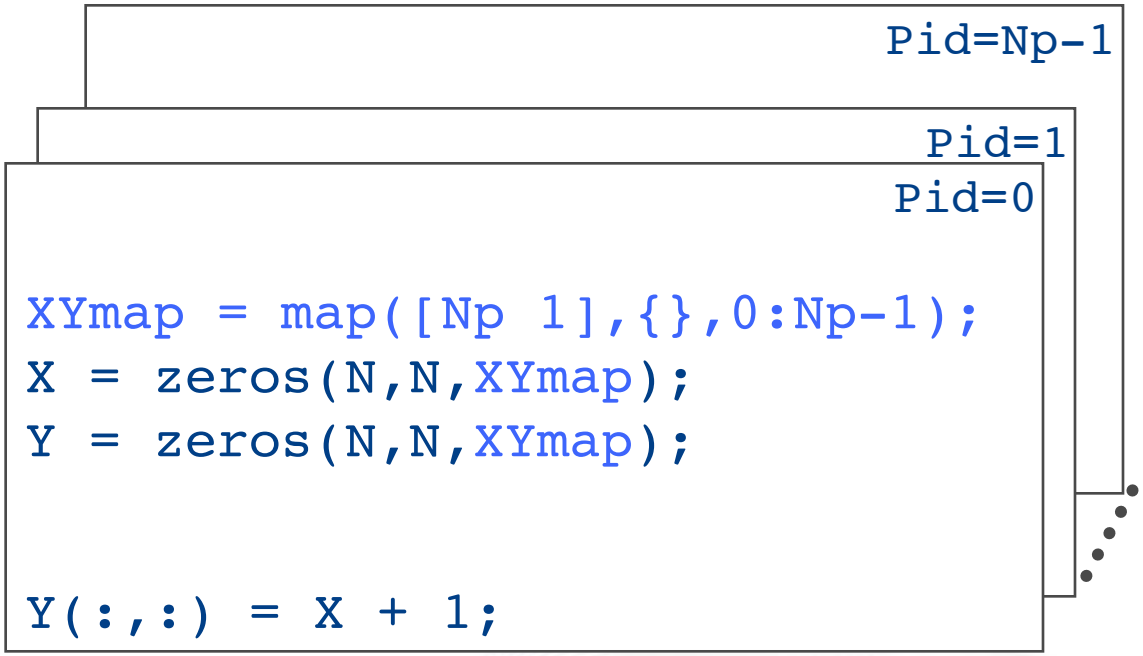
Parallel Execution



- Run N_P (or `Np`) copies of same program
  - Single Program Multiple Data (SPMD)
- Each copy has a unique P_{ID} (or `Pid`)
- Every array is *replicated* on each copy of the program

Distributed Array Program

pMatlab



- Use `map` to make a distributed array
- Tells program which dimension to distribute data
- Each program implicitly operates on only its own data (owner computes rule)

Explicitly Local Program

pMatlab

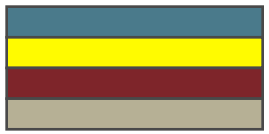
```
XYmap = map([Np 1],{},0:Np-1);
Xloc = local(zeros(N,N,XYmap));
Yloc = local(zeros(N,N,XYmap));

Yloc(:,:) = Xloc + 1;
```

- Use `local` function to explicitly retrieve local part of a distributed array
- Operation is the same as serial program, but with different data in each process (recommended approach)

Parallel Data Maps

Array

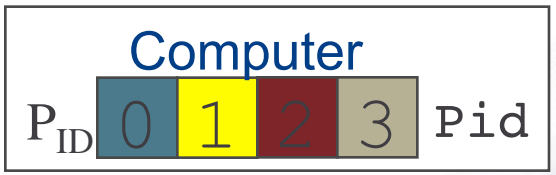


Matlab

```
Xmap=map([Np 1],{},0:Np-1)
```

```
Xmap=map([1 Np],{},0:Np-1)
```

```
Xmap=map([Np/2 2],{},0:Np-1)
```



- A map is a mapping of array indices to processes
- Can be block, cyclic, block-cyclic, or block w/overlap
- Use `map` to set which dimension to split among processes

Maps and Distributed Arrays

A process ***map*** for a numerical array is an *assignment of blocks of data to processes*.

```
Amap = map([Np 1],{},0:Np-1);
```

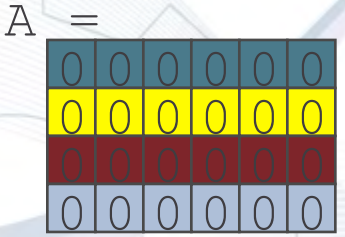
Process Grid

Distribution
{}=default=block

List of processes

```
A = zeros(4,6,Amap);
```

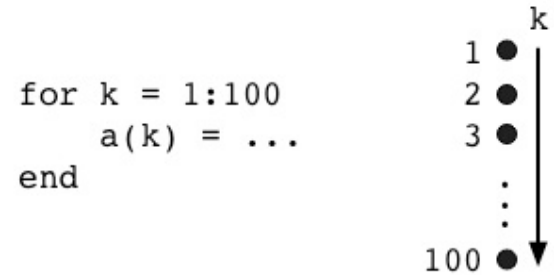
pMatlab constructors are overloaded to take a `map` as an argument, and return a distributed array.



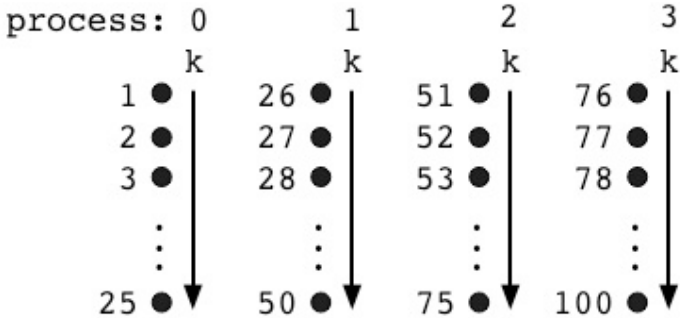
Parallelizing Loops

- The set of loop index values is known as an iteration space
- In parallel programming, a set of processes cooperate in order to complete a single task
- To parallelize a loop, we must split its iteration space among processes

```
for k = 1:100
    a(k) = ...
end
```

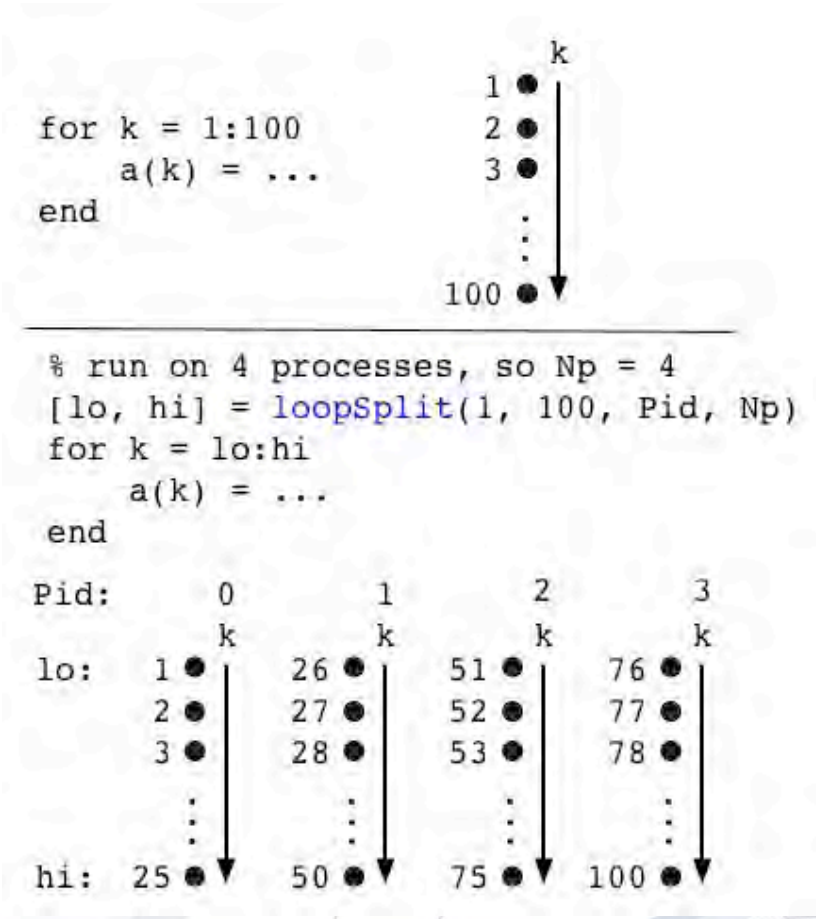



```
% run on 4 processes
parfor k = 1:100
    a(k) = ...
end
```



loopSplit Construct

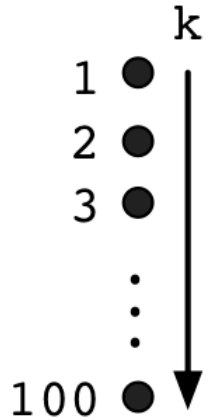
- parfor is a neat construct that is supported by Mathworks' PCT
- ParaM's equivalent is called loopSplit
- Why loopSplit and not parfor? That is a subtle question…



