Lecture 23:

Shading Languages

(+ mapping shader programs to GPU processor cores)

Visual Computing Systems
CMU 15-769, Fall 2016

The course so far

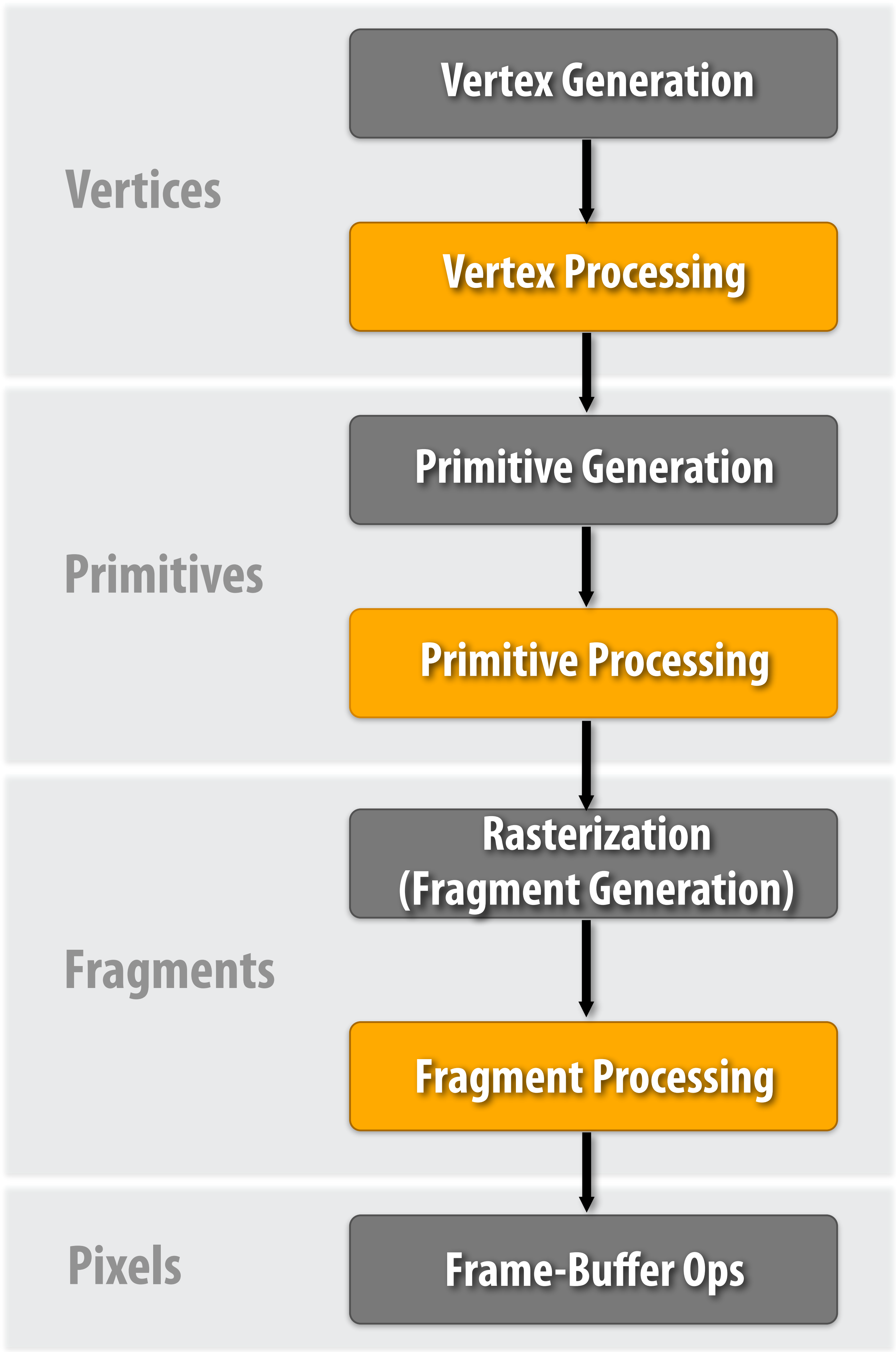
So far in this section of the course: focus has been on non-programmable parts of the graphics pipeline

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

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

And hardly mentioned programmable GPUs

Basic Graphics Pipeline



Review: the rendering equation *

[Kajiya 86]

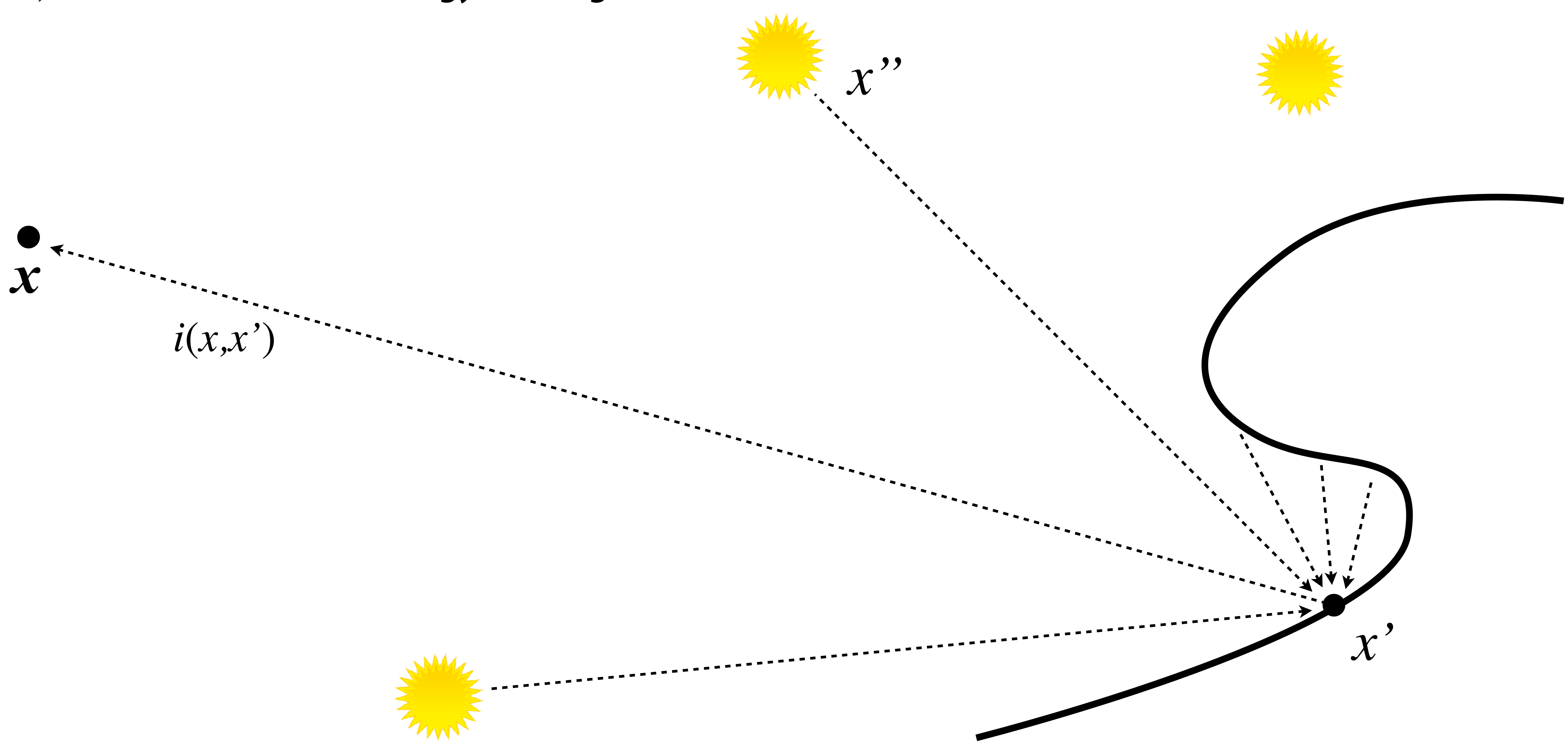
$$i(x,x') = v(x,x')\left[l(x,x') + \int r(x,x',x'')\, i(x',x'')\, dx''\right]$$

$i(x,x')$ = 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

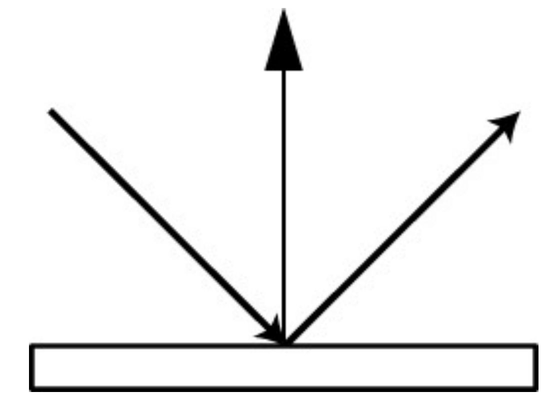


* Note: using notation from Hanrahan 90 (to match reading)

