Stanford Real-Time Programmable Shading Project

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Sponsors:
3dfx, NVIDIA, SGI, Sun

Web page:
http://graphics.stanford.edu/projects/shading/

Motivation

Toy Story
Disney

Binary Neutron Star Collision
David Bock

Quake 3 Arena
id Software

Bump and Shadow Mapping
NVIDIA

Hardware trends

Increasing hardware functionality

- Multiple textures
- Advanced texture combining operations

Increasing fill rate

- Multiple rendering passes

But…

- Programming graphics hardware is like writing microcode
- Decomposing computations into multiple passes is time-consuming
- Functionality varies between chipsets

Higher-level hardware abstractions

Problem:

Current hardware abstractions (e.g. OpenGL) use a configurable pipeline model that is too low-level

Solution:

Use a shading language as a higher-level hardware abstraction

Hardware abstractions

Hardware abstractions:

- Provide a standard interface
- Simplify underlying complexities
- Hide differences in implementations
- Help to define hardware behavior
- Drive new architectures

Hardware abstractions make hardware easier or harder to use

Project goals

- Provide a shading language as an abstraction layer between programmer and graphics hardware
- Explore how current hardware may be used to implement shading language abstractions
- Investigate new hardware architectures optimized for programmable shading
- Create new interactive applications based on shading languages

Our first system

Arbitrary expressions of:

- Constant colors, lit materials, and textures
- Operators: +, *, and over

Expressions compiled to multiple rendering passes

```
// pool ball shader

// material properties (to configure lighting model)
material Diffuse { diffuse .5 .5 .5; specular 0 0 0; … }
material Specular { diffuse 0 0 0; specular 1 1 1; … }

// texture declaration (to configure a texture object)
texture POOLONE { image “one.ppm”; transform { … }; … }

// shader definition
shader poolball { Diffuse * POOLONE + Specular; }
```

Limitations of pure multipass

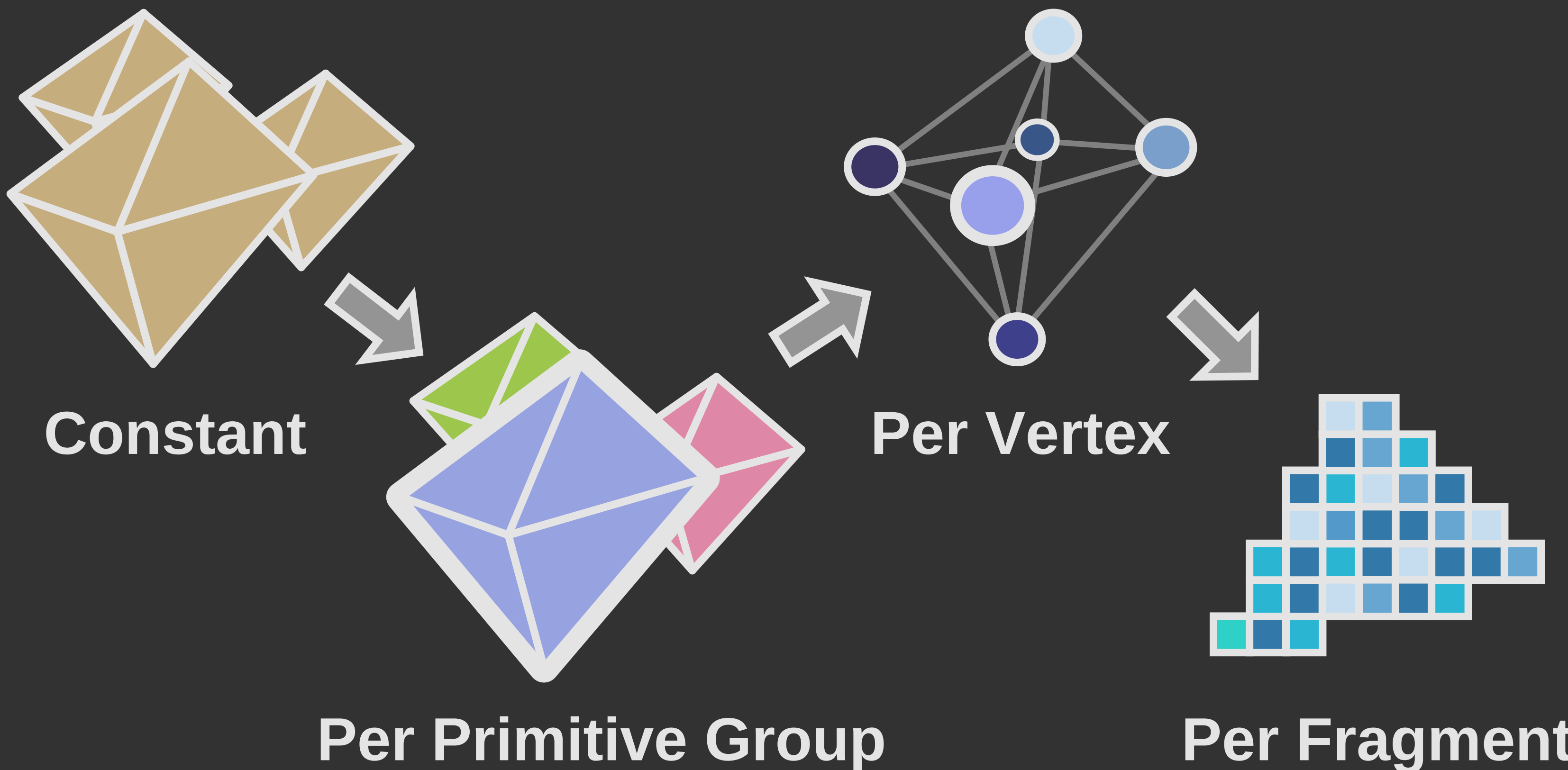
Problem:

- Pure multipass rendering only allows fragment programmability
- Today’s fragment operations are limited: fixed point, simple set of operators
- Fragment lighting and texture coordinate generation can be very expensive
- No support for future programmable vertex hardware (e.g. DirectX 8)

Solution:

- Add vertex and primitive-group programmability

Multiple computation frequencies



Evaluated less often

More complex operations

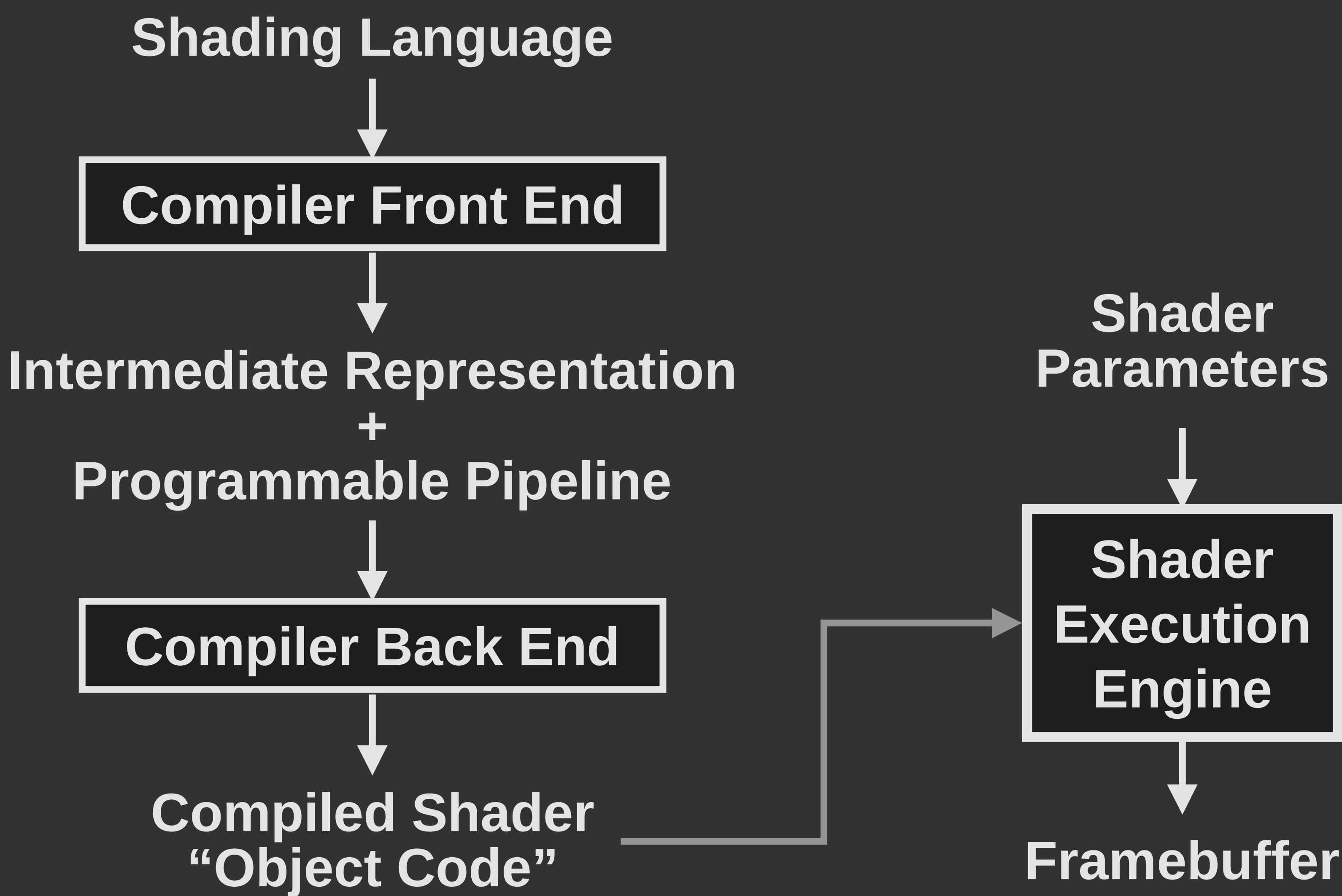
Floating point

Evaluated more often

Simpler operations

Fixed point

System overview



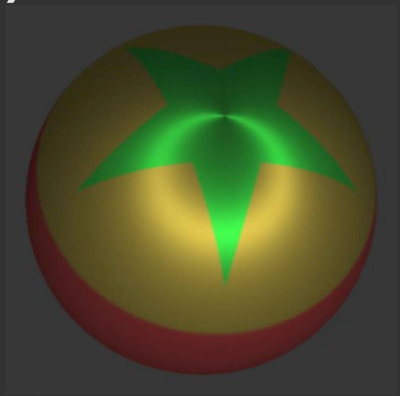
Anisotropic ball example

```
surface shader floatv
anisotropic_ball (texref anisotex, texref star)
{
    // generate texture coordinates
    perlight floatv uv = { center(dot(B, E)),
                           center(dot(B, L)),
                           0, 1 };

    // compute reflection coefficient
    perlight floatv fd = max(dot(N, L), 0);
    perlight floatv fr = fd * texture(anisotex, uv);

    // compute amount of reflected light
    floatv lightcolor = 0.2 * Ca + integrate(Cl * fr);

    // modulate reflected light color
    floatv uv_base = { center(Pobj[2]), center(Pobj[0]),
                       0, 1 };
    return lightcolor * texture(star, uv_base);
}
```



Managing computation frequencies

Given: a system with multiple computation frequencies

How to specify how often to compute something?