Global View vs. Local View

- In parallel programming, a set of processes cooperate in order to complete a single task
- The *global view* of the program refers to actions and data from the task perspective
  - OpenMP programming is an example of global view
- parfor is a global view construct

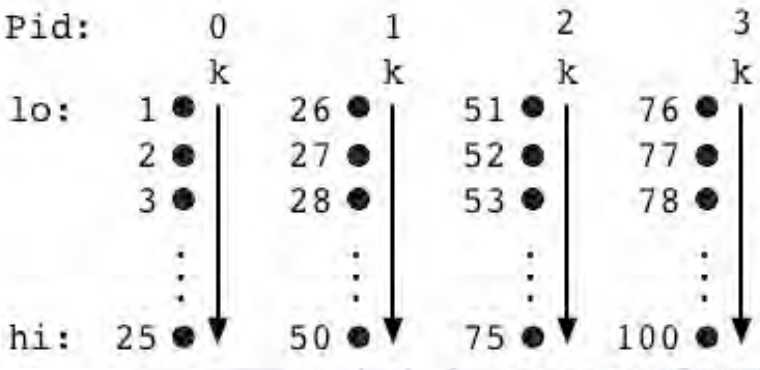
```
for k = 1:100
    a(k) = ...
end
```



Gobal View vs. Local View (con't)

- The *local view* of the program refers to actions and data within an individual process
- Single Program-Multiple Data (SPMD) programs provide a local view
  - Each process is an independent execution of the same program
  - MPI programming is an example of SPMD
- ParaM uses SPMD
- loopSplit is the SPMD equivalent of parfor

```
% run on 4 processes, so Np = 4
[lo, hi] = loopSplit(1, 100, Pid, Np)
for k = lo:hi
    a(k) = ...
end
```



loopSplit Example

- Monte Carlo approximation of π
- Algorithm
  - Consider a circle of radius 1
  - Let N = some large number (say 10000) and count = 0
  - Repeat the following procedure N times
    - Generate two random numbers x and y between 0 and 1 (use the **`rand`** function)
    - Check whether (x,y) lie inside the circle
    - Increment count if they do
  - Pi_value = 4 * count / N

Monte Carlo Example: Serial Code

```
N = 1000;
count = 0;
radius = 1;
fprintf('Number of iterations : %.0f\n', N);
for k = 1:N
   % Generate two numbers between 0 and 1
   p = rand(1,2);
   % i.e. test for the condition : x^2 + y^2 < 1
   if sum(p.^2) < radius
      % Point is inside circle : Increment count
      count = count + 1;
   end
End
pival = 4*count/N;
t1 = clock;
fprintf('Calculated PI = %f\nError = %f\n', pival, abs(pi-
pival));
fprintf('Total time : %f seconds\n', etime(t1, t0));
```

Monte Carlo Example: Parallel Code

```
if (PARALLEL)
    rand('state', Pid+1);
end
N = 1000000;
count = 0;
radius = 1;
fprintf('Number of iterations : %.0f\n', N);
[local_low, local_hi] = loopSplit(1, N, Pid, Np);
fprintf('Process \t%i\tbegins %i\tends %i\n', Pid, local_low, ...
    local_hi);
for k = local_low:local_hi
   % Here, p(x,y) represents a point in the x-y space
   p = rand(1,2);
   % i.e. test for the condition : x^2 + y^2 < 1
   if sum(p.^2) < radius
      count = count + 1;
   end
end
```

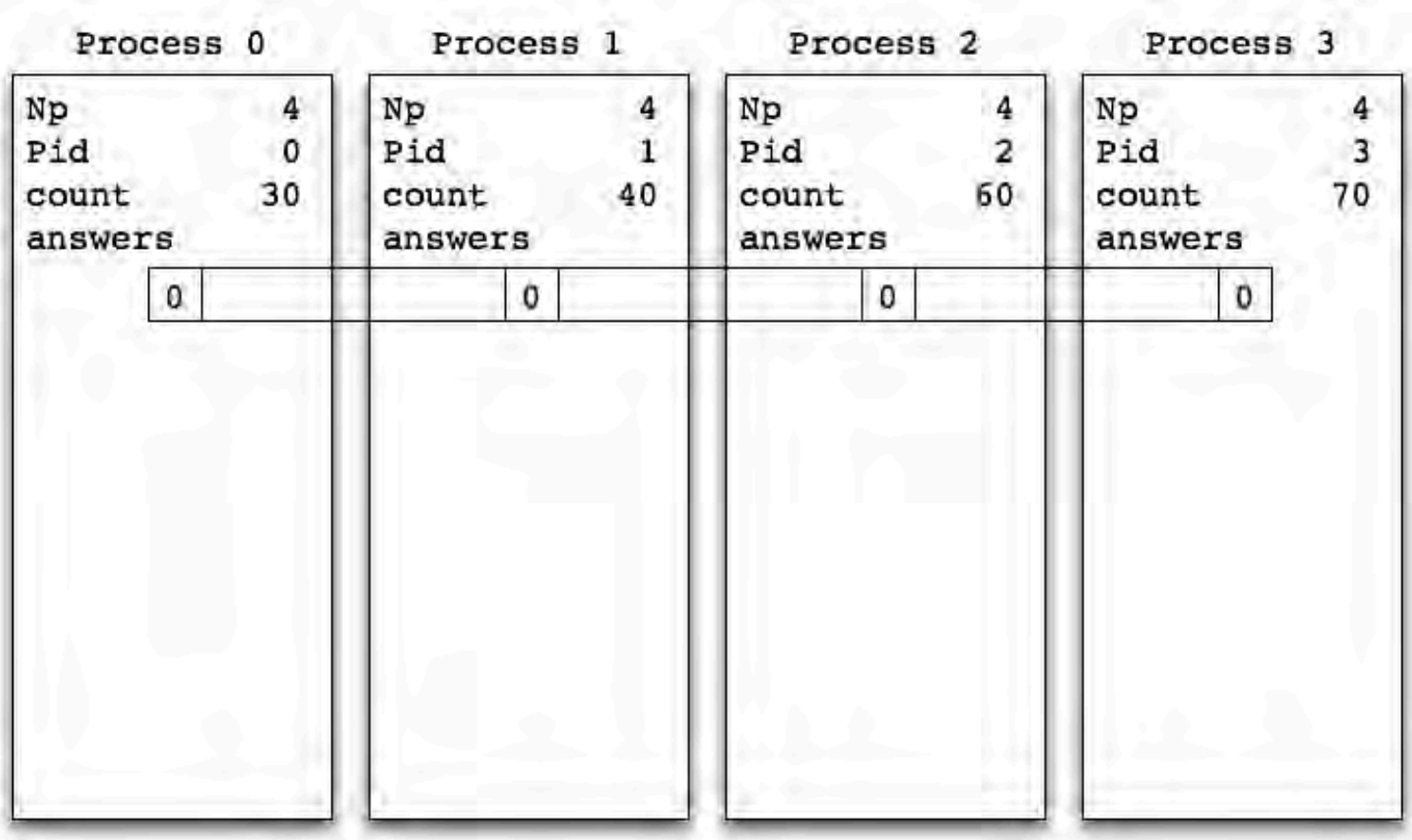
Monte Carlo Example: Parallel Output

```
Number of iterations : 1000000
Process      0    begins 1         ends 250000
Process      1    begins 250001    ends 500000
Process      2    begins 500001    ends 750000
Process      3    begins 750001    ends 1000000
Calculated PI = 3.139616
Error = 0.001977
```

