Lecture 18:

Shading Languages
(+ mapping shader programs to GPU processor cores)

Visual Computing Systems
Stanford CS348V, Winter 2018

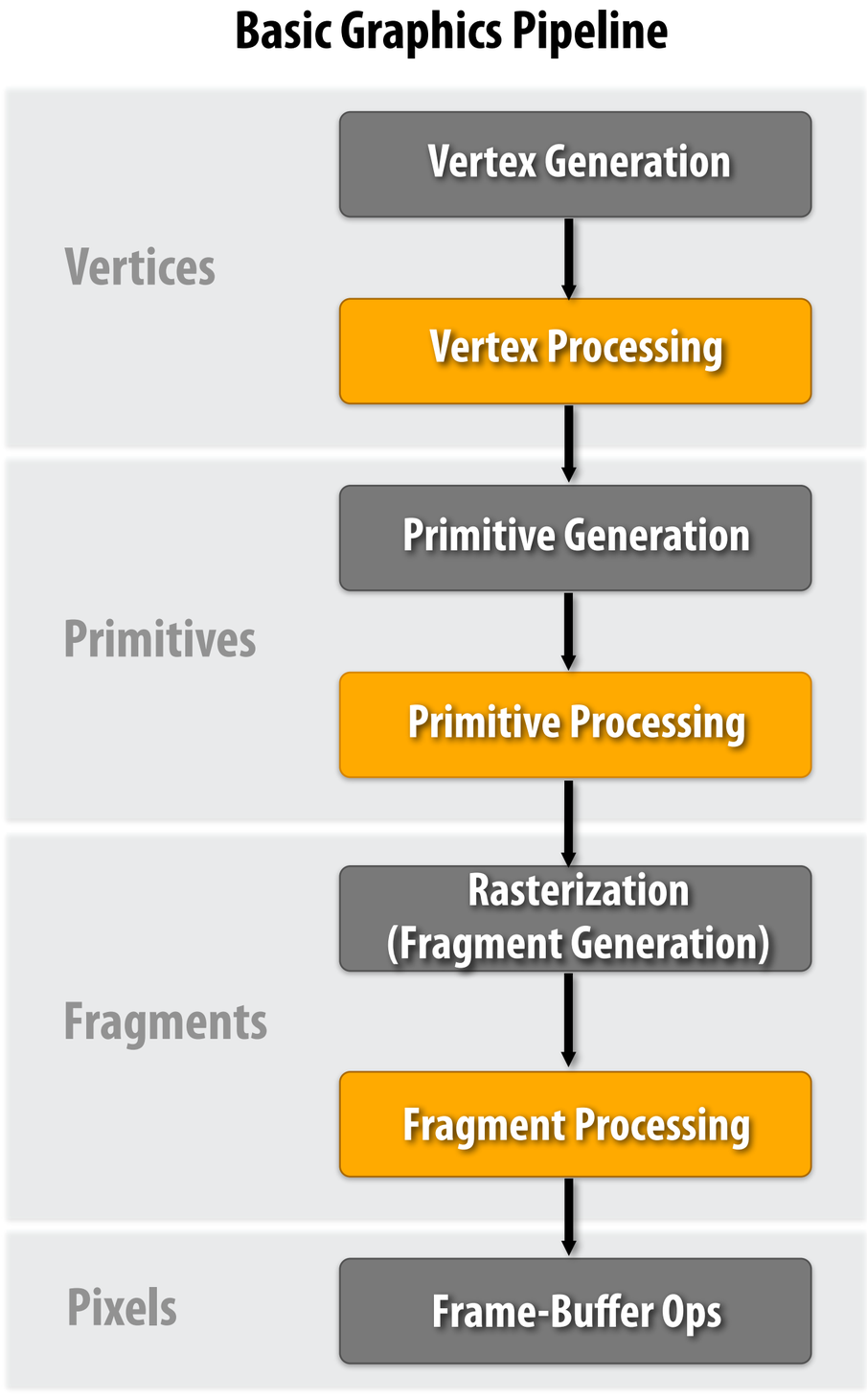
The course so far

So far in this section of the course: our focus has been on non-programmable parts of the graphics pipeline

- **Geometry processing operations**
- **Visibility (coverage, occlusion)**
- **Texturing**

I've said very little about about materials, lights, etc.

And hardly mentioned programmable GPUs



Materials: diffuse

[Slide credit: Matt Pharr]

Materials: plastic

[Slide credit: Matt Pharr]

Materials: red semi-gloss paint

[Slide credit: Matt Pharr]

Materials: mirror

[Slide credit: Matt Pharr]

Materials: gold

[Slide credit: Matt Pharr]

Materials

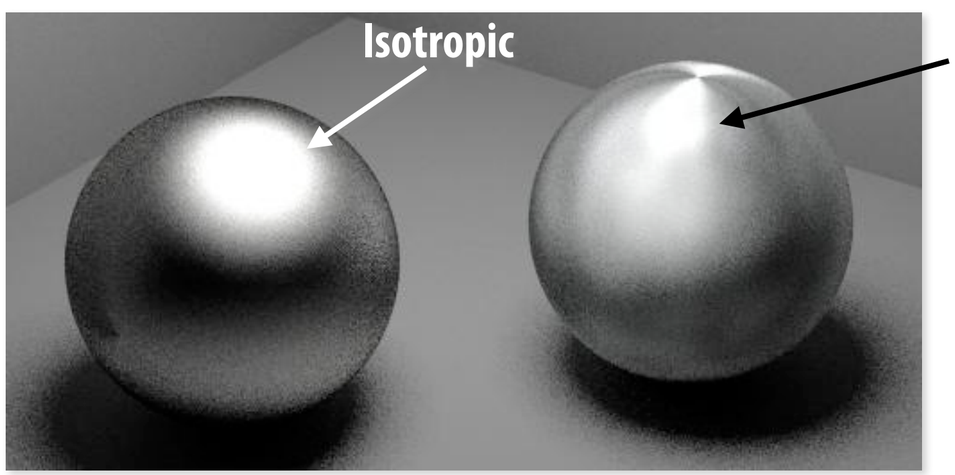
[Image credit: Jakob et al. 2014]

More complex materials

[Images from Lafortune et al. 97]

Fresnel reflection: reflectance is a function of viewing angle (notice higher reflectance near grazing angles)

[Images from Westin et al. 92]



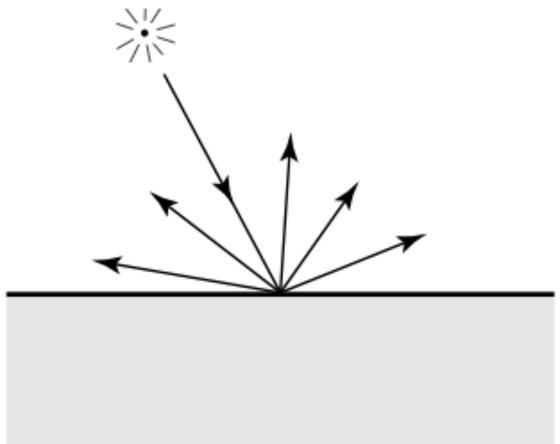
Anisotropic reflection: reflectance depends on azimuthal angle (e.g., oriented microfacets in brushed steel)

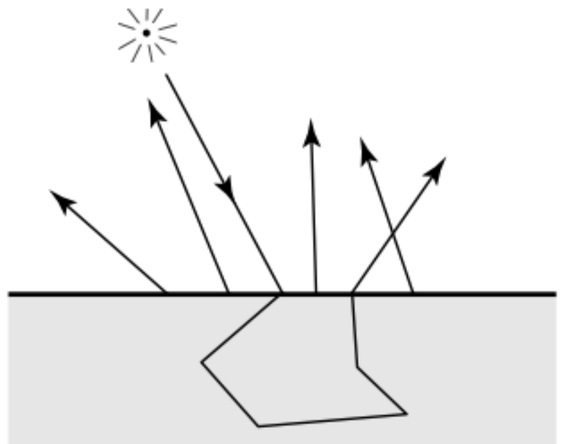
Subsurface scattering materials

[Wann Jensen et al. 2001]

BRDF

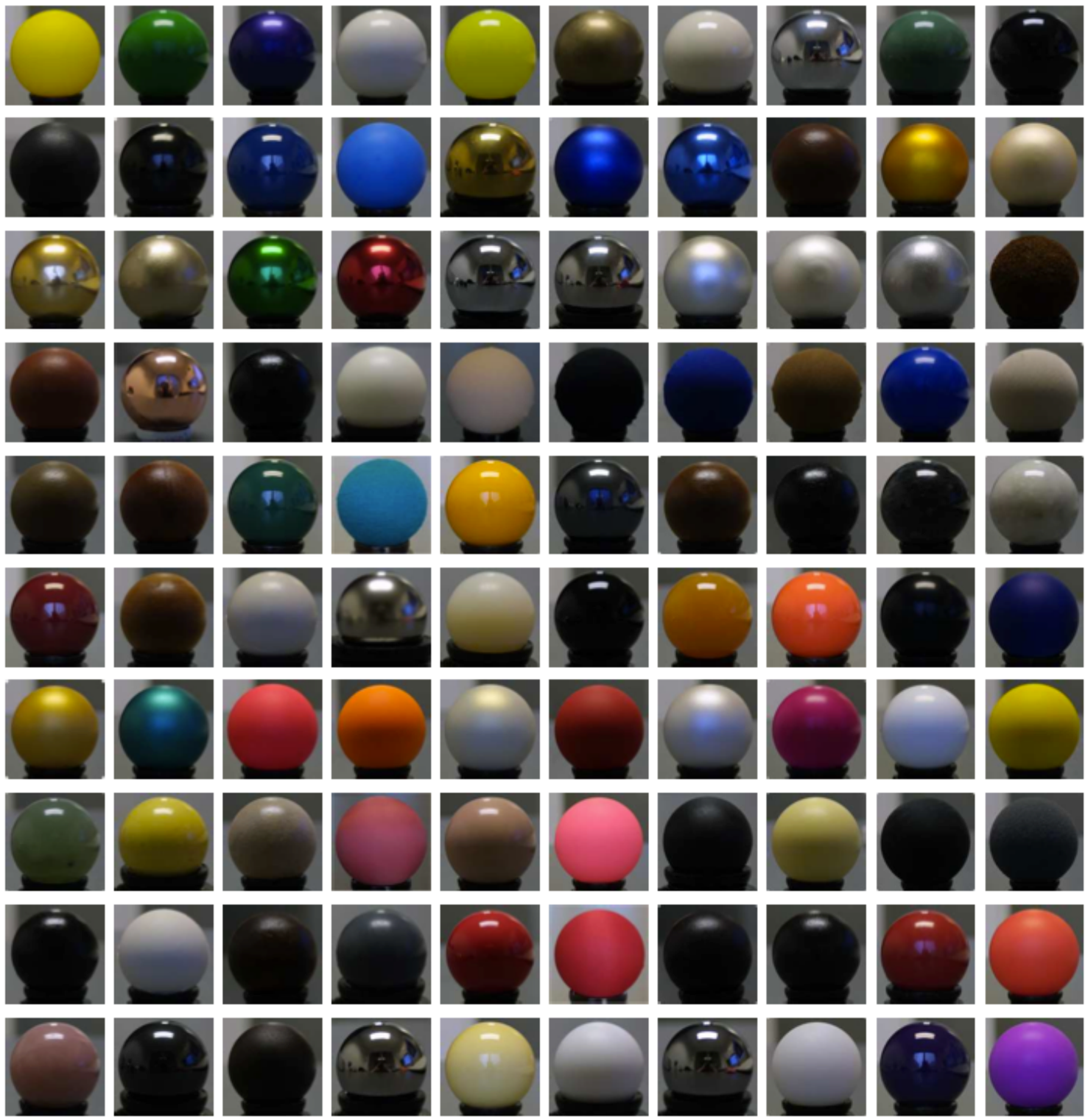
BSSRDF





- **Account for scattering inside surface**
- **Light exits surface from different location it enters**
  - **Very important to appearance of translucent materials (e.g., skin, foliage, marble)**

