King Abdullah University of Science and Technology KAUST

CS 380 - GPU and GPGPU Programming
Lecture 5: GPU Architecture, Pt. 2

Markus Hadwiger, KAUST

Reading Assignment #3 (until Sep 18)

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 4 Shading Language Cookbook, Chapter 2
- OpenGL Shading Language 4.6 (current: Jul 10, 2019) 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`

Read (optional):

- Orange (GLSL) book, Chapter 7 (OpenGL Shading Language API)
- OpenGL 4 Shading Language Cookbook, Chapter 1

GPU Architecture

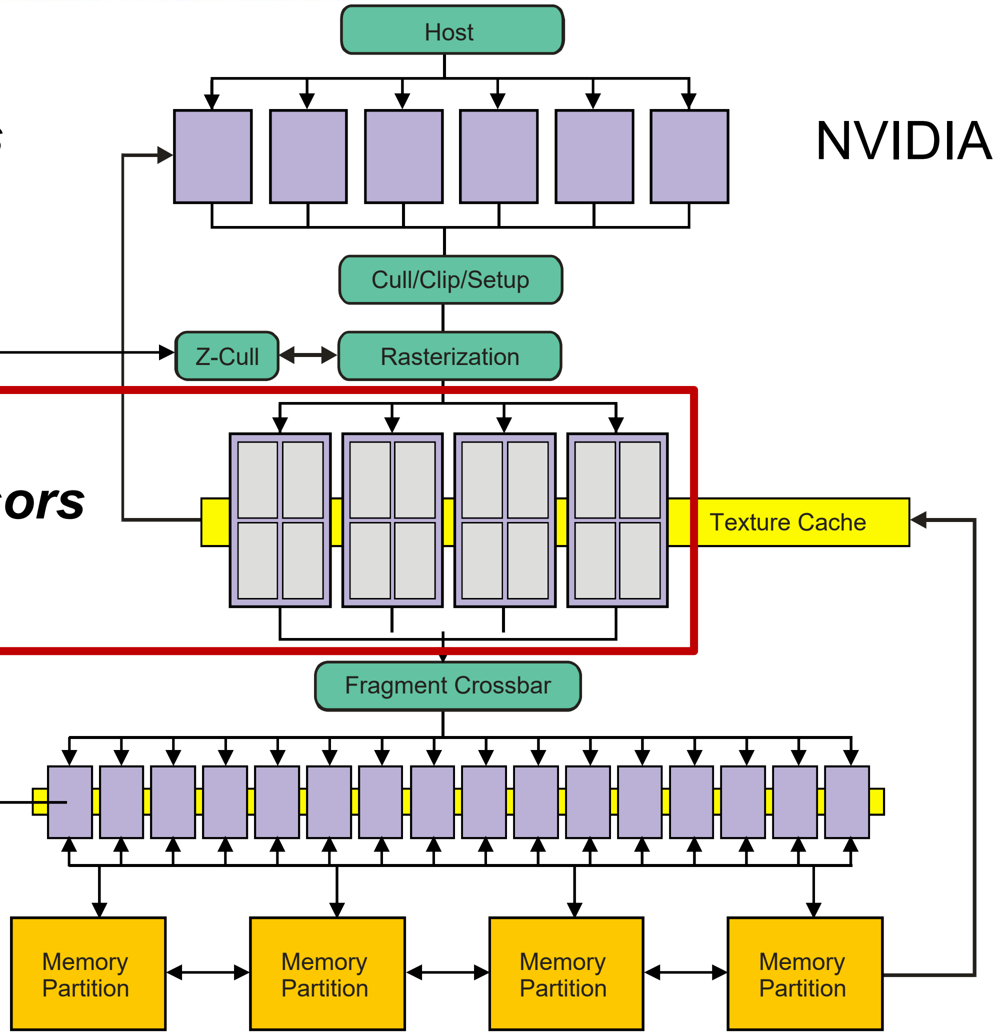
GPU Structure Before Unified Shaders

Vertex Processors

Fragment Processors

Memory Access
Z-Compare and
Blending (ROPs)

NVIDIA Geforce 6/7
(NV40)
2004, 2005

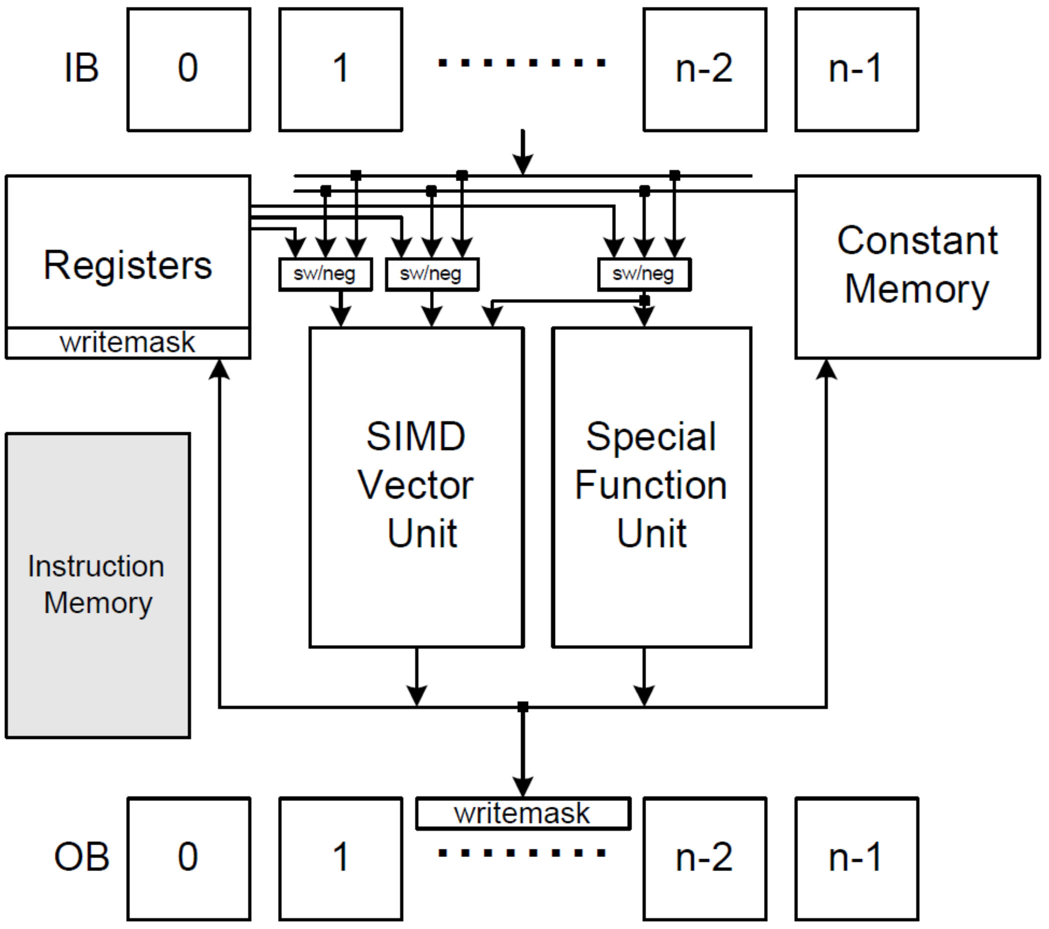


Legacy Vertex Shading Unit (1)

Geforce 3 (NV20), 2001

- floating point 4-vector vertex engine

- still very instructive for understanding GPUs in general



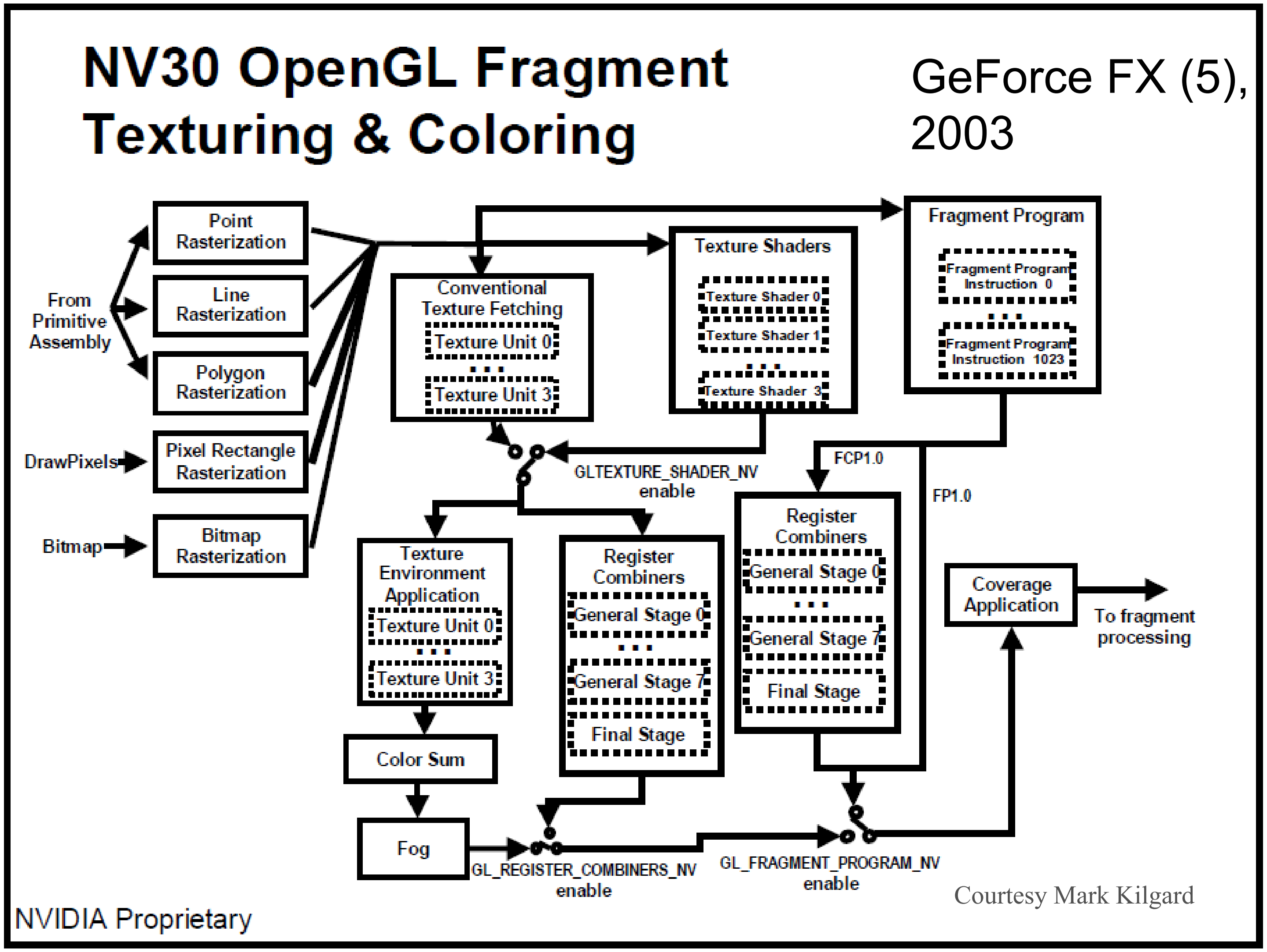
Lindholm et al., A User-Programmable Vertex Engine, SIGGRAPH 2001

Legacy Vertex Shading Unit (3)

Vector instruction set, very few instructions; **no branching** yet!

