Game Developers Conference

Practical Implementation of SH Lighting and HDR Rendering on PlayStation 2

Yoshiharu Gotanda Tatsuya Shoji

Research and Development Dept. tri-Ace Inc.

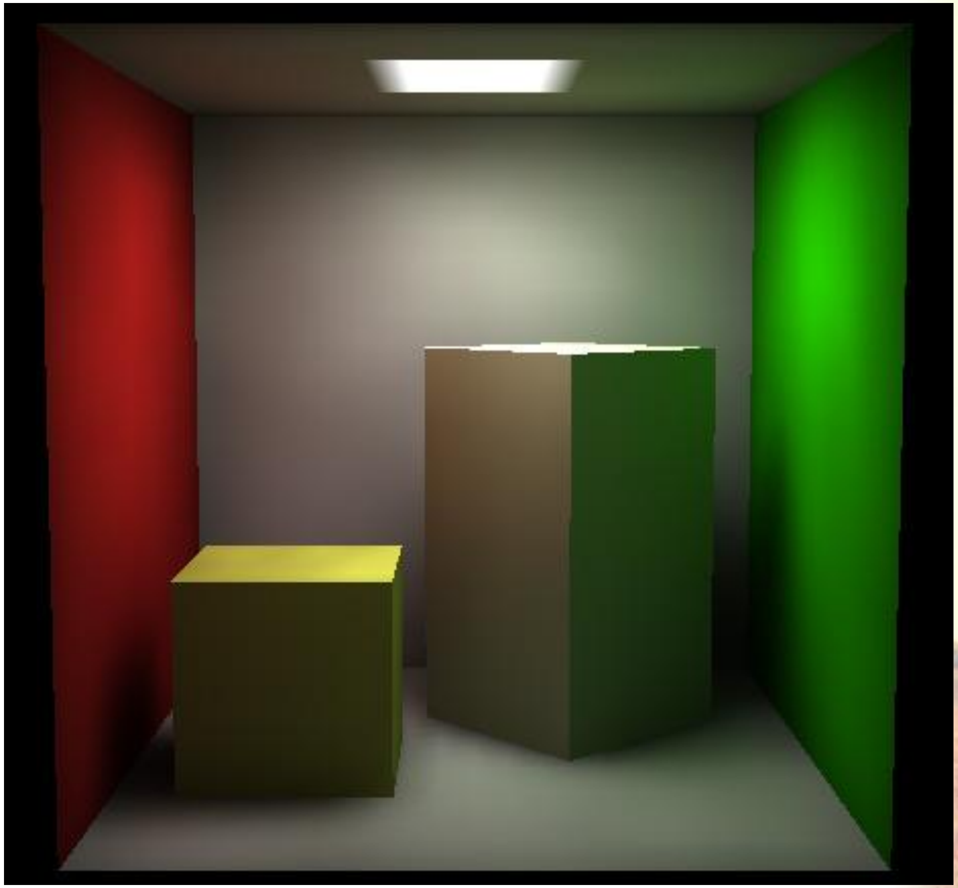
SAN FRANCISCO CA MAR 7-11 GDC 05

This slide

- includes practical examples about
  - SH Lighting for the current hardware (PlayStation 2)
  - HDR Rendering
  - Plug-ins for 3ds max

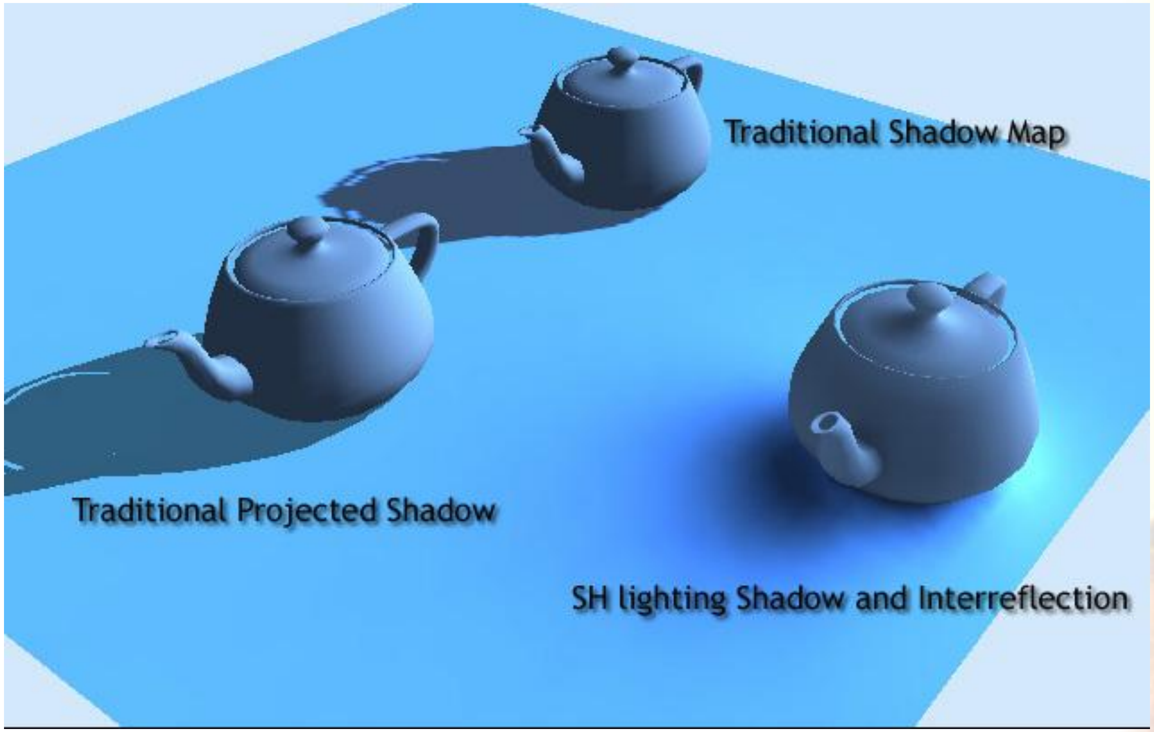
SH Lighting gives you…

- Real-time Global Illumination



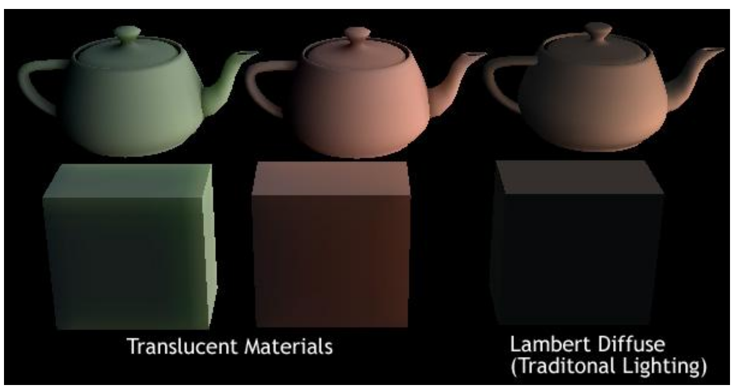
SH Lighting gives you…

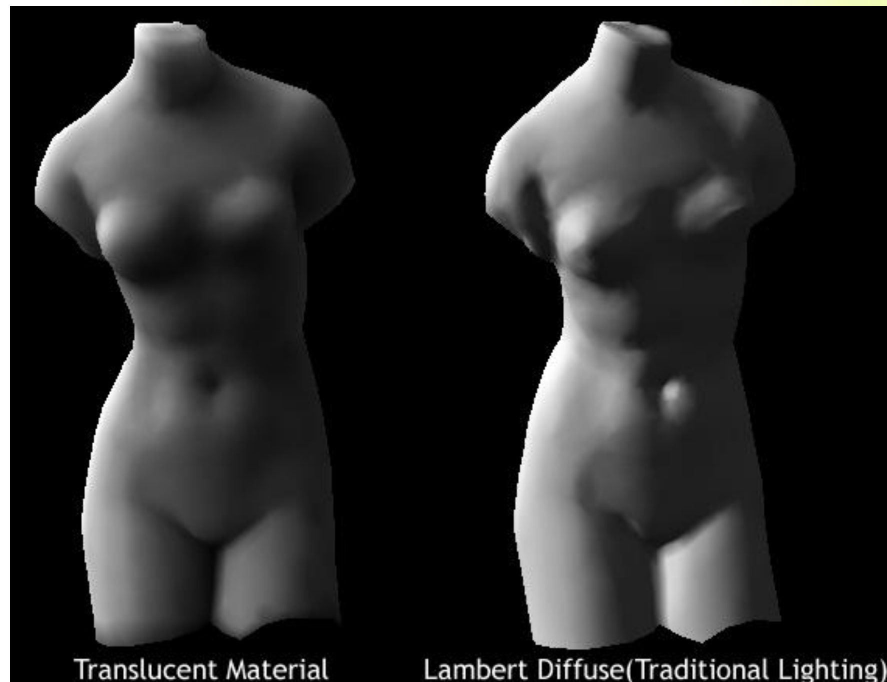
- Soft shadow (but not accurate)



SH Lighting gives you…

- Translucent Materials





HDR Rendering gives you…

- Photo-realistic Light Effect

Original Scene

➤

Bloom Effect added

HDR Rendering gives you…

- Photo-realistic Sunlight Effect

Original Scene

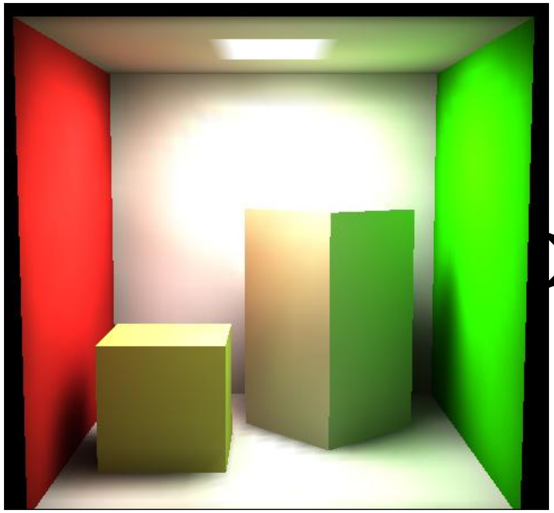
Sunlight and Bloom Effect added

HDR Rendering gives you…

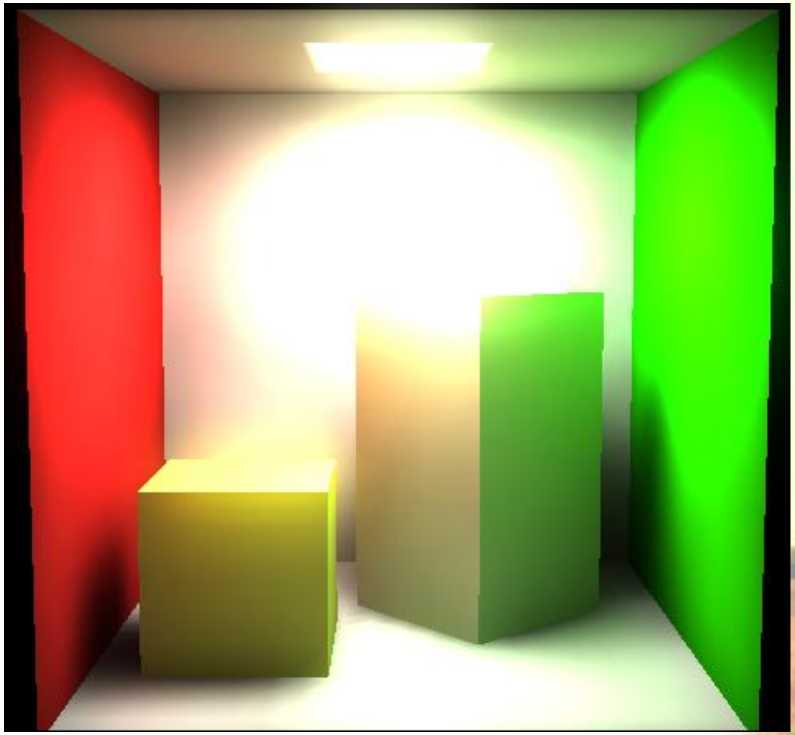
- Photo-realistic Depth of Field Effect
  - adds depth to images

SH and HDR give you…

- Using both techniques shows the synergistic effect



GI without HDR



GI with HDR

Where to use SH and HDR

- Don't have to use all of them
  - SH lighting could be used to represent various light phenomena
  - HDR Rendering could be used to represent various optimal phenomena as well
  - There are a lot of elements (backgrounds, characters, effects) in a game
  - It is important to let artists express themselves easily with limited resources for each element

Engine we've integrated

- Lighting specification (for each object)
  - 4 vertex directional lights (including pseudo point light, spot light)
  - 3 vertex point lights
  - 2 vertex spot lights
  - 1 ambient light (or hemi-sphere light)

Light usage is automatically determined by the engine

Engine we've integrated

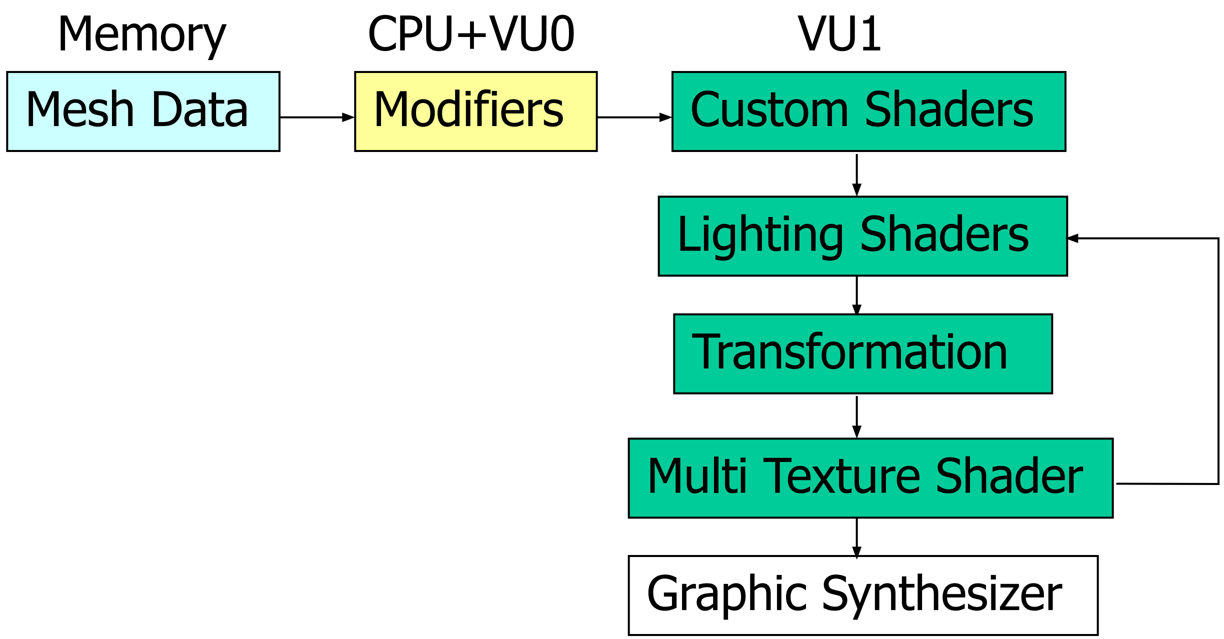
- Lighting Shaders
  - Color Rate Shader (light with intensity only)
  - Lambert Shader
  - Phong Shader

Engine we've integrated

- **Custom Shaders** (up to 4 shaders you can choose for each polygon)
  - Physique Shaders (Skinning Shader)
  - Decompression Shaders
  - Static Phong Shader
  - Fur Shaders
  - Reflection Shaders (Sphere, Dual-Paraboloid and so on)
  - Bump Map Shader
  - Screen Shader
  - Fresnel Shader
  - UV Shift Shader
  - Projection Shader
  - Static Bump Map Shader

Rendering Pipeline

- Our engine has the following rendering pipeline



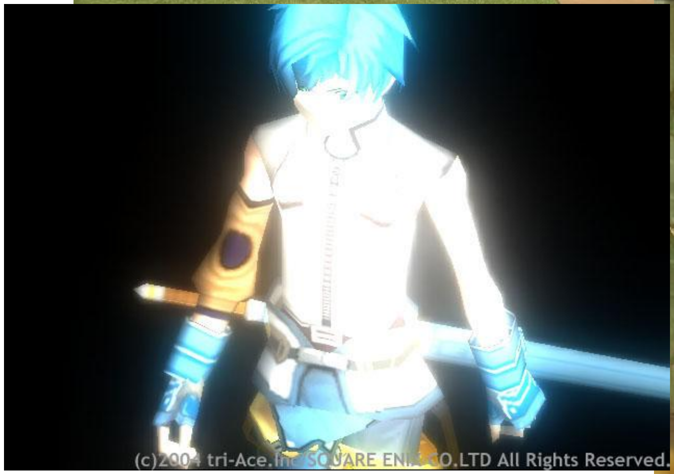
Rendering Pipeline

Mesh Data	Polygon data
Modifiers	They can update any mesh data by CPU+VU0(like skinning, morphing, color animations and so on)
Custom Shaders	They are like the Vertex Shader
Lighting Shaders	They illuminate each vertex
Transform	Transformation to screen space, fogging, clipping and scissoring
Multi Texture Shader	If a polygon has more than 2 textures, go back to the Lighting Shader stage

Where have we integrated?

- HDR :
  - Adapting data for HDR -> Modifying mesh data
  - Applying HDR effects -> Post effect
- SH Lighting :
  - Precomputing -> Plug-in for 3ds max
  - Computing SH coefficients of lights -> CPU
  - SH Shading -> Lighting Shaders

High Dynamic Range Rendering



Representing Intense Light

- Color (255,255,255) as maximum value can't represent dazzle
- How about by a real camera?

Optical Lens Phenomena

- By camera - Various phenomena caused by light reflection, diffraction, and scattering in lens and barrel
- These phenomena are called Glare Effects

Glare Effects

- Visible only when intense light enters
- May occur at any time but are usually invisible when indirect from light sources because of faintness

Depth of Field

- **One of the optical phenomena but not a Glare Effect**
- **DOF generally is used for cinematic pictures**

Representing Intense Light - Bottom Line

- Accurate reproduction of Glare Effects creates realistic intense light representations
- Glare Effects reproduction requires highly intense brightness level
- But the frame buffer ranges only up to 255
- Keep higher level on a separate buffer (HDR buffer)

What is HDR?