More materials



Tabulated BRDFs

Images from Matusik et al. SIGGRAPH 2003

The rendering equation *

[Kajiya 86]

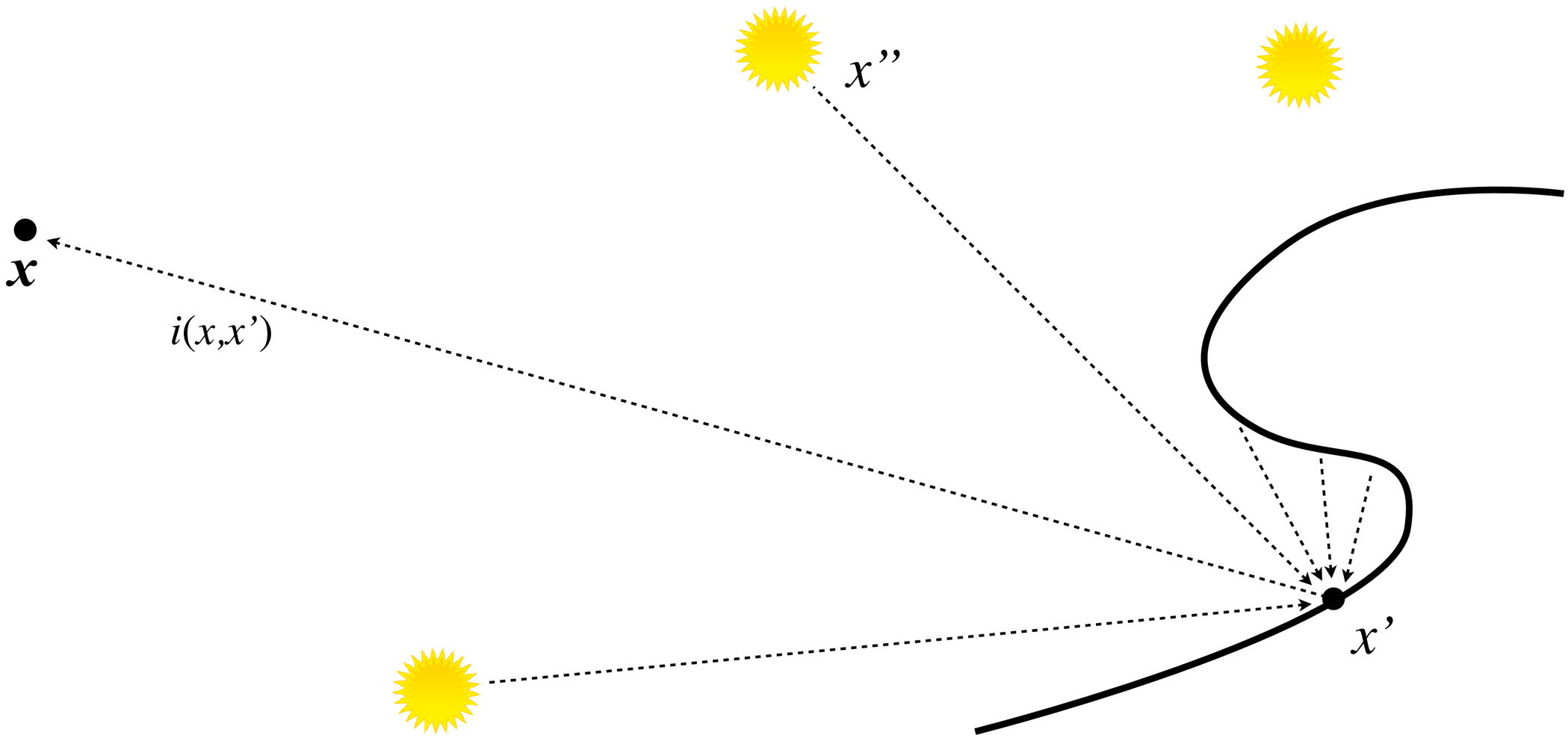
$$i(x,x') = v(x,x')\left[l(x,x') + \int r(x,x',x'')i(x',x'')\,dx''\right]$$

$i(x, x')$ = **Radiance (energy along a ray) from point x′ in direction of point x**

$v(x, x')$ = **Binary visibility function (1 if ray from x′ reaches x, 0 otherwise)**

$l(x, x')$ = **Radiance emitted from x′ in direction of x (if x′ is an emitter)**

$r(x, x', x'')$ = **BRDF: fraction of energy arriving at x′ from x″ that is reflected in direction of x**

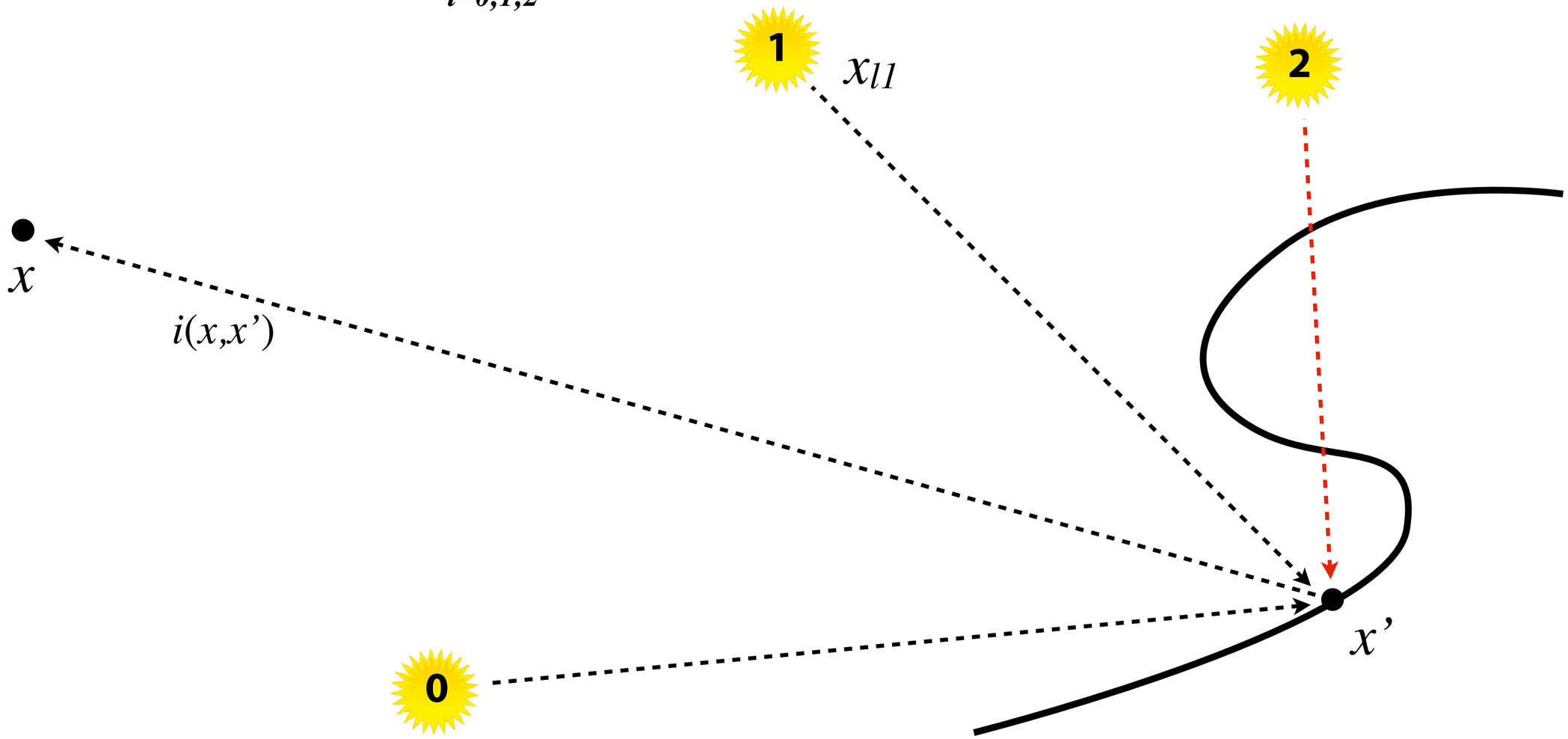


*** Note: using notation from Hanrahan 90 (to match reading)**

The rendering equation (simplified)

- All light sources are point light sources (light i emits from point x_{li})
- Lights emit equally in all directions: radiance from light i: $i(x', x_{l_i}) = L_i$
- Direct illumination only: illumination of x′ comes directly from light sources

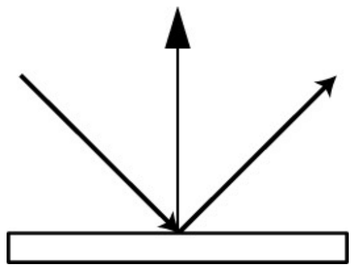
$$i(x,x') = \sum_{i=0,1,2} L_i v(x', x_{l_i}) r(x, x', x_{l_i})$$