Two methods:

- Explicit specification with type modifiers
- Automatic propagation

Computation frequency modifiers

Four type modifiers allow explicit specification:

```
constant
perbegin
vertex
fragment
```

Specification by assignment:

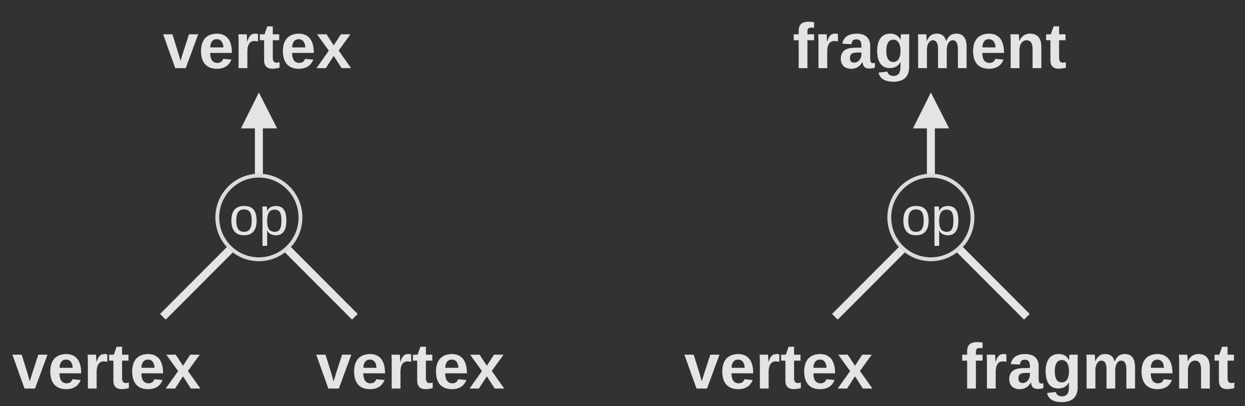
```
fragment float y = x;
```

Specification by type cast:

```
float y = (fragment float)x;
```

Automatic propagation

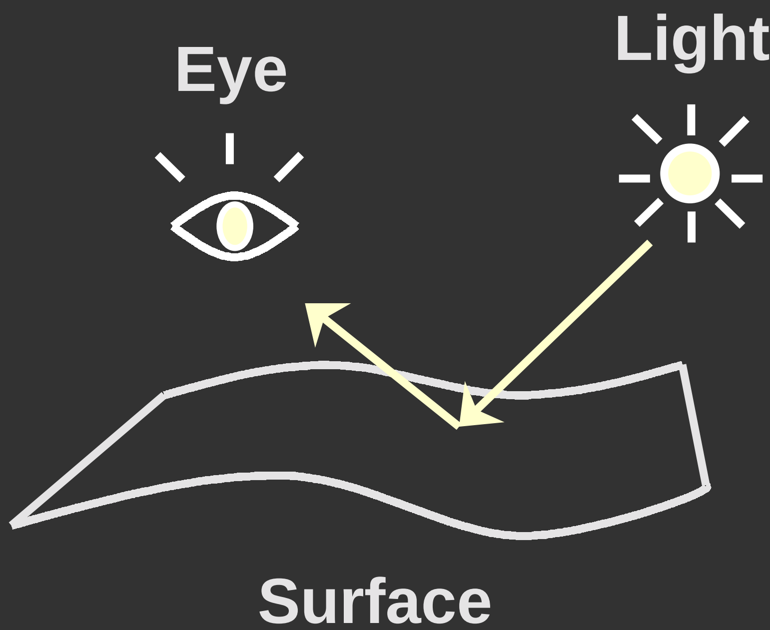
Computation frequencies propagate from operation inputs to operation outputs



All shader inputs have default frequencies

Surfaces and lights

From RenderMan:



Separate surfaces and lights by defining two kinds of shaders

A linear integrate operator

RenderMan combines surfaces and lights using `illuminance`

- Implicit loop over lights
- Unrestricted combining of computed light values

We define a linear `integrate()` operator

```
integrate(a + b) = integrate(a) +
                   integrate(b)
```