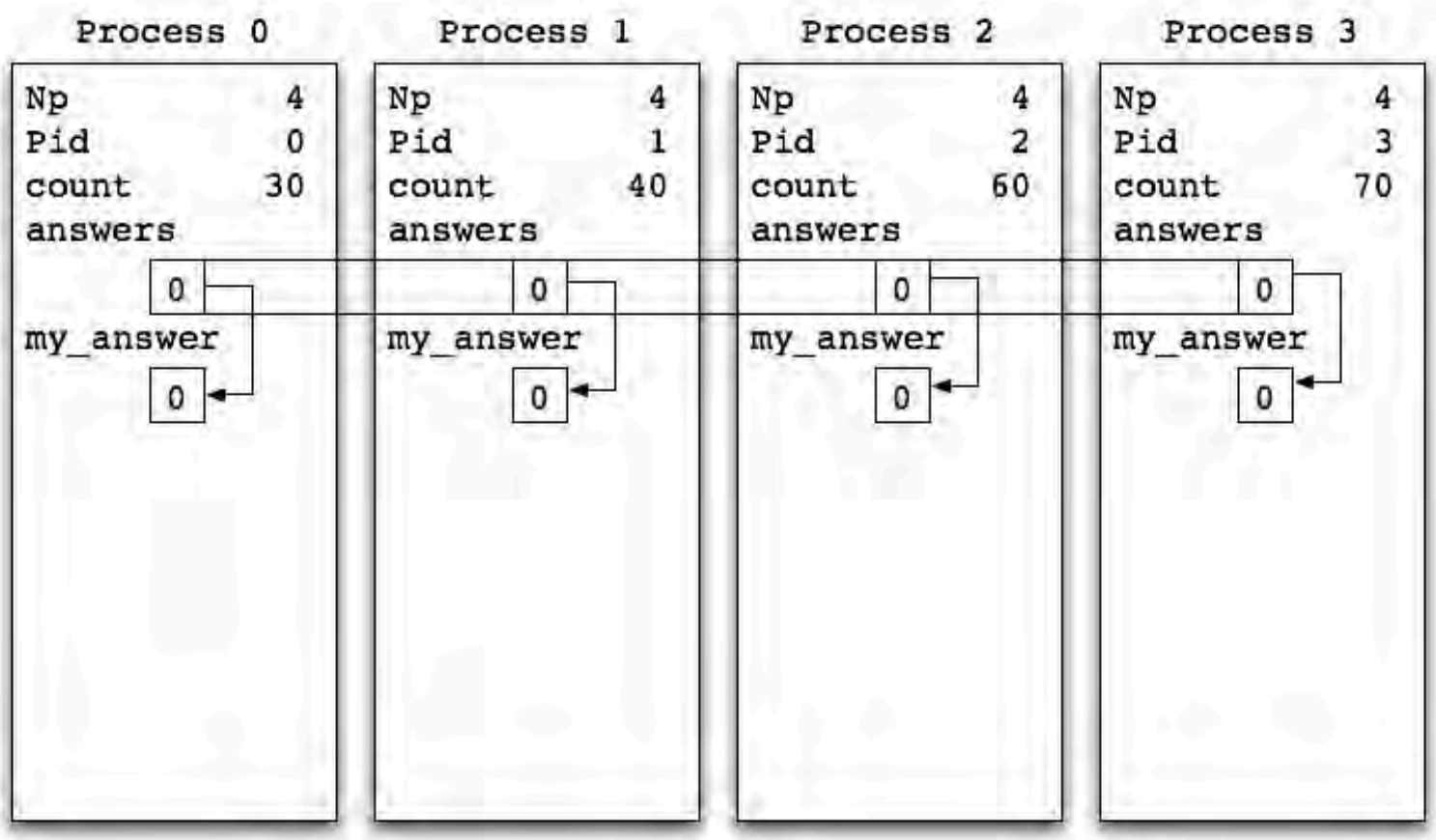
Monte Carlo Example: Total Count

```
if (PARALLEL)
   map1 = map([Np 1], {}, 0:Np-1);
else
    map1 = 1;
end
answers = zeros(Np, 1, map1);
my_answer = local(answers);
my_answer(1,1) = count;
answers = put_local(answers, my_answer);
global_answers = agg(answers);
if (Pid == 0)
   global_count = 0;
   for i = 1:Np
       global_count = global_count + global_answers(i,1);
   end
    pival = 4*global_count/N;
    fprintf('PI = %f\nError = %f\n', pival, abs(pi-pival));
end
```

```
answers = zeros(Np, 1, map1);
my_answer = local(answers);
my_answer(1,1) = count;
answers = put_local(answers, my_answer);
global_answers = agg(answers);
```



```
answers = zeros(Np, 1, map1);
my_answer = local(answers);
my_answer(1,1) = count;
answers = put_local(answers, my_answer);
global_answers = agg(answers);
```



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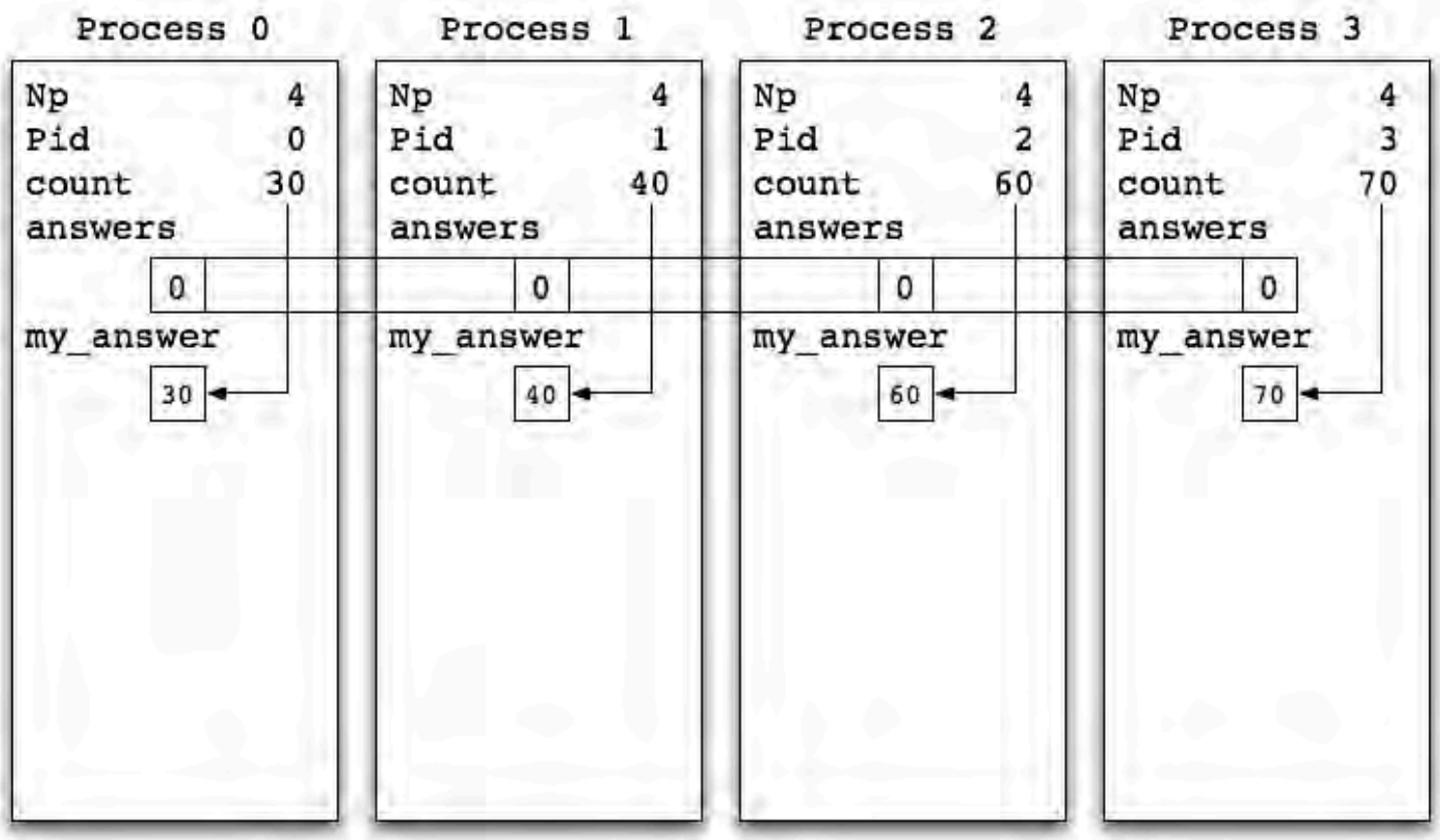

