Memory

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GPU Programming
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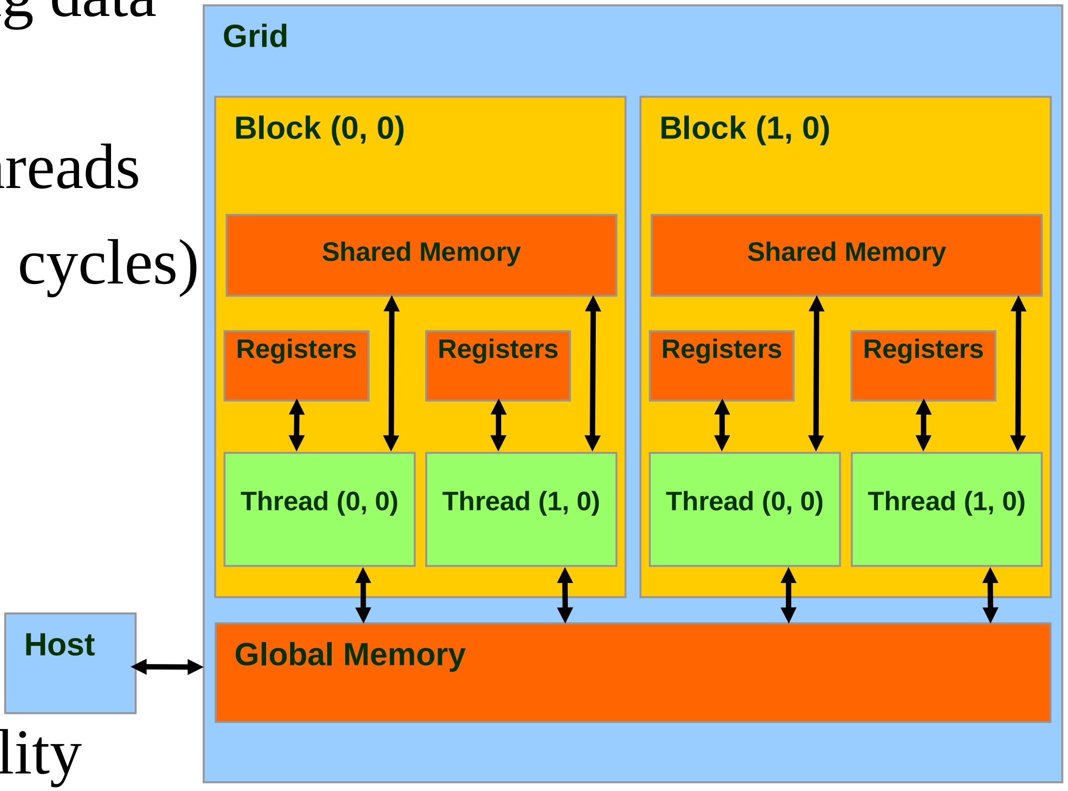
Agenda

- Computation
- **Memory**
- Synchronization
- Functions
- Support
- Streams
- Topics
- Case Study – Graphs