- Stands for High Dynamic Range
- Dynamic Range is the ratio between smallest and largest signal values
- In simple terms, HDR means a greater range of value

- So HDR Buffers can represent a wide range of intensity

Physical Quantity for HDR

Sunlight vs 100-watt bulb	40,000 : 1
Sunlight vs Blue sky	250,000 : 1
100-watt bulb vs Moonlight	25 : 1

- **For example, when you want to handle sunlight and blue sky at the same time accurately, int32 or fp32 are necessary at least**

Implementation of HDR Buffer on PS2

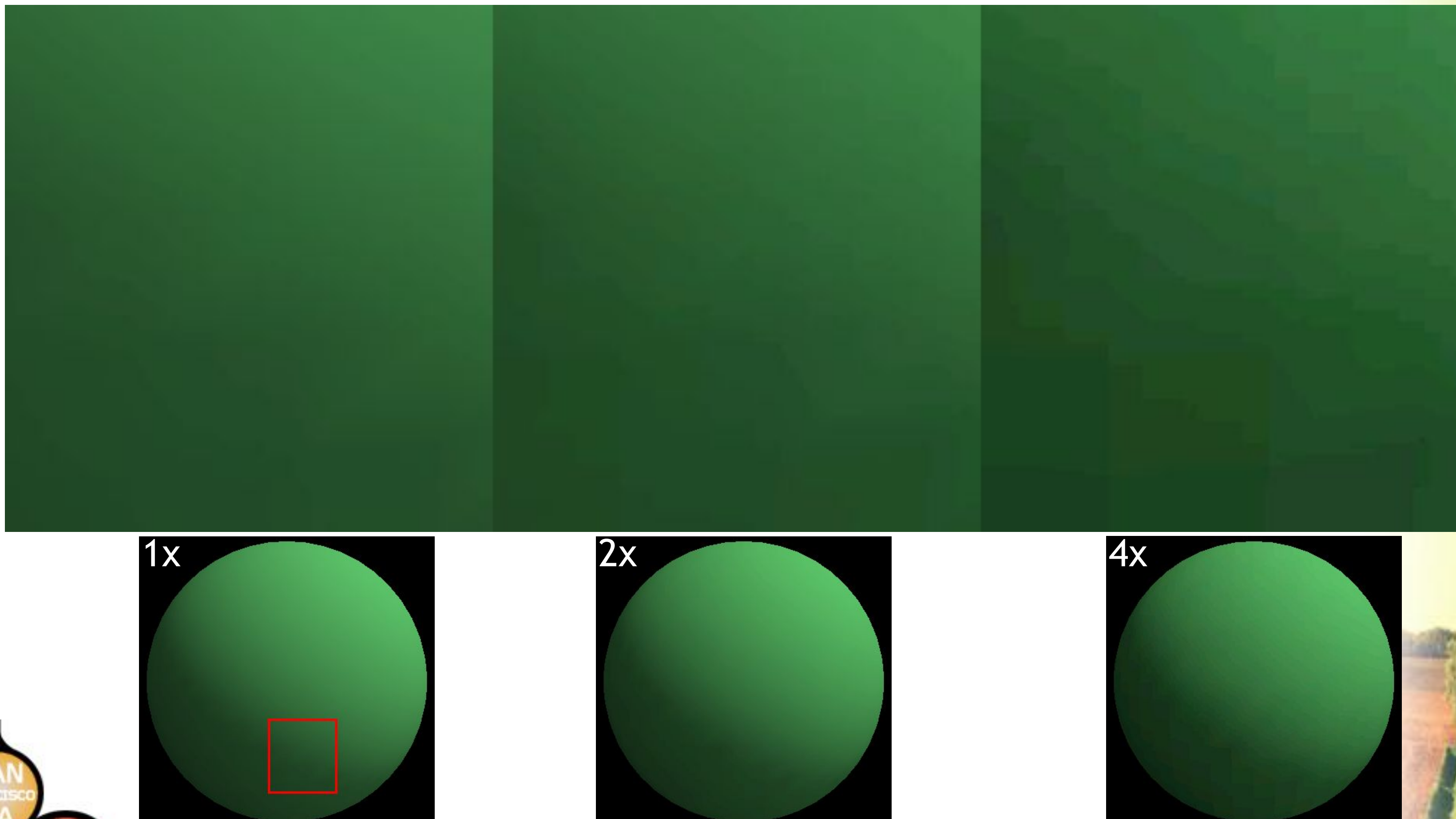
- PS2 has no high precision frame buffer - Have to utilize the 8bit-integer frame buffer
- Adopt a fixed-point-like method to raise maximum level of intensity instead of lowering resolution

  (When usual usage is described as “0:0:8", describe it as “0:1:7" or “0:2:6" in this method)
- Example: If representing regular white by 128, 255 can represent double intensity level of white
- Therefore, this method is not true HDR

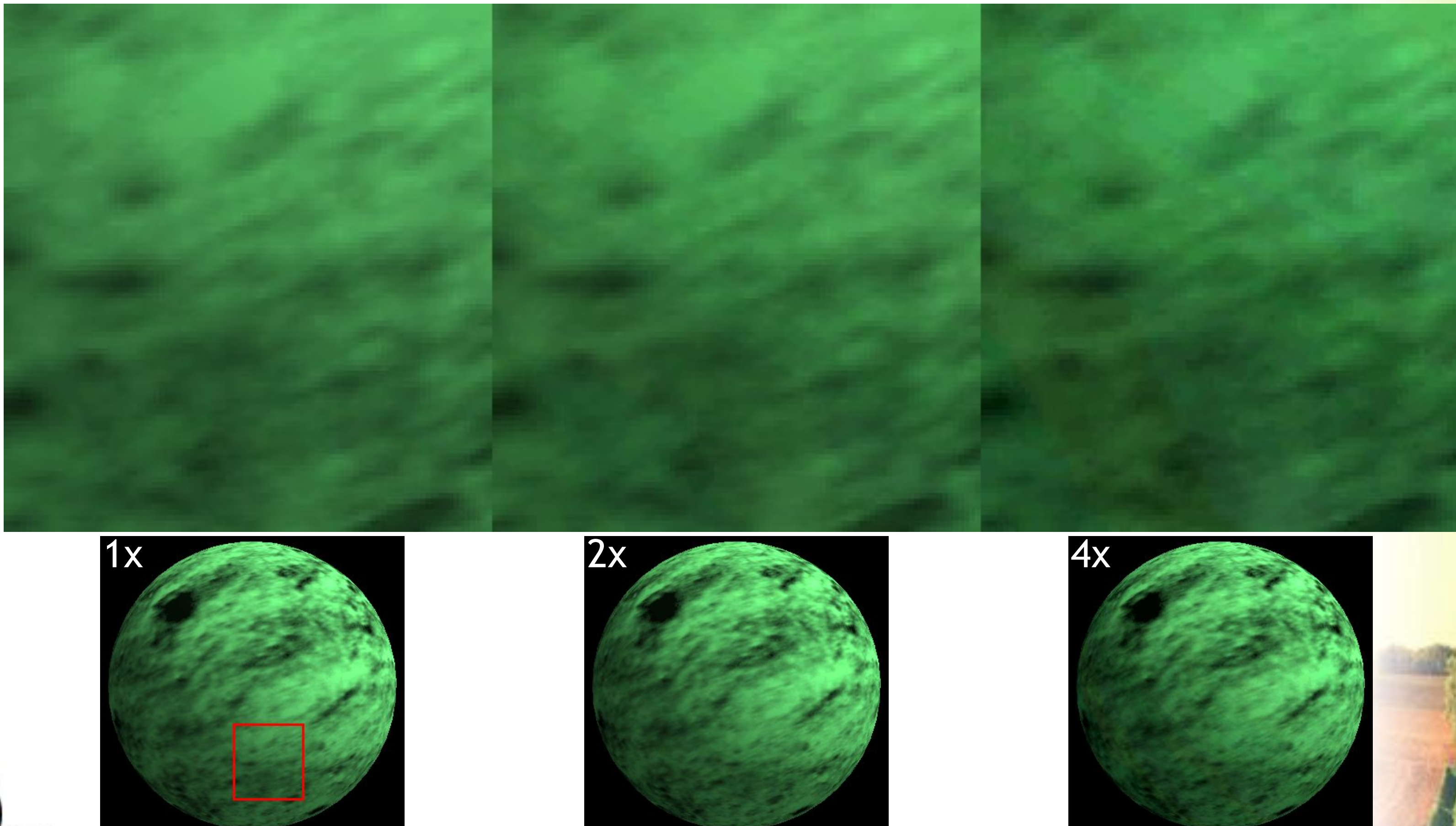
Mach-Band Issue

- Resolution of the visible domain gets worse and Mach-Band is emphasized
- But with texture mapping, double rate will be feasible

Mach-Band Issue

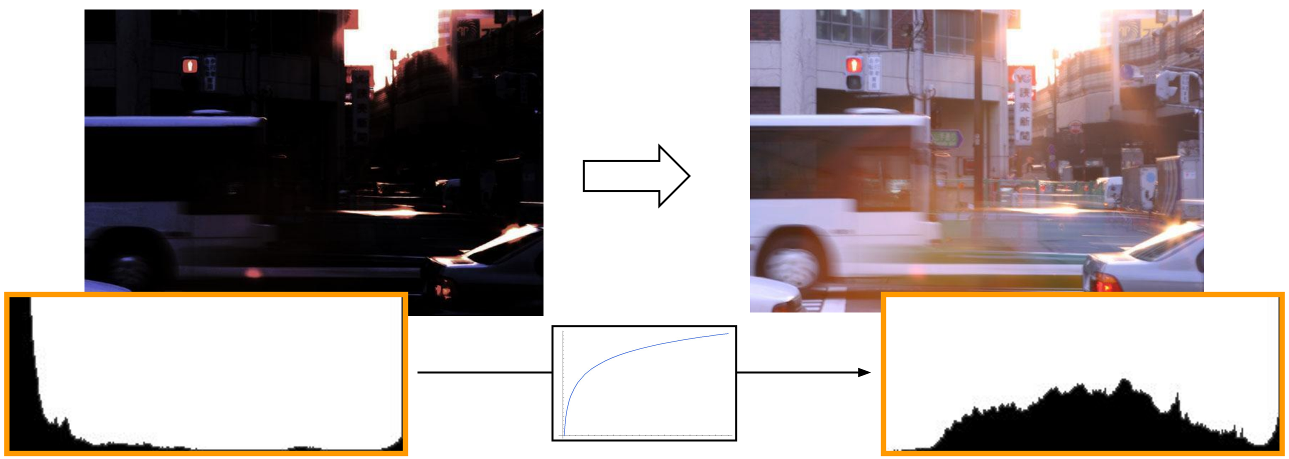


Mach-Band Issue – with Texture



Tone Mapping

- One of the processes in HDR Rendering
- It involves remapping the HDR buffer to the visible domain

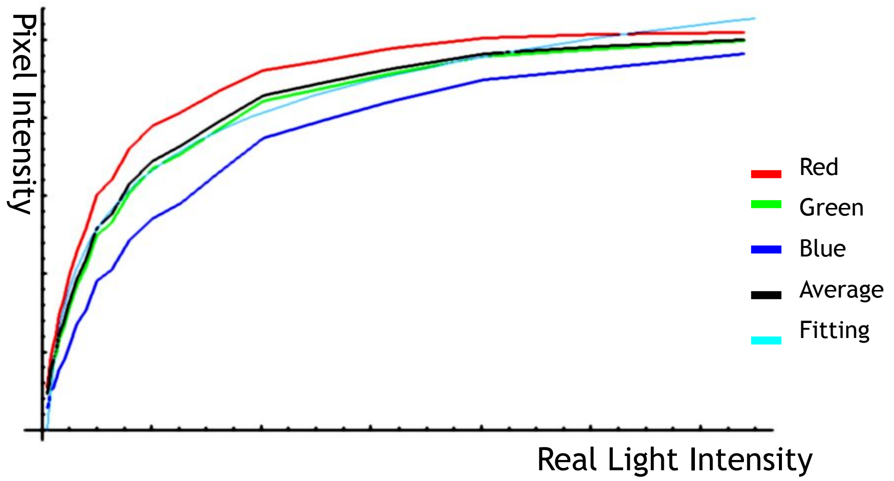


HDR image, visible image
and histogram of intensity

Tone Mapping

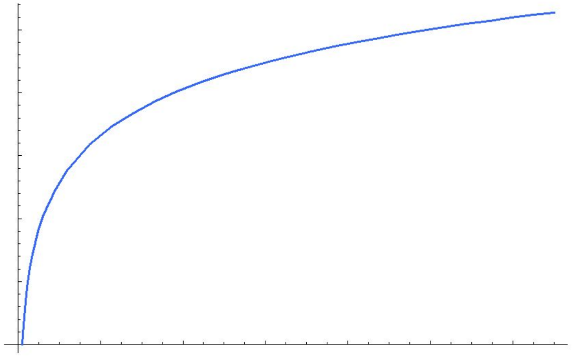
- Typical Tone Mapping curves are nonlinear functions

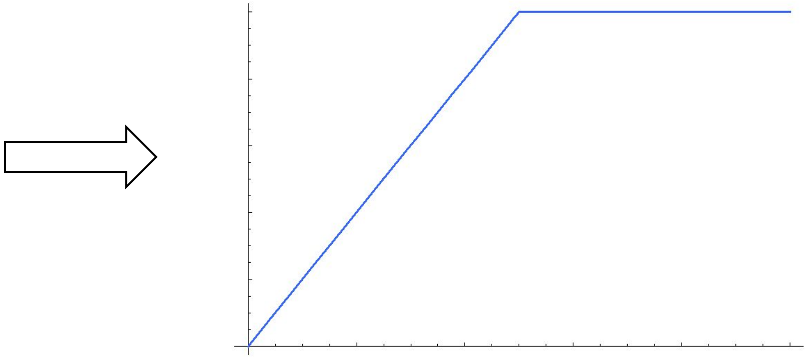
Measurement value of digital camera (EOS 10D)



Tone Mapping on PS2

- But PS2 doesn't have a pixel shader, so simple scaling and hardware color clamping is used



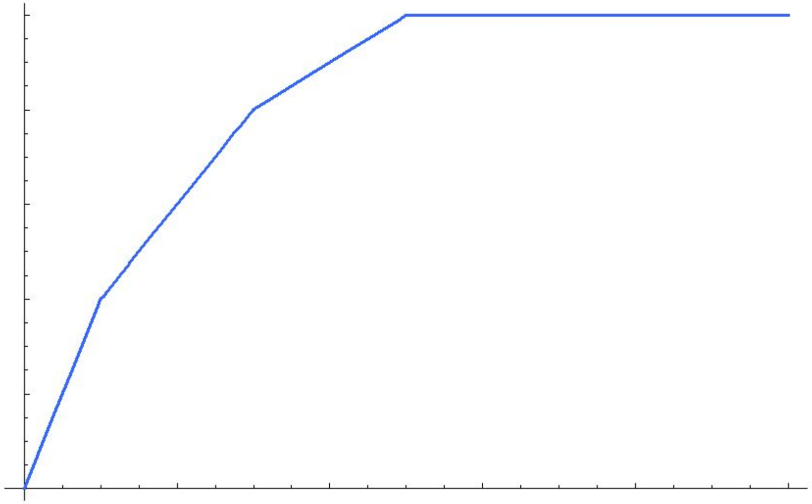


Tone Mapping on PS2

- PS2's alpha blending can scale up about six times on 1 pass
  - dst = Cs*As + Cs
    - Cs = FrameBuffer*2.0
    - As = 2.0
- In practice, you will have a precision problem, so use the appropriate alpha operation:0-1x, 1-2x, 2-4x, 4-6x for highest precision

Tone Mapping - Multiple Bands

- Multiple bands process to represent nonlinear curves



Tone Mapping - Multiple Bands

- But in cases of more than two bands, it is necessary to save the frame buffer and accumulate outcomes of scaling; rendering costs will be much higher
- We don't use Multiple Bands

Rendering costs

	No Band	2 Bands	3 Bands
Actual	2.2	10.2	23.4
Theory value	1.9	9.6	17.2

Unit : HSYNC   Frame Buffer size : 640x448

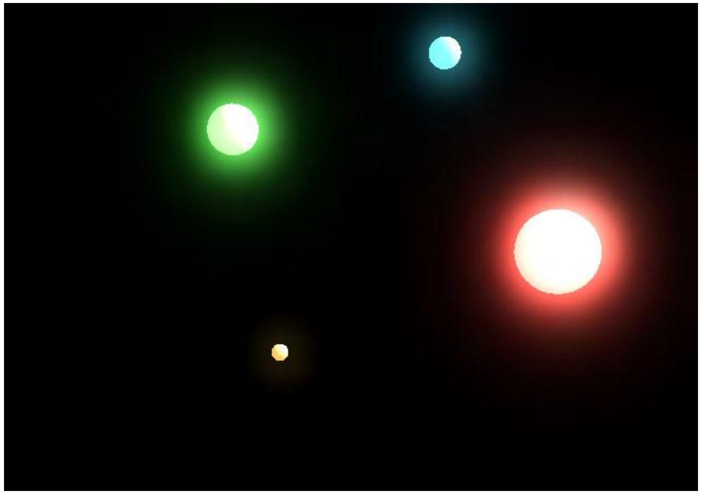
(Theory value is considered for only pixel-fill cycles)

Glare Filters on PS2

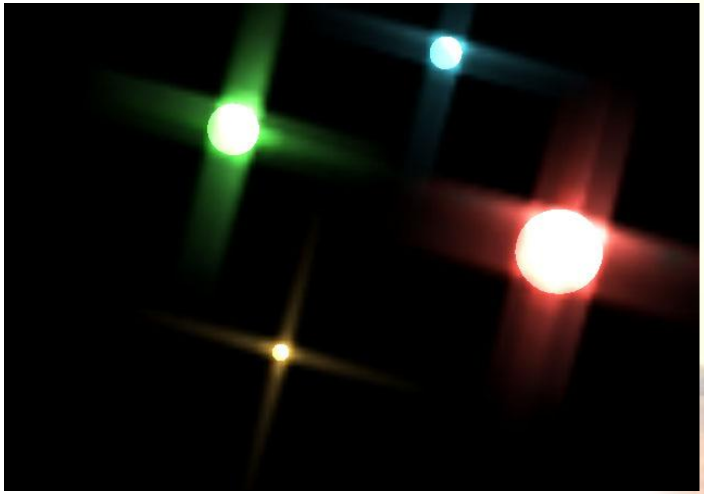
- Rendering costs (Typical)
  - Bloom 5-16Hsync
  - Star (4-way) 7-13Hsync
  - Persistence 1Hsync

  (frame buffer size : 640x448)

Persistence



Bloom



Star

Basic Topics for Glare Filters use

- Reduced Frame Buffer
- Filtering Threshold
- Shared Reduced Accumulation Buffer

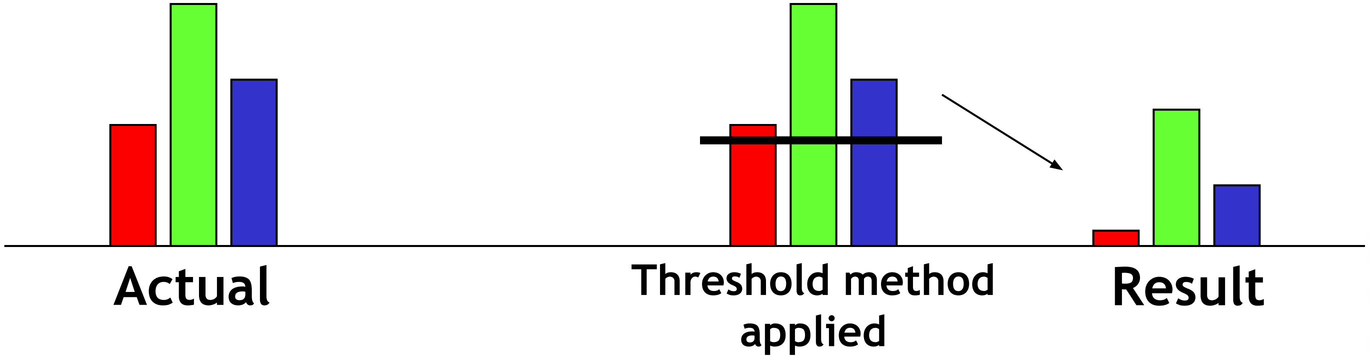
Reduced Frame Buffer

- Using 128x128 Reduced Frame Buffer
- All processes substitute this for the original frame buffer

- The most important tip is to reduce to half repeatedly with bilinear filtering to make the pixels contain average values of the original pixels
- It will improve aliasing when a camera or objects are in motion

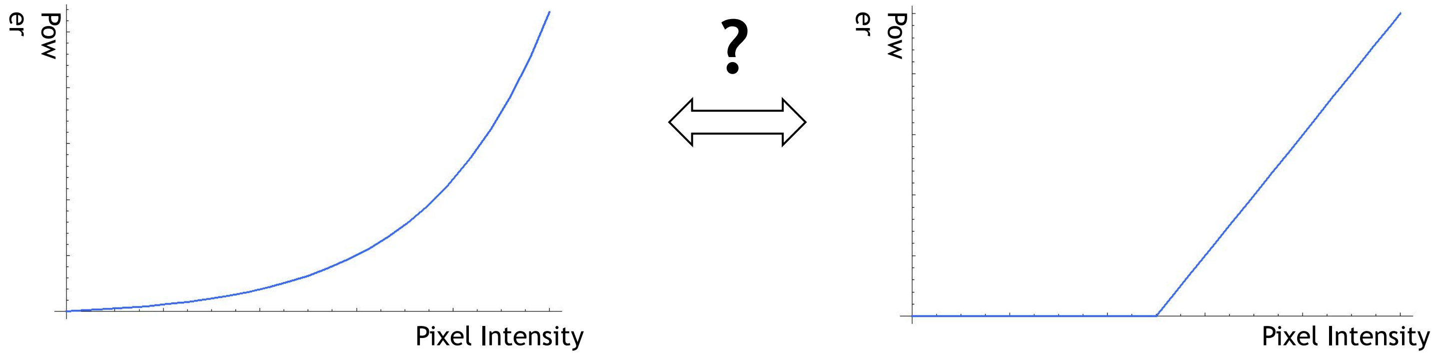
Filtering Threshold

- In practice, the filtering portion of buffer that are over threshold values
- The threshold method causes color bias that actual glare effects don't have



Filtering Threshold

- This method could be an approximation of a logarithmic curve for Tone Mapping ??