If k is the same for every light:

```
integrate(k * a) = k * integrate(a)
```

Restricted to combining light values using addition

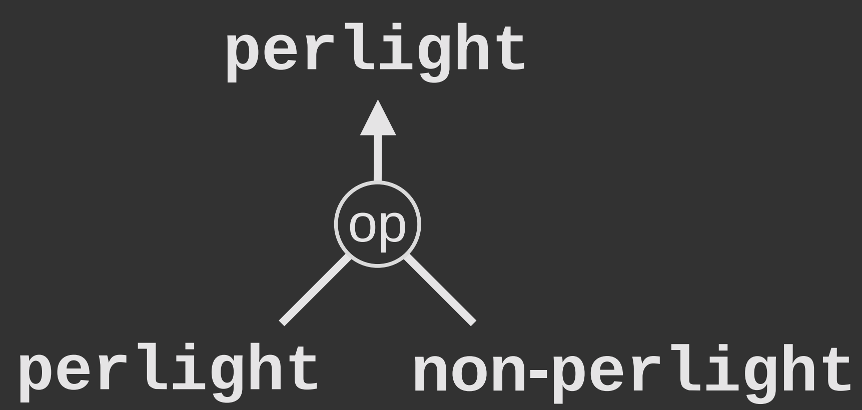
Perlight expressions

The `integrate()` operator evaluates a `perlight` expression once for every light, summing the results

Three builtin `perlight` globals

`L`	light vector
`H`	halfangle vector
`Cl`	light color

Expressions of `perlight` values are themselves `perlight`



Integrate example

Anisotropic ball example:

```
perlight floatv fd = max(dot(N,L),0);
perlight floatv fr = fd * texture(…);
```

} perlight

```
floatv lightcolor = … + integrate(Cl*fr);
```

With two lights, expands to:

floatv fd_0 = max(dot(N,L_0),0);
floatv fr_0 = fd_0 * texture(…);

} light 0

floatv fd_1 = max(dot(N,L_1),0);
floatv fr_1 = fd_1 * texture(…);

} light 1

floatv lightcolor = … + Cl_0*fr_0 + Cl_1*fr_1;

Integrate optimization

A linear integrate allows an optimized light sum:

```
floatv Kd = texture(…); // non-perlight
floatv NdotL = dot(N,L); // perlight
floatv color = integrate(Kd * dot(N,L));
```

No optimization:

$Kd * dot(N,L_0) + Kd * dot(N,L_1)$

2 fragment multiplies
1 fragment add

Factor out non-perlight term:

$Kd * (dot(N,L_0) + dot(N,L_1))$

1 fragment multiply
1 vertex add

Vertex and fragment lights

Vertex lights

- Return a per-vertex light color

Fragment lights

- Return a per-fragment light color
- Usually involves a projective texture

Automatic propagation of computation frequencies allows vertex and/or fragment `integrate()` as appropriate

Sort lights by computation frequency to optimize

Operators and types

Seven basic types:

float, floatv, clampf, clampfv, matrix, bool, texref

Primitive group ops	Vertex ops	Fragment ops
cross product, matrix generation, matrix multiply, sin, cos + vertex ops + fragment ops	divide, compare ops, clamp, dot, length, min, max, normalize, pow, reflect, select, sqrt, vector index, scalar join + fragment ops	add, subtract, multiply, blend Fragment only: texture lookups

See our web page for details

Builtin global variables

For surfaces:

`P`	surface position
`Pobj`	surface position (object space)
`N, T, B`	normal, tangent, binormal vectors
`E`	eye vector
`Ca`	global ambient light color
`L`	light vector
`H`	halfangle vector
`Cl`	light color

For lights:

`S`	surface vector (light space)
`Sdist`	distance to surface

Inspired by RenderMan

Language constraints

Language is constrained to promote SIMD parallelism across vertices and fragments

