GPU Shading and Rendering: Introduction & Graphics Hardware

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Schedule

Shading Technolgy

8:30	Intro/Hardware (Olano)
9:25	Compilers (Bleiweiss)

Shading Languages

10:30	GLSL (Olano)
10:55	Cg (Kilgard)
11:20	HLSL (Sander)
11:45	Sh (McCool)

GPU Rendering

1:45	Rendering Algorithms (Hart)
2:35	GPU Production Rendering (Gritz)

Hardware Systems

3:45	ATI (Sander)
4:25	NVIDIA (Kilgard)
5:05	Panel Q&A (all)

Part I

Introdution

What is a GPU?

- Graphics Processing Unit
  - Graphics accelerator
  - Parallel processing unit
- We're doing graphics, what is it good for?
  - Better real-time graphics
  - Faster non-real-time graphics

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- What color are the pixels
- Programmable
    - Flexible Appearance
    - Arbitrary computation
- Procedural

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Some examples

- More realistic appearance
  - Bump mapping, Anisotropic, Precomputed radiance transfer, ...
- Non-realistic appearance
  - Cartoon, Sketch, Illustration, ...
- Animated appearance
  - Skinning, Water, Clouds, ...
- Visualization
  - Data on surfaces, Volume rendering, ...

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- The rest of the problem!
- In our case, using GPU for other than polygon rendering
  - Curved surfaces
  - Ray tracing
  - Point based rendering
  - ...

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Non-Real Time vs. Real-Time

Real-Time

Tens of frames per second

Thousand instruction shaders

Limited computation, texture, memory, ...

Non-Real-Time

Seconds to hours per frame

Thousands line shaders

"Unlimited" computation, texture, memory, ...

Non-Real Time vs. Real-Time

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How is this possible?

- GPUs are programmable!
  - Per-vertex programs
  - Per-fragment programs

Research Languages

- Pixel-Planes 5 [Rhoades et al., 1992]
- PixelFlow/pfman [Olano and Lastra, 1998]
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Part II

Graphics Hardware

Outline

Machine Complexity

- Graphics machines are complex
- User does not want to know
  - How machine does what it does
  - Tons of machine-specific differences
- Answer:
  - Simple model of machine

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Simplified Machine

- User's mental model
- Hide details
- Device independent
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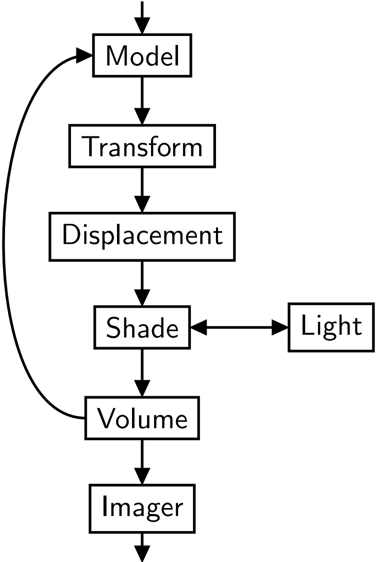

- "Abstract" interface
    - Blocks = procedures
    - Block interfaces well defined
- Connections
    - Inputs & outputs don't have to match
    - System handles conversion

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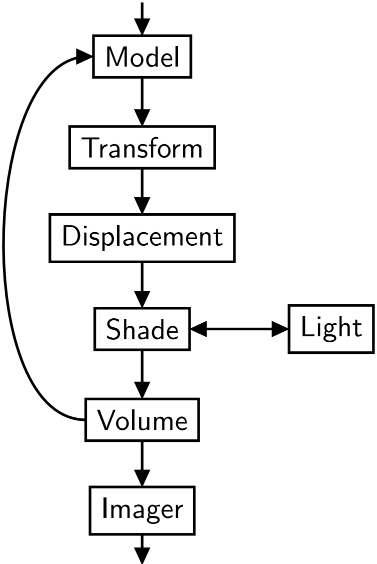

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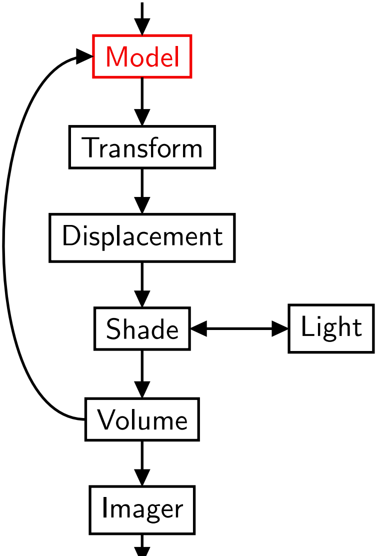

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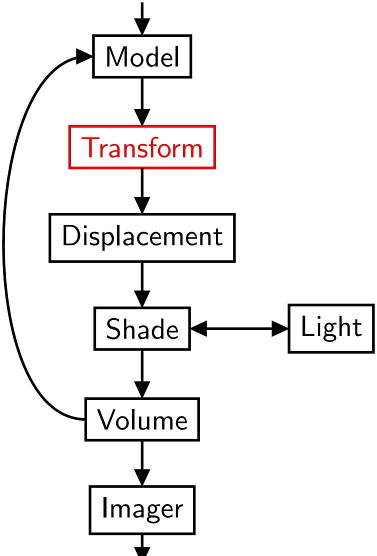

