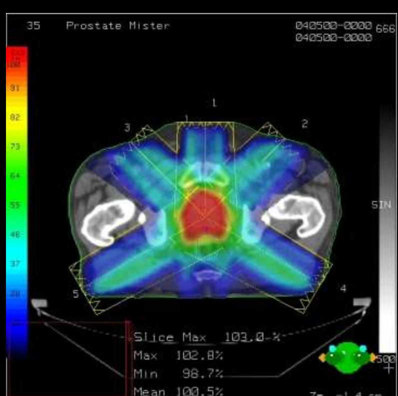
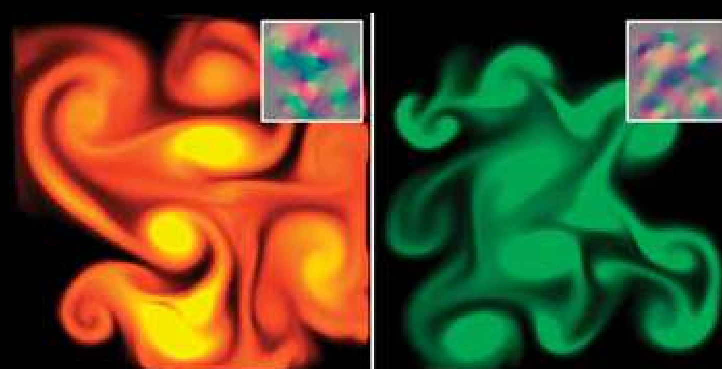
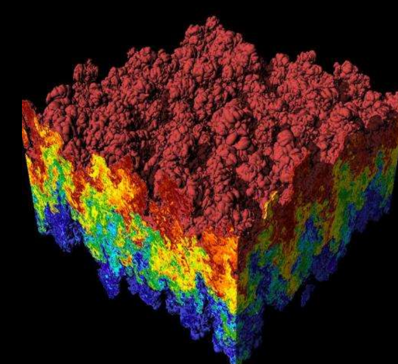
CS 179:
Introduction to GPU Programming.

Lecture 1: Introduction







Images: http://en.wikipedia.org
http://www.pcper.com
http://northdallasradiationoncology.com/

Administration

Main topics covered in course:

- (GP)GPU computing/parallelization
- C++ CUDA (parallel computing platform)

TAs:

- Julian Peres (Head TA) (jbperes@caltech.edu)
- Sam Foxman (sfoxman@caltech.edu)
- Jake Goldman (jgoldman@caltech.edu)
- Khanh Pham (kcpham@caltech.edu)
- Others TBA?

Overseeing Instructor:

Al Barr (barr@cms.caltech.edu)

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- Primary Websites:
  - http://courses.cms.caltech.edu/cs179/
  - http://www.piazza.com/caltech/spring2024/cs179
    - Piazza is the primary forum for the course! Make sure you're enrolled!
  - Also CS179 Canvas Calendar
- Class time:
  - MW(F) 3pm PDT for classes and HW recitations.
  - Also TA office hours, some through Zoom (TBA)

Course Requirements

Homework:

- 6 assignments, first 6 weeks, Due Wed 3pm.
- Each worth 10% of grade
- Students must do their own work
- **Can** use help from Machine Learning for Programming. Jot down which ones you used. Can't blindly copy work from previous years from other students
- ***Need "enough" work before Add Day****, to pass!*

Final project:

- 4-week project
- 40% of grade total

P/F Students must receive at least 60% on every assignment AND the final project.

Homework

Due on Wednesdays 3PM PDT.

First set is due Wednesday April 10th

- Use zip on remote GPU computer in Barr lab to submit HW.

Collaboration policy:

- Discuss ideas and strategies freely, but all code must be your own
- Do NOT look up prior years solutions or reference solution code from github without prior TA approval. May use AI to help!
- Use **additional backup** method for work, on a different computer.
- Make your github repository *Private*!

Office Hours: Most will be in person, some through Zoom.

- Times: TBA

Extensions

- Ask a TA for one if you have a valid reason
- See main website for details.

