COMP 322: Fundamentals of Parallel Programming

Lecture 37: Comparison of Parallel Programming Models

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https://wiki.rice.edu/confluence/display/PARPROG/COMP322

Worksheet #36: UPC data distributions

In the following example from slide 23, assume that each UPC array is distributed by default across threads with a cyclic distribution. In the space below, identify an iteration of the upc_forall construct for which all array accesses are local, and an iteration for which all array accesses are non-local (remote). Explain your answer in each case.

```
shared int a[100],b[100], c[100];
int i;
upc_forall (i=0; i<100; i++; (i*THREADS)/100)
   a[i] = b[i] * c[i];
```

Solution:

- Iteration 0 has affinity with thread 0, and accesses a[0], b[0], c[0], all of which are located locally at thread 0
- Iteration 1 has affinity with thread 0, and accesses a[1], b[1], c[1], all of which are located remotely at thread 1

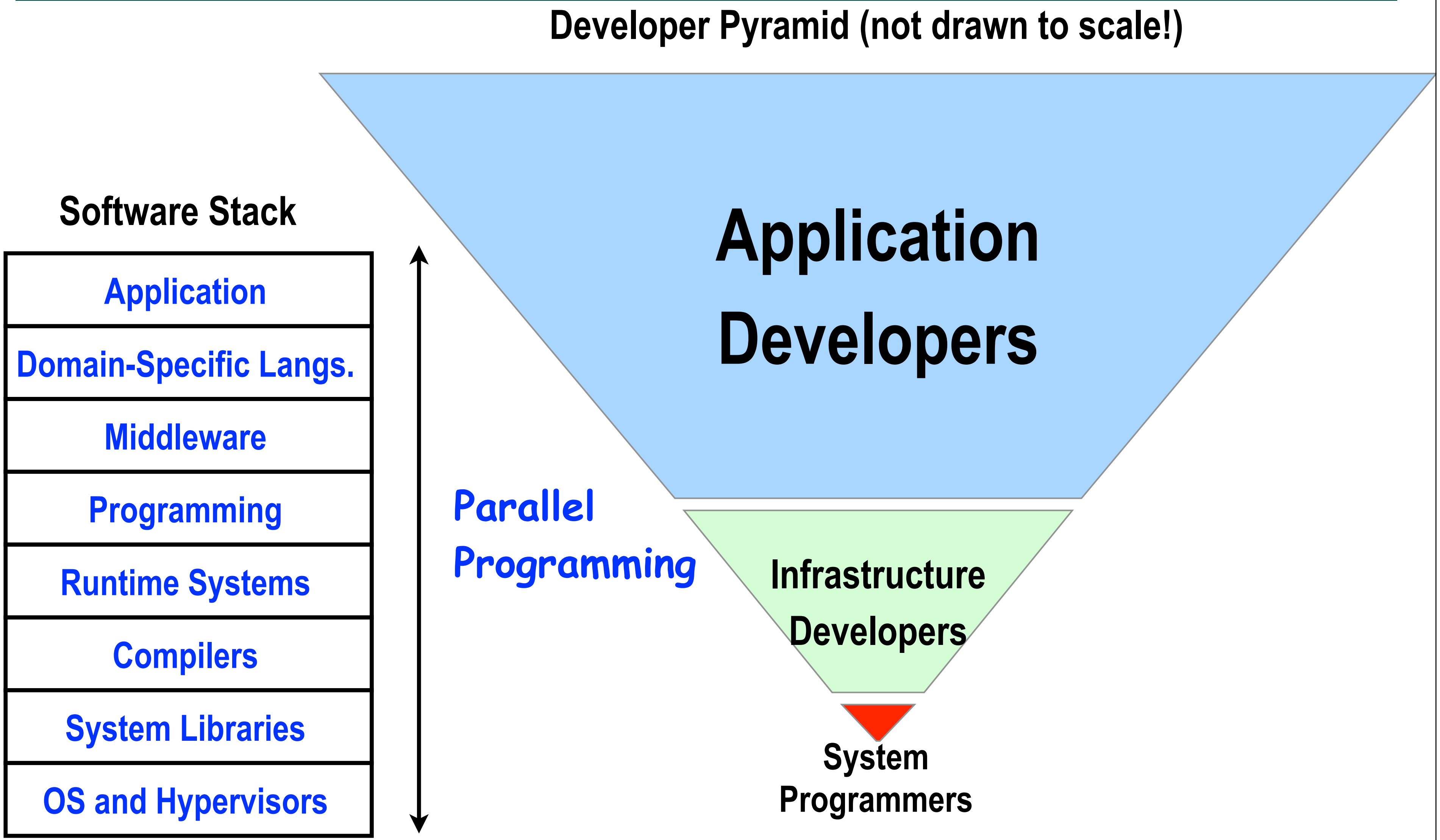
Announcements

- Graded midterm exams can be picked up from Sherry Nassar in Duncan Hall 3139
- Homework 6 is officially due on April 19th, but everyone can get an automatic penalty-free extension till April 26th
- Final exam will be given on April 19th to be taken in any two-hour duration returned to Sherry Nassar by April 26th (as was done with midterm exams)
  - Final exam will cover material from Lectures 19 - 37
- Next lecture (April 19th) is the last lecture!

Acknowledgments

- "Introduction to Parallel Computing" by Ananth Grama, Anshul Gupta, George Karypis, and Vipin Kumar. Addison Wesley, 2003, and accompanying slides
  - http://www-users.cs.umn.edu/~karypis/parbook/
- Slides from COMP 422 course at Rice University
  - http://www.clear.rice.edu/comp422/
- Bradford Nichols, Dick Buttlar, Jacqueline Proulx Farrell. "Pthreads Programming: A POSIX Standard for Better Multiprocessing." O'Reilly Media, 1996
- Slides from OpenMP tutorial given by Ruud van der Paas at HPCC 2007
  - http://www.tlc2.uh.edu/hpcc07/Schedule/OpenMP
- "Towards OpenMP 3.0", Larry Meadows, HPCC 2007 presentation
  - http://www.tlc2.uh.edu/hpcc07/Schedule/speakers/hpcc07_Larry.ppt
- Pthreads: A Brief Introduction, CSCI 8530 lecture, University of Nebraska Omaha
  - http://cs.unomaha.edu/~stanw/053/csci8530/pthreads.pdf
- "Principles of Parallel Programming", Calvin Lin & Lawrence Snyder
  - Includes resources available at http://www.pearsonhighered.com/educator/academic/product/0,3110,0321487907,00.html
- Tim Warburton, Rice University, "Introduction to GPGPU Programming"
  - 5-day course taught at Danish Technical University (DTU) in May 2011
- David B. Kirk and Wen-mei W. Hwu. Programming Massively Parallel Processors: A Hands-on Approach. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1st edition, 2010.