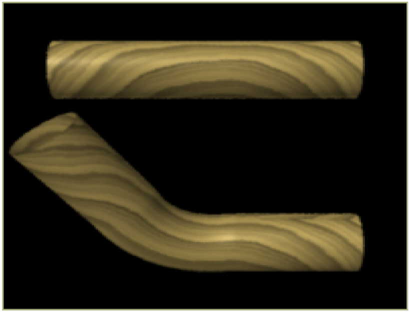

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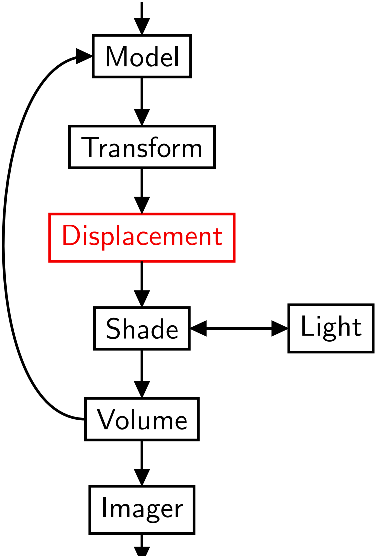

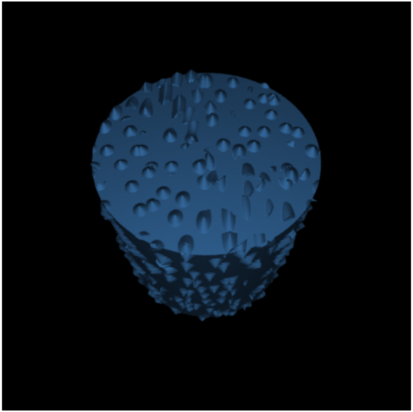

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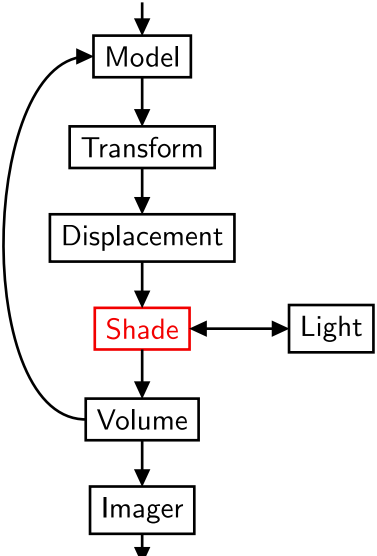

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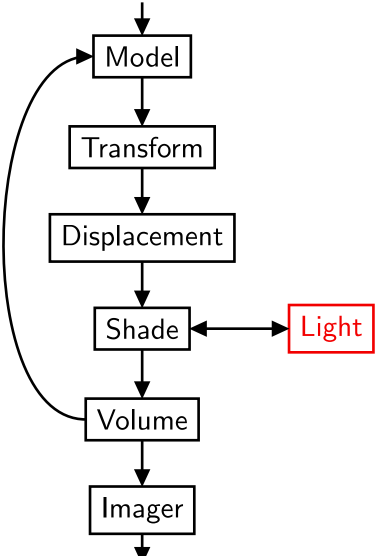

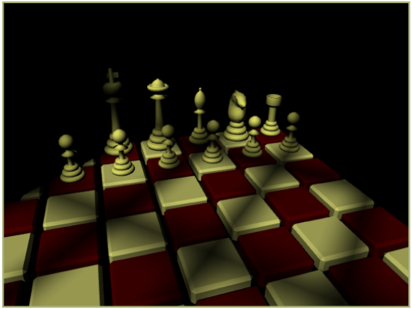

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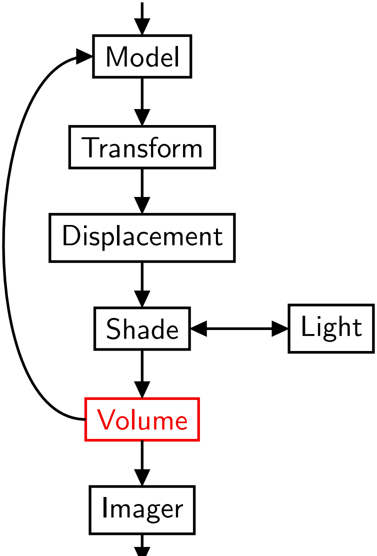

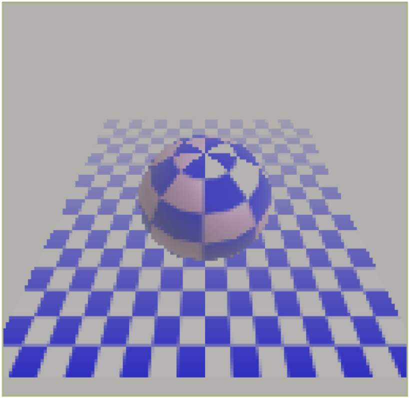

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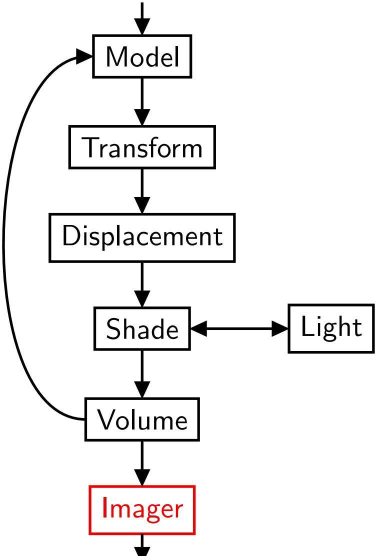