Categories of reflection functions

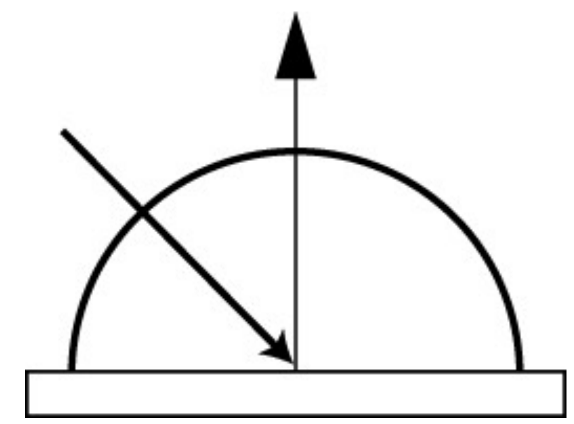
- **Ideal specular**

  Perfect mirror



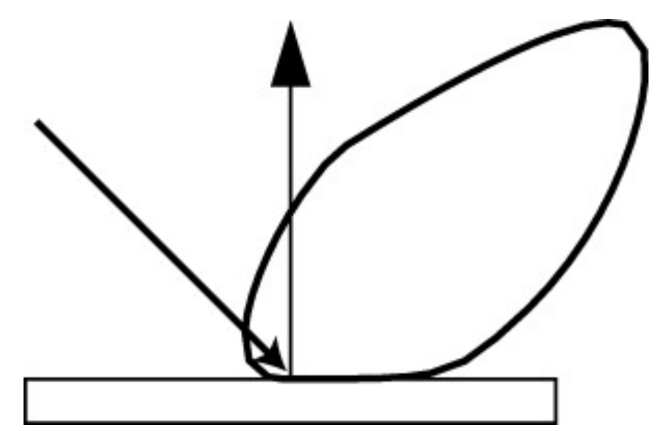
- **Ideal diffuse**

  Uniform reflection in all directions



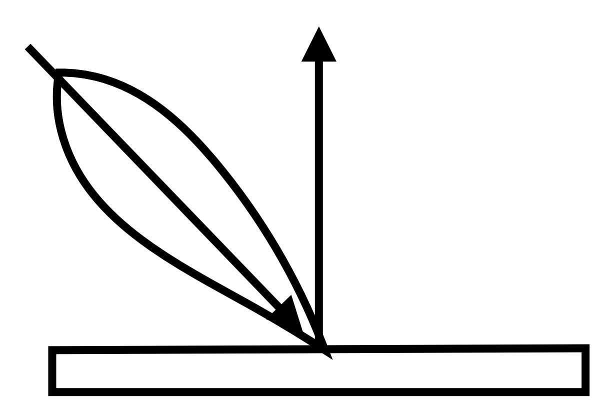

- **Glossy specular**

  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.

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

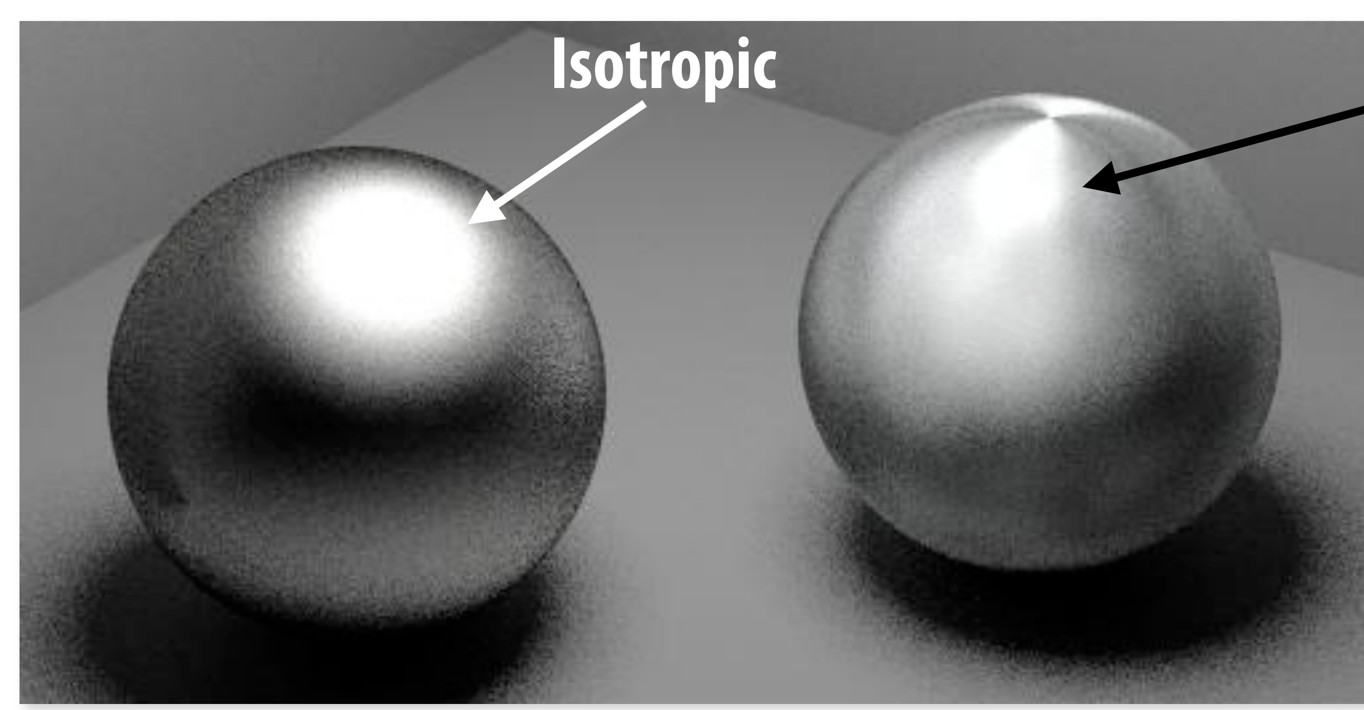
[Image credit: Jakob et al. 2014]

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]



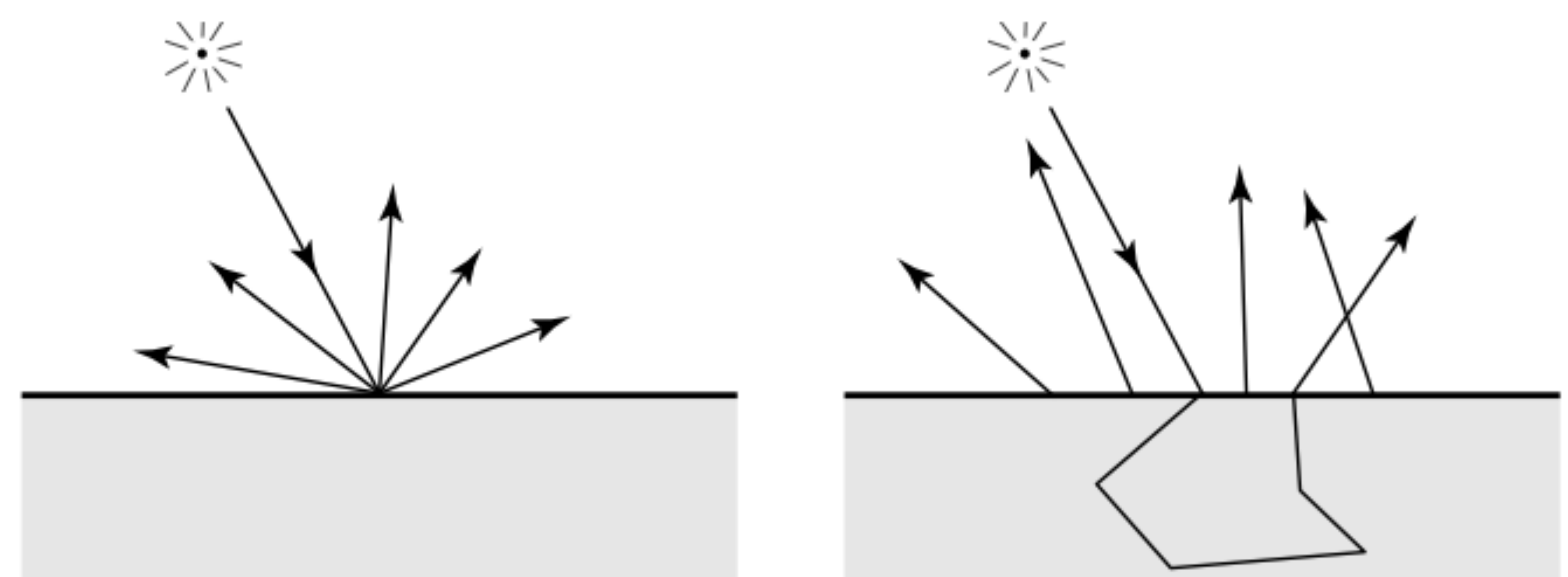
Anisotropic reflection: reflectance depends on azimuthal angle (e.g., oriented microfacets in brushed steel)

Subsurface scattering materials

[Wann Jensen et al. 2001]

