GPU Compiler Construction at Arm

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Agenda

- About Arm and Mali
- Graphics APIs and Rasterization
- The Compiler
- Day-to-day Challenges of a GPU Compiler Engineer
- Opportunities for Students at Arm
- Wrap up and Questions

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About Arm and Mali

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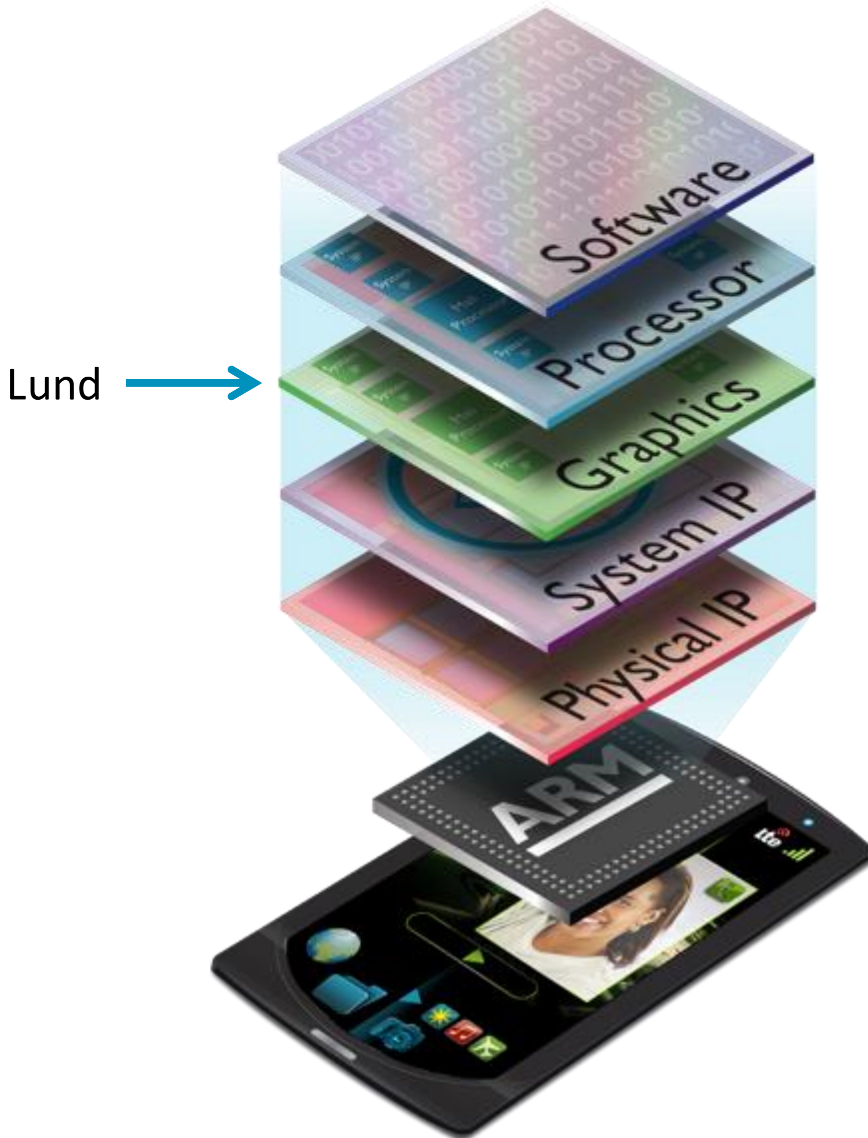
What do we do, in Lund in Specific?

Lund



- Part of MPG – Media Processing Group
- Products:
  - Mali GPUs
  - Mali VPUs (Video Processing Units)
- SW engineering
  - Including the **compiler**
  - Also hardware modelling, video driver etc.
- HW engineering
  - System design, RTL design and verification etc.
- Test development
  - Both SW and HW

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Arm’s Partnership Model

Arm’s partners shipped nearly **15 billion chips** with ARM technology in 2015.

