Lecture 13: Post-processing and Imaging pipeline

DHBW, Computer Graphics

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29.3.2023.

Syllabus

- 3D scene
  - Object
  - Light
  - Camera
- Rendering
- Image and display

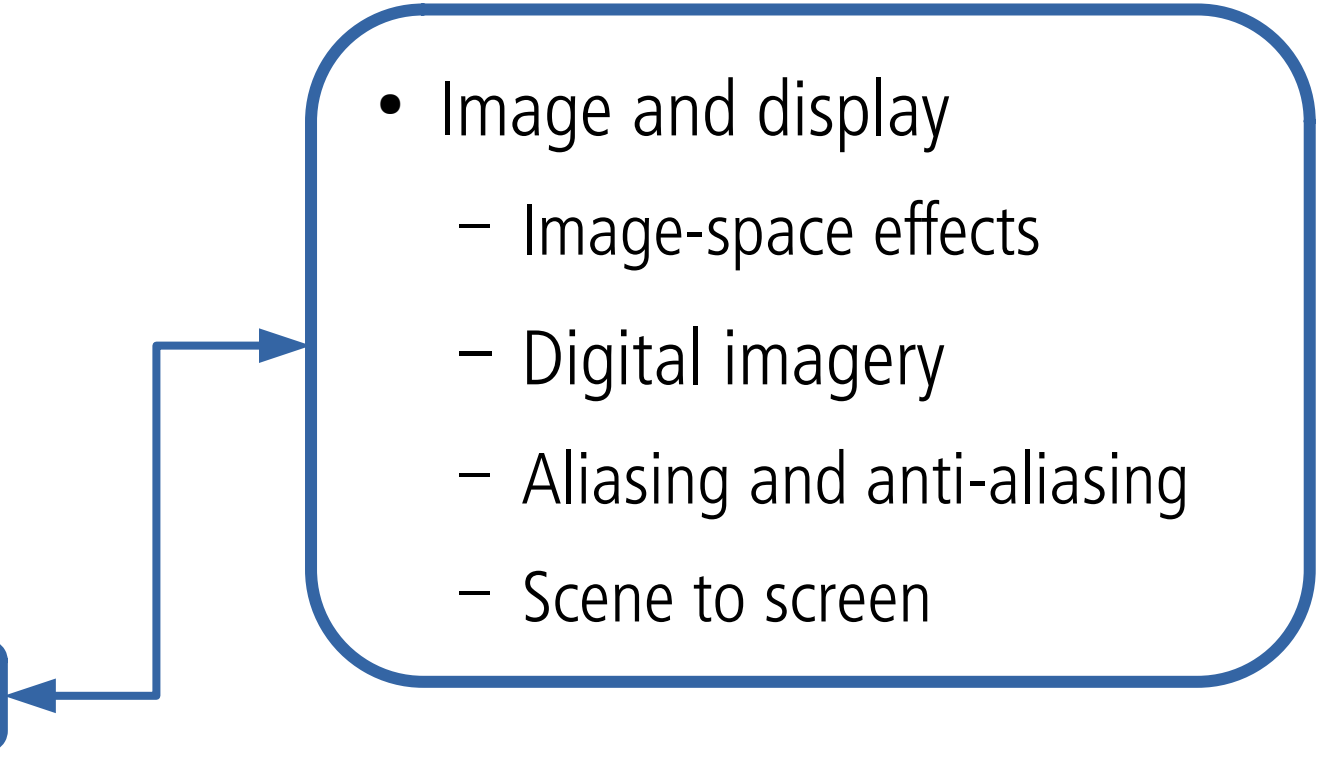
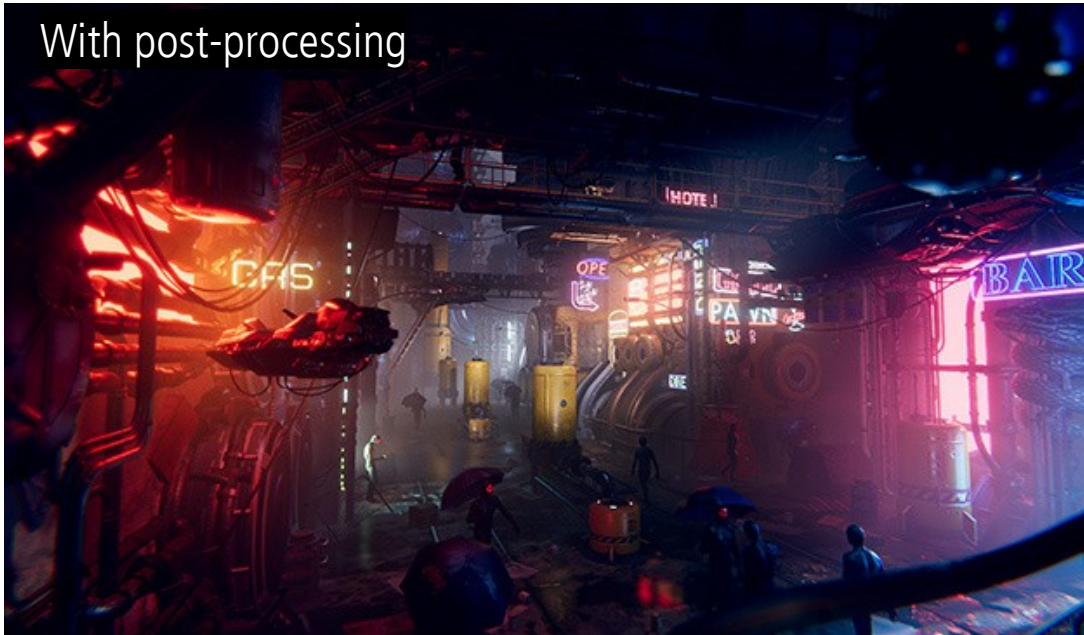


Image-space effects

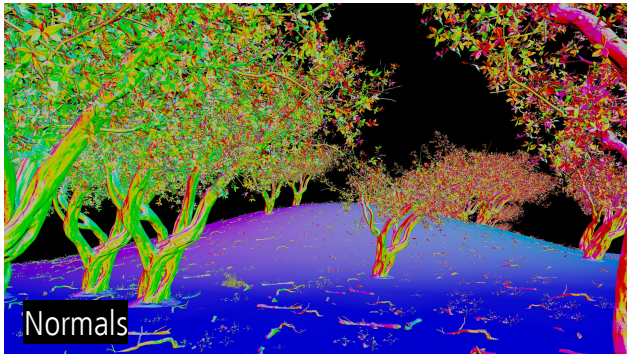
Image-space effects

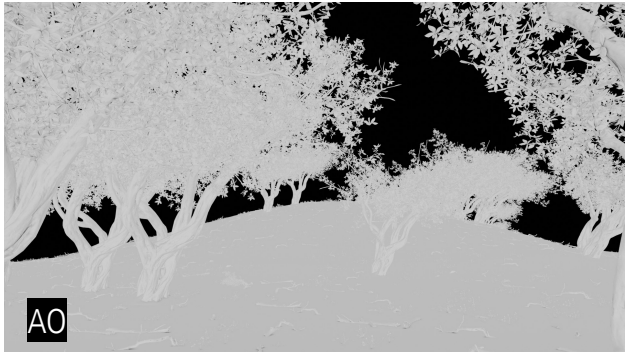
- Rendered image can be directly sent to display or additionally modified before display → **post-processing**
- Post-processing is set of operations performed on a rendered image → **image-space effects**
  - This way, additional effects for achieving realism or artistic styles is possible



Post-processing data

- Post-processing of **one frame** can use **multiple buffers (images) obtained during rendering containing 3D scene information**:
  - Color, diffuse, normal, AO, depth, environment, etc.





Performing post-processing

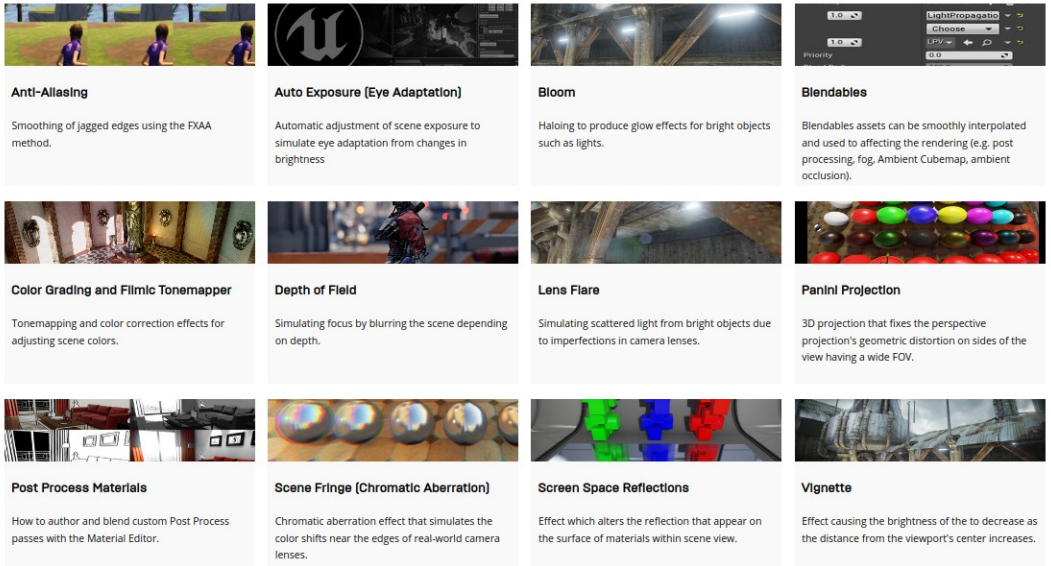
- Depending on rendering environment, post-processing of frame can be performed:
  - **Real-time, multi-pass, render-time**
    - **3D scene is rendered to an offscreen buffer**, such as color (image) buffer
    - Resulting image is treated as image texture which is **applied on screen filling quad**
    - **Post-processing** is done on this texture **using programmable GPU shaders** (e.g., fragment or compute shaders)
  - **Offline, compositing software**
    - 3D scene is rendered to image file
    - Post-processing is done on images which are stored as separate frames


