CS 380 - GPU and GPGPU Programming
Lecture 1: Introduction

Markus Hadwiger, KAUST

Lecture Overview

Goals

- Learn GPU architecture and programming; both for graphics and for compute (GPGPU)
- Shading languages (GLSL, HLSL, MSL, Cg), compute APIs (CUDA, OpenCL, DirectCompute)

Time and location

- Monday + Thursday, 10:00 – 11:30, Room 3120, Bldg. 9

Webpage: `https://vccvisualization.org/CS380_GPU_and_GPGPU_Programming/`

Contact:

- **Markus Hadwiger:** `markus.hadwiger@kaust.edu.sa`
- **Peter Rautek** (main contact assignments): `peter.rautek@kaust.edu.sa`
- **Julio Rey Ramirez** (programming questions): `julio.reyramirez@kaust.edu.sa`
- **Reem Alghamdi** (programming questions): `reem.alghamdi@kaust.edu.sa`

Prerequisites:

C/C++ programming (!), basic computer graphics, basic linear algebra

Lecture Structure

Lectures

- Part 1: GPU Basics and Architecture (both: graphics, compute)
- Part 2: GPUs for Compute
- Part 3: GPUs for Graphics

Some lectures might be on research papers (both seminal and current)

Assignments

- 5 programming assignments
- Weekly reading assignments (required; also some optional)

Quizzes

- 4 quizzes, throughout the semester, 30 min each; announced at least a week in advance
- From lectures and (required) reading assignments

Semester project + final presentations, but no mid-term/final exam!

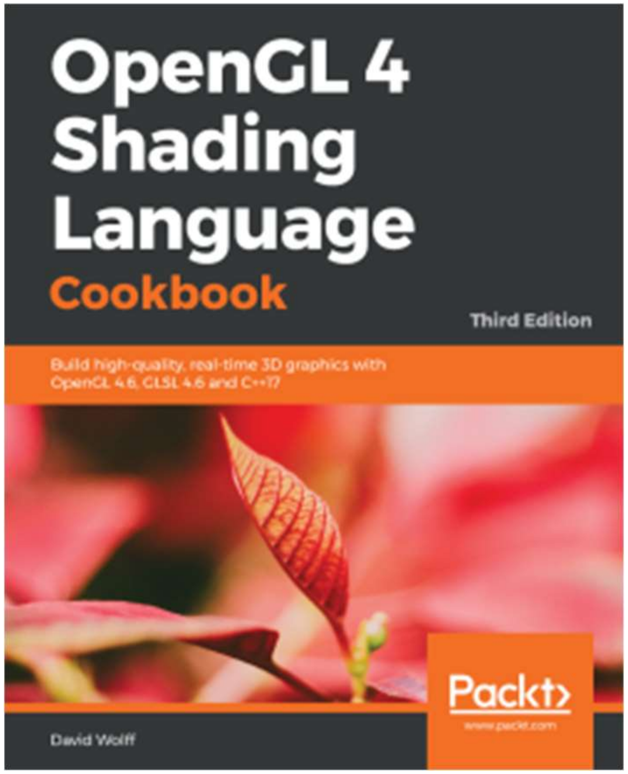
Grading: 40% programming assignments; 30% semester project; 30% quizzes

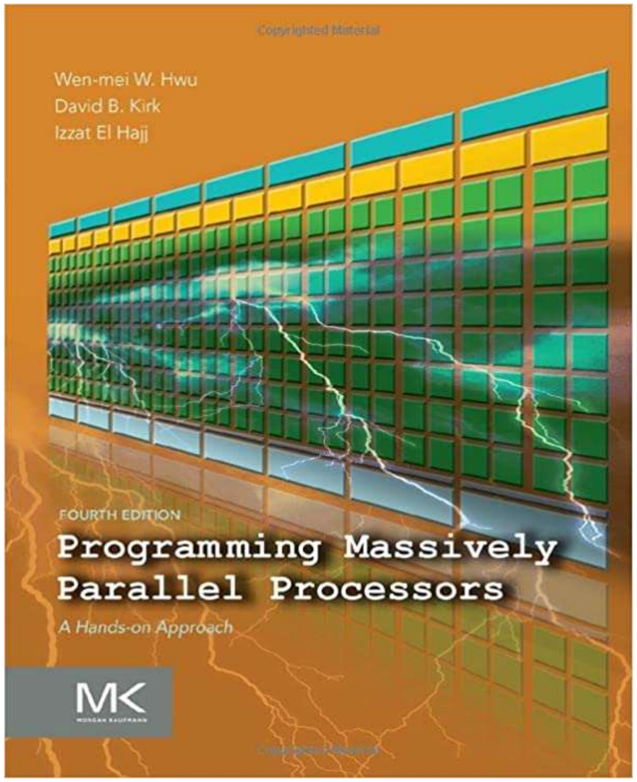
Resources (1)

Textbooks

- GPUs for Graphics: OpenGL 4 Shading Language Cookbook, 2nd or 3rd ed.
- GPU Computing / GPGPU: Programming Massively Parallel Processors, 4th ed.

3rd ed.





4th ed.

Resources (1)

Textbooks

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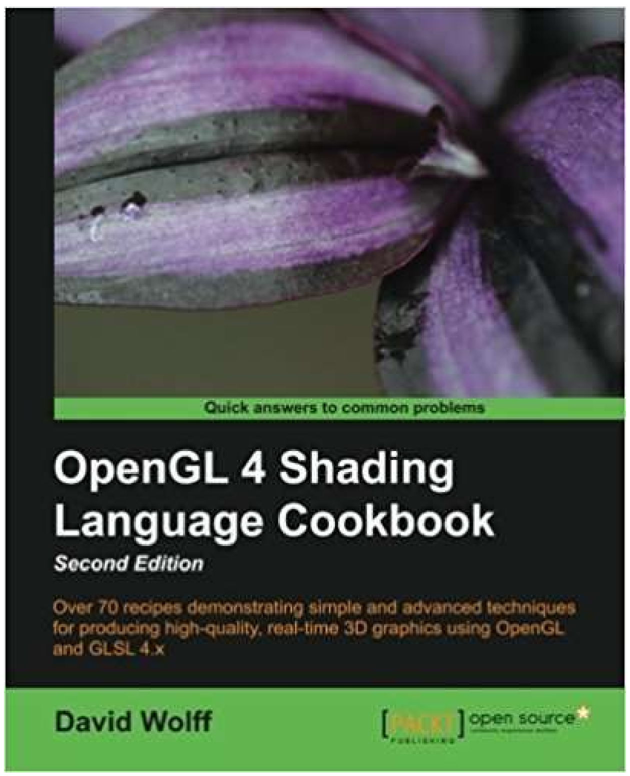
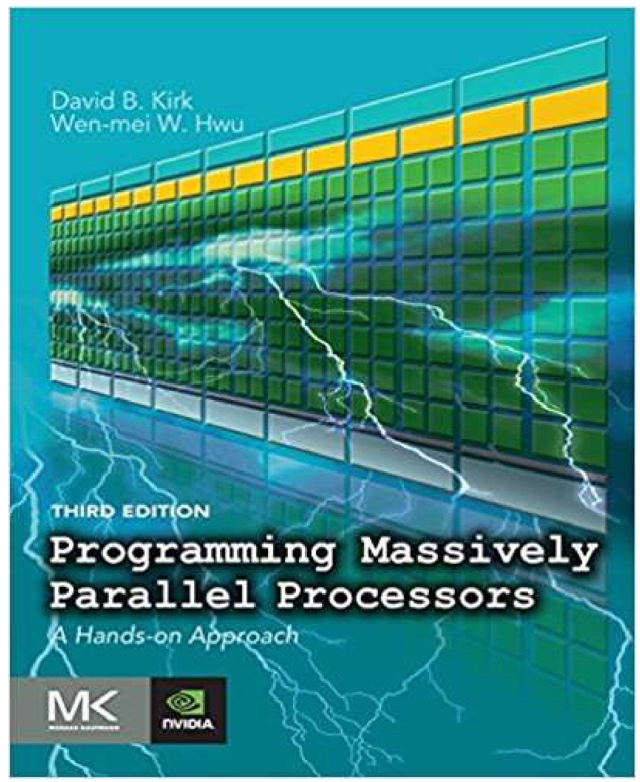
- GPU Computing / GPGPU: Programming Massively Parallel Processors, 4th ed.

2nd ed.





3rd ed.