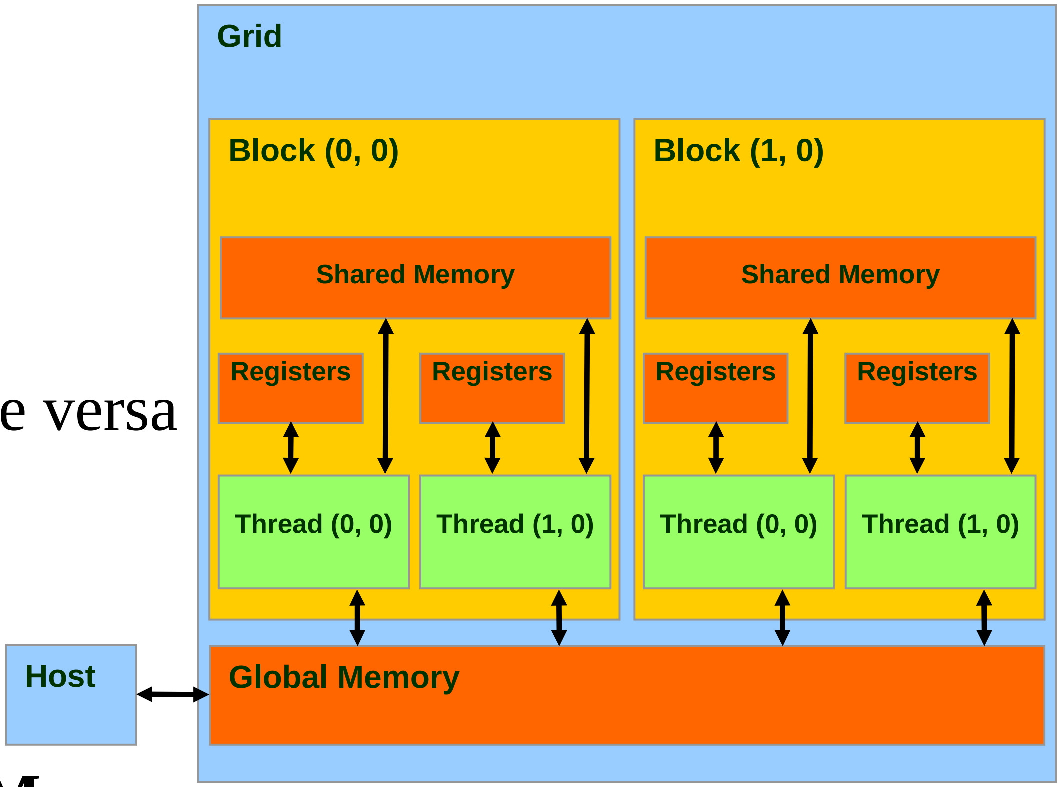
CUDA Memory Model Overview

- Global / Video memory
  - Main means of communicating data between host and device
  - Contents visible to all GPU threads
  - Long latency access (400-800 cycles)
  - Throughput ~200 GBPS
- Texture Memory
  - Read-only (12 KB)
  - ~800 GBPS
  - Optimized for 2D spatial locality
- Constant Memory
  - Read-only (64 KB)



CUDA Memory Model Overview

- L2 Cache
  - 768 KB
  - Shared among SMs
  - Fast atomics
- L1 / Shared Memory
  - Configurable 64 KB per SM
  - 16 KB shared+48 KB L1 or vice versa
  - Low latency (20-30 cycles)
  - High bandwidth (~1 TBPS)
- Registers
  - 32 K in number, unified, **per SM**
  - ~Max. 21 registers per thread
  - Very high bandwidth (~8 TBPS)