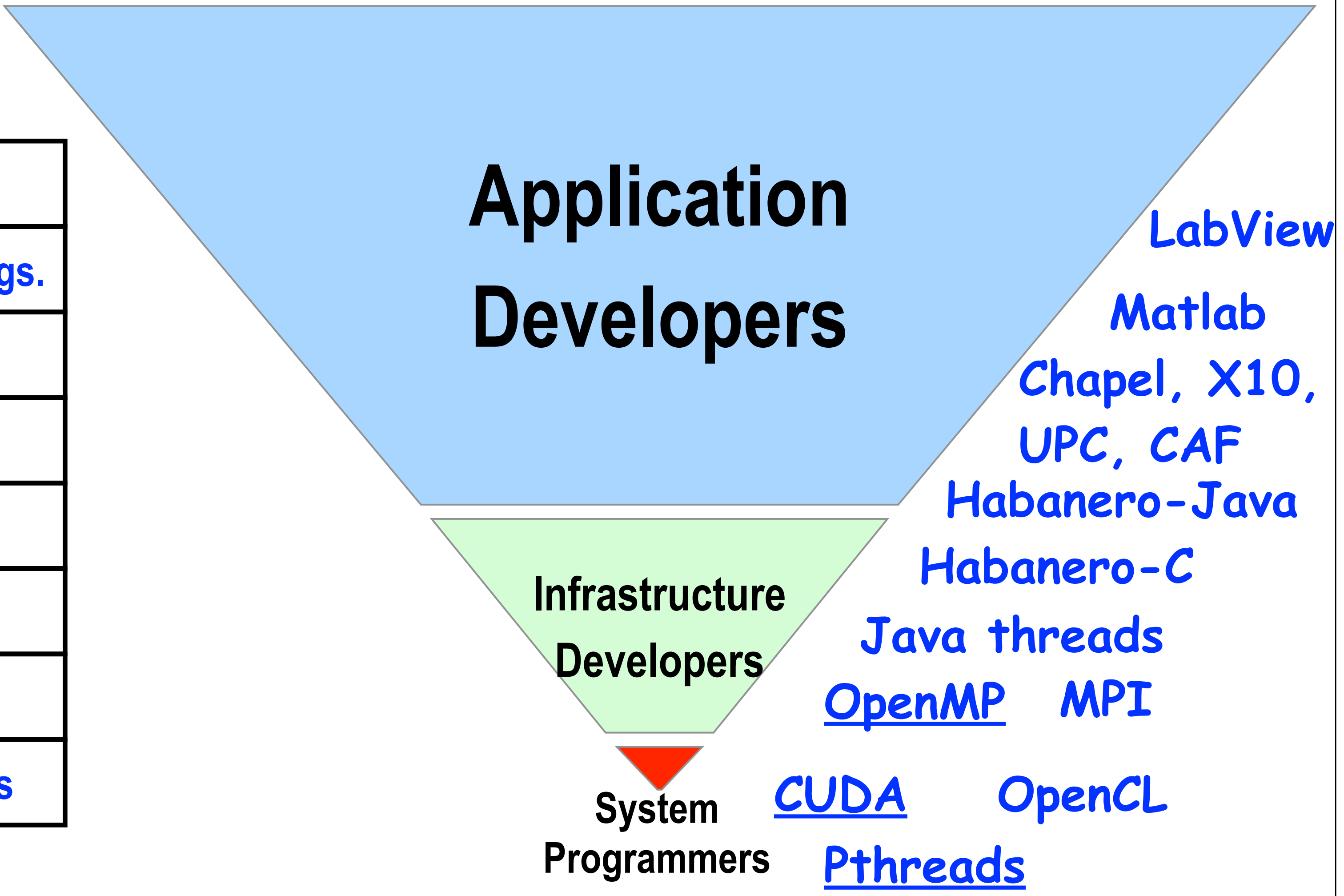
Parallel Programming is a Cross-Cutting Concern



Different Parallel Programming Models for different Levels of Developer Pyramid and Software Stack

Software Stack

Application
Domain-Specific Langs.
Middleware
Programming
Runtime Systems
Compilers
System Libraries
OS and Hypervisors



Outline

- <u>**Pthreads**</u>
- **OpenMP**
- **CUDA**

POSIX Thread API (Pthreads)

- **Standard user threads API supported by most vendors**
- **Library interface, intended for system programmers**
- **Concepts behind Pthreads interface are broadly applicable**
  - **—largely independent of the API**
  - **—useful for programming with other thread APIs as well**
    - **Windows threads**
    - **Solaris threads**
    - **Java threads**
    - **…**
- **Threads are peers, unlike Linux/Unix processes**
  - **—no parent/child relationship**

PThread Creation

Asynchronously invoke `thread_function` in a new thread (like an async)

```
#include <pthread.h>
int pthread_create(
   pthread_t *thread_handle,  /* returns handle here */
   const pthread_attr_t *attribute,
   void * (*thread_function)(void *),
   void *arg);  /* single argument; perhaps a structure */
```

`attribute` created by `pthread_attr_init`

contains details about

- whether scheduling policy is inherited or explicit
- scheduling policy, scheduling priority
- stack size, stack guard region size

Can use NULL for `pthread_attr_init` for default values

Pthread Termination

- A thread terminates by calling the function `pthread_exit()`. A single argument, a pointer to a void* object, is supplied as the argument to pthread_exit. This value is returned to any thread that has blocked while waiting for this thread to exit.

- Suspend parent thread until child thread terminates (like Thread.join() in Java)

```
#include <pthread.h>
int pthread_join (
  pthread_t thread,  /* thread id */
  void **ptr);  /* ptr to location for return code a terminating
                   thread passes to pthread_exit */
```

Example: Creation and Termination (main)

```
#include <pthread.h>
#include <stdlib.h>
#define NUM_THREADS 32
void *compute_pi (void *);
...
int main(...) {
    ...
    pthread_t p_threads[NUM_THREADS];
    pthread_attr_t attr;
    pthread_attr_init(&attr);
    for (i=0; i< NUM_THREADS; i++) {
      hits[i] = i;
      pthread_create(&p_threads[i], &attr, compute_pi,
          (void*) &hits[i]);
    }
    for (i=0; i< NUM_THREADS; i++) {
      pthread_join(p_threads[i], NULL);
      total_hits += hits[i];
    }
    ...
}
```

default attributes

thread function

thread argument

Example of Implementing a Reduction Using Mutex Locks

```
pthread_mutex_t cost_lock;
...
int main() {
   ...
   pthread_mutex_init(&cost_lock, NULL);
   ...
}
void *find_best(void *list_ptr) {
   ...
   pthread_mutex_lock(&cost_lock);   /* lock the mutex */
   if (my_cost < best_cost)
       best_cost = my_cost;
   pthread_mutex_unlock(&cost_lock); /* unlock the mutex */
}
```

use default (normal) lock type

critical section

Composite Synchronization Constructs

- **Pthreads provides only basic synchronization constructs**
- **Build higher-level constructs from basic ones e.g., *barriers***
  - —Pthreads extension includes barriers as synchronization objects (available in Single UNIX Specification)
    - – Enable by #define _XOPEN_SOURCE 600 at start of file
  - —Initialize a barrier for count threads
    - – `int pthread_barrier_init(pthread_barrier_t *barrier, const pthread_barrier attr_t *attr, int count);`
  - —Each thread waits on a barrier by calling
    - – `int pthread_barrier_wait(pthread_barrier_t *barrier);`
  - —Destroy a barrier
    - – `int pthread_barrier_destroy(pthread_barrier_t *barrier);`
- **NOTE: Java threads and HJ worker threads are also implemented as pthreads**

Summary of key features in Pthreads

Pthreads construct	Related HJ/Java constructs
pthread_create()	HJ's async; Java's "new Thread" and "Thread.start()"
pthread_join()	HJ's finish & future get(); Java's "Thread.join()"
pthread_mutex_lock()	HJ's begin-isolated, actors; Java's begin-synchronized, and lock() library calls
pthread_mutex_unlock()	HJ's end-isolated, actors; Java's end-synchronized, and unlock() library calls
pthread_cond_signal()	Deterministic use: HJ's phasers; Nondeterministic use: j.u.c.locks.condition
pthread_cond_wait()	Deterministic use: HJ's phasers; Nondeterministic use: j.u.c.locks.condition

Outline

- Pthreads
- <u>OpenMP</u>
- CUDA

What is OpenMP?