Shared Reduced ACC Buffer

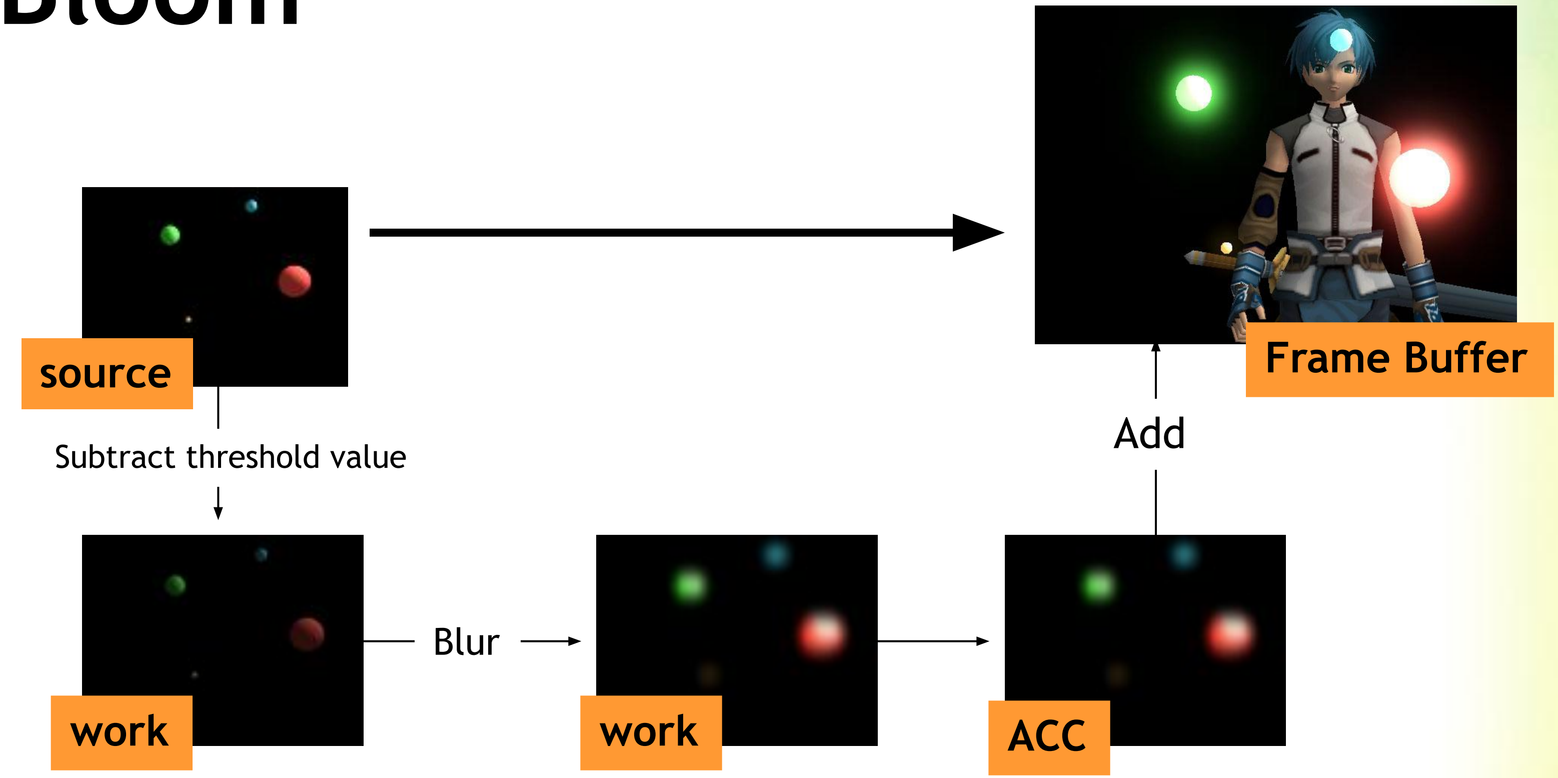
- Main frame buffers take a large area so fill costs are expensive
- Use the Shared Reduced Accumulation Buffer to streamline the main frame buffer once

Work Buffer List

Usage	Size	Scope
Reduced Frame Buffer (source)	128x128	Glare Filters & DOF (Shared with DOF)
Shared Reduced ACC	128x128	Glare Filters
Bloom work	128x128 – 64x64	Temp.
Star Stroke work	256x256 – 64x16	Temp.
Persistence	64x32	Continuous

- **Buffer sizes depend on PSMCT32 Page unit**
- **Buffer sizes will be 128x96 or 128x72, an aspect ratio of 4:3 or 16:9, considering maximum allocation**

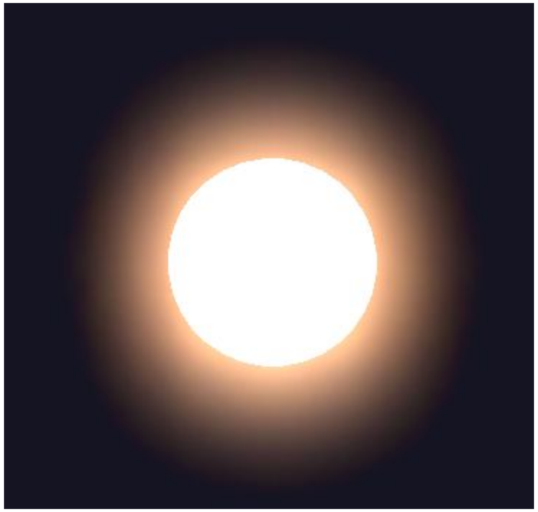
Bloom



- Using Gaussian Blur (Detail later)
- The work buffer size is 128x128 - 64x64

Bloom - Multiple Gaussian Filters

- Use Multiple Gaussian Filters
- MGF can reduce a blur radius compared with single Gaussian. Specifically, it helps reduce rendering costs and modifies filter characteristics



Single Gaussian
blur radius: 20 pixels

Multiple Gaussian (3 filters)
blur radii: 8, 4, 2 pixels

Bloom - Multiple Gaussian Filters

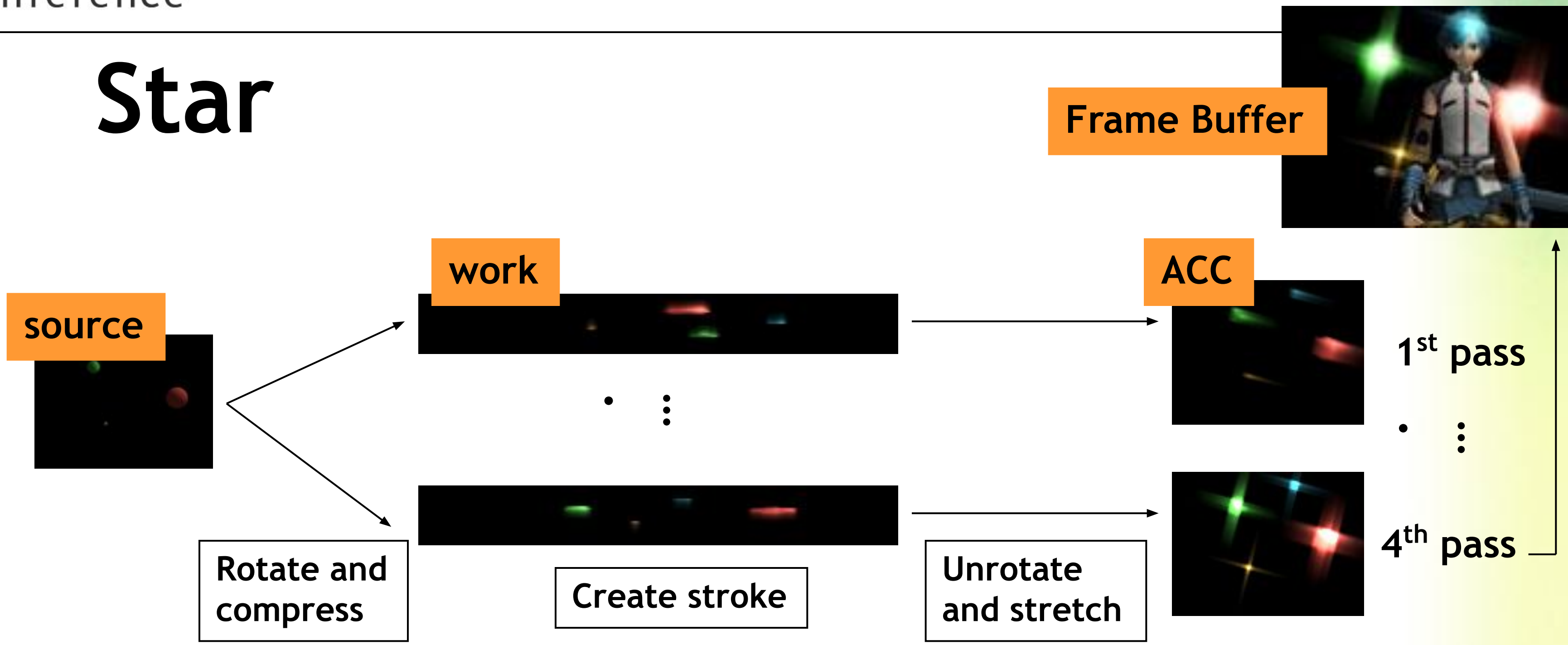
- Use 3 Gaussian filters in our case
- Radii are: 1st:40%, 2nd:20%, 3rd:10% of single Gaussian

Rendering costs

Blur radius (Pixel)	2	5	10	20
Single Gaussian	2.5	4.1	6.6	10.8
Multiple Gaussian	2.8	3.9	4.8	8.1

Unit : HSYNC Work Buffer Size : 128x128

Star

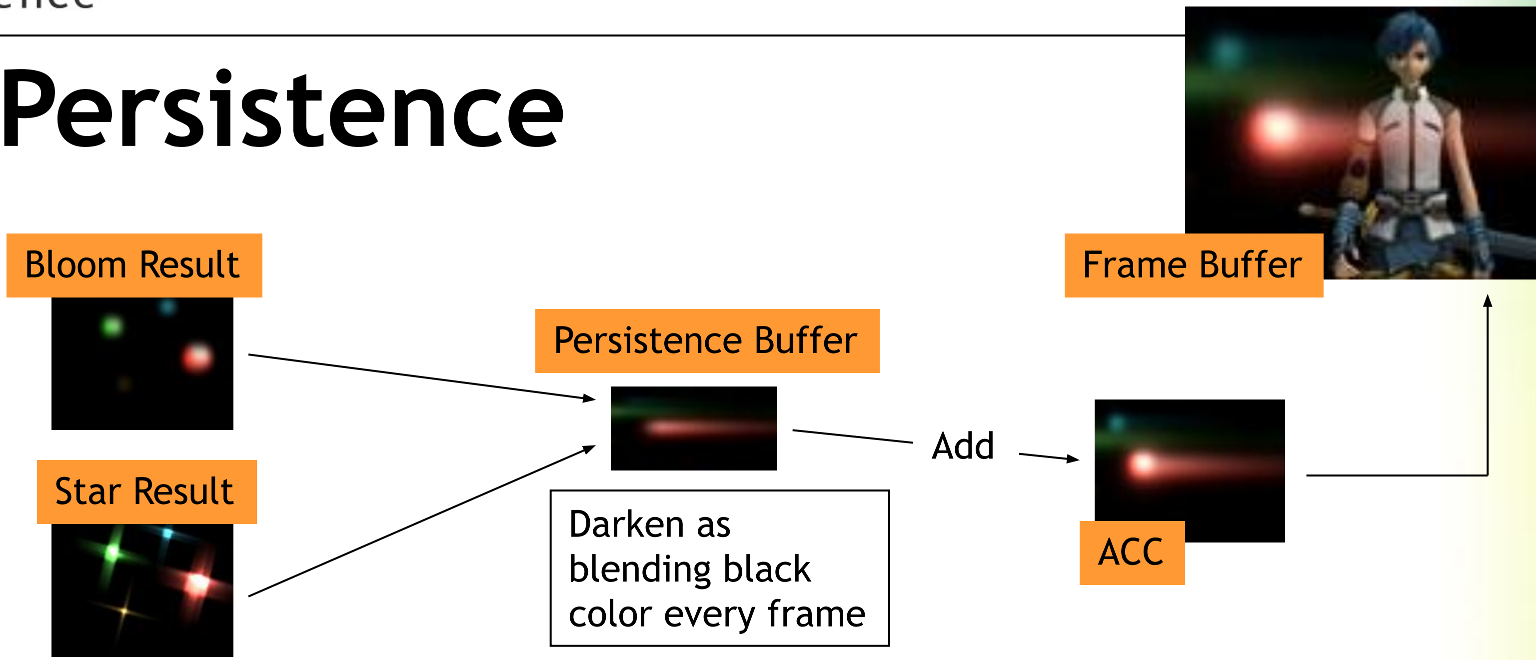


- Create each stroke on the work buffer and then accumulate it on the ACC Buffer
- Use a non-square work buffer that is reduced in the stroke's direction to save taps of stroke creation
- Vary buffer height in order to fix the tap count

Star Issue

- Can't draw sharp edges on Reduced ACC buffer
- Copying directly from a work buffer to the main frame buffer can improve quality
- But fill costs will increase

Persistence



- Send outcomes of filtering to Persistence Buffer as well as ACC Buffer
- Persistence Buffer size is 64x32
- A little persistence sometimes improves aliasing in motion

More Details for Glare Filters

- Multiple Gaussian Filters
- How to create star strokes
- and so on..

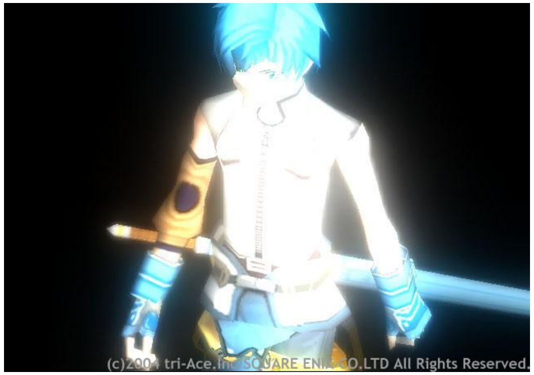
See references below

– Masaki Kawase. "Frame Buffer Postprocessing Effects in DOUBLE-S.T.E.A.L (Wreckless)“ GDC 2003.

– Masaki Kawase. "Practical Implementation of High Dynamic Range Rendering“ GDC 2004.

Gaussian Blur for PS2

- Gaussian Blur is possible on PS2
- It creates beautiful blurs
- Good match with Bilinear filtering and Reduced Frame Buffer



Gaussian Blur

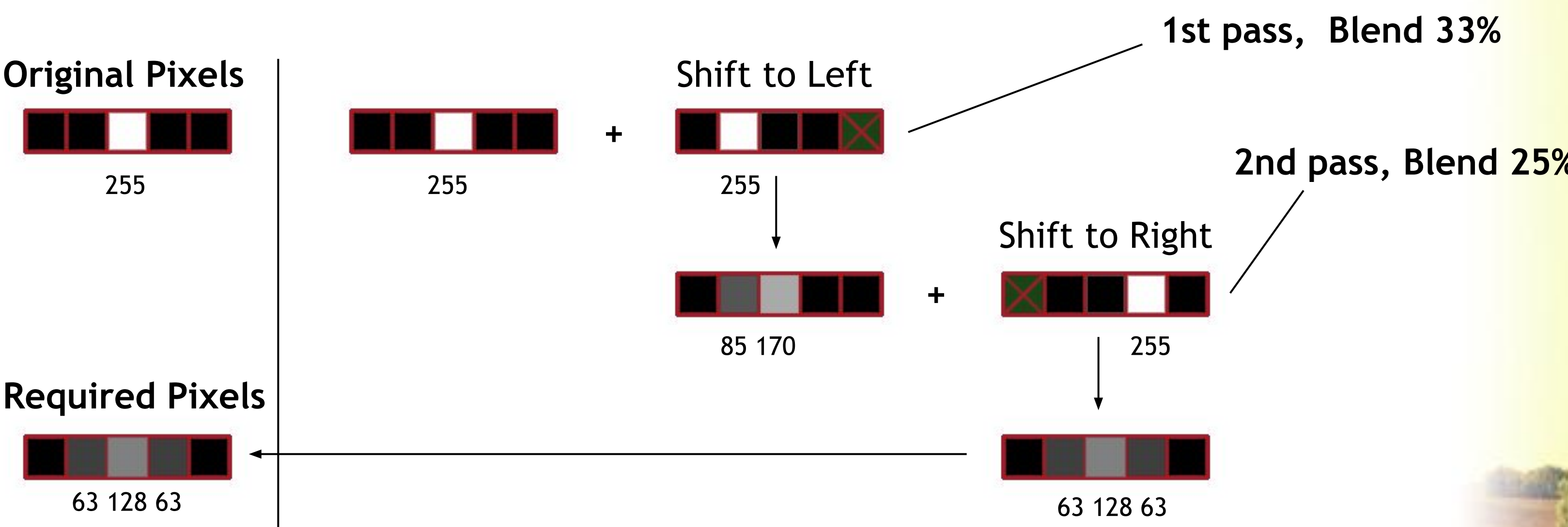
- Use Normal Alpha Blending
- Requires many taps, so processing on Reduced Work Buffer is recommended
- Costs are proportional to blur radii
- Various uses:
  - Bloom, Depth of Field, Soft Shadow, and so on

Gaussian Filter on PS2

- Compute Normal blending coefficients to distribute the pixel color to nearby pixels according to Gaussian Distribution
- Don't use Additive Alpha Blending

Gaussian Filter on PS2

Example: To distribute 25% to both sides
- 1st pass, blend 25% / (100%-25%)=33% to one side
- 2nd pass, blend 25% to the other side



Left Pixel : (0*(1-0.77) + 255 * 0.33) * (1-0.25) + 0 * 0.25 = 63
Right Pixel : 0 * (1-0.25) + 255 * 0.25 = 63

Gaussian Filter on PS2

- Gaussian Distribution can separate to X and Y axis

$$e^{-r^2} \qquad r = \sqrt{x^2 + y^2} \qquad e^{-r^2} = e^{-\left(x^2+y^2\right)} = e^{-x^2} \cdot e^{-y^2}$$