Your GPU Project

Project can be a topic of your choice

- We will also provide many options

Teams of up to 2 people

- 2-person teams will be held to higher expectations

Requirements

- Project Proposal
- Progress report(s) and Final Presentation
- More info later…

Caltech Machine and your accounts now available.

The Primary GPU machine is set up and available

- You will soon receive a user account in email.
- Please test access and change your password.
- GPU-enabled machine is on the Caltech campus.
- Let us know if you have problems!
- You'll be submitting HW on this computer.

Alternative GPU Machines

Alternative: Use your own machine.

You will still have to submit and test HW on the Caltech GPU machine.

- Must have an NVIDIA CUDA-capable GPU
  - At least Compute 3.0
- Virtual machines generally won't work
  - Exception: Machines with I/O MMU virtualization and certain GPUs
- Special requirements for:
  - Hybrid/Optimus systems (laptops)
  - Mac/OS X (probably no longer supported?)

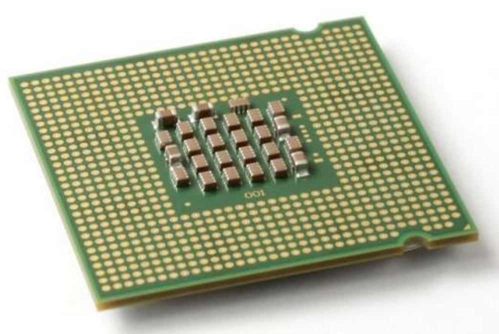
Setup guide on the website is likely outdated. Can follow NVIDIA's posted installation instructions (linked on page). Ubuntu 22.04 or later ay be easiest to install!

The CPU

The "Central Processing Unit"

Traditionally, applications use CPU for primary calculations

- General-purpose capabilities, mostly sequential operations
- Established technology
- Usually equipped with 8 or fewer, powerful cores
- Optimal for some types of concurrent processes but not large scale parallel computations



Wikimedia commons: Intel_CPU_Pentium_4_640_Prescott_bottom.jpg

The GPU

The "Graphics Processing Unit"

Relatively new technology designed for parallelizable problems

- Initially created specifically for graphics
- Became more capable of general computations
- Very fast and powerful, computationally
- Uses lots of electrical power

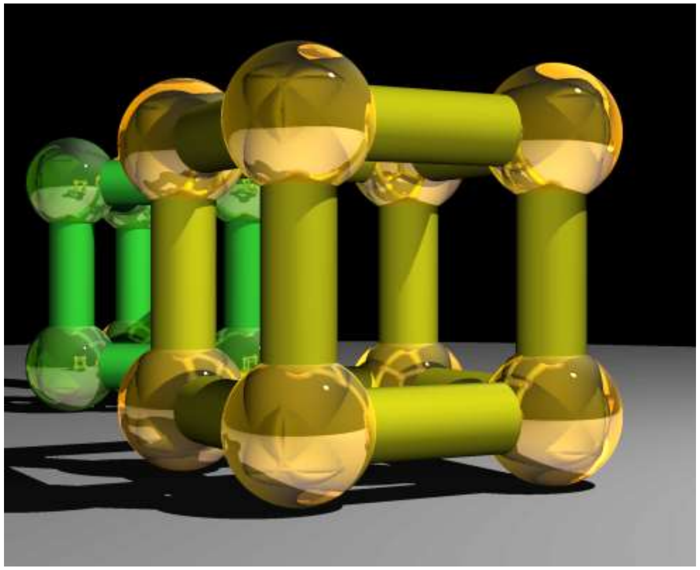
GPUs – Some of the Motivation

Raytracing:

```
for all pixels (i,j) in image:
    From camera eye point,
      calculate ray point and direction in 3d space
    if ray intersects object:
      calculate lighting at closest object point
      store color of (i,j)
Assemble into image file
```

Each pixel could be computed simultaneously, with enough parallelism!