- Well-established standard for writing shared-memory parallel programs in C, C++ Fortran
- Programming model is expressed via
  - —Pragmas/directives (not language extensions)
  - —Runtime routines
  - —Environment variables

—Specification maintained by the OpenMP Architecture Review Board (http://www.openmp.org)
  - —Latest specification: Version 3.0 (May 2008)
  - —Previous specification: Version 2.5 (May 2005)

A first OpenMP example

For-loop with independent iterations

```
  for (i = 0; i < n; i++)
    c[i] = a[i] + b[i];
```

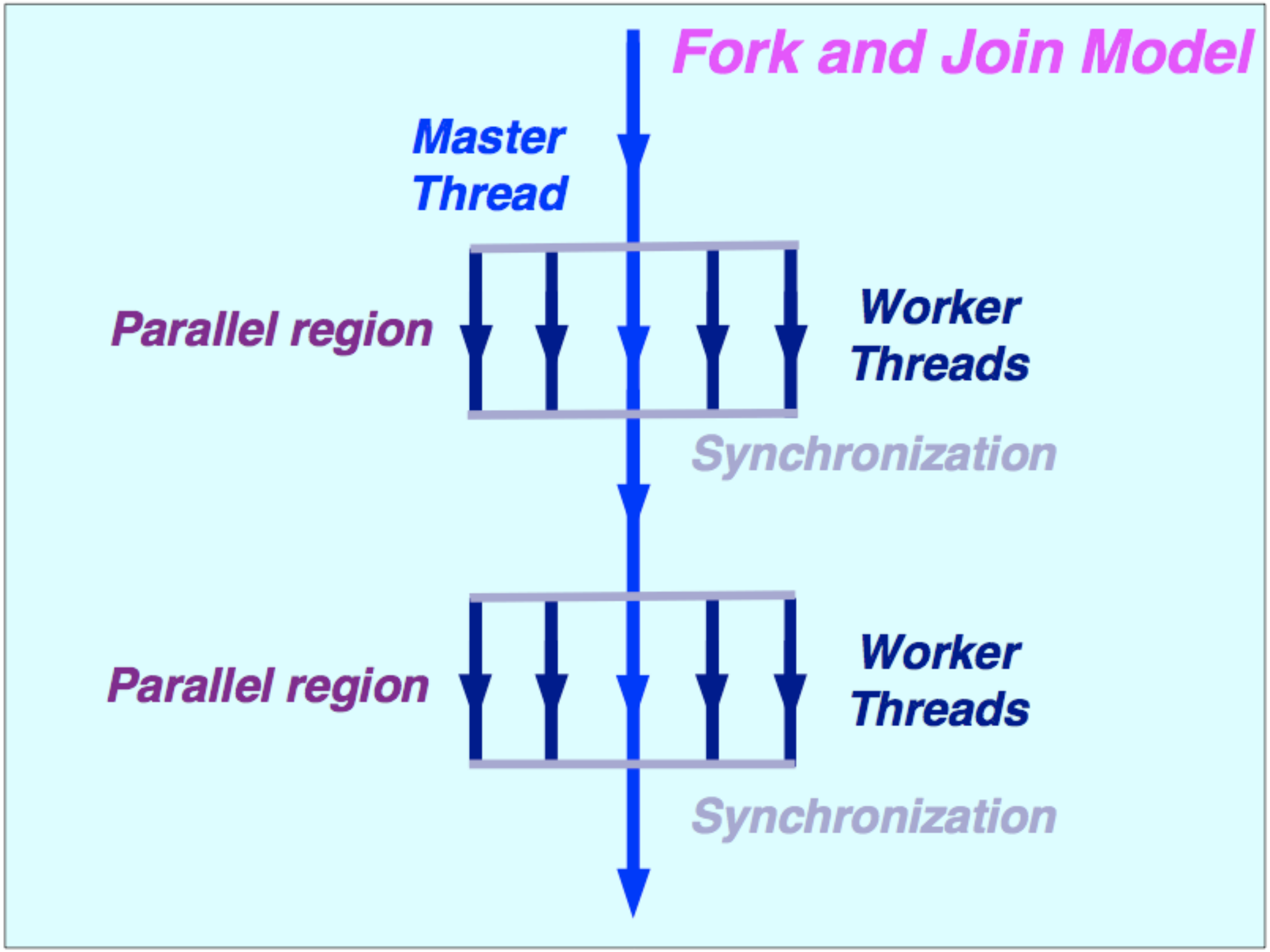
For-loop parallelized using an OpenMP pragma

```
#pragma omp parallel for  \
        shared(n, a, b, c)\
        private(i)
for (i = 0; i < n; i++)
    c[i] = a[i] + b[i];
```

```
% cc -xopenmp source.c
% setenv OMP_NUM_THREADS 4
% a.out
```

OpenMP parallel for loop is like a forall loop in HJ

The OpenMP Execution Model



Terminology

- ***OpenMP Team := Master + Workers***
- ***A Parallel Region is a block of code executed by all threads simultaneously***
  - *The master thread always has thread ID 0*
  - *Thread adjustment (if enabled) is only done before entering a parallel region*
  - *Parallel regions can be nested, but support for this is implementation dependent*
  - *An "if" clause can be used to guard the parallel region; in case the condition evaluates to "false", the code is executed serially*
- ***A work-sharing construct divides the execution of the enclosed code region among the members of the team; in other words: they split the work***

Parallel Region

```
#pragma omp parallel [clause[[,] clause] ...]
{
    "this is executed in parallel"

} (implied barrier)
```

A parallel region is a block of code executed by multiple threads simultaneously in SPMD mode, and supports the following clauses:

if	*(scalar expression)*	
private	*(list)*	
shared	*(list)*	
default	*(none|shared)*	*(C/C++)*
default	*(none|shared|private)*	*(Fortran)*
reduction	*(operator: list)*	
copyin	*(list)*	
firstprivate	*(list)*	
num_threads	*(scalar_int_expr)*	

Work-sharing constructs in a Parallel Region

```
#pragma omp for
{
    ....
}
```

```
#pragma omp sections
{
        ....
}
```

```
#pragma omp single
{
        ....
}
```