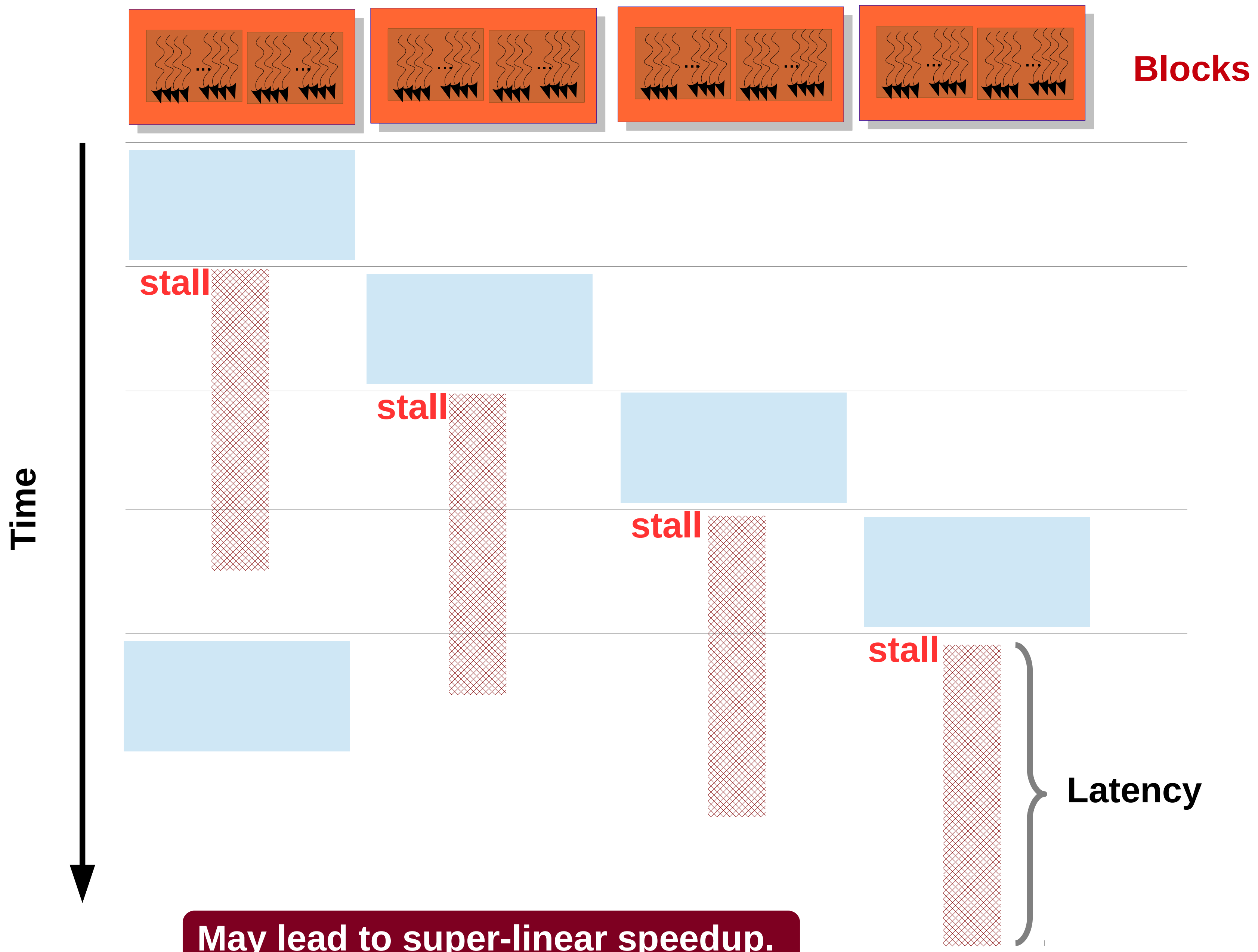
Bandwidth

- Big (wide) data bus rather than fast data bus
- Parallel data transfer
- Techniques to improve bandwidth:
  - Share / reuse data
  - Data compression
  - Recompute than store + fetch

Latency

- Latency is time required for I/O.
- Latency should be minimized; ideally zero.
  - Processor should have data available in no time.
  - In practice, memory I/O becomes the bottleneck.
- Latency can be reduced using caches.
  - CPU: Registers, L1, L2, L3, L4, RAM
  - GPUs have small L1 and L2, and many threads.
- Latency hiding on GPUs is done by exploiting massive multi-threading.

Latency Hiding



May lead to super-linear speedup.

Locality

- Locality is important on GPUs also.
- All threads in a thread-block access their L1 cache.
  - This cache on Pascal GPU is 64 KB.
  - It can be configured as 48 KB L1 + 16 KB scratchpad or 16 KB L1 + 48 KB scratchpad.
- Programmer can help exploit locality.
- In the GPU setting, another form of spacial locality is critical.

Locality

Spatial

If **a[i]** is accessed, **a[i+k]** would also be accessed.

```
for (i = 0; i < N; ++i)
    a[i] = 0;
```

Temporal

If a[i] is accessed **now**, it would be accessed soon **again**.

```
for (i = 0; i < N; ++i) {
    a[i]  = i;
    a[i] += N;
    b[i]  = a[i] * a[i];
}
```

The localities are applicable on both CPU as well as GPU. But more applicable on CPUs.

Classwork

- Check how the localities are in the following matrix multiplication programs (on CPU).

```
for (i = 0; i < M; ++i)
    for (j = 0; j < N; ++j)
        for (k = 0; k < P; ++k)
            C[i][j] += A[i][k] * B[k][j];
```

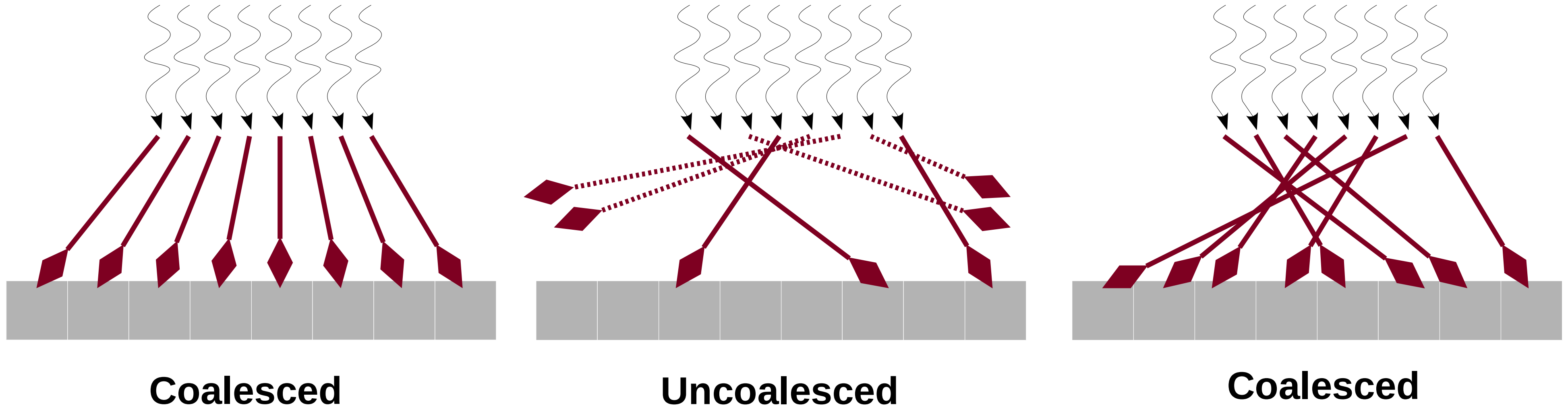
```
for (i = 0; i < M; ++i)
    for (k = 0; k < P; ++k)
        for (j = 0; j < N; ++j)
            C[i][j] += A[i][k] * B[k][j];
```

Times taken for (M, N, P) = (1024, 1024, 1024) are 9.5 seconds and 4.7 seconds.