Categories of reflection functions

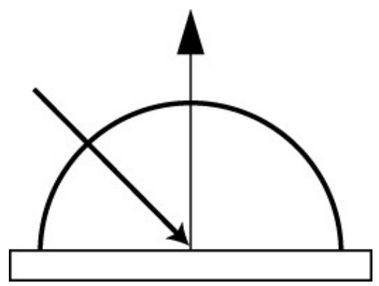
- **Ideal specular**

  Perfect mirror



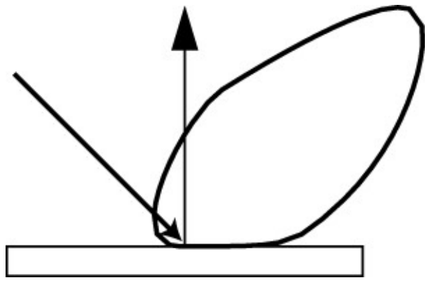
- **Ideal diffuse**

  Uniform reflection in all directions



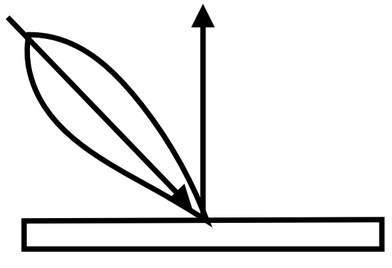
- **Glossy specular**

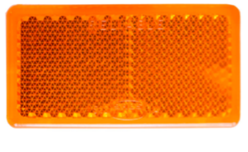
  Majority of light distributed in reflection direction



- **Retro-reflective**

  Reflects light back toward source



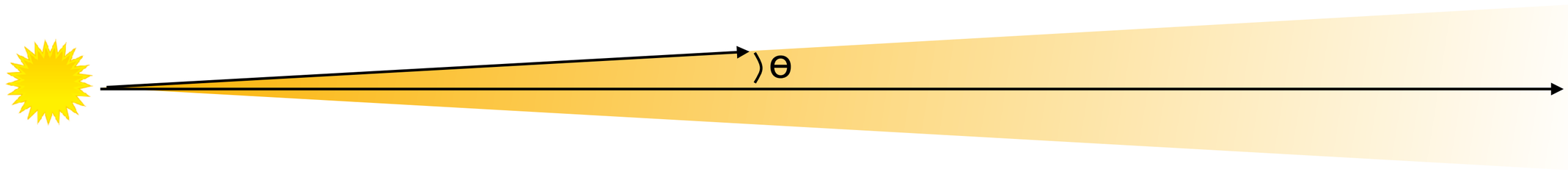


Diagrams illustrate how incoming light energy from given direction is reflected in various directions.

Types of lights

- **Attenuated omnidirectional point light**
  (emits equally in all directions, intensity falls off with distance: $1/R^2$ falloff)

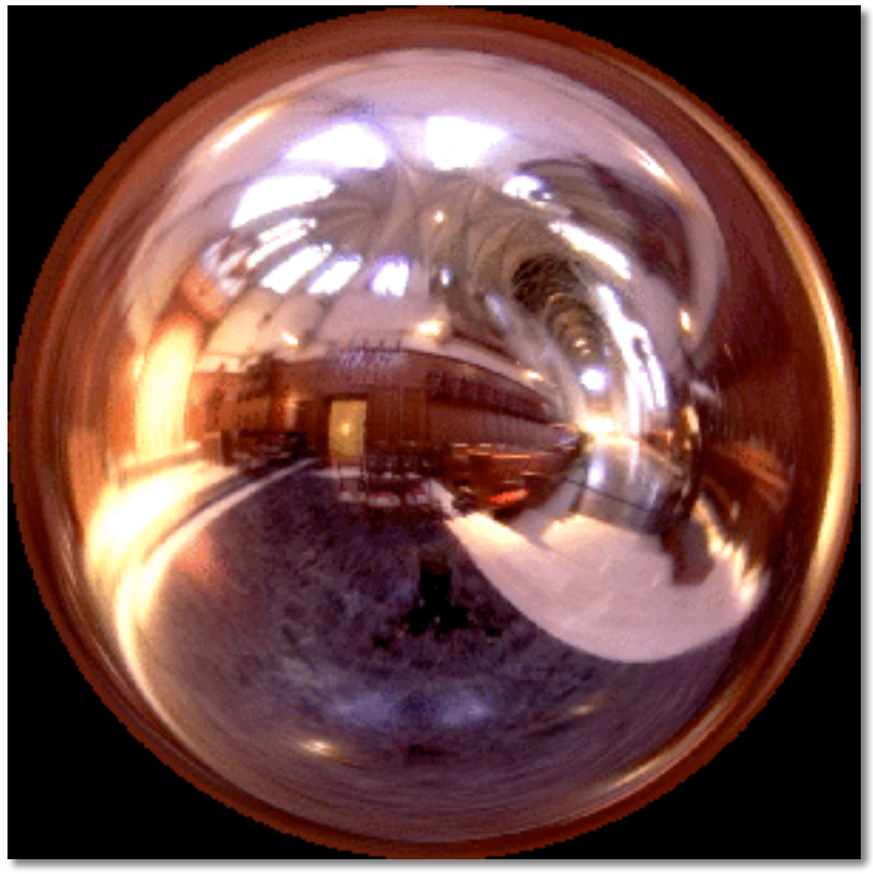
- **Spot light**
  (does not emit equally in all directions)



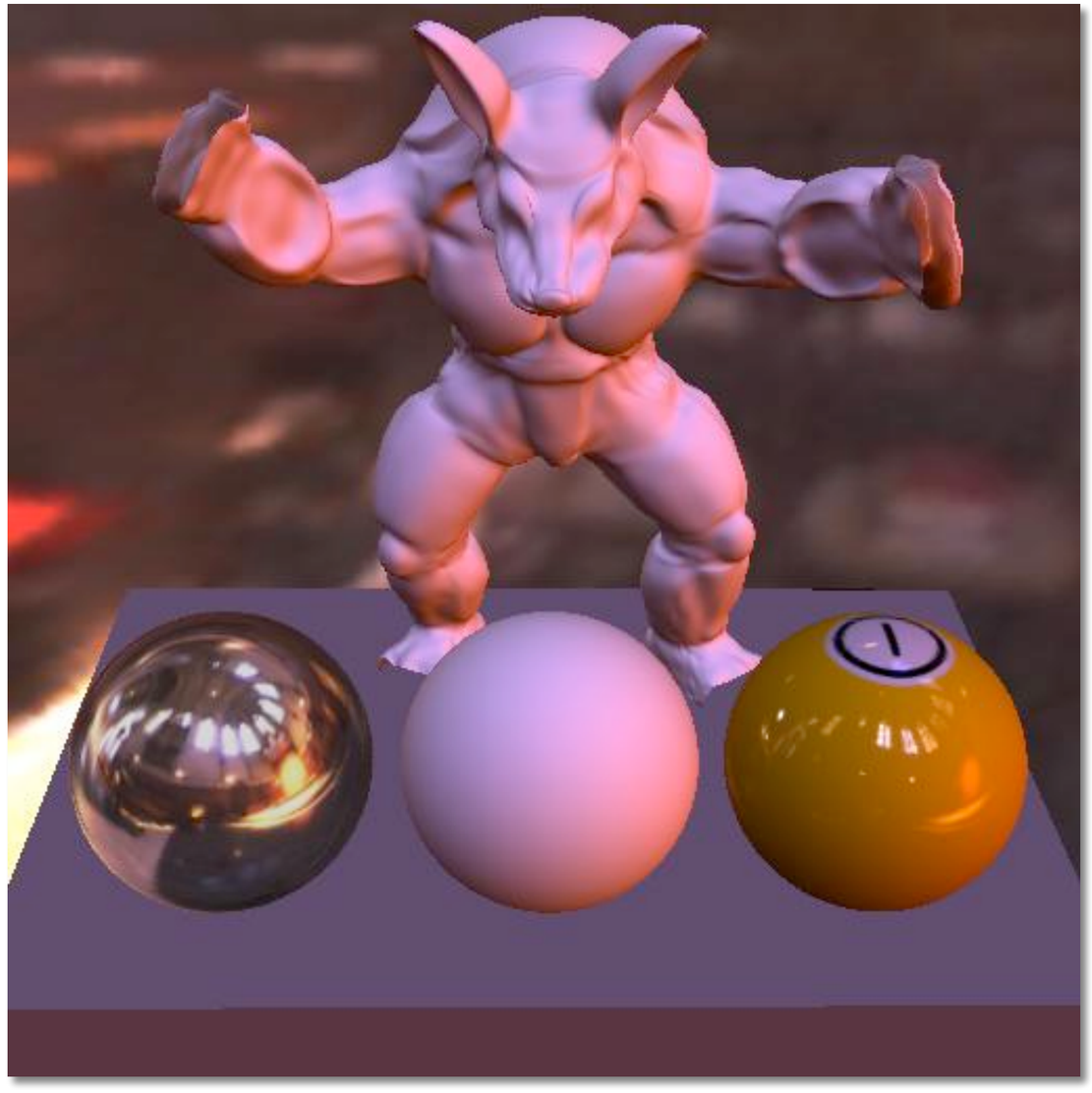
More sophisticated lights

- **Environment light**

  (not a point light source: defines incoming light from all directions)



Environment Map
(Grace cathedral)



Rendering using environment map
(pool balls have varying material properties)
[Ramamoorthi et al. 2001]

Environment map

Image credit: USC High-Resolution Light Probe Image Gallery

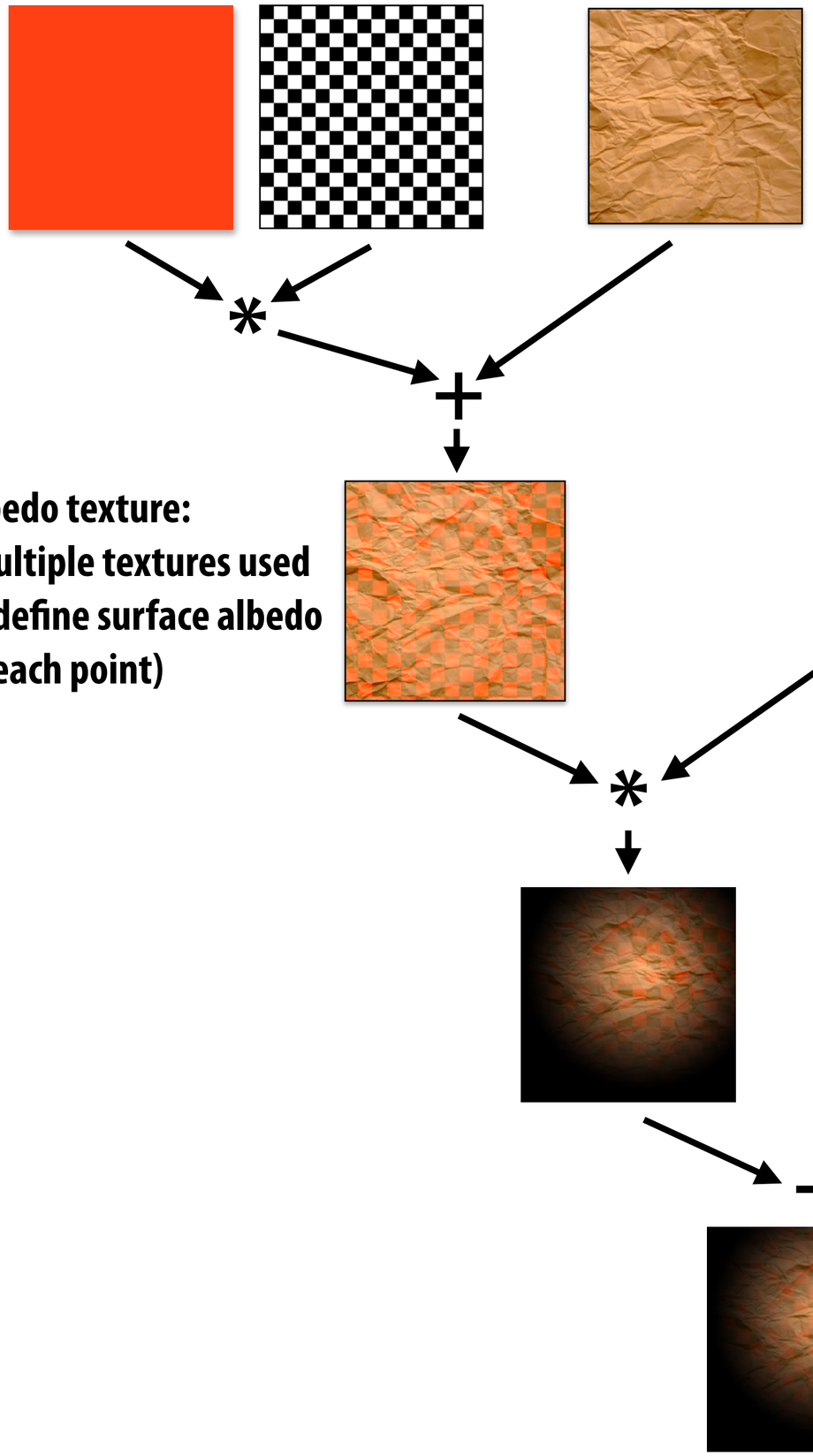
Early graphics APIS: parameterized materials and lighting (prior to programmable shading)