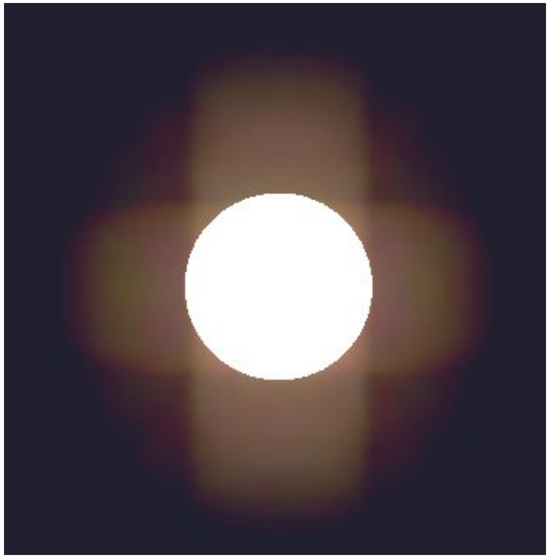
- This way, you can blur an area of 3x3 (the radius of 1 pixel) with only 4 taps of up, down, left and right
- Otherwise, blurring the area takes 9 taps

Gaussian Filter on PS2

- In addition, using bilinear filtering you can blur 2 pixels once
- That is …
  - 5x5 area with 4 taps
  - 7x7 area with 8 taps
  - 15x15 area with 28 taps
  - …

Lack of Buffer Precision

- 8-bit integer does not have enough precision to blur a wide radius. it can blur only about 30 pixels
- Precision in the process of calculations is preserved when using Normal Blending, but it's not preserved when using Additive Blending



Broken to X and Y axis
Blur radius : 40 pixels

Gaussian Filter Optimization

- Of course using VU1 saves CPU
- Avoiding Destination Page Break Penalty of a frame buffer is effective for those filters
- In addition, avoiding Source Page Break Penalty reduces rendering costs by 40%

Depth of Field

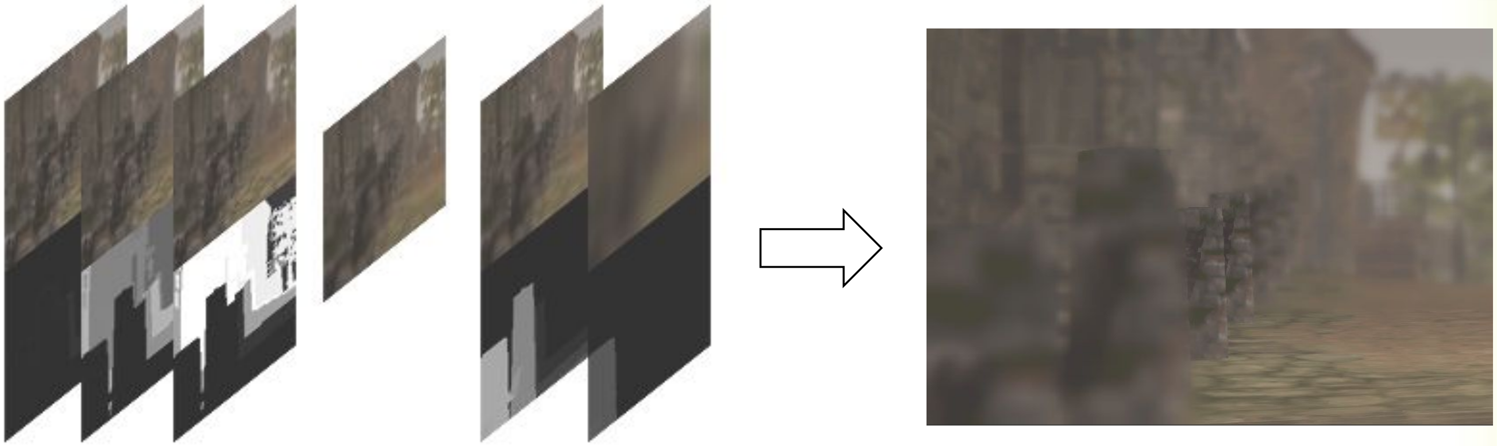
- Achievements of our system:
  - Reasonable rendering costs:
    - 8-24Hsync(typically), 35Hsync
    - (frame buffer size : 640x448)
  - Extreme blurs
  - Accurate blur radii and handling by real camera parameters
    - Focal length and F-stop

Depth of Field

Depth of Field overview

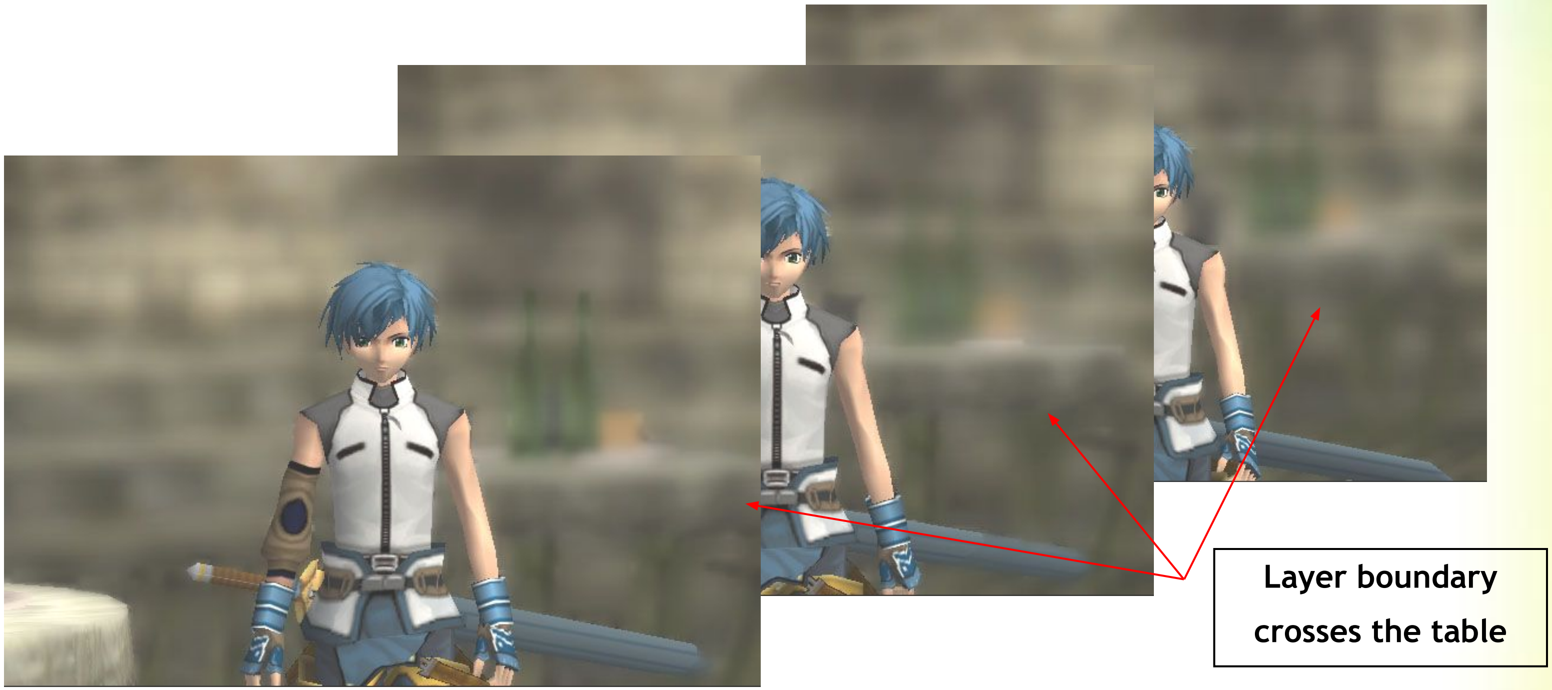
- Basically, blend a frame image and a blurred image based on alpha coefficients computed from Z values
- Use Gaussian Filter for blurring
- Use reduced work buffers : 128x128 - 64x64

Multiple Blurred Layers



- There are at most 3 layers as the background and 2 layers as the foreground in our case
- We use Blend and Blur Masks to improve some artifacts

Hopping Issue with Layers



- But hopping tends to occur when using more than two layers
- We usually use 1 BG and 1 FG layers or 1BG and 2FG layers

Formula for Blur Radius

- The optical formula for DOF below is acquired from The Thin Lens Formula and the formulas for camera structure relativity

$$x = \left| \frac{of}{o-f} - f\left(\frac{f}{p-f} + 1\right) \right| \cdot \frac{1}{F}$$

x: diameter of blur in projector (circle of confusion)
o: object distance
p: plane in focus
f: focal length
F: F-stop

Conversions of Frame Buffers

- DOF uses the conversions of frame buffers below (details later)
  - Swizzling Each Color Element from G to A or A to G
  - Converting Z to RGB with CLUT
  - Shifting Z bits toward upper side

Pixel-Bleeding Artifacts

Solved

- **With wider blurs, Pixel-Bleeding Artifacts were fatally emphasized**

Pixel-Bleeding Artifacts

- Solve it by blurring with a mask
- Use normal alpha blending so put masks in alpha components of a source buffer
- Gaussian Distribution is incorrect near the borders of the mask but looks OK

Edge on Blurred Foreground

- Generally, blurred objects in the foreground have sharp edges
- Need to expand Blending Alpha Mask for the foreground layers

Edge on Blurred Foreground

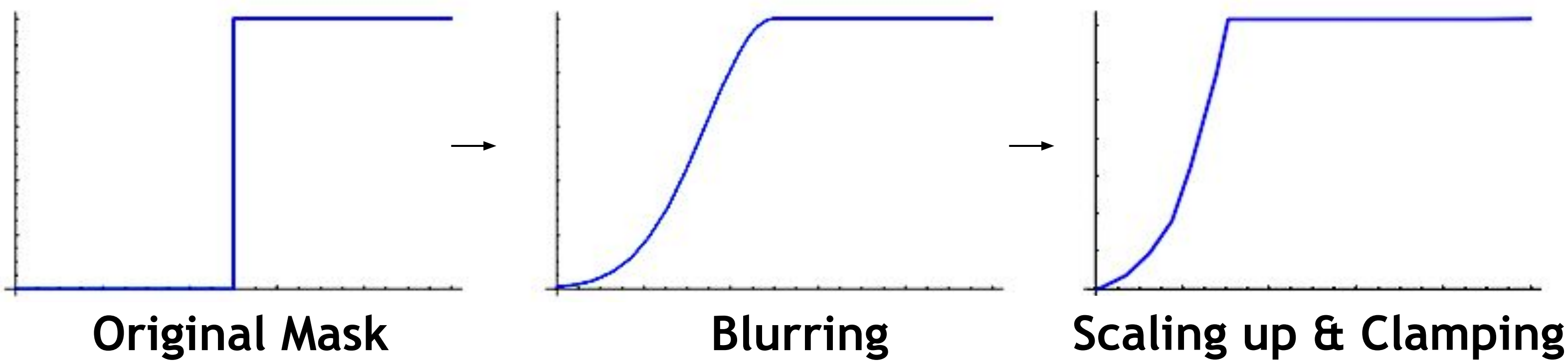
Not expanded

Expanded

- But using the reduced Z buffer leaves the masks a little blurred
- To expand or not is up to you

Expand Mask

- Our way also blurs and scales Blending Alpha Mask but intermediate values are broken
- Maybe there are better ways of expanding Blending Alpha Mask



Unexpected Soft Focus

In focus | Intermediate | Out of focus

- Appears among layers or between a layer and the midground, or appears a little blurred
- Emphasized when a blur is wide

Unexpected Soft Focus

- One solution is to increase the number of layers

- Another way is to put intermediate values on the blurring mask
- But it causes incorrect Gaussian blurring areas

Intermediate Mask of Gaussian

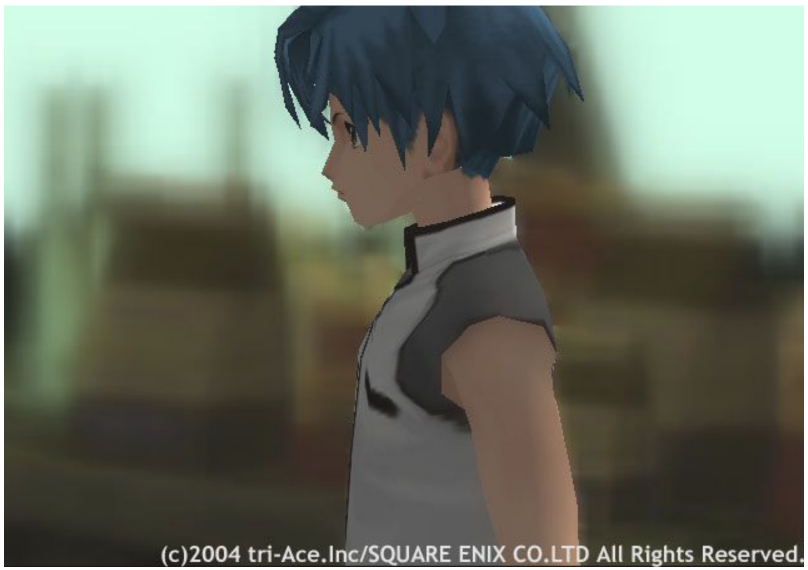
With intermediate values

Regular Gaussian

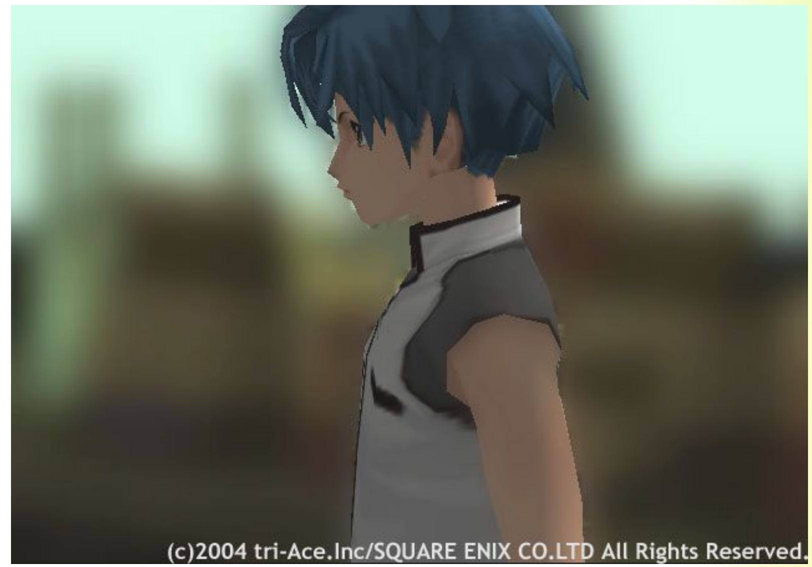
The apparent difference of depth with single layer … a little better

Intermediate Mask of Gaussian

With intermediate values



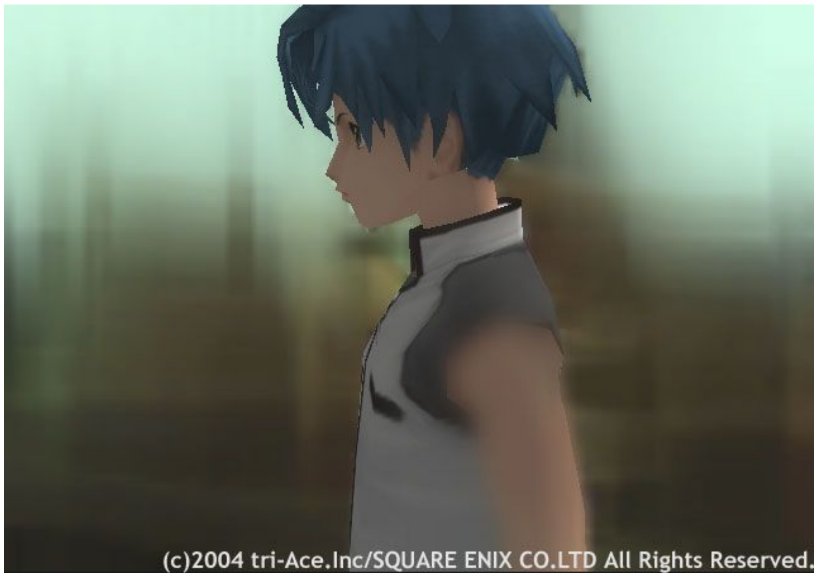
Regular Gaussian



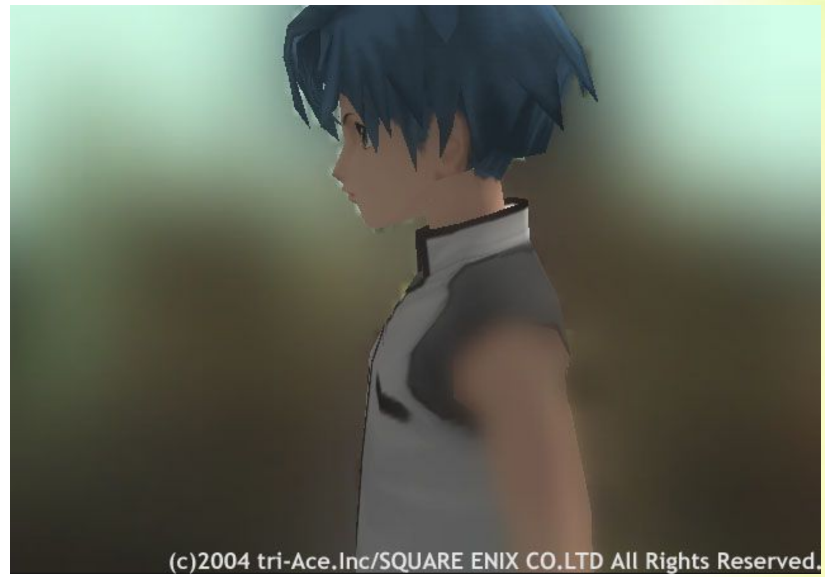
The apparent distance of objects …
but with a slight dirty blur

Intermediate Mask of Gaussian

With intermediate values



Regular Gaussian

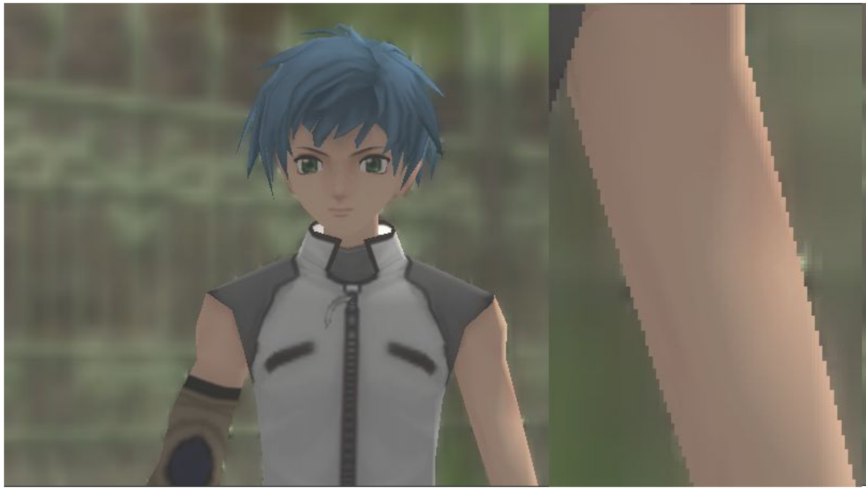


Wider blur … oops!