Over **86 billion chips** accumulated over 26 years

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Arm Offices Worldwide

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Graphics APIs and Rasterization

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GPUs and Software

GPUs are built to support specific graphics (and compute) APIs

- Hardware is thus always licensed together with a software driver, implementing the interface to the hardware through these APIs
- Example: OpenGL, DirectX, Vulkan, OpenCL
- The graphics API provides a set of C function calls that implements a technique called rasterization

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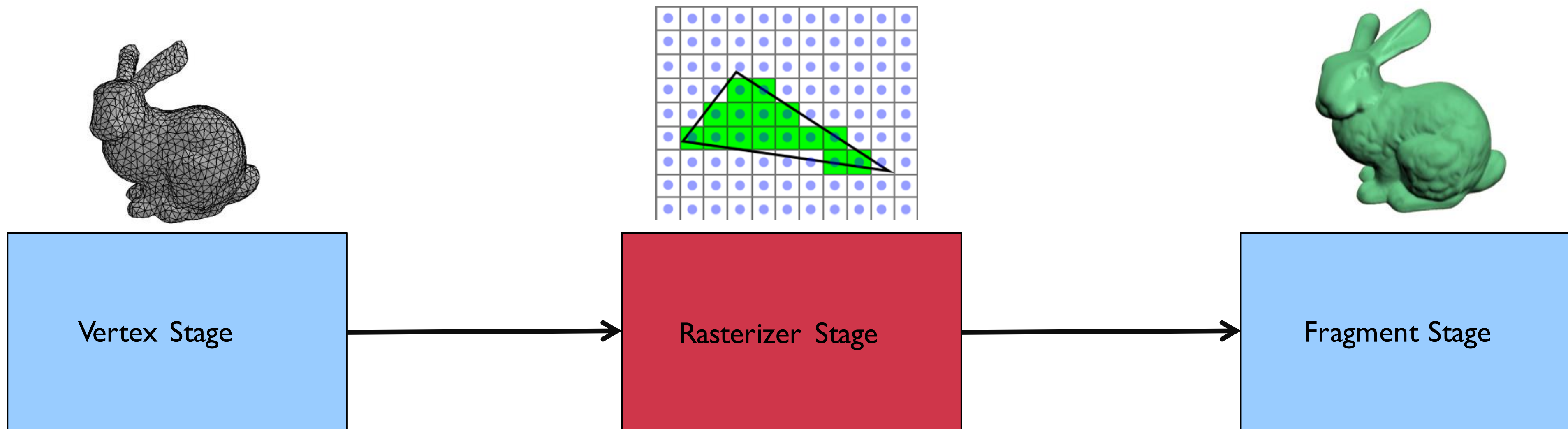
The Rasterization Pipeline

- 3D models to be rendered consist of vertices and primitives (triangles)
- Vertex stage: Transform the position of each vertex depending on the camera
- Rasterizer stage: Compute covered pixels from the resulting vertex positions
- Fragment stage: compute a color for each resulting fragment (pixel)