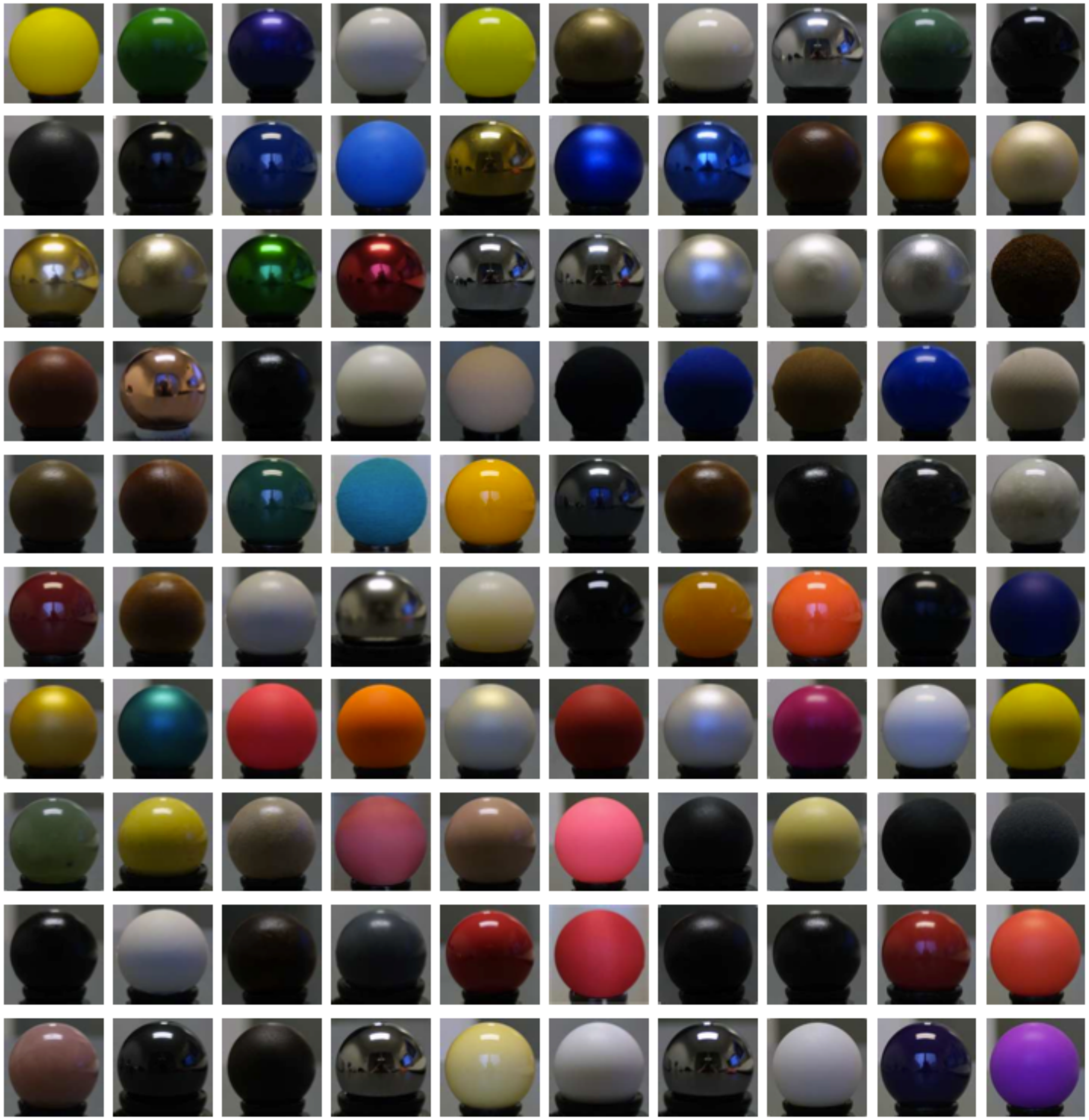
BRDF

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



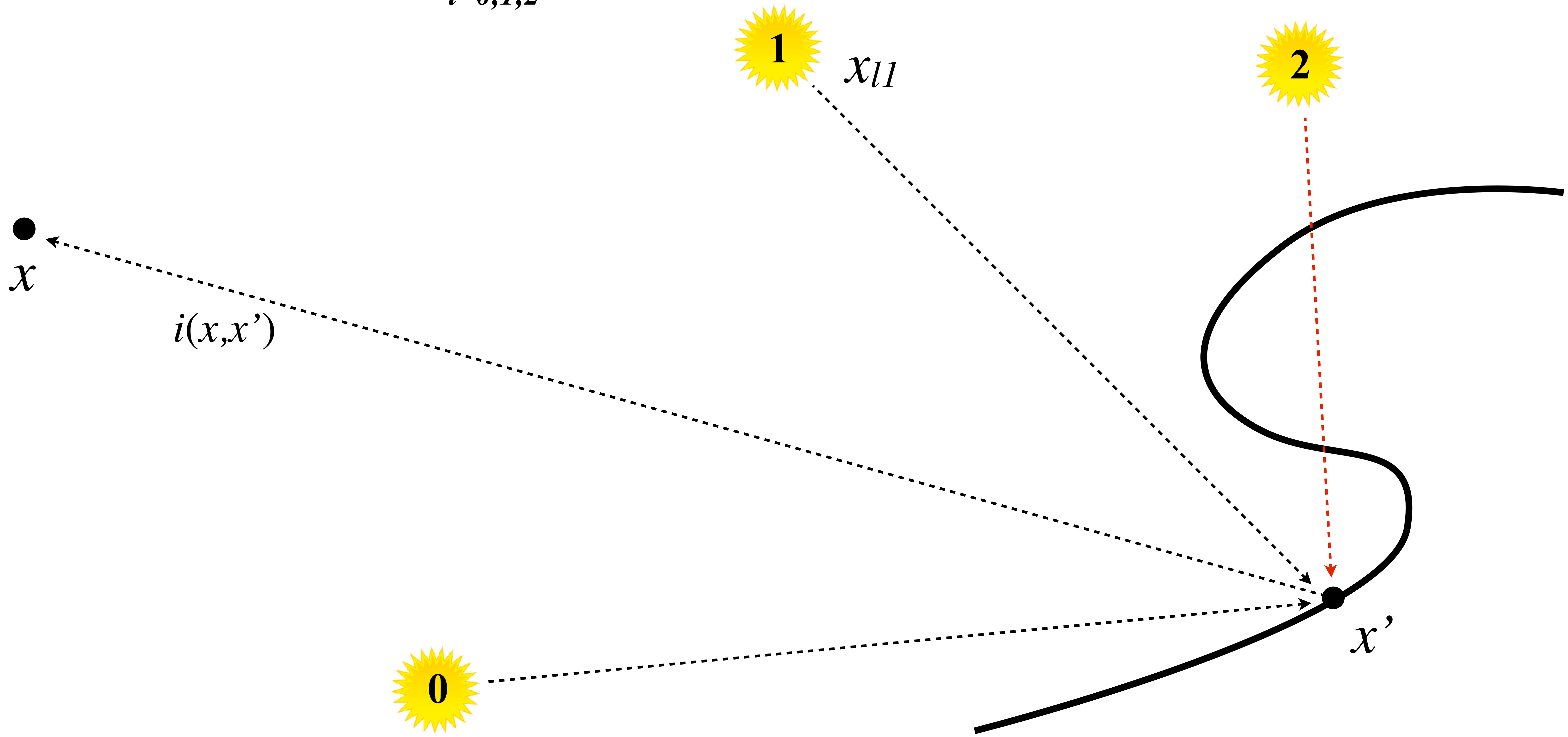
Tabulated BRDFs

Images from Matusik et al. SIGGRAPH 2003

Simplification of the rendering equation

- All light sources are point 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

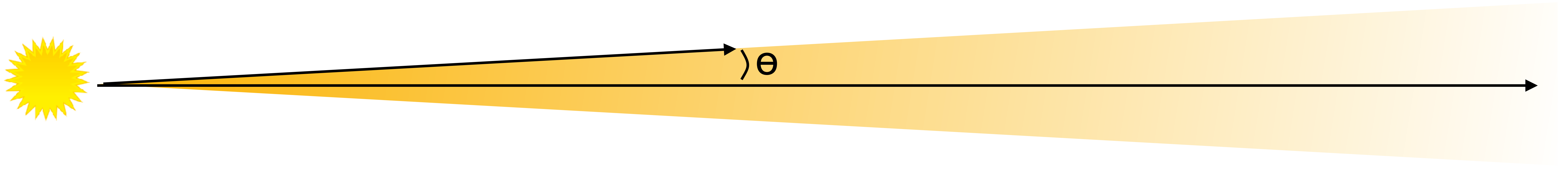
$$i(x,x') = \sum_{i=0,1,2} L_i v(x', x_{l_i}) r(x, x', x_{l_i})$$



More light types

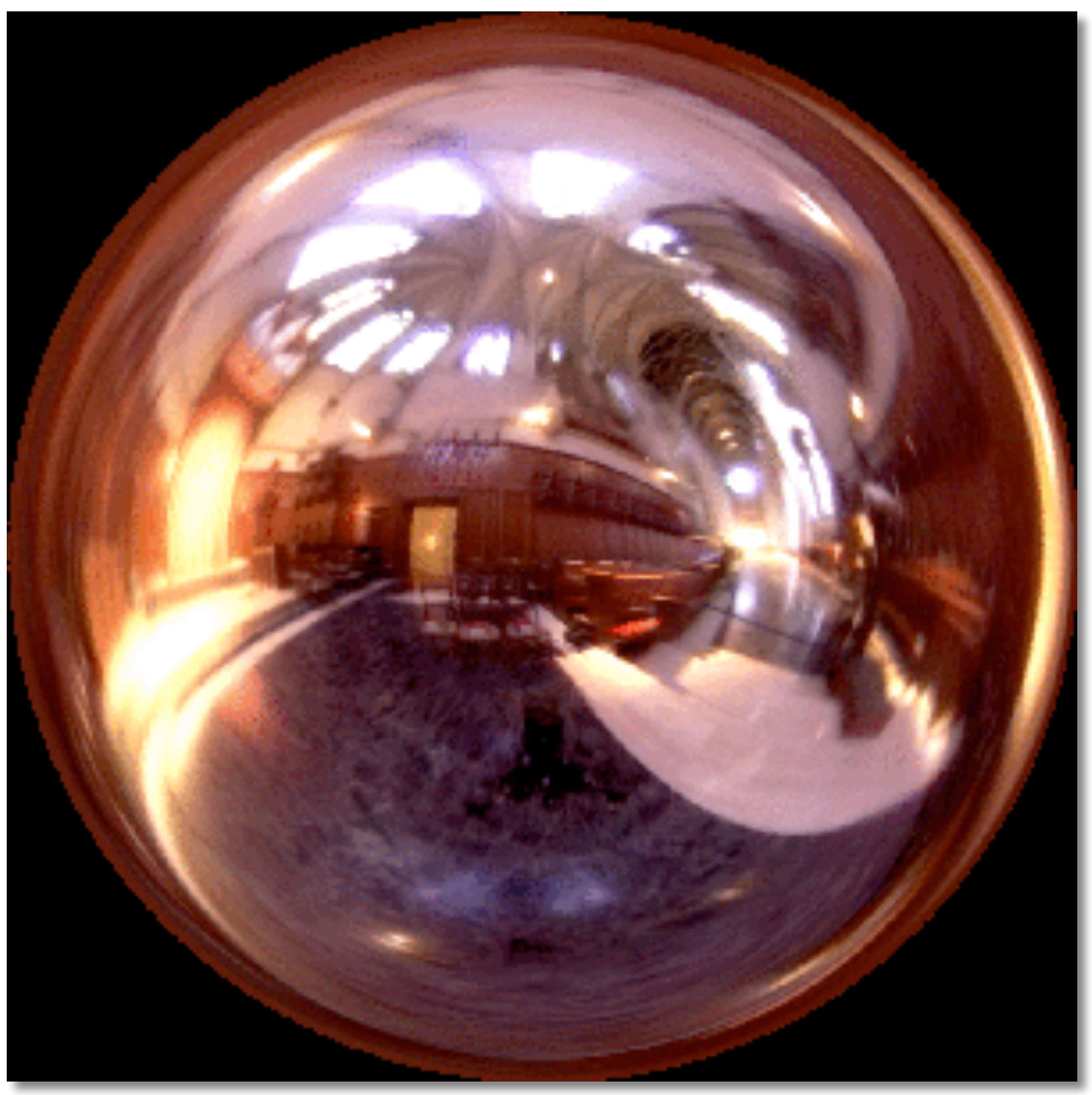
- **Attenuated omnidirectional point light**
  (emits equally in all directions, intensity falls off with distance: $1/R^2$ falloff)