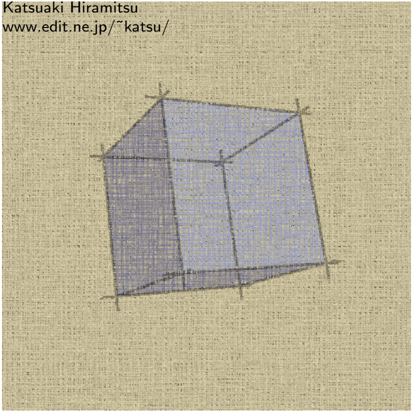

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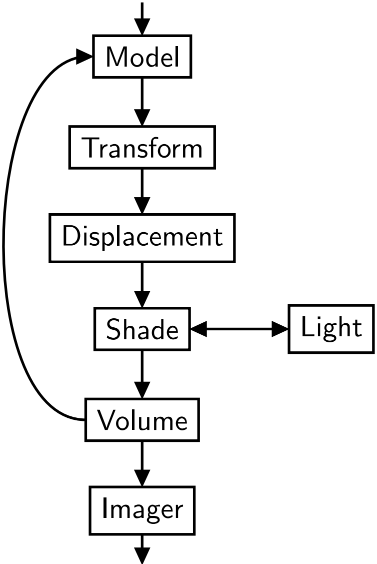

- What it says:
  - Input and output of each block
  - What each block should do
- What it doesn't say:
  - Order or grouping of processing

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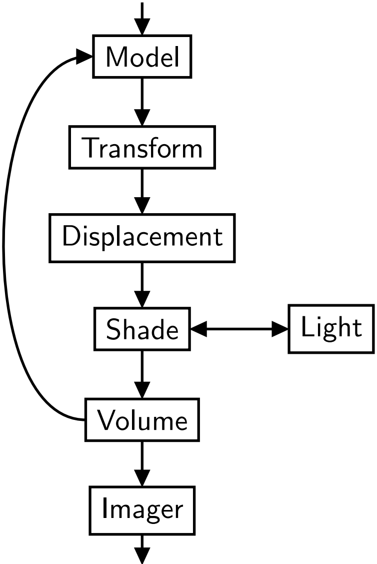

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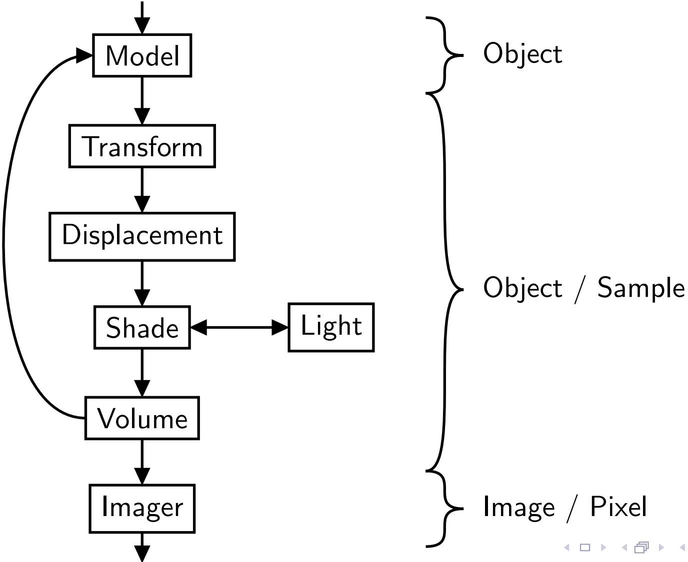
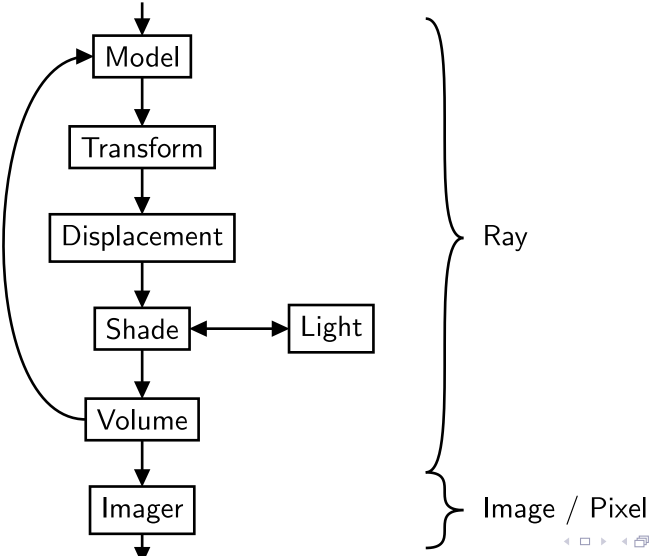
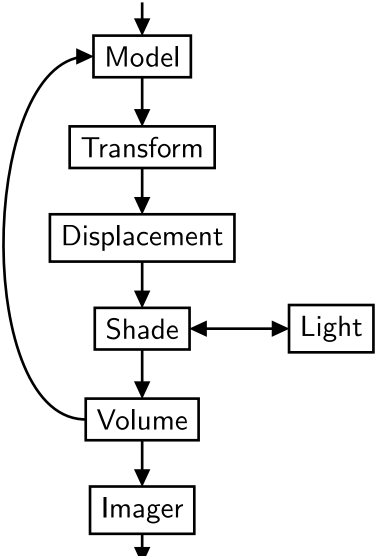
RenderMan
REYES