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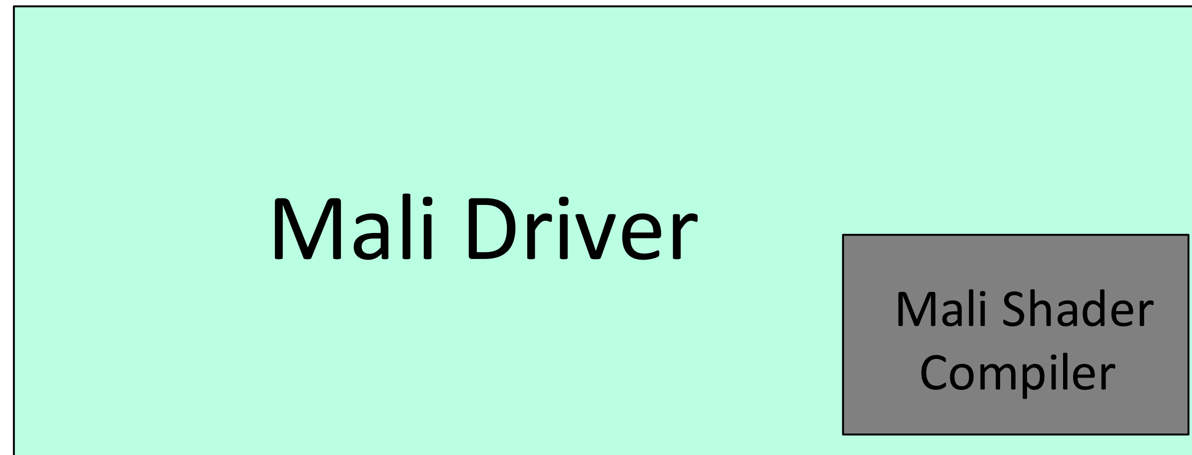
The Mali Shader Compiler

The Mali Shader Compiler transforms **ESSL** source into binary executables for the GPU

- Compiler is just one part of a larger driver
  - Development requires cooperation with other software teams
  - Compiler is shipped together with rest of driver on mobile phones and other devices



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Compiler Performance

- Competitors implement the same APIs, compete on performance
- The code is almost always hot
- If the compiler perfoms badly, it will reduce the frame rate

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The Compiler

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The Compiler Frontends

We implement several frontends with many different configurations

- OpenGL ES Shading Language
  - Defines several shader types, versions and extensions on top of the core language
- SPIR-V (intermediate representation used in Vulkan)
  - The newest graphics frontend, feature-wise similar to OpenGL ES Shading Language
- OpenCL/Vulkan Compute Kernels
  - C/C++-style compute language

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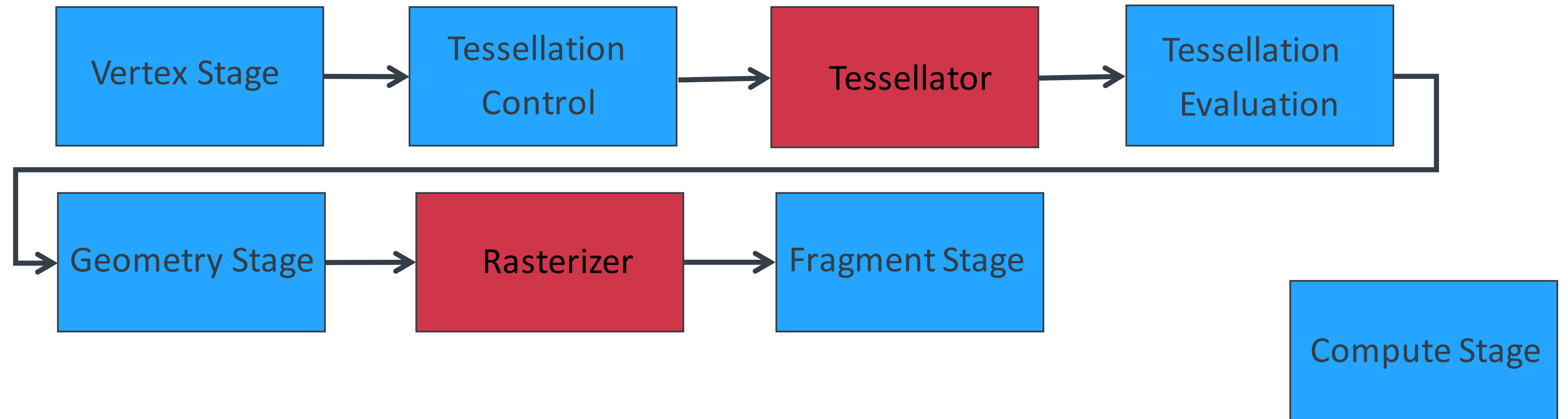
OpenGL ES Shading Language