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

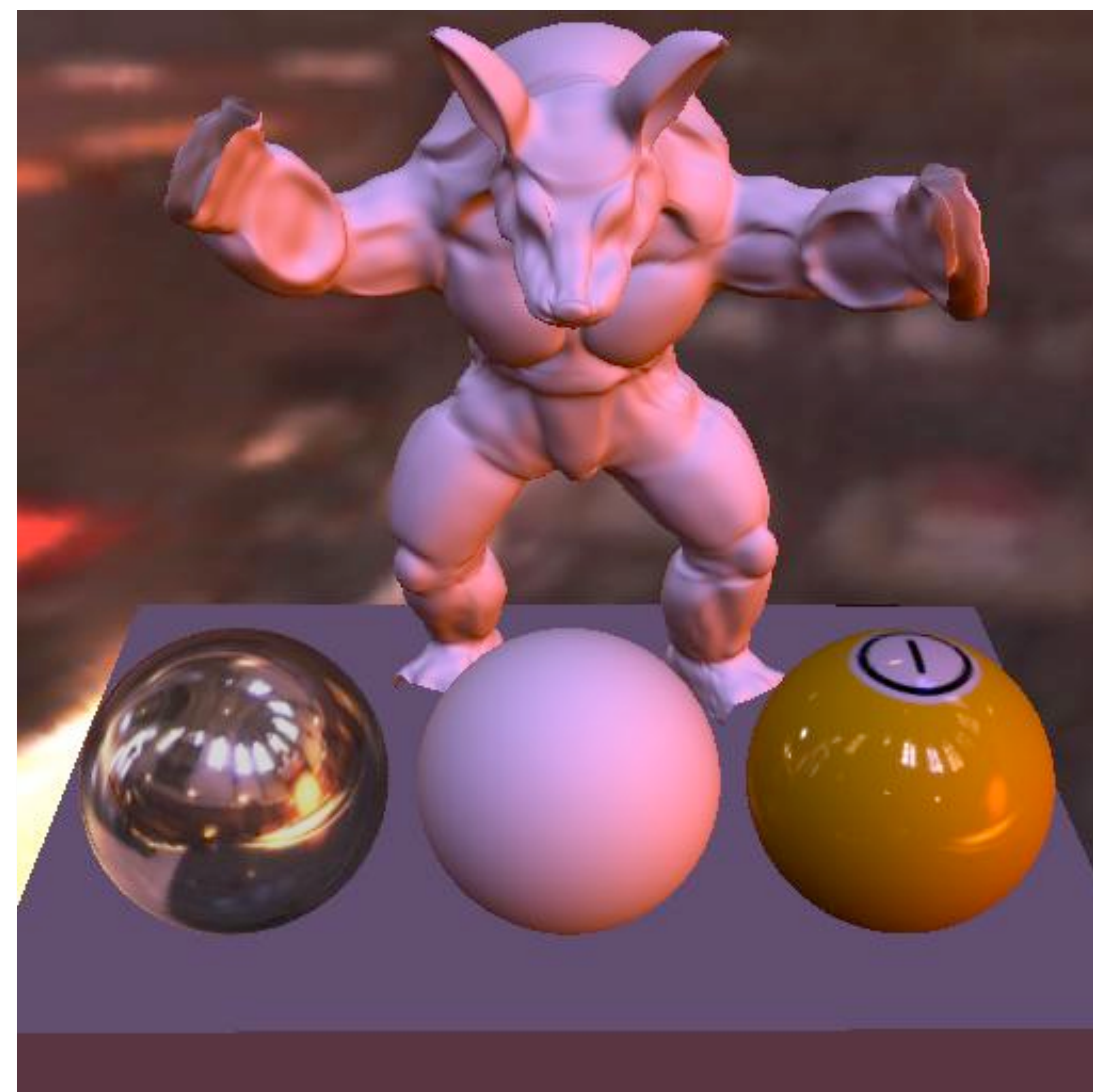


More sophisticated lights

- **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]

Parameterized materials and lighting in early OpenGL (prior to programmable shading)

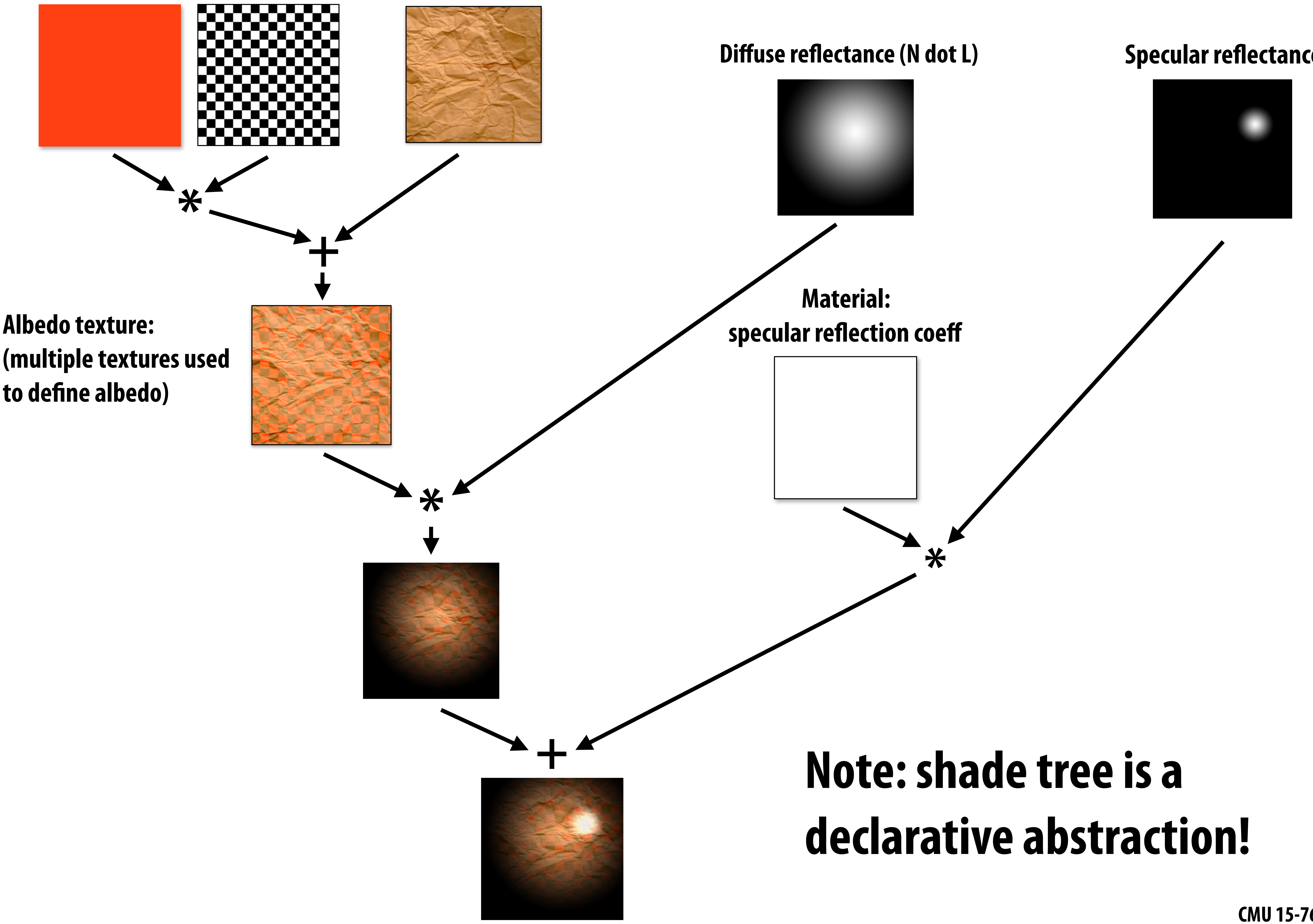
- `glLight(light_id, parameter_id, parameter_value)`
  - 10 parameters (e.g., ambient/diffuse/specular color, position, direction, attenuation coefficient)

- `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

- Parameterized shading function evaluated at each vertex
  - Summation over all enabled lights
  - Resulting per-vertex color modulated by result of texturing

Precursor to shading languages: shade trees

[Cook 84]



Note: shade tree is a declarative abstraction!