Unnatural Blur

- Gaussian Function is different from a real camera blur
- The real blur function is more flat
- Maybe the difference will be conspicuous using HDR values

Z Testing when Blending Layers



With Z test

Without

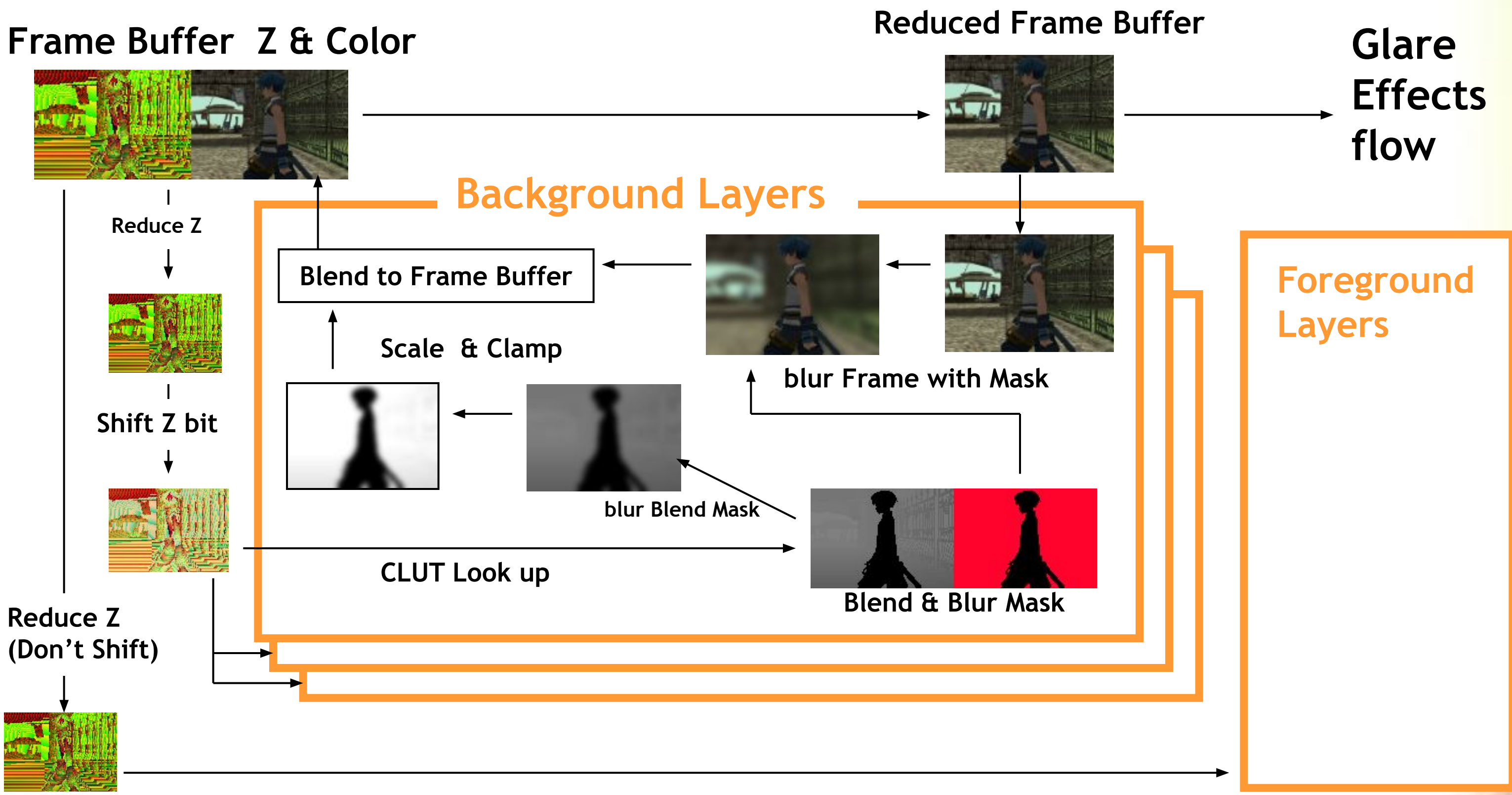
- Advantage
  - Clearer edge with a reduced Z buffer

Z Testing when Blending Layers

- Disadvantage
  - Hopping results when objects cross the borders of layers

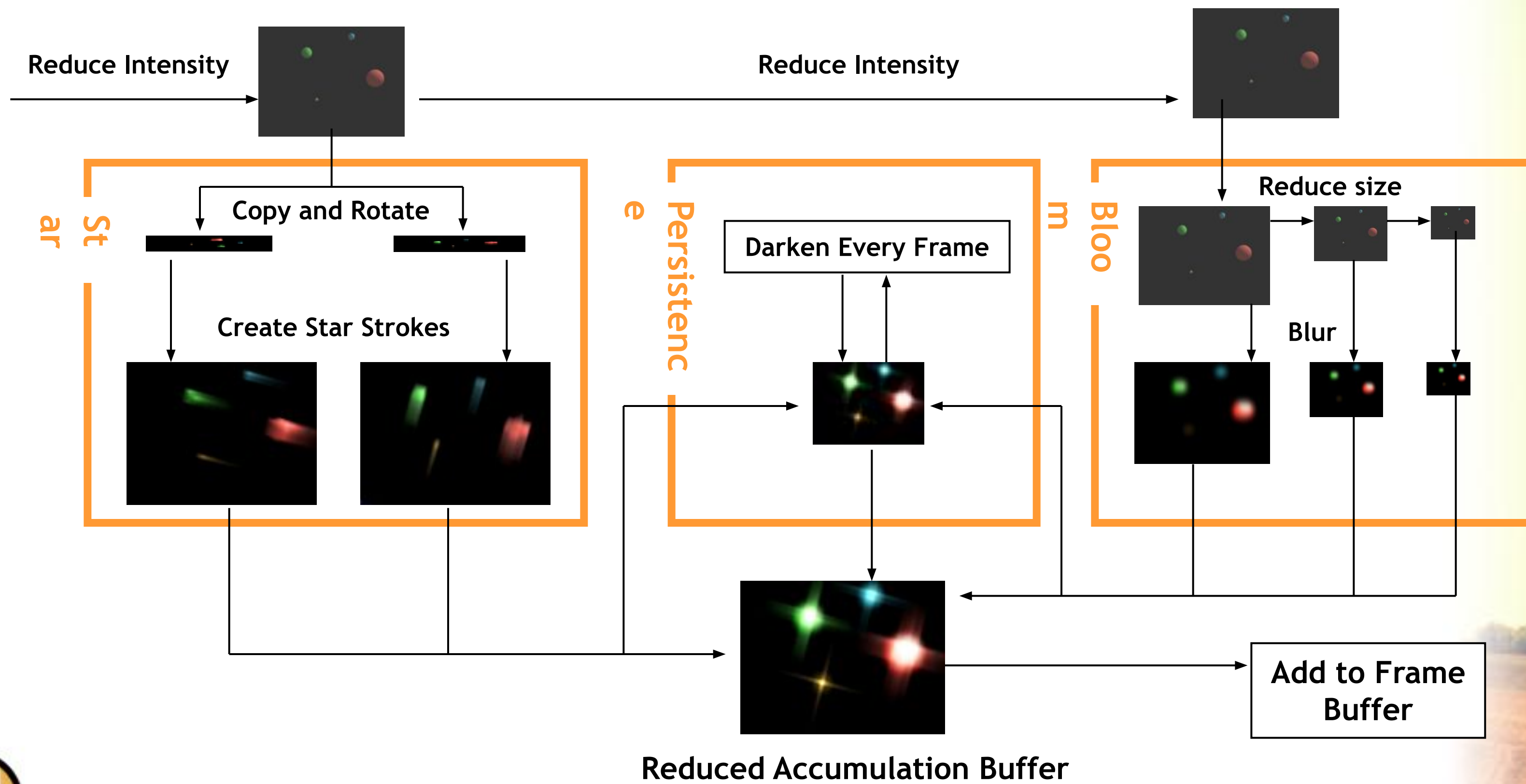
Converting Flow Overview

- DOF flow



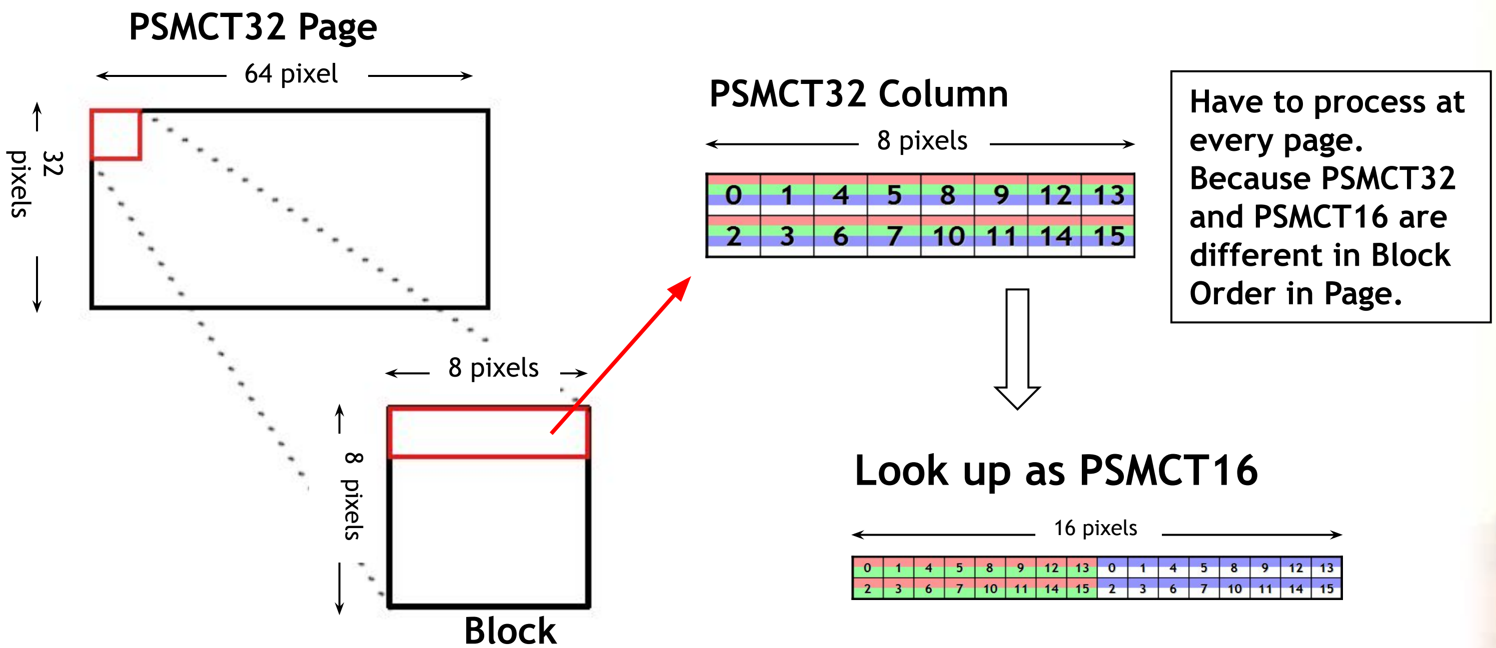
Converting Flow Overview

- Glare Effects flow



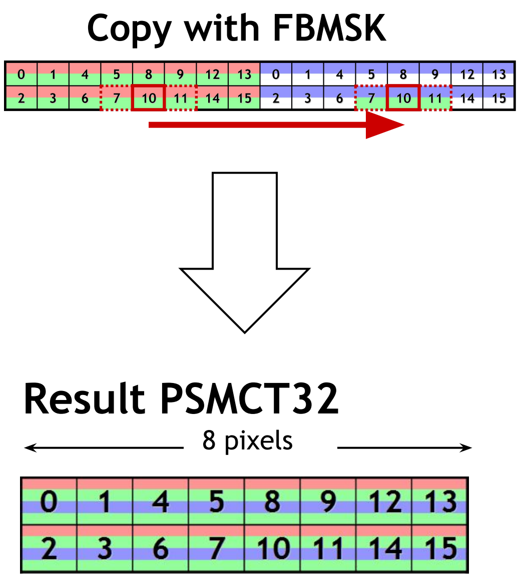
Swizzling Each Color Element from G to A or A to G

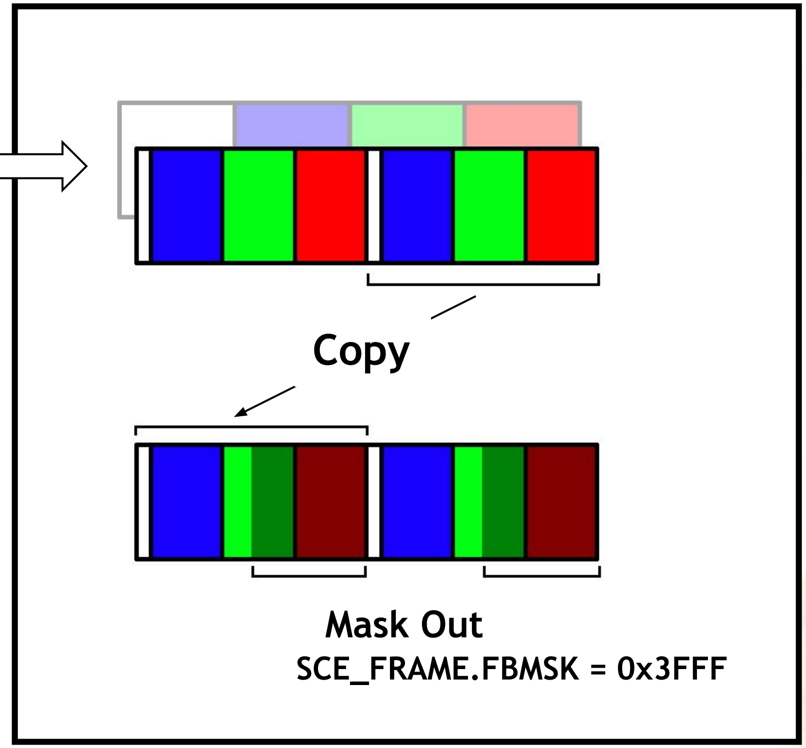
- Look up a PSMCT32 page as a PSMCT16 page



Swizzling Each Color Element from G to A or A to G

- Copy with FBMSK

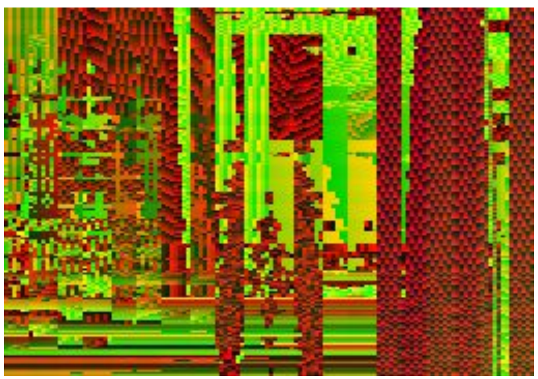




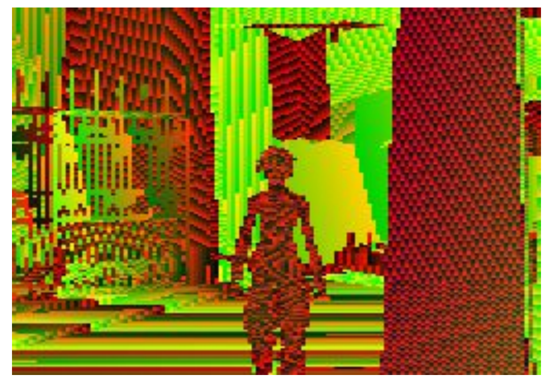
Converting Z to RGB with CLUT

- Convert PSMZ24 to PSMCT32

Native PSMZ24



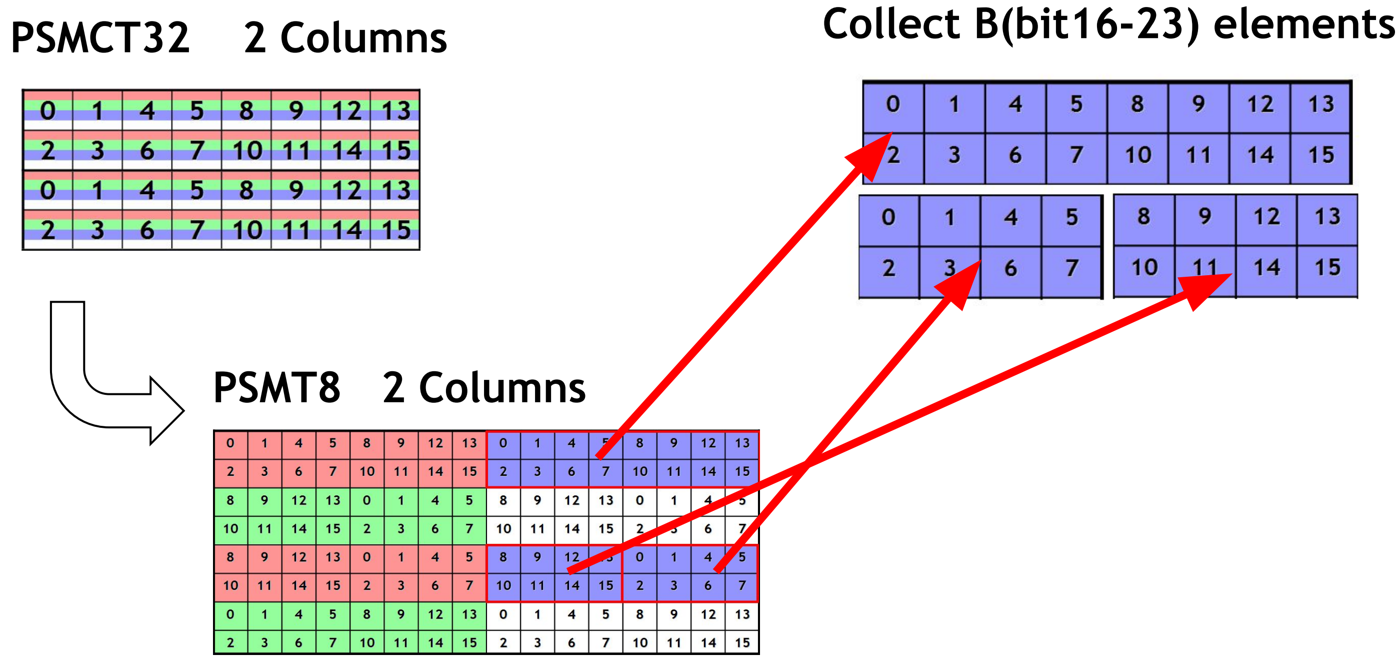
PSMCT32 Block order



Copy with
SCE_GS_SET_TEX0_1(srcTBP, width, PSMZ24, 10, 10, 1,0,0,0,0,0)

Converting Z to RGB with CLUT

- Look up as PSMT8



Converting Z to RGB with CLUT

- Requires many tiny sprites such as 8x2 or 4x2, so it's inefficient if creating on VU
- When converting a larger area, using Tile Base Processing for sharing a packet is recommended

Issue of Converting Z to RGB

Not shifted

Shifted

- Use CLUT to convert Z to RGB, so it can take only upper 8-bit from Z bits
- Upper Z bits tend not to contain enough depth because of bias of a Z-buffer
- Solve by shifting bits of the Z-buffer to upper
- BETTER WAY is setting more suitable Near Plane or Far Plane

Shifting Z bits toward Upper Side

Step1 Save G of the Z-buffer in alpha plane

Step2 Add B the same number of times as shift bits to itself for biasing B

Step3 Put saved G into lower B with alpha blending (protect upper B by FBMASK of FRAME register)