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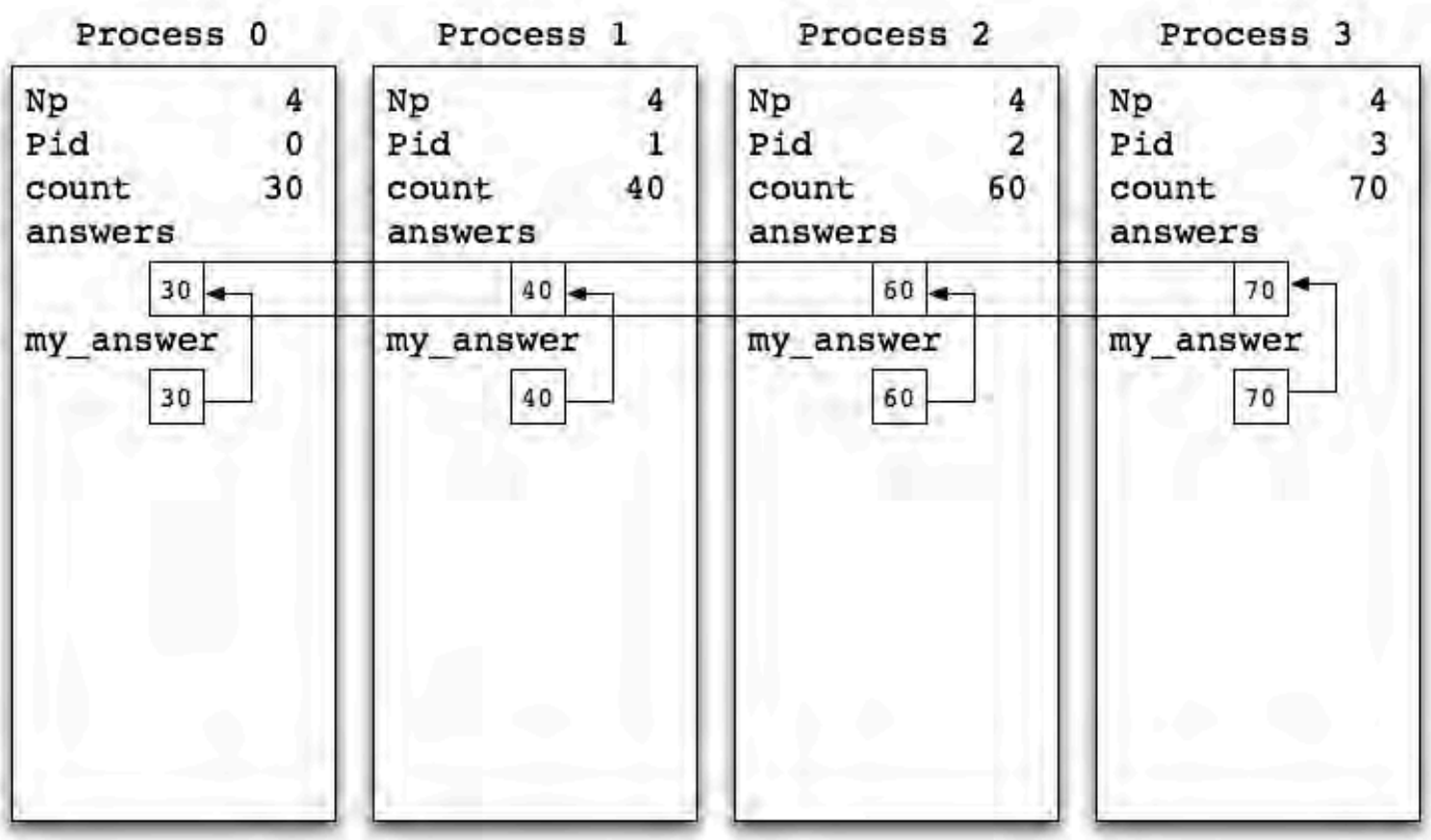

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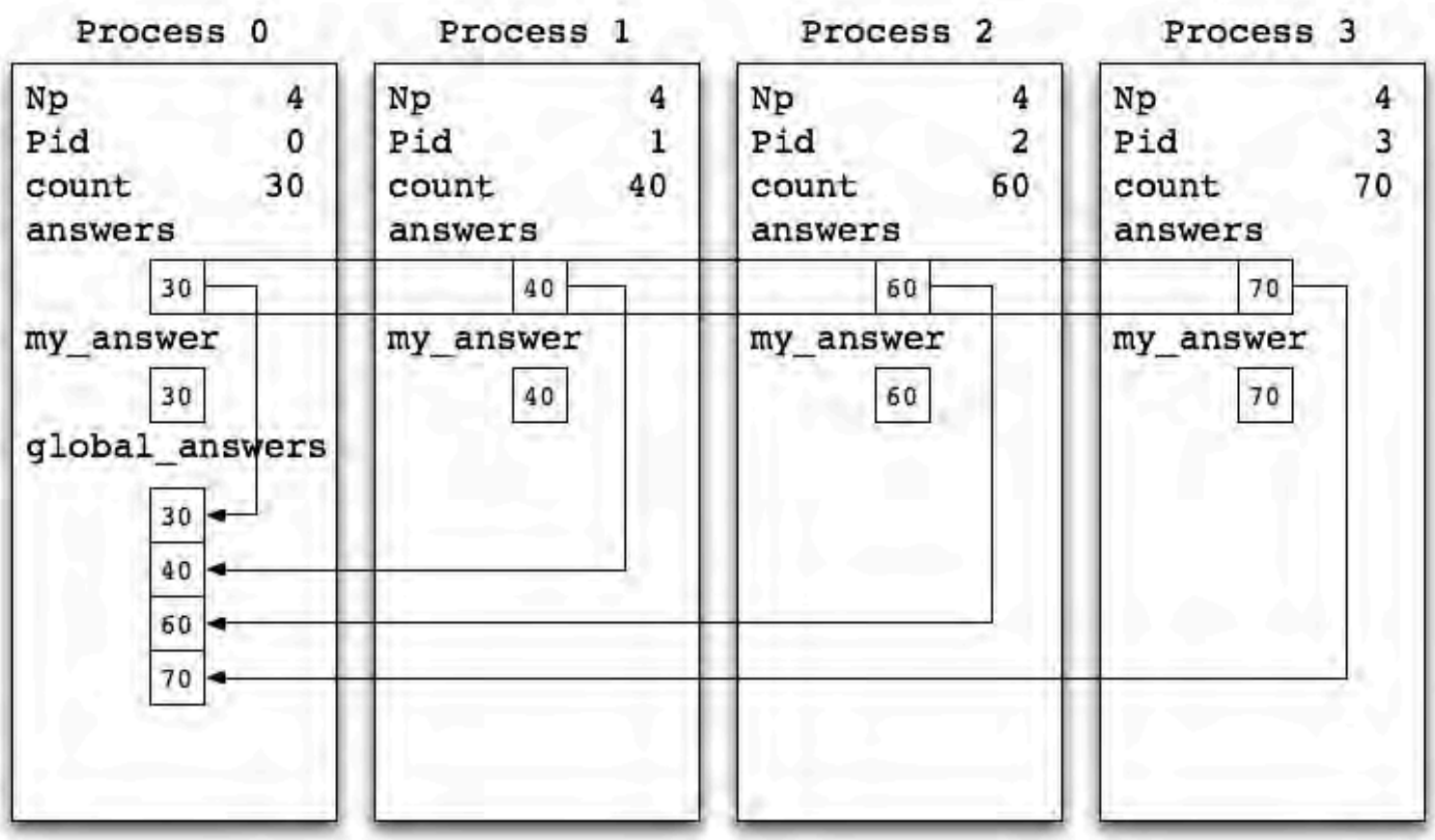
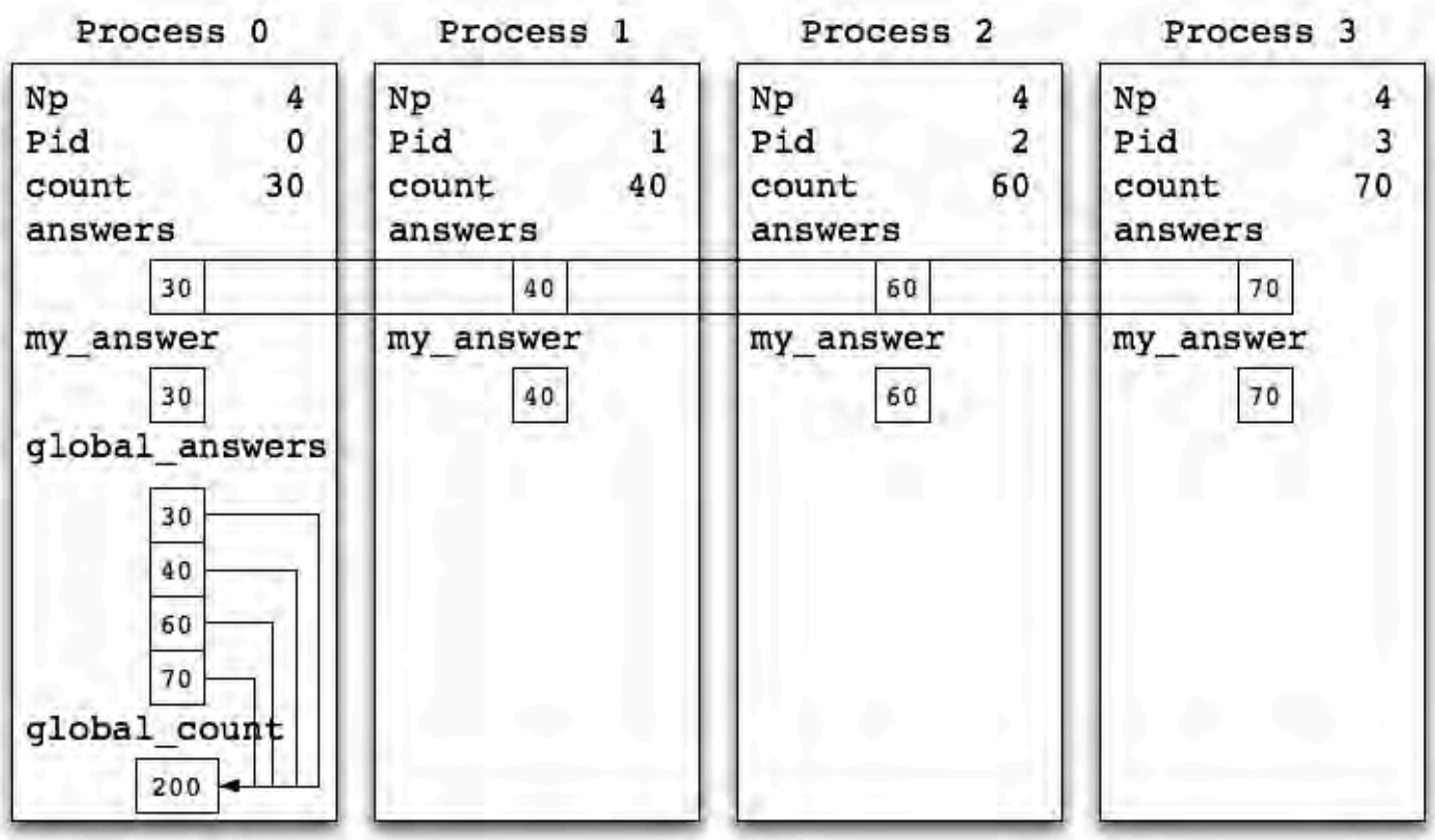
my_answer = local(answers);
my_answer(1,1) = count;
answers = put_local(answers, my_answer);
global_answers = agg(answers);
```