Most widely used graphics programming language for mobile

- Six shader stages
- Several extensions on top of the core language



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OpenGL ES Shading Language Features

Core language is similar to C, but with some differences

- Significantly simpler (no pointers or recursive function calls)
- Provides an in/out interface for each stage in the graphics pipeline
  - In/out variables to communicate with other stages
  - Read-only memory that is shared between threads
  - Global memory that can be both read and written
- The language defines a large number of built-in functions
  - Mathematical functions, such as 'cos' and 'normalize‘
  - Texture lookups, to read color values from textures
  - Atomic operations
- Available features can be configured through extensions

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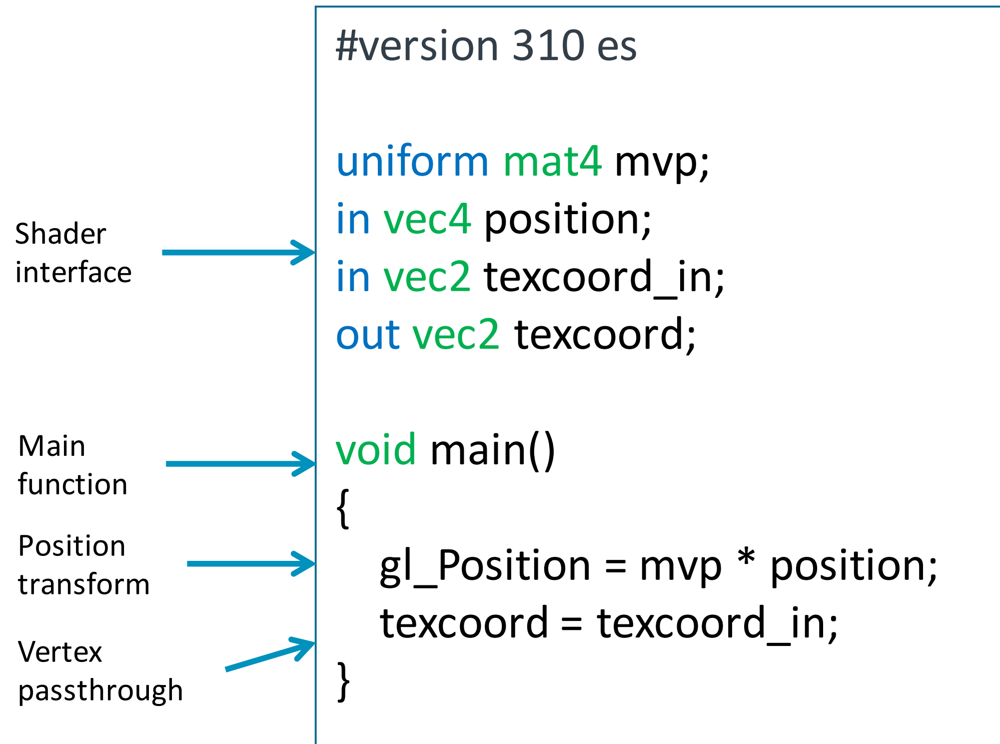
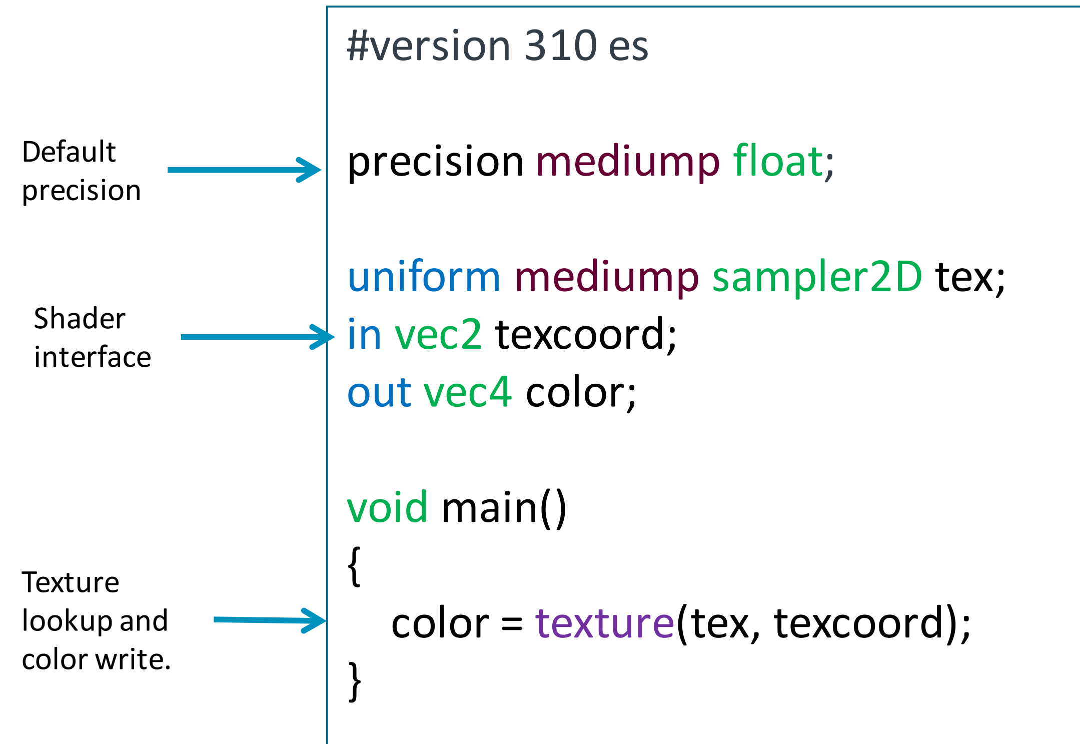
Shader Examples




```
#version 310 es

uniform mat4 mvp;
in vec4 position;
in vec2 texcoord_in;
out vec2 texcoord;

void main()
{
    gl_Position = mvp * position;
    texcoord = texcoord_in;
}
```




```
#version 310 es

precision mediump float;

uniform mediump sampler2D tex;
in vec2 texcoord;
out vec4 color;

void main()
{
    color = texture(tex, texcoord);
}
```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Vulkan and SPIR-V