- `glLight(light_id, parameter_id, parameter_value)`
  - 10 parameters (e.g., ambient/diffuse/specular color, position, direction, attenuation coefficient)

- `glMaterial(face, parameter_id, parameter_value)`
  - Face specifies front or back facing geometry
  - Parameter examples (ambient/diffuse/specular reflectance, shininess)
  - Material value could be modulated by texture data

Precursor to shading languages: shade trees

[Cook 84]



Note: shade tree is a declarative abstraction!

Shading languages

- Goal: support description of a diverse set of materials and lighting conditions

- Idea: allow application to extend graphics pipeline by providing a programmatic definition of shading function logic

Tension: flexibility vs. performance

- Graphics pipeline provides highly optimized implementations of specific visibility operations
  - Examples: clipping, culling, rasterization, z-buffering
  - Highly optimized implementations for a few canonical data structures (triangles, fragments, and pixels)
  - Recall how much the implementation of these functions (including specialized hardware) was deeply intertwined with overall pipeline scheduling/ parallelization decisions

- Impractical for rendering system to constrain application to use a single parametric model for surface definitions, lighting, and shading
  - Must allow applications to define these behaviors programmatically
  - Shading language is the interface between application-defined surface, lighting, material reflectance functions and the graphics pipeline

Renderman shading language (RSL)

[Hanrahan and Lawson 90]

- **High-level, domain-specific language**
  - **Domain: describing propagation of light through scene**

- **Developed as interface to extend Pixar's Renderman renderer**

Key question:
what is the structure of the problem we are trying to write programs for?

Quick discussion

Abstract

A shading language provides a means to extend the shading and lighting formulae used by a rendering system. This paper discusses the design of a new shading language based on previous work of Cook and Perlin. This language has various types of shaders for light sources and surface reflectances, point and color data types, control flow constructs that support the casting of outgoing and the integration of incident light, a clearly specified interface to the rendering system using global state variables, and a host of useful built-in functions. The design issues and their impact on the implementation are also discussed.

CR Categories: I.3.3 [Computer Graphics] Picture/Image Generation- Display algorithms; I.3.5 [Computer Graphics] Three-Dimensional Graphics and Realism - Color, shading, shadowing and texture.

Additional Keywords and Phrases: Shading language, little language, illumination, lighting, rendering

1. Introduction

The appearance of objects in computer generated imagery, whether they be realistic or artistic looking, depends both on their shape and shading. The shape of an object arises from the geometry of its surfaces and their position with respect to the camera. The shade or color of an object depends on its illumination environment and its optical properties. In this paper the term *shading* refers to the combination of light, shade (as in shadows), texture and color that determine the appearance of an object. Many remarkable pictures can be created with objects having a simple shape and complex shading. A well-designed, modular rendering program provides clean interfaces between the geometric processing, which involves transformation, hidden surface removal, etc., and the optical processing, which involves the propagating and filtering of light. This paper describes a language for programming shading computations, and hence, extending the types of materials and light sources available to a rendering system. In Bentley's terminology it would be called a "little" language[3], since, because it is based on a simple subset of C, it easy to parse and implement, but, because it has many high-level features that customize it for shading and lighting calculations, it is easy to use.

Two major aspects of shading are the specification of surface reflectance and light source distribution functions. The earliest surface reflectance models have terms for ambient, diffuse and specular reflection. More recent research has added anisotropic scattering terms[14, 16, 21] and made explicit wavelength and polarization effects. Although not nearly as well publicized, many improvements have also been made in light source description. The earliest light source models consisted of distant or point light sources. Verbeck and Greenberg[29] introduced a general framework for describing light sources which includes attaching them to geometric primitives and specifying their intensity distribution as a function of direction and wavelength.

Light sources and surface reflectance functions are inherently *local processes*. However, many lighting effects arise because light rays traveling from light to surface are blocked by intervening surfaces or because light arriving at a surface comes indirectly via another surface. Turner Whitted termed these effects *global illumination processes*. Kajiya introduced the general light transport equation, which he aptly termed the *rendering equation*, and showed how all these techniques are tied together[15]. Most recent research in shading and lighting calculations is now being focussed on making these global illumination algorithms efficient. Note that global and local illumination processes are independent aspects of the general illumination process.

In parallel to the development of specific shading models is the development of shading systems. Most current systems implement a single parameterized shading model. There are several problems with this approach. First, there is little agreement on what this shading model should be. Almost every rendering system written has used a slightly different shading model. Second, it seems unlikely that a single parameterized model could ever be sufficient. As mentioned earlier, the development of shading models is an active area of research and new material models are continually being developed. Shading also involves many *tricks*, one major example being texture mapping, and the use of rendering tricks is completely open ended. Furthermore, the surface reflectance models of simple and composite materials are phenomenologically based and not derivable from first principles. Shading models that capture the effects of applying varnish or lac-

RSL programming model

- Structures shading computations using two types of functions: surface shaders and light shaders

- Structure of shaders corresponds to structure of the rendering equation:
  - Surface shaders integrate incoming light and compute the reflectance (from a surface point) in the direction of the camera
  - Light shaders compute emitted light in the direction of surface point

Key RSL abstractions

- Shaders
  - Surface shaders:
    - Define surface reflection function (BRDF)
    - Integrate contribution of light from all light sources
  - Light shaders: define directional distribution of energy emitted from lights

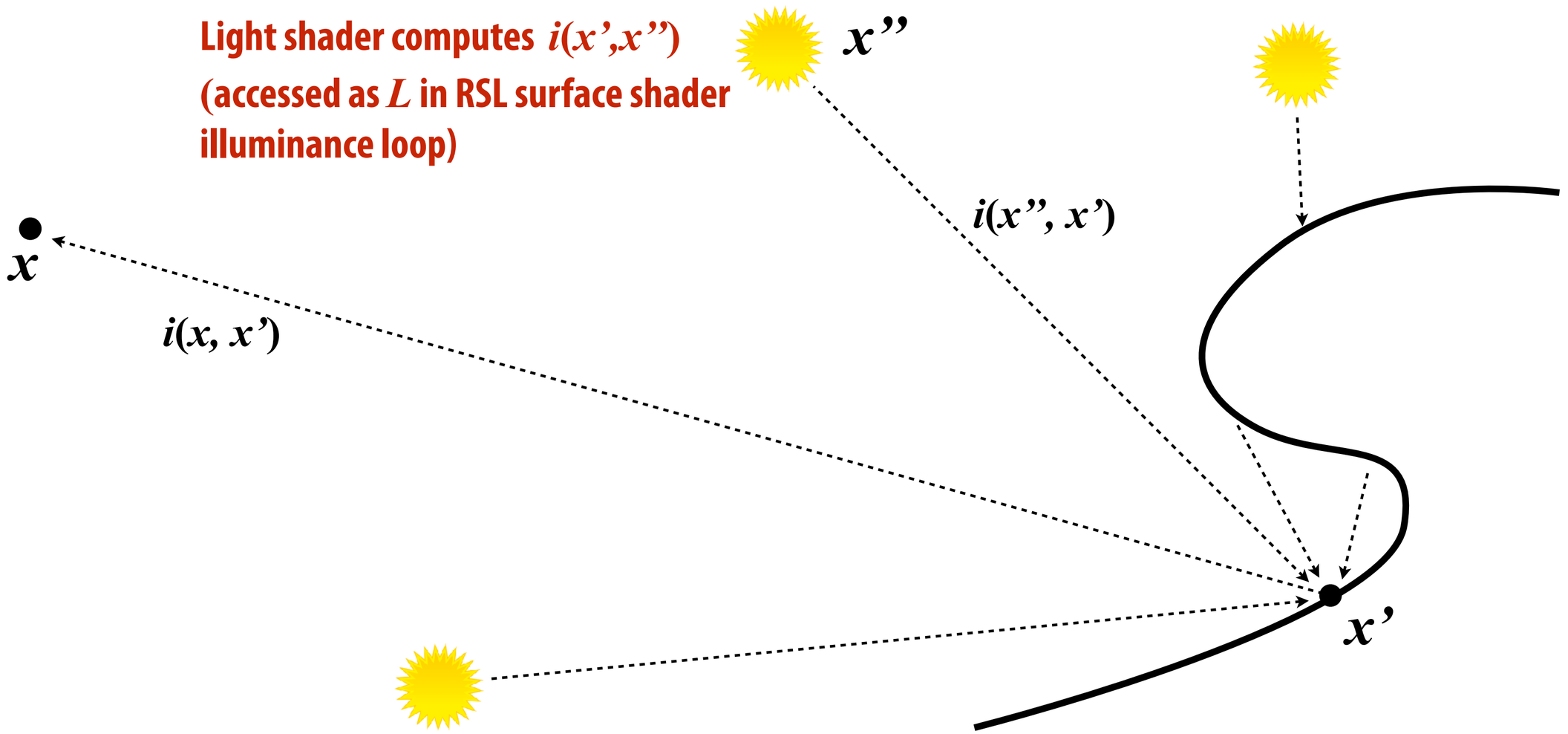
- First-class color and point abstract data types
- First-class texture sampling functions
- Light shader's `illuminate` construct
- Surface shader's `illuminance` loop
  - integrates reflectance over all lights