What happens on a GPU?

Memory Coalescing

- If *consecutive threads* access words from the same block of 32 words, their memory requests are clubbed into one.
  - That is, the memory requests are coalesced.
- This can be effectively achieved for regular programs (such as dense matrix operations).



Degree of Coalescing

- DoC is the inverse of (32 -) the number of memory transactions required for a warp to execute an instruction.
  - a[threadIdx.x] has DoC of 31.
  - a[rand()] likely has a DoC of 0.
- **Classwork:** Write a kernel to vary the degree of coalescing from 0 to 31 based on an input argument.

Memory Coalescing

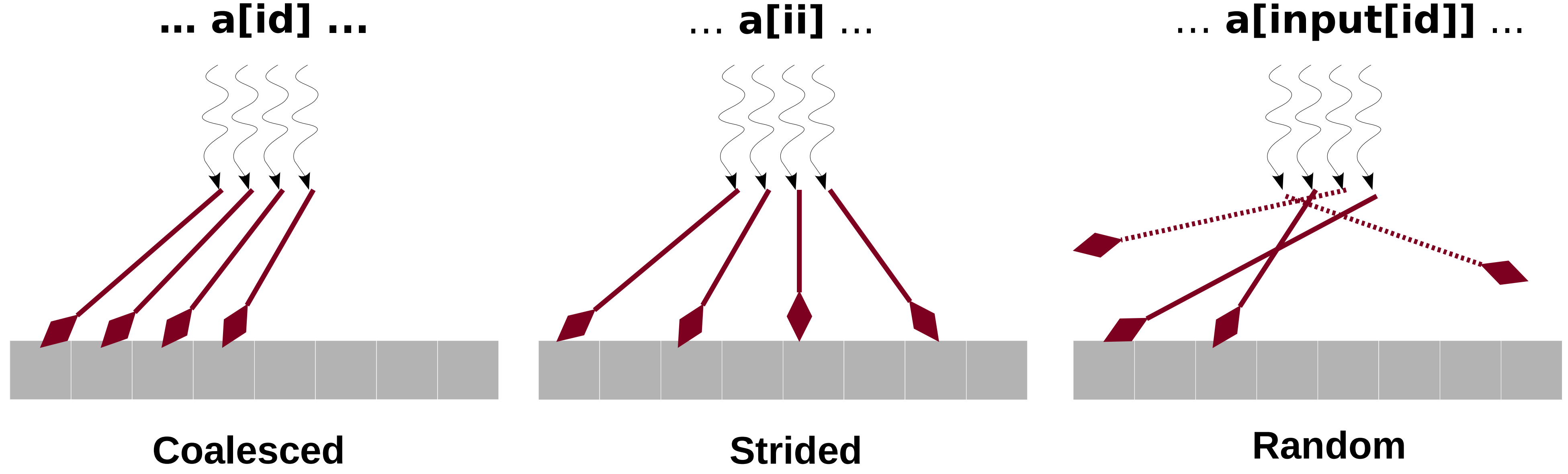
CPU

- Each thread should access consecutive elements of a chunk (strided).
- Array of Structures (AoS) has a better locality.

GPU

- A chunk should be accessed by consecutive threads (coalesced).
- Structures of Arrays (SoA) has a better performance.

```
start = id * chunksize;
end = start + chunksize;
for (ii = start; ii < end; ++ii)
```



AoS versus SoA

```
struct node {
        int a;
        double b;
        char c;
};
struct node allnodes[N];
```

```
struct node {
        int alla[N];
        double allb[N];
        char allc[N];
};
```

Expectation: When a thread accesses an attribute of a node, *it* also accesses *other attributes* of the *same node*.

Better locality (on CPU).

Expectation: When a thread accesses an attribute of a node, its *neighboring thread* accesses the *same attribute* of the *next node*.

Better coalescing (on GPU).

Classwork: Write code for the two types using cudaMemcpy.
(note that all arrays would be pointers)

AoS versus SoA

```
struct nodeAOS {
        int a;
        double b;
        char c;
} *allnodesAOS;
```

```
__global__ void dkernelaos(struct nodeAOS *allnodesAOS) {
        unsigned id = blockIdx.x * blockDim.x + threadIdx.x;
        allnodesAOS[id].a = id;
        allnodesAOS[id].b = 0.0;
        allnodesAOS[id].c = 'c';
}
```

```
struct nodeSOA {
        int *a;
        double *b;
        char *c;
} allnodesSOA;
```

```
__global__ void dkernelsoa(int *a, double *b, char *c) {
        unsigned id = blockIdx.x * blockDim.x + threadIdx.x;
        a[id] = id;
        b[id] = 0.0;
        c[id] = 'd';
}
```

AOS time = 61 units, SOA time = 22 units

Classwork

- Copy a linked-list from CPU to GPU.
  - Each node contains roll number, name, facad.
- Given a large character string ending with \0, find the length of the string.
  - without an array-out-of-bounds exception.