```
if (Pid == 0)
   global_count = 0;
   for i = 1:Np
       global_count = global_count + global_answers(i,1);
```



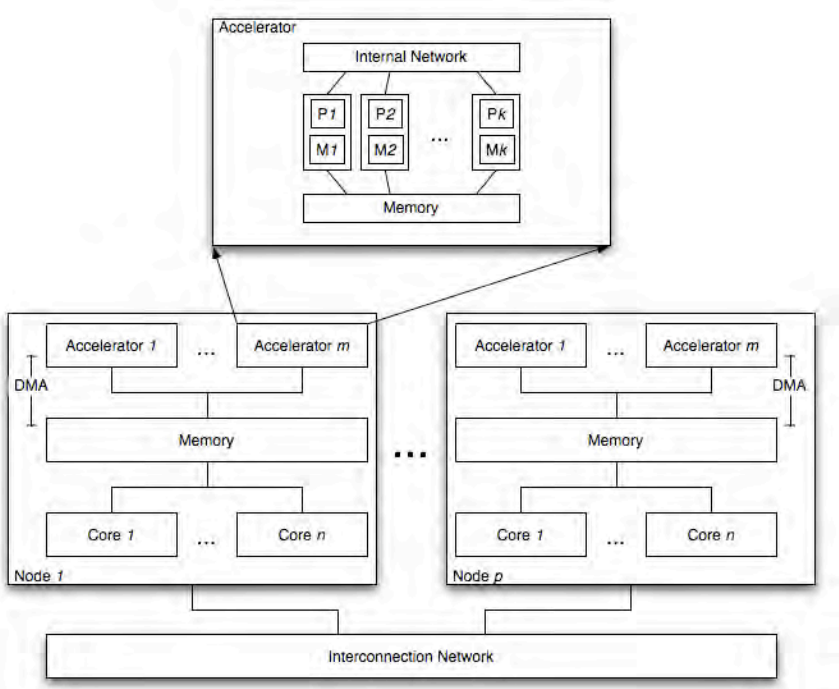
Introduction to PGAS - APGAS and the X10 Language

Credit: Slides based on some from David Grove, et.al.
http://x10.codehaus.org/Tutorials

Outline

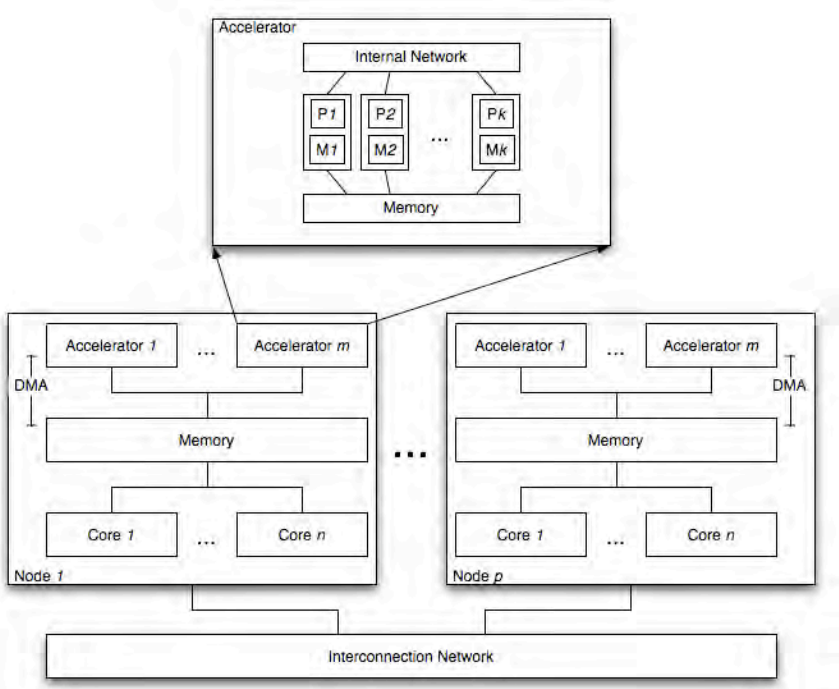
- MASC architectures and APGAS
- X10 fundamentals
- Data distributions (points and regions)
- Concurrency constructs
- Synchronization constructs
- Examples

Multicore/Accelerator multiSpace Computing (MASC)



- Cluster of nodes
- Each node
  - Multicore processing
    - 2 to 4 sockets/board now
    - 2, 4, 8 cores/socket now
  - Manycore accelerator
    - Discrete device (GPU)
    - Integrated w/CPU (Intel “Knights Corner”)
- Multiple memory spaces
  - Per node memory (accessible by local cores)
  - Per accelerator memory

Multicore/Accelerator multiSpace Computing (MASC)



- Achieving high performance requires detailed, system-dependent specification of data placement and movement
- Programmability Challenges
  - exhibit multiple levels of parallelism
  - synchronize data motion across multiple memories
  - regularly overlap computation with communication

Every Parallel Architecture has a dominant programming model

Parallel Architecture	Programming Model
Vector Machine (Cray 1)	Loop vectorization (IVDEP)
SIMD Machine (CM-2)	Data parallel (C*)
SMP Machine (SGI Origin)	Threads (OpenMP)
Clusters (IBM 1350)	Message Passing (MPI)
GPGPU (nVidia Tesla)	Data parallel (CUDA)
MASC	Asynchronous PGAS?

- MASC Options
  - Pick a single model (MPI, OpenMP)
  - Hybrid code
    - MPI at node level
    - OpenMP at core level
    - CUDA at accelerator
  - Find a higher-level abstraction, map it to hardware

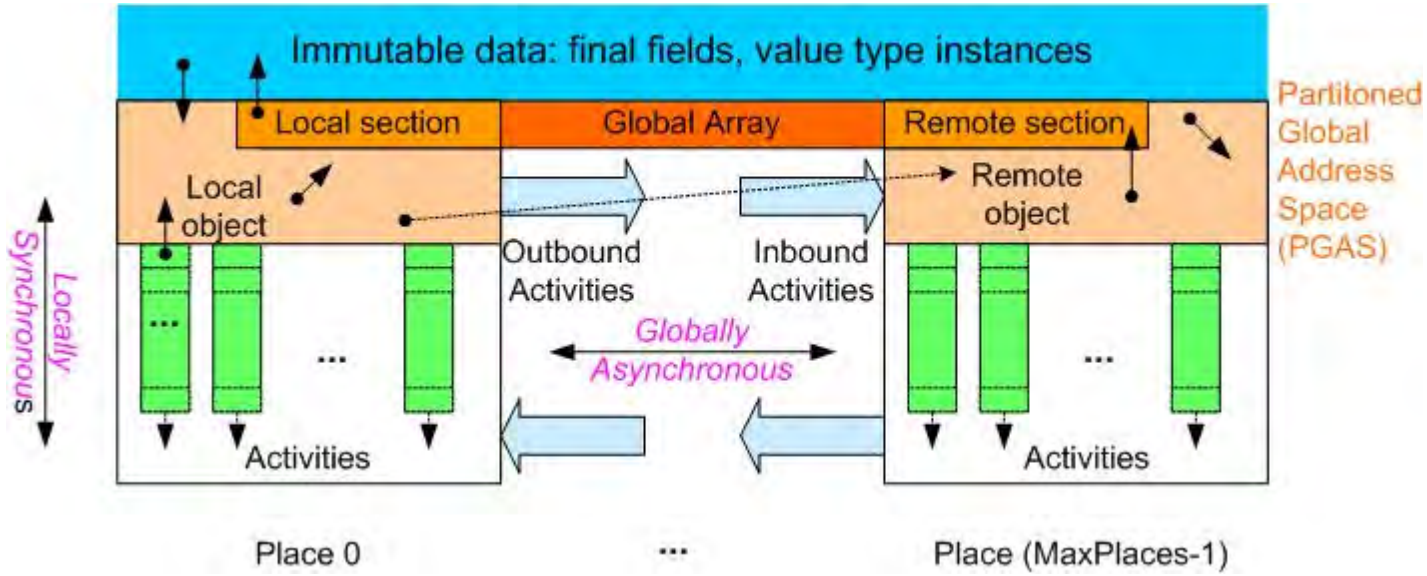
X10 Concepts

- Asynchronous PGAS
  - PGAS model in which threads can be dynamically created under programmer control
  - p distinct memories, q distinct threads (p <> q)
- PGAS memories are called *places* in X10
- PGAS threads are called *activities* in X10

What is X10?

- X10 is a new language developed in the IBM PERCS project as part of the DARPA program on High Productivity Computing Systems (HPCS)
- X10 is an instance of the APGAS framework in the Java family
- X10
  - Is more productive than current models
  - Can support high levels of abstraction
  - Can exploit multiple levels of parallelism and non-uniform data access
  - Is suitable for multiple architectures, and multiple workloads.

X10 Constructs



Fine grained concurrency • async S	**Atomicity** • atomic S • when (c) S	**Global data-structures** • points, regions, distributions, arrays
Place-shifting operations • at (P) S	**Ordering** • finish S • clock	

Two basic ideas: Places and Activites

X10 Project Status

- X10 is an open source project (Eclipse Public License)
  - Documentation, releases, mailing lists, code, etc. all publicly available via http://x10-lang.org
- XRX: X10 Runtime in X10 (14kloc and growing)
- X10 1.7.x releases throughout 2009 (Java & C++)
- X10 2.0 released November 6, 2009
  - Java: Single process (all places in 1 JVM)
    - any platform with Java 5
  - C++: Multi-process (1 place per process)
    - aix, linux, cygwin, solaris
    - x86, x86_64, PowerPC, Sparc
    - x10rt: APGAS runtime (binary only) or MPI (open source)

Overview of Features

- Many sequential features of Java inherited unchanged
  - Classes (w/ single inheritance)
  - Interfaces, (w/ multiple inheritance)
  - Instance and static fields
  - Constructors, (static) initializers
  - Overloaded, over-rideable methods
  - Garbage collection
- Structs
- Closures
- Points, Regions, Distributions, Arrays

- Substantial extensions to the type system
  - Dependent types
  - Generic types
  - Function types
  - Type definitions, inference
- Concurrency
  - Fine-grained concurrency:
    - async (p,l) S
  - Atomicity
    - atomic (s)
  - Ordering
    - L: finish S
  - Data-dependent synchronization
    - when (c) S

Points and Regions

- A point is an element of an n-dimensional Cartesian space (n>=1) with integer-valued coordinates e.g., [5], [1, 2], …
- A point variable can hold values of different ranks e.g.,
  - var p: Point = [1]; p = [2,3]; …
- Operations
  - p1.rank
    - returns rank of point p1
  - p1(i)
    - returns element (i mod p1.rank) if i < 0 or i >= p1.rank
  - p1 < p2, p1 <= p2, p1 > p2, p1 >= p2
    - returns true iff p1 is lexicographically <, <=, >, or >= p2
    - only defined when p1.rank and p2.rank are equal

- Regions are collections of points of the same dimension
- Rectangular regions have a simple representation, e.g. [1..10, 3..40]
- Rich algebra over regions is provided

Distributions and Arrays

- Distributions specify mapping of points in a region to places
  - E.g. Dist.makeBlock(R)
  - E.g. Dist.makeUnique()
- Arrays are defined over a distribution and a base type
  - A:Array[T]
  - A:Array[T](d)
- Arrays are created through initializers
  - Array.make[T](d, init)
- Arrays are mutable (considering immutable arrays)
- Array operations
- A.rank ::= # dimensions in array
- A.region ::= index region (domain) of array
- A.dist ::= distribution of array A
- A(p) ::= element at point p, where p belongs to A.region
- A(R) ::= restriction of array onto region R
  - Useful for extracting subarrays

async

- async S
  - Creates a new child activity that executes statement S
  - Returns immediately
  - S may reference final variables in enclosing blocks
  - Activities cannot be named
  - Activity cannot be aborted or cancelled

Stmt ::= **async(p,l)** ***Stmt***

cf Cilk's spawn