Render-time post-processing (e.g., Unity)

Offline post-processing (e.g., Blender compositor)

Post-processing in practice

- **Real-time, multi-pass:**
  - Unity: https://docs.unity3d.com/Manual/PostProcessingOverview.html
  - Godot: https://docs.godotengine.org/en/stable/tutorials/shaders/custom_postprocessing.html
  - Unreal: https://docs.unrealengine.com/4.27/en-US/RenderingAndGraphics/PostProcessEffects/
  - OpenGL: https://learnopengl.com/In-Practice/2D-Game/Postprocessing
- **Offline**:
  - Blender: https://docs.blender.org/manual/en/latest/compositing/introduction.html
  - Nuke: https://www.foundry.com/products/nuke-family/nuke
  - After Effects: https://www.adobe.com/products/aftereffects.html
  - Discussion: https://www.youtube.com/watch?v=7g4xCV0iv4w&ab_channel=InspirationTuts

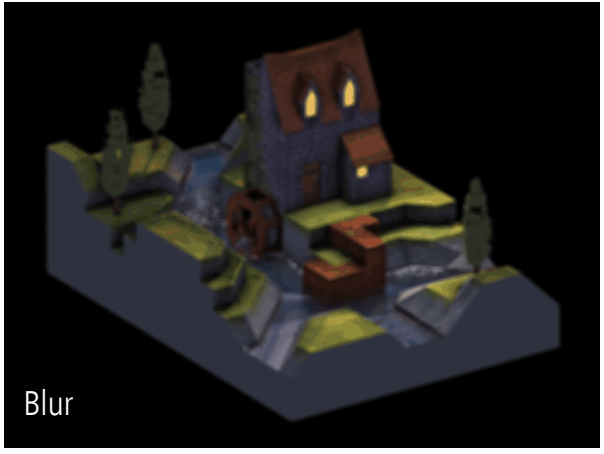


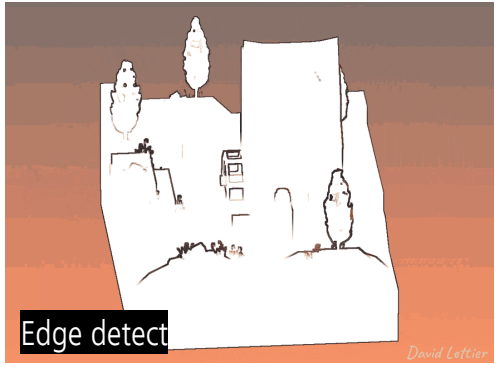
Unreal post-process

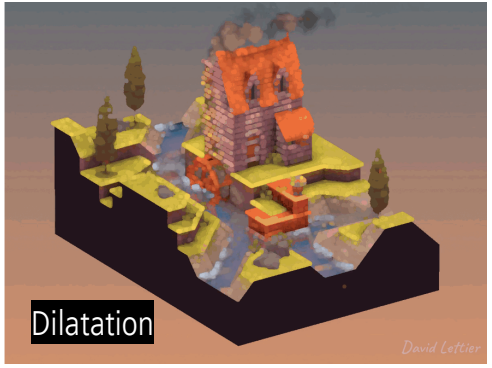
Nuke post-process

Post-processing using image processing

- Rendered image can be post-processed as any other image using image processing techniques (filtering kernels) in shader or CPU.



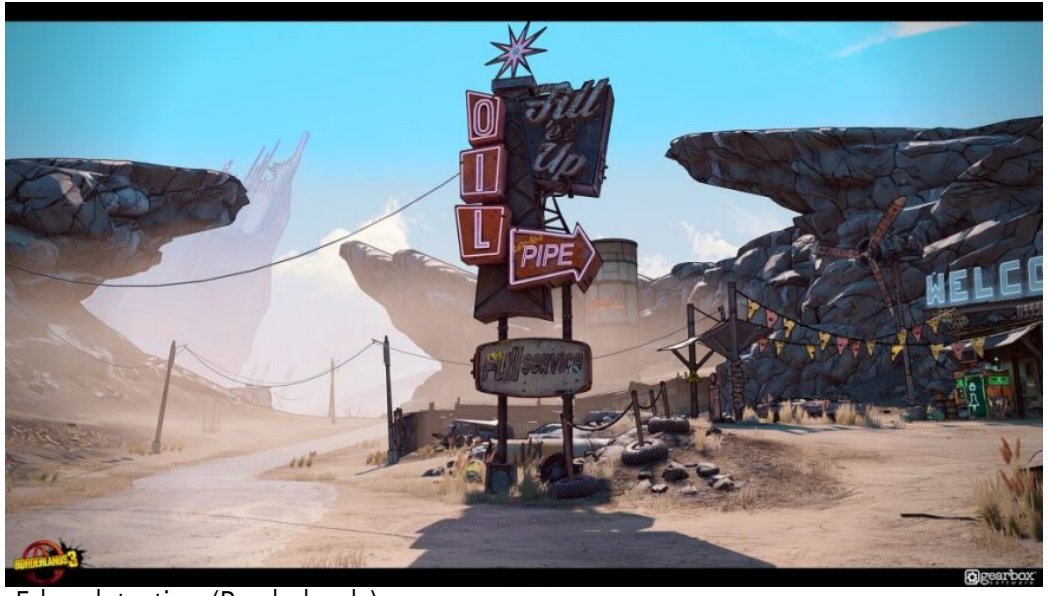




https://lettier.github.io/3d-game-shaders-for-beginners/posterization.html

Post-processing and NPR

- Often image processing techniques are used to achieve **non-photo realistic rendering effects**

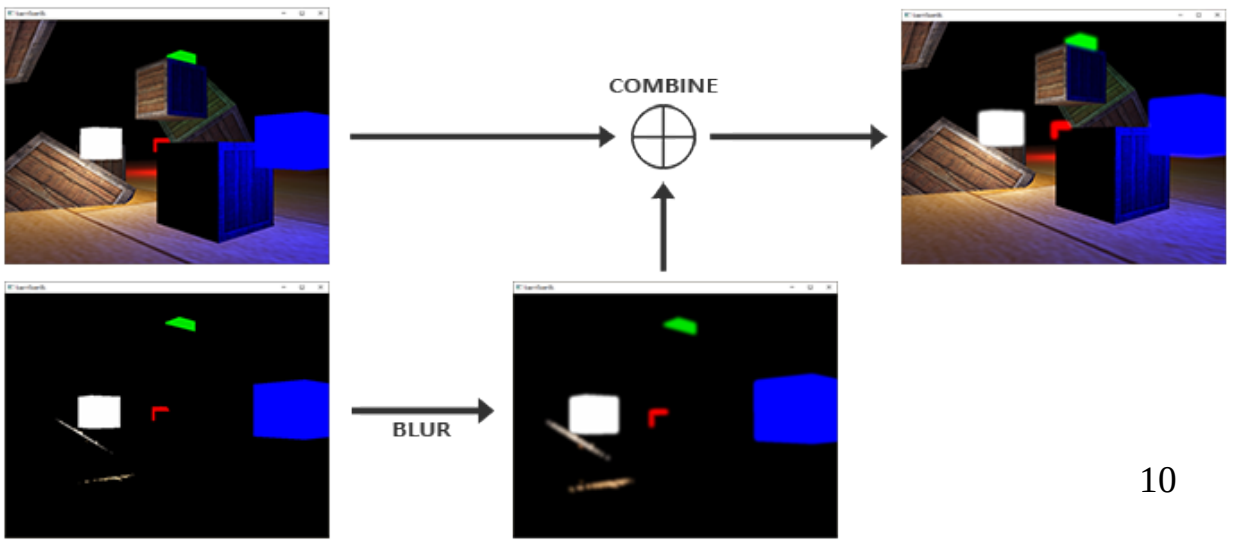


Edge detection (Borderlands)


Edge detection and quantization (Okami)

Post-processing: bloom

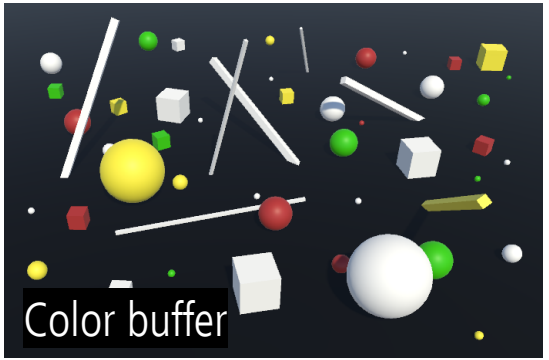
- **Bloom** occurs in camera when charged site in CCD gets saturated and overflows into neighboring sites
- Effect where **extremely bright area spills over adjoining pixels** → making image look overexposed where it is bright
- Concept:
  - Render whole scene in color buffer
  - Render only bright objects into separate buffer
  - Blur buffer with bright objects only (e.g., Gaussian Blur)
  - Combine buffers

