Imaging pipeline and post-processing

Display and images

Digital imagery

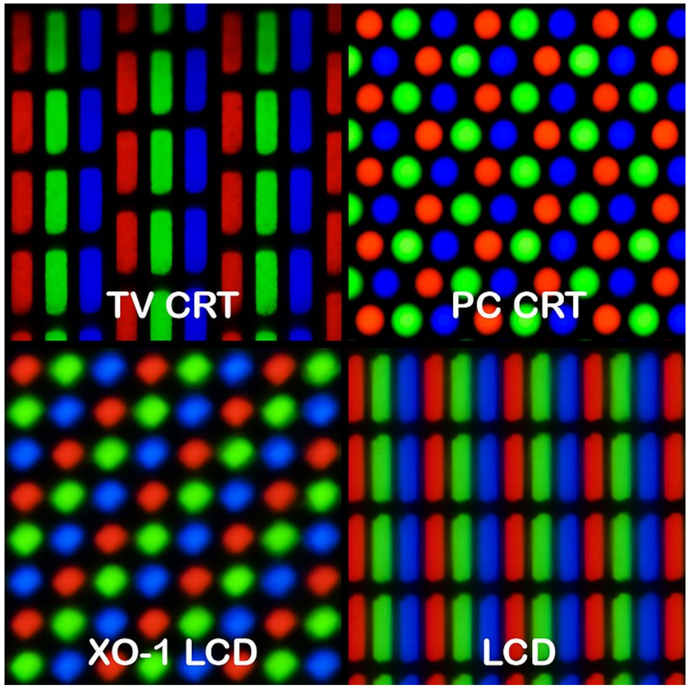
- Digital imagery appears in all forms of media. Most of these are:
  - Digital photos or other types of 2D pictures scanned or loaded in computer
  - **Generated in 3D using modeling and rendering software**

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

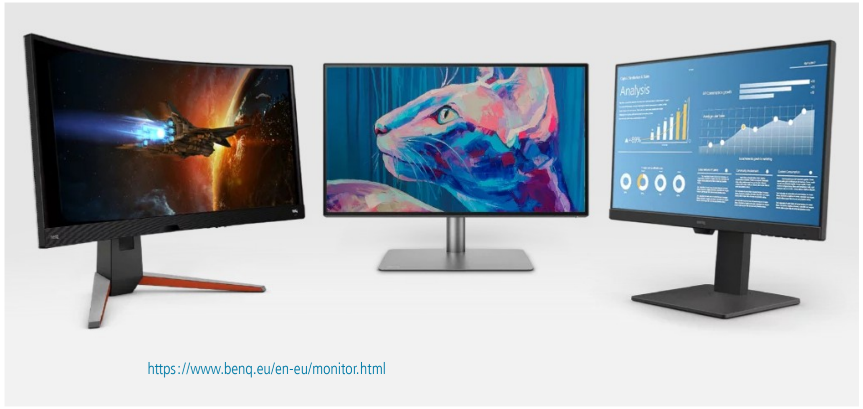
https://www.thewitcher.com/en/witcher3

Display device

- Digital images are shown 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.



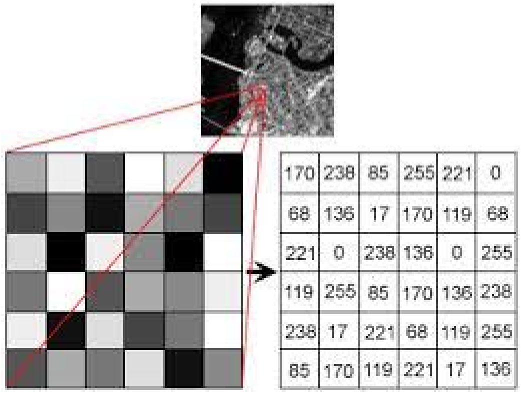
https://en.wikipedia.org/wiki/Pixel_geometry