Recall: rendering equation

$$i(x,x') = v(x,x')\left[l(x,x') + \int r(x,x',x'')i(x',x'')\,dx''\right]$$

Surface shader integrates contribution to reflection from all lights

Light shader computes $i(x',x'')$ (accessed as L in RSL surface shader illuminance loop)



Shading objects in RSL

Shaders are closures:
Shading function code +
values of shader parameters

compiled code
(e.g., plastic material)

current transforms

bound parameters
kd = 0.5
ks = 0.3

Surface shader object

compiled code
(spotlight)

current transforms

bound parameters
intensity =0.75
color = (1.0, 1.0, 0.5)
position = (5,5,10)
axis = (1.0, 1.0, 0)
angle = 35

compiled code
(point light)

current transforms

bound parameters
position = (5,5,5)
intensity =0.75
color = (1.0, 1.0, 0.5)

compiled code
(point light)

current transforms

bound parameters
position = (20,20,100)
intensity =0.5
color = (0.0, 0.0, 1.0)

Light shader objects

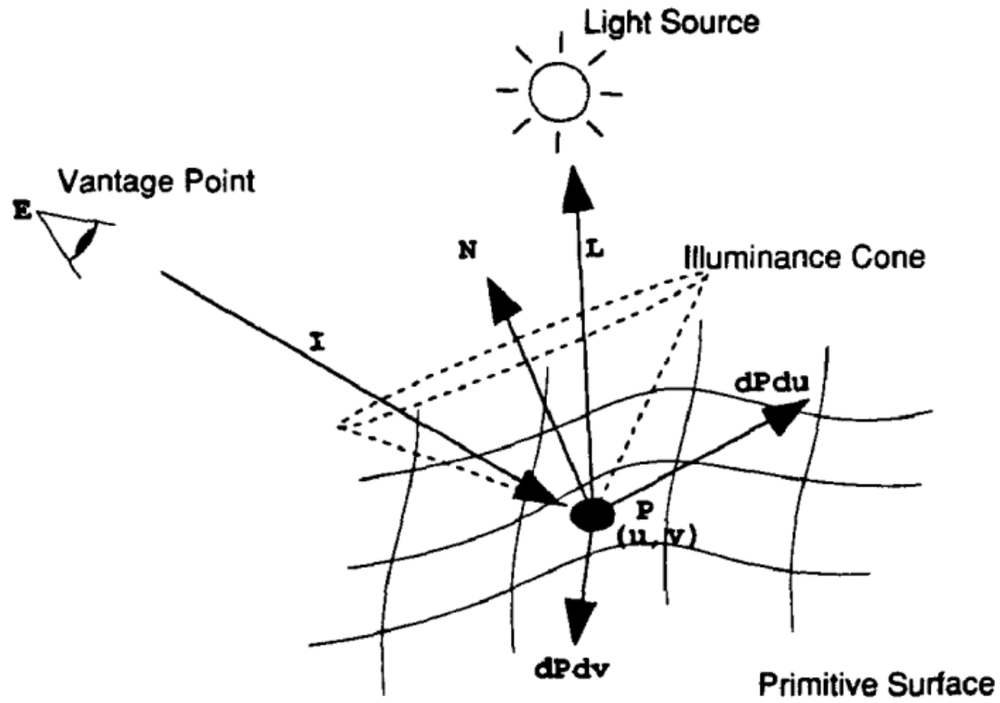
RSL surface shaders

Executed once per point to shade

Key abstraction: illuminance loop — iterate over illumination sources (but no explicit enumeration of sources: surface definition is agnostic to what lights are linked)

```
illuminance (position, axis, angle)
{

}
```



Example: computing diffuse reflectance

```
surface diffuseMaterial(color Kd)
{
   Ci = 0;

   // integrate light from all lights (over hemisphere of directions)
   illuminance (P, Nn, PI/2)
   {
      Ci += Kd * Cl * (Nn . normalize(L));
   }
}
```

Cl = Value computed by light shader

L = Vector from light position (recall `light_pos` argument to light shader's `illuminate`) to surface position being shaded (see P argument to `illuminance`)

Surface shader computes Ci

RSL light shaders

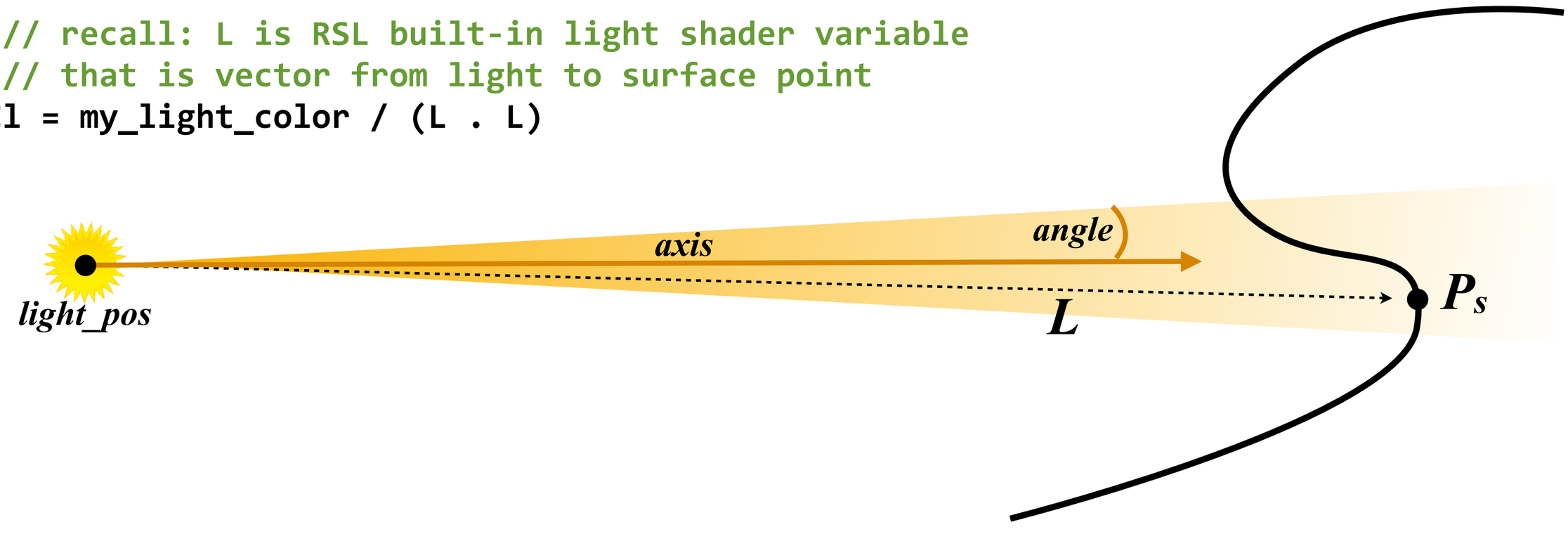
Key abstraction: illuminate block

```
illuminate (light_pos, axis, angle)
{

}
```

Example: attenuating spot-light (no area fall off)

```
illuminate (light_pos, axis, angle)
{
   // recall: L is RSL built-in light shader variable
   // that is vector from light to surface point
  Cl = my_light_color / (L . L)
}
```



GPU shading languages today: e.g., HLSL

HLSL shader program example: defines logic of fragment processing stage

"Uniform" parameters (same value for all fragments)

```
sampler mySampler;
Texture2D<float3> myTex;
float3 lightDir[4];

float4 diffuseShader(float3 norm, float2 uv)
{
   float3 kd = myTex.Sample(mySampler, uv);
   float3 lighting = 0.0;
   for (int i=0; i<4; i++)
      lighting += clamp(dot(-lightDir, norm), 0.0, 1.0);
   return float4(lighting * kd, 1.0);
}
```

Varying "per-fragment" arguments

Sample surface albedo from texture

Shader returns surface reflectance (float4)

Modulate surface albedo by incident irradiance

Note: Imperative abstraction for defining logic within a shader!

Short discussion

Cg: A system for programming graphics hardware in a C-like language

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This paper discusses the Cg programmer interfaces (i.e. Cg language and APIs) and the high-level Cg system architecture. We focus on describing the key design choices that we faced and on explaining why we made the decisions we did, rather than providing a language tutorial or describing the system's detailed implementation and internal architecture. More information about the Cg language is available in the language specification [NVIDIA Corp. 2003a] and tutorial [Fernando and Kilgard 2003].

Clear articulation of goals/constraints

The language and system design was guided by a handful of high-level goals:

- **Ease of programming.**
  Programming in assembly language is slow and painful, and discourages the rapid experimentation with ideas and the easy reuse of code that the off-line rendering community has already shown to be crucial for shader design.
- **Portability.**
  We wanted programs to be portable across hardware from different companies, across hardware generations (for DX8-class hardware or better), across operating systems (Windows, Linux, and MacOS X), and across major 3D APIs (OpenGL [Segal and Akeley 2002] and DirectX [Microsoft Corp. 2002a]). Our goal of portability across APIs was largely motivated by the fact that GPU programs, and especially "shader" programs, are often best thought of as art assets – they are associated more closely with the 3D scene model than they are with the actual application code. As a result, a particular GPU program is often used by multiple applications (e.g. content-creation tools), and on different platforms (e.g. PCs and entertainment consoles).
- **Complete support for hardware functionality.**
  We believed that developers would be reluctant to use a high-level language if it blocked access to functionality that was available in assembly language.
- **Performance.**
  End users and developers pay close attention to the performance of graphics systems. Our goal was to design a language and system architecture that could provide performance equal to, or better than, typical hand-written GPU assembly code. We focused primarily on interactive applications.
- **Minimal interference with application data.**
  When designing any system layered between applications and the graphics hardware, it is tempting to have the system manage the scene data because doing so facilitates resource virtualization and certain global optimizations. Toolkits such as SGI's Performer [Rohlf and Helman 1994] and Electronic Arts's EAGL [Lalonde and Schenk 2002] are examples of software layers that successfully manage scene data, but their success depends on both their domain-specificity and on the willingness of application developers to organize their code in conforming ways. We wanted Cg to be usable in existing applications, without the need for substantial reorganization. And we wanted Cg to be applicable to a wide variety of interactive and non-interactive application categories. Past experience suggests that these goals are best achieved by avoiding management of scene data.
- **Support for non-shading uses of the GPU.**
  Graphics processors are rapidly becoming sufficiently flexible that they can be used for tasks other than programmable transformation and shading (e.g. [Boltz et al. 2003]). We wanted to design a language that could support these new uses of GPUs.

Some of these goals are in partial conflict with each other. In cases of conflict, the goals of high performance and support for hardware functionality took precedence, as long as doing so did not fundamentally compromise the ease-of-use advantage of programming in a high-level language.