※ 24-bit Z-buffer case
B:17-23 bit G:8-16 bit R:0-7 bit

Outdoor Light Scattering

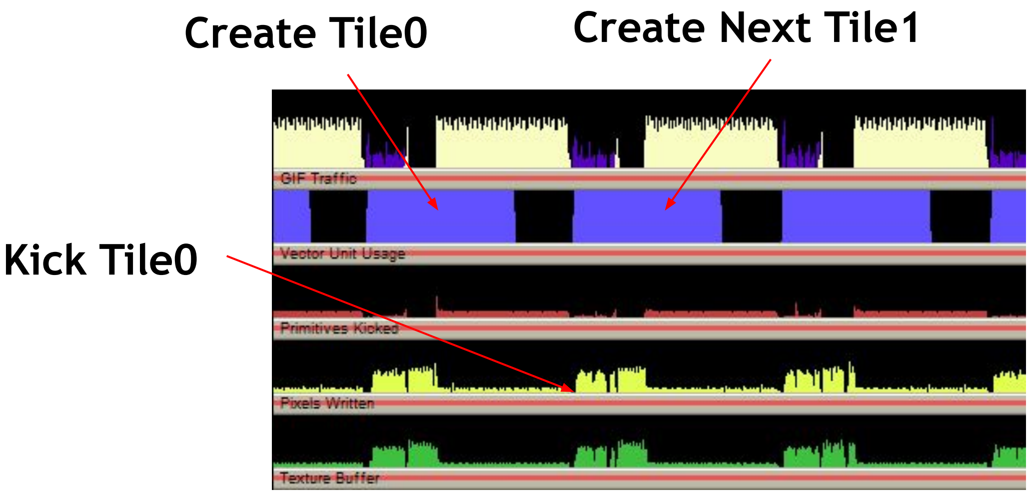
Outdoor Light Scattering

- Implementation of:
  - Naty Hoffman, Arcot J Preetham. "Rendering Outdoor Light Scattering in Real Time“ GDC 2002.
- Glare Effects and DOF work good enough on Reduced Frame Buffer,

  but OLS requires higher resolution, so OLS tends to need more pixel-fill costs
- Takes 13-39Hsync (typically), 57Hsync

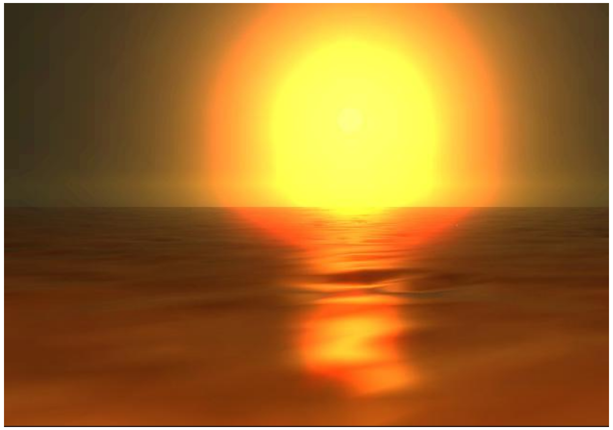
Outdoor Light Scattering

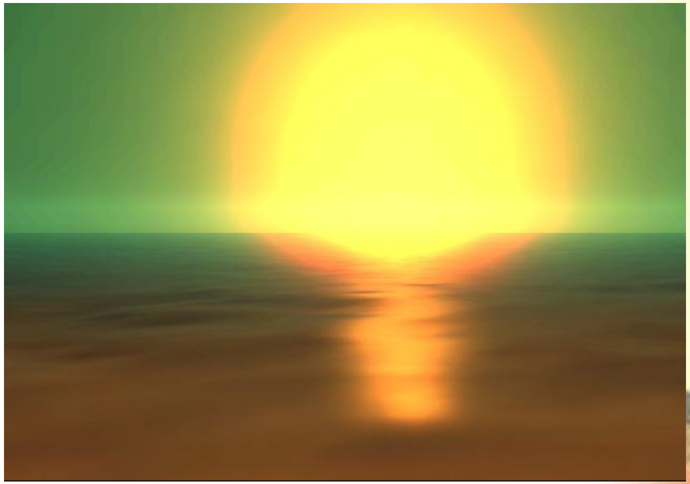
- Adopting Tile Base Processing
- High OLS fillrate causes a bottleneck, so computing colors and making primitives are processed by VU1 during previous tile rendering



Additional Parameters

- 2^{nd} Mie Coefficients
  - Can represent more complex coloring
  - No change to fill costs





Green color added by 2^{nd} Mie

Additional Parameters

- Gamma
  - It's fake. It isn't correct physically
  - But it would be most useful

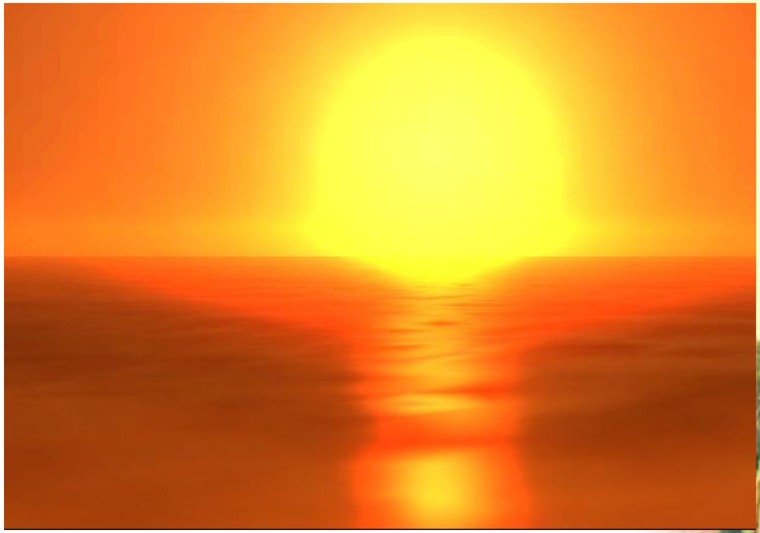
Gamma 0.68

Gamma 2.00

Additional Parameters

- Horizontal Slope & Gain
  - **Use the function from "Perez all weather luminance model" with a modification**

$$F(\theta) = 1 + 2g \cdot e^{\frac{s}{s+|\cos\theta|}}$$



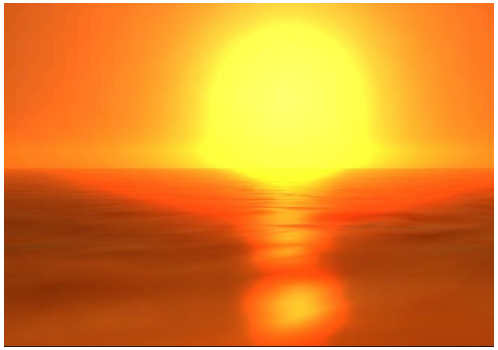
Theta : The angle formed by zenith and ray

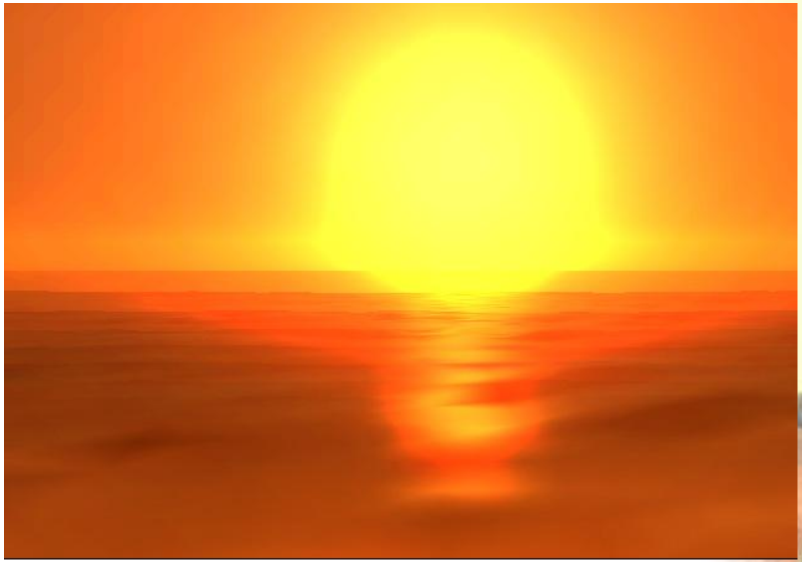
g : gain

s : gradient

Additional Parameters

- Z bit Shift
  - Is more important than using it with DOF





Not Shifted

OLS - Episode

- Shifting Z bits causes a side effect where objects in the foreground tend to be colored by clamping values
- Artists found and started shifting Z bits as color correction, so we provided inexpensive emulation of coloring

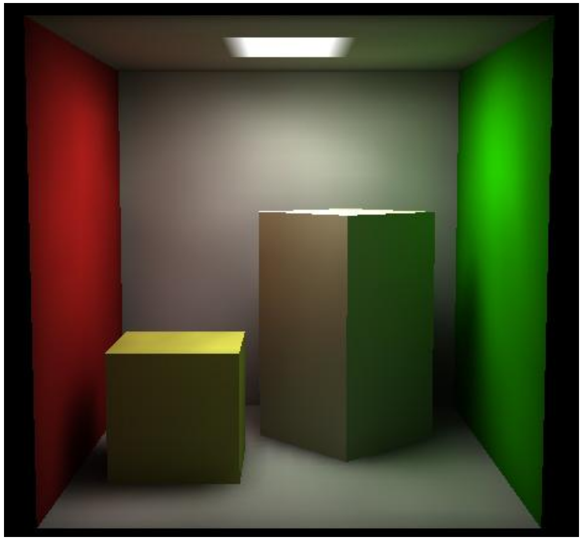
Spherical Harmonics Lighting

How to use SH Lighting easily?

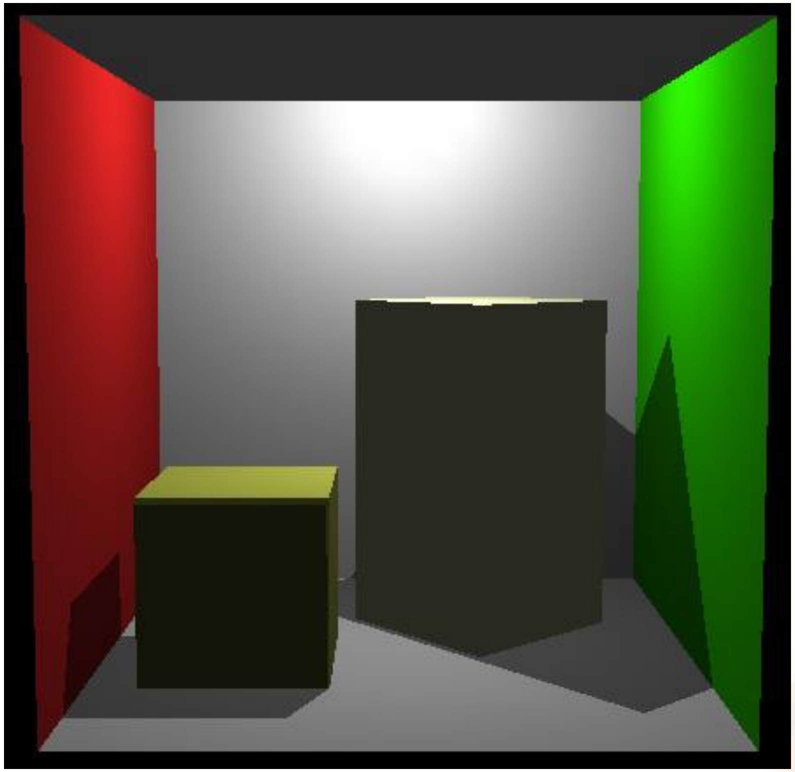
- Use DirectX9c!
  - Of course, we know you want to implement it yourselves
  - But SH Lighting implementation on DirectX9c is useful to understand it
  - You should look over its documentation and samples

Reason to use SH Lighting on PS2

- Photo-realistic lighting



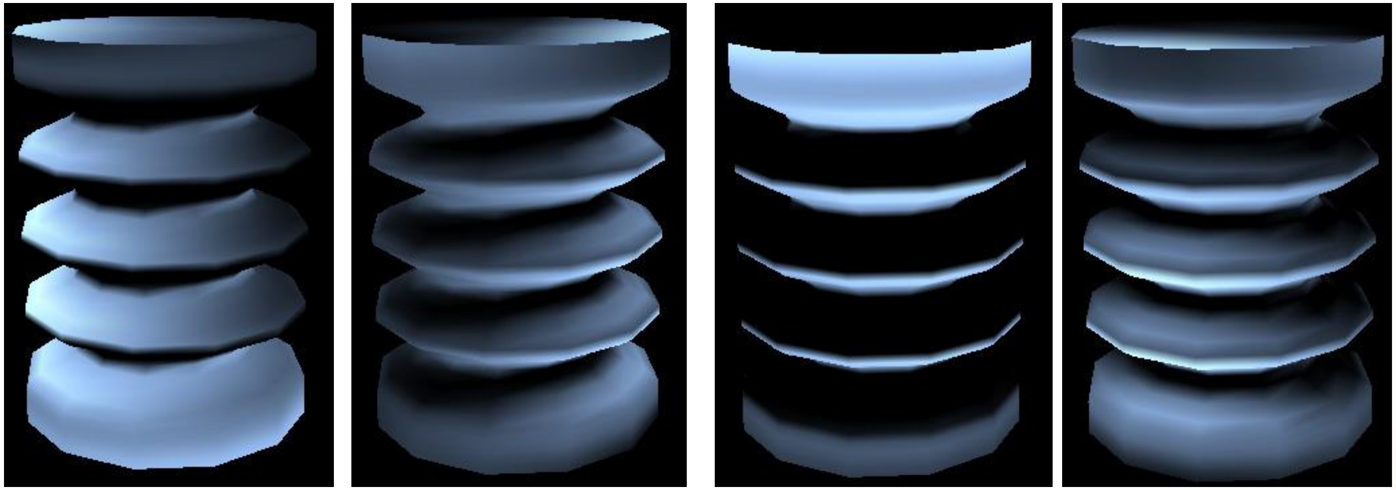
Global Illumination with Light Transport



Traditional Lighting with an omni-directional light and Volumetric Shadow

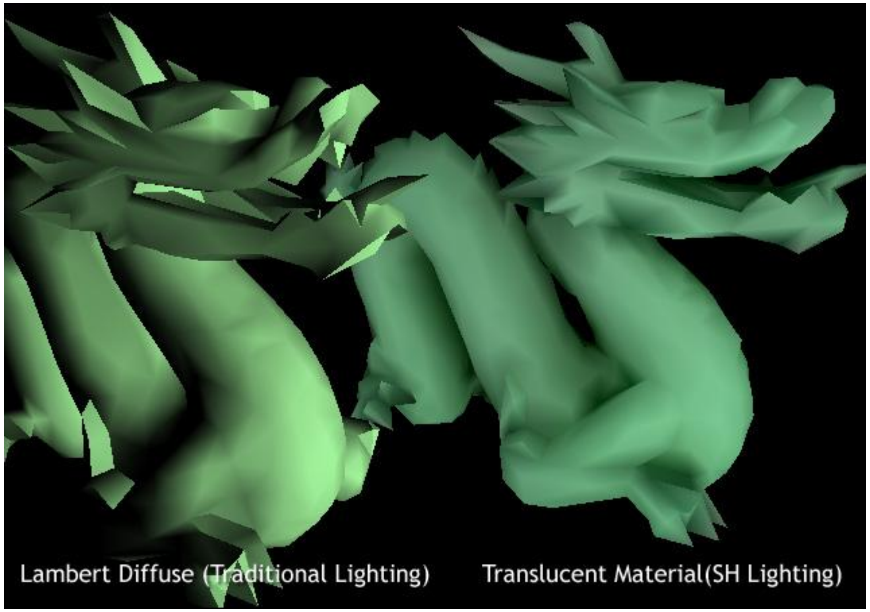
Reason to use SH Lighting on PS2

- Dynamic light



Reason to use SH Lighting on PS2

- Subsurface scattering



PRT

- Precomputed Radiance Transfer was published by Peter Pike Sloan et al. in SIGRAPH 2002
  - Compute incident light from all directions off line and compress it
  - Use compressed data for illuminating surfaces in real-time

What to do with PRT

- Limited real-time global illumination
  - Basically objects mustn't deform
  - Basically objects mustn't move
- Limited B(SS)RDF simulation
  - Lambertian Diffuse
  - Glossy Specular
  - Arbitrary (low frequency) BRDF

Limited Animation

- SH Light position can move or rotate
  - But SH lights are regarded as infinite distance lights (directional light)
- SH Light color and intensity can be animated
  - IBL can be used
- Objects can move or rotate
  - But if objects affect each other, those objects can't move
- Because light effects are pre-computed!

SH

- Spherical Harmonics : $Y_l^m(\theta,\phi)$
  - are thought to be like a 2-dimensional Fourier Transform in spherical coordinates
  - are orthogonal linear bases
  - This time, we used them for compression of PRT data and representation of incident light

$$Y_l^m(\theta,\phi) \equiv \sqrt{\frac{2l+1(l-m)!}{4\pi(l+m)!}} P_l^m(\cos\theta)e^{im\phi}$$

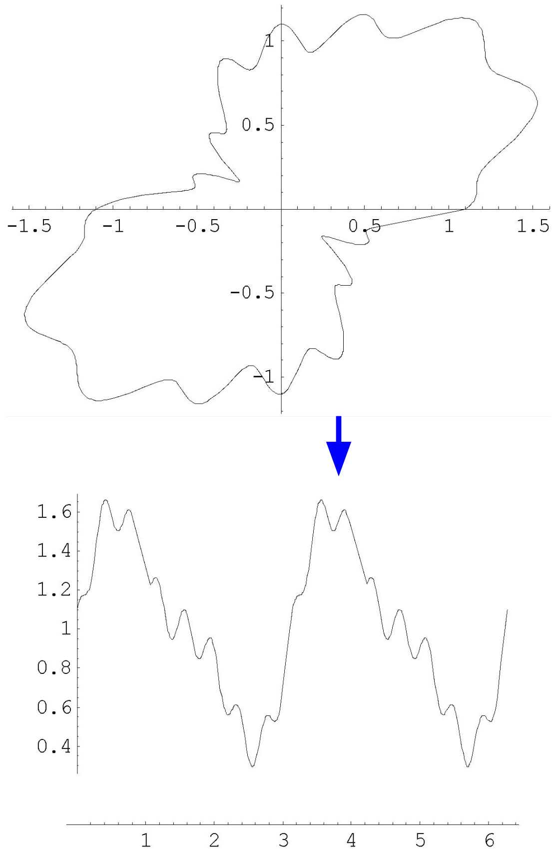
where $m = -l, -(l-1), \ldots 0, \ldots (l-1), l$ and

$P_l^m(z)$ is an associated Legendre Polynomial

How is data compressed?

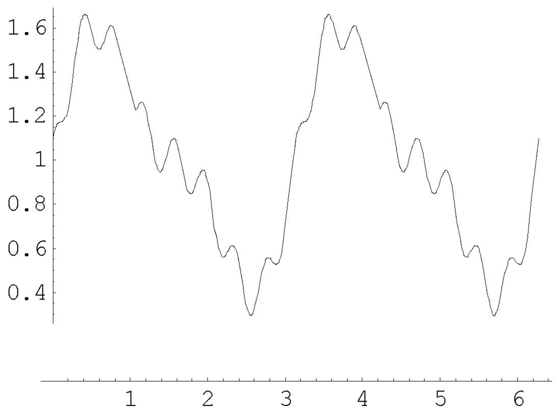
- PRT data is considered as a response to rays from all directions in 3D-space
- Think of it as 2D-space, so as to understand easily

How is data compressed?



- This is an example of response to light from all directions in 2D-space
- It is in circular coordinates
- Therefore it can be expanded like this graph

How is data compressed?



- This function can be represented by the Fourier series (set of infinite trig functions)

- If there is a function like 2D Fourier Transform in spherical coordinates; PRT data can be compressed with it

How is data compressed?

- You could think of Spherical Harmonics as a 2D Fourier Transform in spherical coordinates, so as to understand easily

How data is compressed?

- Use lower order coefficients of SH to compress data (It is like JPEG)
- Use this method for compression of PRT data and light

Use some of these p coefficients for object data

$$f(\vec{v}) = p_0 \cdot l_0 \cdot Y_0^0(\vec{v}) + p_1 \cdot l_1 \cdot Y_{-1}^1(\vec{v}) + p_2 \cdot l_2 \cdot Y_0^1(\vec{v}) + p_3 \cdot l_3 \cdot Y_1^1(\vec{v}) + p_4 \cdot l_4 \cdot Y_{-2}^2(\vec{v}) \ldots + p_n \cdot l_n \cdot Y_m^l(\vec{v})$$

$f(\vec{x})$: **Illuminated color** p_k : **SH coefficients on a vertex of object**

l_k : **SH coefficients of light** $Y_m^l(\vec{x})$: **SH functions**

Why use linear transformations?