OpCode	Full Name	Description
MOV	Move	vector -> vector
MUL	Multiply	vector -> vector
ADD	Add	vector -> vector
MAD	Multiply and add	vector -> vector
DST	Distance	vector -> vector
MIN	Minimum	vector -> vector
MAX	Maximum	vector -> vector
SLT	Set on less than	vector -> vector
SGE	Set on greater or equal	vector -> vector
RCP	Reciprocal	scalar-> replicated scalar
RSQ	Reciprocal square root	scalar-> replicated scalar
DP3	3 term dot product	vector-> replicated scalar
DP4	4 term dot product	vector-> replicated scalar
LOG	Log base 2	miscellaneous
EXP	Exp base 2	miscellaneous
LIT	Phong lighting	miscellaneous
ARL	Address register load	miscellaneous

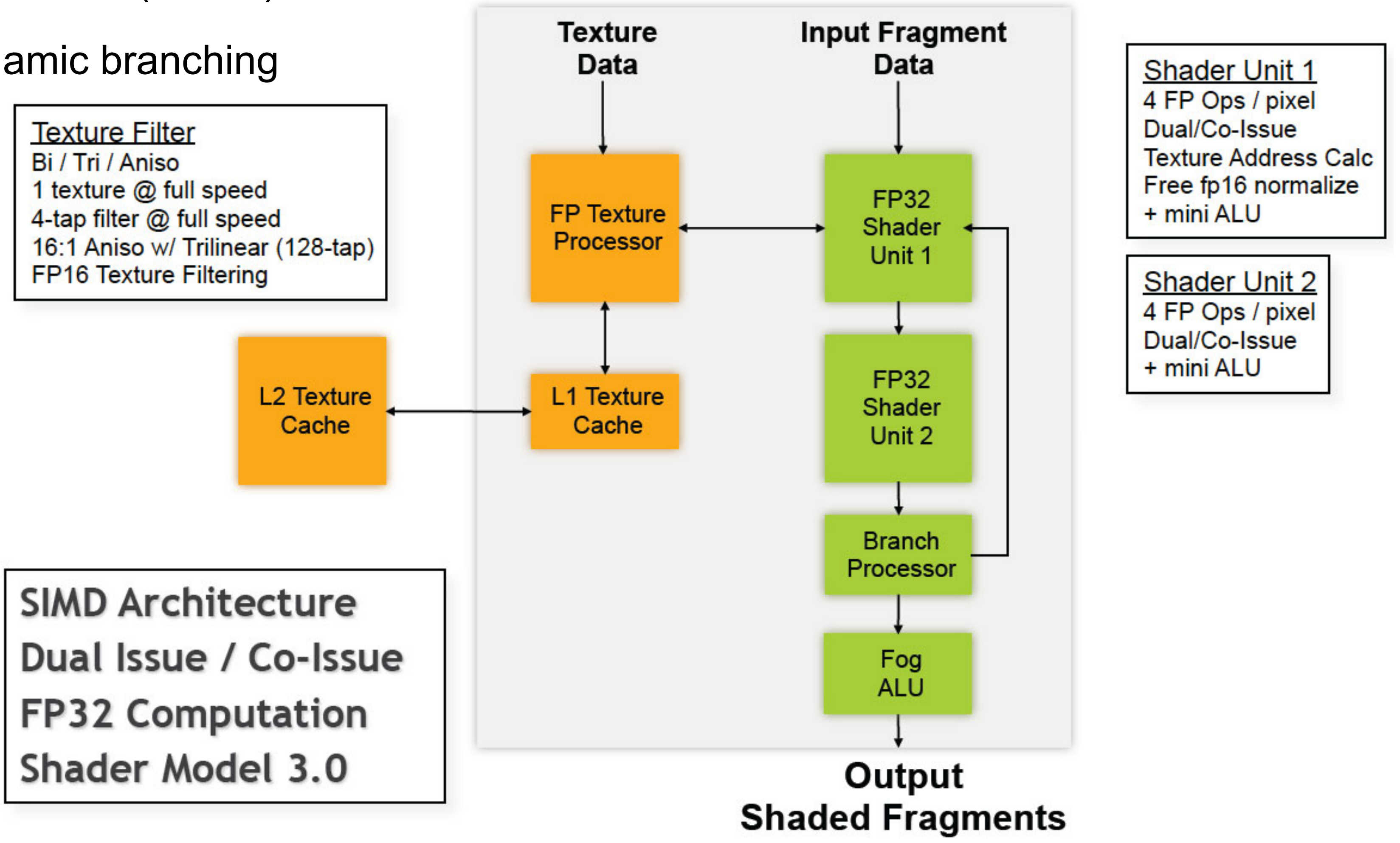
Fast Forward to Programm. Fragment Shading



Legacy Fragment Shading Unit (1)

GeForce 6 (NV40), 2004

- dynamic branching



Legacy Fragment Shading Unit (2)

Example code

```
!!ARBfp1.0

ATTRIB unit_tc = fragment.texcoord[ 0 ];
PARAM  mvp_inv[]  = { state.matrix.mvp.inverse };
PARAM  constants  = {0, 0.999, 1, 2};

TEMP pos_win, temp;

TEX pos_win.z, unit_tc, texture[ 1 ], 2D;

ADD pos_win.w, constants.y, -pos_win.z;
KIL pos_win.w;

MOV result.color.w, pos_win.z;

MOV pos_win.xyw, unit_tc;
MAD pos_win.xyz, pos_win, constants.a, -constants.b;

DP4 temp.w, mvp_inv[ 3 ], pos_win;
RCP temp.w, temp.w;

MUL pos_win, pos_win, temp.w;

DP4 result.color.x, mvp_inv[ 0 ], pos_win;
DP4 result.color.y, mvp_inv[ 1 ], pos_win;
DP4 result.color.z, mvp_inv[ 2 ], pos_win;

END
```

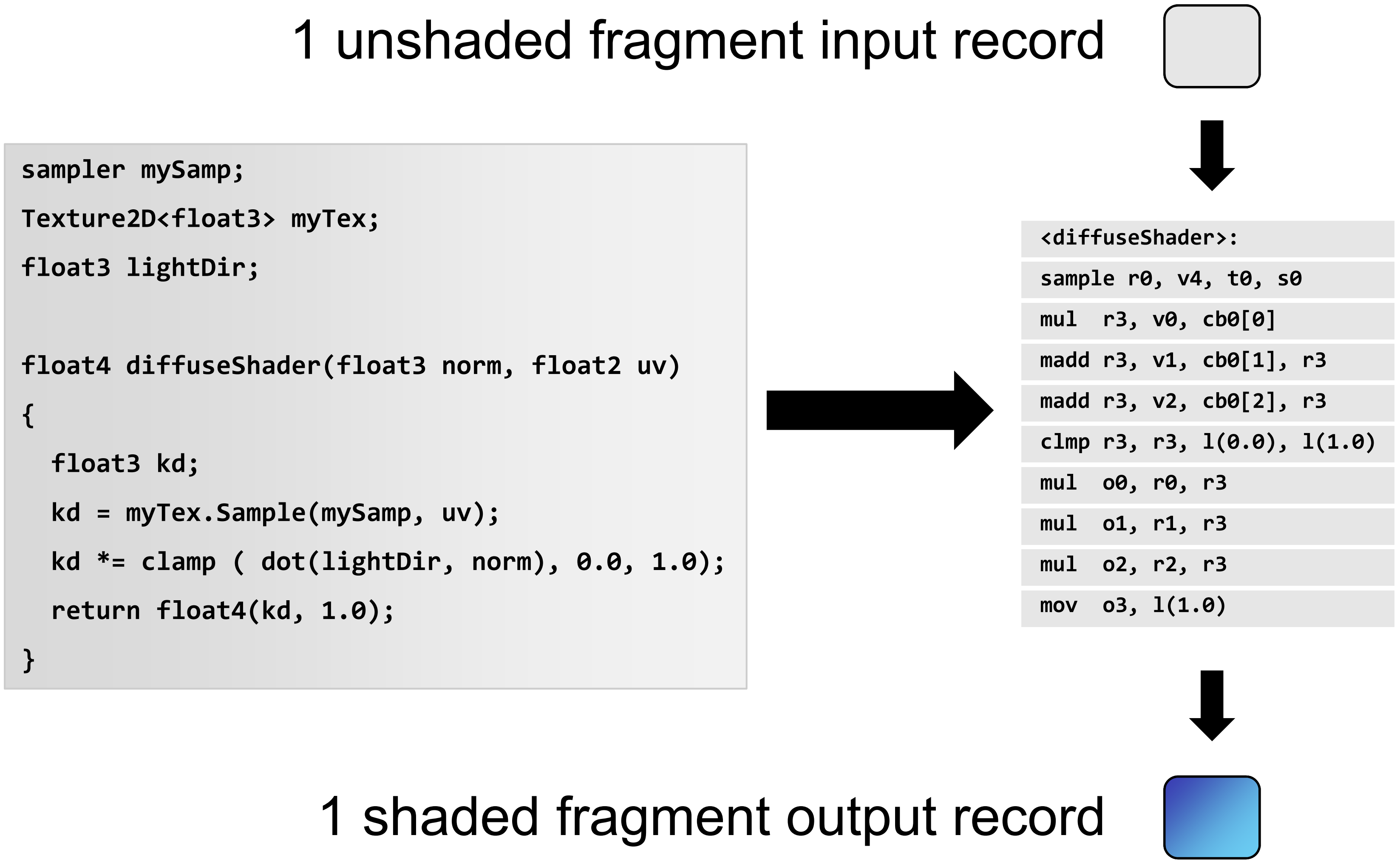
A diffuse reflectance shader

```
sampler mySamp;
Texture2D<float3> myTex;
float3 lightDir;

float4 diffuseShader(float3 norm, float2 uv)
{
  float3 kd;
  kd = myTex.Sample(mySamp, uv);
  kd *= clamp( dot(lightDir, norm), 0.0, 1.0);
  return float4(kd, 1.0);
}
```