Philosophy of addressing conflicts

Often system designers must preserve substantial compatibility with old system interfaces (e.g. OpenGL is similar to IRIS GL). In our case, that was a non-goal because most pre-existing high level shader code (e.g. RenderMan shaders) must be modified anyway to achieve real-time performance on today's graphics architectures.

← Non-goals

Key design decisions

4 Key Design Decisions

4.1 A "general-purpose language", not a domain-specific "shading language"

Computer scientists have long debated the merits of domain-specific languages vs. general-purpose languages. We faced the same choice – should we design a language specifically tailored for shading computations, or a more general-purpose language intended to expose the fundamental capabilities of programmable graphics architectures?

Paper states plausible alternatives to decisions ultimately made.

4.2 A program for each pipeline stage

The user-programmable processors in today's graphics architectures use a stream-processing model [Herwitz and Pomerene 1960; Stephens 1997; Kapasi et al. 2002], as shown earlier in Figure 2. In this model, a processor reads one element of data from an input stream, executes a program (*stream kernel)* that operates on this data, and writes one element of data to an output stream.

Choosing a programming model to layer on top of this stream-processing architecture was a major design question. We initially considered two major alternatives. The first, illustrated by RTSL and to a lesser extent by RenderMan, is to require that the user write a single program, with some auxiliary mechanism for specifying whether particular computations should be performed on the vertex processor or the fragment processor. The second, illustrated by the assembly-level interfaces in OpenGL and Direct3D, is to use two separate programs. In both cases, the programs consume an element of data from one stream, and write an element of data to another stream.

The unified vertex/fragment program model has a number of advantages. It encapsulates all of the computations for a shader in one piece of code, a feature that is particularly comfortable for programmers who are already familiar with RenderMan. It

Shading language design questions

- **Design issue: programmer convenience vs. application scope**
  - **Should we adopt high-level (graphics-specific) or low-level (more general and flexible) abstractions?**
  - **e.g., Should graphics concepts such as materials and lights be first-class primitives in the programming model?**

- **Design issue: preserving high performance**
  - **Abstractions must permit wide data-parallel implementation of fragment shader stage (to utilize many programmable cores)**
  - **Abstractions must permit use of fixed-function hardware for key shading operations (e.g., texture filtering)**

Efficiently mapping of shading computations to GPU hardware

Shading typically has very high arithmetic intensity

```
sampler mySamp;
Texture2D<float3> myTex;
float3 ks;
float  shinyExp;
float3 lightDir;
float3 viewDir;

float4 phongShader(float3 norm, float2 uv)
{
  float result;
  float3 kd;
  kd = myTex.Sample(mySamp, uv);
  float spec = dot(viewDir, 2 * dot(-lightDir, norm) * norm + lightDir);
  result = kd * clamp(dot(lightDir, norm), 0.0, 1.0);
  result += ks * exp(spec, shinyExp);
  return float4(result, 1.0);
}
```

Image credit: http://caig.cs.nctu.edu.tw/course/CG2007

3 scalar float operations + 1 exp()
8 float3 operations + 1 clamp()
1 texture access

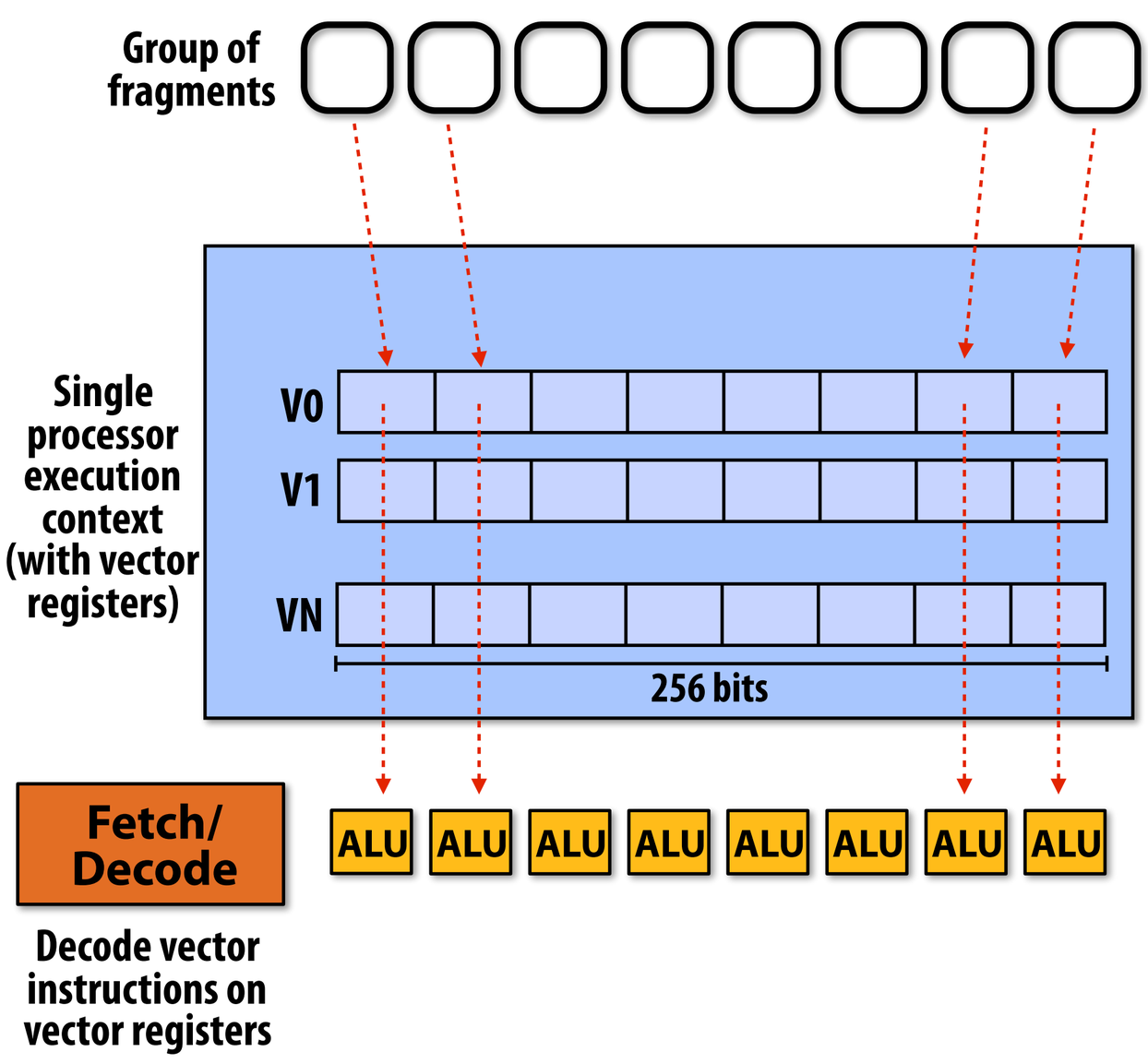
Vertex processing often has even higher arithmetic intensity than fragment processing (less use of texturing)

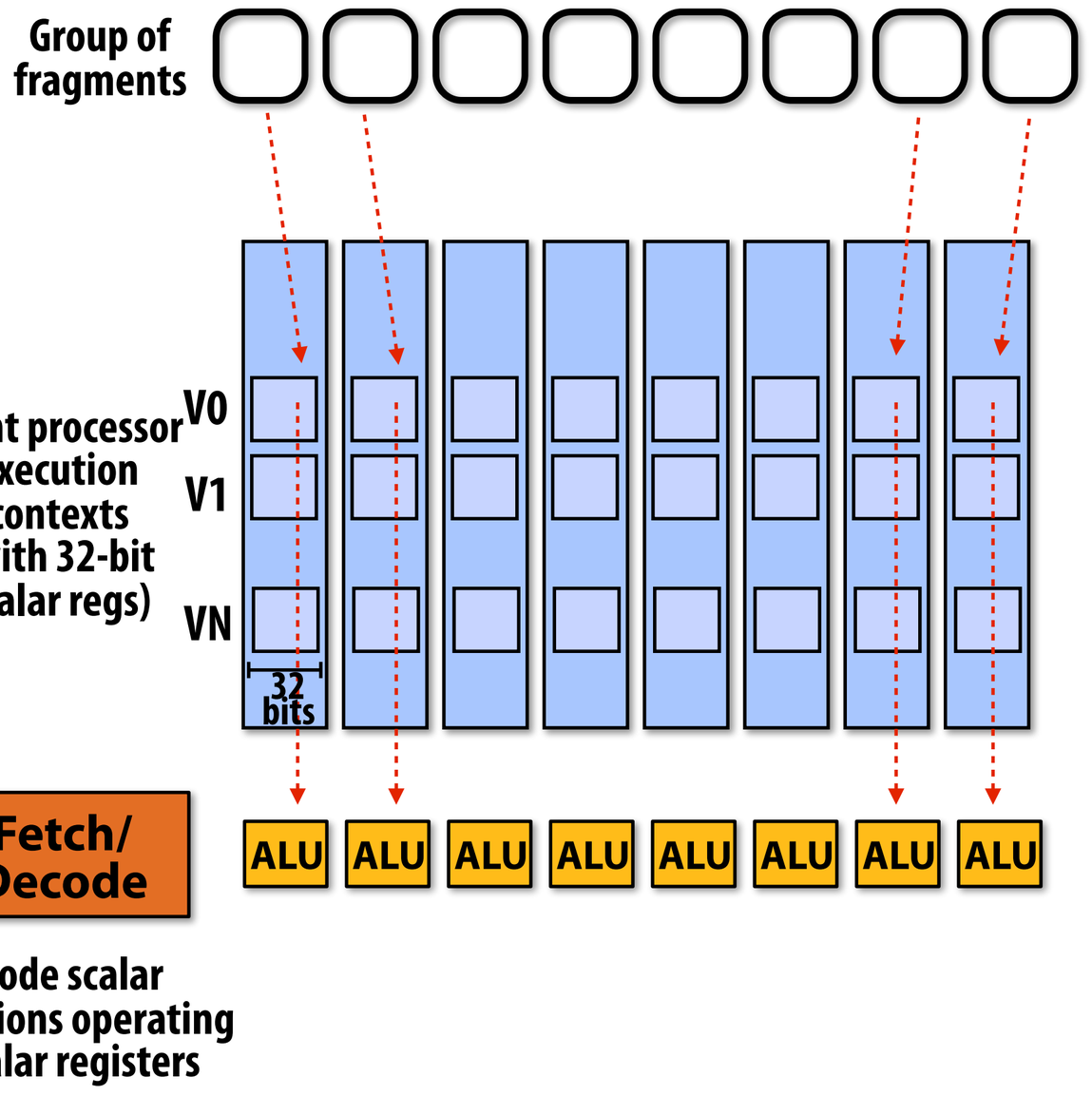
Review: fictitious throughput processor

- Processor decodes one instruction per clock
- Instruction controls all eight SIMD execution units
  - SIMD = "single instruction multiple data"
- "Explicit" SIMD:
  - Vector instructions manipulate contents of 8x32-bit (256 bit) vector registers
  - Execution is all within one hardware execution context
- "Implicit" SIMD (SPMD, "SIMT"):
  - Hardware executes eight unique execution contexts in "lockstep"
  - Program binary contains scalar instructions manipulating 32-bit registers

Mapping fragments to execution units:

Map fragments to "vector lanes" within one execution context (explicit SIMD parallelism) or to unique contexts that share an instruction stream (parallelization by hardware)





GLSL/HLSL shading languages employ a SPMD programming model

- SPMD = single program, multiple data
  - Programming model used in writing GPU shader programs
    - What's the program?
    - What's the data?
  - Also adopted by CUDA and ISPC

- How do we implement a SPMD program on SIMD hardware?