- It is easy to handle with vector processors
  - A linear transformation is a set of dot products (f = a*x0 + b*x1 + c*x2….)
  - Use only MULA, MADDA and MADD (PS2) to decompress data (and light calculation)
    - For the Vertex (Pixel) Shader, dp4 is useful for linear transformations

Compare linear transformations

	SH	Wavelet	PCA basis
Rotation	invariant	variant	variant
With few coef	soft (but usable)	jaggy (depends on a basis)	useless (depends on complexity)
High frequency (specular)	useless (lots of coef)	support	support
Specular interreflection	possible	difficult	difficult
Handiness for artists	easy	?	?

This comparison is based on current papers. Recent papers hardly take up Spherical Harmonics, but we think it is still useful for game engines

Details of SH we use

- It is tough to use SH Lighting on PlayStation 2
  - Therefore we used only a few coefficients
  - Coefficient format : 16bit fixed point (1:2:13)
- PlayStation 2 doesn't have a pixel shader
  - Only per-vertex lighting

Details of SH we use

	Num of coef	size of SH data	Num of VU1 instructions	Actual speed ratio	Actual size ratio (Example with no texture)
Traditional light	0	0	10(15)	1.00	1.00
SH : 2bands - 1ch	4	8	6(13)	1.05	1.37
SH : 3bands - 1ch	9	18	13(20)	1.56	2.05
SH : 4bands - 1ch	16	32	21(28)	2.07	2.83
SH : 2bands - 3chs	12	24	9(16)	1.57	2.00

( ) including Secondary Light Shader

Secondary Light Shader does light clamping and calculation of final color

Details of SH we use

- This is the SH Basis we use (Cartesian coordinate)
  - SH[0] = 1.1026588 * x
  - SH[1] = 1.1026588 * y
  - SH[2] = 1.1026588 * z
  - SH[3] = 0.6366202
  - SH[4] = 2.4656168 * xy
  - SH[5] = 2.4656168 * yz
  - SH[6] = 0.7117635 * (3z^2 - 1)
  - SH[7] = 2.4656168 * zx
  - SH[8] = 1.2328084 * (x^2 – y^2)
  - SH[9] = 1.3315867 * y(3x^2-y)
  - SH[10] = 6.5234082 * yxz
  - SH[11] = 1.0314423 * y(5z^2 – 1)
  - SH[12] = 0.8421680 * z(5z^2 – 3)
  - SH[13] = 1.0314423 * x(5z^2 – 1)
  - SH[14] = 3.2617153 * z(x^2 – y^2)
  - SH[15] = 1.3315867 * x(x^2 – 3y^2)

Details of SH we use

- Our SH Shader(2bands, 1ch) code for VU1 (Main loop is 6ops)

```
    NOP                   LQ   VF20, SHCOEF+0(VI00)
    NOP                   LQ   VF21, SHCOEF+1(VI00)
    NOP                   LQ   VF22, SHCOEF+2(VI00)
    ITOF12     VF14, VF13      LQI  VF13, (VI02++)
    NOP                   LQ   VF23, SHCOEF+3(VI00)
    NOP                   IADDIU   VI07, VI07, 1
tls1_loop:
    MADDw.xyz  VF30, VF23, VF15w   LQI.xyz  VF29, (VI03++)
    MULAx.xyz  ACC, VF20, VF14x    MOVE.zw  VF15, VF14
    MADDAy.xyz ACC, VF21, VF14y    ISUBIU   VI07, VI07, 1
    ITOF12     VF14, VF13      LQI  VF13, (VI02++)
    MADDAw.xyz ACC, VF29, VF00w    IBNE VI07, VI00, tls1_loop
    MADDAz.xyz ACC, VF22, VF15z    SQ.xyz   VF30, -2(VI03)
```

Details of SH we use

- Our SH Shader(3bands, 1ch) code for VU1 (Main loop is 13ops)

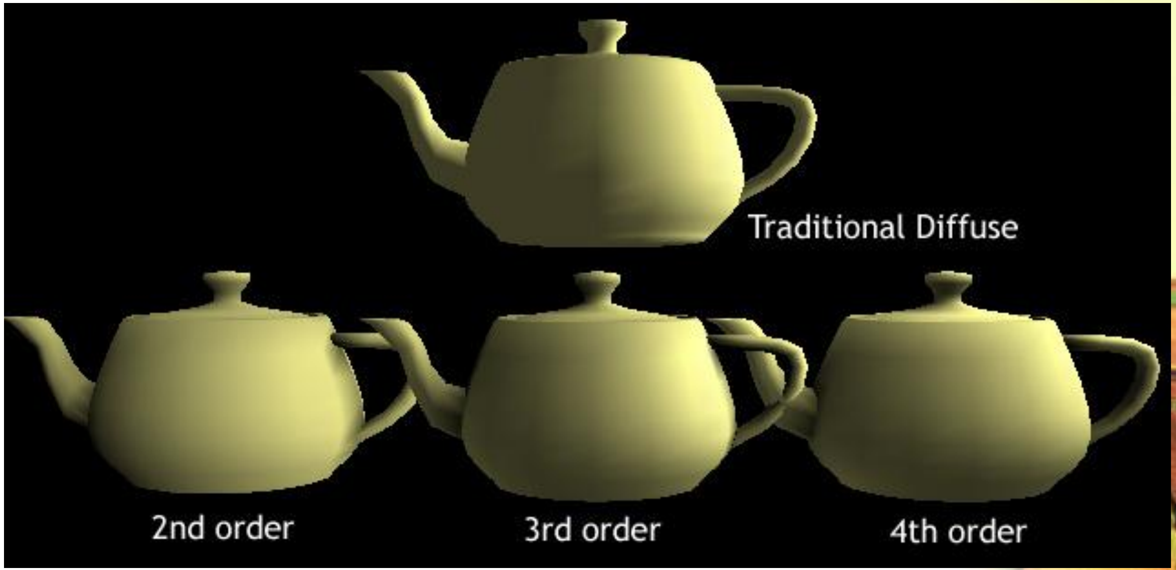
```
    NOP                LQI    VF14, (VI02++)
    NOP                LQI    VF15, (VI02++)
    NOP                LQ     VF29, 0(VI03)
    ITOF12    VF25, VF13       LQ     VF16, SHCOEF+0(VI00)
    ITOF12    VF26, VF14       LQ     VF17, SHCOEF+1(VI00)
    ITOF12    VF27, VF15       LQ     VF18, SHCOEF+2(VI00)
    MULAw.xyz ACC, VF29, VF00w LQ     VF19, SHCOEF+3(VI00)
 tls2_loop:
    MADDAx.xyz ACC, VF16, VF25x     LQ     VF20, SHCOEF+4(VI00)
    MADDAy.xyz ACC, VF17, VF25y     LQ     VF21, SHCOEF+5(VI00)
    MADDAz.xyz ACC, VF18, VF25z     LQ     VF22, SHCOEF+6(VI00)
    MADDAx.xyz ACC, VF19, VF26x     LQ     VF23, SHCOEF+7(VI00)
    MADDAy.xyz ACC, VF20, VF26y     LQ     VF24, SHCOEF+8(VI00)
    MADDAz.xyz ACC, VF21, VF26z     LQI    VF13, (VI02++)
    MADDAx.xyz ACC, VF22, VF27x     LQI    VF14, (VI02++)
    MADDAy.xyz ACC, VF23, VF27y     LQI    VF15, (VI02++)
    MADDz.xyz  VF30, VF24, VF27z    LQ     VF29, 1(VI03)
    ITOF12     VF25, VF13      ISUBIU VI07, VI07, 1
    ITOF12     VF26, VF14      NOP
    ITOF12     VF27, VF15      IBNE   VI07, VI00, tls2_loop
    MULAw.xyz  ACC, VF29, VF00w     SQI.xyz VF30, (VI03++)
```

Details of SH we use

- Engineers think that SH can be used with at least the 5^{th} order (25 coefficients for each channel)
- Practically, artists think SH is useful with even the 2^{nd} order (4 coefficients)
- Artists will think about how to use it efficiently

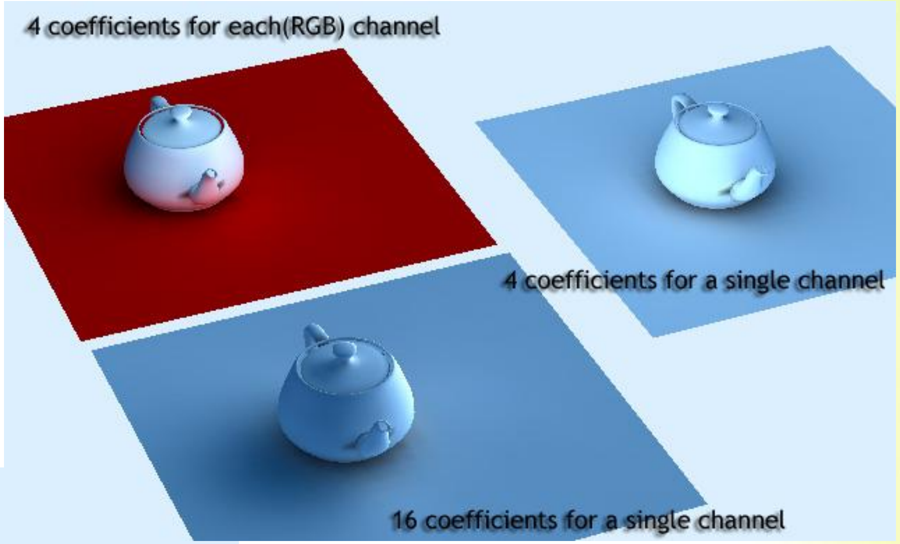
Differences in appearance

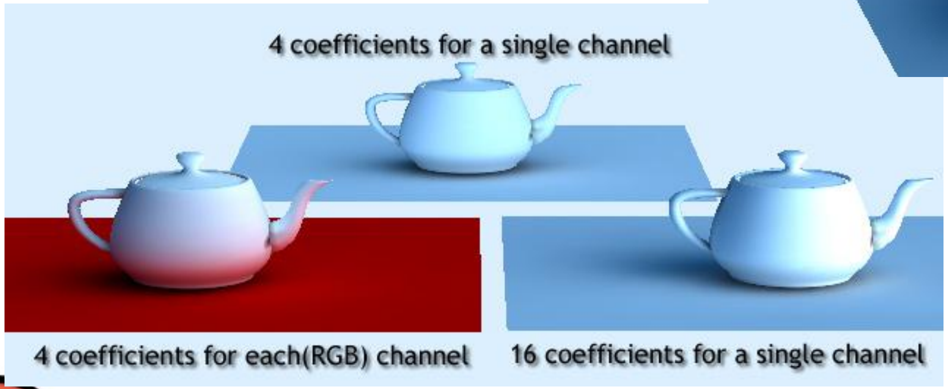
- The 2nd order is inaccurate
  - However, it's useful (soft shading)
- The 3rd and 4th are similar
  - The 3rd is useful considering costs



Differences in appearance

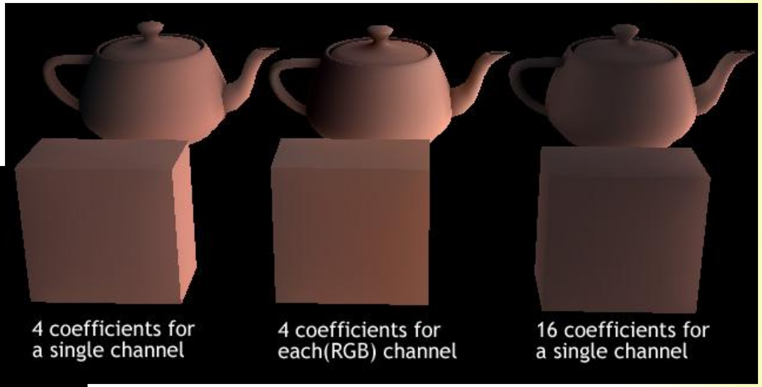
- The number of channels mainly influences color bleeding (Interreflection)
- The number of coefficients mainly influences shadow accuracy

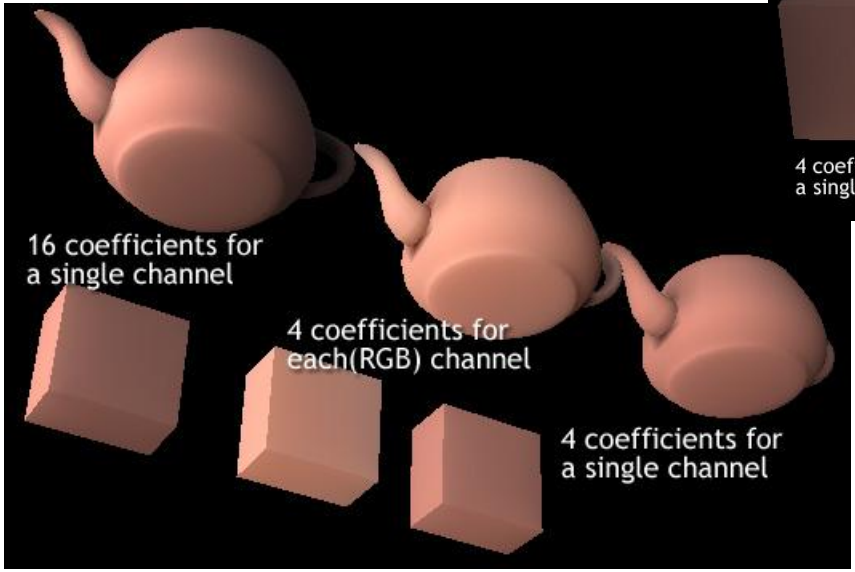




Differences in appearance

- **For sub-surface scattering, color channels tend to be more important than the number of coefficients**



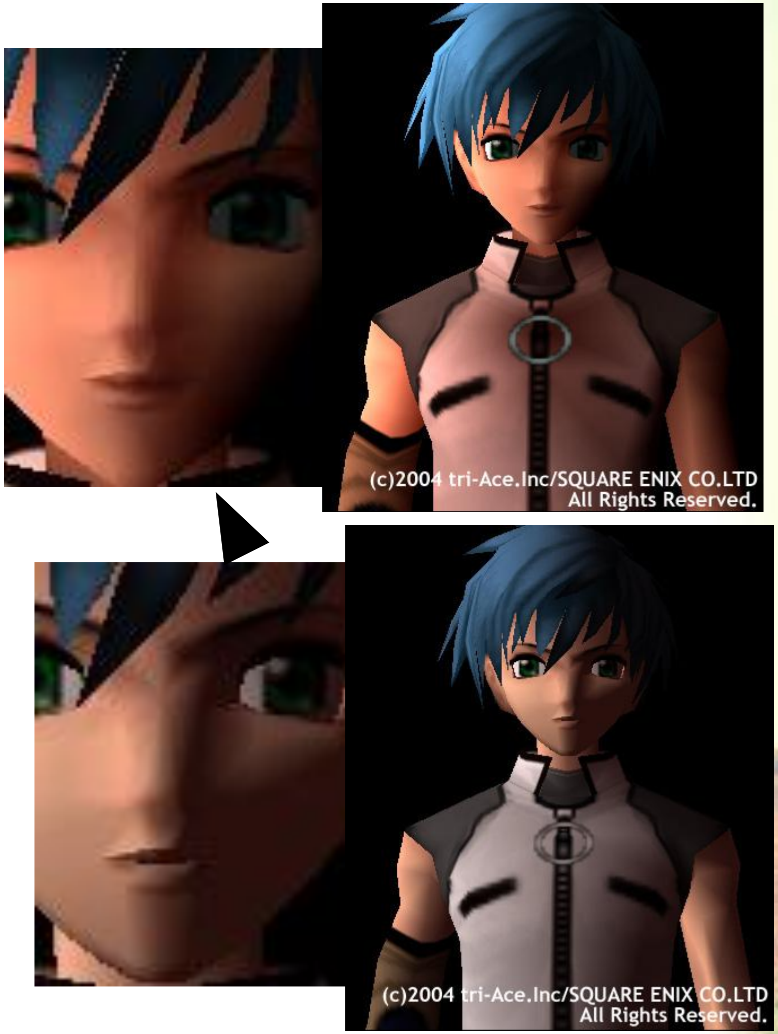


Harmonize SH traditionally

- We harmonize SH Lighting with traditional lights:
  - There is a function by which hemisphere light coefficients come from linear coefficients of Spherical Harmonics
  - For Phong (Specular) lighting, we process diffuse and ambient with SH Shader, and process specular with traditional lighting

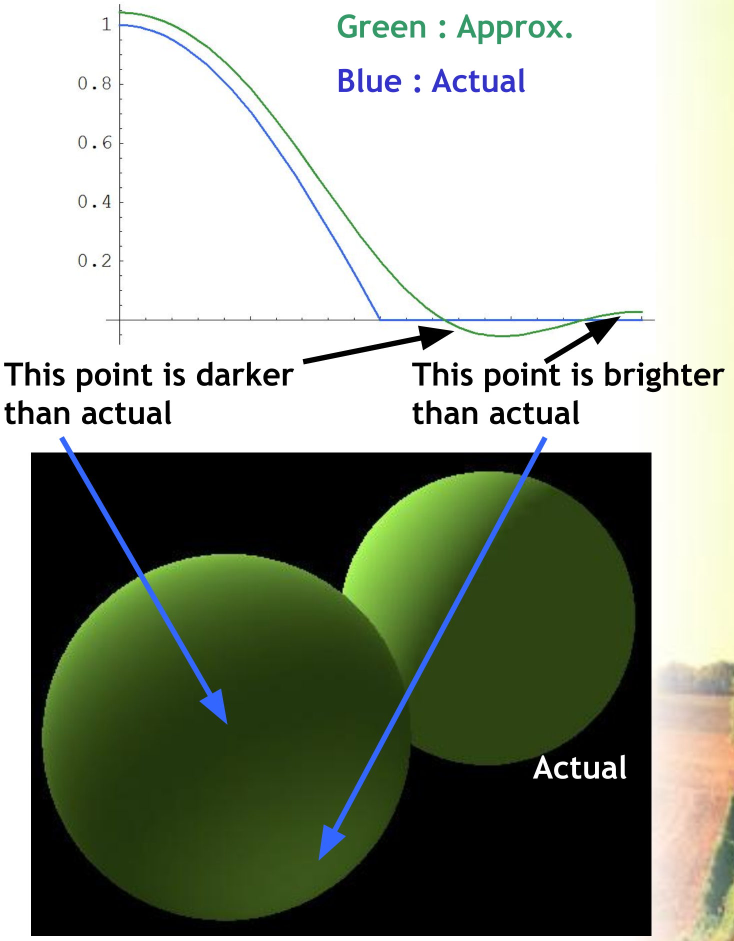
Side effects of SH Lighting

- Useful
  - SH Lighting (Shading) is smoother than traditional lighting
  - Especially, it is useful for low-poly-count models
  - It works as a low pass filter



Side effects of SH Lighting

- Disadvantage
  - SH is an approximation of BRDF
  - But using only a few coefficients causes incorrect approximation