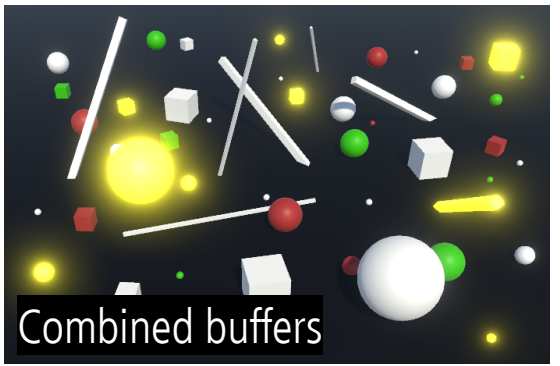


https://learnopengl.com/Advanced-Lighting/Bloom

Bloom: examples

- Bloom is one type of **glare effects**. Other glare effects are lens flare: halo and ciliary corona





https://catlikecoding.com/unity/tutorials/advanced-rendering/bloom/

Post-processing: lens flare

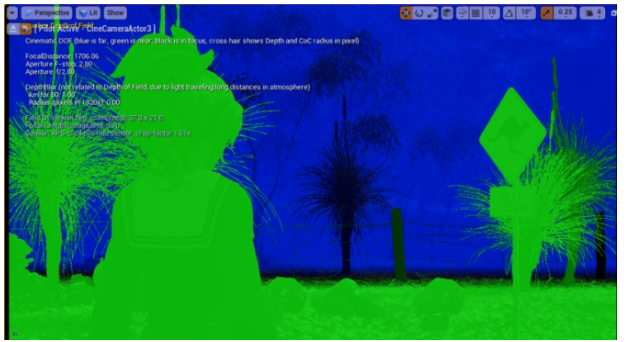
- **Flare phenomena**: caused by light traveling through a lens system
- Main types: halo (ring around light) and ciliary corona (rays radiating from a point)
  - Dependent on light source position
- Various approaches exist. Examples:
  - Set of squares with different textures, oriented on a line going from the light source potion screen through the screen's center
  - Light streaks from bright object can be simulated using steerable filter on a down sampled image

Lens flare (Battlefield)

Lens flare simulation https://resources.mpi-inf.mpg.de/lensflareRendering/pdf/flare.pdf

Depth of field

- **Depth of field: range where objects are in focus. Outside objects are blurred**
- **Smaller camera aperture size → increased depth of field**
  - Pinhole cameras: infinite depth of field
- Various methods exist. One solution:
  - Create separate image layers: e.g. near, far
  - Blur near or far layers
  - Final image is made by combining layers using back to front compositing



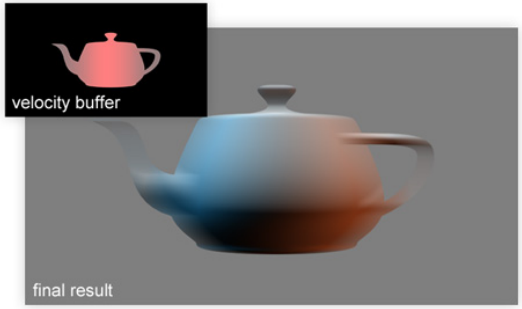
https://www.versluis.com/2022/01/ue4-dof/
https://catlikecoding.com/unity/tutorials/advanced-rendering/depth-of-field/
https://developer.nvidia.com/gpugems/gpugems/part-iv-image-processing/chapter-23-depth-field-survey-techniques

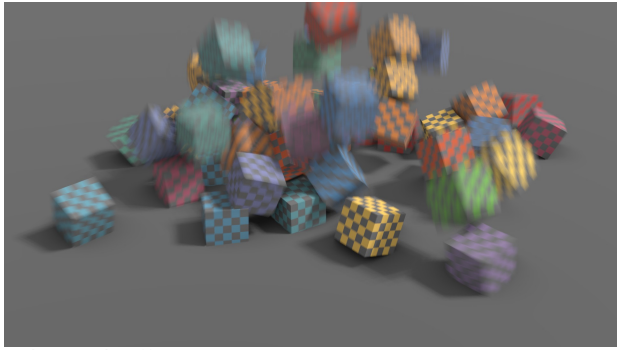
Motion blur

- Motion blur comes from **movement of an object** across the screen or from **camera movement**
- Different sources of motion blur require different methods
  - **Camera orientation changes** → e.g., **directional blur** based on orientation direction
  - **Camera position changes** → **radial blur**
  - **Object position/orientation changes** → motion of each object is computed using **depth or velocity buffer buffer** for determining amount of blur

Directional blur due to camera orientation change (Tomb raider)

Radial blur due to camera position change (Need for speed)





Object rotation and position change blur using velocity buffer
http://john-chapman-graphics.blogspot.com/2013/01/per-object-motion-blur.html

Digital imagery

Digital imagery

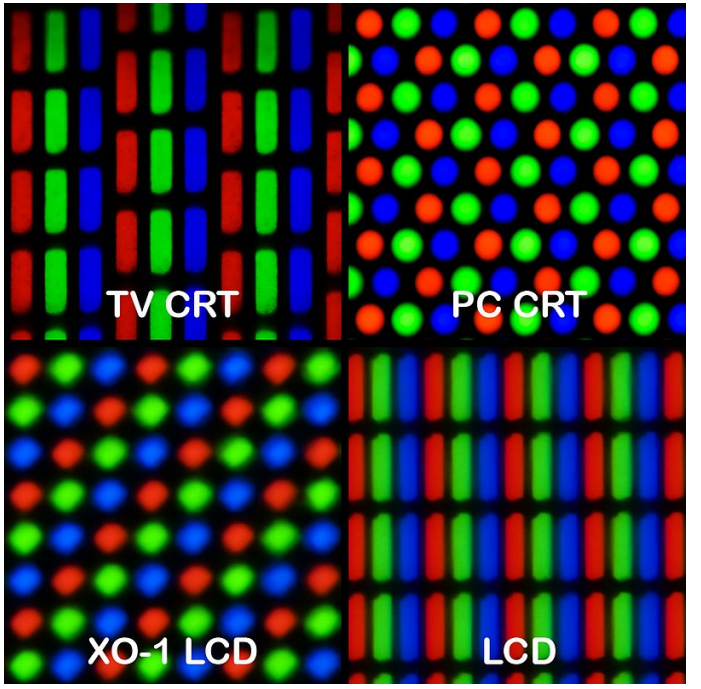
- Most sources of digital imagery are:
  - Digital photographs or other types of 2D pictures scanned or loaded in computer
  - **Images generated using computer graphics: 3D modeling and rendering software**

Digital photography https://www.warnerbros.com/movies/blade-runner-2049

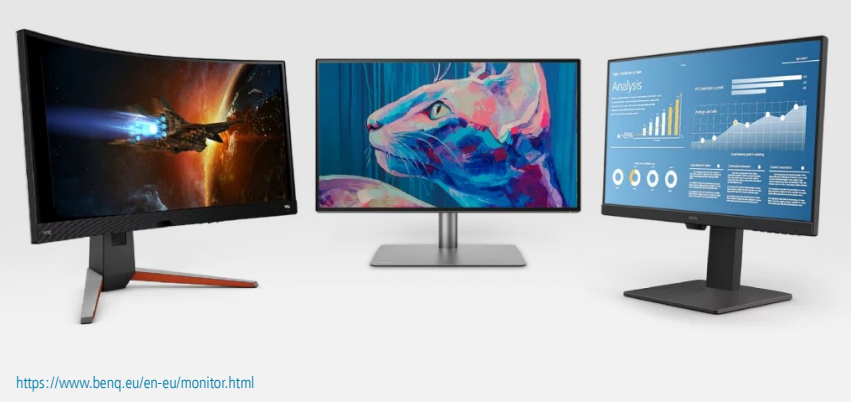
Rendered image: https://www.thewitcher.com/en/witcher3

Display device

- Digital images are displayed on a **raster display device ➞ raster images**
  - e.g., monitor, television screen, etc.
- Raster display device is made of **arrays of pixels ➞ discrete representation**
  - For example, each pixel of image created with digital camera (or rendering) stores red, green and blue value used to drive the red, green and blue values of screen pixel



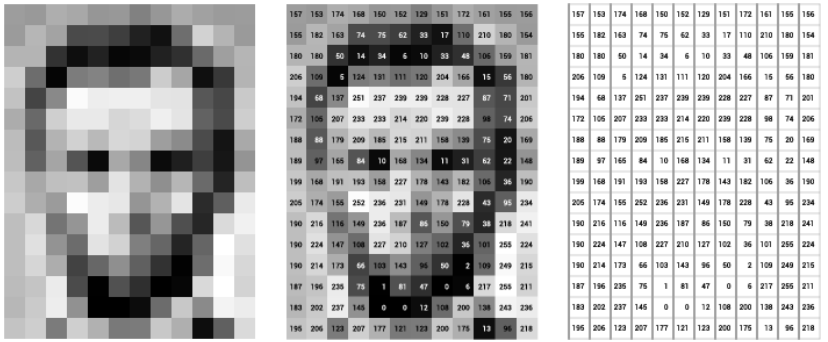
https://en.wikipedia.org/wiki/Pixel_geometry

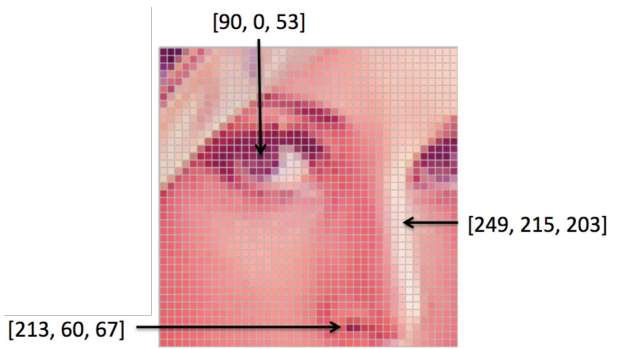


https://www.benq.eu/en-eu/monitor.html

Raster image graphics

- Pixels in raster image have the same type, examples:
  - Floating point numbers representing levels of **gray**
  - Floating point triplets representing mixture of red, green and blue (**RBG**)
  - Floating point numbers representing **depth** from camera
- Values in raster images can be interpreted in different ways
  - Arbitrary information can be stored/encoded in such array (e.g., normal maps)
  - Numbers in array do not have particular significance until stored in certain **standardized file format**