Example 1: shader with a conditional

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

float4 fragmentShader(float3 norm, float2 st, float4 frontColor, float4 backColor)
{
  float4 tmp;
  if (norm[2] < 0)  // sidedness check (direction of Z component of normal)
  {
     tmp = backColor;
  }
  else
  {
     tmp = frontColor;
     tmp *= myTex.sample(mySamp, st);
  }
  return tmp;
}
```

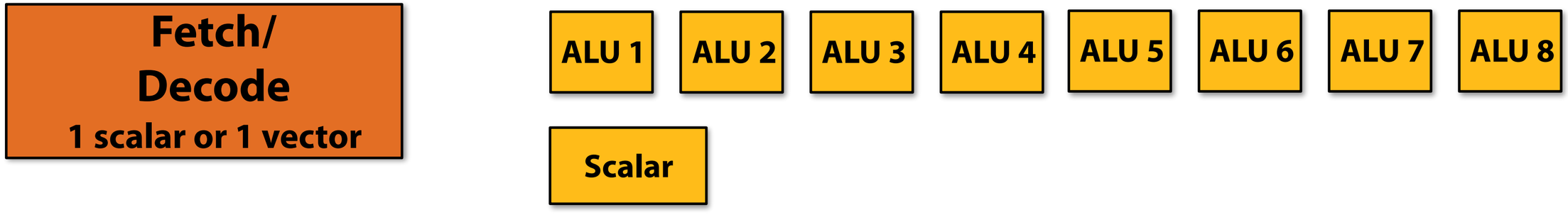
Example 2: predicate is uniform expression

```
sampler mySamp;
Texture2D<float3> myTex;
float myParam;       // uniform value
float myLoopBound;