Independent, but no explicit parallelism

Compile shader



1 unshaded fragment input record

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<diffuseShader>:
sample r0, v4, t0, s0
mul  r3, v0, cb0[0]
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clmp r3, r3, l(0.0), l(1.0)
mul  o0, r0, r3
mul  o1, r1, r3
mul  o2, r2, r3
mov  o3, l(1.0)
```

1 shaded fragment output record

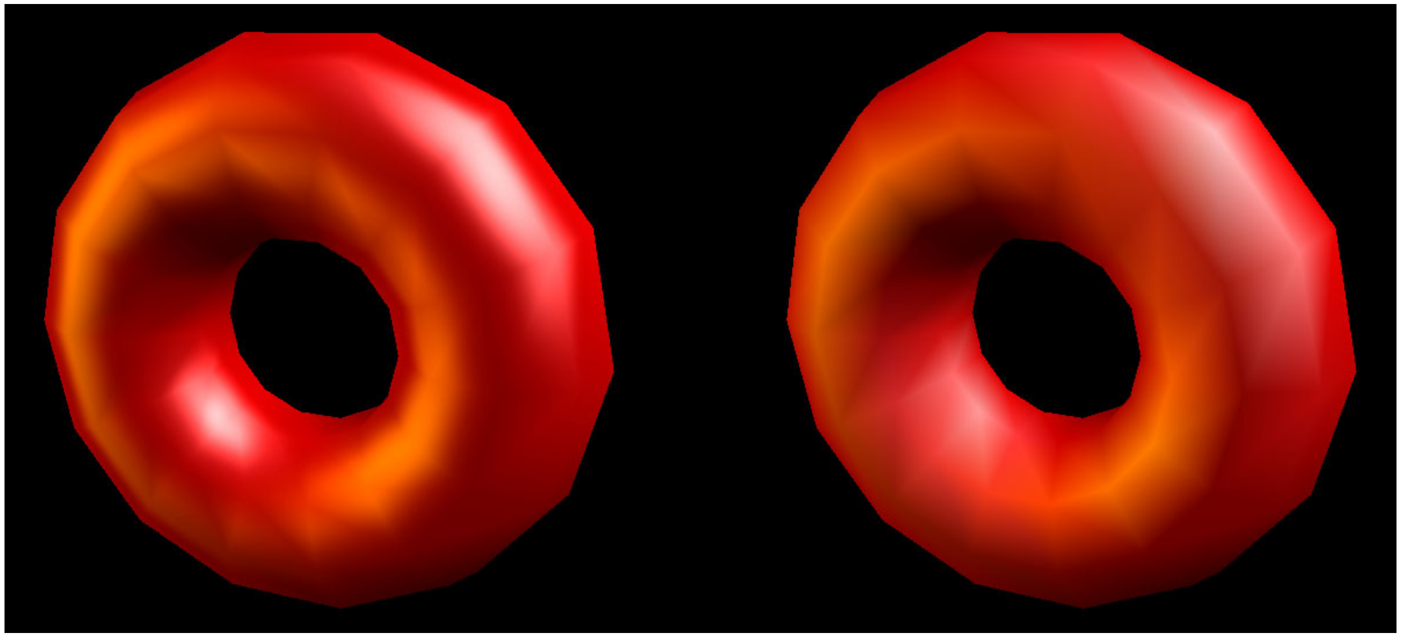
Per-Pixel(Fragment) Lighting

Simulating smooth surfaces by calculating illumination for each fragment

Example: specular highlights (Phong illumination/shading)

Phong shading:
per-fragment evaluation

Gouraud shading:
linear interpolation from vertices



Per-Pixel Phong Lighting (Cg)

```
void main(float4 position   : TEXCOORD0,
          float3 normal     : TEXCOORD1,

       out float4 oColor     : COLOR,

   uniform float3 ambientCol,
   uniform float3 lightCol,
   uniform float3 lightPos,
   uniform float3 eyePos,
   uniform float3 Ka,
   uniform float3 Kd,
   uniform float3 Ks,
   uniform float  shiny)
{
```

Per-Pixel Phong Lighting (Cg)

```
  float3 P = position.xyz;
  float3 N = normal;
  float3 V = normalize(eyePosition - P);
  float3 H = normalize(L + V);

  float3 ambient = Ka * ambientCol;

  float3 L         = normalize(lightPos - P);
  float  diffLight = max(dot(L, N), 0);
  float3 diffuse   = Kd * lightCol * diffLight;

  float specLight = pow(max(dot(H, N), 0), shiny);
  float3 specular = Ks * lightCol * specLight;

  oColor.xyz = ambient + diffuse + specular;
  oColor.w = 1;
}
```

GPU Architecture: General Architecture

SIGGRAPH2009 NEW ORLEANS

From Shader Code to a **Teraflop**: How Shader Cores Work

Kayvon Fatahalian
Stanford University

Part 1: throughput processing

- Three key concepts behind how modern GPU processing cores run code

- Knowing these concepts will help you:
  1. Understand space of GPU core
     (and throughput CPU processing core) designs
  2. Optimize shaders/compute kernels
  3. Establish intuition: what workloads might benefit from the design of these architectures?

Where this is going...

Summary: three key ideas for high-throughput execution

1. Use many "slimmed down cores," run them in parallel

2. Pack cores full of ALUs (by sharing instruction stream overhead across groups of fragments)
   - Option 1: Explicit SIMD vector instructions
   - Option 2: Implicit sharing managed by hardware

3. Avoid latency stalls by interleaving execution of many groups of fragments
   - When one group stalls, work on another group

Where this is going...

Summary: three key ideas for high-throughput execution

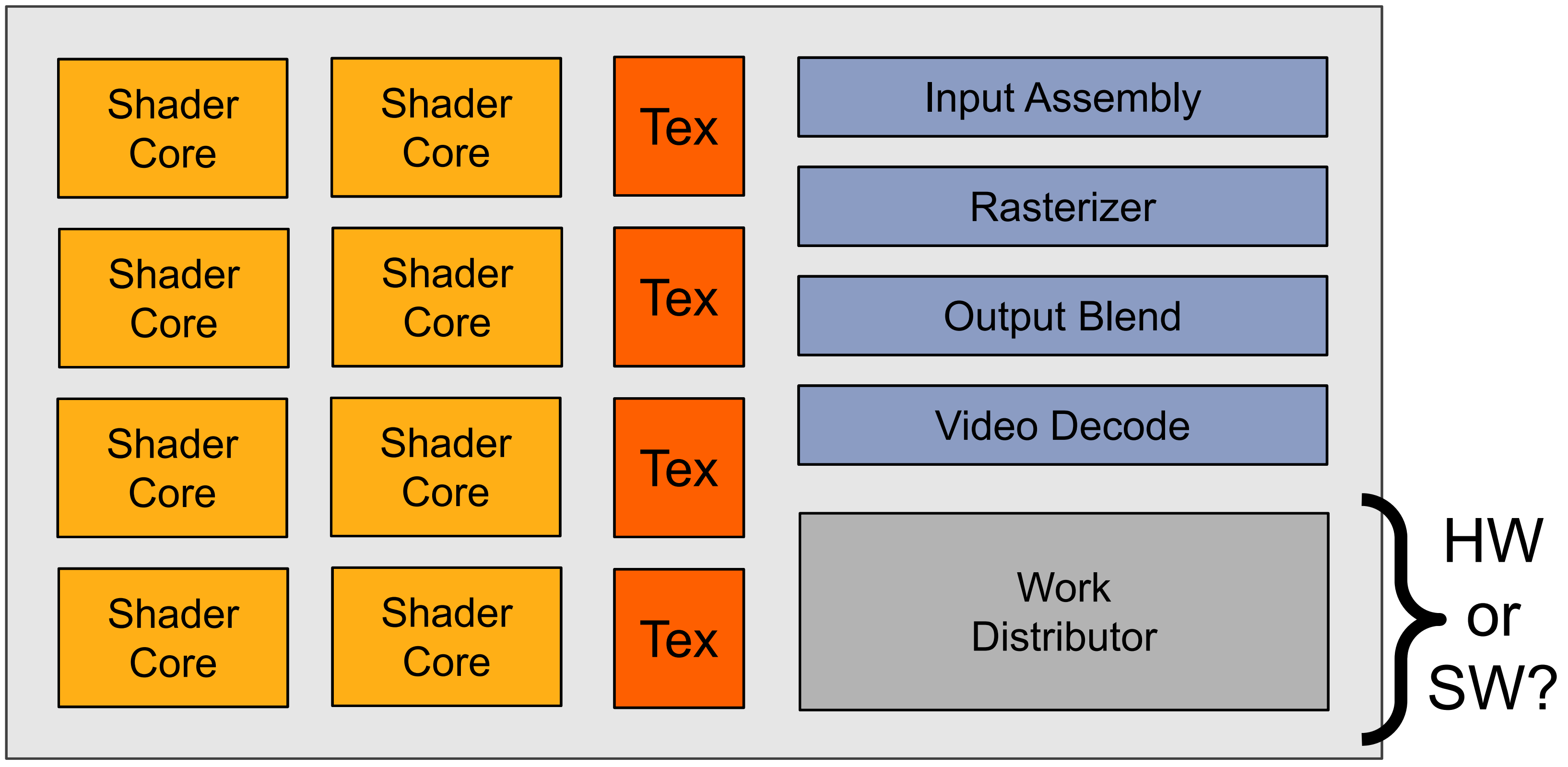
1. Use many "slimmed down cores," run them in parallel

2. Pack cores full of ALUs (by sharing instruction stream overhead across groups of fragments)
   - Option 1: Explicit SIMD vector instructions
   - Option 2: Implicit sharing managed by hardware

GPUs are here! (usually)

3. Avoid latency stalls by interleaving execution of many groups of fragments
   - When one group stalls, work on another group

What’s in a GPU?



Heterogeneous chip multi-processor (highly tuned for graphics)

A diffuse reflectance shader