- The work is distributed over the threads
- Must be enclosed in a parallel region
- Must be encountered by all threads in the team, or none at all
- No implied barrier on entry; implied barrier on exit (unless nowait is specified)
- *A work-sharing construct does not launch any new threads*

```
#pragma omp parallel
#pragma omp for
 for (...)
```

```
#pragma omp parallel for
for (....)
```

Legality constraints for work-sharing constructs

- **Each worksharing region must be encountered by all threads in a team or by none at all.**
- **The sequence of worksharing regions and barrier regions encountered must be the same for every thread in a team.**

```
#pragma omp parallel
{
  do {
    // c1 and c2 may depend on the OpenMP thread-id
    boolean c1 = … ; boolean c2 = … ;
    . . .
    if (c2) {
      // Start of work-sharing region with no wait clause
      #pragma omp …
      . . . // Worksharing statement
    } // if (c2)
  } while (! c1);
}
```

==> No OpenMP implementation checks for conformance with this rule (unlike HJ's runtime check for phaser single statements)

Example of work-sharing "omp for" loop

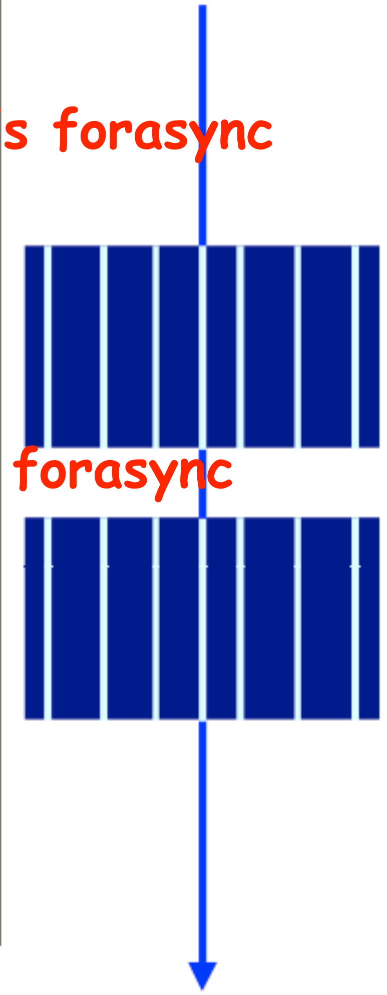
```
#pragma omp parallel default(none)\
        shared(n,a,b,c,d) private(i)
  {
    #pragma omp for nowait
     for (i=0; i<n-1; i++)
         b[i] = (a[i] + a[i+1])/2;
    #pragma omp for nowait
     for (i=0; i<n; i++)
         d[i] = 1.0/c[i];

  } /*-- End of parallel region --*/
```

(implied barrier)

Implicit finish

Like HJ's forasync

Like HJ's forasync



`task` Construct

```
#pragma omp task [clause[[,]clause] ...]
          structured-block
```

where *clause* can be one of:

```
if (expression)
untied
shared (list)
private (list)
firstprivate (list)
default( shared | none  )
```

Example – parallel pointer chasing using tasks

```
#pragma omp parallel
{
  #pragma omp single private(p)
   {
    p = listhead ;
    while (p) {
       #pragma omp task
              process (p);
        p= p->next ;
       }
     }
}
```

Spawn call to process(p)

Implicit finish at end of parallel region

Summary of key features in OpenMP

OpenMP construct	Related HJ/Java constructs
Parallel region #pragma omp parallel	HJ forall (forall iteration = OpenMP thread)
Work-sharing constructs: parallel loops, parallel sections	No direct analogy in HJ or Java
Barrier #pragma omp barrier	HJ forall-next on implicit phaser
Single #pragma omp single	HJ's forall-next-single on implicit phaser (but HJ does not support single + nowait)
Reduction clauses	HJ's finish accumulators (in forall)
Critical section #pragma omp critical	HJ's isolated statement
Task creation #pragma omp task	HJ's async statement
Task termination #pragma omp taskwait	HJ's finish statement

Outline

- Pthreads
- OpenMP
- <u>CUDA</u>

Flynn's Taxonomy for Parallel Computers

	Single Instruction	Multiple Instructions
Single Data	SISD	MISD
Multiple Data	SIMD	MIMD

Single Instruction, Single Data stream (SISD)

A sequential computer which exploits no parallelism in either the instruction or data streams. e.g., old single processor PC

Single Instruction, Multiple Data streams (SIMD)

A computer which exploits multiple data streams against a single instruction stream to perform operations which may be naturally parallelized. e.g. graphics processing unit

Multiple Instruction, Single Data stream (MISD)

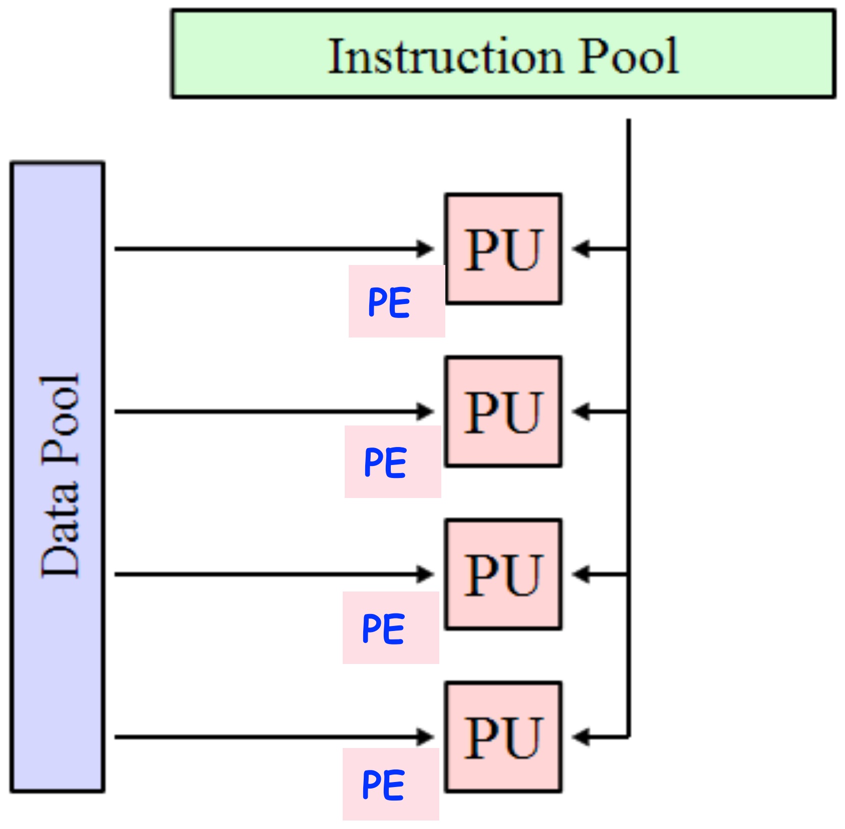
Multiple instructions operate on a single data stream. Uncommon architecture which is generally used for fault tolerance. Heterogeneous systems operate on the same data stream and must agree on the result. e.g. the Space Shuttle flight control computer.

Multiple Instruction, Multiple Data streams (MIMD)

Multiple autonomous processors simultaneously executing different instructions on different data. e.g. a PC cluster memory space.