```
// Compute the Fibonacci
// sequence in parallel.
def run() {
  if (r < 2) return;
  val f1 = new Fib(r-1),
      f2 = new Fib(r-2);
  finish {
    async f1.run();
    f2.run();
  }
  r = f1.r + f2.r;
}
```

finish

- L: finish S
  - Execute S, but wait until all (transitively) spawned asyncs have terminated.
- Rooted exception model
  - Trap all exceptions thrown by spawned activities.
  - Throw an (aggregate) exception if any spawned async terminates abruptly.
  - Implicit finish at main activity
- finish is useful for expressing "synchronous" operations on (local or) remote data.

Stmt ::= **finish** ***Stmt***

cf Cilk's sync

```
// Compute the Fibonacci
// sequence in parallel.
def run() {
  if (r < 2) return;
  val f1 = new Fib(r-1),
      f2 = new Fib(r-2);
  finish {
    async f1.run();
    f2.run();
  }
  r = f1.r + f2.r;
}
```

at

- at(p) S
  - Execute statement S at place p
  - Current activity is blocked until S completes

Stmt ::= at(p) Stmt

```
// Copy field f from a to b
def copyRemoteFields(a, b) {
  at (b.loc) b.f =
    at (a.loc) a.f;
}

// Increment field f of obj
def incField(obj, inc) {
  at (obj.loc) obj.f += inc;
}