Resources (2)

`https://vccvisualization.org/CS380_GPU_and_GPGPU_Programming/`

- OpenGL (4.6): www.opengl.org
  www.khronos.org/files/opengl46-quick-reference-card.pdf
- CUDA (12.6): developer.nvidia.com/cuda-toolkit/
- Vulkan (1.3): www.vulkan.org
- OpenCL (3.0): www.khronos.org/opencl/

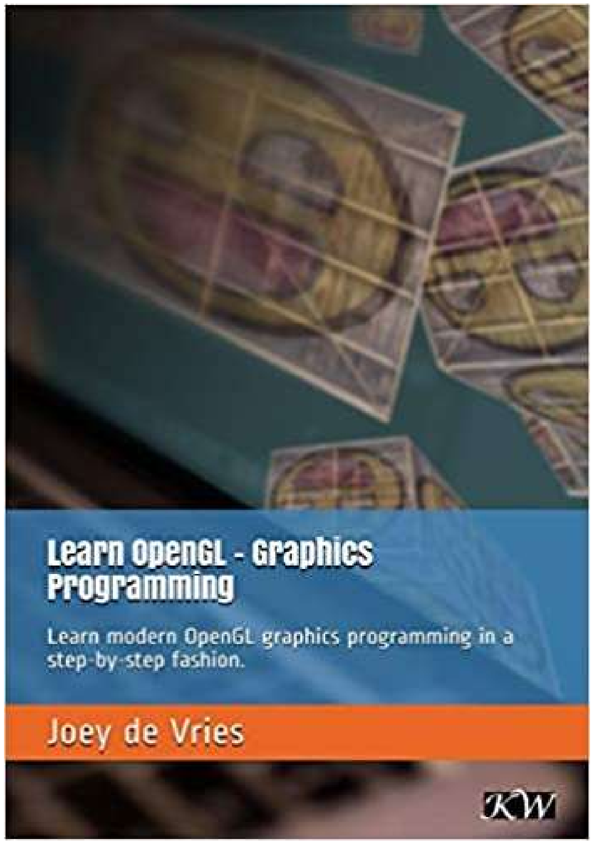
Very nice resources for examples:

- *GPU Gems* books 1-3 (available online)
- *GPU Computing Gems*, Vol. 1 + 2 (Emerald/Jade edition)
- *Ray Tracing Gems* (2019) and *Ray Tracing Gems II* (2021)

Resources (3)

Learn OpenGL

Nice recent introduction to OpenGL



Webpage:

`https://learnopengl.com/`

Free book as pdf:

`https://learnopengl.com/book/book_pdf.pdf`

Resources (4)

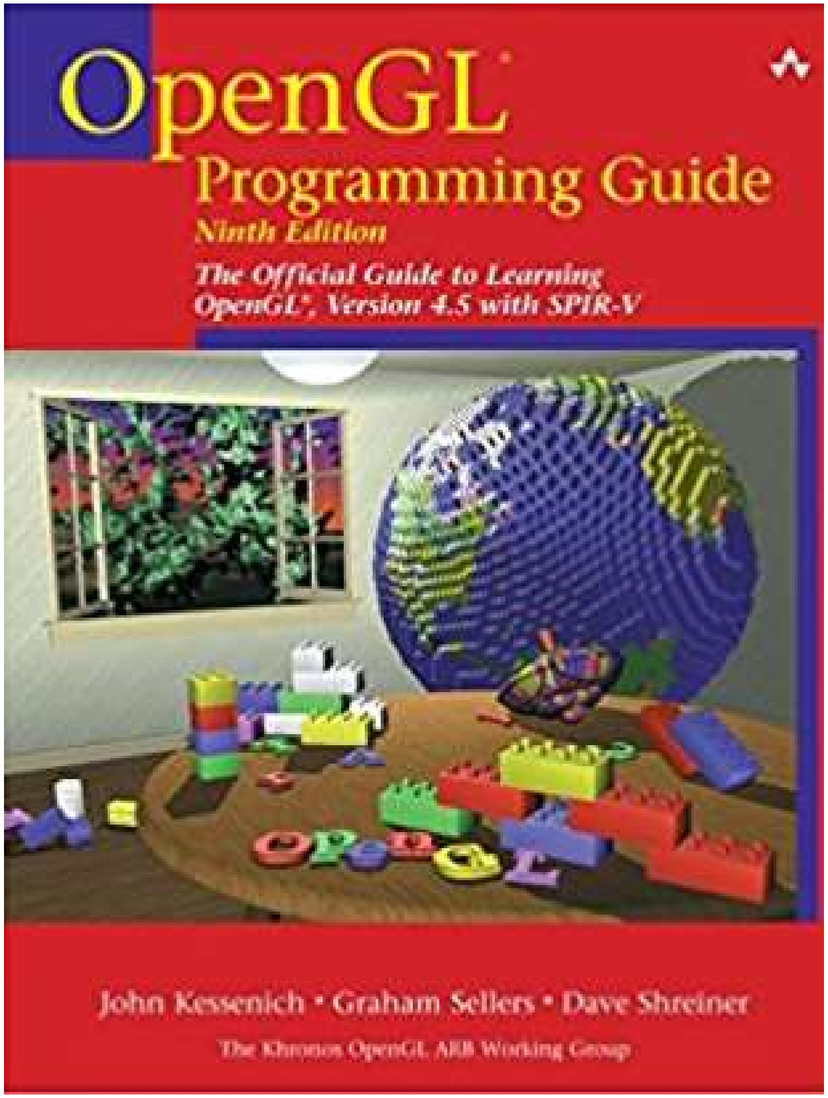
OpenGL Programming Guide (red book)

`http://www.opengl-redbook.com/`

Computer graphics and OpenGL

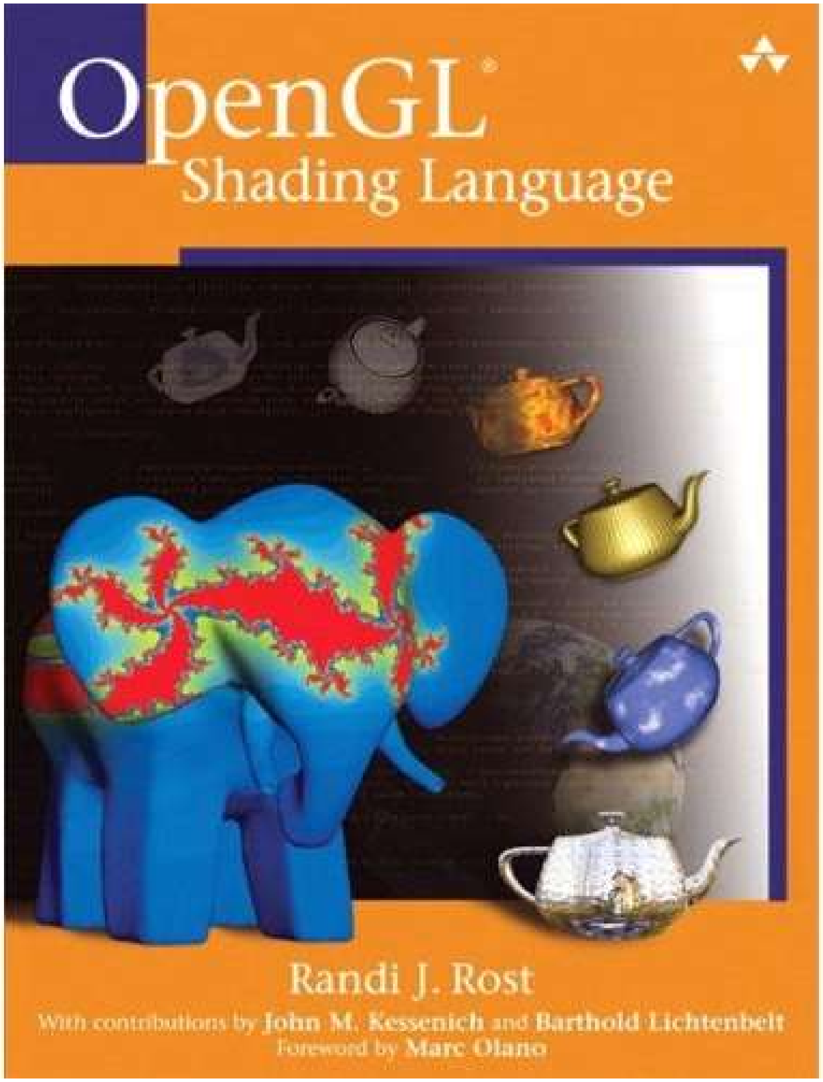
Current edition: 9th
OpenGL 4.5 (with SPIR-V)
contains extended chapters on GLSL