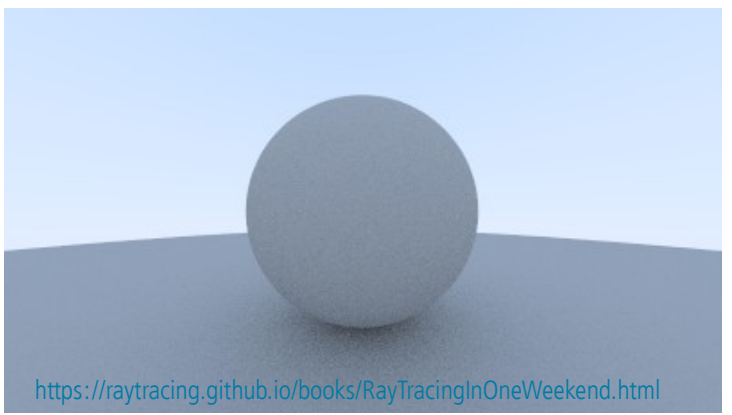


https://ai.stanford.edu/~syyeung/cvweb/tutorial1.html

Naive image file format: PPM

- **Portable Pixel Map (PPM):** text-based (P3) image file format
- **Header**:
  - Width `(w)` and height `(h)` of image is specified
  - Maximum color value
- **Pixel values**:
  - `3 * w * h` color values representing red, green and blue components of pixel
  - Pixel values ordering: left-to-right, top-to-bottom
  - Separated by white-space
- **Naive image file format:**
  - Easy to write and analyze
  - Inefficient and highly redundant (compression is not present)
  - Little information about image

```
P3
# feep.ppm
4 4
15
 0  0  0    0  0  0    0  0  0   15  0 15
 0  0  0    0 15  7    0  0  0    0  0  0
 0  0  0    0  0  0    0 15  7    0  0  0
15  0 15    0  0  0    0  0  0    0  0  0
```



Text-based version carries code P3, binary version carries code P5. More information: https://netpbm.sourceforge.net/doc/ppm.html

Raster image file formats

Format	Channel Depth	Alpha	Meta data	DPI	Extensions
BMP	8bit	✗	✗	✓	`.bmp`
Iris	8, 16bit	✓	✗	✗	`.sgi` `.rgb` `.bw`
PNG	8, 16bit	✓	✓	✓	`.png`
JPEG	8bit	✗	✓	✓	`.jpg` `.jpeg`
JPEG 2000	8, 12, 16bit	✓	✗	✗	`.jp2` `.jp2` `.j2c`
Targa	8bit	✓	✗	✗	`.tga`
Cineon & DPX	8, 10, 12, 16bit	✓	✗	✗	`.cin` `.dpx`
OpenEXR	float 16, 32bit	✓	✓	✓	`.exr`
Radiance HDR	float	✓	✗	✗	`.hdr`
TIFF	8, 16bit	✓	✗	✓	`.tif` `.tiff`
WebP	8bit	✓	✓	✓	`.webp`

https://docs.blender.org/manual/en/latest/files/media/image_formats.html

Raster image file formats

- **Images are stored in many formats,** closely related to the **display format**
- File formats use different **compression strategies**:
  - **Lossless** compression is one in which data occupies less space but from which original data can be reconstructred.
  - **Lossy** compression is resulting in even less occupied space, but original data can not be restored. Nevertheless, existing data is enough for intended use
- Content is described in terms of **channels**
  - e.g., red values for all pixels represents red **color channel**
  - e.g., depth values form **depth channel**
  - e.g., transparency values from **alpha channel**
- Some formats additionally store **metadata**
  - e.g., bit depth of color channel (e.g., 8 bit)
  - e.g. information on when and with which program the image was produced

https://www.gimp.org/tutorials/ImageFormats/

File formats in production

- **Digital painting and image manipulation**
  - Krita: bmp, jp2, **jpeg**, ora, pdf, **png**, ppm, raw, **tiff**, xcf https://krita.org/en/item/krita-features/
  - Gimp: XCF, **JPG**, **PNG**, GIF, **TIFF**, Raw, etc. https://www.gimp.org/tutorials/ImageFormats/
- **3D modeling**
  - Blender: BMP, Iris, **PNG**, **JPEG**, Targa, OpenEXR , **TIFF**, HDR, etc. https://docs.blender.org/manual/en/latest/files/media/image_formats.html
  - Houdini: **png**, gif, **jpg**, **tiff**, etc. https://www.sidefx.com/docs/houdini/io/formats/image_formats.html
- **Game engines:**
  - Unity: BMP, **TIF**, TGA, **JPG**, **PNG**, PSD, etc. https://docs.unity3d.com/2019.2/Documentation/Manual/AssetTypes.html
  - Godot: BMP, OpenEXR, **JPEG**, **PNG**, SVG, etc. https://docs.godotengine.org/en/stable/tutorials/assets_pipeline/importing_images.html

Raster image file formats

- Often used raster image file formats are:
  - Joint Photographic Experts Group - **JPEG**
  - Portable Network Graphics - **PNG**
  - Tag Image File Format - **TIFF/TIF**
- Advanced image file formats:
  - **OpenEXR** (https://github.com/AcademySoftwareFoundation/openexr)
  - **HDRI**: High Dynamic Range Image
- Library for handling different file formats for computer graphics applications: https://github.com/OpenImageIO/oiio

JPEG

- Recommended for display and storage of photography

Pros:

- Efficient file **compression**
- **Universally** supported for display
- Most **digital cameras** produce JPEG images

Cons:

- **Lossy**
  - Problematic for comparing the image due to differences in compression algorithm
  - Repeated editing degrades image quality
- **Artifacts** can be seen for computer generated graphics and text
- **Doesn't support transparency**
- Color channels are coded on 8 bits

http://www.faqs.org/faqs/jpeg-faq/part1/

PNG

- Developed as an improved replacement for Graphics Interchange Format (GIF)
- Recommended for web page widgets, computer graphics and screenshots

Pros:

- **Lossless** format
- Supports **transparency**
- **Small file size** for most computer graphics generated images
- Support by all **browsers**
- PNG file format is more compact than PPM and equally **easy to use**
- Support for **RGB(A) and grayscale images**

Cons:

- Complex images are heavier
- Color channels coded in **8 bits**

TIFF

- Used for storage and exchange of high quality images
- TIFF is ideal for representing intermediate or final results
  - In image editing and compositing tools, multiple images are often blended or laid atop one another

Pros:

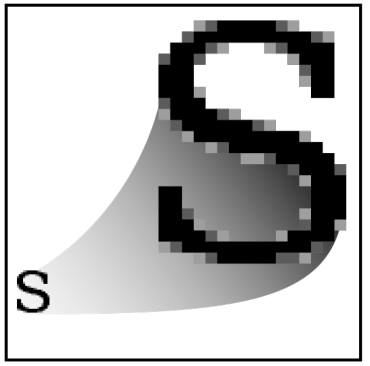
- Color coding in **16 bits**
- **Supported** by all image processing software
- TIFF images store **multiple channels** (images/layers)
  - Each channel store description of contents
- Various **compression** schemes
  - **uncompressed**
  - Compressed with **lossless** scheme
  - Compressed with **lossy** scheme

Cons:

- **Heavier** on complex images

Vector graphics images

- Alternative to raster graphics image is **vector graphics image**
  - Images are created directly from **geometric shapes defined on 2D Cartesian coordinate system**
  - Information in such image is **stored as points, lines, curves and polygons**
- Today, raster-based monitors and printers are typically used
  - Nevertheless, vector data and software is **used in applications where geometric precision is required**: **engineering**, **architecture**, **typography, etc.**
  - To display an image, **rendering** is performed to evaluate analytically defines shapes on raster display



Raster

GIF, JPEG, PNG

Vector

SVG

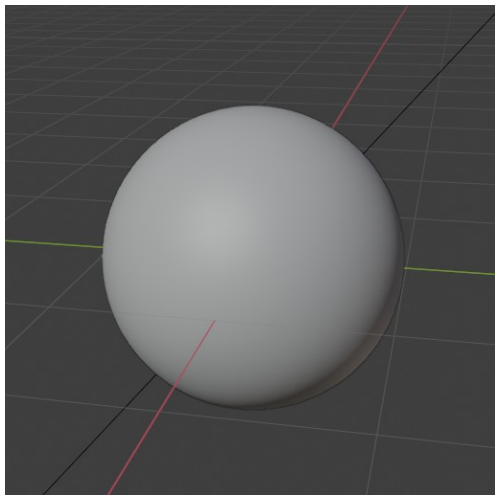
https://en.wikipedia.org/wiki/Vector_graphics

Aliasing and anti-aliasing

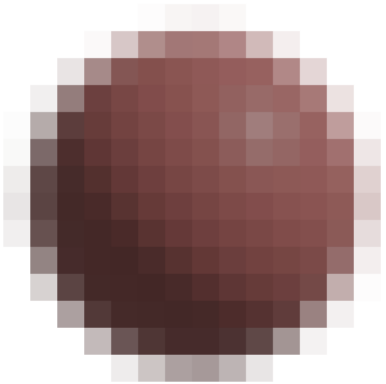
When continuous becomes discrete

Continuous and discrete

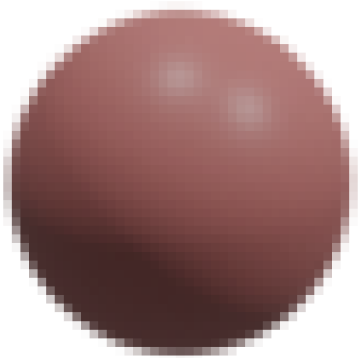
- **Images** are **discrete** array of pixels
- **3D scene objects**, lights and thus color values are **continuously** changing
- Rendering process, in order to create a discrete image of 3D scene, **samples the pixels on image plane**, finds corresponding sample in 3D scene and calculates color of the sample.