// Invoke method m on obj
def invoke(obj, arg) {
  at (obj.loc) obj.m(arg);
}
```

atomic

- atomic S
  - Execute statement S atomically
  - Atomic blocks are conceptually executed in a single step while other activities are suspended: *isolation* and *atomicity*.
- An atomic block body (S) ...
  - must be *nonblocking*
  - must not create concurrent activities (*sequential*)
  - must not access remote data (*local*)

Stmt ::= **atomic** ***Statement***
MethodModifier ::= **atomic**

```
// target defined in lexically
// enclosing scope.
atomic def CAS(old:Object,
               n:Object) {
  if (target.equals(old)) {
    target = n;
    return true;
  }
  return false;
}

// push data onto concurrent
// list-stack
val node = new Node(data);
atomic {
  node.next = head;
  head = node;
}
```

when

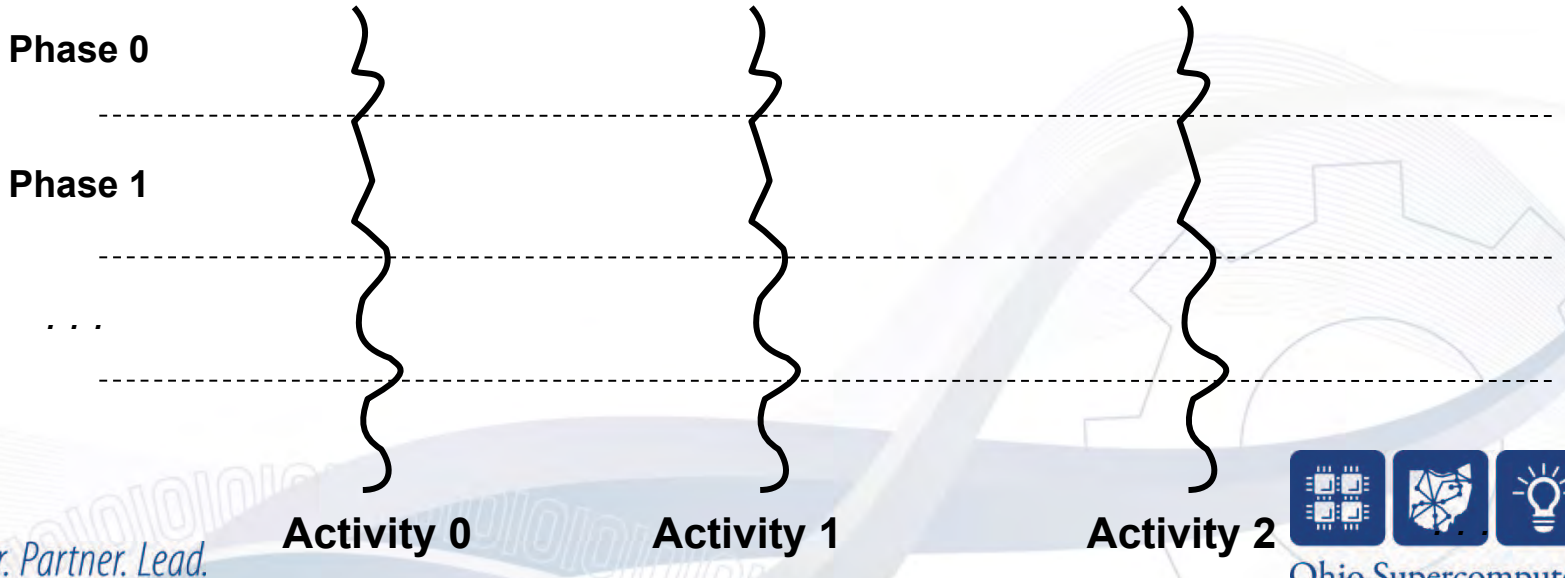
- when (E) S
  - Activity suspends until a state in which the guard E is true.
  - In that state, S is executed *atomically* and in *isolation*.
  - Guard E is a boolean expression
    - must be *nonblocking*
    - must not create concurrent activities (*sequential*)
    - must not access remote data (*local*)
    - must not have side-effects (const)
- await (E)
  - syntactic shortcut for when (E) ;

Stmt ::= WhenStmt
WhenStmt ::= when (Expr) Stmt
| WhenStmt or (Expr) Stmt

```
class OneBuffer {
  var datum:Object = null;
  var filled:Boolean = false;
  def send(v:Object) {
    when ( !filled ) {
      datum = v;
      filled = true;
    }
  }
  def receive():Object {
    when ( filled ) {
      val v = datum;
      datum = null;
      filled = false;
      return v;
    }
  }
}
```

Clocks: Motivation

- Activity coordination using finish is accomplished by checking for activity termination
- But in many cases activities have a producer-consumer relationship and a "barrier"-like coordination is needed without waiting for activity termination
  - The activities involved may be in the same place or in different places
- Design clocks to offer determinate and deadlock-free coordination between a dynamically varying number of activities.



Clocks: Main operations

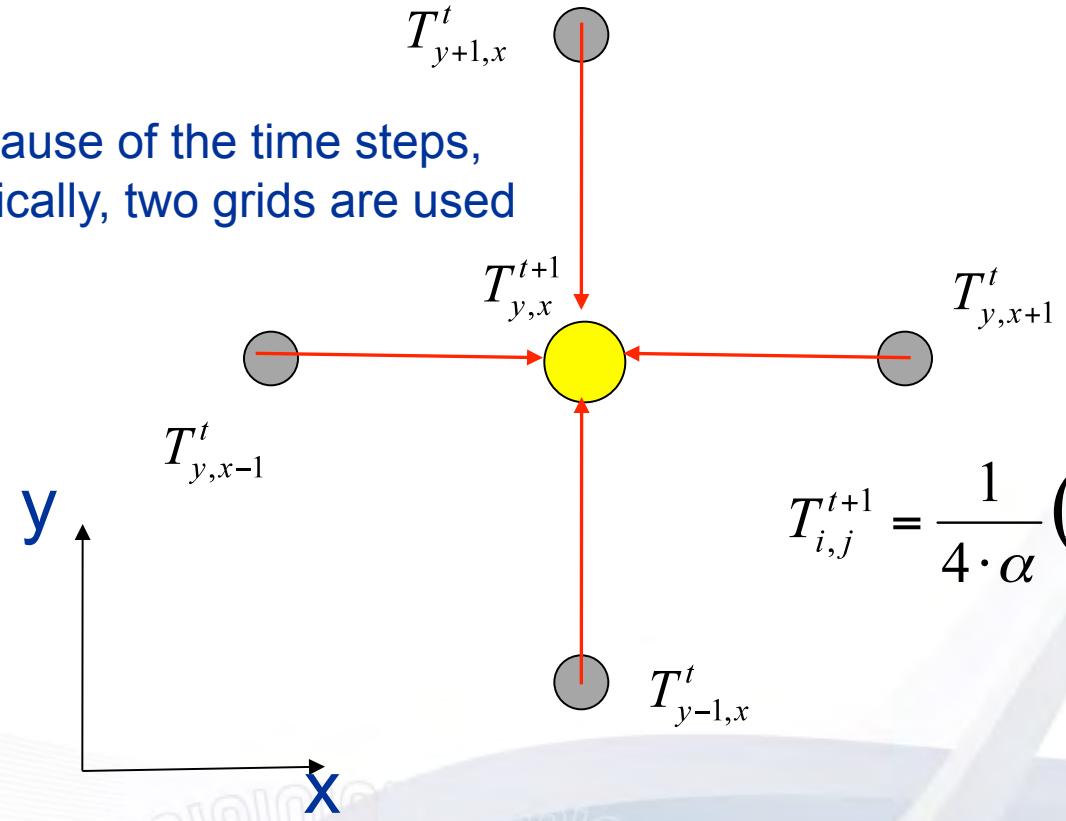
- var c = Clock.make();
  - Allocate a clock, register current activity with it. Phase 0 of c starts.
- async(…) clocked (c1,c2,…) S
- ateach(…) clocked (c1,c2,…) S
- foreach(…) clocked (c1,c2,…) S
- Create async activities registered on clocks c1, c2, …
- c.resume();
  - Nonblocking operation that signals completion of work by current activity for this phase of clock c
- next;
  - Barrier — suspend until all clocks that the current activity is registered with can advance. c.resume() is first performed for each such clock, if needed.
- next can be viewed like a "finish" of all computations under way in the current phase of the clock

Fundamental X10 Property

- Programs written using async, finish, at, atomic, clock *cannot* deadlock
- Intuition: cannot be a cycle in waits-for graph

2D Heat Conduction Problem

- Based on the 2D Partial Differential Equation (1), 2D Heat Conduction problem is similar to a 4-point stencil operation, as seen in (2):

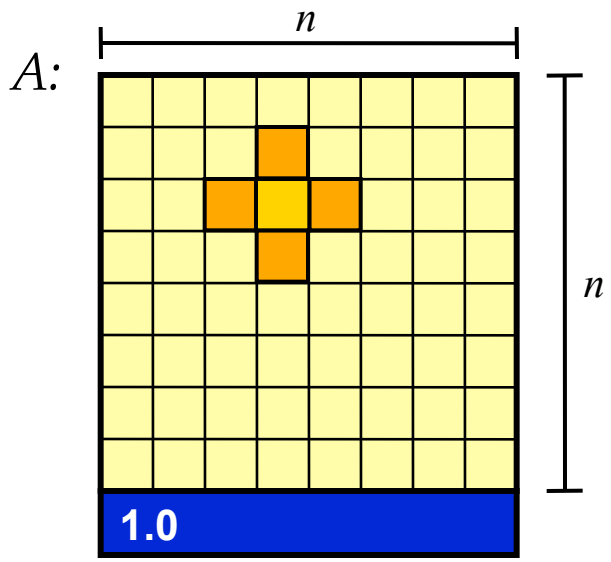


Because of the time steps,
Typically, two grids are used

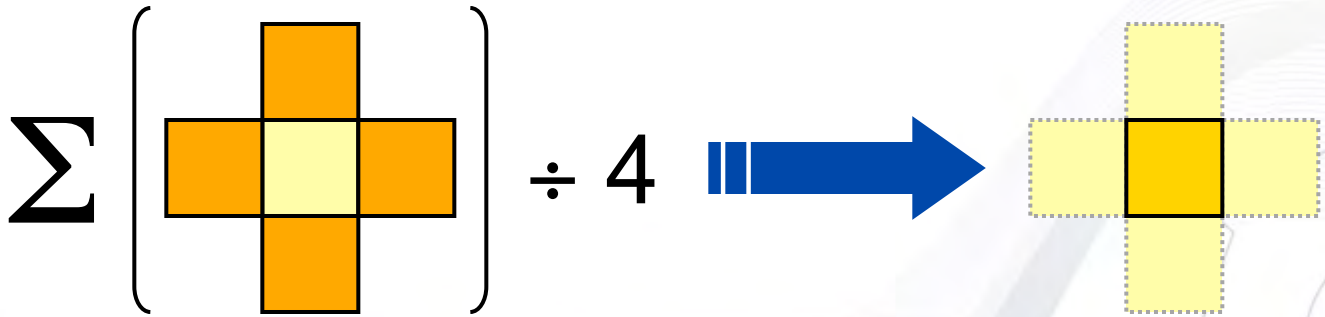
$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

$$T^{t+1}_{i,j} = \frac{1}{4 \cdot \alpha}\left(T^t_{i-1,j} + T^t_{i+1,j} + T^t_{i,j-1} + T^t_{i,j+1}\right) \quad (2)$$

Heat Transfer in Pictures



repeat until max change < ε



Heat transfer in X10

- X10 permits smooth variation between multiple concurrency styles
  - "High-level" ZPL-style (operations on global arrays)
    - Chapel "global view" style
    - Expressible, but relies on "compiler magic" for performance
  - OpenMP style
    - Chunking within a single place
  - MPI-style
    - SPMD computation with explicit all-to-all reduction
    - Uses clocks
  - "OpenMP within MPI" style
    - For hierarchical parallelism
    - Fairly easy to derive from ZPL-style program.

Heat Transfer in X10 – ZPL style