```
sampler mySamp;
Texture2D<float3> myTex;
float3 lightDir;

float4 diffuseShader(float3 norm, float2 uv)
{
  float3 kd;
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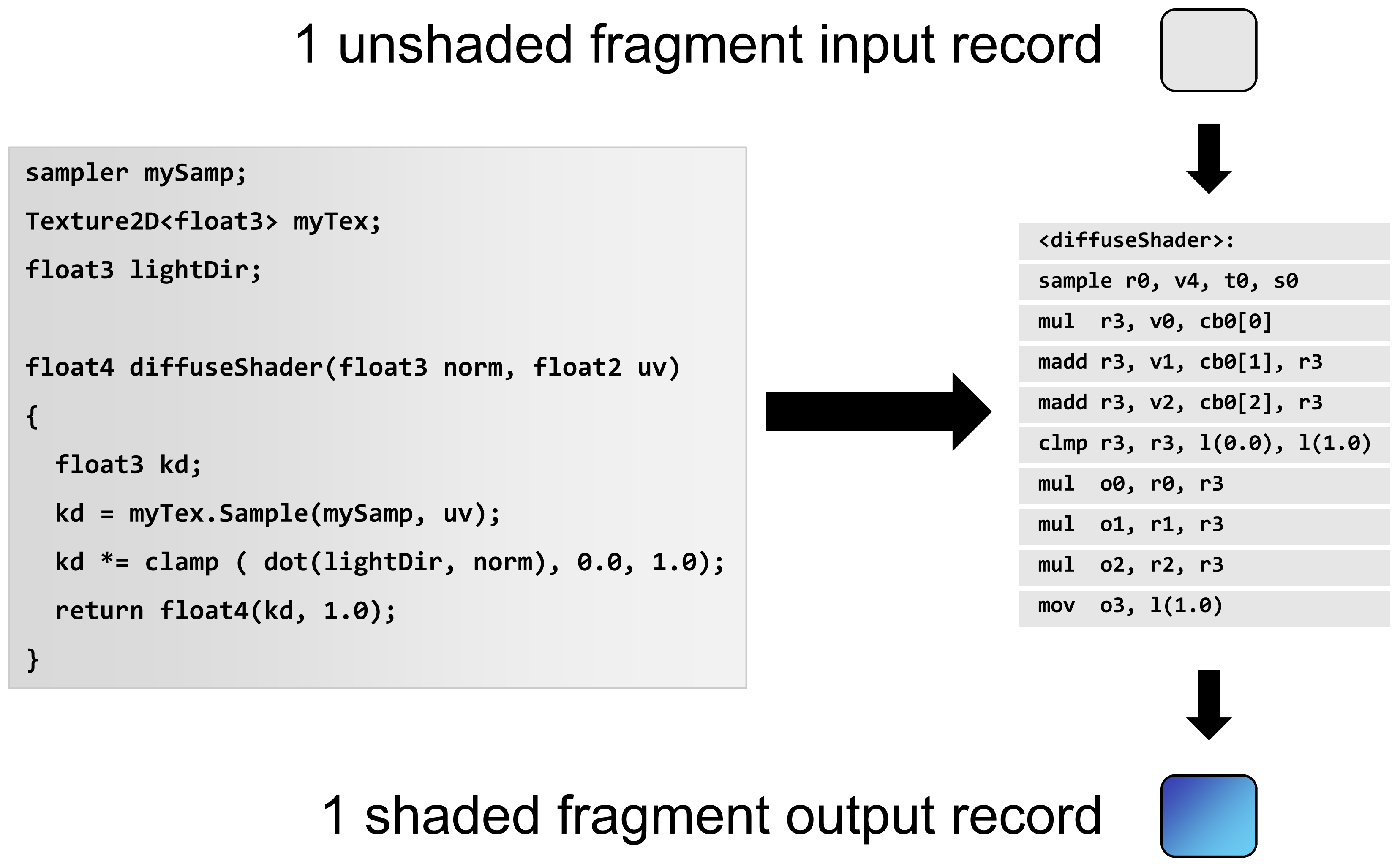
  kd *= clamp( dot(lightDir, norm), 0.0, 1.0);
  return float4(kd, 1.0);
}
```

Independent, but no explicit parallelism

Compile shader



1 unshaded fragment input record

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```