RenderMan
Ray Tracing



RenderMan
SGI Multi-pass RenderMan

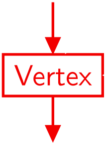


Object

Object / Pass / Pixel

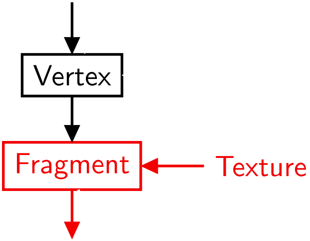
Image / Pixel

Hardware Model



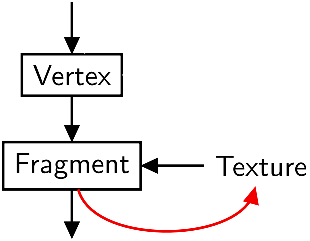
- Vertex shading
  - Transform
    - Procedural transformation
    - Skinning
  - Shade
    - Per-vertex shading
    - Computed texture coordinates

Hardware Model



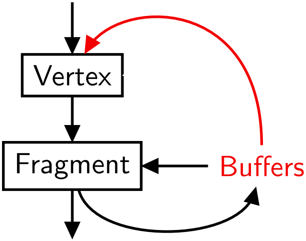
- Fragment shading
  - Per-fragment shading
  - Computed and dependent texture

Hardware Model



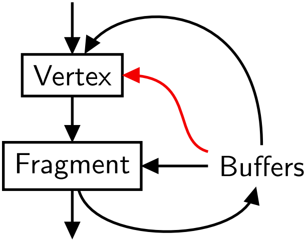
- Render to texture
  - Rendered shadow & environment maps
  - Multi-pass fragment shading [Proudfoot et al., 2001]

Hardware Model



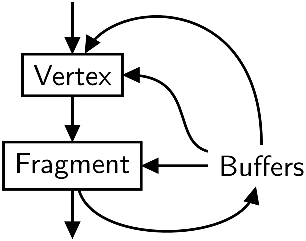
- Render to vertex array / buffer objects
  - Geometry images [Gu et al., 2002]
  - Multi-pass vertex shading
  - Merge vertex & fragment capabilities

Hardware Model



- Vertex texture
  - Texture-based vertex displacement
  - Tabulated functions

Hardware Model



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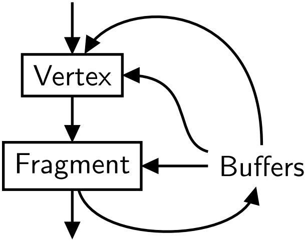

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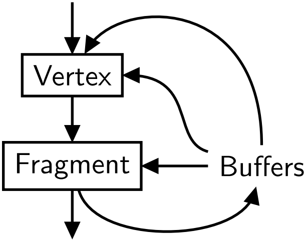

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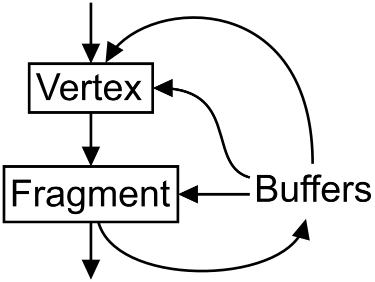

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- Parallelism,
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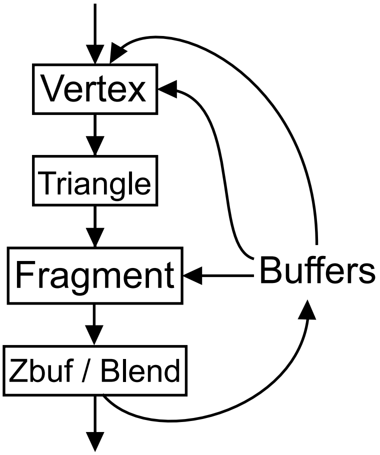

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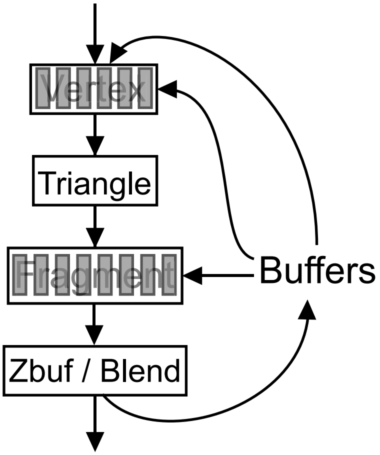

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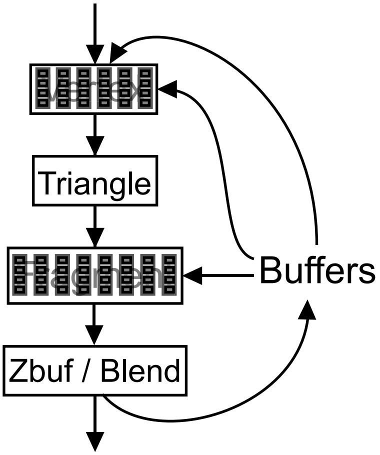

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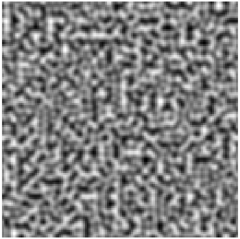
Part III

Noise

Outline

Why Noise?