Shading languages

- **Goal: support wide diversity in 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 on a few canonical data structures (triangles, fragments, and pixels)
  - Recall how much the implementation of these functions 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 <u>interface</u> between application-defined surface, lighting, material reflectance functions and the graphics pipeline

GPU shading languages today: e.g., HLSL

HLSL shader program: defines logic of fragment processing stage

"Uniform" (same for all fragments) arguments

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

float4 diffuseShader(float3 norm, float2 uv)
{
  float3 kd;
  kd = myTex.Sample(mySampler, uv);
  kd *= clamp(dot(-lightDir, norm), 0.0, 1.0);
  return float4(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!

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 higher arithmetic intensity than fragment processing (less use of texturing)

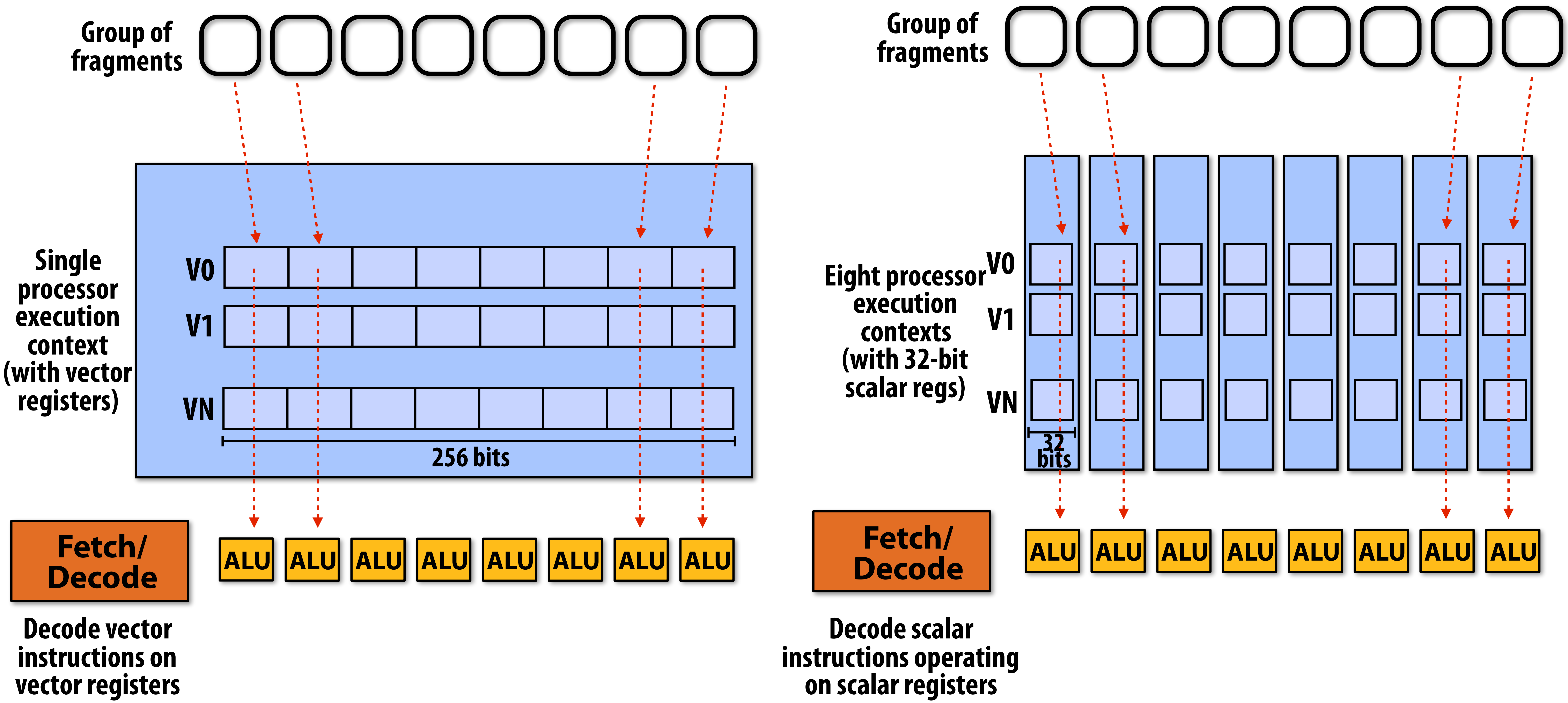
Efficiently mapping of shading computations to GPU hardware

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, Intel's 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;
}
```

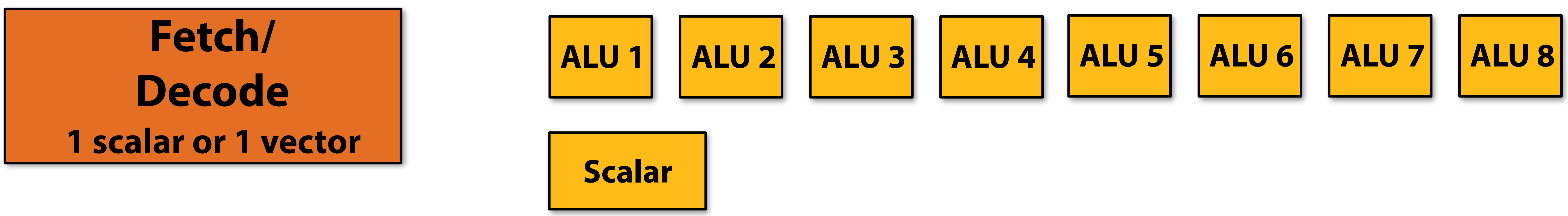
Example 2: predicate is uniform expression

```
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

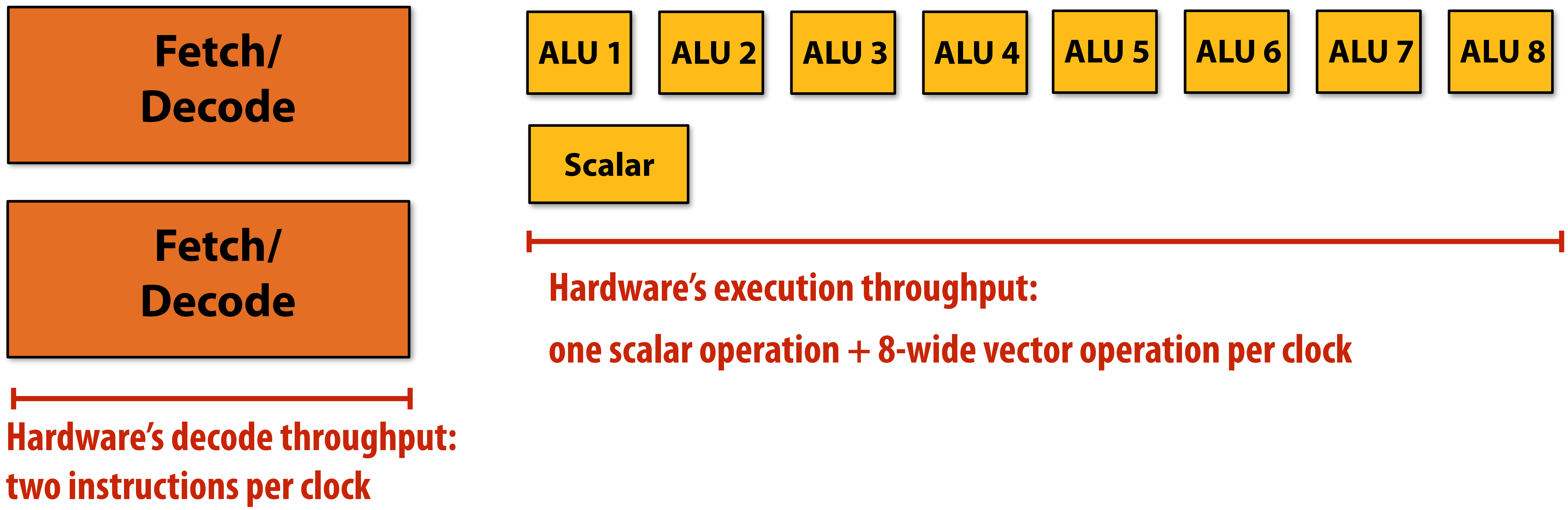


Logic shared across all "vector lanes" need only be performed once (not repeated by every vector ALU)

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

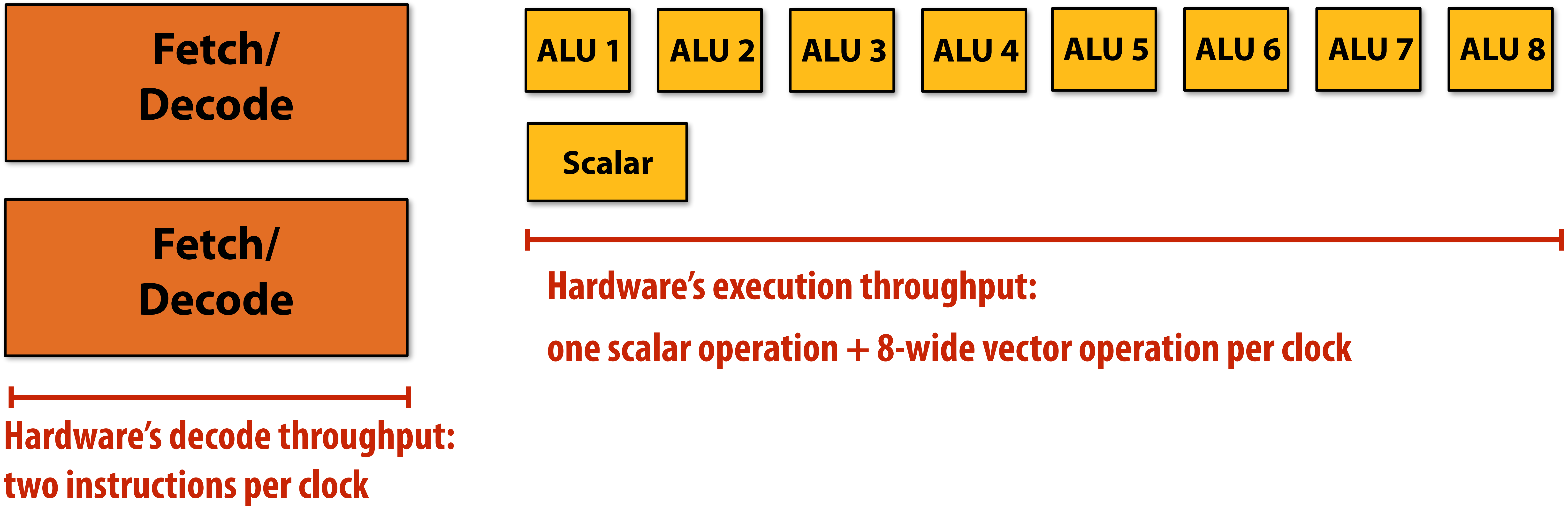
```
float3 lightDir[MAX_NUM_LIGHTS];
int numLights;
float4 multiLightFragShader(float3 norm, float4 surfaceColor)
{
   float4 outputColor;
   for (int i=0; i<num_lights; i++) {
     outputColor += surfaceColor * clamp(0.0, 1.0, dot(norm, lightDir[i]));
   }
}
```

