Parallel Programming Paradigms

A Long History

- IVTRAN (Parallel Fortran) language for the ILLIAC IV (1966-1970)
- Several other Fortran language based programming languages followed (Fortran D, KAP, Vienna Fortran, Paraphrase, Polaris etc. etc.)
- Experimental new approaches: Linda, Irvine Dataflow (Id), Decoupled Access Execute
- Vector Languages: Cray Fortran, FX/Fortran

Most Commonly Used

- MPI: Message Passing Interface
  - ARPA, NSF, Esprit
- Pthreads: POSIX Threads Linux Standard
  - **P**ortable **O**perating-**S**ystem **I**nterface (IEEE, the Open Group)
- OpenMP: Open Multi-Processing
  - AMD, IBM, Intel, Cray, HP, Fujitsu, Nvidia, NEC, Red Hat, Texas Instruments, Oracle Corporation, and more.
- CUDA: Compute Unified Device Architecture
  - Nvidia

MPI

- Communication between processes in a distributed program is typically implemented using MPI: Message Passing Interface.
- MPI is a generic API that can be implemented in different ways:
  - Using specific interconnect hardware, such as InfiniBand.
  - Using TCP/IP over plain Ethernet.
  - Or even used (emulated) on Shared Memory for inter process communication on the same node.

Some MPI basic functions

- `#include <mpi.h>`
- Initialize library:
```
MPI_Init(&argc, &argv);
```
- Determine number of processes that take part:
```
int n_procs;
MPI_Comm_size(MPI_COMM_WORLD,
  &n_procs);
```
(MPI_COMM_WORLD is the initially defined universe intracommunicator for all processes)
- Determine ID of this process:
```
int id;
MPI_Comm_rank(MPI_COMM_WORLD, &id);
```

Sending Messages

```
MPI_Send(buffer,count,datatype,dest,tag,comm);
```

- buffer: pointer to data buffer.
- count: number of items to send.
- datatype: data type of the items (see next slide).
    - All items must be of the same type.
- dest: rank number of destination.
- tag: message tag (integer), may be 0.
    - You can use this to distinguish between different messages.
- comm: communicator, for instance MPI_COMM_WORLD.

- Note: this is a blocking send!

MPI data types

- You must specify a data type when performing MPI transmissions.
- For instance for built-in C types:
  - "int" translates to MPI_INT
  - "unsigned int" to MPI_UNSIGNED
  - "double" to MPI_DOUBLE, and so on.
- You can define your own MPI data types, for example if you want to send/receive custom structures.

Other calls

- `MPI_Recv()`
- `MPI_Isend()`, `MPI_Irecv()`
  - Non-blocking send/receive
- `MPI_Scatter()`, `MPI_Gather()`
- `MPI_Bcast()`
- `MPI_Reduce()`

Shutting down

- `MPI_Finalize()`

Pthreads

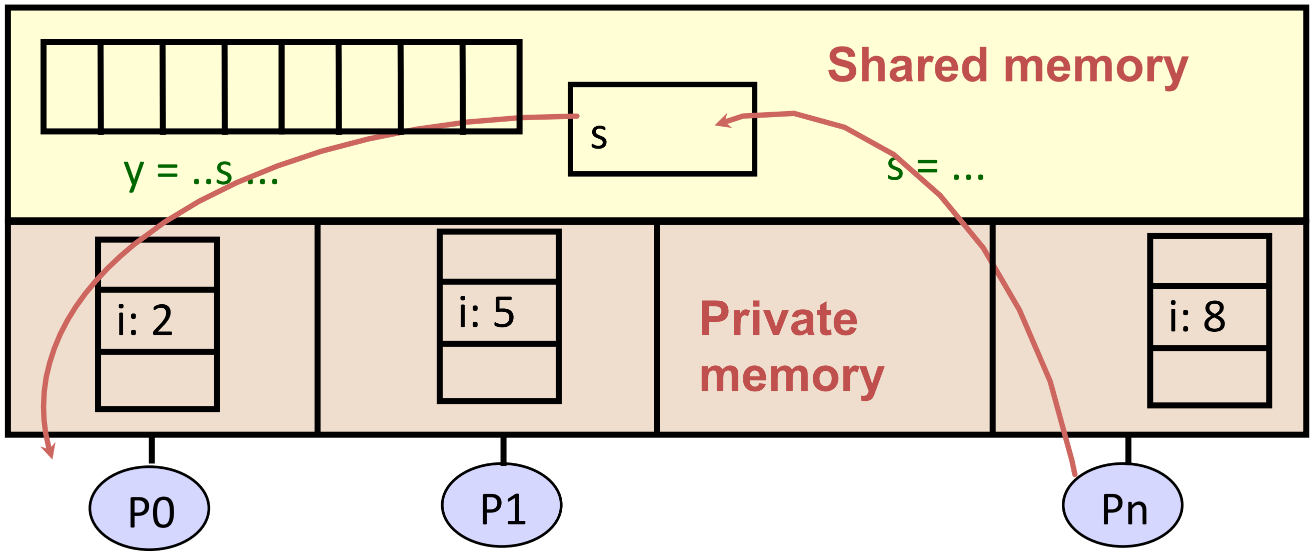
Pthreads defines a set of C programming language types, functions and constants. It is implemented with a pthread.h header and a thread library.

There are around 100 Pthreads procedures, all prefixed "pthread_" and they can be categorized into four groups:

- Thread management - creating, joining threads etc.
- Mutexes
- Condition variables
- Synchronization between threads using read/write locks and barriers

The POSIX semaphore API works with POSIX threads but is not part of threads standard, having been defined in the *POSIX.1b, Real-time extensions (IEEE Std 1003.1b-1993)* standard. Consequently the semaphore procedures are prefixed by "sem_" instead of "pthread_".