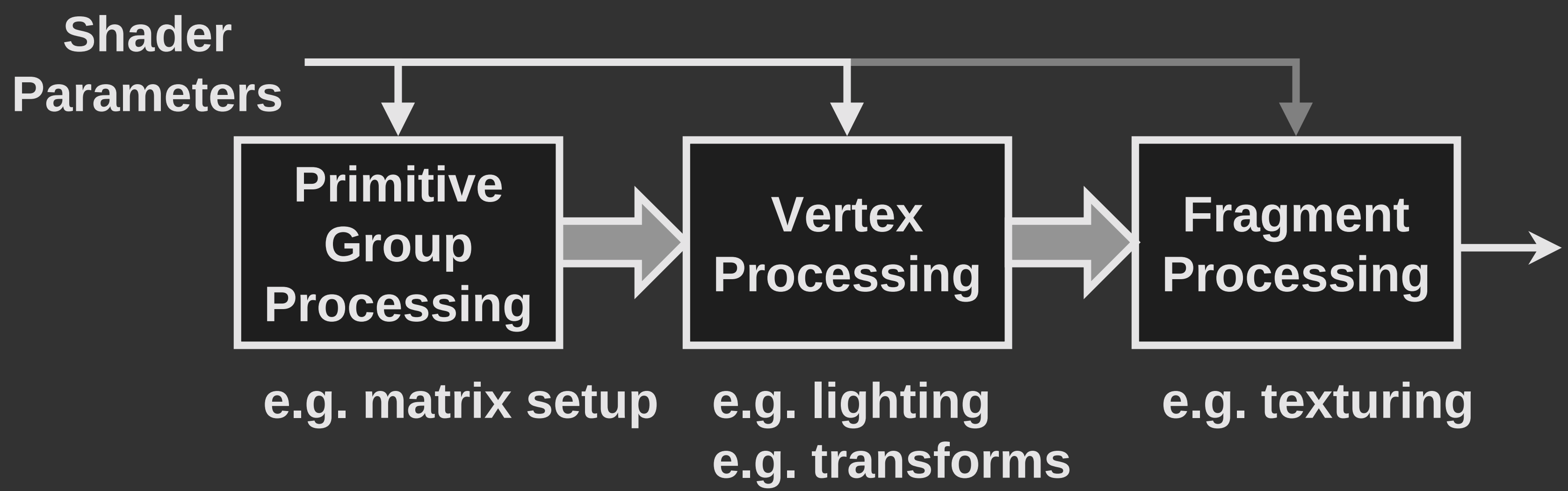
No conditional or loop statements

- A `select` operator enables conditional expressions
- A `repeat(n)` construct could be added to enable limited forms of looping

No explicit communication between data elements

Demo

Programmable pipeline abstraction



Three programmable pipeline stages

Intermediate level abstraction between language and OpenGL

Hardware independent:

- No operation count limits
- No temporary storage limits
- Abstract types: float, clampf

Intermediate representation

A compiler intermediate representation is used to specify programmable pipeline programs

- Same operators and types as language
- Surfaces and lights are combined
- Builtin globals are expanded
- Function calls are inlined
- Constants are fully simplified

Front end compilation

Three steps:

- Parse shader input file, inlining globals and functions, simplifying constants
- Join surface/light shaders together to make a single pipeline program
- Determine computation frequencies and split pipeline program accordingly

Result:

- Three-part pipeline program, one part for each programmable pipeline stage

Back end compilation

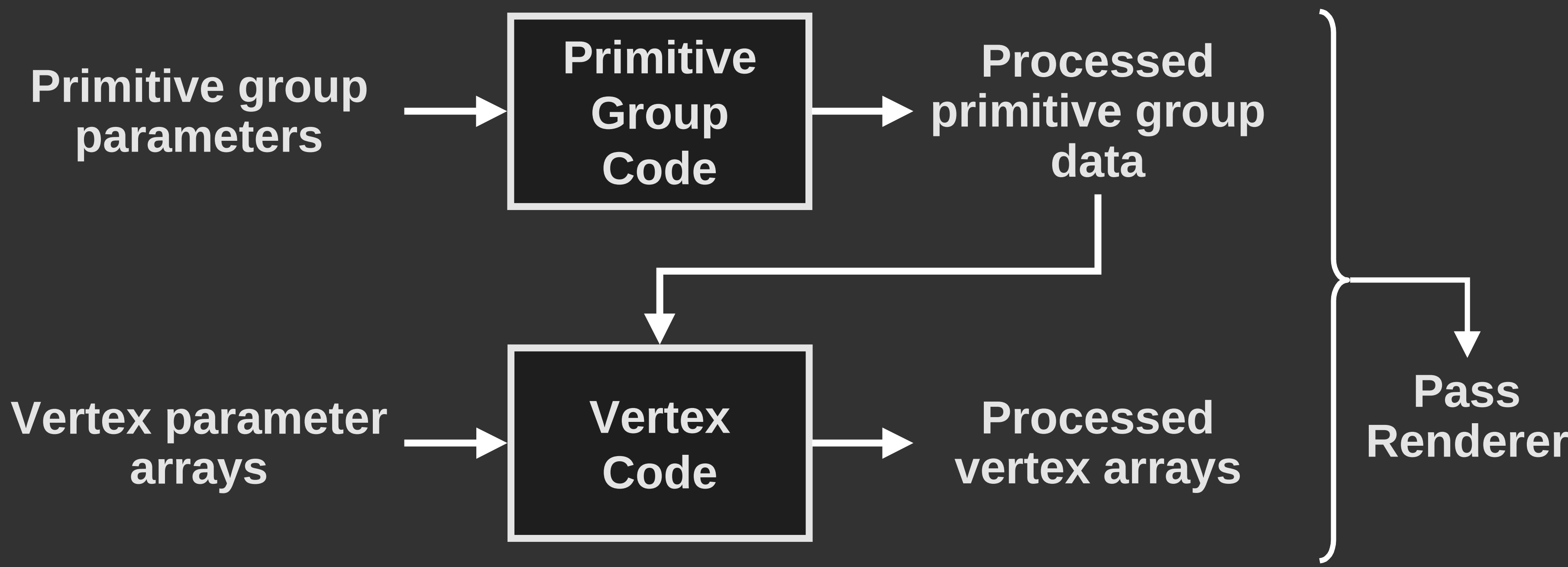
Goal: Produce an executable version of a pipeline program

Hardware mappings by computation frequency:

Primitive group	→	Host processor
Vertex	→	Host processor
Fragment	→	Multiple rendering passes

When hardware becomes available: move host-side computations to graphics processor

Host-side computations



Two techniques for generating code:

- External C compiler
- Internal x86 code generator

Fragment computations

Fragment computations are mapped to multiple rendering passes using *lburg*

- Define rules corresponding to particular configurations of portions of the fragment pipeline
- Dynamic programming optimally covers trees given rules
- Additional rules are enabled if necessary GL extensions are present
- Despite optimal cover, *lburg* isn’t perfect

lburg is from Fraser and Hanson, *A Retargetable C Compiler: Design and Implementation*

OpenGL pipeline operations

We abstract the OpenGL pipeline as implementing two kinds of operations:

$$\text{fb} = \left\{ \begin{array}{c} \text{C} \\ \text{T} \\ \text{C}\ \mathit{op}\ \text{T} \end{array} \right\} \left[\mathit{op}\ \text{T} \right] \left[\mathit{op}\ \text{fb} \right] \qquad \text{(render)}$$