- Introduced by [Perlin, 1985]
  - Heavily used in production animation
  - Technical Achievement Oscar in 1997
- "Salt," adds spice to shaders



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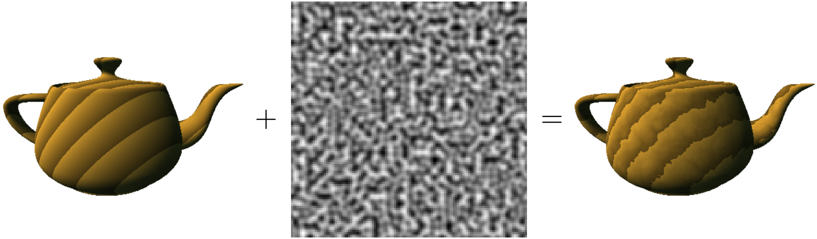
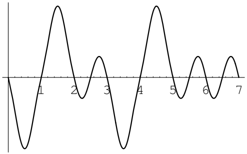


Noise Characteristics

- Random
  - No correlation between distant values
- Repeatable/deterministic
  - Same argument always produces same value
- Band-limited
  - Most energy in one octave (e.g. between f & 2f)



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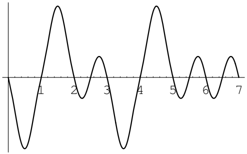

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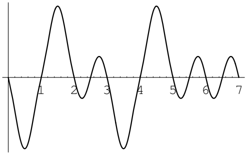
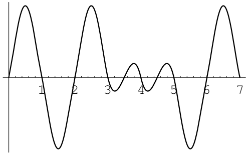
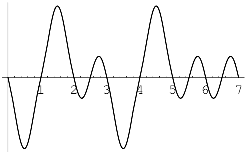


Gradient Noise

- Original Perlin noise [Perlin, 1985]
- Perlin Improved noise [Perlin, 2002]
- *Lattice* based
  - Value=0 at integer lattice points
  - Gradient defined at integer lattice
  - Interpolate between
- 1/2 to 1 cycle each unit



Original



Improved

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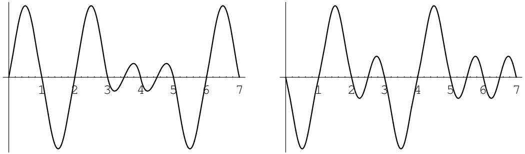
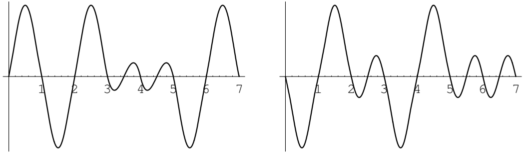


Original Improved

Gradient Noise

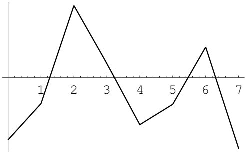
- Original Perlin noise [Perlin, 1985]
- Perlin Improved noise [Perlin, 2002]
- *Lattice* based
    - Value=0 at integer lattice points
    - Gradient defined at integer lattice
    - Interpolate between
- 1/2 to 1 cycle each unit



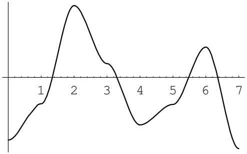
Original Improved

Value Noise

- Lattice based
  - Value defined at integer lattice points
  - Interpolate between
- At most 1/2 cycle each unit
  - Significant low-frequency content
- Easy hardware implementation with lower quality



Linear Interp



Cubic Interp

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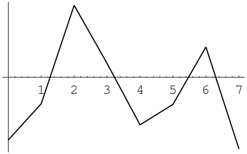

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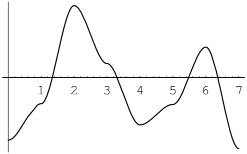

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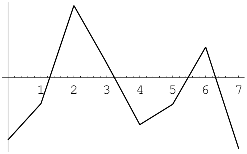

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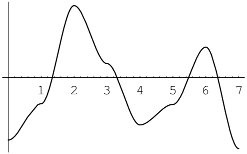

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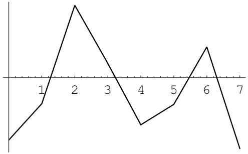

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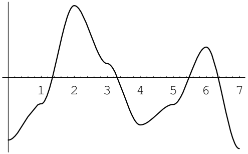


Cubic Interp

Hardware Noise

- Value noise
  - PixelFlow [Lastra et al., 1995]
  - *Perlin Noise* Pixel Shaders [Hart, 2001]
  - Noise textures
- Gradient noise
  - Hardware [Perlin, 2001]
  - Complex composition [Perlin, 2004]
  - Shader implementation [Green, 2005]

Outline

What is this Noise?