- Program is a collection of threads of control.
  - Can be created dynamically, mid-execution, in some languages
- Each thread has a set of private variables, e.g., local stack variables
- Also a set of shared variables, e.g., static variables, shared common blocks, or global heap.
  - Threads communicate implicitly by writing and reading shared variables.
  - Threads coordinate by synchronizing on shared variables



Pthreads Supports

- Creating parallelism
- Synchronizing

No explicit support for communication, because shared memory is implicit; a pointer to shared data is passed to a thread

“Forking” Threads

Signature:

```
int pthread_create(pthread_t *thread_id,
                   const pthread_attr_t *thread_attribute,
                   void * (*thread_fun)(void *),
                   void *funarg);
```

Example call:

```
errcode = pthread_create(&thread_id, &thread_attribute,
                         thread_fun, &fun_arg);
```

thread_id is the thread id or handle (used to halt, etc.)

thread_attribute various attributes

- Standard default values obtained by passing a NULL pointer
- Sample attribute: minimum stack size

thread_fun the function to be run (takes and returns void*)

fun_arg an argument can be passed to thread_fun when it starts

errorcode will be set nonzero if the create operation fails

Example

```
void* SayHello(void *foo) {
  printf( "Hello, world!\n" );
  return NULL;
}

int main() {
  pthread_t threads[16];
  int tn;
  for(tn=0; tn<16; tn++) {
    pthread_create(&threads[tn], NULL, SayHello,
  NULL);
  }
  for(tn=0; tn<16 ; tn++) {
    pthread_join(&threads[tn], NULL);
  }
  return 0;
}
```

Some More Functions

- **`pthread_yield();`**
  - Informs the scheduler that the thread is willing to yield its quantum, requires no arguments.
- **`pthread_exit(void *value);`**
  - Exit thread and pass value to joining thread (if exists)
- **`pthread_join(pthread_t *thread, void **result);`**
  - Wait for specified thread to finish. Place exit value into *result.

Others:

- **`pthread_t me; me = pthread_self();`**
  - Allows a pthread to obtain its own identifier pthread_t thread;
- **`pthread_detach(thread);`**
  - Informs the library that the threads exit status will not be needed by subsequent pthread_join calls resulting in better threads performance. For more information consult the library or the man pages, e.g., man -k pthread..

Shared Data and Threads

- Variables declared outside of main are shared
- Object allocated on the heap may be shared (if pointer is passed)
- Variables on the stack are private: passing pointer to these around to other threads can cause problems

- Often done by creating a large “thread data” struct
  - Passed into all threads as argument
  - Simple example:

```
char *message = "Hello World!\n";

pthread_create(&thread1,
               NULL,
               print_fun,
               (void*) message);
```

Basic Types of Synchronization: Barrier

- Especially common when running multiple copies of the same function in parallel
  - SPMD "Single Program Multiple Data"
- simple use of barriers -- all threads hit the same one

```
work_on_my_subgrid();
barrier;
read_neighboring_values();
barrier;
```

- more complicated -- barriers on branches (or loops)

```
if (tid % 2 == 0) {
  work1();
  barrier
} else { barrier }
```

- barriers are not provided in all thread libraries

Creating and Initializing a Barrier

- To (dynamically) initialize a barrier, use code similar to this (which sets the number of threads to 3):

```
pthread_barrier_t b;
pthread_barrier_init(&b,NULL,3);
```

- The second argument specifies an attribute object for finer control; using NULL yields the default attributes.

- To wait at a barrier, a process executes:

```
pthread_barrier_wait(&b);
```

Basic Types of Synchronization: Mutexes

– Threads are working mostly independently
– There is a need to access common data structure

```
lock *l = alloc_and_init();    /* shared */
acquire(l);
 access data
release(l);
```

– Locks only affect processors using them:
  - If a thread accesses the data without doing the acquire/ release, locks by others will not help
– Semaphores generalize locks to allow k threads simultaneous access; good for limited resources

Mutexes in POSIX Threads

- To create a mutex:

```
#include <pthread.h>
pthread_mutex_t amutex = PTHREAD_MUTEX_INITIALIZER;
   // or pthread_mutex_init(&amutex, NULL);
```

- To use it:

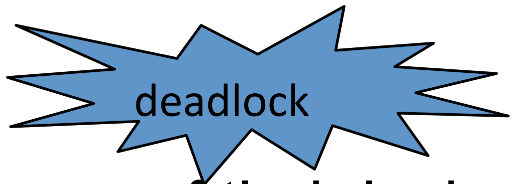
```
int pthread_mutex_lock(amutex);
int pthread_mutex_unlock(amutex);
```

- To deallocate a mutex

```
int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

- Multiple mutexes may be held, but can lead to problems:

```
thread1        thread2
lock(a)        lock(b)
lock(b)        lock(a)
```



- Deadlock results if both threads acquire one of their locks, so that neither can acquire the second

Summary of Programming with Threads

- POSIX Threads are based on OS features
  - Can be used from multiple languages (need appropriate header)
  - Familiar language for most of program
  - Ability to shared data is convenient

- OpenMP is commonly used today as an alternative

Introduction to OpenMP

- What is OpenMP?
  - Open specification for Multi-Processing
  - “Standard” API for defining multi-threaded shared-memory programs
  - openmp.org – Talks, examples, forums, etc.

- High-level API
  - Preprocessor (compiler) directives (~ 80%)
  - Library Calls (~ 19%)
  - Environment Variables (~ 1%)

A Programmer's View of OpenMP

- OpenMP is a portable, threaded, shared-memory programming *specification* with "light" syntax
  - Exact behavior depends on OpenMP *implementation*!
  - Requires compiler support (C or Fortran)
- OpenMP will:
  - Allow a programmer to separate a program into *serial regions* and *parallel regions*, rather than T concurrently-executing threads.
  - Hide stack management
  - Provide synchronization constructs
- OpenMP will not:
  - Parallelize automatically
  - Guarantee speedup
  - Provide freedom from data races

Programming Model – Concurrent Loops

- OpenMP easily parallelizes loops
  - Requires: No data dependencies (reads/write or write/write pairs) between iterations!

- Preprocessor calculates loop bounds for each thread directly from *serial* source