Shared Memory

- Programmable L1 cache / Scratchpad memory
- Accessible only in a thread block
- Useful for repeated small data or coordination

```
__shared__ float a[N];
__shared__ unsigned s;

a[id] = id;
if (id == 0) s = 1;
```

Classwork

- You are given a 1024x1024 integer matrix M.
- Each row is assigned to a thread block.
- Each thread is assigned a matrix element M[i][j].
- It changes M[i][j] to M[i][j] + M[i][j+1] (where possible).
- Exploit shared memory.

Shared Memory

```
#include <stdio.h>
#include <cuda.h>

#define BLOCKSIZE       1024

__global__ void dkernel() {
        __shared__ unsigned s;

        if (threadIdx.x == 0) s = 0;

        if (threadIdx.x == 1) s += 1;

        if (threadIdx.x == 100) s += 2;

        if (threadIdx.x == 0) printf("s=%d\n", s);
}
int main() {
        dkernel<<<1, BLOCKSIZE>>>();
        cudaDeviceSynchronize();
}
```

```
s=3
```

Shared Memory

```
#include <stdio.h>
#include <cuda.h>

#define BLOCKSIZE       1024

__global__ void dkernel() {
        __shared__ unsigned s;

        if (threadIdx.x == 0) s = 0;

        if (threadIdx.x == 1) s += 1;

        if (threadIdx.x == 100) s += 2;

        if (threadIdx.x == 0) printf("s=%d\n", s);
}
int main() {
        dkernel<<<2, BLOCKSIZE>>>();
        cudaDeviceSynchronize();
}
```

```
s=3
s=3
```

Shared Memory

```
#include <stdio.h>
#include <cuda.h>

#define BLOCKSIZE       1024

__global__ void dkernel() {
        __shared__ unsigned s;

        if (threadIdx.x == 0) s = 0;

        if (threadIdx.x == 1) s += 1;

        if (threadIdx.x == 100) s += 2;

        if (threadIdx.x == 0) printf("s=%d\n", s);
}
int main() {
        int i;
        for (i = 0; i < 10; ++i) {
                dkernel<<<2, BLOCKSIZE>>>();
                cudaDeviceSynchronize();
        }
}
```

```
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=1
s=3
s=3
s=3
```

Shared Memory

```
#include <stdio.h>
#include <cuda.h>

#define BLOCKSIZE       1024

__global__ void dkernel() {
        __shared__ unsigned s;

        if (threadIdx.x == 0) s = 0;
      __syncthreads(); // barrier across threads in a block
        if (threadIdx.x == 1) s += 1;
      __syncthreads();
        if (threadIdx.x == 100) s += 2;
      __syncthreads();
        if (threadIdx.x == 0) printf("s=%d\n", s);
}
int main() {
        int i;
        for (i = 0; i < 10; ++i) {
                dkernel<<<2, BLOCKSIZE>>>();
                cudaDeviceSynchronize();
        }
}
```

This one is redundant.

```
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
s=3
```

What is the output of this program?

```
#include <stdio.h>
#include <cuda.h>

#define BLOCKSIZE       26

__global__ void dkernel() {
        __shared__ char str[BLOCKSIZE+1];
        str[threadIdx.x] = 'A' + (threadIdx.x + blockIdx.x) % BLOCKSIZE;
        if (threadIdx.x == 0) {
                str[BLOCKSIZE] = '\0';
        }

        if (threadIdx.x == 0) {
                printf("%d: %s\n", blockIdx.x, str);
        }
}
int main() {
        dkernel<<<10, BLOCKSIZE>>>();
        cudaDeviceSynchronize();
}
```

What is the bug in this code?

What is the output of this program?

```
#include <stdio.h>
#include <cuda.h>

#define BLOCKSIZE       26

__global__ void dkernel() {
        __shared__ char str[BLOCKSIZE+1];
        str[threadIdx.x] = 'A' + (threadIdx.x + blockIdx.x) % BLOCKSIZE;
        if (threadIdx.x == 0) {
                str[BLOCKSIZE] = '\0';
        }
      __syncthreads();     // barrier across threads in a block
        if (threadIdx.x == 0) {
                printf("%d: %s\n", blockIdx.x, str);
        }
}
int main() {
        dkernel<<<10, BLOCKSIZE>>>();
        cudaDeviceSynchronize();
}
```

This is redundant if BLOCKSIZE <= 32.

L1 versus Shared

- On CPU:
  - cudaDeviceSetCacheConfig(*kernelname*, *param*);
  - *kernelname* is the name of your kernel.
  - *param* is {cudaFuncCachePreferNone, L1, Shared}.
  - 3.x onward, one may also configure it as 32KB L1 + 32KB Shared. This is achieved using cudaFuncCachePreferEqual.