Vulkan is the newest graphics API, and provides a slightly different approach to programmable pipeline stages

- Uses the “Standard Portable Intermediate Representation”, or SPIR-V, as shader language
- An intermediate representation is typically used in compilers to represent code closer to assembly than the original source, but still high level enough to not be too HW specific
- Feature-wise very similar to OpenGL ES Shading Language
  - Same shader types
  - Supports similar built-in operations
  - Also supports extensions for added features in the future

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SPIR-V Intermediate Language

Vulkan shaders are supplied directly in IR form

- Easier to parse than OpenGL ES Shaders, but still contains many high-level operations
- Optimally code generation could be done directly on SPIR-V IR, but not possible in practice
  - No guarantee input is optimized for our HW
  - Several operations cannot necessarily be natively transformed into GPU HW instructions
- Then what are the benefits?
  - Tools in the graphics ecosystem targeting SPIR-V can be shared between different vendors.

```
%1 = OpLabel
%2 = OpLoad %11 %samp
%3 = OpLoad %v2f32type %out_texcoord0
%4 = OpImageSampleImplicitLod %v4f32type %2 %3
%5 = OpLoad %v2f32type %out_texcoord0
%6 = OpVectorShuffle %v4f32type %5 %5 0 0 1 1
%7 = OpFAdd %v4f32type %4 %6
     OpStore %color %7
     OpReturn
     OpFunctionEnd
```


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OpenCL

General purpose compute on GPUs.