float4 fragmentShader(float3 norm, float2 st, float4 frontColor, float4 backColor)
{
   float4 tmp;
   if (myParam < 0.5)
   {
      float scale = myParam * myParam;
      tmp = scale * frontColor;
   }
   else
   {
      tmp = backColor;
   }
   return tmp;
}
```

Notice:
predicate is uniform expression
(same result for all fragments)

Improved efficiency: processor executes uniform instructions using scalar execution units

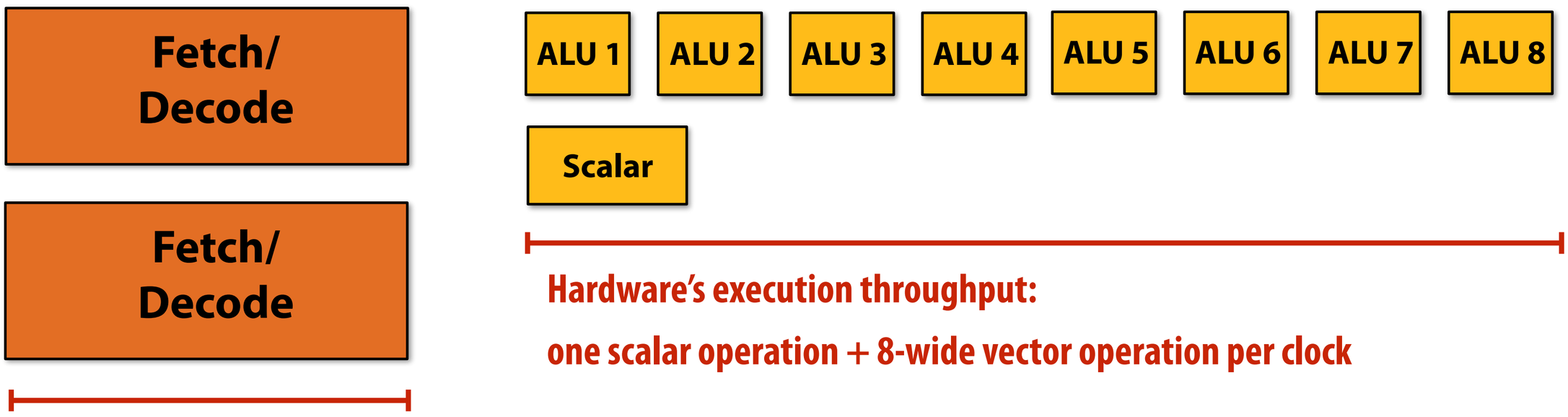


Logic shared across all "vector lanes" need only be performed once (not repeated by every vector ALU)

Scalar logic identified at compile time (compiler generates different instructions)

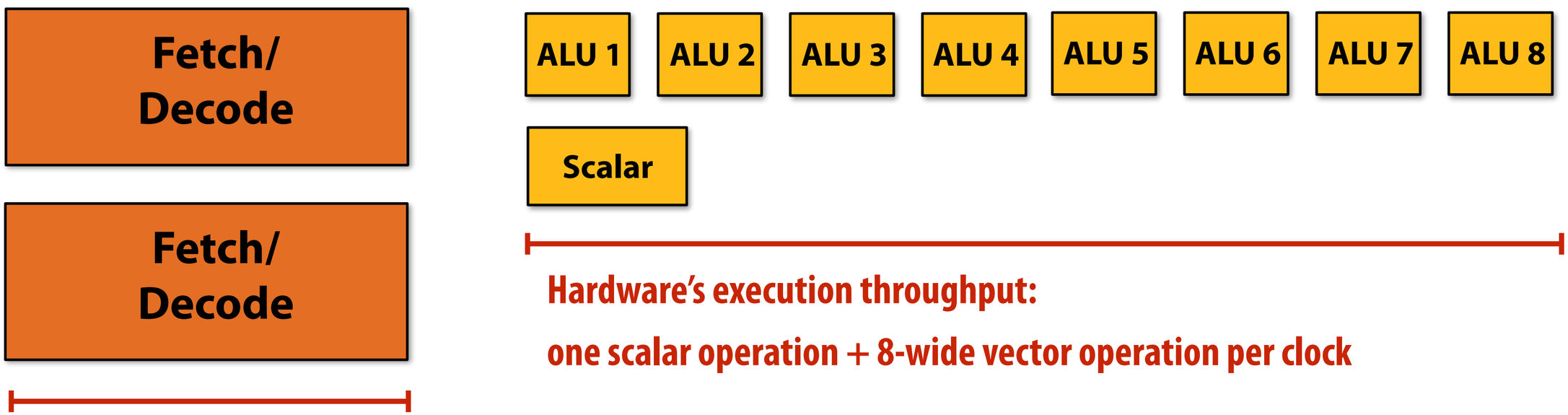
```
float3 lightDir[MAX_NUM_LIGHTS];
int numLights;
float4 multiLightFragShader(float3 norm, float4 surfaceColor)
{
   float4 outputColor;
   for (int i=0; i<num_lights; i++) {
     outputColor += surfaceColor * clamp(0.0, 1.0, dot(norm, lightDir[i]));
   }
}
```

Improving the fictitious throughput processor



- **Now decode two instructions per clock**
  - How should we organize the processor to execute those instructions?

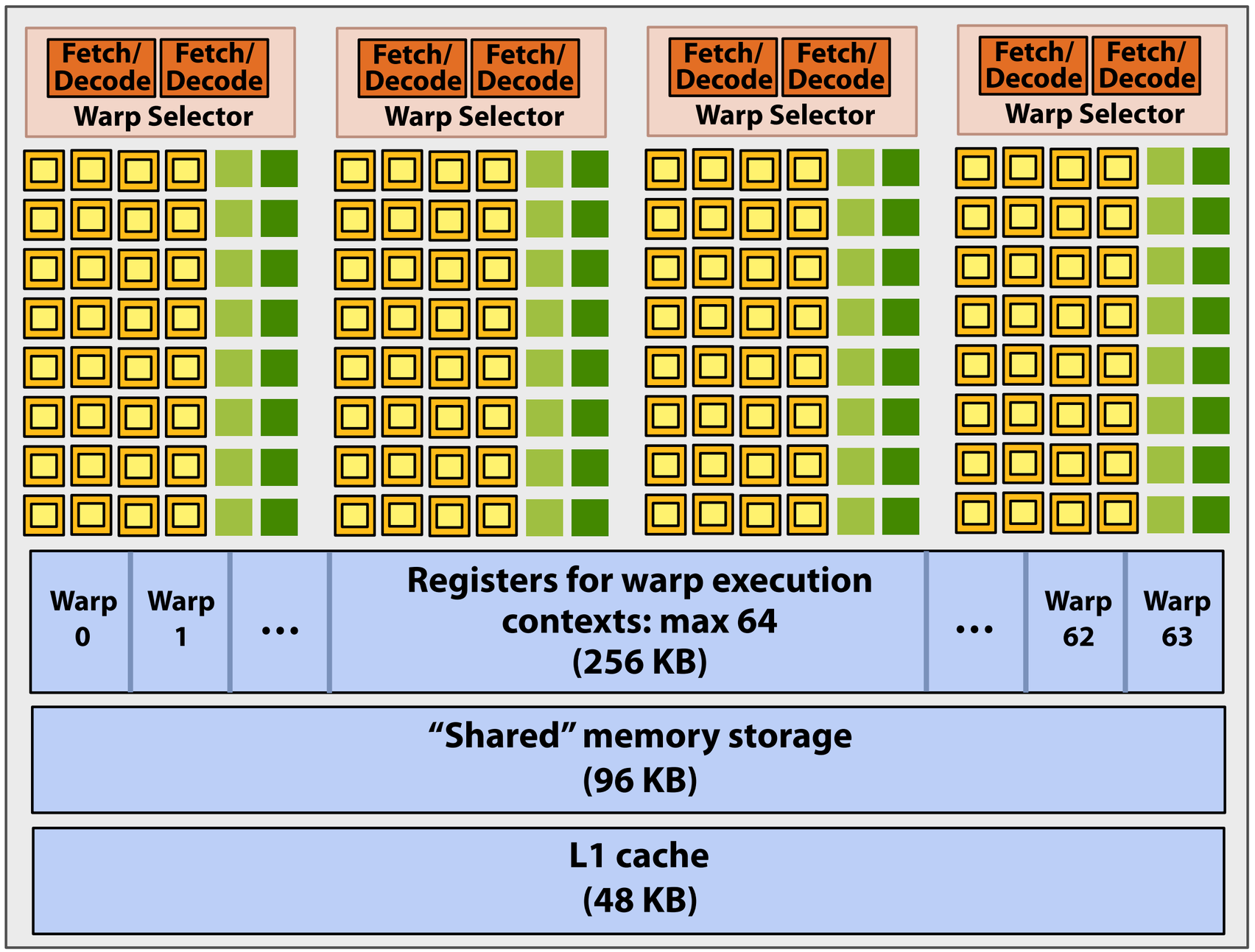
Three possible organizations



- **Execute two instructions (one scalar, one vector) from same execution context**
  - One execution context can fully utilize the processor's resources, but requires instruction-level-parallelism in instruction stream
- **Execute unique instructions in two different execution contexts**
  - Processor needs two runnable execution contexts (twice as much parallel work must be available)
  - But no ILP in any instruction stream is required to run machine at full throughput
- **Execute two SIMD operations in parallel (e.g., two 4-wide operations)**
  - Significant change: must modify how ALUs are controlled: no longer 8-wide SIMD
  - Instructions could be from same execution context (ILP) or two different ones

NVIDIA GTX 1080 (2016)

This is one NVIDIA Pascal GP104 streaming multi-processor (SM) unit



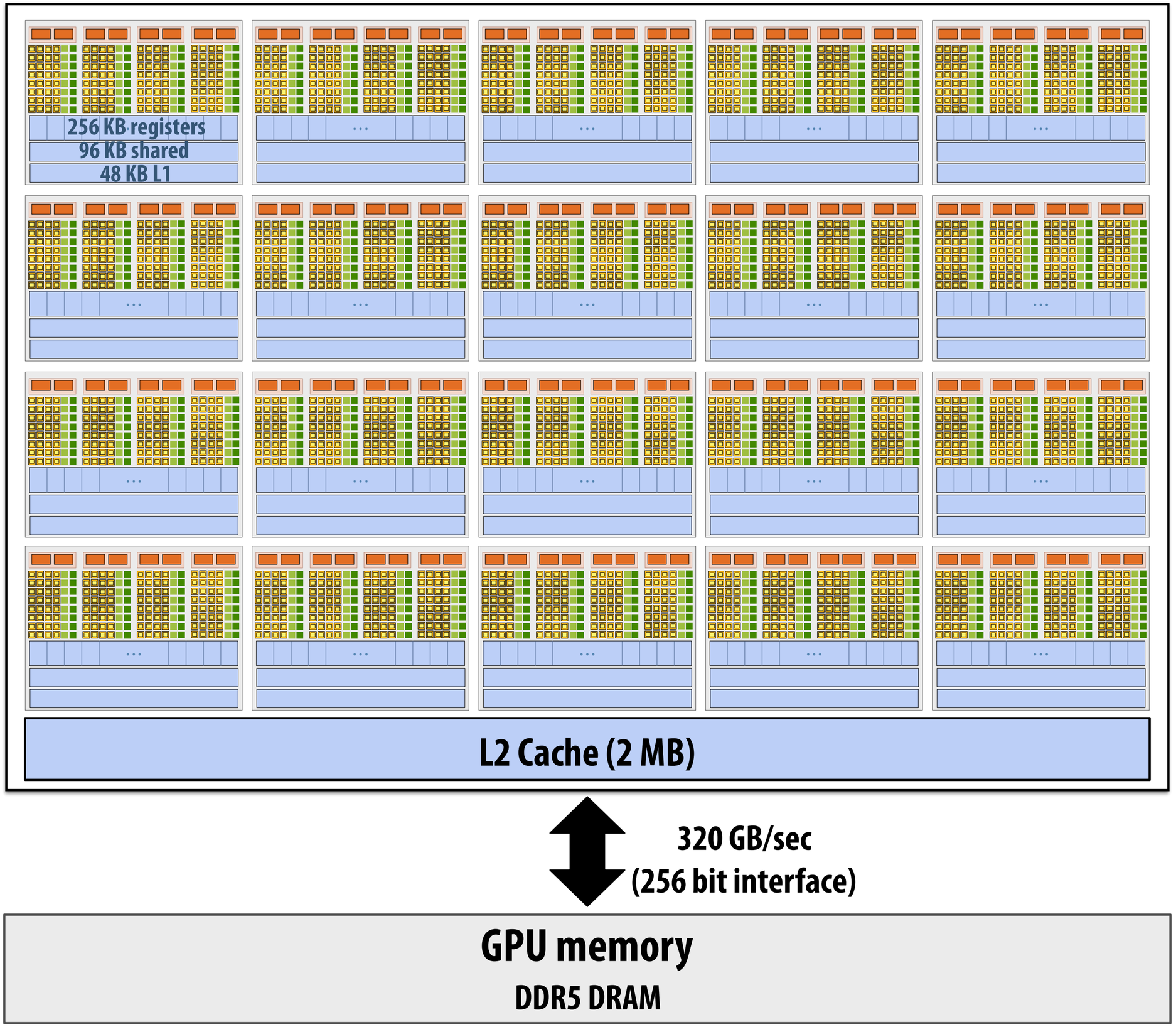
= SIMD functional unit, control shared across 32 units (1 MUL-ADD per clock)

= load/store

= SIMD special function unit (sin, cos, etc.)

- Instructions operate on 32 pieces of data at a time (instruction streams called "warps").
- Different instructions from up to four warps can be executed simultaneously (simultaneous multi-threading)
- Up to 64 warps are interleaved on the SM (interleaved multi-threading)
- Over 2,048 fragments/ vertices/etc can be processed concurrently by a core

NVIDIA GTX 1080 (20 SMs)

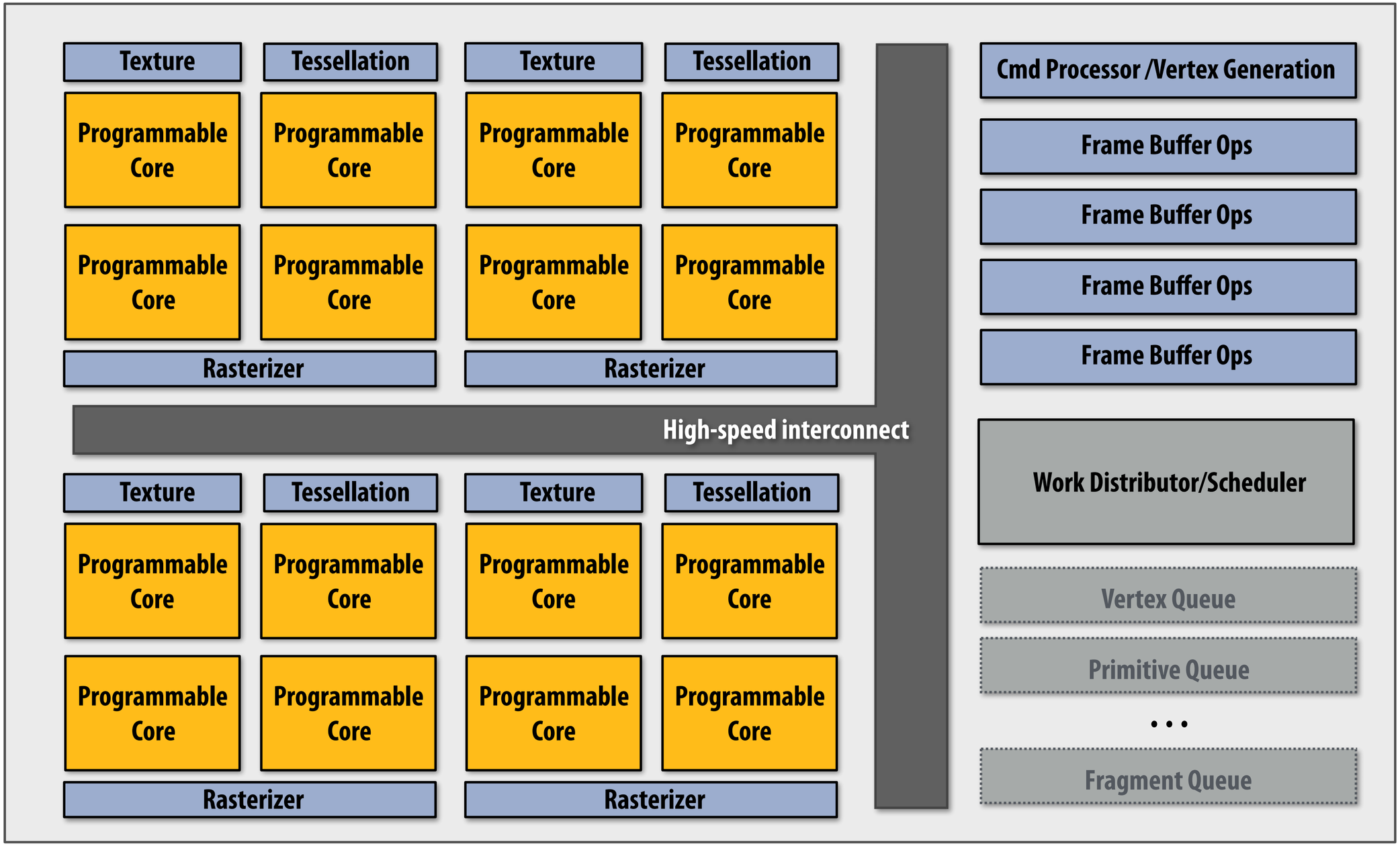


Shading languages summary

- **Convenient/simple abstraction:**
  - Wide application scope: implement any logic within shader function subject to input/output constraints.
  - Independent per-element SPMD programming model (no loops over elements, no explicit parallelism)
  - Built-in primitives for texture mapping
- **Facilitate high-performance implementation:**
  - SPMD shader programming model exposes parallelism (independent execution per element)
  - Shader programming model exposes texture operations (can be scheduled on specialized HW)
- **GPU implementations:**
  - Wide SIMD execution (shaders feature coherent instruction streams)
  - High degree of multi-threading (multi-threading to avoid stalls despite large texture access latency)
    - e.g., NVIDIA GPU: 16 times more warps (execution contexts) than can be executed per clock
  - Fixed-function hardware implementation of texture filtering (efficient, performant)
  - High performance implementations of transcendentals (sin, cos, exp) -- common operations in shading

One important thought

Recall: modern GPU is a heterogeneous processor



An unusual aspect of the graphics pipeline architectures' design

- **Fixed-function components on a GPU control the operation of the programmable components**
  - Fixed-function logic generates work (input assembler, tessellator, rasterizer generate elements)
  - Programmable logic defines how to process generated elements

- **Application-programmable logic forms the inner loops of the rendering computation, not the outer loops!** ← Think: contrast this design to video decode interfaces on a SoC

- **Ongoing debate: can we flip this design around?**
  - Maintain efficiency of heterogeneous hardware implementation, but give software control of how pipeline is mapped to hardware resources