Improving the fictitious throughput processor



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

Three possible organizations

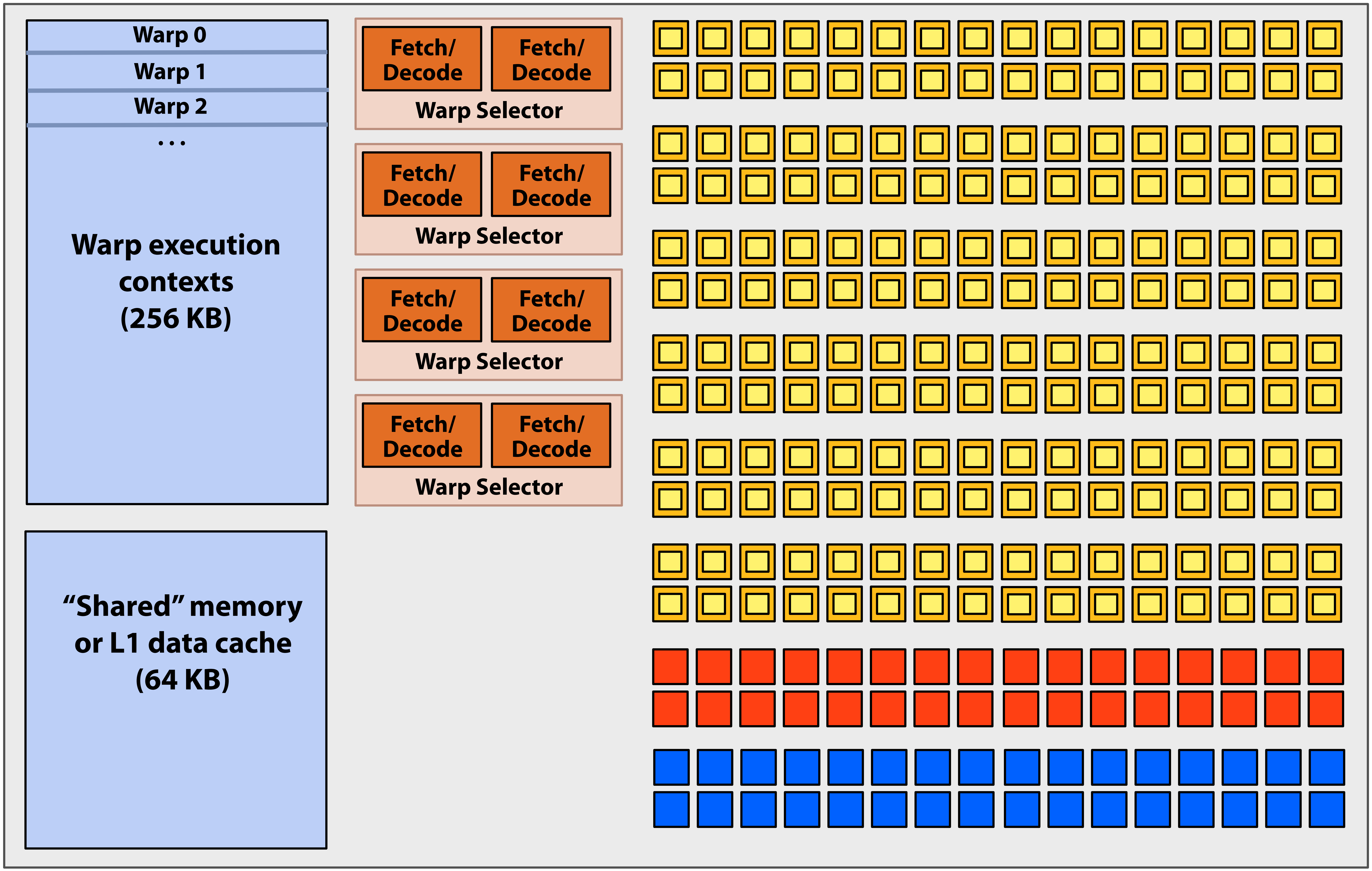


- **Execute two instructions (one scalar, one vector) from same execution context**
  - One execution context can fully utilize the processor's resources, but requires instruction-level-parallelism in instruction stream
- **Execute unique instructions in two different execution contexts**
  - Processor 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 680 (2012)

NVIDIA Kepler GK104 architecture SMX unit (one "core")

Core executes two independent instructions from four warps in a clock (eight total instructions / clock)



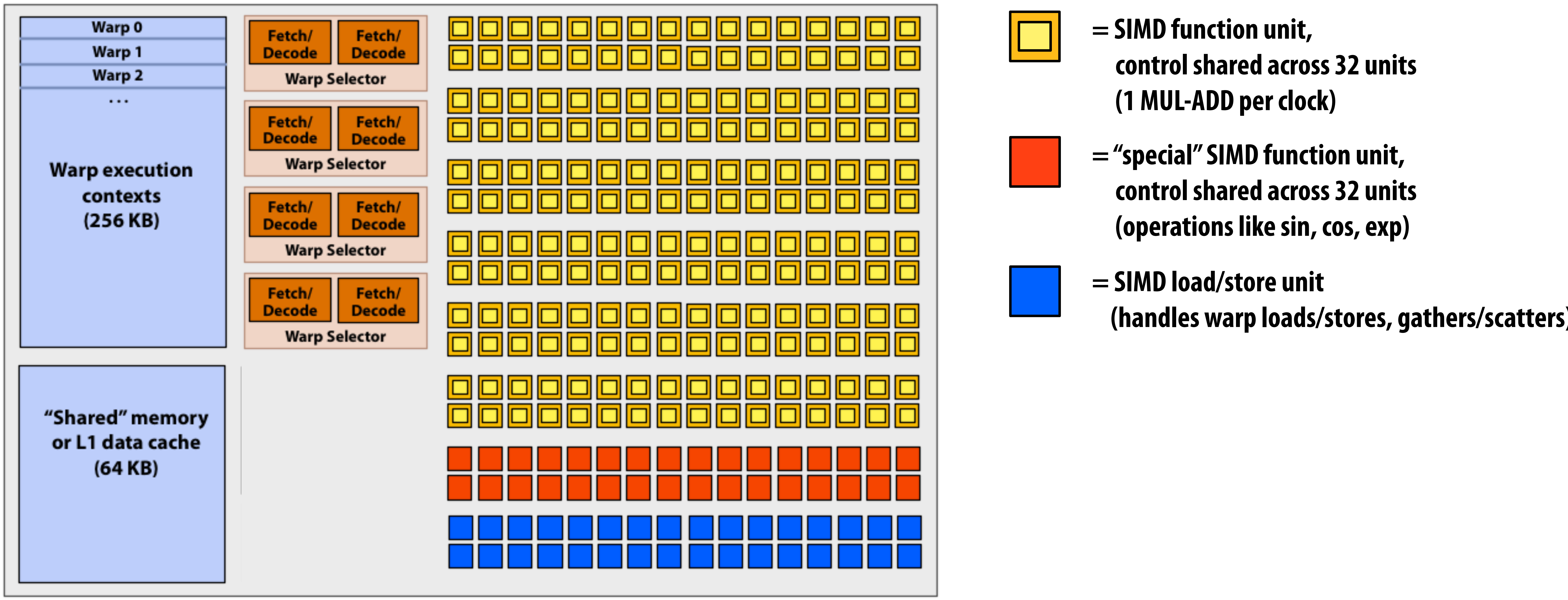
= SIMD function unit, control shared across 32 units (1 MUL-ADD per clock)

= "special" SIMD function unit, control shared across 32 units (operations like sin, cos, exp)

= SIMD load/store unit (handles warp loads/stores, gathers/scatters)

NVIDIA GTX 680 (2012)

NVIDIA Kepler GK104 architecture SMX unit (one "core")