- API + programming languages for general purpose compute on GPUs
- Programming languages are based on C99 and C++
- Same API as on desktop, but different set of extensions
- SPIR-V support
- Coming up: Compute on Vulkan?
- A common application on mobile devices is image filtering

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The OpenCL C++ Kernel Language

- New in OpenCL 2.1, C++14 subset
- No virtual functions (override), no function pointers unless compile-time constant expression, no recursive calls
  - Means everything can be inlined into every entrypoint (kernel)
- Templates, lambda expressions and function overloading are available
  - Enables generic and meta programming
- Built-in vector data types similar to GLES

```
template <typename T, size_t Rows, size_t Columns>
class Matrix {
...
};

template <typename T, size_t Rows, size_t Columns>
Matrix<T, Rows, Columns> operator*(
    const Matrix<T, Rows, Columns>& x,
    const Matrix<T, Rows, Columns>& y) {
...
}

kernel void matrix_mult(float4 *A_vec,
                        float4 *B_vec,
                        float4 *Res) {
  size_t ID = get_global_id(0);

  Matrix<float, 2, ,2> A = to_matrix(A_vec[ID]);
  Matrix<float, 2, ,2> B = to_matrix(B_vec[ID]);

  Res[ID] = to_vector(A * B);
}
```


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OpenCL Support in the Mali Compiler

- Leverages the Clang frontend
  - Our colleague is Code Owner for OpenCL in Clang
- Mostly supported in Cambridge

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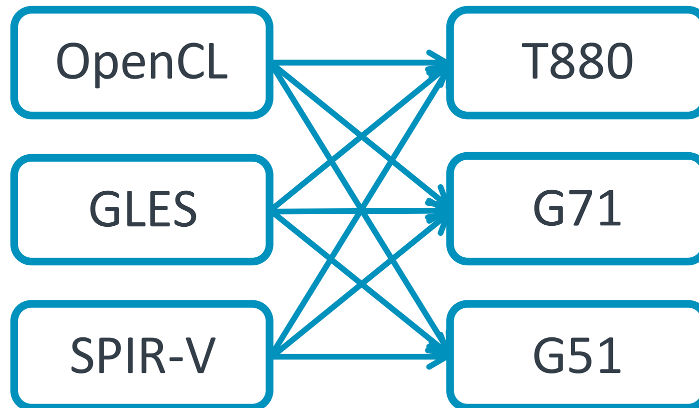
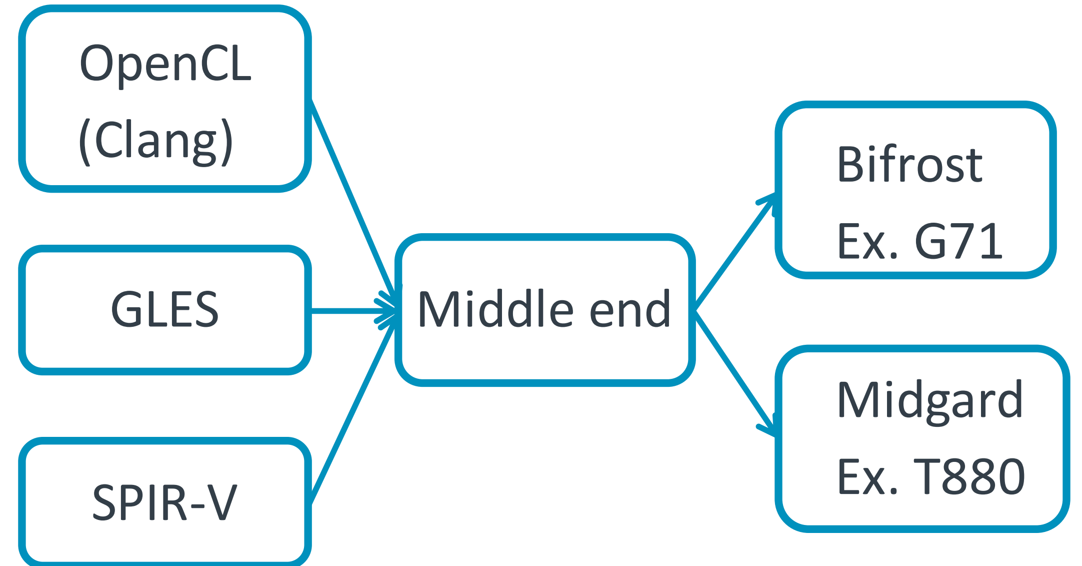
Handling Multiple APIs and Targets