```
<diffuseShader>:
sample r0, v4, t0, s0
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madd r3, v1, cb0[1], r3
madd r3, v2, cb0[2], r3
clmp r3, r3, l(0.0), l(1.0)
mul  o0, r0, r3
mul  o1, r1, r3
mul  o2, r2, r3
mov  o3, l(1.0)
```
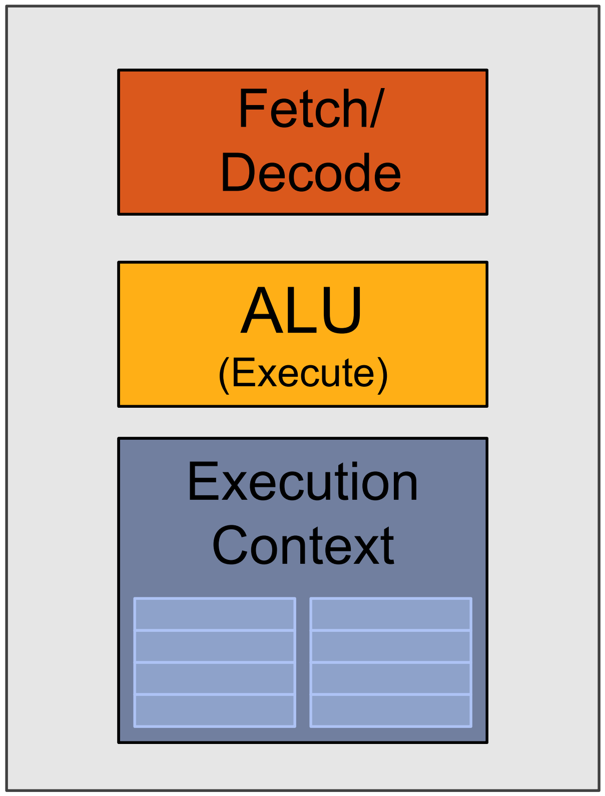
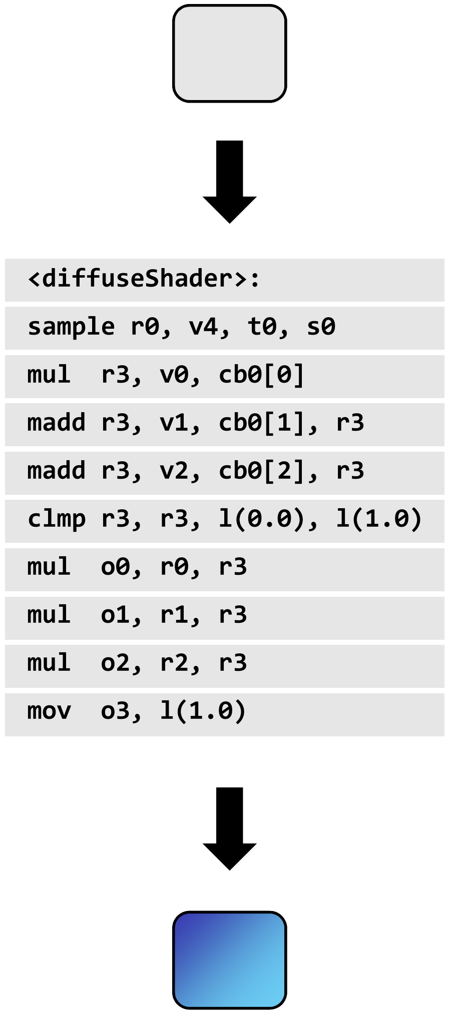

1 shaded fragment output record

Execute shader





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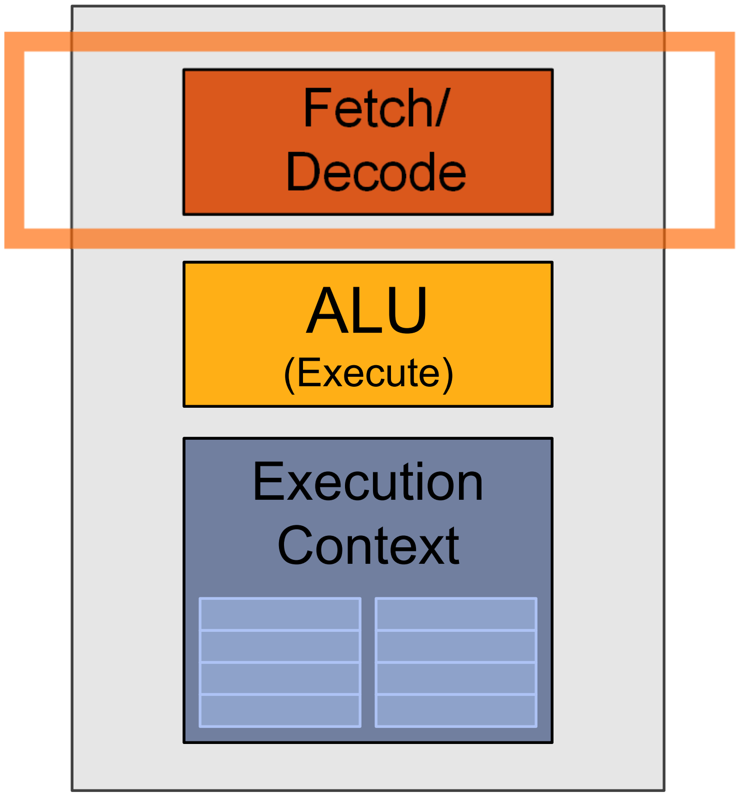
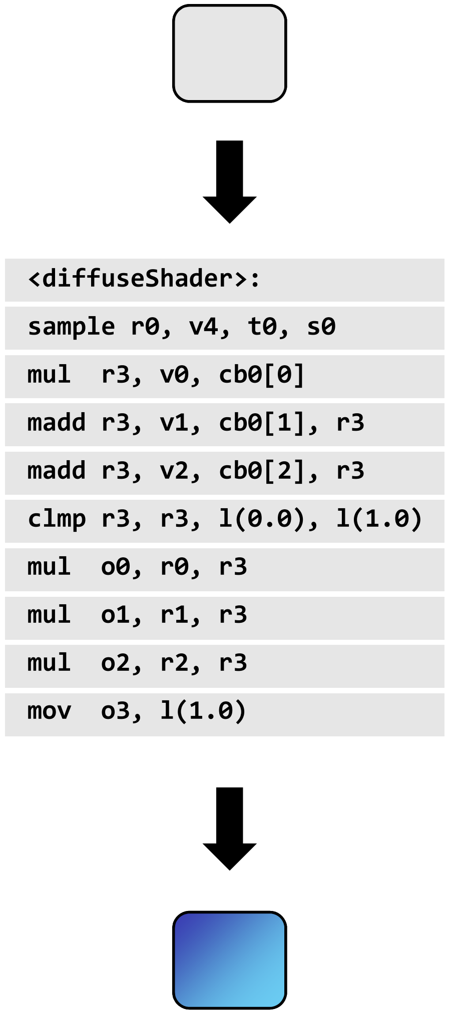
Execute shader





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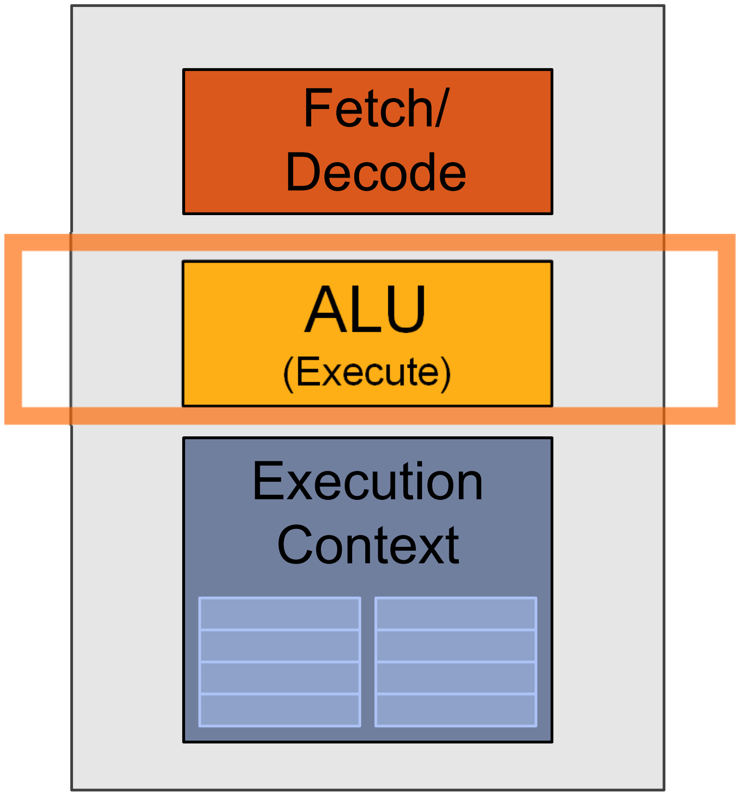
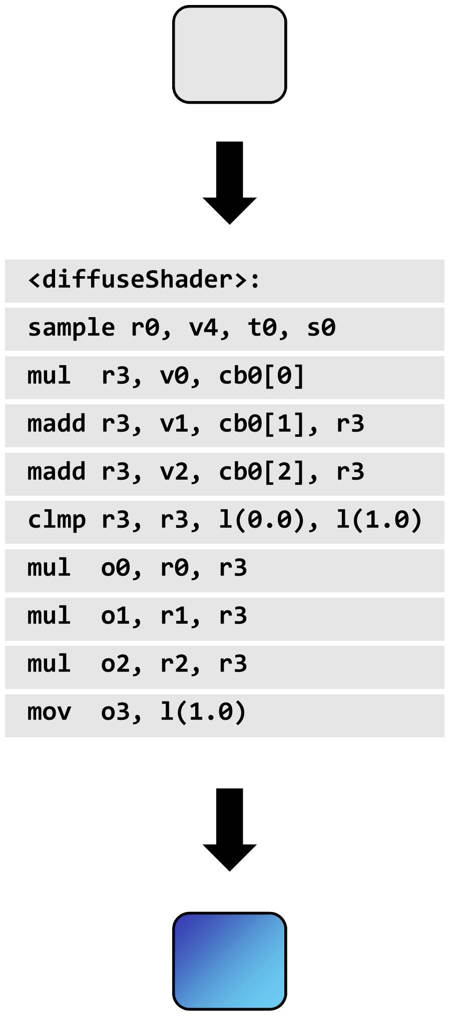
Execute shader





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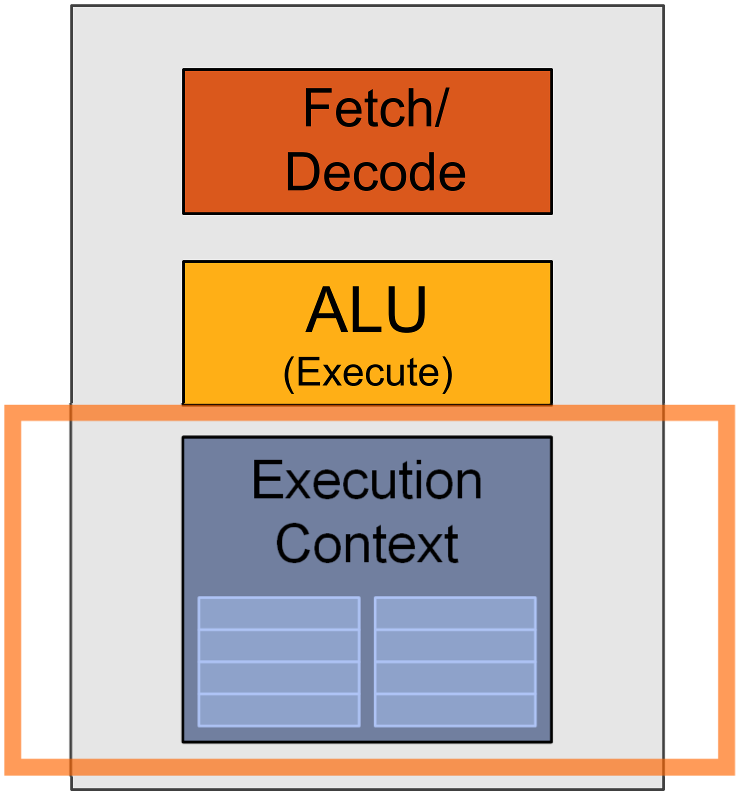

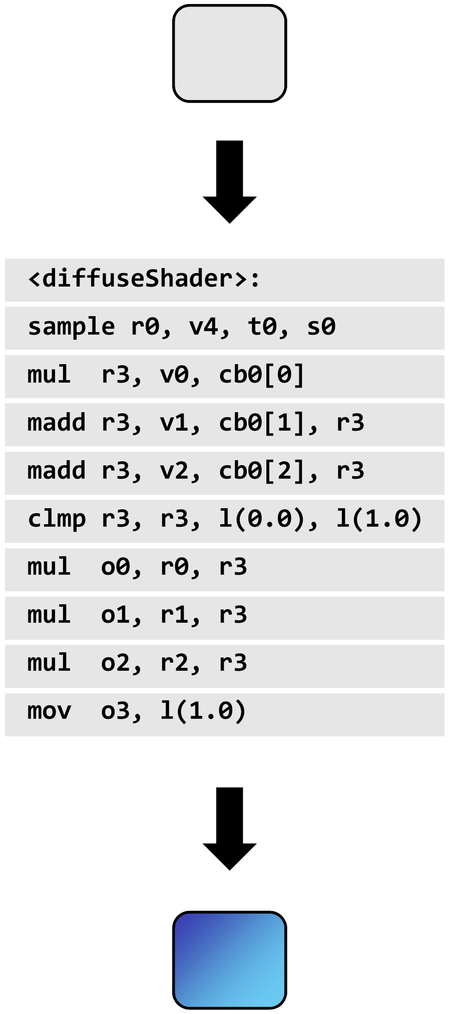