Available in the KAUST library
also electronically



Resources (5)

OpenGL Shading Language (orange book)



Current edition: 3rd
OpenGL 3.1, GLSL 1.4
no geometry shaders

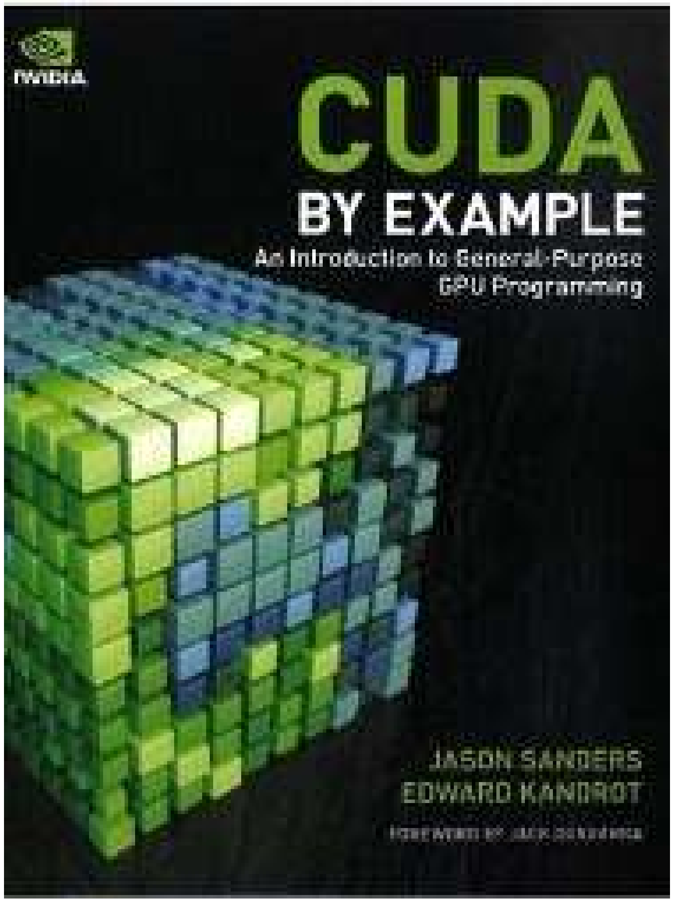
(outdated in several aspects,
but the basics are still very nice!)

Available in the KAUST library
also electronically

Resources (6)

CUDA by Example: An Introduction to General-Purpose GPU Programming, Jason Sanders, Edward Kandrot

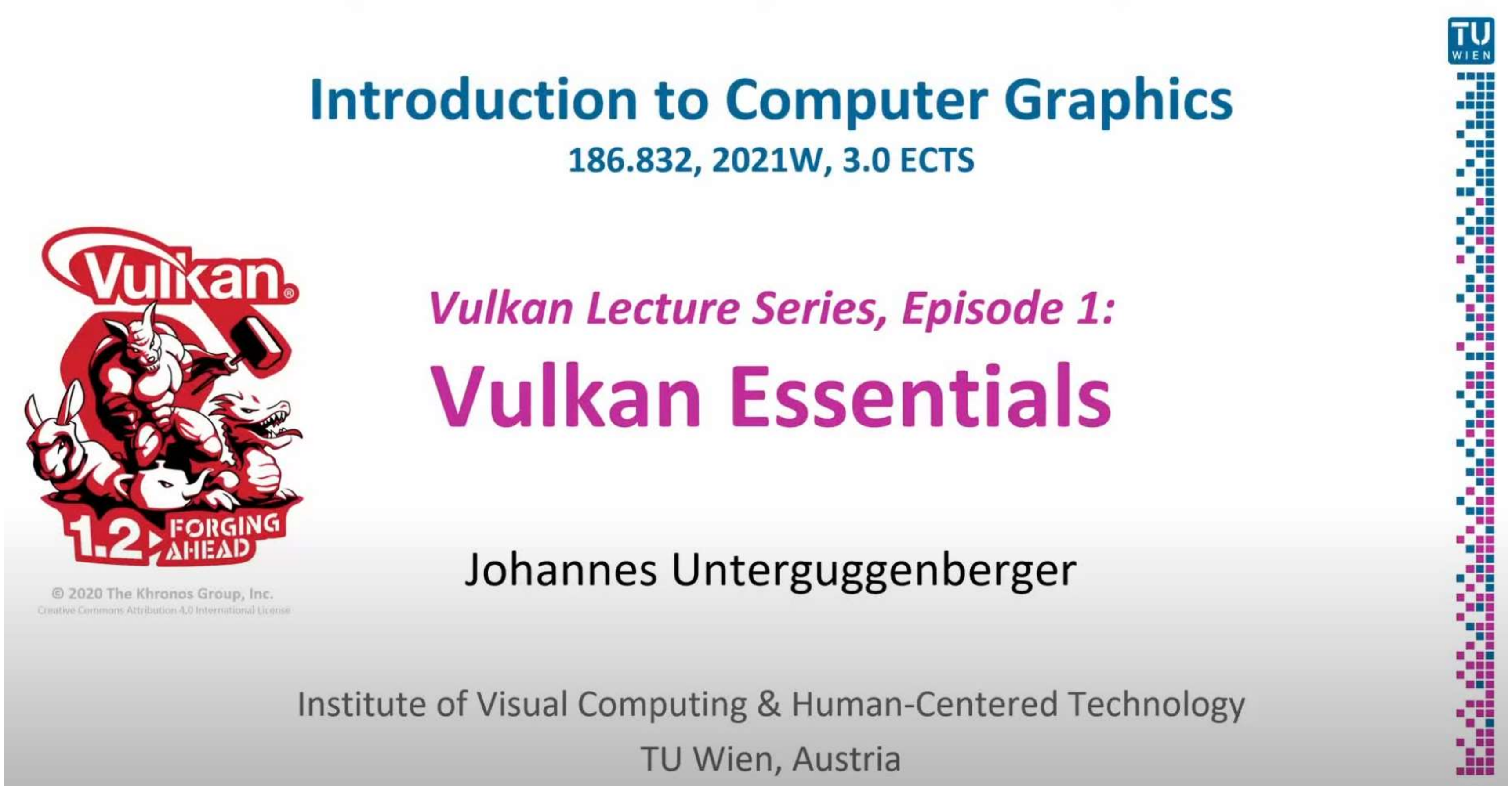
See reference section of KAUST library



Resources (7)

YouTube lecture series on ***Vulkan***:

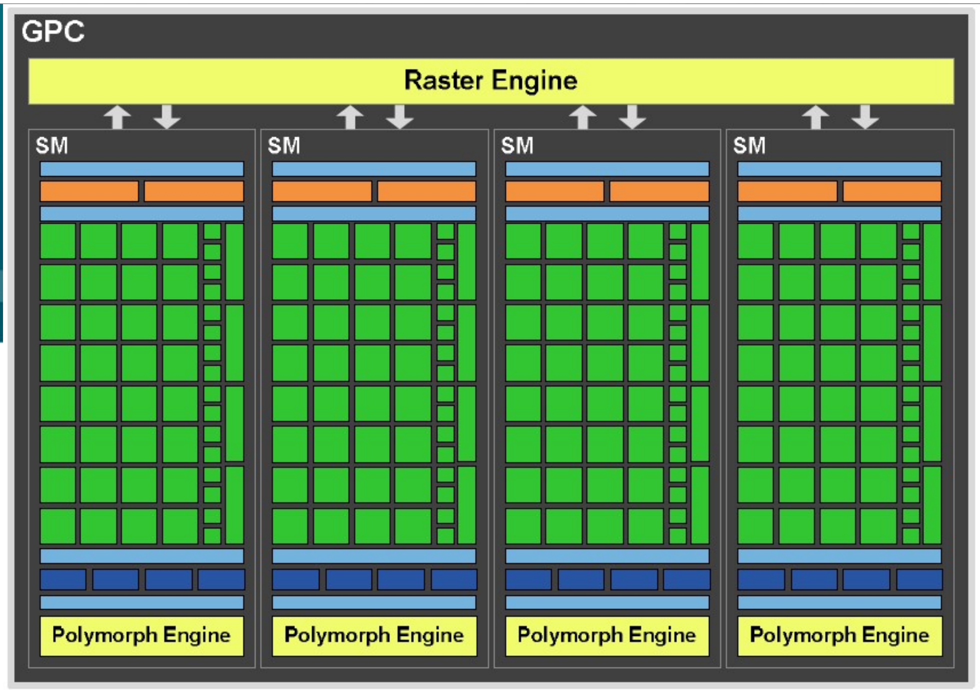
`https://youtu.be/tLwbj9qys18`

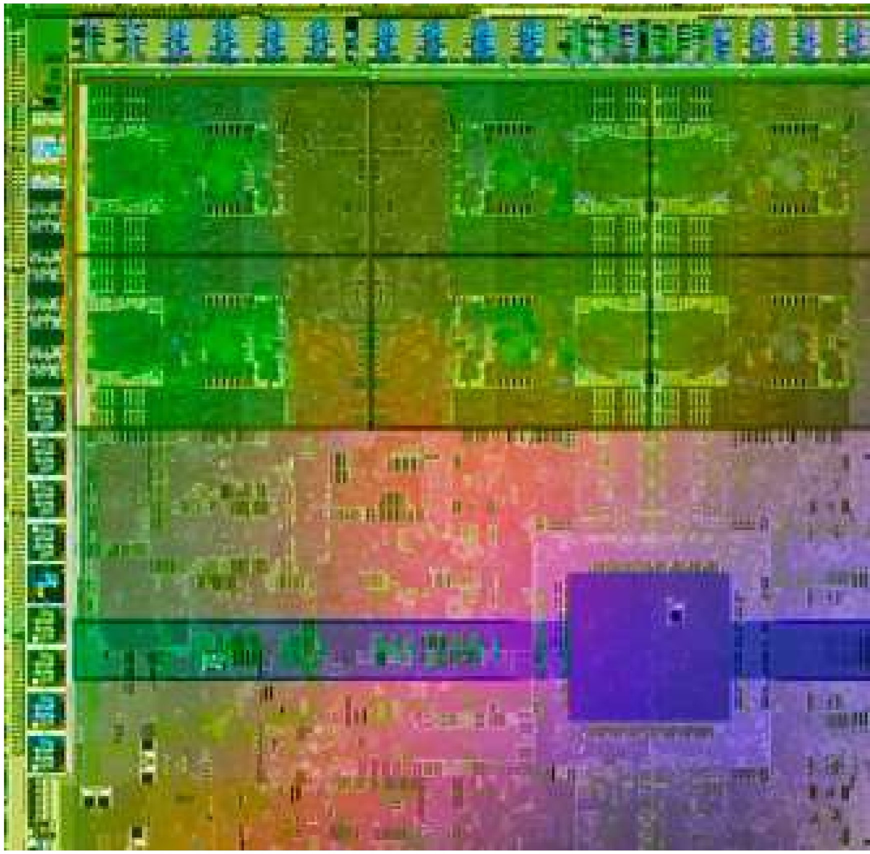


Syllabus (1)

GPU Basics and Architecture
(~September, early October)

- Introduction
- **GPU architecture**
- How compute/shader cores work
- GPU shading and GPU compute APIs
  - General concepts and overview
  - Learn syntax details on your own !
    - CUDA book
    - GLSL book
    - Vulkan tutorial
    - online resources, ...





NVIDIA Architectures (since first CUDA GPU)

Tesla [CC 1.x]: 2007-2009

- G80, G9x: 2007 (Geforce 8800, ...)
  GT200: 2008/2009 (GTX 280, ...)

Fermi [CC 2.x]: 2010 (2011, 2012, 2013, …)

- GF100, ... (GTX 480, ...)
  GF104, ... (GTX 460, ...)
  GF110, ... (GTX 580, ...)

Kepler [CC 3.x]: 2012 (2013, 2014, 2016, …)

- GK104, ... (GTX 680, ...)
  GK110, ... (GTX 780, GTX Titan, ...)

Maxwell [CC 5.x]: 2015

- GM107, ... (GTX 750Ti, ...)
  GM204, ... (GTX 980, Titan X, ...)

Pascal [CC 6.x]: 2016 (2017, 2018, 2021, 2022, …)

- GP100 (Tesla P100, ...)
- GP10x: x=2,4,6,7,8, ...
  (GTX 1060, 1070, 1080, Titan X *Pascal*, Titan Xp, ...)

Volta [CC 7.0, 7.2]: 2017/2018

- GV100, ...
  (Tesla V100, Titan V, Quadro GV100, ...)

Turing [CC 7.5]: 2018/2019

- TU102, TU104, TU106, TU116, TU117, ...
  (Titan RTX, RTX 2070, 2080 (Ti), GTX 1650, 1660, ...)

Ampere [CC 8.0, 8.6, 8.7]: 2020

- GA100, GA102, GA104, GA106, ...
  (A100, RTX 3070, 3080, 3090 (Ti), RTX A6000, ...)

Hopper [CC 9.0], Ada Lovelace [CC 8.9]: 2022/23

- GH100, AD102, AD103, AD104, ...
  (H100, L40, RTX 4080 (12/16 GB), 4090, RTX 6000, ...)

Blackwell [CC 10.0]: *coming in 2024/25*

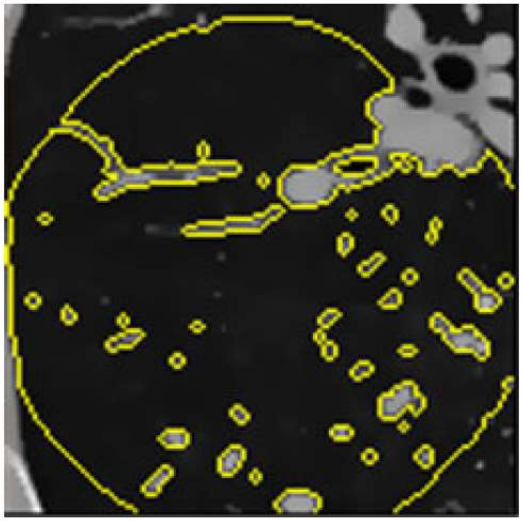
- GB200/GB202, GB20x, ...?
  (RTX 5080/5090, GB200 NVL72, HGX B100/200, ...?)

see `https://en.wikipedia.org/wiki/List_of_Nvidia_graphics_processing_units`
and `https://en.wikipedia.org/wiki/CUDA`

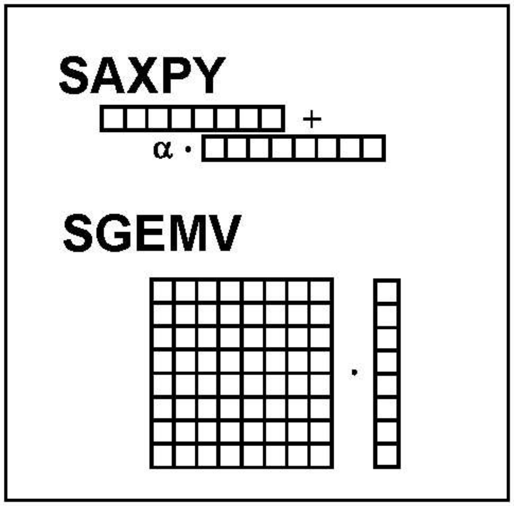
Syllabus (2)

More GPU Computing (~October)

- GPGPU, important parallel programming concepts
- CUDA memory access
- Reduction, scan
- Linear algebra on GPUs
- Deep learning on GPUs
- Combining graphics and compute
  - Display the results of computations
  - Interactive systems (fluid flow, ...)



segmentation



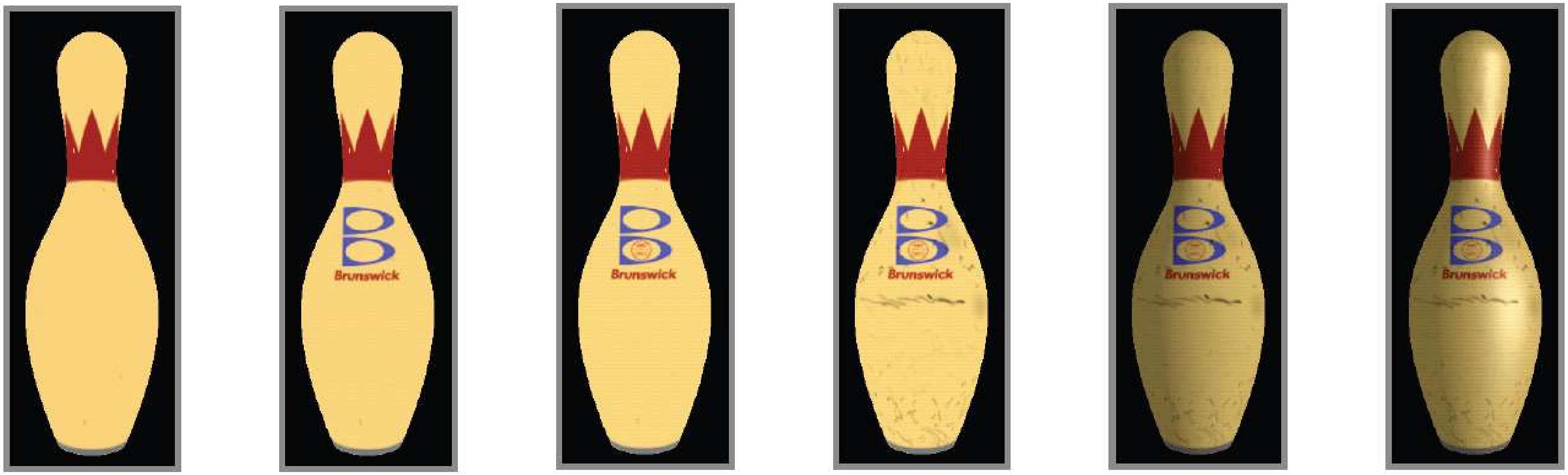
linear algebra

Syllabus (3)