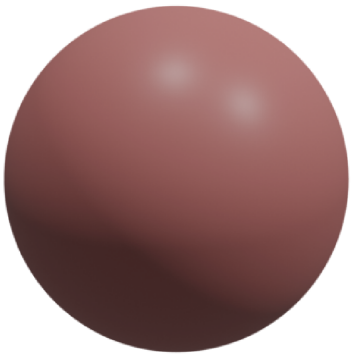
Continuous object in 3D scene



Render: 20x20px image size



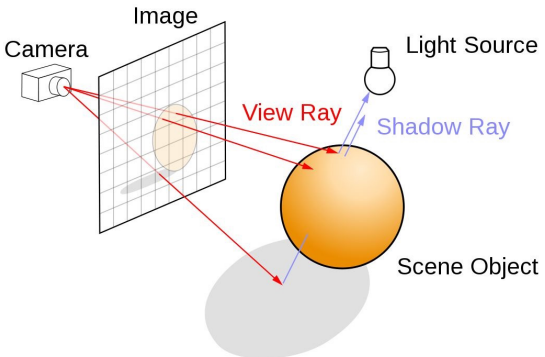
Render: 64x64px image size

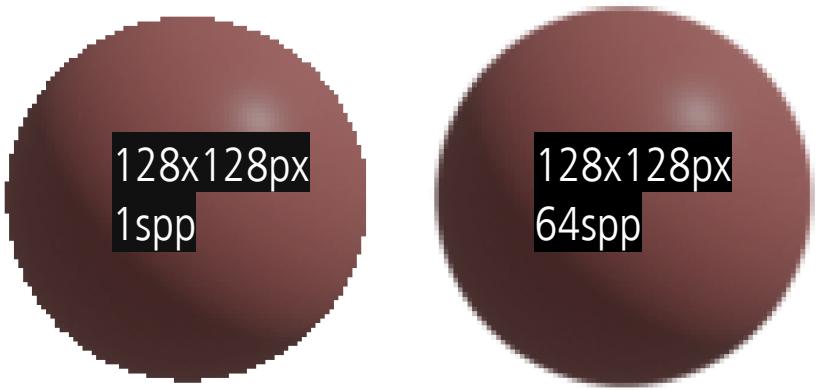


Render: 512x512px image size

Scene sampling and Image buffer

- Process of **rendering** images is inherently a **sampling task**
- Rendering is the process of **sampling a 3D scene** in order to obtain **colors for each pixel** in the image
  - Using camera information, **samples per image pixel** are generated
  - For each sample, **corresponding 3D scene point** is found and color is calculated (ray-tracing, rasterization)
  - Color of each pixel for each sample is combined into **color buffer**

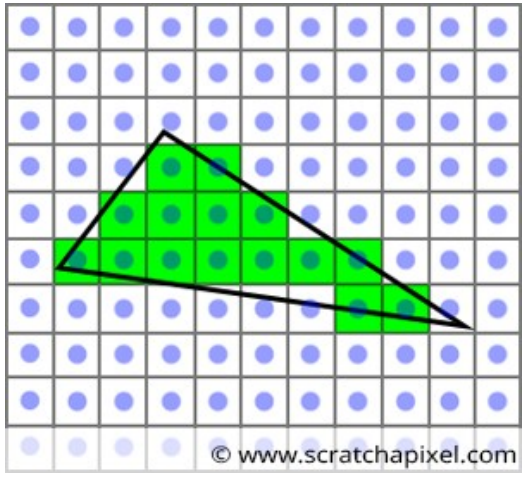




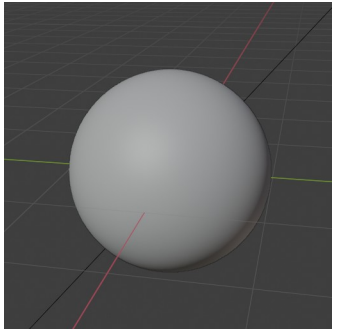
Note that pixel can have only one color!
Pixels overlapping multiple objects/textures in 3D scene must be sampled with multiple rays to obtain correct representation.

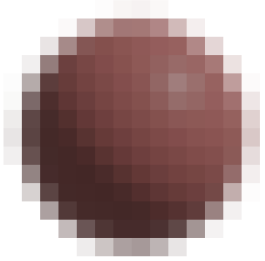
Aliasing

- Discretizing 3D scene (continuous information) may cause **Aliasing**
  - Jagged edges, flickering highlights (firelfys), Moiré pattern

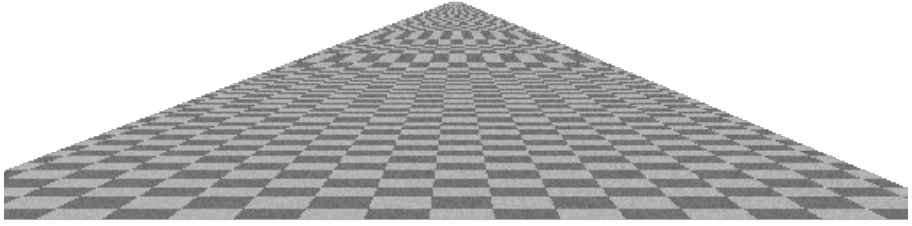


Discretization





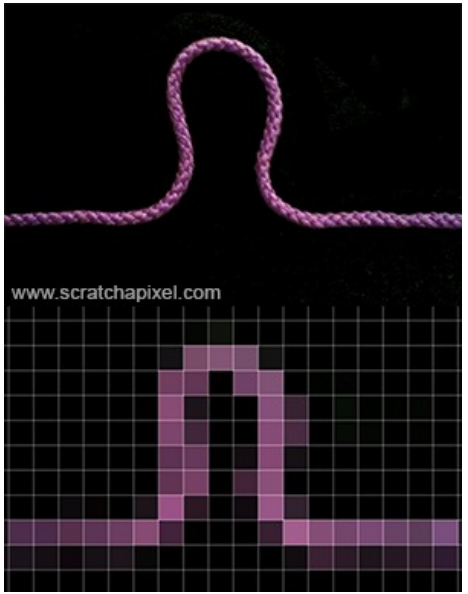
Problem: Jagged edges



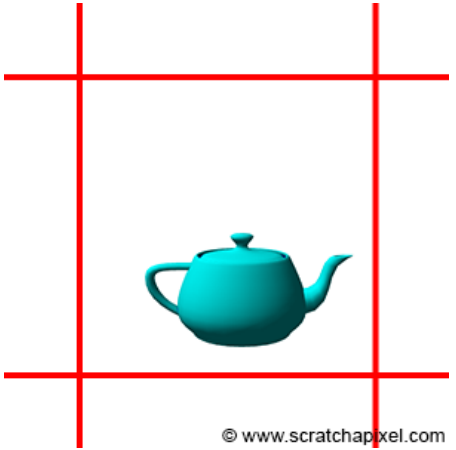
Problem: Moiré pattern

Aliasing: intuition

- Projecting pixel into 3D scene can cover larger portion of 3D scene which contain multiple objects and thus color variation.
- Any kind of rapid (high-frequency) change in geometry edges, textures, shadows, highlights can cause aliasing.



Thread contains large amount of details covered by only one pixel



Extreme example: one whole object in pixel footprint.

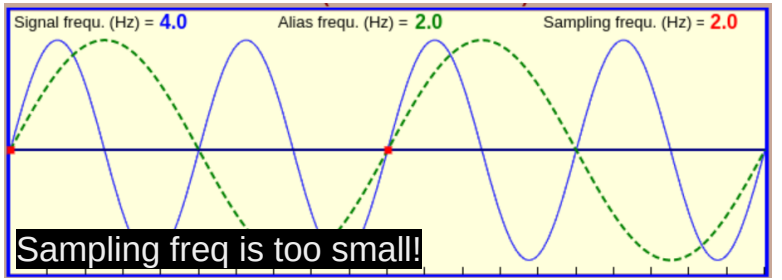
Changes in geometry, textures, highlights → sources of aliasing.

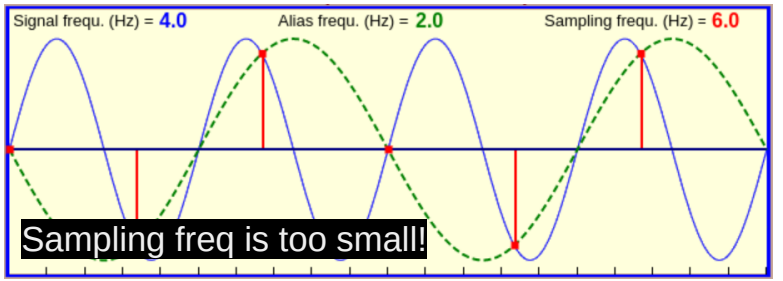
Aliasing

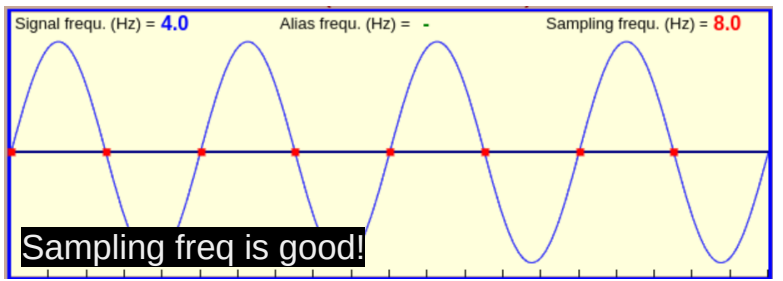
Blue: original signal
Red: samples
Green: reconstructed signal