L1 versus Shared

```
__global__ void dkernel() {
        __shared__ unsigned data[BLOCKSIZE];
        data[threadIdx.x] = threadIdx.x;
}
int main() {
        cudaFuncSetCacheConfig(dkernel, cudaFuncCachePreferL1);
        //cudaFuncSetCacheConfig(dkernel, cudaFuncCachePreferShared);
        dkernel<<<1, BLOCKSIZE>>>();
        cudaDeviceSynchronize();
}
```

Dynamic Shared Memory

- When the amount of shared memory required is unknown at compile-time, dynamic shared memory can be used.
- This is specified as the **third** parameter of kernel launch.

Dynamic Shared Memory

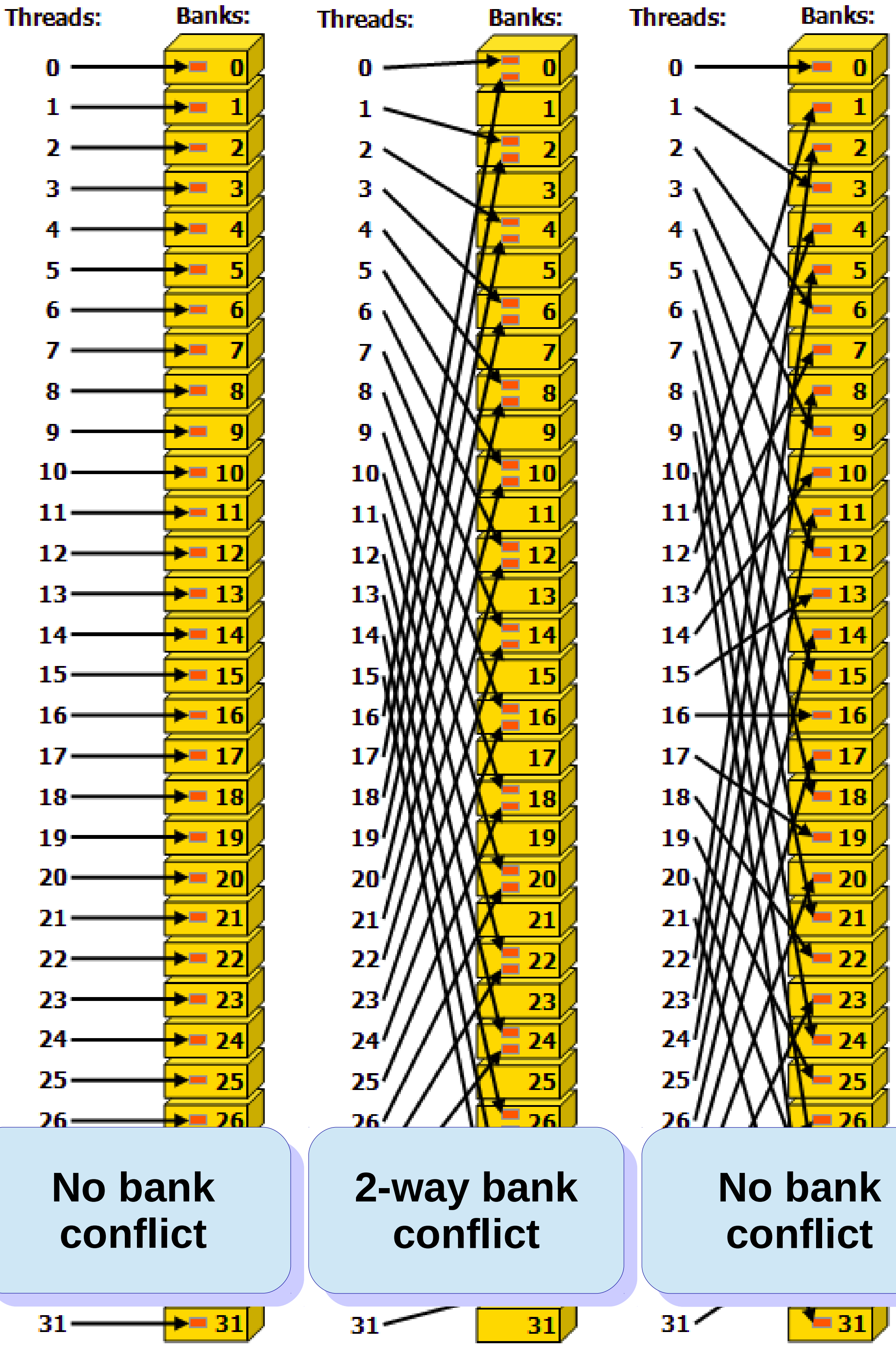
```
#include <stdio.h>
#include <cuda.h>

__global__ void dynshared() {
        extern __shared__ int s[];

        s[threadIdx.x] = threadIdx.x;
        __syncthreads();

        if (threadIdx.x % 2) printf("%d\n", s[threadIdx.x]);
}
int main() {
        int n;
        scanf("%d", &n);
        dynshared<<<1, n, n * sizeof(int)>>>();
        cudaDeviceSynchronize();

        return 0;
}
```