GPU Graphics (~November)

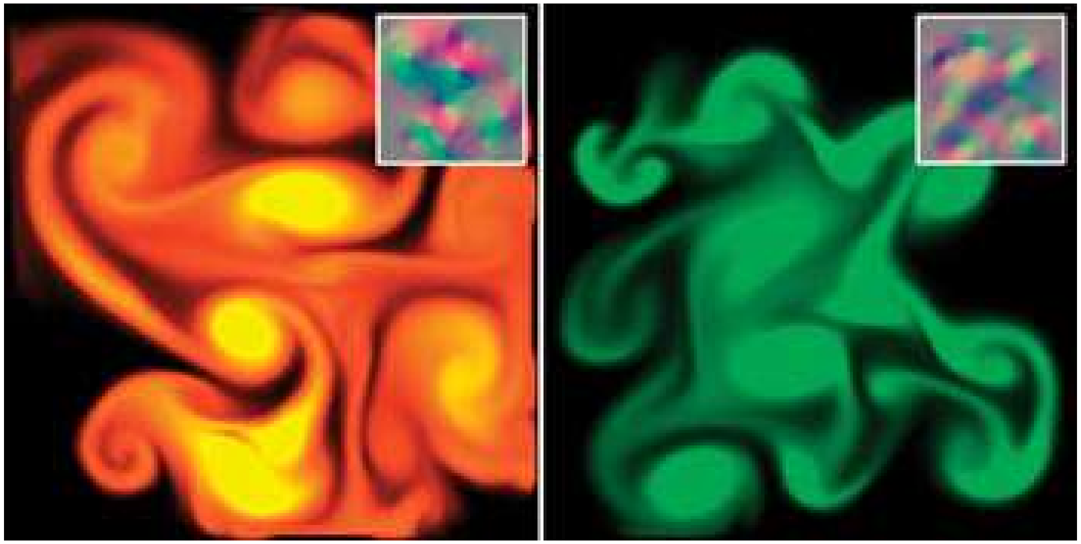
- GPU (virtual) texturing, filtering
- GPU (texture) memory management
- Modern game engine technologies

Semester project presentations



Example: Fluid Simulation and Rendering

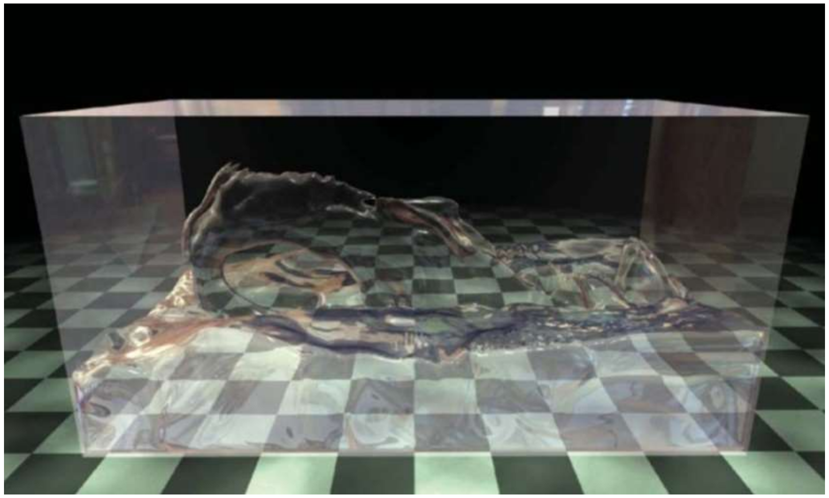
- Compute advection of fluid
  - (Incompressible) Navier-Stokes solvers
  - Lattice Boltzmann Method (LBM)
- Discretized domain; stored in 2D/3D textures
  - Velocity, pressure
  - Dye, smoke density, vorticity, …
- Updates in multi-passes
- Render current frame

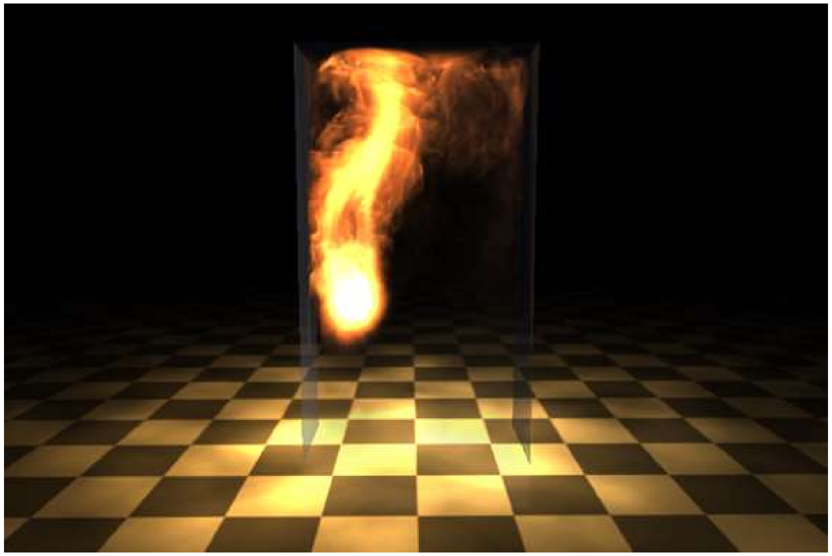


Courtesy Mark Harris

Example: Volumetric Special Effects

- NVIDIA Demos
  - Smoke, water
  - Collision detection with voxelized solid (Gargoyle)
- Ray-casting
  - Smoke: direct volume rendering
  - Water: level set / isosurface





Courtesy Keenan Crane

Example: Ray Tracing

Ray tracing in hardware (ray tracing cores: ray/triangle isect, BVH)

- Microsoft DXR (DX12 Ultimate API), Vulkan, NVIDIA OptiX
- NVIDIA Turing: “World‘s First Ray Tracing GPU“ Quadro RTX, Geforce RTX
- AMD RDNA 2 (also in PS5, Xbox Series X), upcoming Intel Arc (Alchemist, 2022)