- **Aliasing** – Occurs if signal is sampled at too low frequency
  - Reconstruction of signal from samples can not be performed correctly, e.g., reconstructing final image from pixel samples (**filtering**)
- **Sampling theorem: Sampling frequency must be twice the maximum frequency of sampled signal**; **Nyquist** rate/limit
  - As maximum frequency must be known for determining the sampling rate, **signal must be band-limited**
- **3D scenes are normally never band-limited** when rendering with point samples
  - **Sharp triangle or shadow edges** → discontinuous changes → infinite frequencies
  - **Rapid change of color**, e.g., specular highlights
- Point sampling is almost always used and entirely avoiding aliasing is not possible
  - Sampling pixel footprint which may contain lots of information requires a lot of samples

http://195.134.76.37/applets/AppletNyquist/Appl_Nyquist2.html

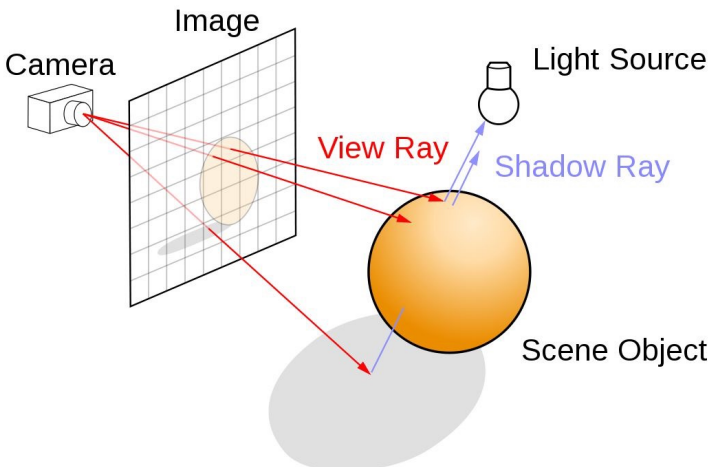






Anti-aliasing

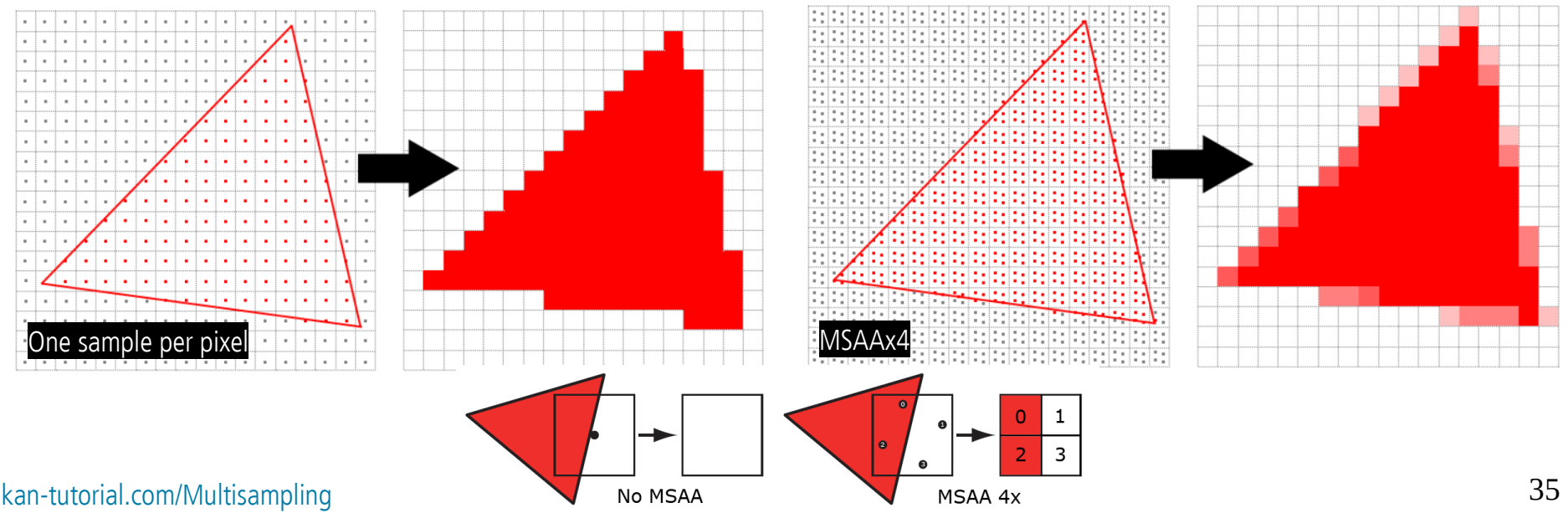
- Most common anti-aliasing method: **screen-based anti-aliasing**
  - **Using multiple samples per pixel during rendering**
- Anti-aliasing can be applied on: geometry, textures, shadows, highlights, etc.
  - At times, when it is possible to know if the signal is band limited and then anti-aliasing is performed
  - Trade-off between: quality, ability to capture sharp details or other phenomena, appearance, memory and speed



Instead of one ray per pixel, generate multiple rays - samples

Multisample anti-aliasing

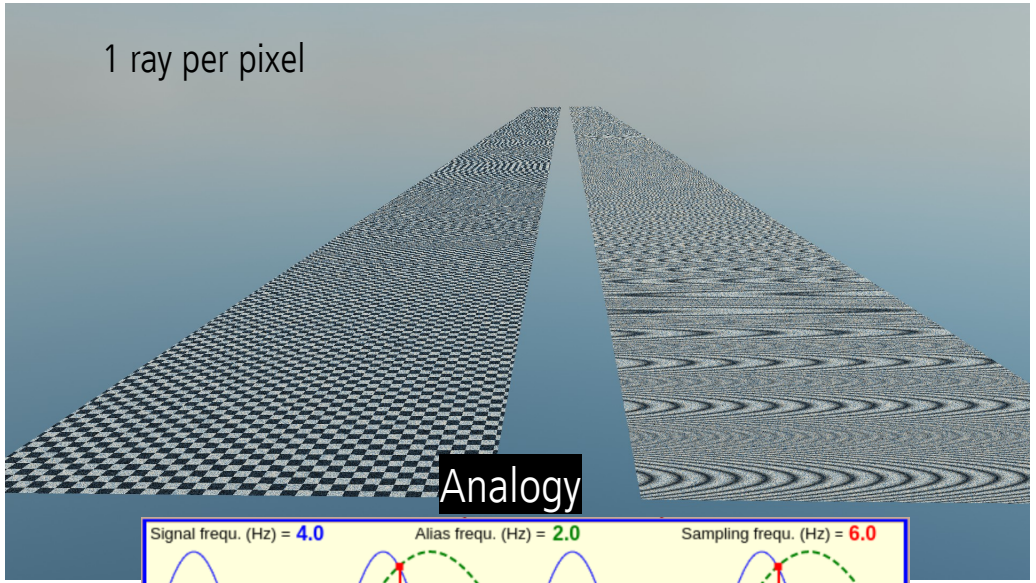
- Aliasing appears always when there are a lot of details under a pixel footprint in the scene
- To solve this, multiple sample per pixels can be used to "catch" high frequency details.
  - This method is called Multisample anti-aliasing (MSAA)

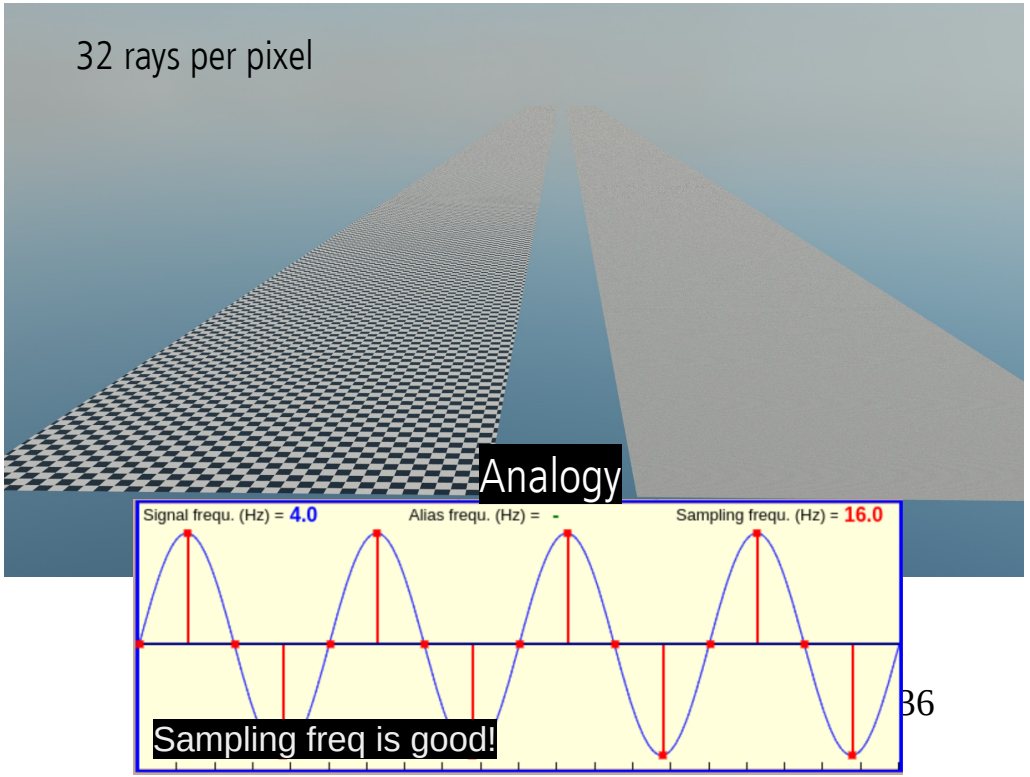


https://vulkan-tutorial.com/Multisampling
https://therealmjp.github.io/posts/msaa-overview/

Multisample anti-aliasing

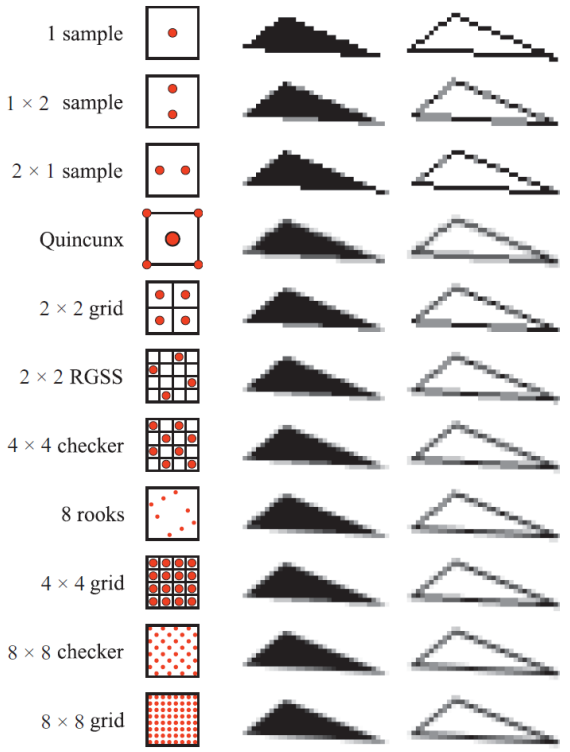
- Using more samples per pixel reduces aliasing.
  - One sample per pixel is often not enough to reconstruct the image