Bank Conflicts

- Shared memory is organized into banks.
- Accesses to the same bank are sequential.
- Consecutive words are stored in adjacent banks.
  - Useful for coalesced access.
- **Exception:** Warp accesses to the same word are not sequentialized.

```
__global__ void bankNOconflict() {
        __shared__ unsigned s[1024];
        s[1 * threadIdx.x] = threadIdx.x;
}
```

```
__global__ void bankconflict() {
        __shared__ unsigned s[1024];
        s[32 * threadIdx.x] = threadIdx.x;
}
```

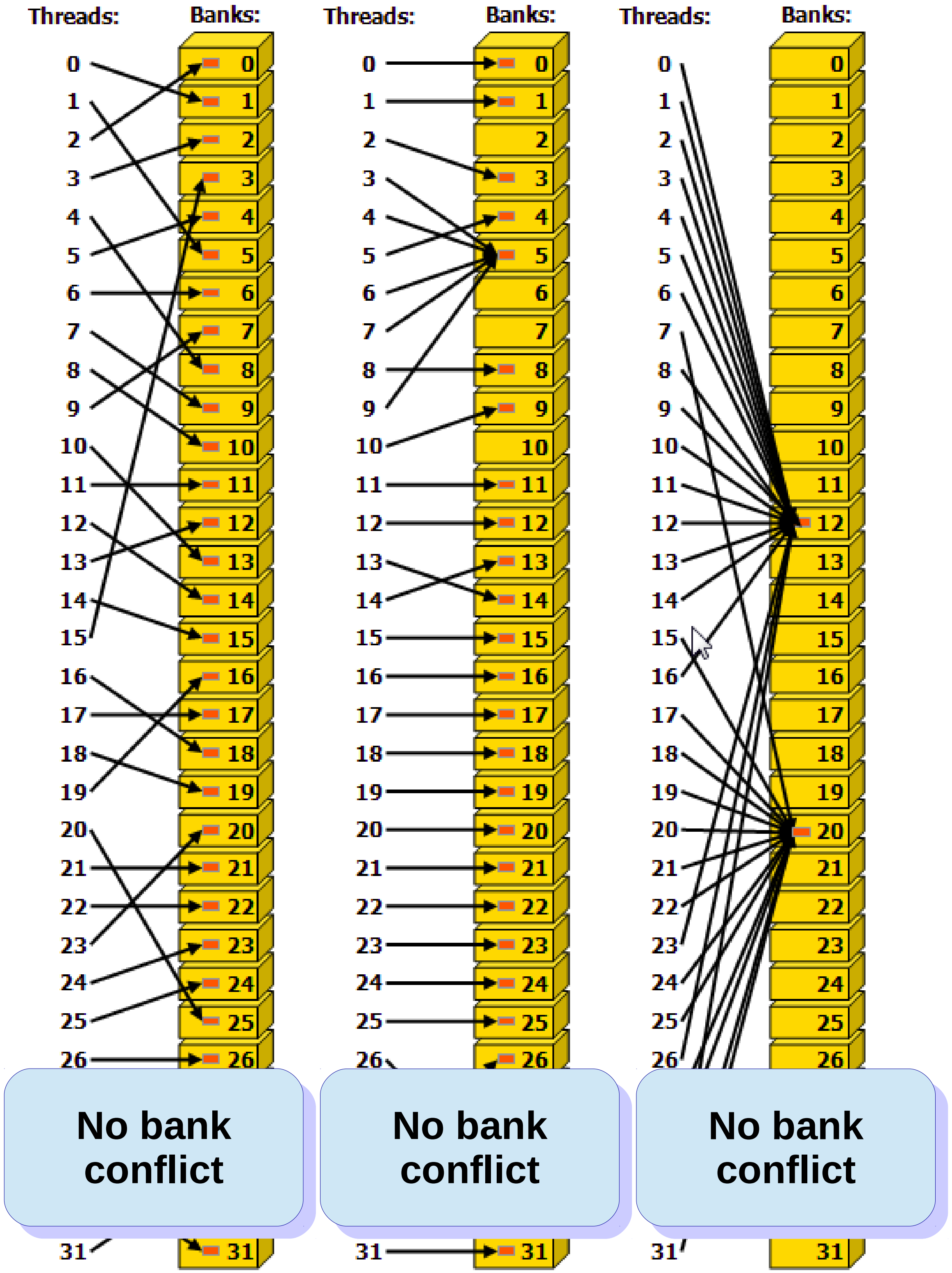


Source: CUDA Programming Guide

No bank conflict

2-way bank conflict

No bank conflict



Source: CUDA Programming Guide

No bank conflict

No bank conflict

No bank conflict

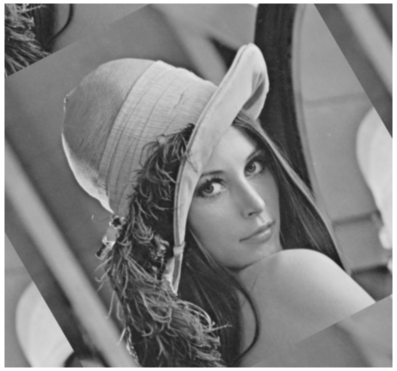
Texture Memory

- Fast read-only memory
- Optimized for 2D spatial access
- Definition: texture<float, 2, cudaReadModeElementType> *tex*;
- In main: cudaBindTextureToArray(*tex*, cuArray, ...);
- In kernel: ... = tex2D(*tex*, ...);

Texture Memory

- Example from CUDA SDK

```
__global__ void transformKernel(float *output, int width, int height, float theta)
{
        unsigned x = blockIdx.x * blockDim.x + threadIdx.x;
        unsigned y = blockIdx.y * blockDim.y + threadIdx.y;

        float u = (float)x - (float)width / 2;
        float v = (float)y - (float)height / 2;
        float tu = (u * cosf(theta) - v * sinf(theta)) / width;
        float tv = (v * cosf(theta) + u * sinf(theta)) / height;

        output[y * width + x] = tex2D(tex, tu + 0.5, tv + 0.5);
}
```



Constant Memory

- Read-only Memory
- 64KB per SM
- Definition: **__constant__** unsigned meta;
- Main: **cudaMemcpyToSymbol**(meta, &hmeta, sizeof(unsigned));
- Kernel: data[threadIdx.x] = meta[0];

Constant Memory

```
#include <cuda.h>
#include <stdio.h>

__constant__ unsigned meta[1];

__global__ void dkernel(unsigned *data) {
	data[threadIdx.x] = meta[0];
}
__global__ void print(unsigned *data) {
	printf("%d %d\n", threadIdx.x, data[threadIdx.x]);
}
int main() {

	unsigned hmeta = 10;
	cudaMemcpyToSymbol(meta, &hmeta, sizeof(unsigned));
	unsigned *data;
	cudaMalloc(&data, 32 * sizeof(unsigned));
	dkernel<<<1, 32>>>(data);
	cudaDeviceSynchronize();
	print<<<1, 32>>>(data);
	cudaDeviceSynchronize();
	return 0;
}
```

Compute Capability