```
#pragma omp parallel for

for( i=0; i < 25; i++ )
{
  printf("Foo");
}
```

Programming Model – Loop Scheduling

- `Schedule` Clause determines how loop iterations are divided among the thread team
  - **`static([chunk])`** divides iterations statically between threads
    - Each thread receives `[chunk]` iterations, rounding as necessary to account for all iterations
    - Default **`[chunk]`** is **`ceil( # iterations / # threads )`**
  - **`dynamic([chunk])`** allocates **`[chunk]`** iterations per thread, allocating an additional **`[chunk]`** iterations when a thread finishes
    - Forms a logical work queue, consisting of all loop iterations
    - Default **`[chunk]`** is 1
  - **`guided([chunk])`** allocates dynamically, but **`[chunk]`** is exponentially reduced with each allocation

Data Sharing

.

PThreads:

- Global-scoped variables are shared
- Stack-allocated variables are private

OpenMP:

- shared variables are shared
- private variables are private

OpenMP Synchronization

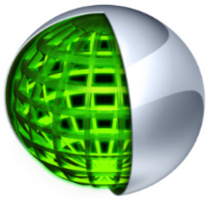
- OpenMP Critical Sections
  - Named or unnamed
  - No *explicit* locks / mutexes
- Barrier directives
- Explicit Lock functions
  - When all else fails – may require `flush` directive
- Single-thread regions *within* parallel regions
  - **`master, single`** directives

CUDA NVIDIA

Programming Approaches

Libraries	OpenACC Directives	Programming Languages
"Drop-in" Acceleration	**Easily Accelerate Apps**	**Maximum Flexibility**

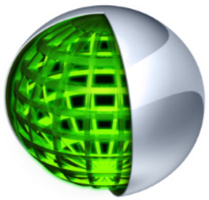
Development Environment



Nsight IDE
Linux, Mac and Windows
GPU Debugging and Profiling

CUDA-GDB debugger
NVIDIA Visual Profiler

Development Environment



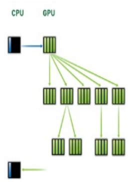
Nsight IDE
Linux, Mac and Windows
GPU Debugging and Profiling

CUDA-GDB debugger
NVIDIA Visual Profiler

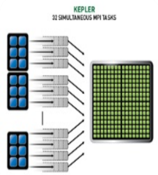
Hardware Capabilities

SMX

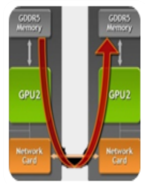
Dynamic Parallelism



HyperQ

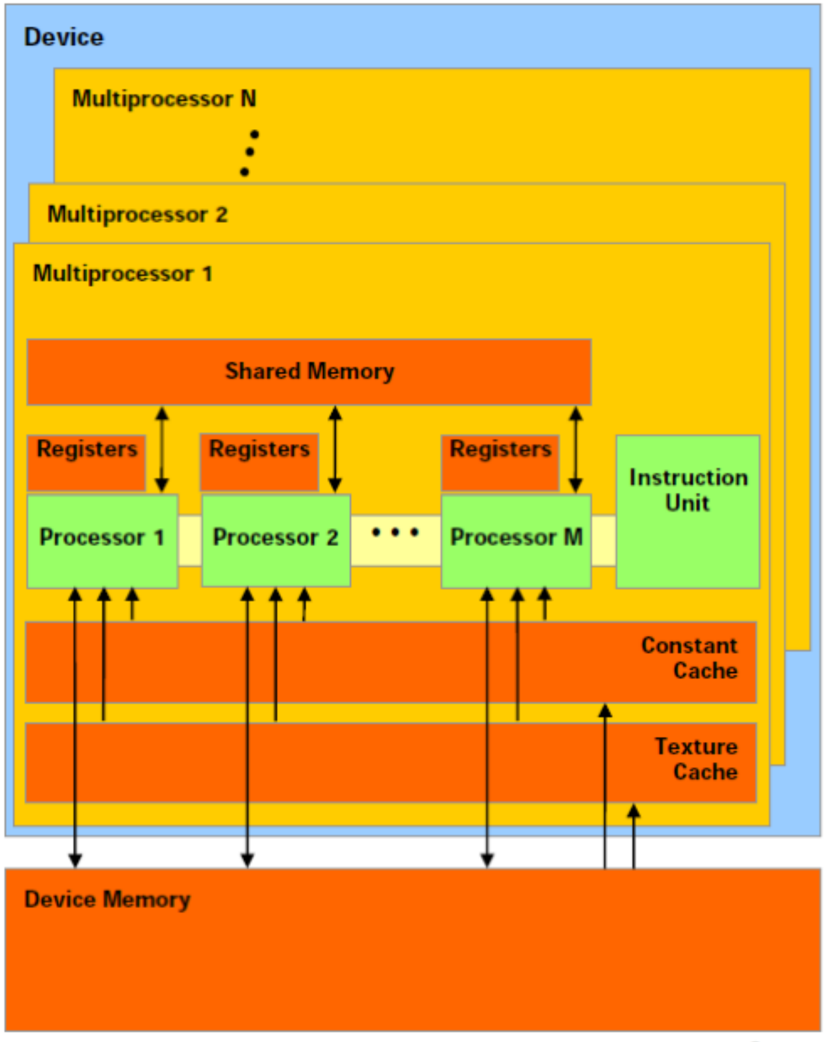


GPUDirect



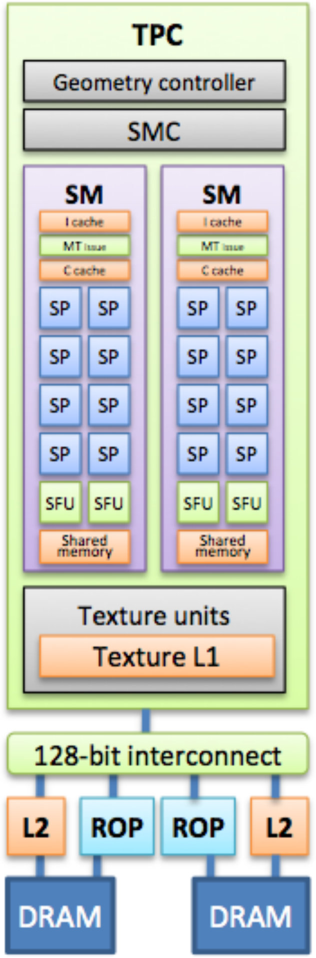
NVIDIA GPU Platform