Perlin noise

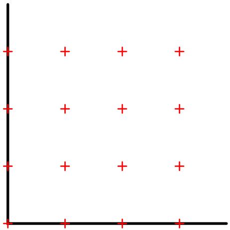
Modifications

Noise Details

- Subclass of *gradient noise*
  - Original Perlin
  - Perlin Improved
  - All of our proposed modifications

Find the Lattice

- Lattice-based noise: must find nearest lattice points
- Point $\vec{p} = (\vec{p}^x, \vec{p}^y, \vec{p}^z)$
- has integer lattice location
  $\vec{p}_i = (\lfloor \vec{p}^x \rfloor, \lfloor \vec{p}^y \rfloor, \lfloor \vec{p}^z \rfloor) = (X, Y, Z)$
- and fractional location in cell
  $\vec{p}_f = \vec{p} - \vec{p}_i = (x, y, z)$



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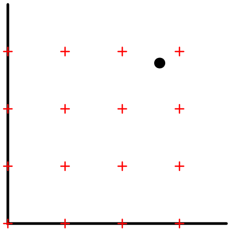

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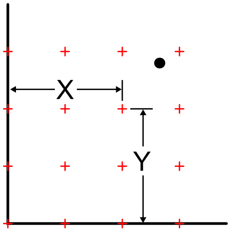

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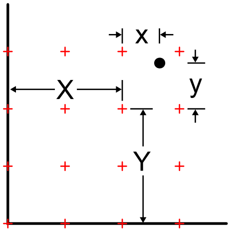

Gradient

- Random vector at each lattice point is a function of $\vec{p}_i$

$$g(\vec{p}_i)$$

- A function with that gradient

$$\begin{aligned} grad(\vec{p}) &= g(\vec{p}_i) \bullet \vec{p}_f \\ &= g^x(\vec{p}_i) * x + g^y(\vec{p}_i) * y + g^z(\vec{p}_i) * z \end{aligned}$$

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- Interpolate nearest 2^n gradient functions
- 2D $noise(\vec{p})$ is influenced by $\vec{p}_i + (0,0)$; $\vec{p}_i + (0,1)$; $\vec{p}_i + (1,0)$; $\vec{p}_i + (1,1)$
- Linear interpolation
  - $lerp(t, a, b) = (1 - t)\ a + t\ b$
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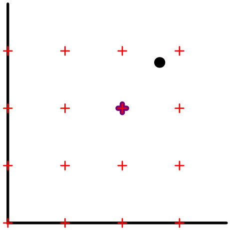

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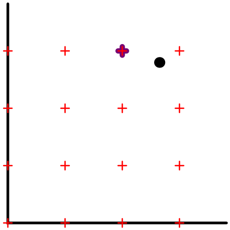

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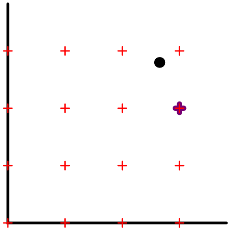

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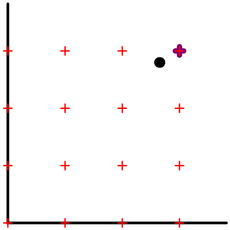

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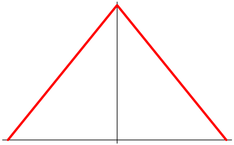

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  - $fade(t) = \begin{cases} 3t^2 - 2t^3 & \text{for original noise} \\ 10t^3 - 15t^4 + 6t^5 & \text{for improved noise} \end{cases}$
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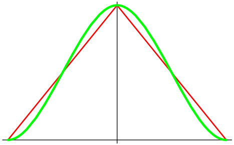

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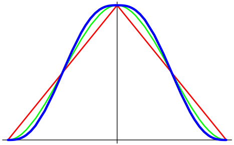

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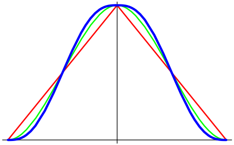

Hash

- n-D gradient function built from 1D components

$$g(\vec{p}_i)$$

- Both original and improved use a permutation table *hash*
- Original: g is a table of unit vectors
- Improved: g is derived from bits of final hash

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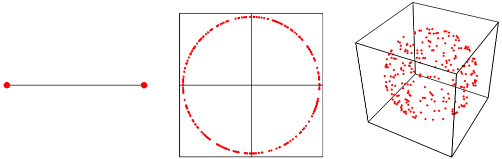
Outline

Gradient Vectors of n-D Noise

- Original: on the surface of a n-sphere
  - Found by hash of $\vec{p}_i$ into gradient table
- Improved: at the edges of an n-cube
  - Found by decoding bits of hash of $\vec{p}_i$



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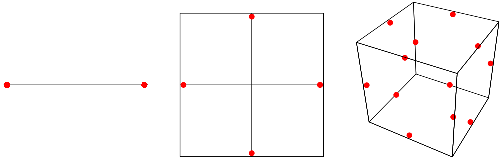

Gradients of noise(x,y,0) or noise(x,0)

- Why?
  - Cheaper low-D noise matches slice of higher-D
  - Reuse textures (for full noise or partial computation)
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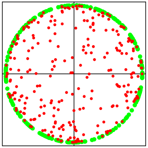

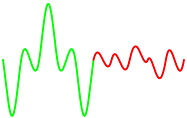

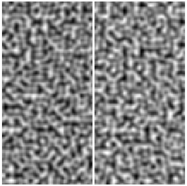

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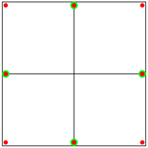

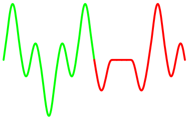

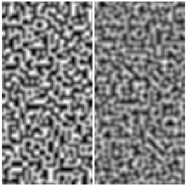

Solution?