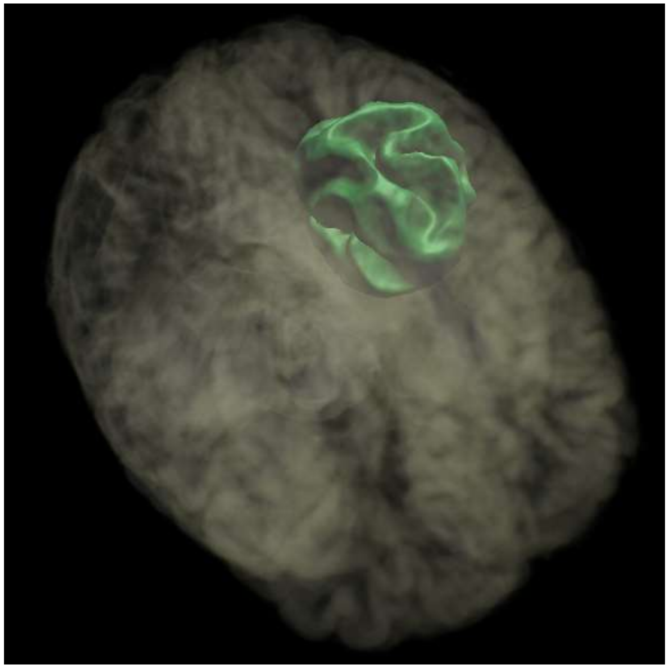
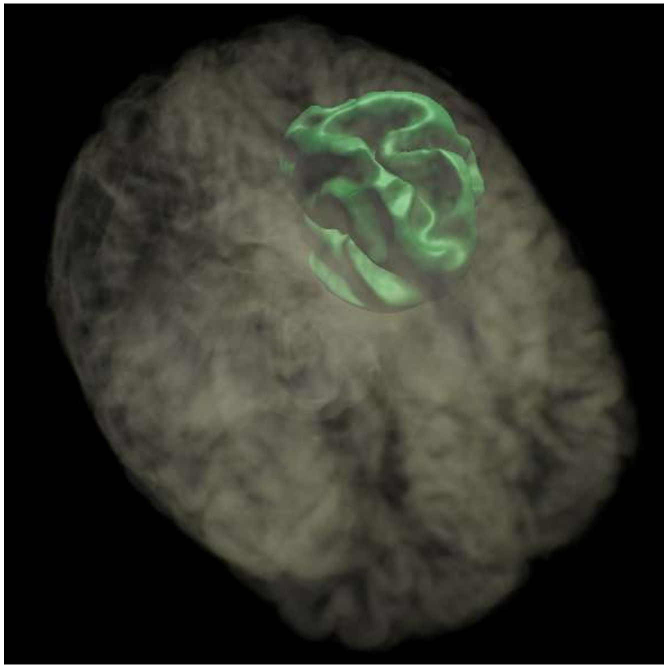
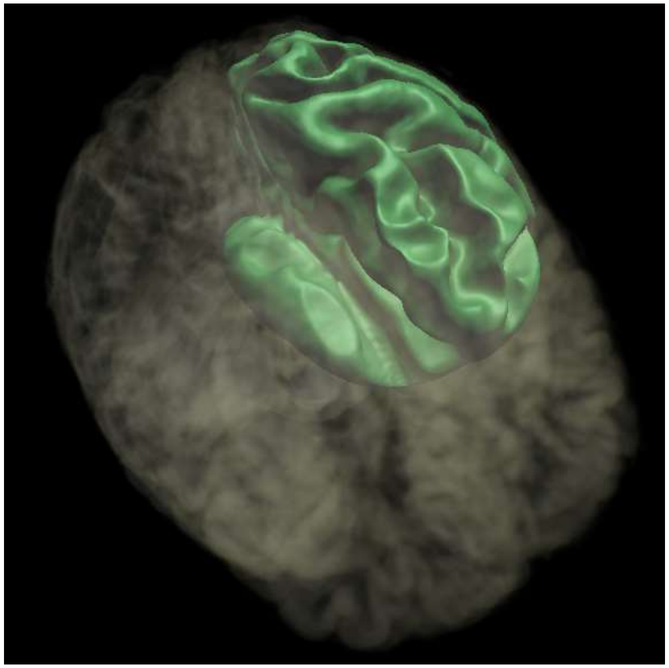
Epic Games Unreal Engine 4 with MS DXR

Example: Particle Simulation and Rendering

- NVIDIA Particle Demo

Example: Level-Set Computations

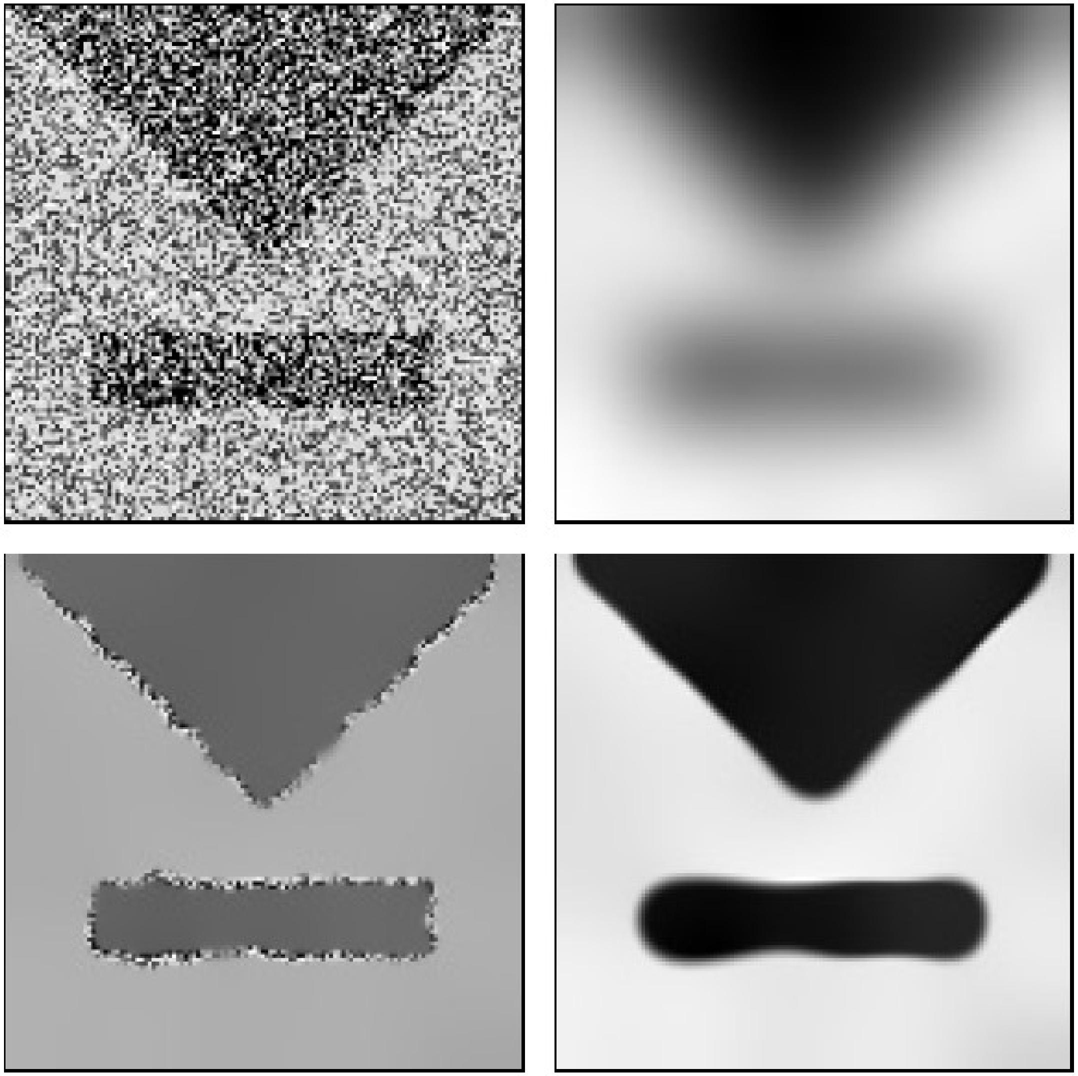
- Implicit surface represented by distance field
- The level-set PDE is solved to update the distance field
- Basic framework with a variety of applications