- Version number: Major.minor (e.g., 3.5)
- Features supported by the GPU hardware.
- Used by the application at runtime (-*arch=sm_35*).

Major number	Architecture
1	Tesla
2	Fermi
3	Kepler
5	Maxwell
6	Pascal
7	Volta

- CUDA version is the software version (e.g., CUDA 7.0).
- __CUDA_ARCH__ is defined (e.g., 350) in device code.

Compute Capability

Feature	2.x	3.0	3.2	3.5, 3.7, 5.0, 5.2	5.3	6.x
Atomics int, float	Yes	Yes	Yes	Yes	Yes	Yes
Atomics double						Yes
warp-vote	Yes	Yes	Yes	Yes	Yes	Yes
__syncthreads functions	Yes	Yes	Yes	Yes	Yes	Yes
Unified memory		Yes	Yes	Yes	Yes	Yes
Dynamic parallelism				Yes	Yes	Yes

Classwork

- Write CUDA code for the following functionality.
  - Assume following data type, filled with some values.

    `struct Point { int x, y; } arr[N];`
  - Each thread should operate on 4 elements.
  - Find the average AVG of x values.
  - If a thread sees y value above the average, it replaces all 4 y values to AVG.
  - Otherwise, it adds y values to a global sum.
  - Host prints the number of elements set to AVG.

CUDA, in a nutshell

- Compute Unified Device Architecture. It is a hardware and software architecture.
- Enables NVIDIA GPUs to execute programs written with C, C++, Fortran, OpenCL, and other languages.
- A CUDA program calls parallel kernels. A kernel executes in parallel across a set of parallel threads.
- The programmer or compiler organizes these threads in thread blocks and grids of thread blocks.
- The GPU instantiates a kernel program on a grid of parallel thread blocks.
- Each thread within a thread block executes an instance of the kernel, and has a thread ID within its thread block, program counter, registers, per-thread private memory, inputs, and output results.
- A thread block is a set of concurrently executing threads that can cooperate among themselves through barrier synchronization and shared memory.
- A grid is an array of thread blocks that execute the same kernel, read inputs from global memory, and write results to global memory.
- Each thread has a per-thread private memory space used for register spills, function calls, and C automatic array variables.
- Each thread block has a per-block shared memory space used for inter-thread communication, data sharing, and result sharing in parallel algorithms.