SIMD pattern: Single Instruction Multiple Data

- **Definition: A single instruction stream is applied to multiple data elements.**
  - One program text
  - One instruction counter
  - Distinct data streams per Processing Element (PE)



Matrix Multiplication (with multiple sources of parallelism)

```
double[][] a, b, c;  // three 2D arrays : a,b,c
int n; // Assume that all arrays are of size n*n

forall(point[i,j] : [0:n-1,0:n-1] {

        c[i][j] = sum(a[i][0:n-1] * b[0:n-1][j]);

}
```

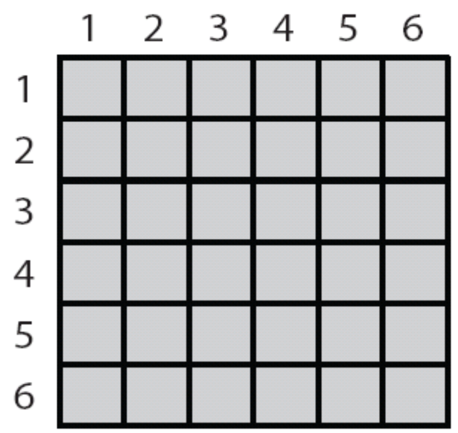
Loop parallelism

Dot product is expressed as SIMD parallelism

(This is pseudocode, not real HJ code)

Array slice notation

- **Designating different slices of an array.**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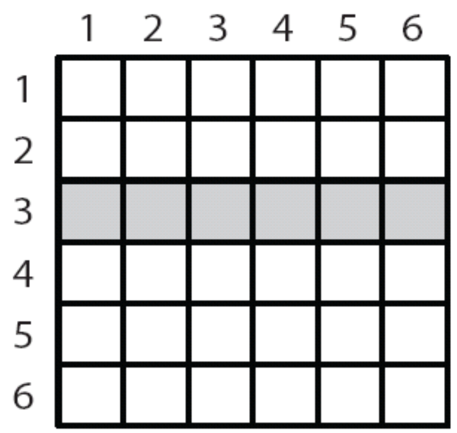
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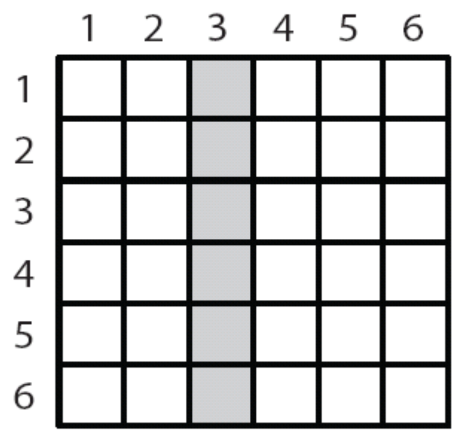
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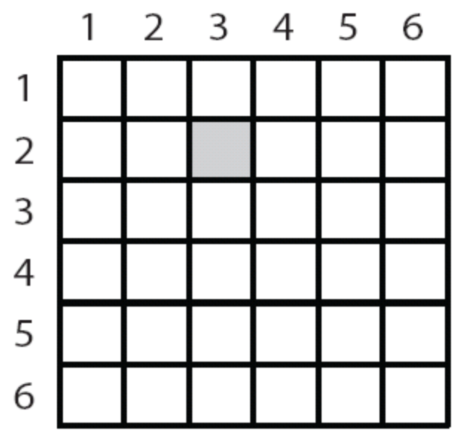
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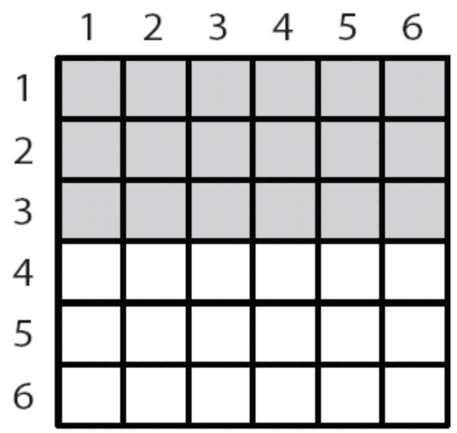
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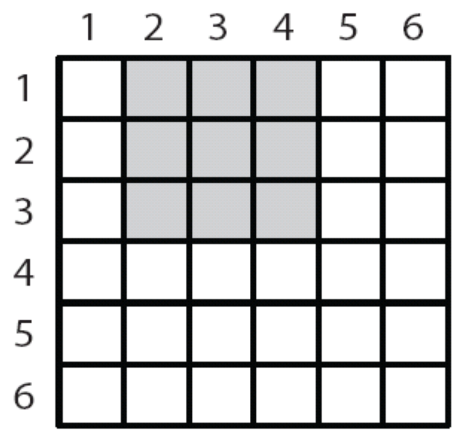
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SPMD Pattern

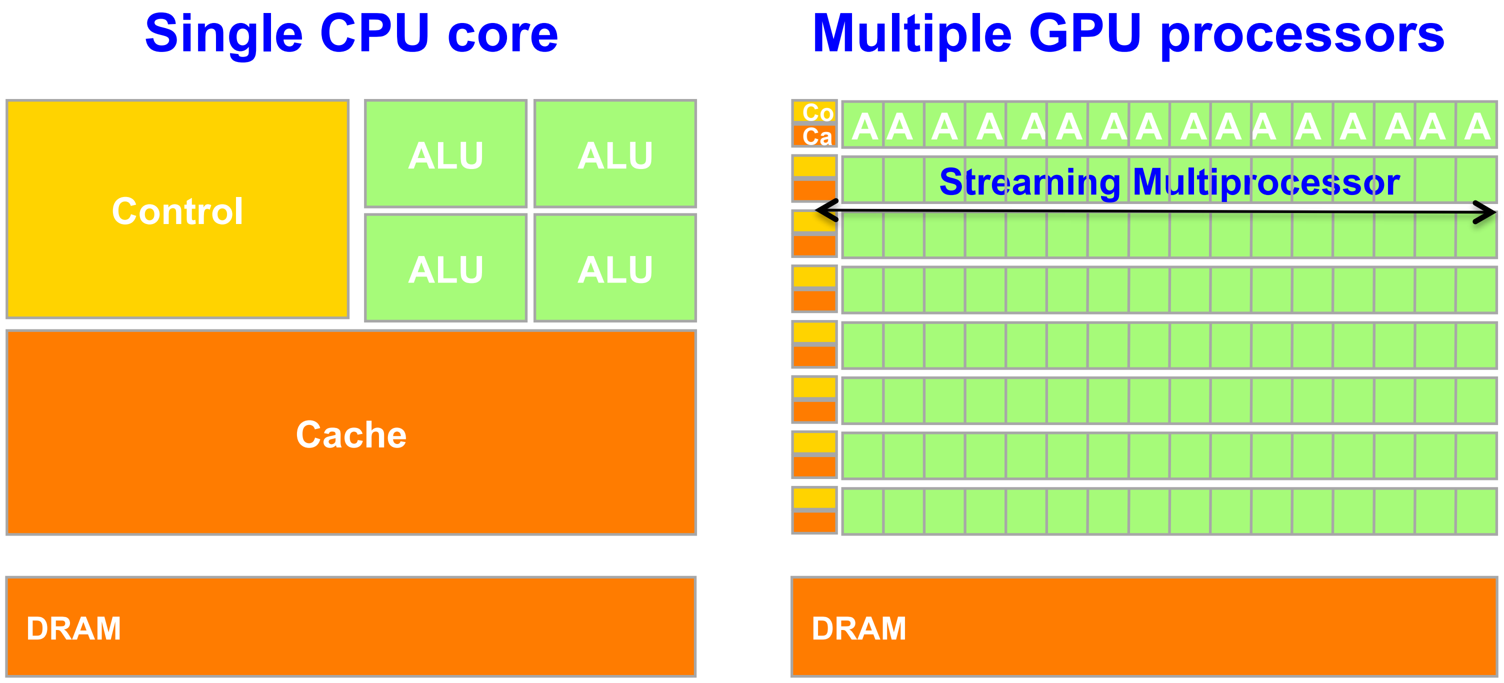
- SPMD: Single Program Multiple Data
- Run the same program on P processing elements (PEs)
- Use the "rank" … an ID ranging from 0 to (P-1) … to determine what computation is performed on what data by a given PE
- Different PEs can follow different paths through the same code (unlike the SIMD pattern)
- 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 --- what data and computation should be replicated or partitioned across PEs?