$$\text{T} = \text{fb} \qquad \text{(save)}$$

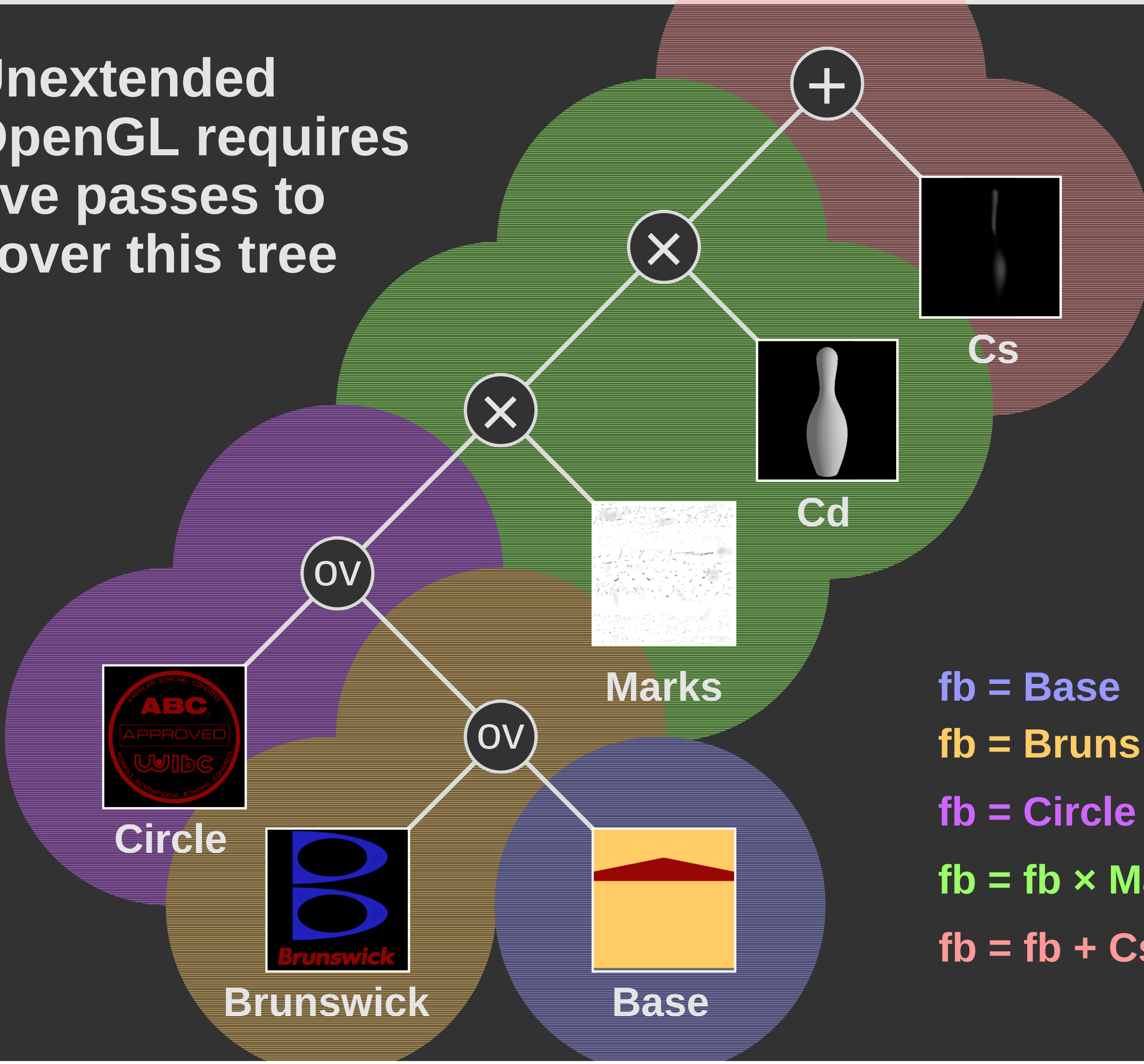
fb = framebuffer color
C = triangle color
T = texture

op is one of: +, –, ×, blend

All of our *lburg* rules are derived from this abstraction

Pass generation example

Unextended OpenGL requires five passes to cover this tree



fb = Base

fb = Bruns over fb

fb = Circle over fb

fb = fb × Marks × Cd

fb = fb + Cs

API

Primary differences compared to current APIs:

- Support for compiling pipeline programs
- Support for arbitrary per-primitive-group and per-vertex parameters
- Hidden multipass rendering

Our system provides immediate mode and vertex array interfaces

- Both result in buffers filled with primitive group and vertex data to be processed and rendered

Review

Multiple computation frequencies

- Support for computing values at different rates allows for a much broader set of operations and types with reasonable cost

Shading language abstraction

- User-level abstraction layer
- Type system for multiple computation frequencies
- Linear integrate operator

Hardware-independent programmable pipeline

- Intermediate abstraction layer to separate language from hardware

Take-home message

Real-time programmable shading

- Can be implemented today
- Makes complicated hardware easy to use
- Simplifies multipass rendering
- Hides hardware dependencies
- Will drive future generations of graphics hardware

Real-time programmable shading is the next big thing!!!

Try it

http://graphics.stanford.edu/projects/shading/