- A scalable array of multithreaded Streaming Multiprocessors (SMs), each SM consists of
  - 8 Scalar Processor (SP) cores
  - 2 special function units for transcendentals
  - A multithreaded instruction unit
  - On-chip shared memory
- GDDR3 SDRAM
- PCIe interface



Sample Platforms

NVIDIA GeForce9400M G GPU

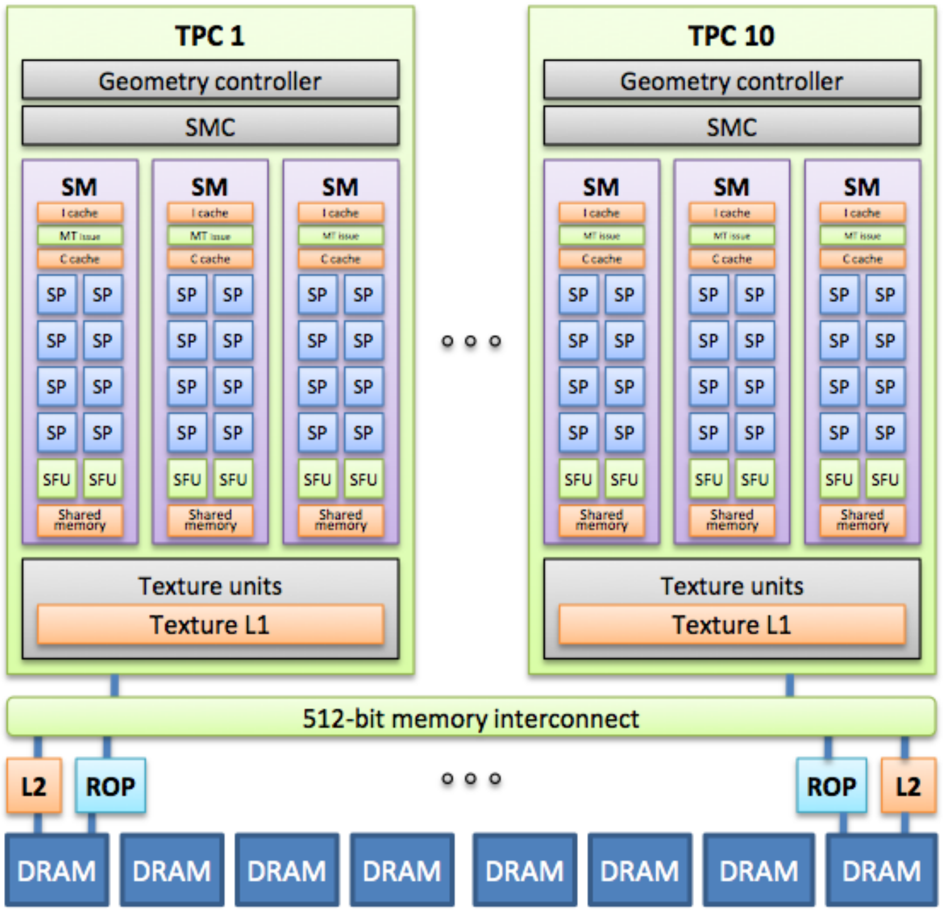


Render Output Unit (ROP)

- 16 streaming processors arranged as 2 streaming multiprocessors
- At 0.8 GHz this provides
  - 54 GFLOPS in single-precision (SP)
- 128-bit interface to off-chip GDDR3 memory
  - 21 GB/s bandwidth

Sample Platforms

NVIDIA Tesla C1060 GPU

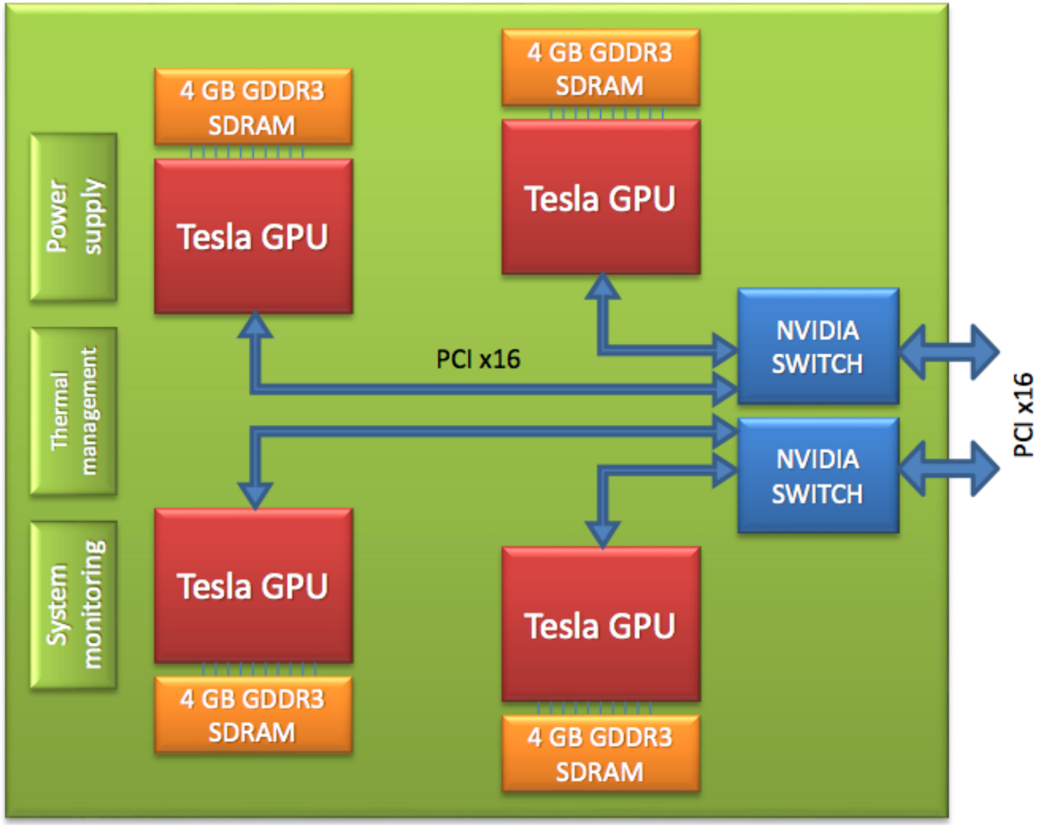


- 240 streaming processors arranged as 30 streaming multiprocessors
- At 1.3 GHz this provides
  - 1 TFLOPS SP
  - 86.4 GFLOPS DP
- 512-bit interface to off-chip GDDR3 memory
  - 102 GB/s bandwidth

Sample Platforms

NVIDIA Tesla S1070 Computing Server

- 4 T10 GPUs



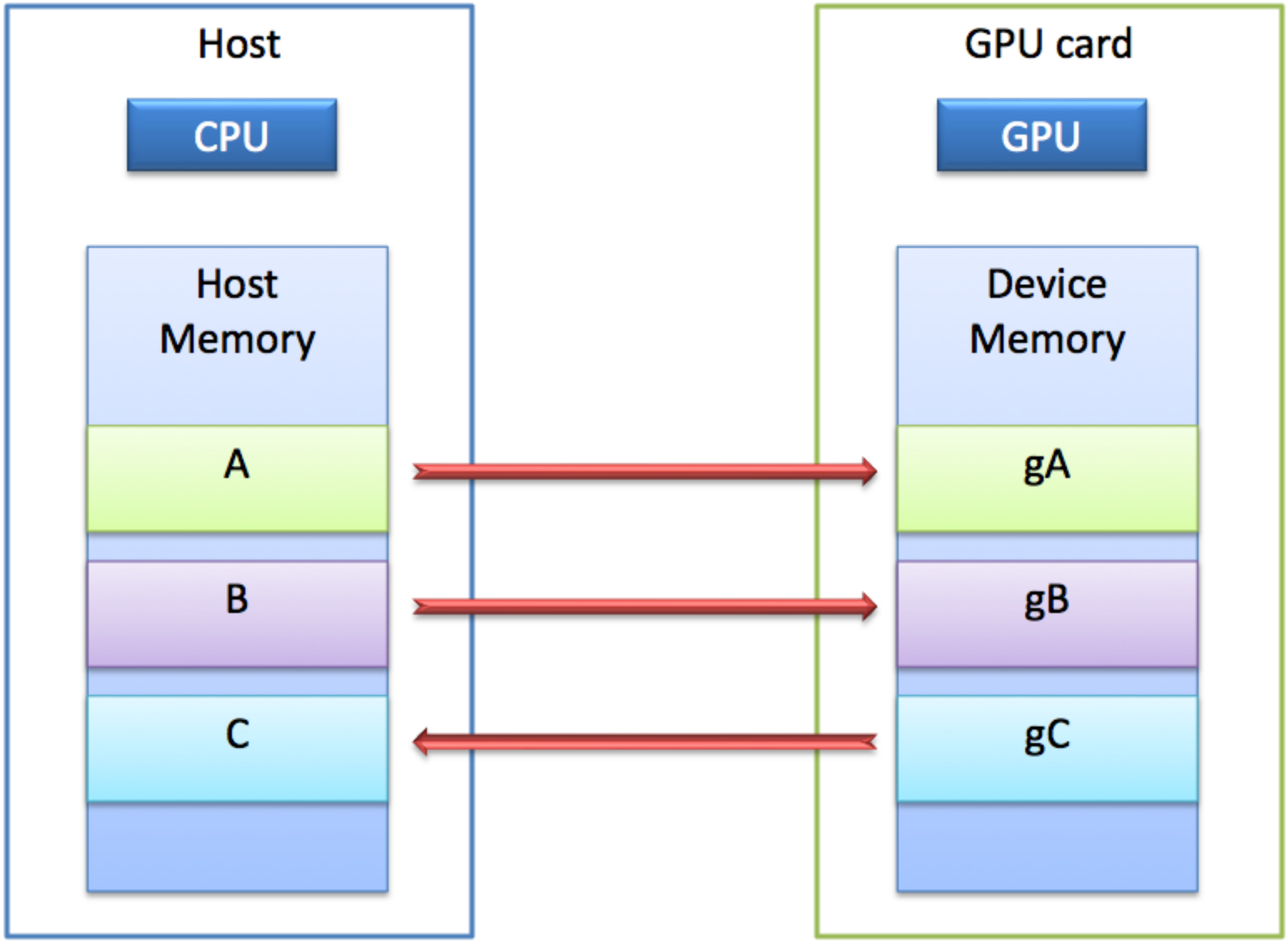
How to program GPU's

Let's take Vector Addition written in C for a CPU:

```
void vecAdd(int N, float* A, float* B, float* C) {
   for (int i = 0; i < N; i++)  C[i] = A[i] + B[i];
}

int  main(int argc, char **argv)
{
   int N = 16384;  // default vector size

   float *A = (float*)malloc(N * sizeof(float));
   float *B = (float*)malloc(N * sizeof(float));
   float *C = (float*)malloc(N * sizeof(float));

   vecAdd(N, A, B, C);  // call compute kernel

   free(A); free(B); free(C);
}
```

- Computational kernel
- Memory allocation
- Kernel invocation
- Memory de-allocation

How to get the GPU involved



Memory Spaces

- CPU and GPU have separate memory spaces
  - Data is moved across PCIe bus
  - Use functions to allocate/set/copy memory on GPU
- Host (CPU) manages device (GPU) memory
  - cudaMalloc(void** pointer, size_t nbytes)
  - cudaFree(void* pointer)
  - cudaMemcpy(void* dst, void* src, size_t nbytes, enum cudaMemcpyKind direction);
    - returns after the copy is complete
    - blocks CPU thread until all bytes have been copied
    - does not start copying until previous CUDA calls complete
  - enum cudaMemcpyKind
    - cudaMemcpyHostToDevice
    - cudaMemcpyDeviceToHost
    - cudaMemcpyDeviceToDevice

Example

```
int  main(int argc, char **argv)
{
   int  N = 16384;  // default vector size

   float *A = (float*)malloc(N * sizeof(float));
   float *B = (float*)malloc(N * sizeof(float));
   float *C = (float*)malloc(N * sizeof(float));

   float *devPtrA, *devPtrB, *devPtrC;

   cudaMalloc((void**)&devPtrA, N * sizeof(float));
   cudaMalloc((void**)&devPtrB, N * sizeof(float));
   cudaMalloc((void**)&devPtrC, N * sizeof(float));

   cudaMemcpy(devPtrA, A, N * sizeof(float),  cudaMemcpyHostToDevice);
   cudaMemcpy(devPtrB, B, N * sizeof(float),  cudaMemcpyHostToDevice);
```

Memory allocation on the GPU card

Copy data from the CPU (host) memory to the GPU (device) memory

Example continued

```
vecAdd<<<N/512, 512>>>(devPtrA, devPtrB, devPtrC);
```

Kernel invocation

```
cudaMemcpy(C, devPtrC, N * sizeof(float),  cudaMemcpyDeviceToHost);
```

Copy results from device memory to the host memory

```
cudaFree(devPtrA);
cudaFree(devPtrB);
cudaFree(devPtrC);
```

Device memory de-allocation

```
  free(A);
  free(B);
  free(C);
}
```

Example continued: VecAdd

- **CPU version**

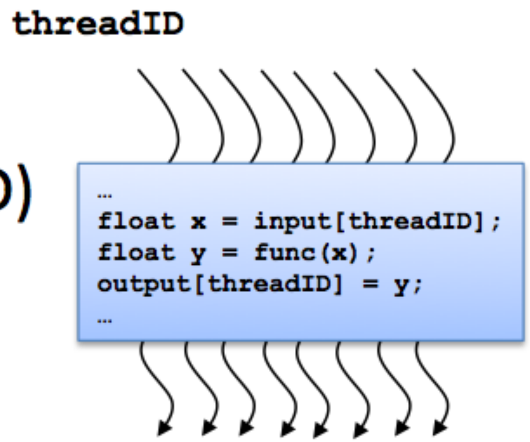
```
void vecAdd(int N, float* A, float* B, float* C)
{
    for (int i = 0; i < N; i++)
        C[i] = A[i] + B[i];
}
```

- **GPU version**

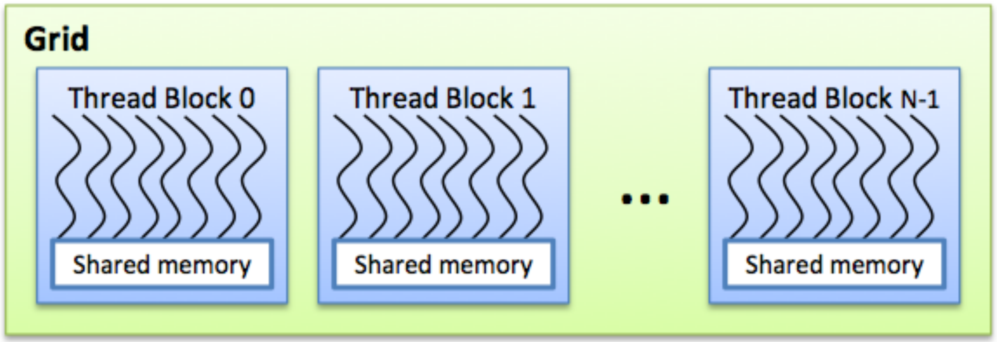
```
__global__ void vecAdd(float* A, float* B, float* C)
{
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    C[i] = A[i] + B[i];
}
```

Example continued: Threads

- A CUDA kernel is executed by an array of threads
  - All threads run the same code (SPMD)
  - Each thread has an ID that it uses to compute memory addresses and make control decisions



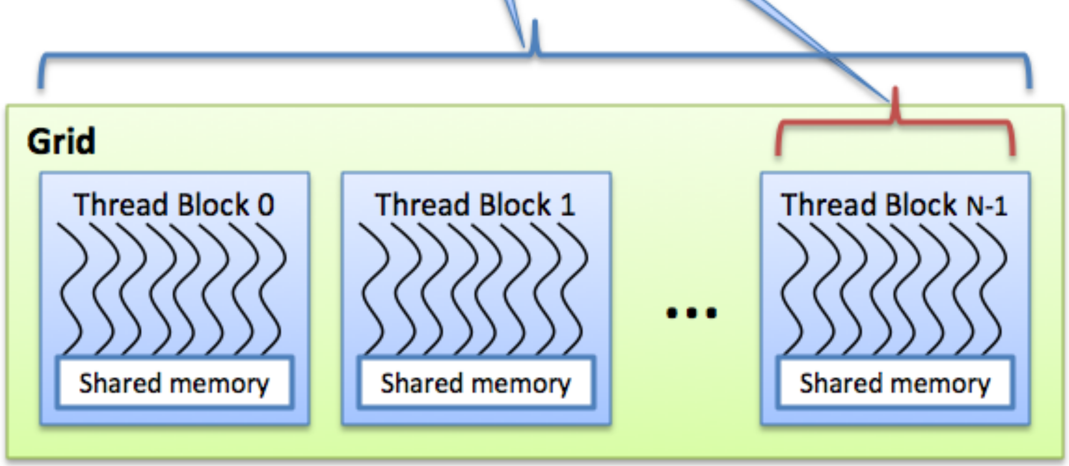
- Threads are arranged as a grid of thread blocks
  - Threads within a block have access to a segment of shared memory



Example continued: Kernel Invocation

grid & thread block dimensionality