SPMD Example: Iterative Averaging

```
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
  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
```

CPUs and GPUs have fundamentally different design philosophies

GPU = Graphics Processing Unit



GPUs are provided to accelerate graphics, but they can also be used for non-graphics applications that exhibit large amounts of data parallelism and require large amounts of "streaming" throughput
⇒ SIMD parallelism within an SM, and SPMD parallelism across SMs

Process Flow of a CUDA Kernel Call (Compute Unified Device Architecture)

- Data parallel programming architecture from NVIDIA
  - Execute programmer-defined kernels on extremely parallel GPUs
  - CUDA program flow:
    1. Push data on device
    2. Launch kernel
    3. Execute kernel and memory accesses in parallel
    4. Pull data off device
- Device threads are launched in batches
  - Blocks of Threads, Grid of Blocks
- Explicit device memory management
  - cudaMalloc, cudaMemcpy, cudaFree, etc.
- NOTE: OpenCL is a newer standard for GPU programming that is more portable than CUDA

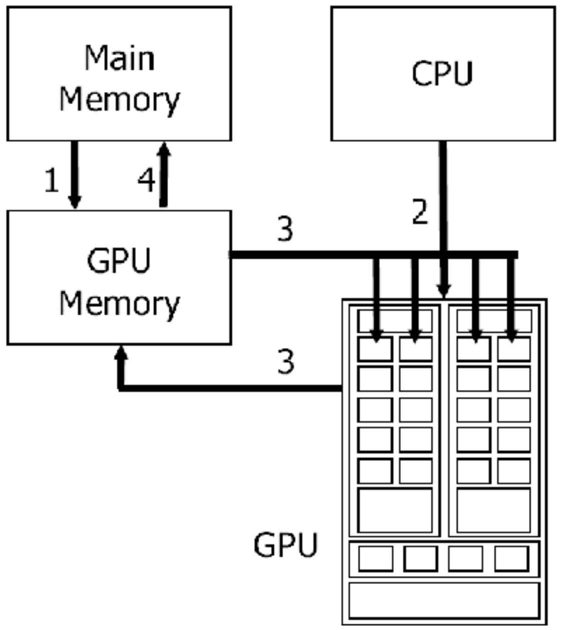


Figure source: Y. Yan et. al "JCUDA: a Programmer Friendly Interface for Accelerating Java Programs with CUDA." Euro-Par 2009.

Execution of a CUDA program

- **Integrated host+device application**
  - **Serial or modestly parallel parts on CPU host**
  - **Highly parallel kernels on GPU device**

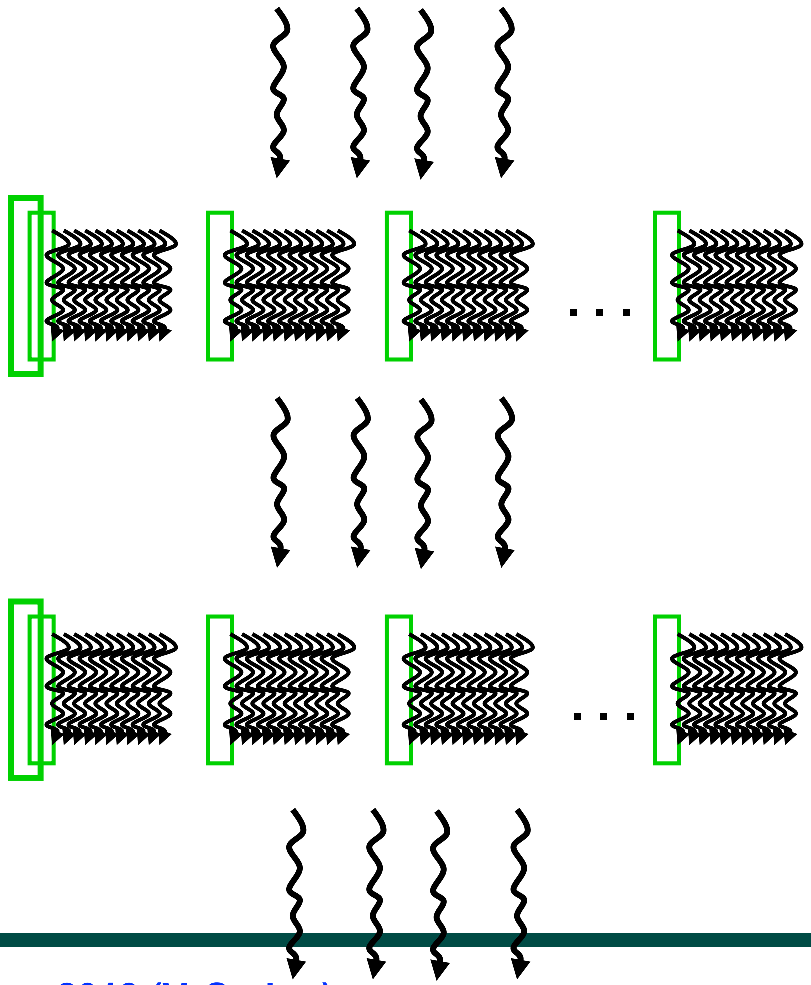
Host Code
(small number of threads)

Device Kernel
(large number of threads)

Host Code
(small number of threads)

Device Kernel
(large number of threads)

Host Code
(small number of threads)