Superquadric Cylinders, exponent 0.1, yellow glass balls, Barr, 1981



SIMPLE EXAMPLE

Add two arrays, A and B to produce array C

- A[ ] + B[ ] -> C[ ]

On the CPU:

```
float *C = malloc(N * sizeof(float));
for (int i = 0; i < N; i++)
C[i] = A[i] + B[i];
return C;
```

On CPUs the above code operates ***sequentially****, but can we do better, still on CPUs?*

A simple problem…

- On the CPU (multi-threaded, pseudocode):

```
(allocate memory for array C)
Create # of threads equal to number of cores on processor
(around 2, 4, perhaps 8?)
(Indicate portions of arrays A, B, C to each thread...)

...

In each thread,
For (i from beginning region of thread)
C[i] <- A[i] + B[i]
//lots of waiting involved for memory reads, writes, ...
Wait for threads to synchronize...
```

This is ***slightly*** *faster – 2-8x (can be slightly more with other tricks)*

A simple problem…

- How many threads are available on the CPUs? How can the performance scale with thread count?
  - (Each CPU can generally have two threads).

- Context switching:
  - The action of switching which thread is being processed
  - **High penalty** on the CPU (main computer)
  - Not a big issue on the GPU

A simple problem…

- On the GPU:

```
(allocate memory for arrays A, B, C on GPU)
Create the "kernel" – where each thread will perform one (or a
few) additions
    Specify the following kernel operation:

    For all i's (indices) assigned to this thread:
            C[i] <- A[i] + B[i]

Start ~20000 (!) threads all at the same time!
Wait for threads to synchronize...
```

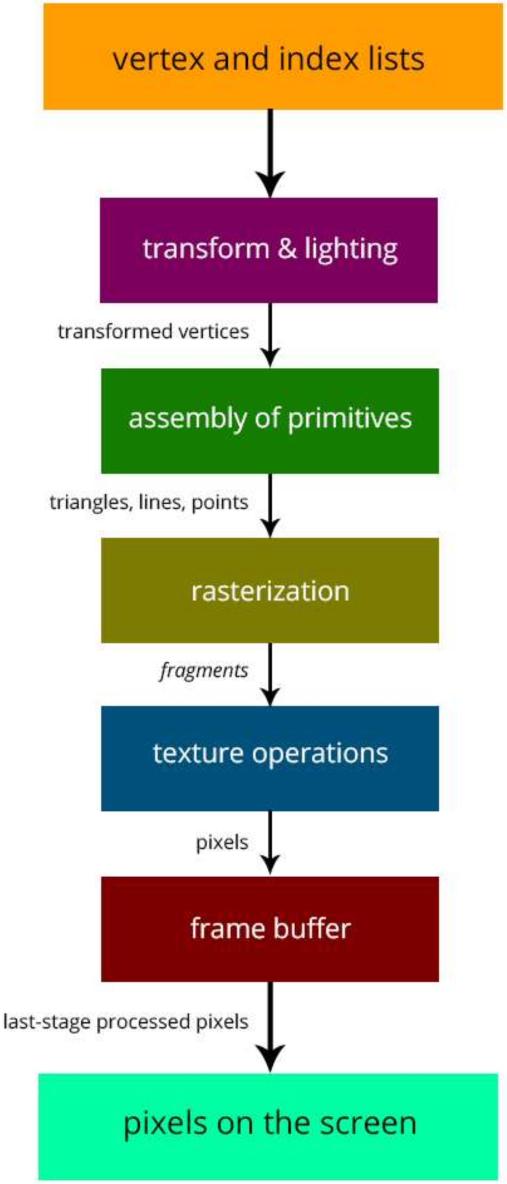
GPU: Strengths Revealed

- Emphasis on parallelism on GPUs means we have lots of cores
- This allows us to run many threads simultaneously with virtually no context switches

GPUs – Brief History

- Initially based on graphics focused fixed-function pipelines (history)
  - Pre-set pixel/vertex functions, limited options

http://gamedevelopment.tutsplus.com/articles/the-end-of-fixed-function-rendering-pipelines-and-how-to-move-on--cms-21469
Source: Super Mario 64, by Nintendo