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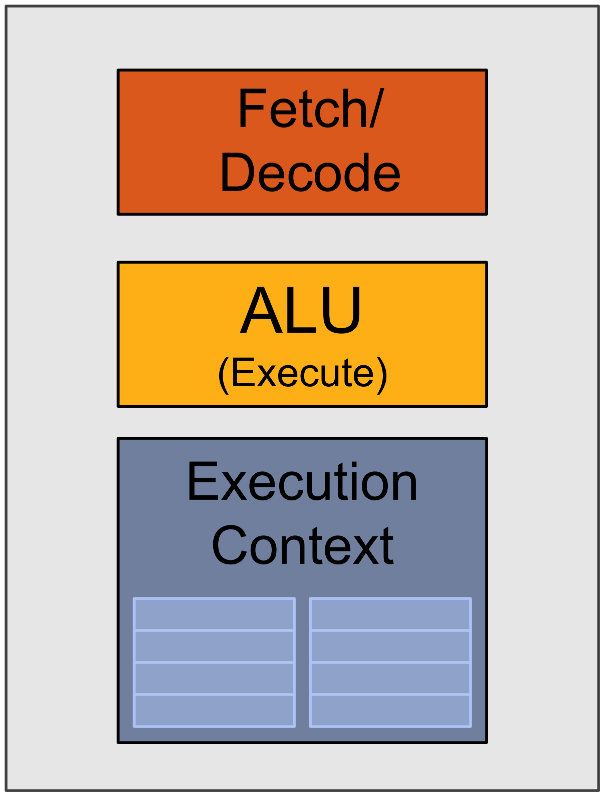

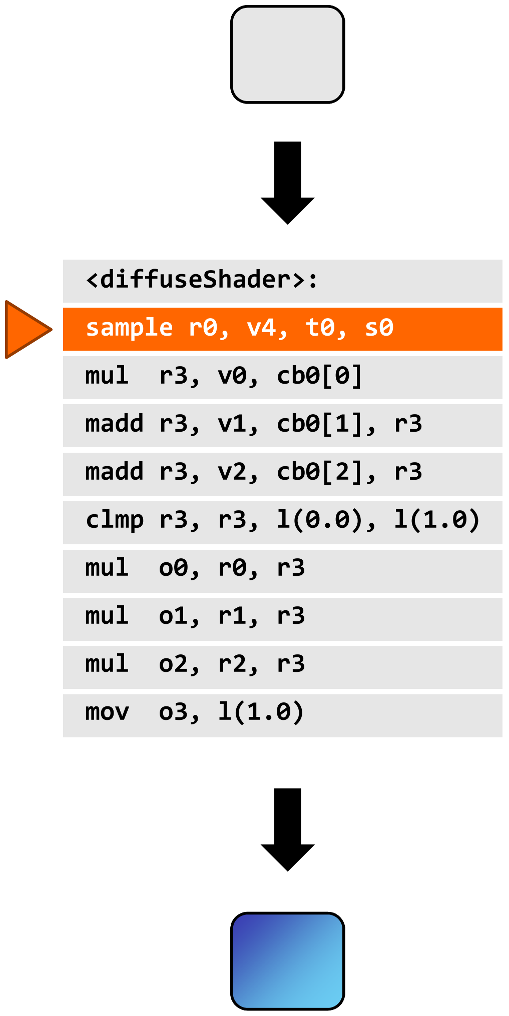

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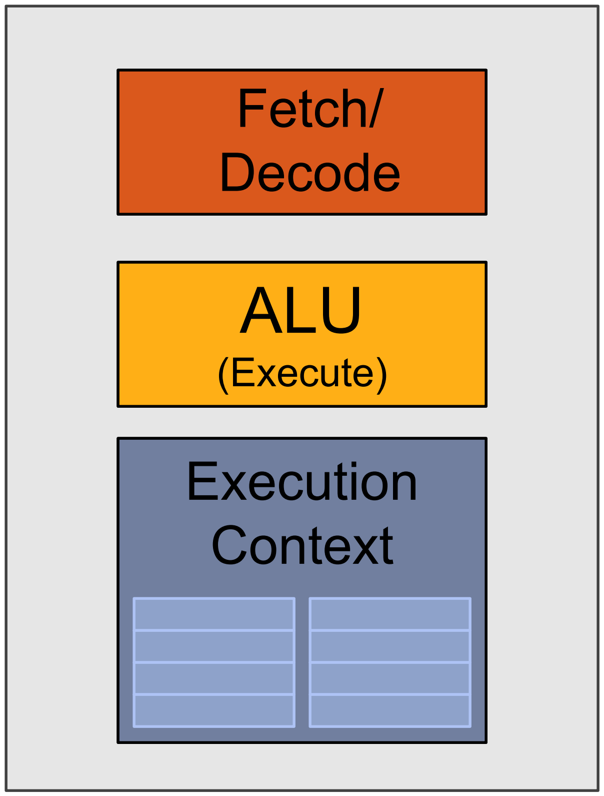

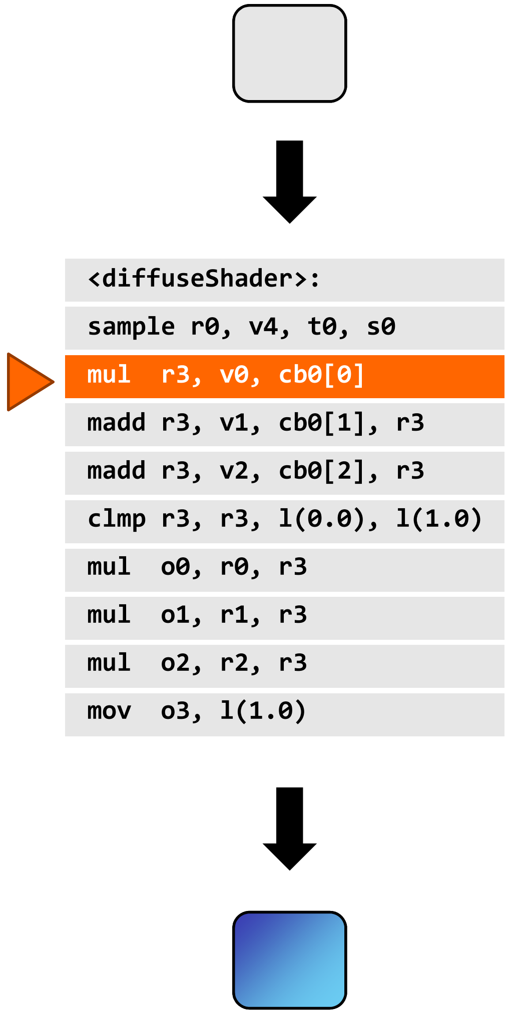

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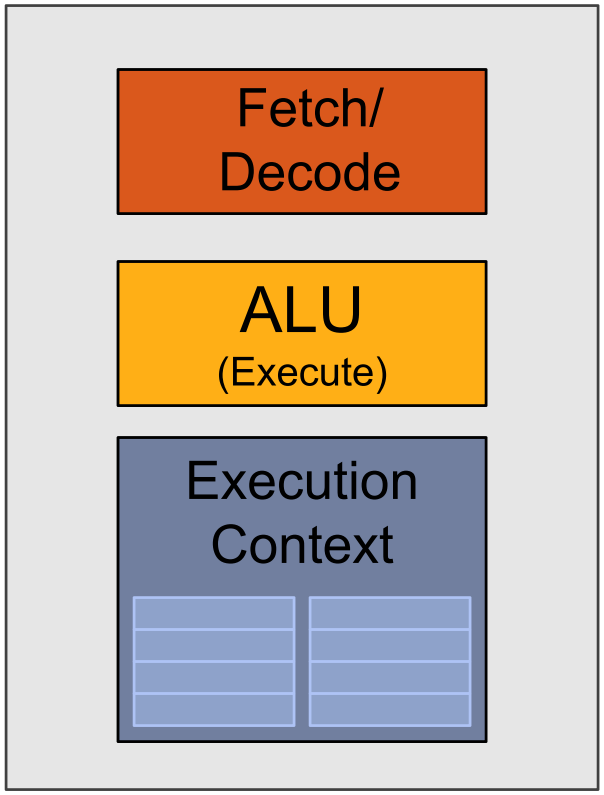

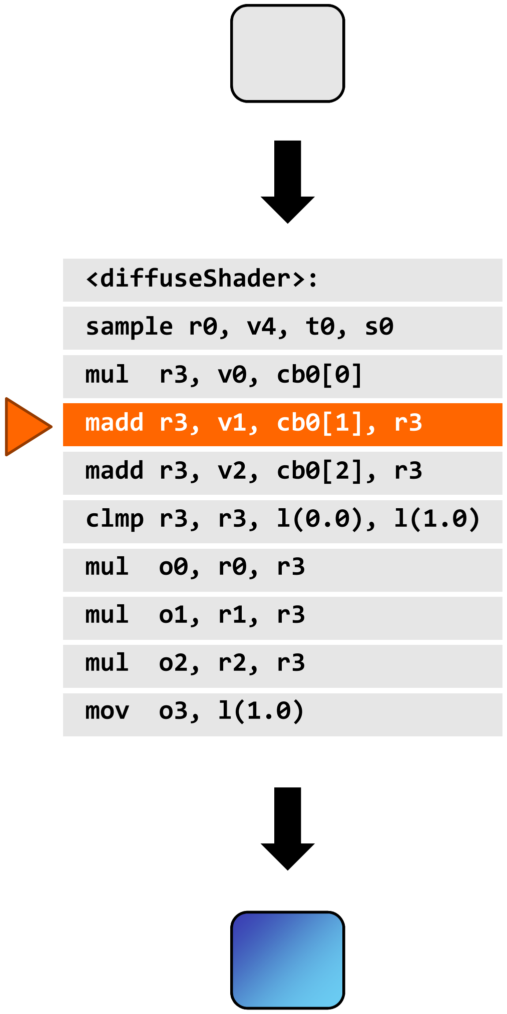

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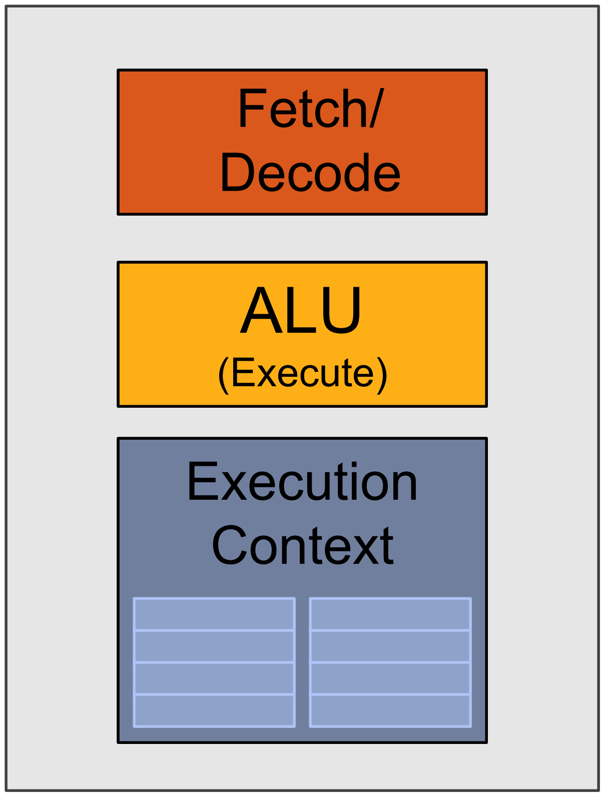
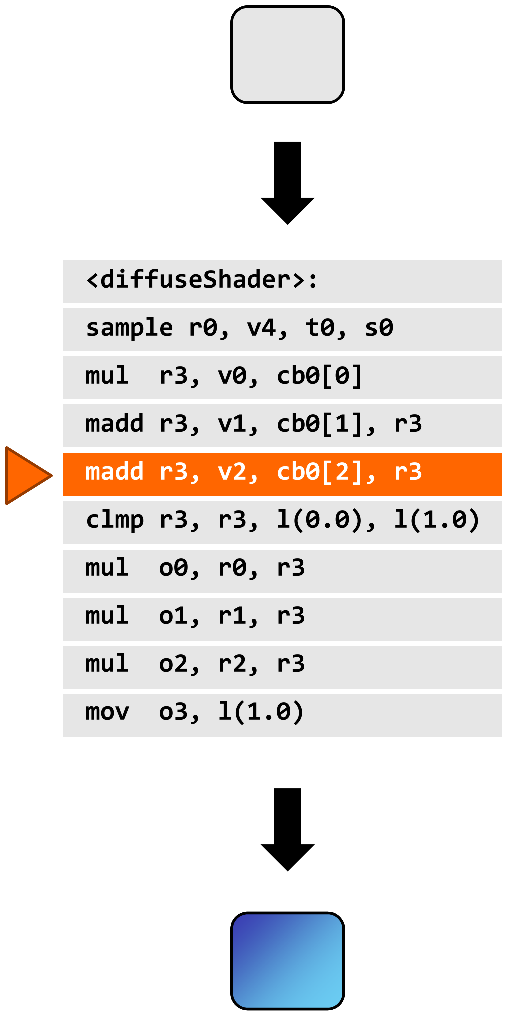
Execute shader





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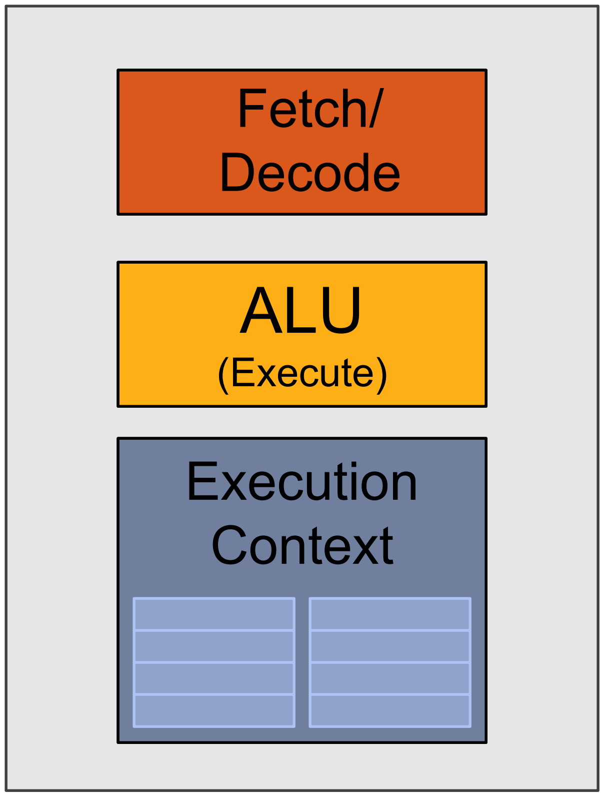
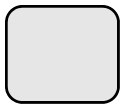
Execute shader





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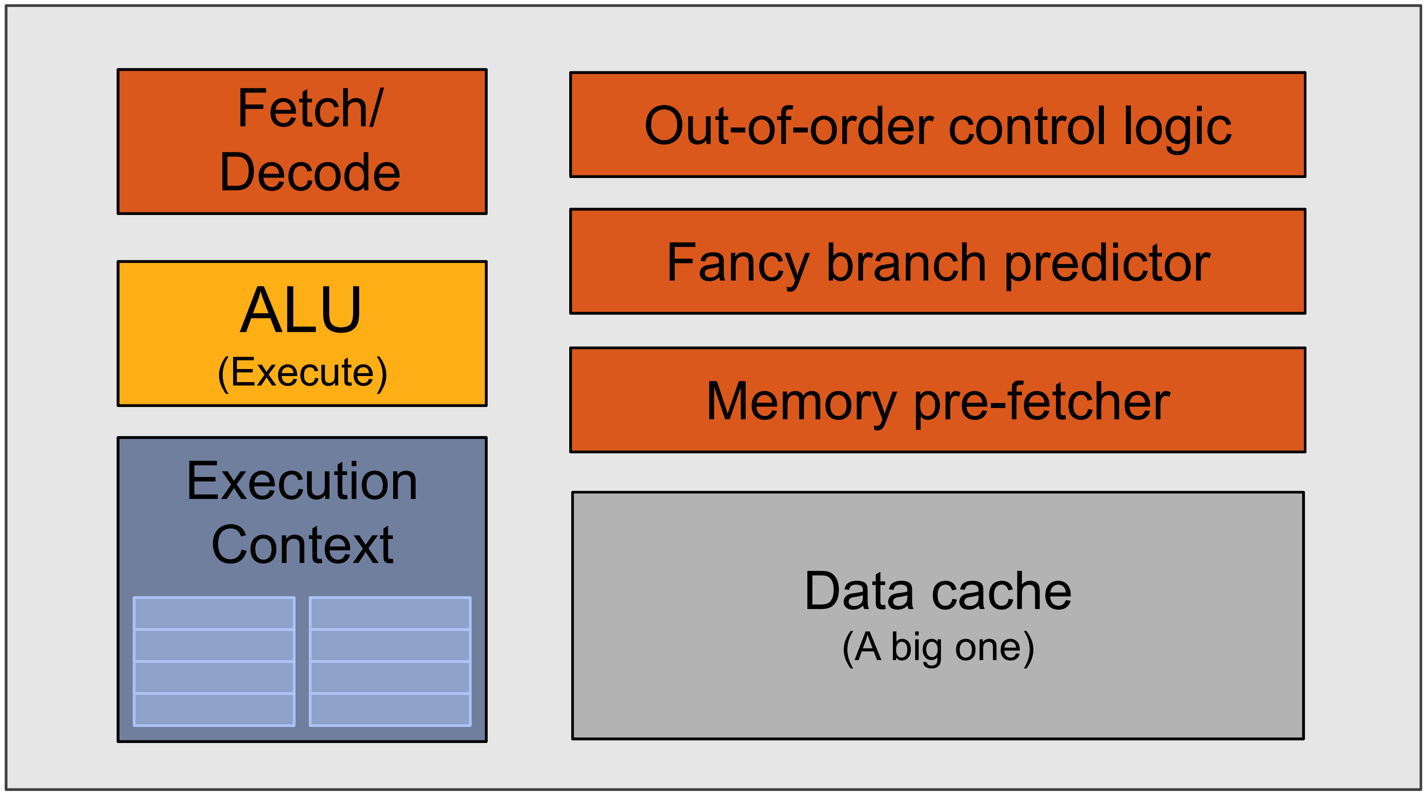
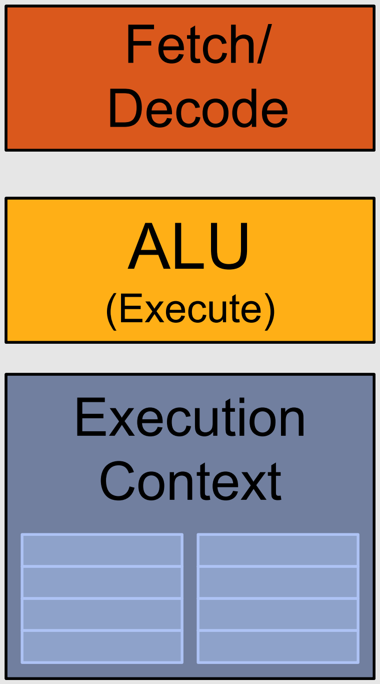
```