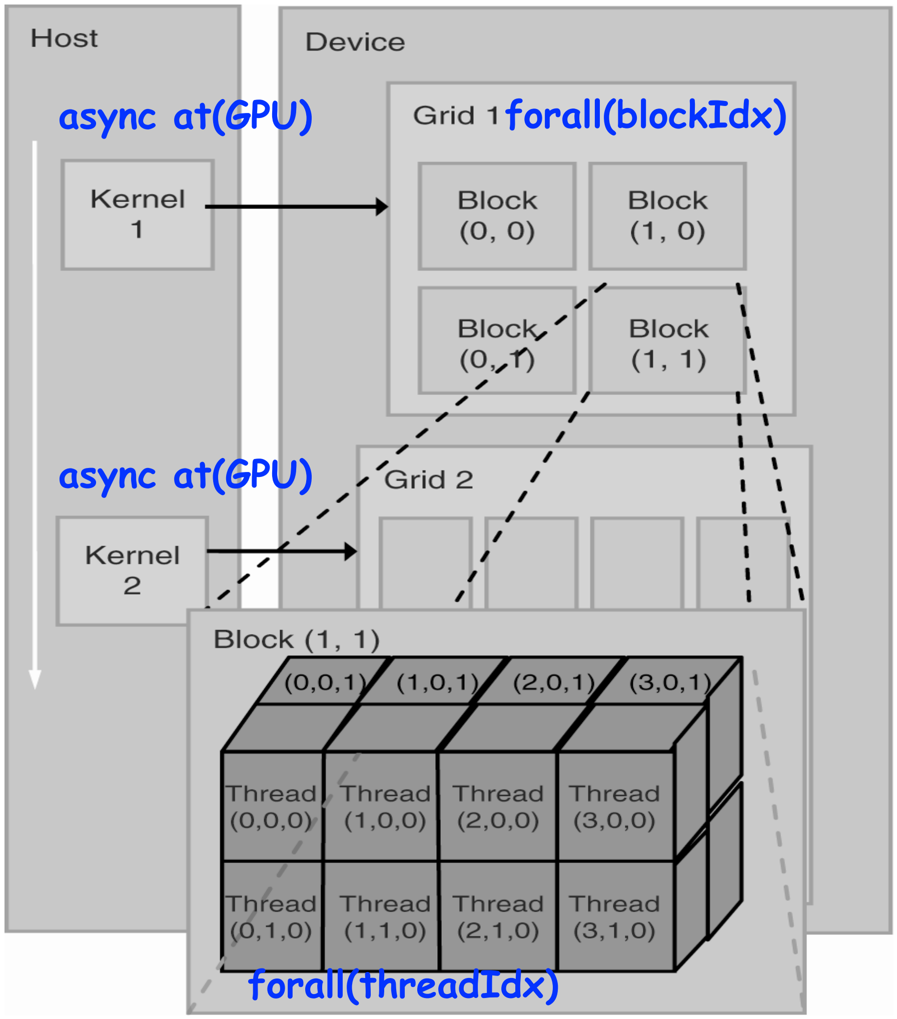
Matrix multiplication kernel code in CUDA (SPMD model with index = threadIdx)

```
// Matrix multiplication kernel - thread specification
__global__ void MatrixMulKernel(float* Md, float* Nd, float* Pd, int Width)
{
  // 2D Thread ID
  int tx = threadIdx.x;
  int ty = threadIdx.y;

  // Pvalue stores the Pd element that is computed by the thread
  float Pvalue = 0;

  for (int k = 0; k < Width; ++k)
  {
     float Mdelement = Md[ty * Width + k];
     float Ndelement = Nd[k * Width + tx];
     Pvalue += Mdelement * Ndelement;
  }

  // Write the matrix to device memory each thread writes one element
  Pd[ty * Width + tx] = Pvalue;
}
```

Host Code in C for Matrix Multiplication

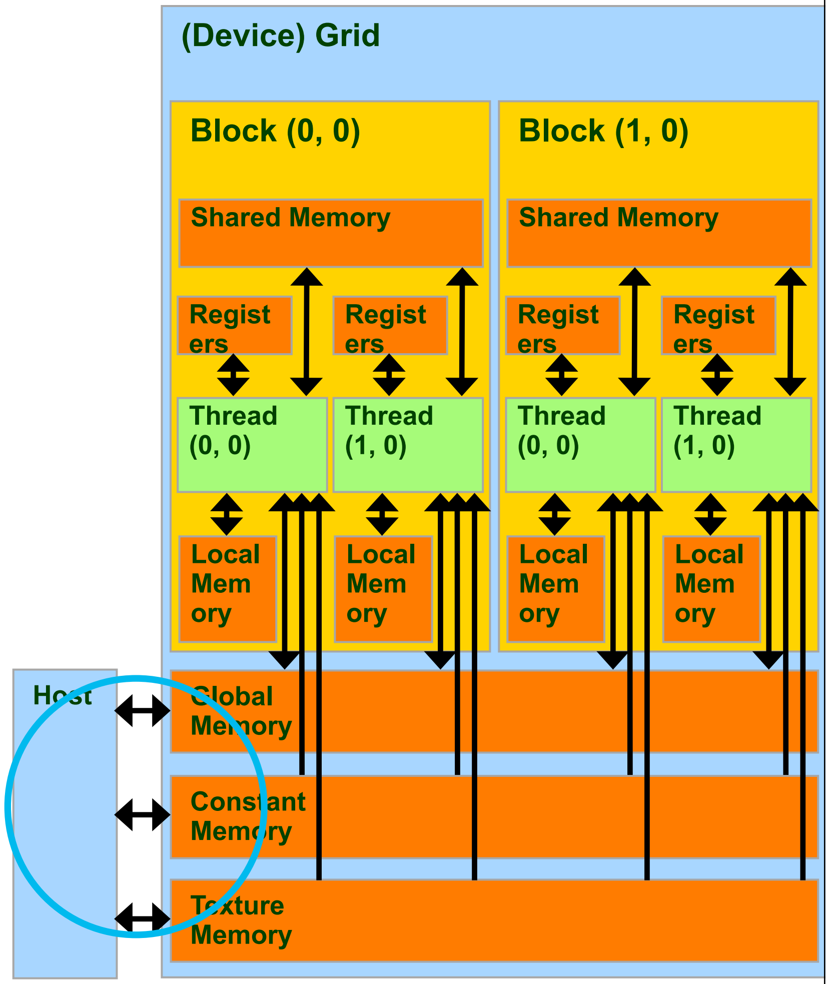
```
void MatrixMultiplication(float* M, float* N, float* P, int Width)
{
  int size = Width*Width*sizeof(float); // matrix size
  float* Md, Nd, Pd; // pointers to device arrays
  cudaMalloc((void**)&Md, size); // allocate Md on device
  cudaMemcpy(Md, M, size, cudaMemcpyHostToDevice); // copy M to Md
  cudaMalloc((void**)&Nd, size); // allocate Nd on device
  cudaMemcpy(Nd, M, size, cudaMemcpyHostToDevice); // copy N to Nd
  cudaMalloc((void**)&Pd, size); // allocate Pd on device
  dim3 dimBlock(Width,Width); dim3 dimGrid(1,1);
  // launch kernel (equivalent to "async at(GPU), forall, forall"
  MatrixMulKernel<<<dimGrid,dimBlock>>>(Md, Nd, Pd, Width);
  cudaMemcpy(P, Pd, size, cudaMemcpyDeviceToHost); // copy Pd to P
  // Free device matrices
  cudaFree(Md); cudaFree(Nd); cudaFree(Pd);
}
```

HJ abstraction of a CUDA kernel invocation: async at + forall + forall



CUDA Host-Device Data Transfer

- cudaError_t cudaMemcpy(void* dst, const void* src, size_t count, enum cudaMemcpyKind kind)
- copies count bytes from the memory area pointed to by src to the memory area pointed to by dst, where kind is one of
  - —cudaMemcpyHostToHost
  - —cudaMemcpyHostToDevice
  - —cudaMemcpyDeviceToHost
  - —cudaMemcpyDeviceToDevice
- The memory areas may not overlap
- Calling cudaMemcpy() with dst and src pointers that do not match the direction of the copy results in an undefined behavior.