```
vecAdd<<<32, 512>>>(devPtrA, devPtrB, devPtrC);
```

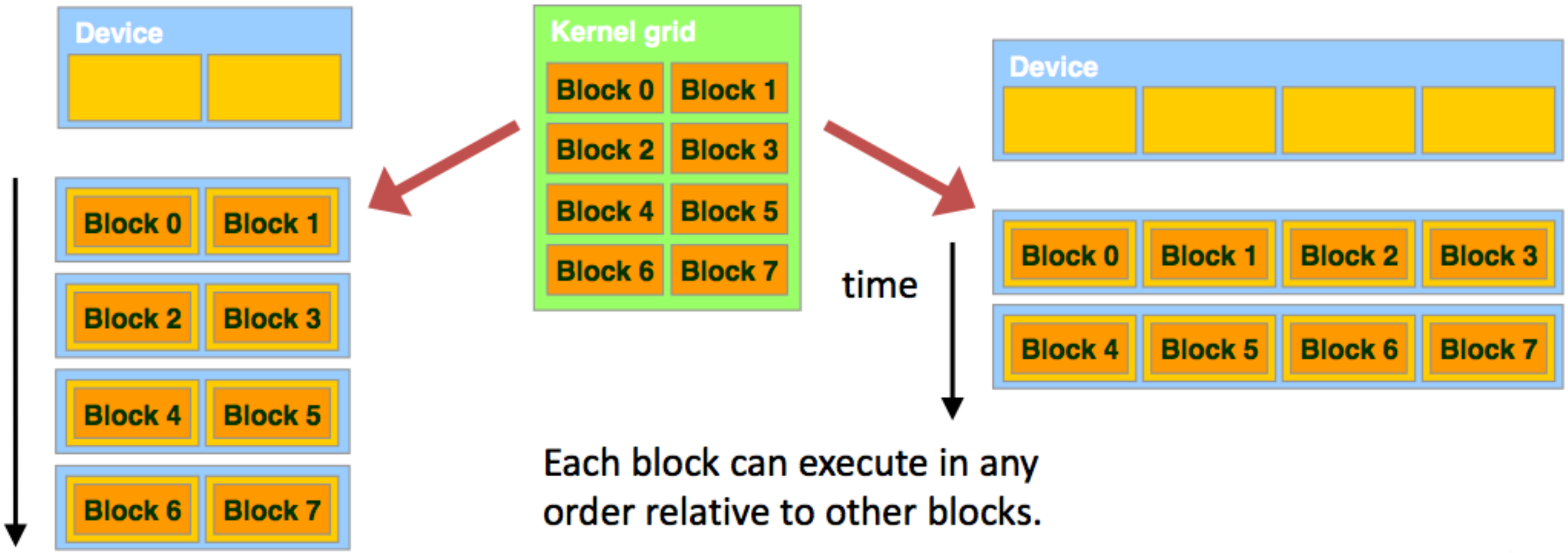