- Handle several APIs using IR and middle end





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Day-to-day Challenges of a GPU Compiler Engineer

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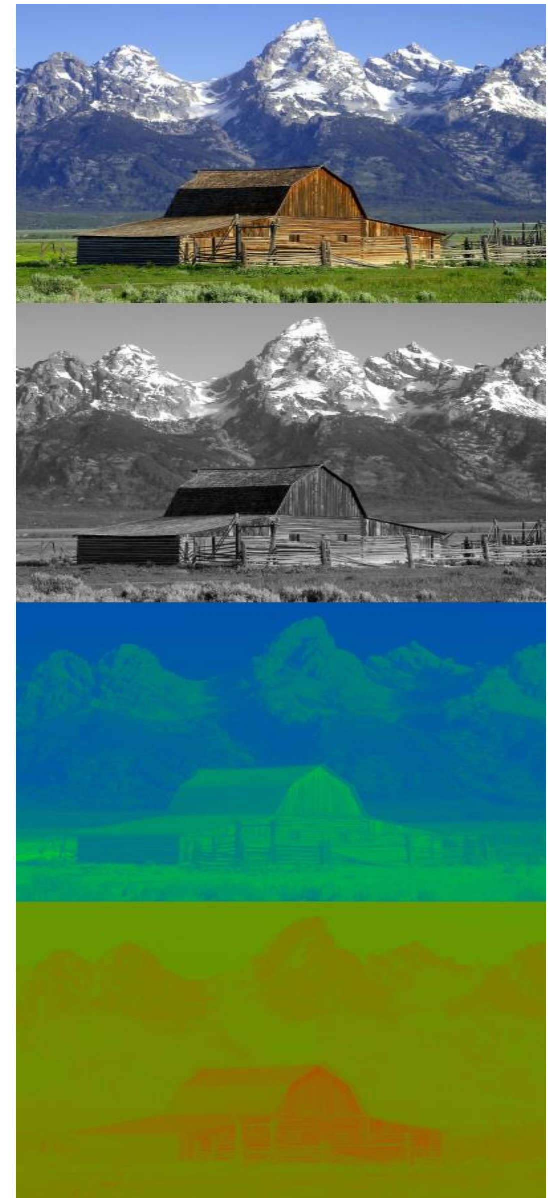
Implementing New Graphics Features

- New features are sometimes added, for example an update to the API, new extensions or even completely new APIs.
- This requires analyzing and understanding the features, and to create a plan on how the implementation should be done.



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Implementing New Graphics Features

- Typically new built-in constructs in the language
  - New built-in variables or functions, texture formats etc.
- Correctness of course important, but also performance
  - Are the new features optimized for the important use cases?
  - What are these important use cases?

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Performance Work

- One of the biggest selling points, so quite important part of our work
- Includes both analysis and implementation work
- Implementation can be general compiler improvements or more graphics specific optimizations

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Performance Work cont.

- Performance on benchmarks and apps are typically measured in FPS
- Content can include hundreds of shaders, understanding which ones to focus on is important
- Understanding general flow and bottlenecks of content is also important