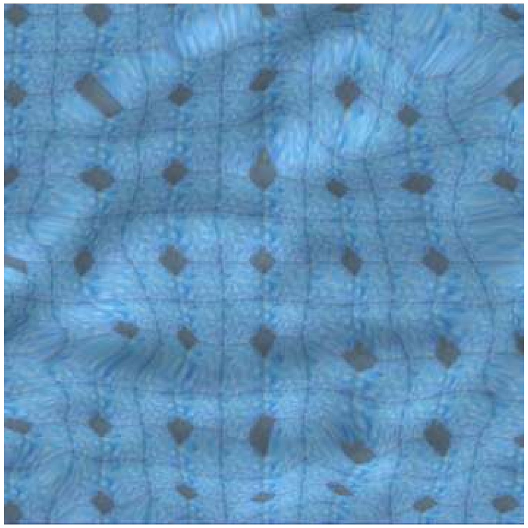
Example: Diffusion Filtering

De-noising

- Original
- Linear isotropic
- Non-linear isotropic
- Non-linear anisotropic

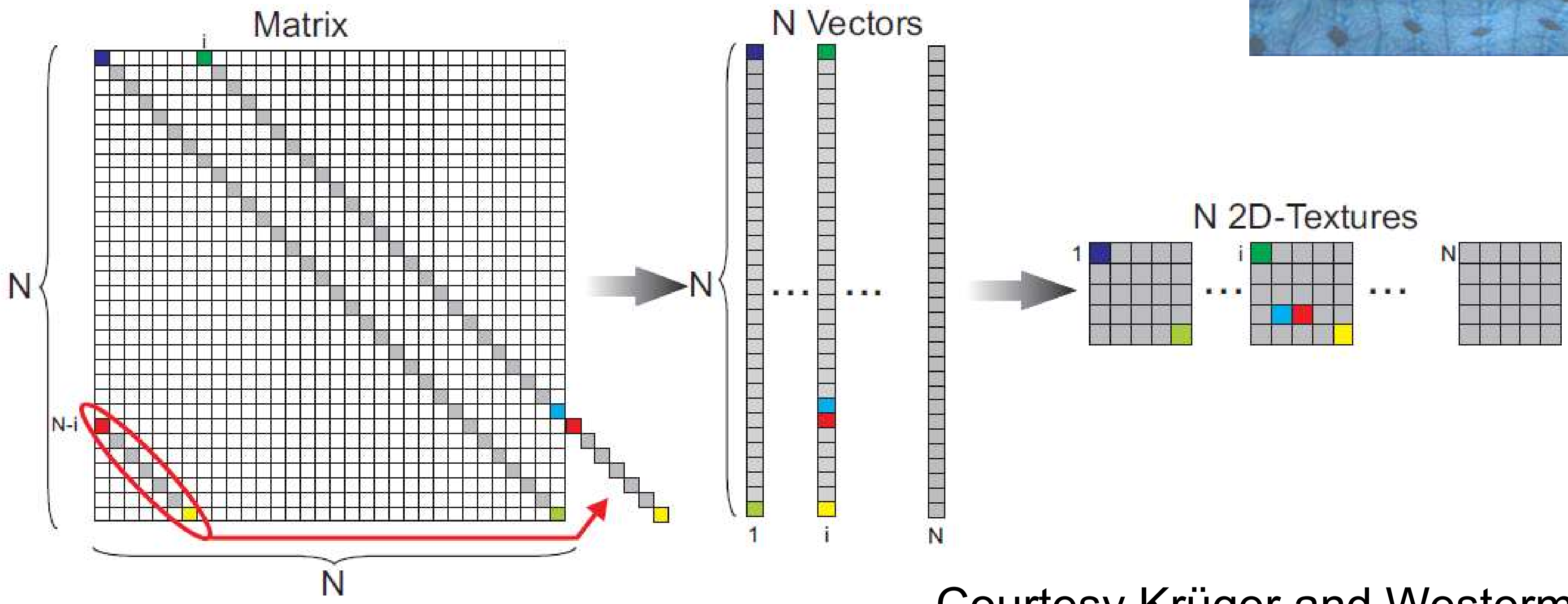


Example: Linear Algebra Operators



Vector and matrix representation and operators

- Early approach based on graphics primitives
- Now CUDA makes this much easier (+ lots of libraries)
- Linear systems solvers



Courtesy Krüger and Westermann

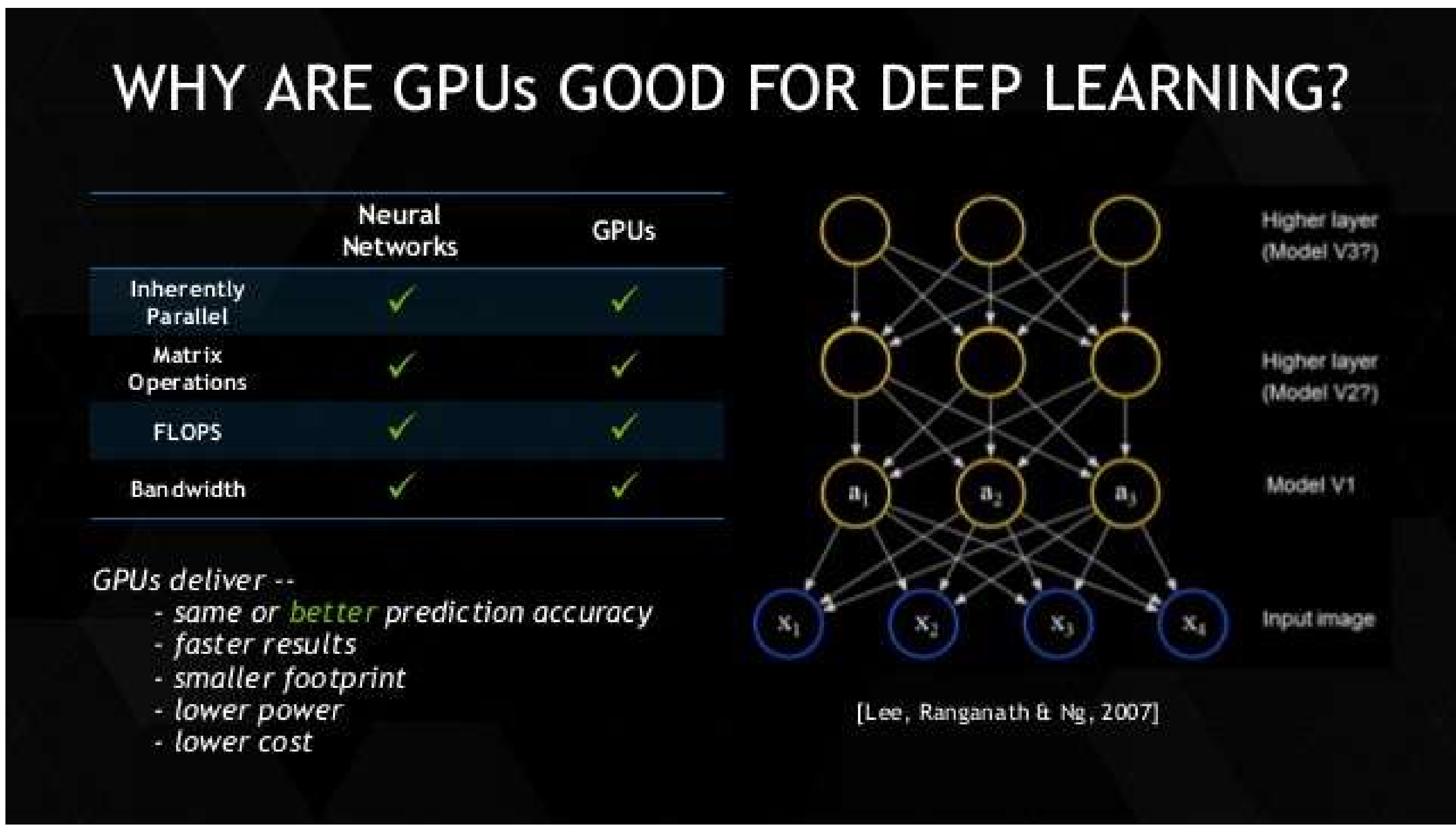
Example: Machine Learning / Deep Learning

Perfect fit for massively parallel computation

- NVIDIA Volta Architecture: Tensor Cores (mixed-prec. 4x4 matrix mult plus add)
- NVIDIA Turing and Ampere architectures: Improved tensor cores, ...

Frameworks

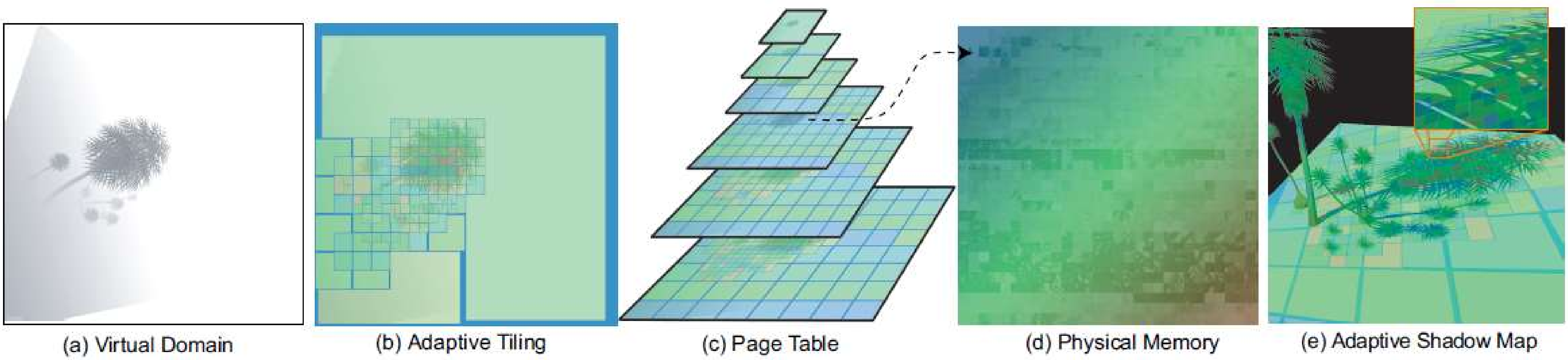
- TensorFlow,
  PyTorch,
  Caffe,
  ...