Antialiasing: sampling schemes

- Using more samples per pixel and combining those results in more representative pixel color
- Different pixel sampling schemes exists: trade-off between quality and speed



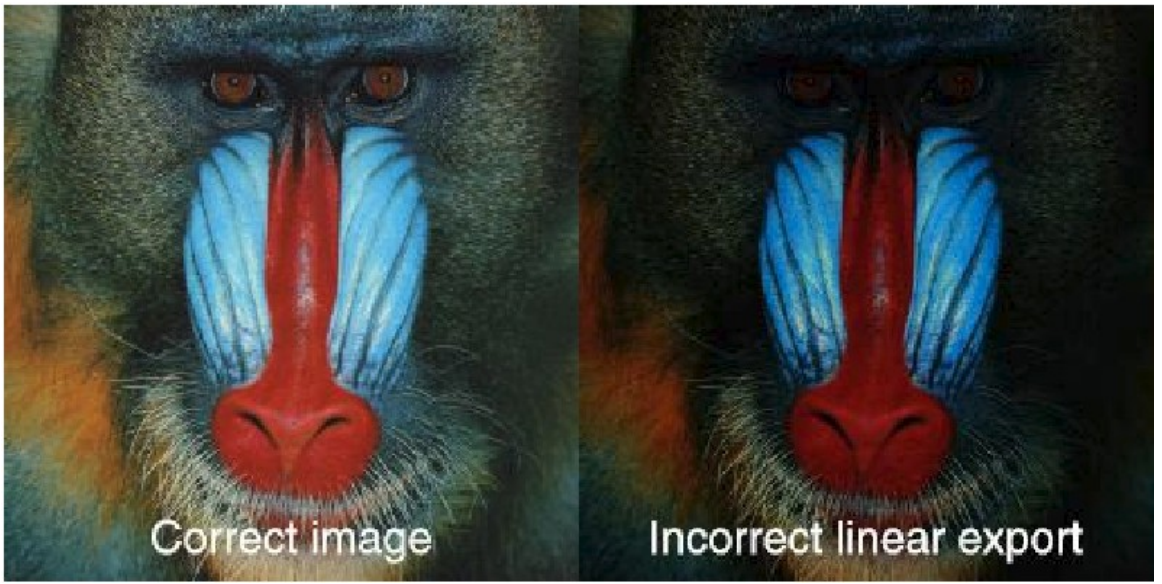
Scene to screen

Limitation of display device

- **3D scene contains:**
  - Continuous description of objects (e.g., triangles, parametric surfaces, etc.)
  - Strong light sources and reflections (e.g., point lights, specular reflections)
- **Display devices are limited (discrete)**:
  - Resolution (number of pixels)
  - Brightness (intensity)
  - Contrast
  - Color (gamut)
- **Rendered images** may contain values which can not be directly shown on display devices
  - Idea: manipulate image values so that image looks as intended when displayed on particular display device

Problem: displaying rendered images

- All input values (e.g., texture image) for rendering and all values during rendering computation must be in **linear** colorspace
  - Linear values are needed for correct addition and multiplication operations
- Rendered image containing **linear color space** will not display correctly if shown directly on a display device
  - Linear values will appear too dim on the screen



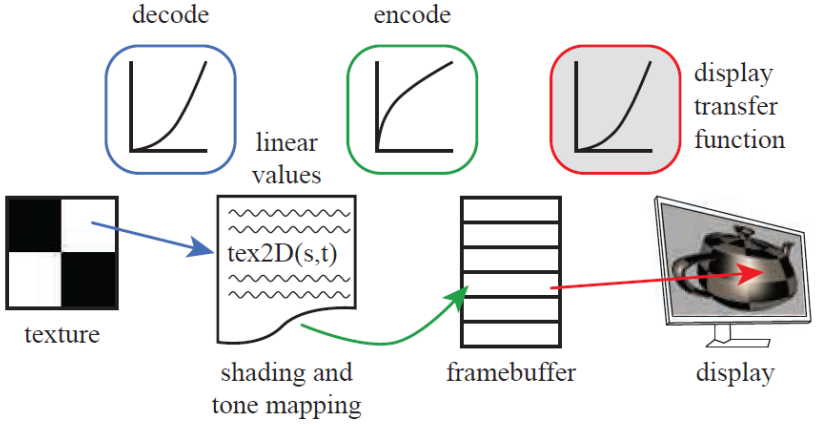
https://www.sidefx.com/docs/houdini/render/linear.html

Display limitations

- **Relationship** between digital **color values in image buffer** and amount of **light emitted from the display** is described with **electrical-optical transfer function (EOTF)**
  - **Standard dynamic range (SDR)** displays (e.g., personal computer display) use **sRGB** display standard
  - **High dynamic range (HDR)** displays uses standard **Rec. 2020 and Rec. 2100**
- Display devices have **nonlinear relationship between input voltage and display amount of light**
  - As energy level applied to pixel is increased, the amount of light emitted doesn't grow linearly but according to power law → **nonlinear relationship**
    - e.g., pixel set to 50% will emit 0.5^2 amount of light

Solution: display encoding

- The goal is to **cancel out the effect of display transfer function (EOTF)**
- **Linear color values are encoded for display**
  - **Inverse of display transfer function (EOTF) is applied** to color values in image buffer → **gamma correction**

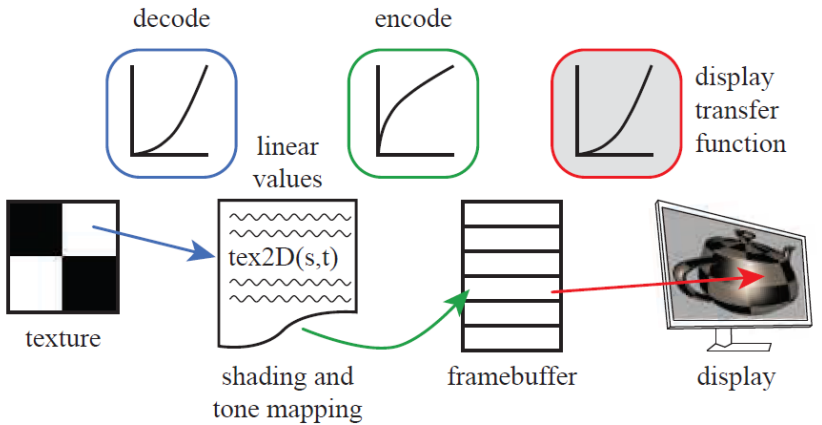


https://www.realtimerendering.com/

Gamma correction

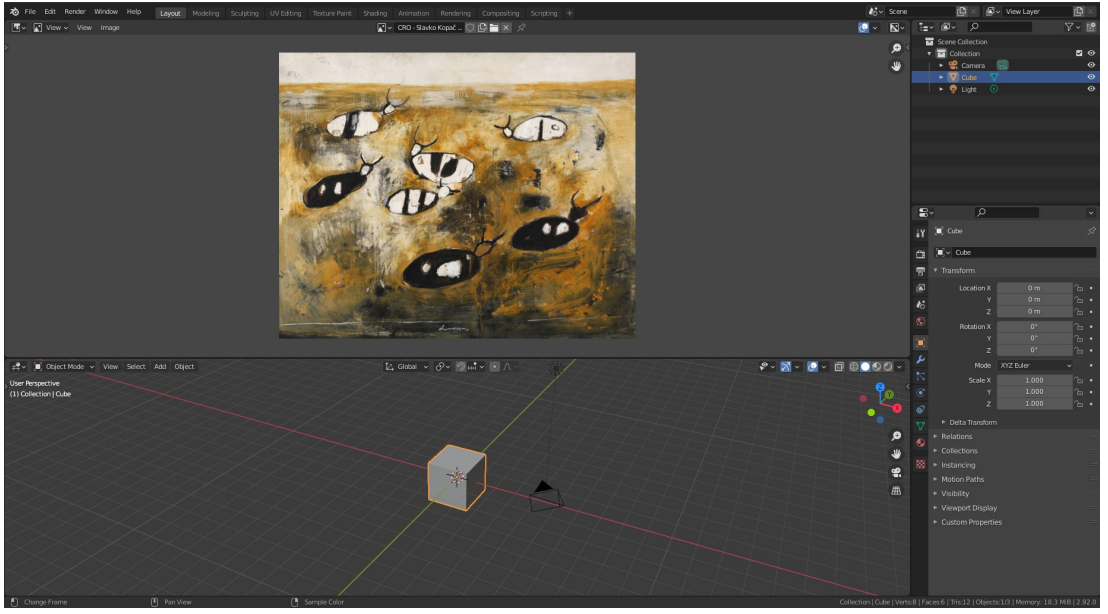
- Gamma correction is **last step in rendering and post-processing** – when everything is computed and image is ready for display.
  - To encode rendered image which is in linear colorspace `(x)` for sRGB display standard `(y)` the following formula is applied to all color values:

$$y = x^{1 / gamma}, \quad gamma = 2.2$$



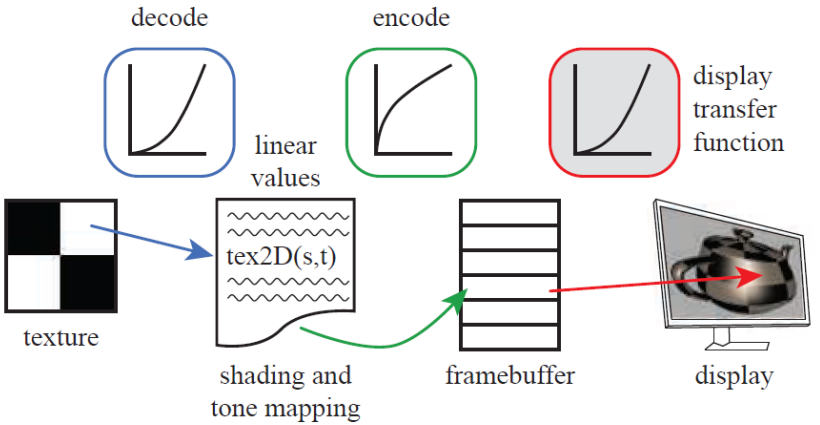
Problem: preparing data for rendering

- When working in modeling tools users pick texture images or colors on screen - those colors are **encoded for display device so we can see them properly**
  - Those colors **can not be used in rendering computation directly because they are in non-linear space**