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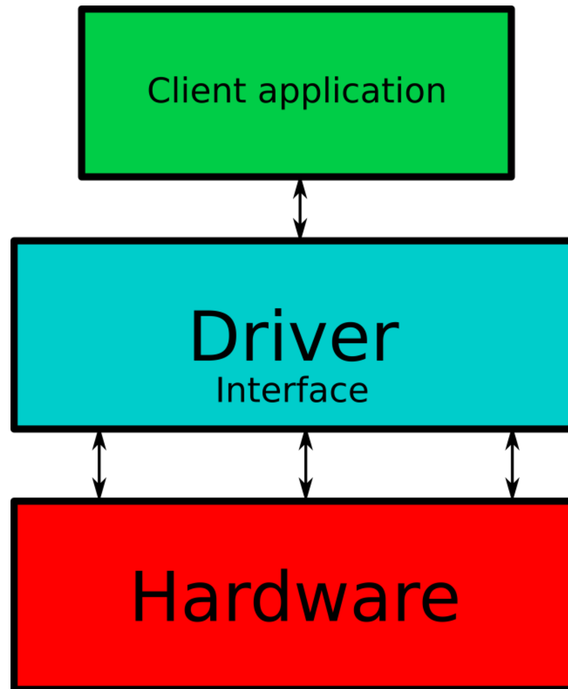
Supporting New Hardware

The APIs implemented in the driver are the interfaces for applications!



The hardware can change a lot!

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Supporting New Hardware

Common changes include:

- Changes to the ISA (new instructions, slight changes to instruction, removed instructions)
  - The ISA can change even between GPUs of the same architecture
- A new hardware feature that the driver needs information from the compiler to utilize
- A new architecture with an entirely new ISA
- Collaboration with the hardware team

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Compilation Time

Since the compiler is running on user devices, reducing compilation time is important

- Normally would be running as a part of the driver, but profiling there is hard
  - Usually use a stand alone compiler program for profiling
- The open source projects we're using don't always fit our use-case
  - Sometimes we need creative solutions for how to adapt them
- Otherwise optimize like any other program
  - Profile using some tools to find problem areas
  - Read the code, see if something can be improved a lot
  - Implement and measure the result

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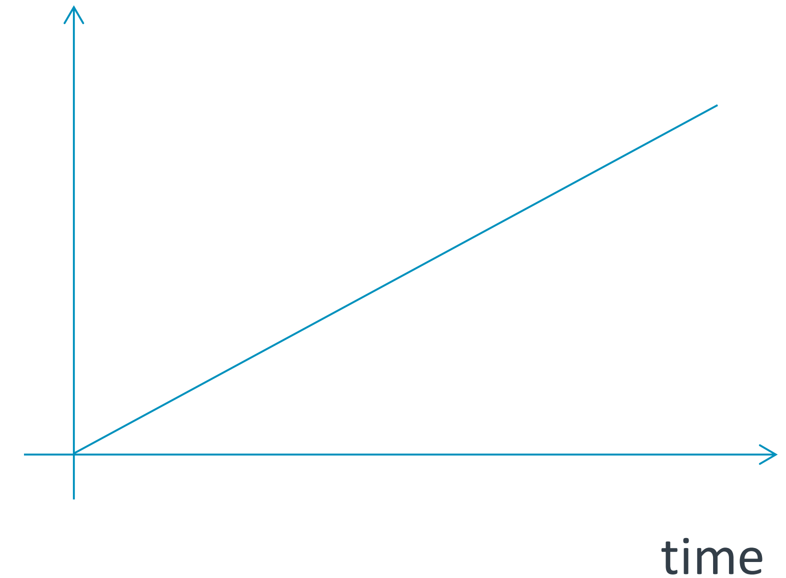
Working Downstream with Upstream Code

- Problem: OS projects we’re using don’t always fit our needs
  - Solution: Add downstream changes (not upstreamed)
- When updating to newer versions such changes can break…
  - …but we want the new features!
- Often when working with a problem we need to consider…
  - …maintainability
  - …performance
  - …compilation time
  - …upstream friendliness



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Opportunities for Students at Arm

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Opportunities

- Internships
  - Part time during a semester or full time during summer
- Thesis
- Graduate positions

- Want to know more?
  - 10 Oct in the entrance of E-huset
  - ARKAD
  - Teknikfokus
  - Email us: karl.hylen@arm.com, erik.hogeman@arm.com

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