```
class Stencil2D {
  static type Real=Double;
  const n = 6, epsilon = 1.0e-5;

  const BigD = Dist.makeBlock([0..n+1, 0..n+1], 0),
        D = BigD | [1..n, 1..n],
        LastRow = [0..0, 1..n] as Region;
  const A = Array.make[Real](BigD, (p:Point)=>(LastRow.contains(p)?
1:0));
  const Temp = Array.make[Real](BigD);

  def run() {
    var delta:Real;
    do {
      finish ateach (p in D)
        Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;

      delta = (A(D)-Temp(D)).lift(Math.abs).reduce(Math.max, 0.0);
      A(D) = Temp(D);
    } while (delta > epsilon);
  }
}
```

Heat Transfer in X10 – ZPL style

- Cast in fork-join style rather than SPMD style
  - Compiler needs to transform into SPMD style
- Compiler needs to chunk iterations per place
  - Fine grained iteration has too much overhead
- Compiler needs to generate code for distributed array operations
  - Create temporary global arrays, hoist them out of loop, etc.
- Uses implicit syntax to access remote locations.

Simple to write — tough to implement efficiently

Heat Transfer in X10 – II

```
def run() {
  val D_Base = Dist.makeUnique(D.places());
  var delta:Real;
  do {
    finish ateach (z in D_Base)
      for (p in D | here)
        Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;

    delta =(A(D) - Temp(D)).lift(Math.abs).reduce(Math.max, 0.0);
    A(D) = Temp(D);
  } while (delta > epsilon);
}
```

- Flat parallelism: Assume one activity per place is desired.
- D.places() returns ValRail of places in D.
  - Dist.makeUnique(D.places()) returns a unique distribution (one point per place) over the given ValRail of places
- D | x returns sub-region of D at place x.

Explicit Loop Chunking

Heat Transfer in X10 – III

```
def run() {
  val D_Base = Dist.makeUnique(D.places());
  val blocks = DistUtil.block(D, P);
  var delta:Real;
  do {
    finish ateach (z in D_Base)
      foreach (q in 1..P)
        for (p in blocks(here,q))
          Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;

    delta =(A(D)-Temp(D)).lift(Math.abs).reduce(Math.max, 0.0);
    A(D) = Temp(D);
  } while (delta > epsilon);
}
```

- Hierarchical parallelism: P activities at place x.
  - Easy to change above code so P can vary with x.
- DistUtil.block(D,P)(x,q) is the region allocated to the q'th activity in place x. (Block-block division.)

Explicit Loop Chunking with Hierarchical Parallelism

Heat Transfer in X10 – IV

```
def run() {
  finish async {
    val c = clock.make();
    val D_Base = Dist.makeUnique(D.places());
    val diff = Array.make[Real](D_Base),
        scratch = Array.make[Real](D_Base);
    ateach (z in D_Base) clocked(c)
      do {
        diff(z) = 0.0;
        for (p in D | here) {
          Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;
          diff(z) = Math.max(diff(z), Math.abs(A(p) - Temp(p)));
        }
        next;
        A(D | here) = Temp(D | here);
        reduceMax(z, diff, scratch);
      } while (diff(z) > epsilon);
  }
}
```

One activity per place == MPI task

Akin to UPC barrier

- reduceMax() performs an all-to-all max reduction.

SPMD with all-to-all reduction == MPI style

Heat Transfer in X10 – V

```
def run() {
  finish async {
    val c = clock.make();
    val D_Base = Dist.makeUnique(D.places());
    val diff = Array.make[Real](D_Base),
        scratch = Array.make[Real](D_Base);
    ateach (z in D_Base) clocked(c)
      foreach (q in 1..P) clocked(c)
        var myDiff:Real = 0;
        do {
          if (q==1) { diff(z) = 0.0}; myDiff = 0;
          for (p in blocks(here,q)) {
            Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;
            myDiff = Math.max(myDiff, Math.abs(A(p) - Temp(p)));
          }
          atomic diff(z) = Math.max(myDiff, diff(z));
          next;
          A(blocks(here,q)) = Temp(blocks(here,q));
          if (q==1) reduceMax(z, diff, scratch);
          next;
          myDiff = diff(z);
          next;
        } while (myDiff > epsilon);
  }
}
```

"OpenMP within MPI style"

Heat Transfer in X10 – VI

- All previous versions permit fine-grained remote access
  - Used to access boundary elements
- Much more efficient to transfer boundary elements in bulk between clock phases.
- May be done by allocating extra "ghost" boundary at each place
  - API extension: Dist.makeBlock(D, P, f)
    - D: distribution, P: processor grid, f: region→region transformer
- reduceMax() phase overlapped with ghost distribution phase