CPU-“style” cores



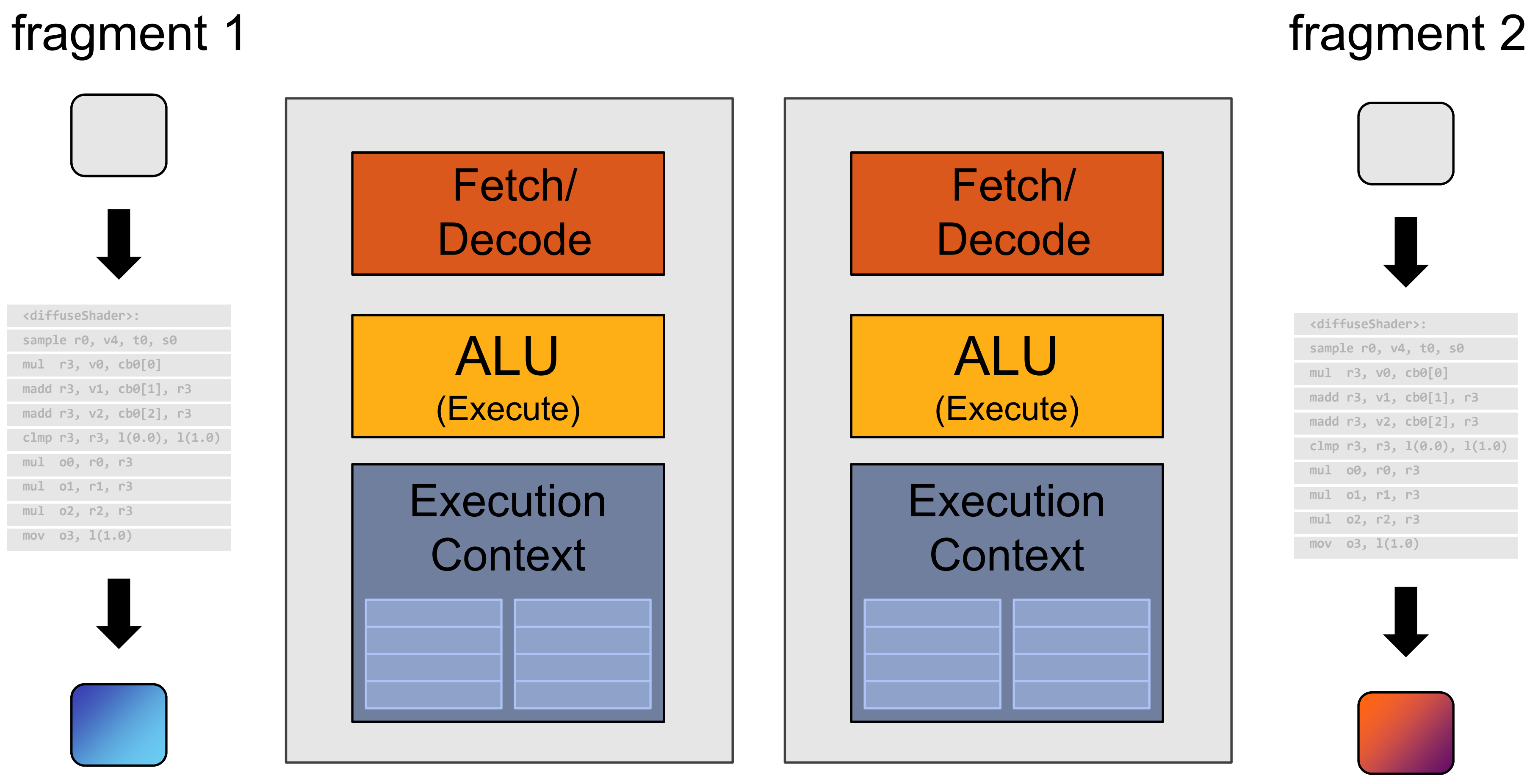
Idea #1: Slim down



Idea #1:

Remove components that help a single instruction stream run fast

Two cores (two fragments in parallel)