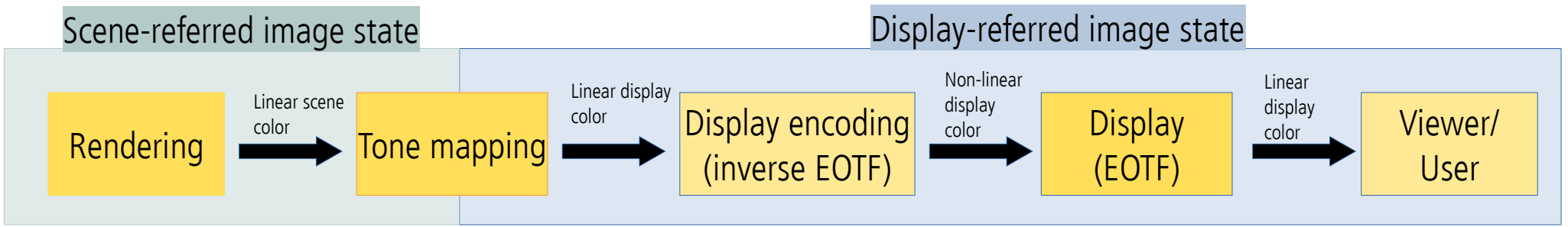
Solution: inverse gamma correction

- **Everything we see on the screen** (e.g., image textures or color-pickers in modeling tools) is display-encoded data and those values **must be decoded to linear values for rendering**
  - To decode sRGB display encoded values `(y)` to linear colorspace `(x)` the following formula is applied to all color values:
    - $x = y^{gamma}$, where `gamma = 2.2`



Imaging pipeline

- **Imaging pipeline:** describes color handling from initial rendering to final display.
- **Rendering:** creating 2D image based on 3D scene description.
  - The results are pixel values in **color buffer** – display results still needs to be determined.
- **Display encoding:** converting linear color (radiance) values to nonlinear values for display
- **Tone mapping:** converting linear scene-referred values to linear display-referred values



- Defined in reference to scene color (radiance) values
- Physically-based rendering computations

- Defined in reference to display color (radiance) values.
- Appropriate for viewing

Tone mapping

- **Tone mapping (reproduction)** is process of converting scene color (radiance) values to display color (radiance) values
  - Transform applied on this step is called end-to-end or scene-to-screen transform
- Two main types:
  - **Image reproduction** - create **display-referred image** that **reproduces**, as closely as possible, given display and viewing properties, **perceptual impression that viewer would have if they were observing original scene**
  - **Preferred image reproduction** – create **display-referred image that looks better** (to some criteria) than original scene.

Tone mapping: (1) image reproduction

- During image reproduction it is important to keep in mind that scene luminance and saturation exceeds display capabilities, that is, **dynamic range of scene is much larger than display device dynamic range**
  - Therefore, **(high) dynamic range of scene must be mapped to (low) dynamic range of the display**
  - This mapping is done using **sigmoid (s-shaped) tone-reproduction curve**, researched for photochemical film, thus name "filmic"
- Further, **exposure** is critical to image reproduction
  - Exposure in **photography** refers to controlling the **amount of light falling on film/sensor**.
  - In **rendering**, **exposure** is a **linear scaling operation performed on scene-referred image before tone reproduction transform is applied**.
- **Tone reproduction transform** and **exposure** are closely tied together
  - Tone transforms are designed to be applied to scene-referred values which have been scaled by certain exposure

Tone-reproduction transform

Scaling by exposure

https://learnopengl.com/Advanced-Lighting/HDR

Image reproduction

- **Global tone mapping** consists of two steps:
  1. **Scaling scene-referred rendered image by exposure**
  2. **Applying tone reproduction transform applied on image**
- In contrast, **local tone mapping:**
  - Uses different mapping pixel-to-pixel based on surrounding pixels and other factors

Global tone mapping: scaling by exposure

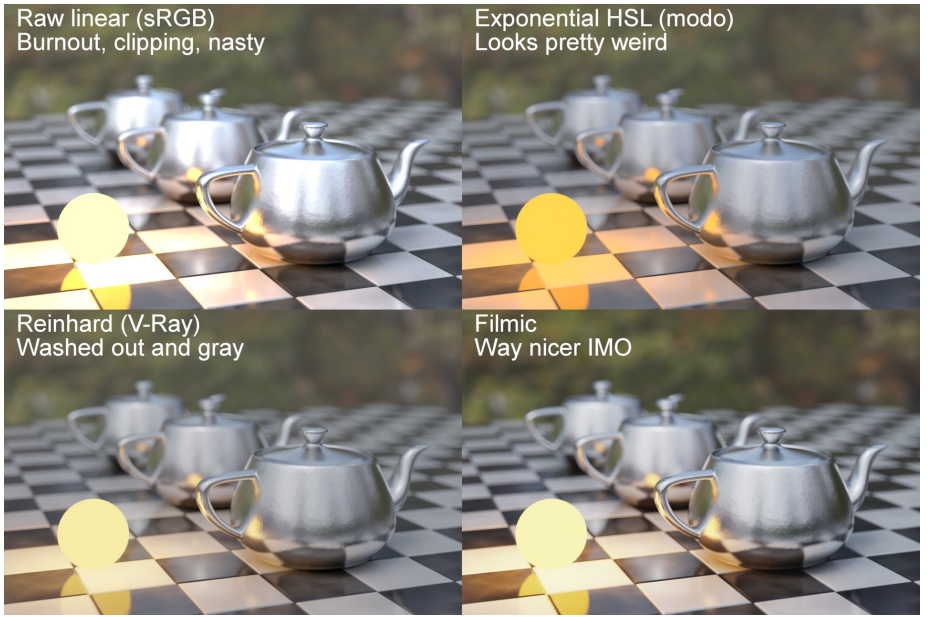
- **Exposure scaling factor is determined by analyzing scene-referred luminance values**
- Analyzing pixel luminance of the **scene-referred pixel values** in the rendered image
  - Metric 1: log-average of scene luminance
    - Problem: sensitive to outliers (e.g., small number of bright pixels that affect the exposure for the whole frame)
  - Metric 2: median of scene luminance by using histogram of luminance values
    - https://cdn.cloudflare.steamstatic.com/apps/valve/2008/GDC2008_PostProcessingInTheOrangeBox.pdf
- Analyzing light luminance alone, that is, exposure scaling based on light intensity
  - https://www.gdcvault.com/play/1018086/Photorealism-Through-the-Eyes-of

Different exposures of the same render:
https://docs.blender.org/manual/en/latest/render/color_management.html

Global tone mapping: tone reproduction transform

- **Tone reproduction transform:** 1D curve mapping scene-referred input values to display-referred output values
  - Transform can be directly applied on R, G, B values: the result will be in display gamut, but hue and transform are shifted
  - Transform can be applied to luminance: hue and saturation will not be shifted, but resulting color might be outside of display gamut
- **Reinhard tone reproduction transform**
  - Leaves dark values unchanged while bright values asymptotically go to white
- **ACES tone mapping**
  - Standard for tone managing for motion picture and television
  - Emerging in real-time applications: Unity and Unreal
- Many **other tone mapping transform exist**, examples:
  - Adaptive Logarithmic Mapping: similar to Reinhard with adjustable output display luminance: https://resources.mpi-inf.mpg.de/tmo/logmap/logmap.pdf
  - Filmic tone mapping: http://duikerresearch.com/2015/09/filmic-tonemapping-ea-2006/

$$V_{\text{out}} = \frac{V_{\text{in}}}{V_{\text{in}} + 1}$$



https://blenderartists.org/t/cycles-tonemapping/566158/89?page=5

Tone mapping: (2) preferred image reproduction

- **Color grading**: creative manipulation of image colors to obtain image desired artistic look
  - https://www.gdcvault.com/play/1012248/Perfecting-the-Pixel-Refining-the
- **Color grading is performed using look-up tables** (LUTs) contain desired tabular color transformations which are applied on image
  - https://renderwonk.com/publications/s2010-color-course/hoffman/s2010_color_enhancement_and_rendering_hoffman_b.pdf
- Color grading can be performed on:
  - Scene-referred image data: produce high fidelity results
  - Display-referred image data: easier to set-up, often was used in real-time applications

https://advances.realtimerendering.com/other/2016/naughty_dog/NaughtyDog_TechArt_Final.pdf

More into topic

- Image space effects:
  - Motion blur: https://www.nvidia.com/docs/io/8230/gdc2003_openglshadertricks.pdf
  - Motion blur: https://developer.nvidia.com/gpugems/gpugems3/part-iv-image-effects/chapter-27-motion-blur-post-processing-effect
  - Motion blur: https://www.bryanmcphail.com/wp/?p=600
  - Motion blur: https://docs.blender.org/manual/en/latest/render/cycles/render_settings/motion_blur.html
  - NPR: https://en.wikipedia.org/wiki/Non-photorealistic_rendering
  - General post-processing: https://docs.unity3d.com/Packages/com.unity.render-pipelines.universal@7.1/manual/integration-with-post-processing.html
- Color:
  - https://developer.nvidia.com/sites/default/files/akamai/gameworks/hdr/UHDColorForGames.pdf
  - https://cinematiccolor.org/
- Color grading:
  - http://filmicworlds.com/blog/minimal-color-grading-tools/
  - https://docs.unrealengine.com/4.27/en-US/RenderingAndGraphics/PostProcessEffects/ColorGrading/

Repository

- https://github.com/lorentzo/IntroductionToComputerGraphics