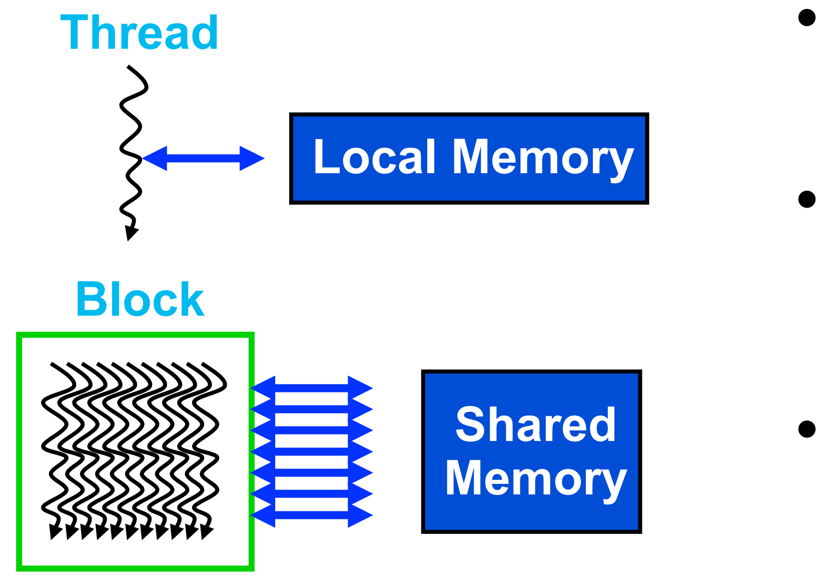
CUDA Variable Type Qualifiers

Variable declaration	Memory	Scope	Lifetime
`__device__ __local__ int LocalVar;`	local	thread	thread
`__device__ __shared__ int SharedVar;`	shared	block	block
`__device__ int GlobalVar;`	global	grid	application
`__device__ __constant__ int ConstantVar;`	constant	grid	application

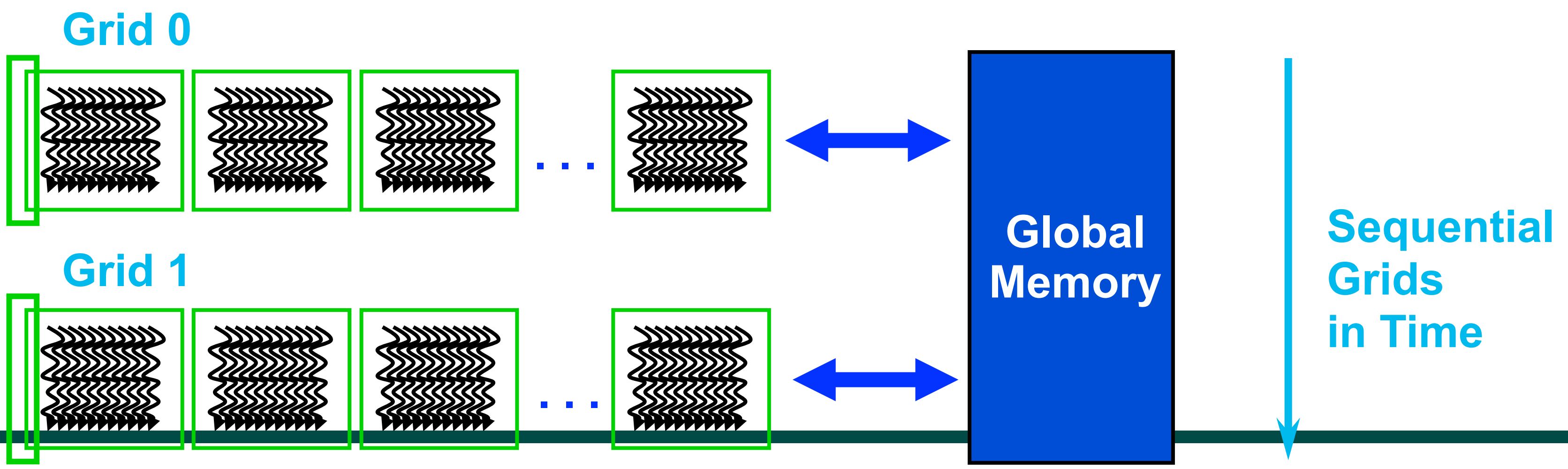
- `__device__` is optional when used with `__local__`, `__shared__`, or `__constant__`
- Automatic variables without any qualifier reside in a register
  - — Except arrays that reside in local memory
- Pointers can only point to memory allocated or declared in global memory:
  - —Allocated in the host and passed to the kernel:

    `__global__ void KernelFunc(float* ptr)`
  - —Obtained as the address of a global variable: `float* ptr = &GlobalVar;`

CUDA Storage Classes



- Local Memory: per-thread
  - Private per thread
  - Auto variables, register spill
- Shared Memory: per-Block
  - Shared by threads of the same block
  - Inter-thread communication
- Global Memory: per-application
  - Shared by all threads
  - Inter-Grid communication



Summary of key features in CUDA

CUDA construct	Related HJ/Java constructs
Kernel invocation, <<<. . .>>>	async at(gpu-place)
1D/2D grid with 1D/2D/3D blocks of threads	Outer 1D/2D forall with inner 1D/2D/3D forall
Intra-block barrier, __syncthreads()	HJ forall-next on implicit phaser for inner forall
cudaMemcpy()	No direct equivalent in HJ/Java (can use System.arraycopy() if needed)
Storage classes: local, shared, global	No direct equivalent in HJ/Java (method-local variables are scalars)

Comparison of Multicore Programming Models along Selected Dimensions

	Dynamic Parallelism	Locality Control	Mutual Exclusion	Collective & Point-to-point Synchronization	Data Parallelism
Cilk	Spawn, sync	None	Locks	None	None
Java Concurrency	Executors, Task Queues	None	Locks, monitors, atomic classes	Synchronizers	Concurrent collections
Intel C++ Threading Building Blocks	Generic algorithms, tasks	None	Locks, atomic classes	None	Concurrent containers
.Net Parallel Extensions	Generic algorithms, tasks	None	Locks, monitors	Futures	PLINQ
OpenMP	SPMD (v2.5), Tasks (v3.0)	None	Locks, critical, atomic	Barriers	None
CUDA	None until recently (v5)	Device, grid, block, threads	None	Barriers	SPMD
Habanero-Java (builds on Java Concurrency)	Async, finish	Places	Isolated blocks, Java atomic classes	Phasers, futures, data-driven tasks	Parallel array operations, Java concurrent collections