Our precomputation engine

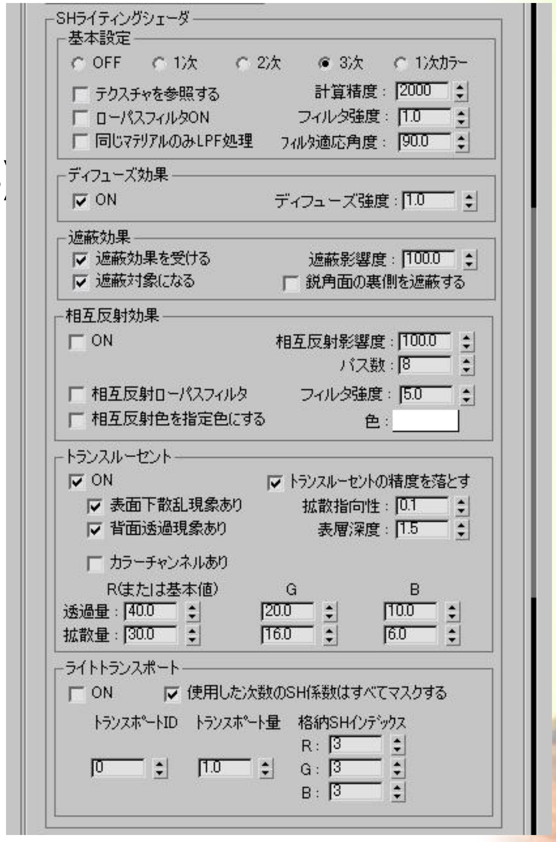
- supports :
  - Lambert diffuse shading
  - Soft-edged shadow
  - Sub-surface scattering
  - Diffuse interreflection
  - Light transport (detail later)

Materials

- Basic settings
  - SH coefficient setting
  - Computation precision (Number of rays)
  - Low Pass Filter settings
  - Texture setting

- Diffuse settings
  - Diffuse intensity

- Occlusion settings
  - Occlusion emitter
  - Occlusion receiver
  - Occlusion opacity



Materials

- Interreflection settings
  - Interreflection intensity
  - Number of passes
  - Interreflection low pass filter
  - Color settings

- Translucent settings
  - Enabling single scattering
  - Enabling multi scattering
  - Diffusion directivity
  - Surface thickness
  - Permeability
  - Diffusion amount

- Light Transport settings

Algorithms for PRT

- Based on (Stratified) Monte Carlo ray-tracing

PRT Engine [1st stage]

- Calculate diffuse and occlusion coefficients by Monte Carlo ray-tracing:
  - Cast rays for all hemispherical directions
  - Then integrate diffuse BRDF with the SH basis and calculate occlusion SH coefficients (occluded = 1.0, passed = 0.0)

PRT Engine [2nd stage]

- Calculate sub-surface scattering coefficients with diffuse coefficients by ray-tracing
  - We used modified Jensen's model (using 2 omni-directional lights) for simulating sub-surface scattering

PRT Engine [3rd stage]

- Calculate interreflection coefficients from diffuse and sub-surface scattering coefficients:
  - Same as computing diffuse BRDF coefficients
  - Cast rays for other surfaces and integrate their SH coefficients with diffuse BRDF

PRT Engine [4th stage]

- Repeat from the 2nd stage for number of passes
- After that, Final Gathering (gather all coefficients and apply a low pass filter)

Optimize precomputation

- To optimize finding of rays and polygon intersection, we used those typical approaches (nothing special)
  - Multi-threading
  - Using SSE2 instructions
  - Cache-caring data

Optimize precomputation

- Multi-threading for every calculation was very efficient
  - Example result (with dual Pentium Xeon 3.0GHz)

Number of threads	1	2	3	4	5
Speed ratio	1.0	1.8	2.0	2.2	2.1

Optimize precomputation

- SSE2 (inline assembler) for finding intersections was quite efficient
  - **Example result** (with dual Pentium Xeon 3.0GHz)

	No SSE2	SSE2 for tree traversal	SSE2 for ray-polygon intersection	Both
Speed ratio	1.0	5.0	2.4	12.0

Optimize precomputation

- File Caching System
  - SH coefficients and object geometry are cached in files for each object
  - Use cache files unless parameters are changed

What is the problem

- It is still slow to maximize quality with many rays
  - Decreasing the number of rays causes noisy images
  - How to improve quality without many rays?

600rays for each vertex

3,000rays for each vertex

Solving the problem

- We used 2-stage low pass filters to solve it
  - Diffuse interreflection low pass filter
  - Final low pass filter

Solving the problem

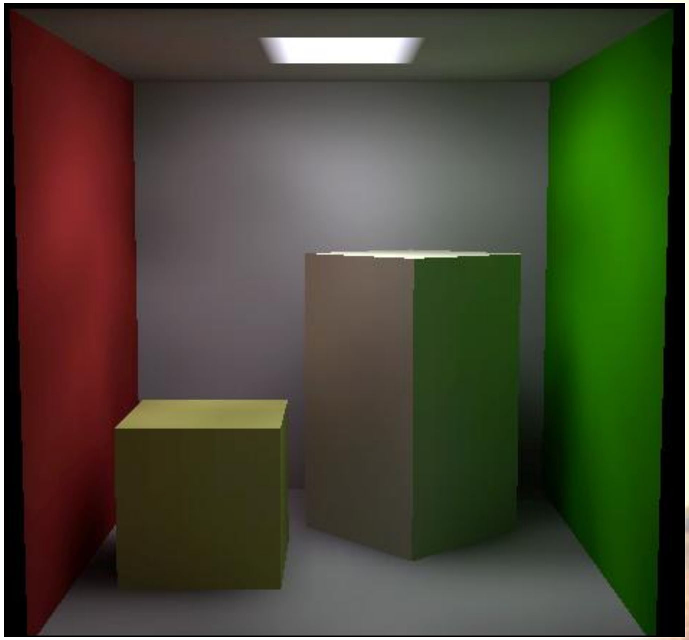
- We used Gaussian Filter for a low pass filter
  - Final LPF was efficient to reduce noise
  - But it caused inaccurate result
- Therefore we used a pre-filter for diffuse interreflection
  - Diffuse interreflection LPF works as irradiance caching
  - Diffuse interreflection usually causes noisy images
  - Reducing diffuse interreflection noise is efficient

Solving the problem

- Using too strong LPF causes inaccurate images
  - Be careful using LPF

3,000rays without LPF

(61seconds)



600rays with LPF

(22seconds)

Light Transport

- It is our little technique for expanding SH Lighting Shader
  - It is feasible to represent all frequency lighting (not specular) and area lights
  - BUT! Light position can't be animated
  - Only light color and intensity can be animated
  - Some lights don't move
    - For example, torch in a dungeon, lights in a house
    - Particularly, most light sources in the background don't need to move

Details of Light Transport

- It is not used on the Spherical Harmonic basis
  - Spherical Harmonics are orthogonal
  - It means that the coefficients are independent of each other
  - You can use some of (SH) coefficients for other coefficients on a different basis

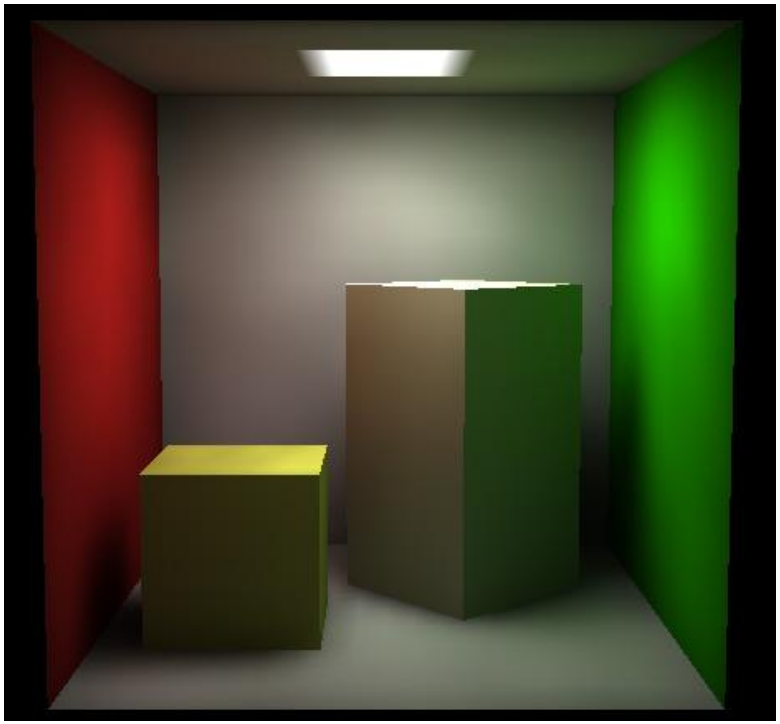
Details of Light Transport

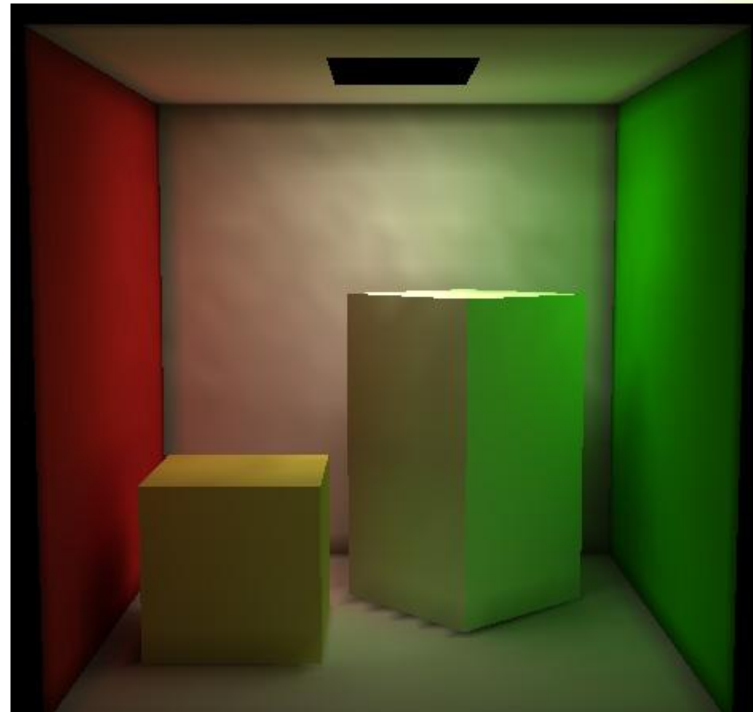
- To obtain Light Transport coefficients, the precomputation engine calculates all their incoming coefficients from other surfaces
  - It means that Light Transport coefficients have the same Light Transport energy that the surfaces collect from other surfaces
  - And surfaces which emit light give energy to other surfaces
- Without modification to existing SH Lighting Shader, it multiplies Light Transport coefficients by light color and intensity
  - They are just like vertex color multiplied by specific intensity and color

Details of Light Transport

- They are automatically computed by existing global illumination engine
  - When you set energy parameters into some coefficients, a precomputation engine for diffuse interreflection will transmit them to other surfaces

Result of Light Transport





Light Transport

- 11.29Hsync 6,600vertices
- 9,207,000vertices/sec

Spherical Harmonics
(4 coefficients for each channel)

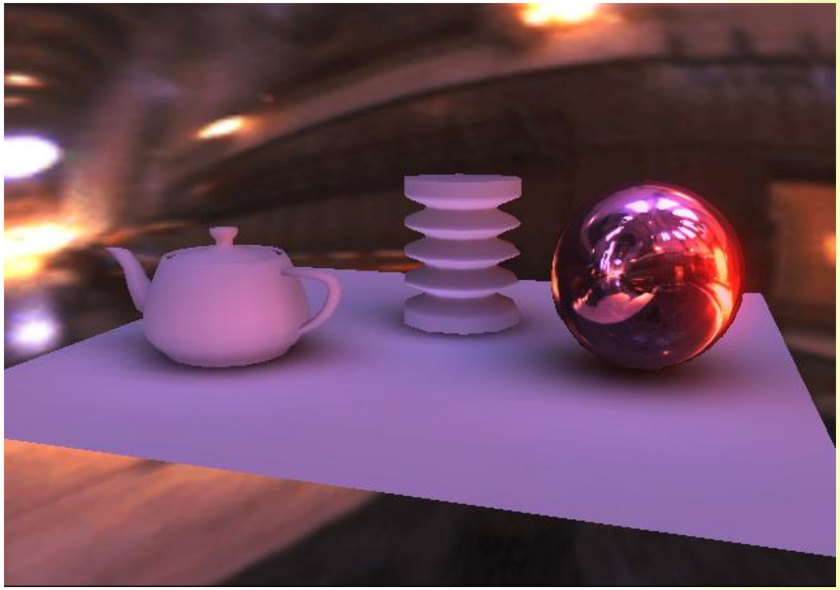
- 15.32Hsync 7,488vertices
- 7,698,000vertices/sec

Image Based Lighting

- Our SH Lighting engine supports Image Based Lighting
  - It is too expensive to compute light coefficients in every frame for PlayStation 2
  - Therefore light coefficients are precomputed off line
  - IBL lights can be animated with color, intensity, rotation, and linear interpolation between different IBL lights

Image Based Lighting

- IBL light coefficients are precomputed in world coordinates
  - It means they have to be transformed to local coordinates for each object
  - Therefore, IBL on our engine requires Spherical Harmonic rotation matrices



SH rotation

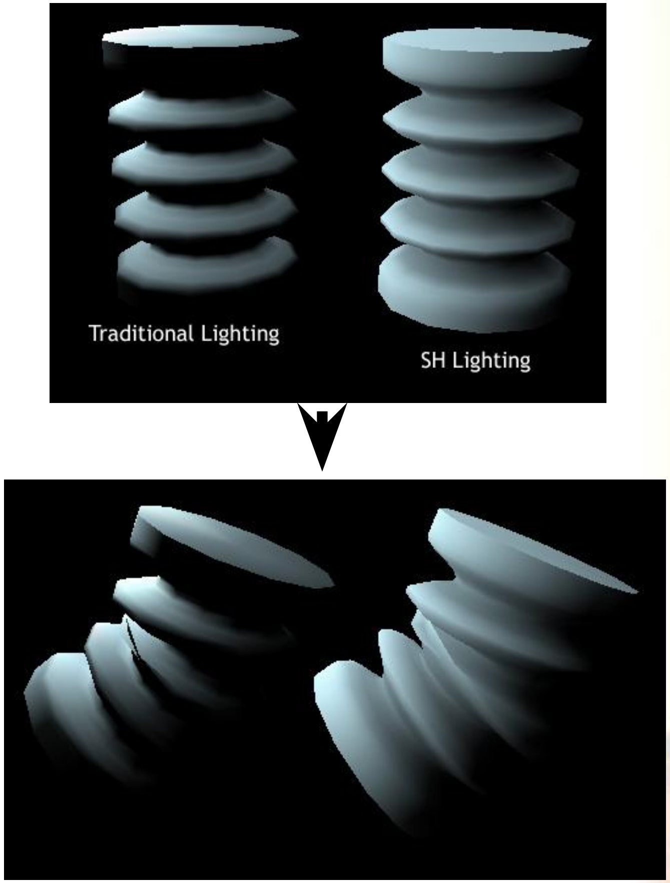
- To obtain Spherical Harmonic rotation matrices is one of the problems of handling Spherical Harmonics
  - We used "Evaluation of the rotation matrices in the basis of real spherical harmonics"
  - It was easy to implement

SH animation

- Our SH Lighting engine supports limited animation
  - Skinning
  - Morphing

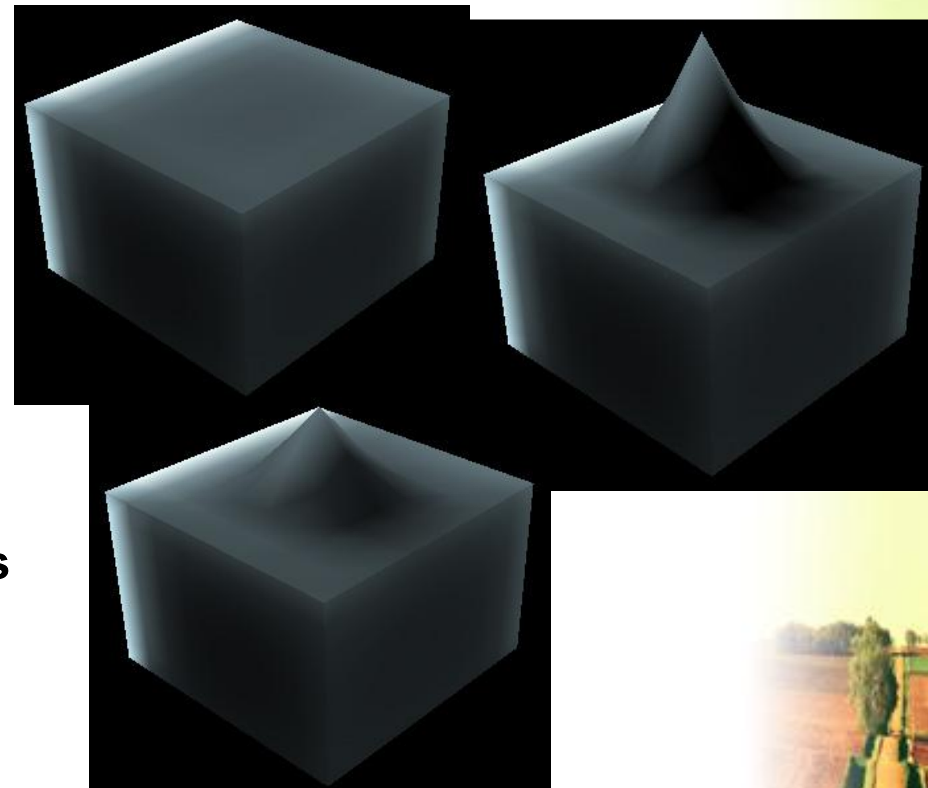
SH skinning

- Skinning is only for the 1st and 2nd order coefficients
  - They are just linear
  - Therefore, you can use regular rotation matrices for skinning
  - If you want to rotate above the 2nd order coefficients (they are non-linear), you have to use SH rotation matrices
  - But it is just rotation
  - Shadow, interreflection and sub-surface scattering are incorrect



SH morphing

- Morphing is linear interpolation between different Spherical Harmonic coefficients
  - It is just linear interpolation, so transitional values are incorrect
  - But it supports all types of SH coefficients (including Light Transport)



Future work

- Using high precision buffer and pixel shader!!
- More precise Glare Effects in optics
- Natural Blur function not Gaussian
- Diaphragm-shaped Blur
- Seamless and Hopping-free DOF along depth direction
- OLS using HDR values
- Higher quality slight blur effect

Future Work

- Distributed precomputation engine
- SH Lighting for next-gen hardware
  - Try: Thomas Annen et al. EGSR 2004 "Spherical Harmonic Gradients for Mid-Range Illumination"
  - More generality for using SH lighting
  - IBL map
- Try other methods for real-time global illumination

References

- Masaki Kawase. "Frame Buffer Postprocessing Effects in DOUBLE-S.T.E.A.L (Wreckless)“ GDC 2003.
- Masaki Kawase. "Practical Implementation of High Dynamic Range Rendering“ GDC 2004.
- Naty Hoffman et al. "Rendering Outdoor Light Scattering in Real Time“ GDC 2002.
- Akio Ooba. “GS Programming Men-keisan: Cho SIMD Keisanho” CEDEC 2002.
- Arcot J. Preetham. "Modeling Skylight and Aerial Perspective" in "Light and Color in the Outdoors" SIGGRAPH 2003 Course.

References

- Peter-Pike Sloan et al. "Precomputed Radiance Transfer for Real-Time Rendering in Dynamic, Low-Frequency Lighting Environments." SIGGRAPH 2002.
- Robin Green. "Spherical Harmonic Lighting: The Gritty Details. " GDC 2003.
- Miguel A. Blanco et al. "Evaluation of the rotation matrices in the basis of real spherical harmonics." ECCC-3 1997.
- Henrik Wann Jensen "Realistic Image Synthesis Using Photon Mapping." A K PETERS LTD, 2001.
- Paul Debevec "Light Probe Image Gallery" http://www.debevec.org/

Acknowledgements

- We would like to thank
  - Satoshi Ishii, Daisuke Sugiura for suggestion to this session
  - All other staff in our company for screen shots in this presentation
  - Mike Hood for checking this presentation
  - Shinya Nishina for helping translation
  - The Stanford 3D Scanning Repository http://graphics.stanford.edu/data/3Dscanrep/

Thank you for your attention.

- This slide presentation is available on http://research.tri-ace.com/