```
int i = blockIdx.x * blockDim.x + threadIdx.x;
```

block ID within a grid | number of threads per block | thread ID within a thread block

Mapping Threads to the Hardware

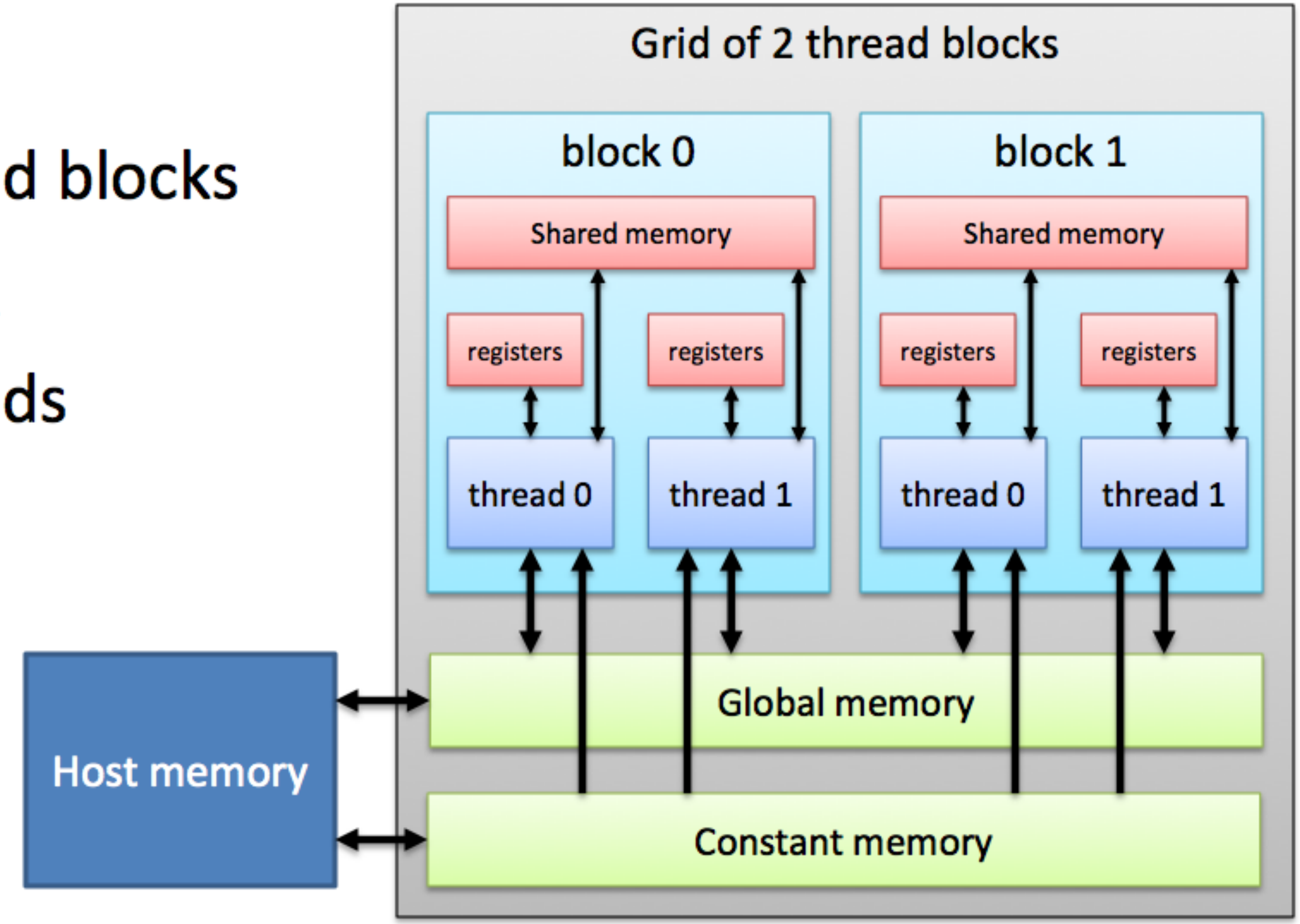
- Blocks of threads are transparently assigned to SMs
  - A block of threads executes on one SM & does not migrate
  - Several blocks can reside concurrently on one SM
- Blocks must be independent
  - Any possible interleaving of blocks should be valid
  - Blocks may coordinate but not synchronize
  - Thread blocks can run in any order



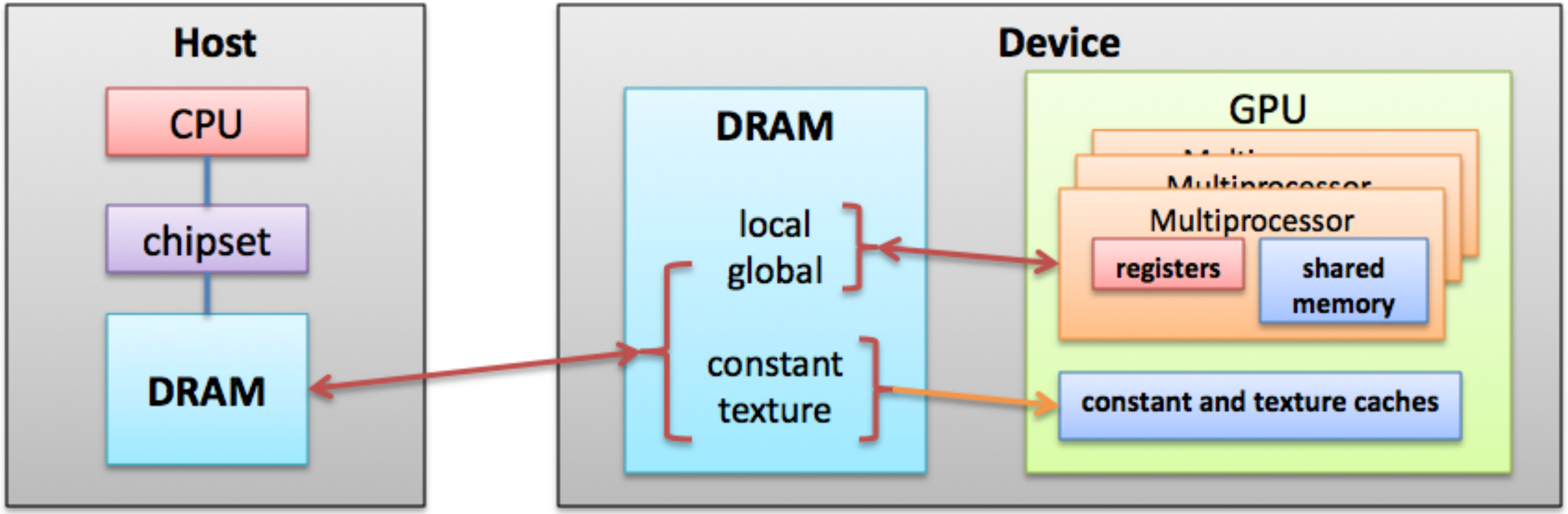
Each block can execute in any order relative to other blocks.

Mapping Threads to the Hardware

- 1D grid
  - 2 thread blocks
- 1D block
  - 2 threads



GPU Memory Hierarchy (Summary)



Memory	Location	Cached	Access	Scope	Lifetime
Register	On-chip	N/A	R/W	One thread	Thread
Local	Off-chip	No	R/W	One thread	Thread
Shared	On-chip	N/A	R/W	All threads in a block	Block
Global	Off-chip	No	R/W	All threads + host	Application
Constant	Off-chip	Yes	R	All threads + host	Application
Texture	Off-chip	Yes	R	All threads + host	Application

Other Parallel Programming Paradigms

- Parallel Functional Programming
- MapReduce: HADOOP
- Coordination Languages: Linda
- Platform Specific: OCCAM (Transputer)