Example: GPU Data Structures

Glift: Generic, Efficient, Random-Access GPU Data Structures

- “STL“ for GPUs
- Virtual memory management



Courtesy Lefohn et al.

Programming Assignments: Basics

5 assignments

Framework based on C/C++ and several GPU APIs
(**CUDA**, **Vulkan**, OpenGL, OpenCL)

Organization

1. Explanation in readme, and during lecture (and Q&A sessions if required)
2. Get framework online (*github+git*)
3. Submit solution and report online (*github+git*) by submission deadline
4. Personal presentation and assessment after submission

Programming Assignments: People

Teaching Assistants:

- Peter Rautek (**`peter.rautek@kaust.edu.sa`**)
  programming assignments, assignment presentations
- Julio Rey Ramirez (**`julio.reyramirez@kaust.edu.sa`**)
  programming questions, general help
- Reem Alghamdi (**`reem.alghamdi@kaust.edu.sa`**)
  programming questions, general help

Need Help?

1. Google, Stackoverflow, ChatGPT, …

2. Ask your fellow students
   Discussions and explanations are encouraged
   (but: copying code is not allowed!)

3. Contact us:
   Peter: peter.rautek@kaust.edu.sa
   Julio: julio.reyramirez@kaust.edu.sa
   Reem: reem.alghamdi@kaust.edu.sa

Playing with the GPU

GPU programming comes in different flavors:

- Compute: CUDA, OpenCL, HIP; compute API parts of Vulkan, OpenGL, etc.
- Graphics: Vulkan, OpenGL, DirectX

In this course we will:

- Learn to use compute APIs like CUDA and OpenCL and graphics APIs like Vulkan and OpenGL
- Wrap our heads around parallelism
- Learn the differences and commonalities of graphics and compute programming

Format:

- 5 Pre-specified programming assignments
- 1 Capstone (semester) project that you can define yourself

Programming Assignments: Where to Start

- Source code is hosted on *github.com*
- Go to the github repo (Peter will send you info)
- Get a git client http://git-scm.com/downloads and clone your own repo
- Follow the readme text-file
- Do your changes in the source code for assignment 1, commit, and push (to your own repo)
- Contact Peter Rautek if you have problems or questions (`peter.rautek@kaust.edu.sa`)

Graphics API Tutorial

One extra session (attendance optional, but highly recommended!)

To make it easier to get started with Vulkan/OpenGL

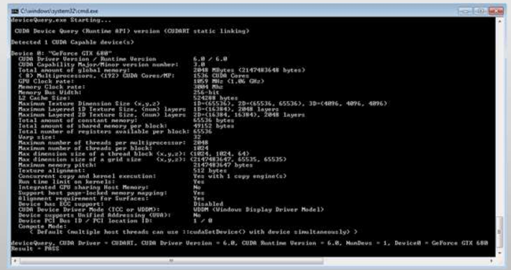
If you already have some questions / problems when you come to the tutorial, that's even better!

Programming Assignment 1

Set up your development environment

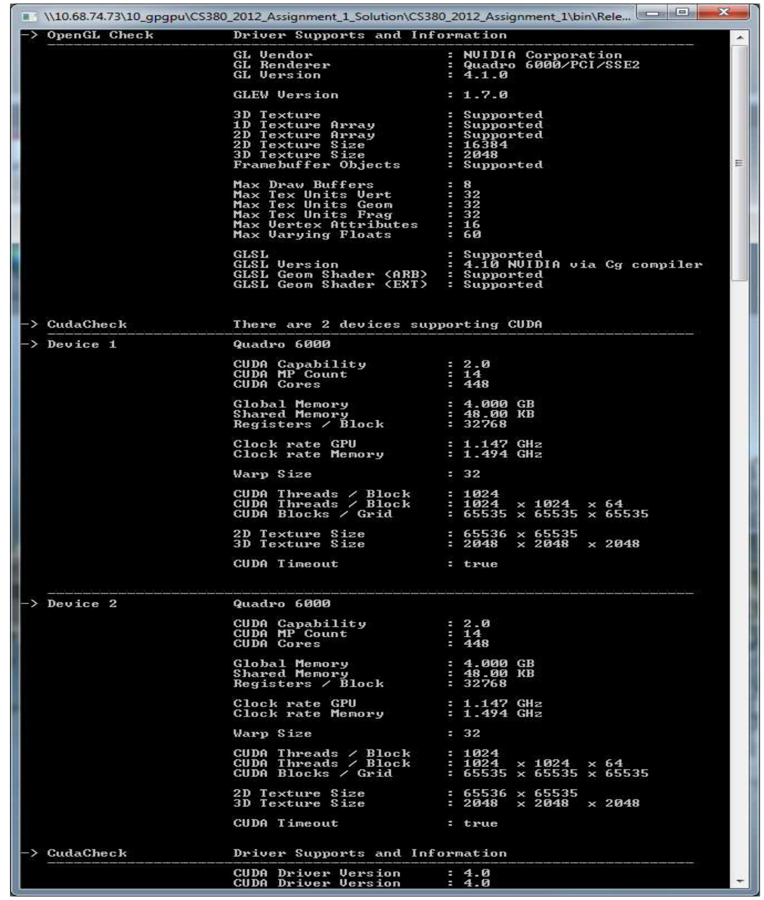
- Visual Studio (either 2019 or 2022) (https://visualstudio.microsoft.com/thank-you-downloading-visual-studio/?sku=Community&rel=16)
- CUDA 12.6 (https://developer.nvidia.com/cuda-downloads)
- git (https://git-scm.com/downloads)
- Fork the CS 380 repository (https://bitbucket.org/rautek/cs380-2024/src/main)
- Follow the readme and start coding

Query your graphics card for its capabilities (CUDA and OpenGL)



Programming Assignment 1 – Setup

- Programming
  - Query hardware capabilities (Vulkan, OpenGL, and CUDA)
  - Instructions in readme.txt file



- Submission (via github)
  - Program
  - Short report (1-2 pages, pdf), including short explanation of program, problems and solutions, how to run it, screenshots, etc.
- Personal assessment
  - Meeting with Peter
  - Max. 15 minutes, present program + source code

Programming Assignments: Grading

- Submission complete, code working for all the required features
- Documentation complete (report, but also source code comments!)
- Personal presentation
- Optional features, coding style, clean solution
- Every day of late submission reduces points by 10%
- No direct copies from the internet or friends!
  You have to understand what you program:
  your explanations during the presentations will be part of the grade!

Programming Assignments: Schedule (tentative)

Assignment #1:

- **Querying the GPU (Graphics and Compute APIs)** due Sep 1

Assignment #2:

- **GPU Compute - Data Parallel Processing** due Sep 15

Assignment #3:

- **GPU Compute - Porting Sequential to Parallel Code** due Oct 6

Assignment #4:

- **Graphics on the GPU - Rasterization Pipeline** due Oct 27

Assignment #5:

- **Graphics on the GPU - Task- and Mesh-Shaders** due Nov 17

Semester / Capstone Project

- Choosing your own topic encouraged!
  (we will also suggest some topics)
  - Pick something that you think is really cool!
  - Can be completely graphics or completely computation, or both combined
  - Can be built on CS 380 frameworks, NVIDIA OpenGL SDK, CUDA SDK, ...
- Write short (1-2 pages) project proposal by end of Sep *(announced later)*
  - Talk to us before you start writing!
    (content and complexity should fit the lecture)
- Submit semester project with report (deadline: Dec 8)
- Present semester project, event in final exams week: Dec 9 (tentative!)

Reading Assignment #1 (until Sep 2)

Read (required):

- Programming Mass. Parallel Proc. book, 4th ed., Chapter 1 (*Introduction*)
- Programming Mass. Parallel Proc. book, 2nd ed., Chapter 2 (*History of GPU Computing*)
- OpenGL Shading Language (orange) book, Chapter 1 (*Review of OpenGL Basics*)

Read (optional):

- OpenGL Shading Language 4.6 (current: Aug 14, 2023) specification: Chapter 2

  `https://www.khronos.org/registry/OpenGL/specs/gl/GLSLangSpec.4.60.pdf`

- Download OpenGL 4.6 (current: May 5, 2022) specification

  `https://www.khronos.org/registry/OpenGL/specs/gl/glspec46.core.pdf`

Thank you.