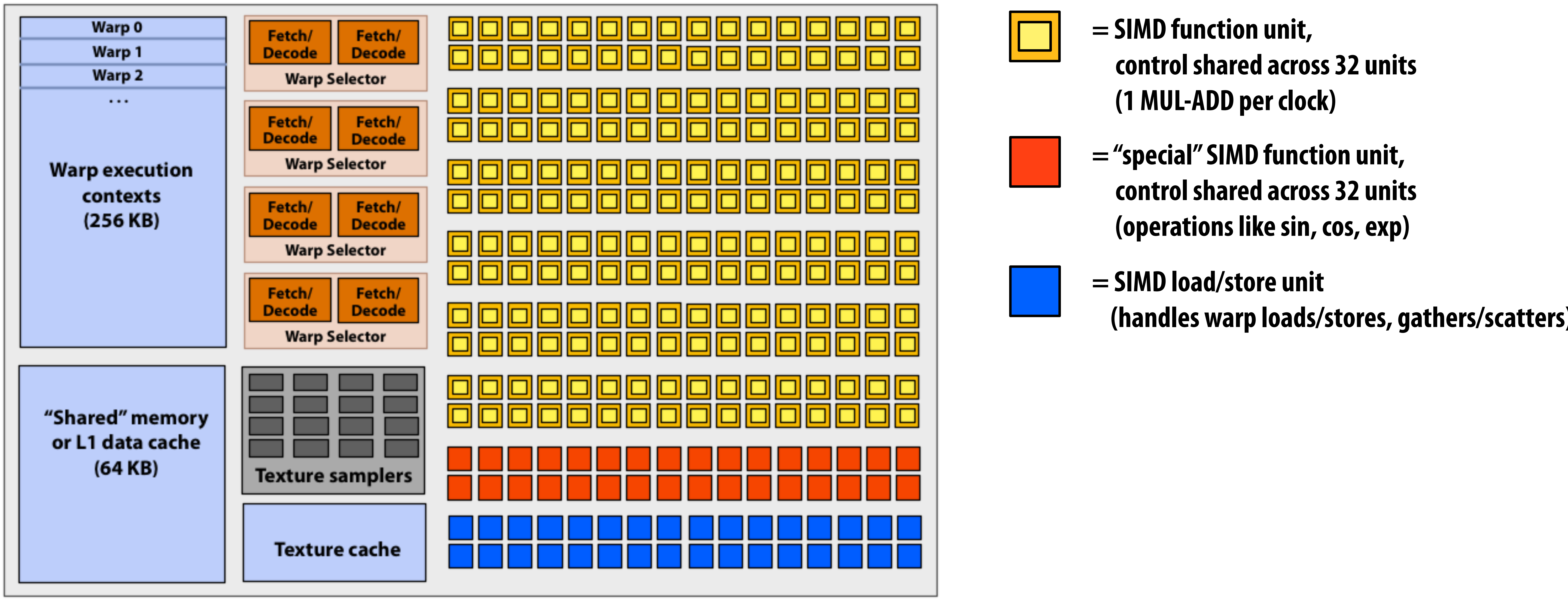


- **SMX core resource limits:**
  - Maximum warp execution contexts: 64 (2,048 total CUDA threads)

- **Why storage for 64 warp execution contexts if only four can execute at once?**
  - Multi-threading to hide memory access latency (in graphics, this is often latency of texture access!)

NVIDIA GTX 680 (2012)

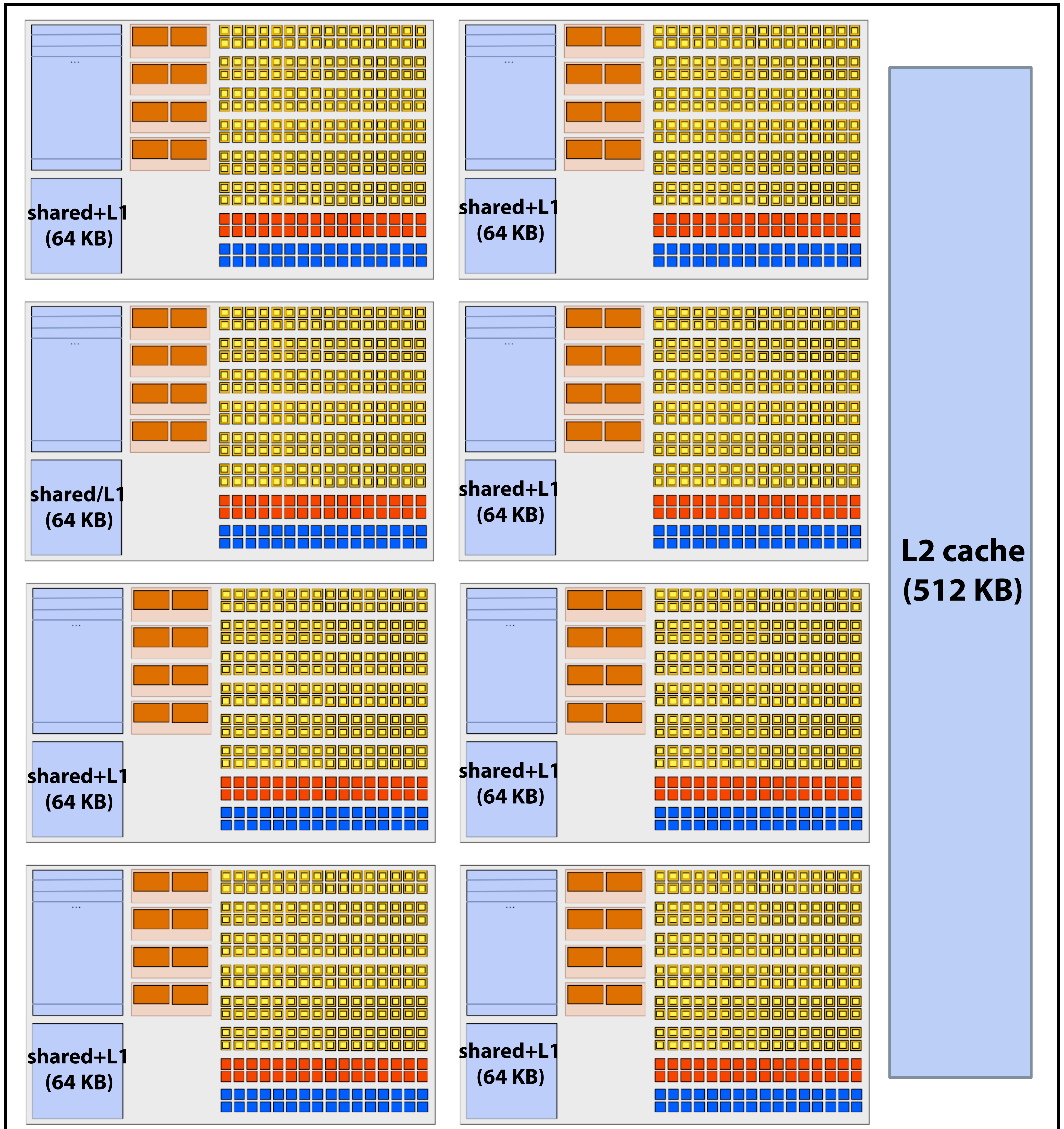
NVIDIA Kepler GK104 architecture SMX unit (one "core")



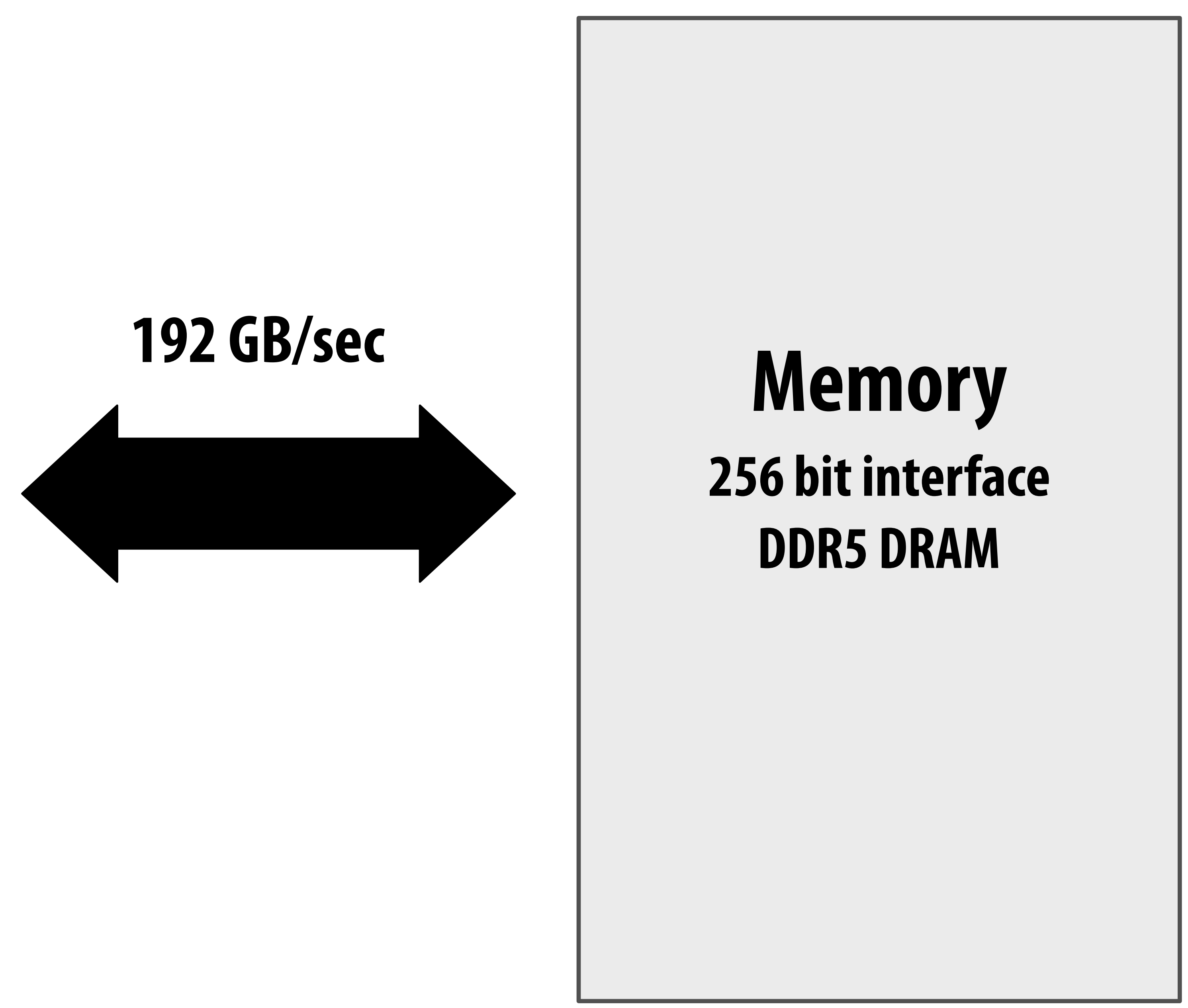
- **SMX programmable core operation each clock:**
  - Select up to four runnable warps from up to 64 resident on core (thread-level parallelism)
  - Select up to two runnable instructions per warp (instruction-level parallelism)
  - Execute instructions on available groups of SIMD ALUs, special-function ALUs, or LD/ST units
- **SMX texture unit throughput:**
  - 16 filtered texels per clock