GPUs – Brief History

- Shaders
  - Can implement one's own functions using graphics routines.
  - GLSL (C-like language), discussed in CS 171
  - Can "sneak in" general-purpose programming! Uses pixel and vertex operations instead of general purpose code. Very crude.
  - Vulkan/OpenCL is the modern multiplatform general purpose GPU compute system, but we won't be covering it in this course

http://minecraftsix.com/glsl-shaders-mod/

Using GPUs as "supercomputers"

"General-purpose computing on GPUs" (GPGPU)

- Hardware has gotten good enough to a point where it's basically having a mini-supercomputer

CUDA (Compute Unified Device Architecture)

- General-purpose parallel computing platform for NVIDIA GPUs

Vulkan/OpenCL (Open Computing Language)

- General heterogenous computing framework

Both are accessible as extensions to various languages

- If you're into python, checkout Theano, pyCUDA.

Upcoming GPU programming environment: Julia Language

GPU Computing: Step by Step

- Setup inputs on the host (CPU-accessible memory)
- Allocate memory for outputs on the host CPU
- Allocate memory for inputs on the GPU
- Allocate memory for outputs on the GPU
- Copy inputs from host to GPU (slow)
- Start GPU kernel (function that executes on gpu – fast!)
- Copy output from GPU to host (slow)

NOTE: Copying can be asynchronous, [and unified memory management]() is available

The Kernel

- This is our "parallel" function
- Given to each thread
- Simple example, implementation:

```
__global__ void
cudaAddVectorsKernel(float * a, float * b, float * c) {
    //Decide an index somehow
    c[index] = a[index] + b[index];
}
```

Indexing

```
__global__ void
cudaAddVectorsKernel(float * a, float * b, float * c) {
    unsigned int index = blockIdx.x * blockDim.x + threadIdx.x;
    c[index] = a[index] + b[index];
}
```

https://cs.calvin.edu/courses/cs/374/CUDA/CUDA-Thread-Indexing-Cheatsheet.pdf
https://en.wikipedia.org/wiki/Thread_block

Calling the Kernel

```
void cudaAddVectors(const float* a, const float* b, float* c, size){
    //For now, suppose a and b were created before calling this function

    // dev_a, dev_b (for inputs) and dev_c (for outputs) will be
    // arrays on the GPU.

    float * dev_a;
    float * dev_b;

    float * dev_c;

    // Allocate memory on the GPU for our inputs:
    cudaMalloc((void **) &dev_a, size*sizeof(float));
    cudaMemcpy(dev_a, a, size*sizeof(float), cudaMemcpyHostToDevice);

    cudaMalloc((void **) &dev_b, size*sizeof(float)); // and dev_b
    cudaMemcpy(dev_b, b, size*sizeof(float), cudaMemcpyHostToDevice);


    // Allocate memory on the GPu for our outputs:
    cudaMalloc((void **) &dev_c, size*sizeof(float));
```

Calling the Kernel (2)

```
    //At lowest, should be 32
    //Limit of 512 (Tesla), 1024 (newer)
    const unsigned int threadsPerBlock = 512;

    //How many blocks we'll end up needing
    const unsigned int blocks = ceil(size/float(threadsPerBlock));

    //Call the kernel!
    cudaAddVectorsKernel<<<blocks, threadsPerBlock>>>
        (dev_a, dev_b, dev_c);

    //Copy output from device to host (assume here that host memory
    //for the output has been calculated)

    cudaMemcpy(c, dev_c, size*sizeof(float), cudaMemcpyDeviceToHost);

    //Free GPU memory
    cudaFree(dev_a);
    cudaFree(dev_b);
    cudaFree(dev_c);
}
```

- Solving PDEs on GPUs
- GPU vs CPU fluid mechanics
- Ray Traced Quaternion fractals and Julia Sets
- Deep Learning and GPUs
- Real-Time Signal Processing with GPUs

Questions can be live and interactive, on Zoom during office hours. Also can be posted on Piazza.