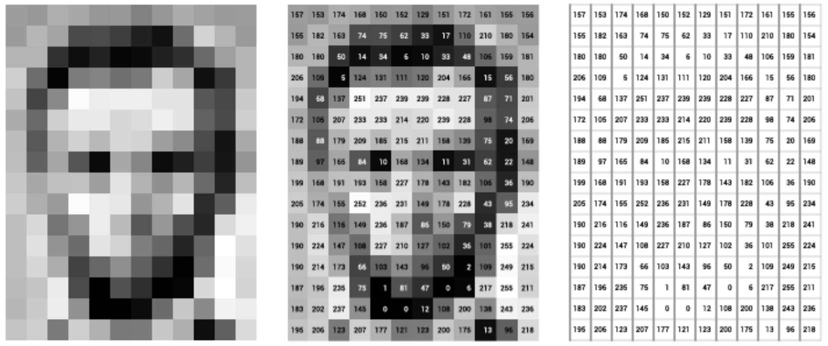
https://www.benq.eu/en-eu/monitor.html

Raster image graphics

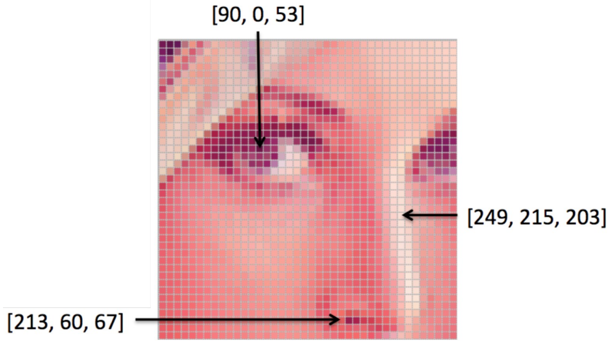
- Raster images are **rectangular array of values** called **pixels.**
- All values in such have same type, examples:
  - Floating point numbers representing levels of **gray**
  - Floating point triplets representing mixture of red, green and blue (**RBG**)
  - Floating point numbers representing **depth** from camera
- Such rectangular array of numbers can be interpreted in many ways
  - This is powerful since we can store/encode any information in such array
  - Numbers in array do not have particular significance until stored in certain **standardized file format**



170	238	85	255	221	0
68	136	17	170	119	68
221	0	238	136	0	255
119	255	85	170	136	238
238	17	221	68	119	255
85	170	119	221	17	136



157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

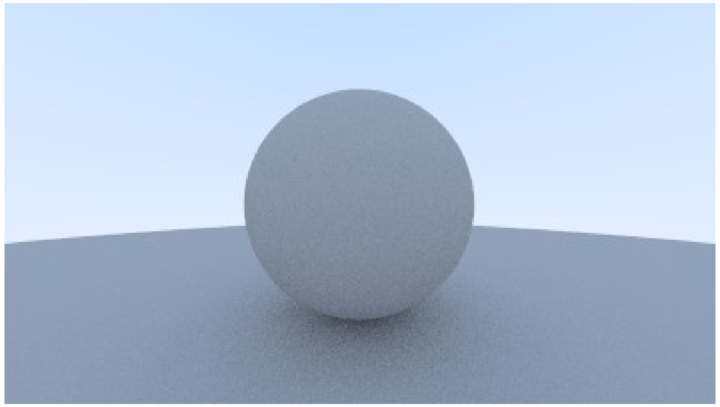


https://ai.stanford.edu/~syyeung/cvweb/tutorial1.html

Naive image file format: PPM

- Portable Pixel Map (PPM) text-based* version file format is useful for understanding how basics of image organization works
- **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

```
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
```