NVIDIA GTX 680 (2012)

NVIDIA Kepler GK104 architecture



- 1 GHz clock
- Eight SMX cores per chip
- 8 x 192 = 1,536 SIMD mul-add ALUs
  = 3 TFLOPs
- Up to 512 interleaved warps per chip
  (16,384 CUDA threads/chip)
- TDP: 195 watts

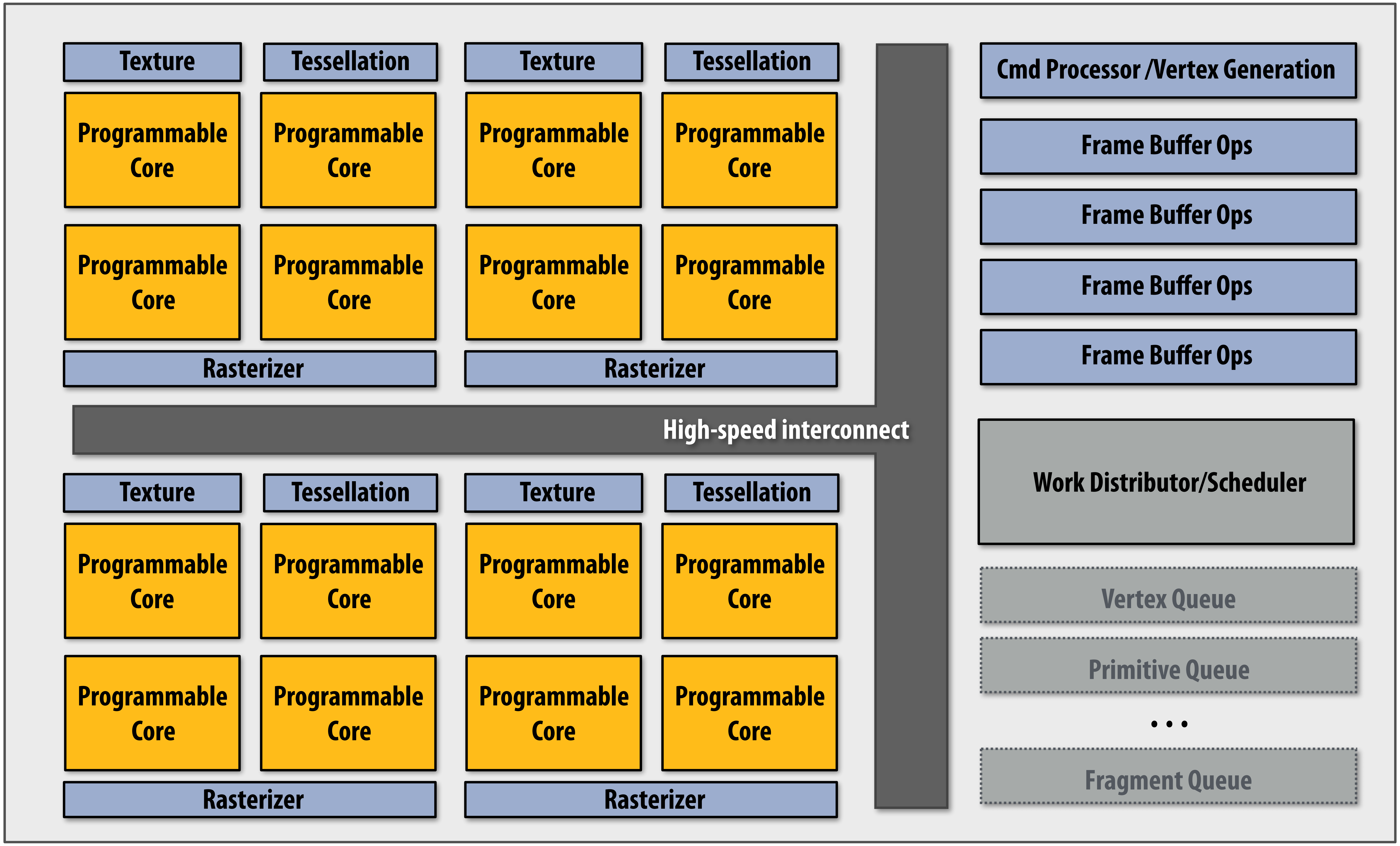


Shading languages summary

- **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 Kepler: 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



A unique (odd) aspect of GPU design

- The 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

Class discussion:
RSL and Cg

Differences in design goals?
How do these differences manifest in different design decisions?

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, triangle attribute interpolation)

Renderman shading language (RSL)

[Hanrahan and Lawson 90]

- High-level, domain-specific language
  - Domain: describing propagation of light through scene
- Developed as interface to Pixar's Renderman renderer

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

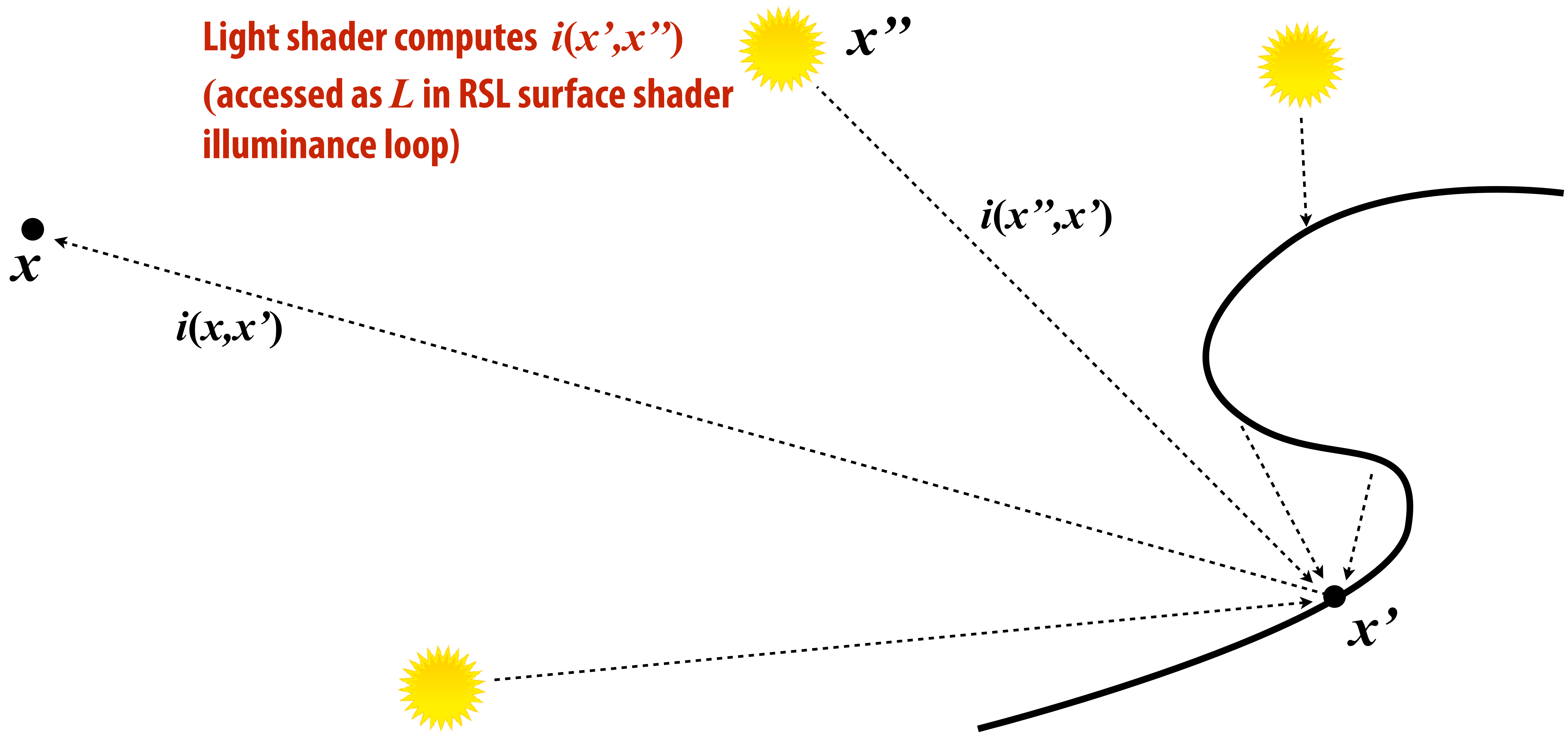
- Shaders: surface shaders and light shaders
  - Surface shaders:
    - Define surface reflection function (BRDF)
    - Integrate contribution of light from all light sources
  - Light shaders: define directional distribution of energy emitted from lights
  - Multiple computation rates:
    - uniform: independent of surface position (per surface)
    - varying: change with position (per shading sample)
- First-class color and point data types
- First-class texture sampling functions
- Light shader's `illuminate` construct
- Surface shader's `illuminance` loop (integrate 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 +
bound parameter values

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
(bound to scene surface)

RSL surface shaders

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)
}
```