- Observe: use gradient function, not vector alone

$$grad = g^x \; x + g^y \; y + g^z \; z$$

- In any integer plane, fractional $z = 0$

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- Any choice keeping projection of vectors the same will work
  - Improved noise uses cube edge centers

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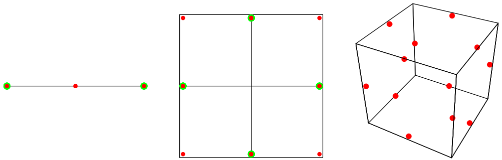

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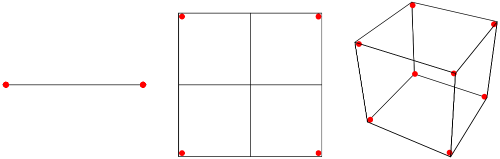

Corner Gradients

- Simple binary selection from hash bits
  $\pm x, \pm y, \pm z$
- Perlin mentions "clumping" for corner gradient selection
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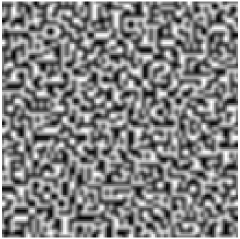
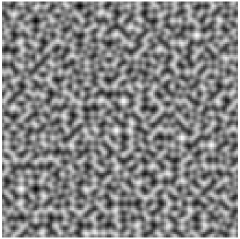


Edge Centers



Corner

Separable Computation

- Like to store computation in texture
  - Texture sampling 3-4x highest frequency
  - 1D & 2D OK size, 3D gets **big**, 4D impossible
- Factor into lower-D textures

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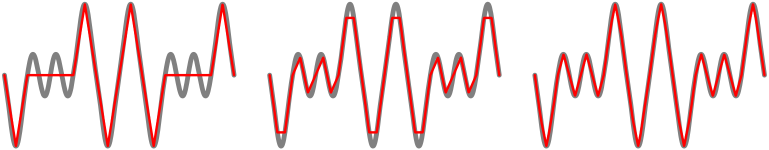

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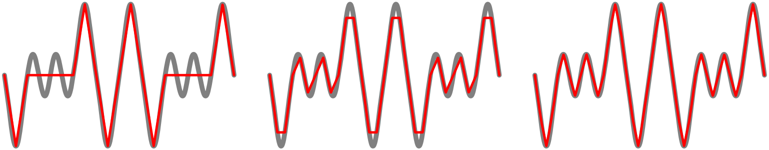

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noise(\vec{p}^x, \vec{p}^y, \vec{p}^z) = flerp(z, & + * z \\
& + * (z - 1))
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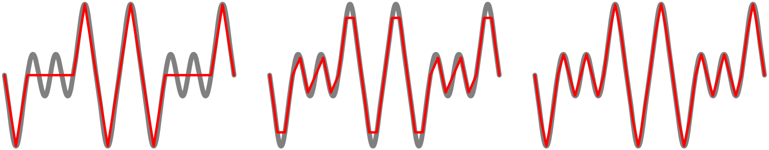

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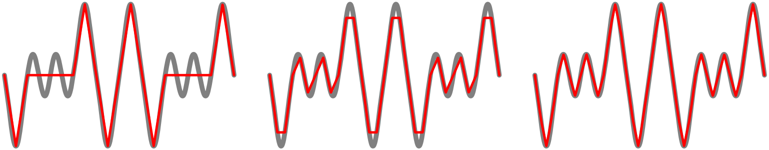

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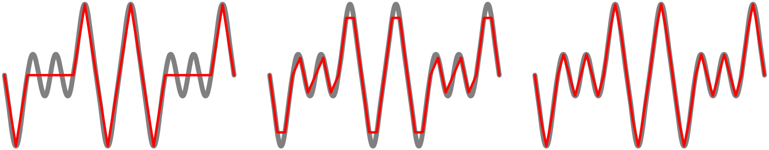

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Factorization Details

$$noise(\vec{p}) = flerp(z, zconst(\vec{p}^x, \vec{p}^y, Z_0) + zgrad(\vec{p}^x, \vec{p}^y, Z_0) * z,$$
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- With nested hash,

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Perlin's Hash

- 256-element *permutation array*
  - Turns each integer 0-255 into a different integer 0-255
- Chained lookups

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Random Number Generator Hash

- Hash argument is seed
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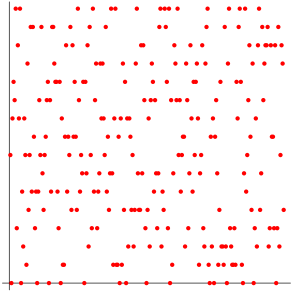
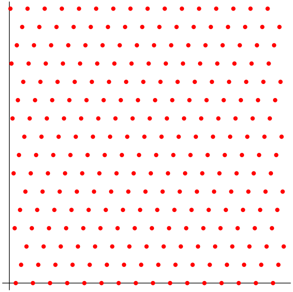
  - Should noise(30) be 30 times slower than noise(1)?



permute table



hash using seed=X

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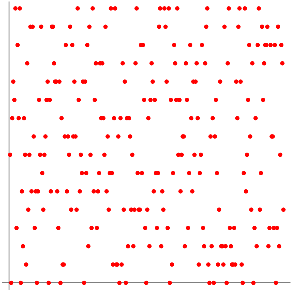