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mov  o3, l(1.0)
```

```
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clmp r3, r3, l(0.0), l(1.0)
mul  o0, r0, r3
mul  o1, r1, r3
mul  o2, r2, r3
mov  o3, l(1.0)
```
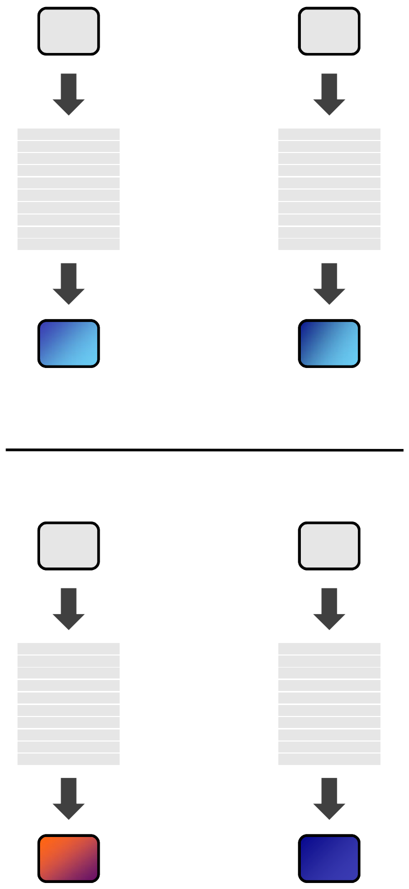
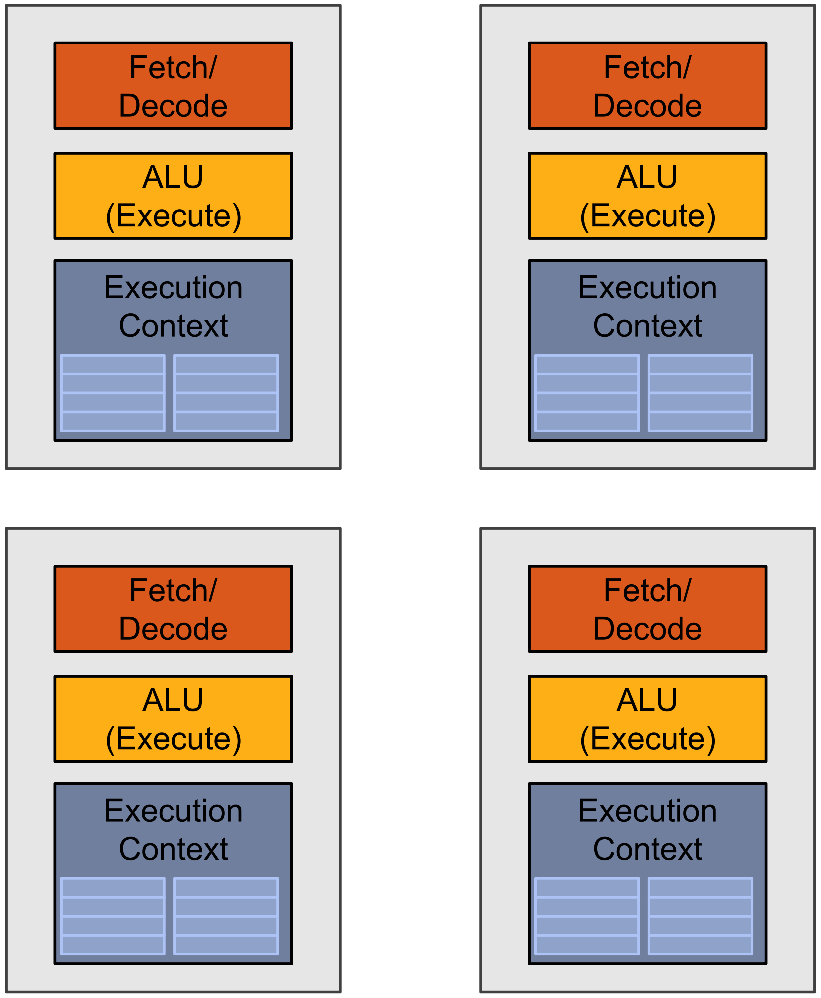
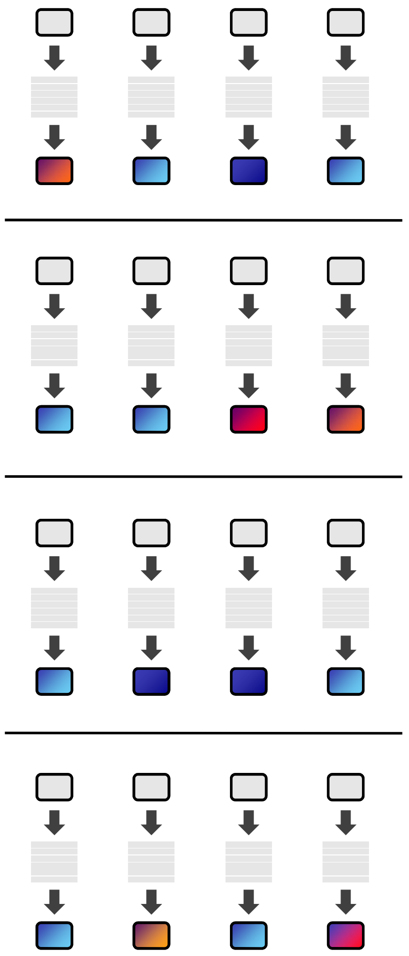
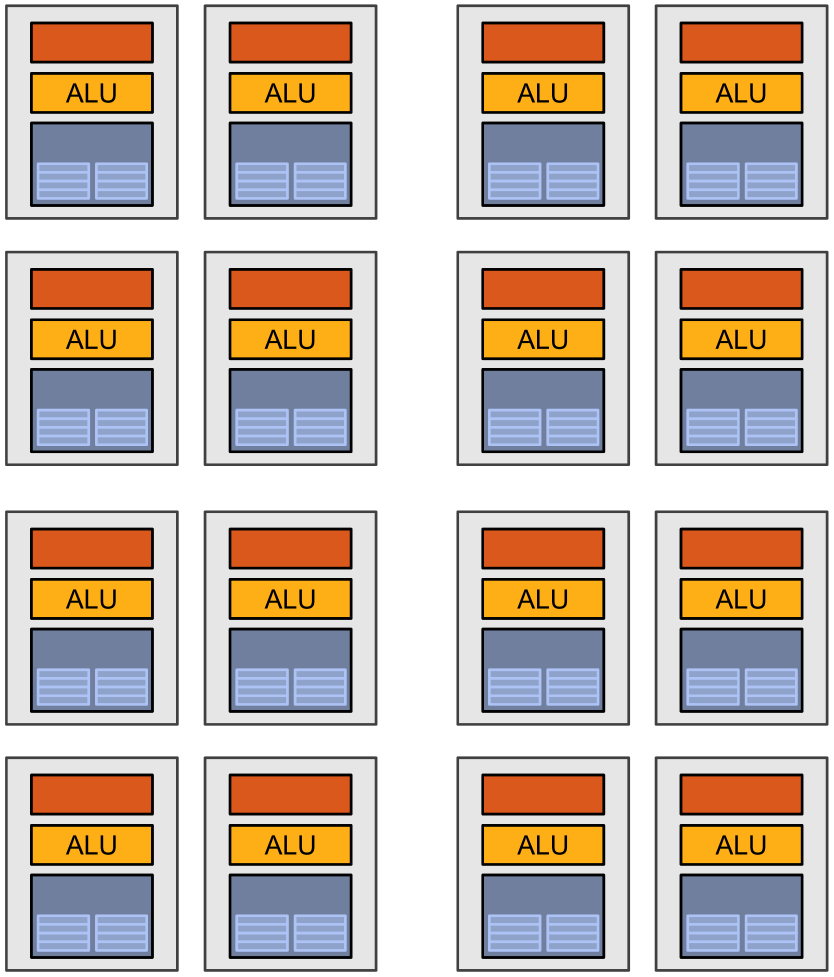

Four cores (four fragments in parallel)





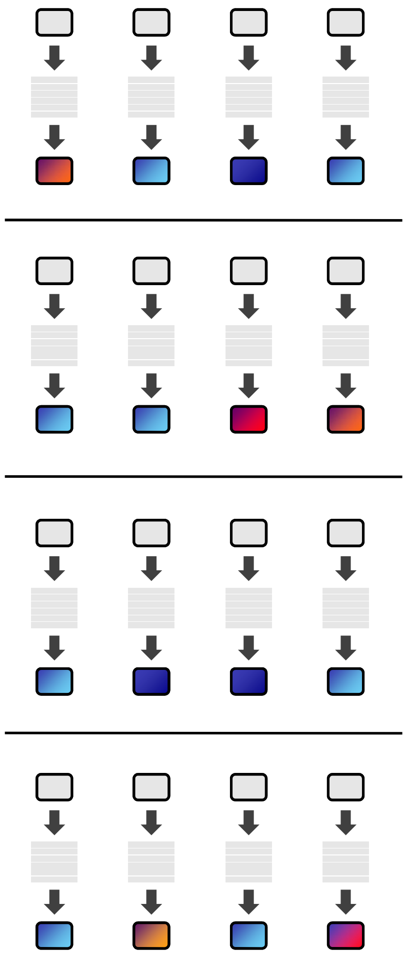
Sixteen cores (sixteen fragments in parallel)





16 cores = 16 simultaneous instruction streams

Instruction stream sharing



But… many fragments should be able to share an instruction stream!

```
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madd r3, v1, cb0[1], r3
madd r3, v2, cb0[2], r3
clmp r3, r3, l(0.0), l(1.0)
mul  o0, r0, r3
mul  o1, r1, r3
mul  o2, r2, r3
mov  o3, l(1.0)
```
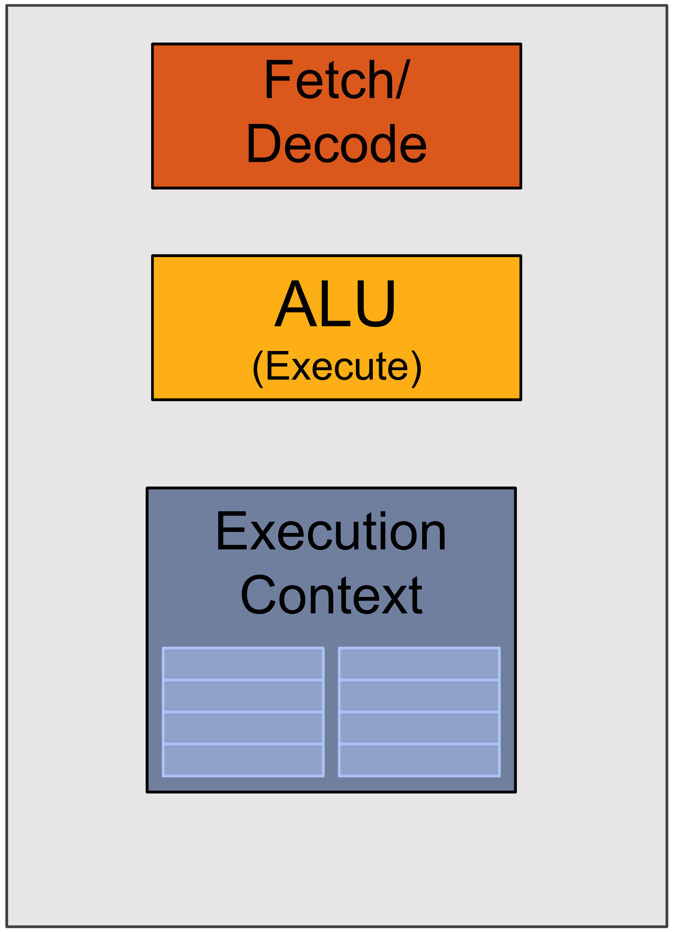
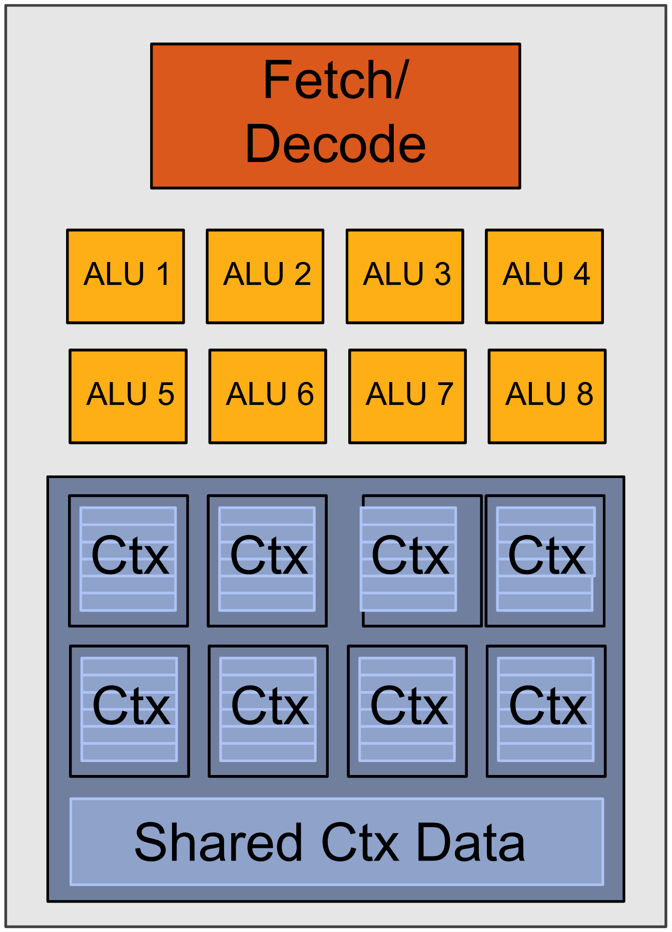

Recall: simple processing core



Idea #2: Add ALUs



Idea #2:

Amortize cost/complexity of managing an instruction stream across many ALUs

SIMD processing

(or SIMT, SPMD)

Thank you.