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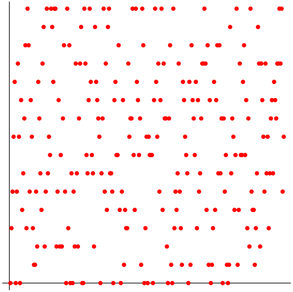

hash using X^{th} random number

Blum-Blum Shub

$$x_{n+1} = x_i^2 \text{ mod } M$$
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- Uncorrelated for nearby seeds...
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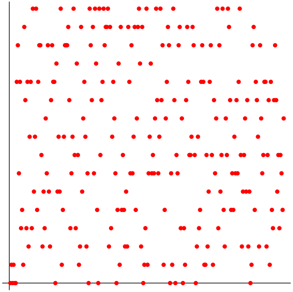

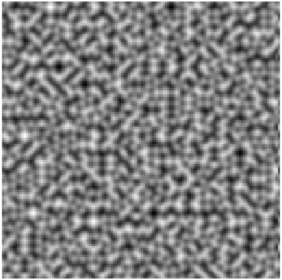

523*527

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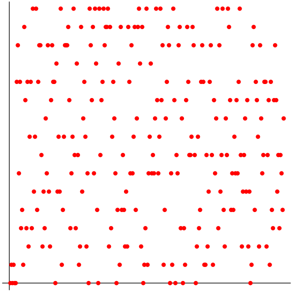

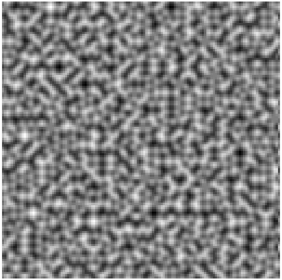

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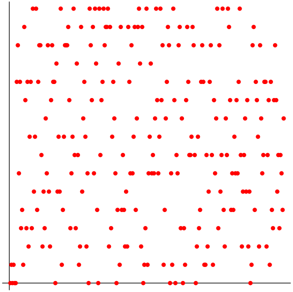

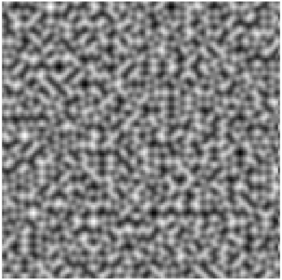

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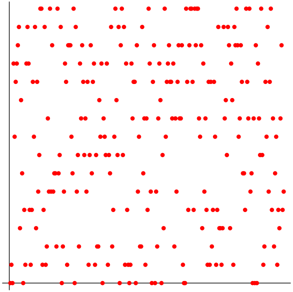
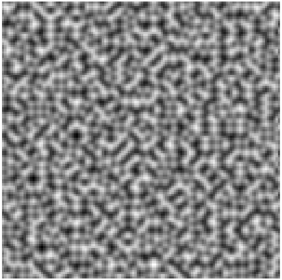

29*31

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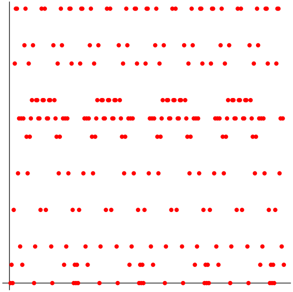
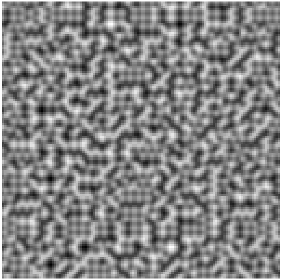
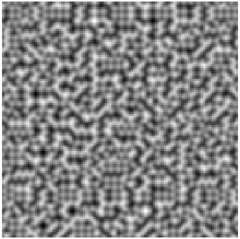


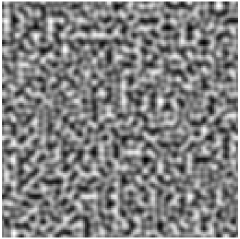


Modified Noise

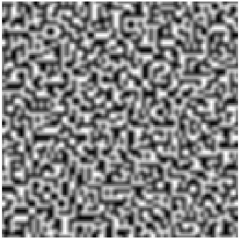
- Square and mod hash
  - $M = 61$
- Corner gradient selection
  - One 2D texture for both 1D and 2D
- Factor
  - Construct 3D and 4D from 2 or 4 2D texture lookups



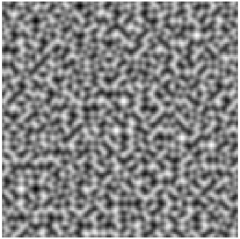
Comparison



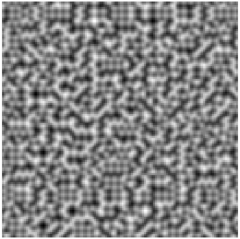
Perlin original



Perlin improved



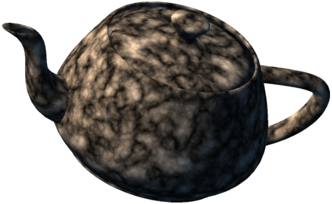
Corner gradients



Corner+Hash

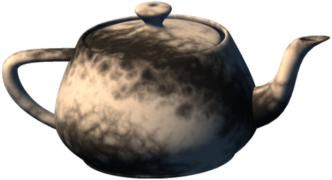
Using Noise

3D noise



3D turbulence

Wood



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