https://raytracing.github.io/books/RayTracingInOneWeekend.html

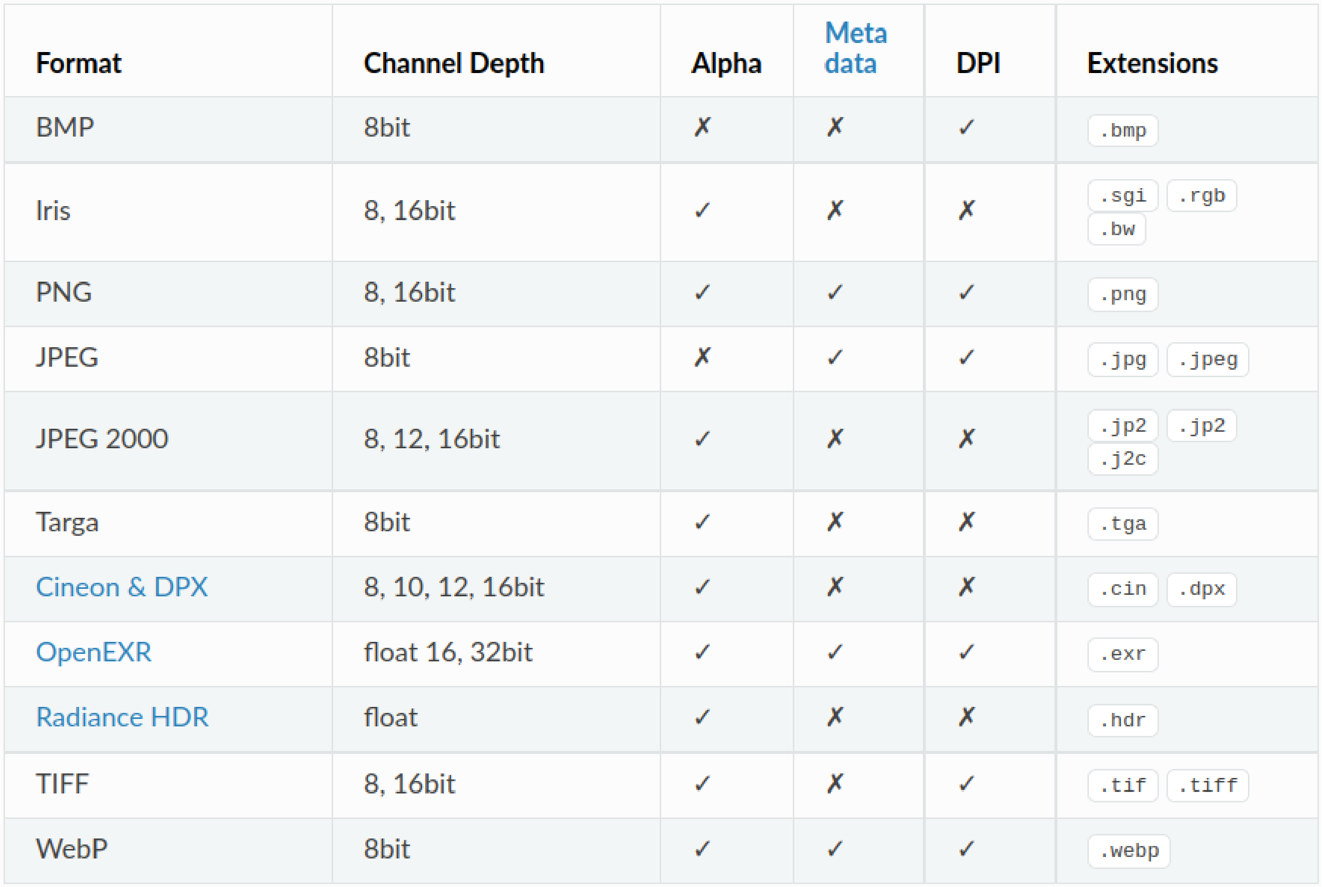
* Text-based version carries code P3, binary version carries code P5. More information: https://netpbm.sourceforge.net/doc/ppm.html

Naive image file format: PPM

- Characteristics:
  - 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
```

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; typically the storage format 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
- In some cases, 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 store **metadata**
  - e.g., bit depth of color channed (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:
  - Tag Image File Format - **JPEG**
  - Portable Network Graphics - **PNG**
  - Tag Image File Format - **TIFF/TIF**
- Advanced image file formats:
  - **OpenEXR** (https://github.com/AcademySoftwareFoundation/openexr)
  - High Dynamic Range Image - **HDRI**
- Library for handling different file formats for computer graphics applications: https://github.com/OpenImageIO/oiio

JPEG

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

Pros:

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

- Recommended for display and storage of photography

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

PNG

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

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

TIFF

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

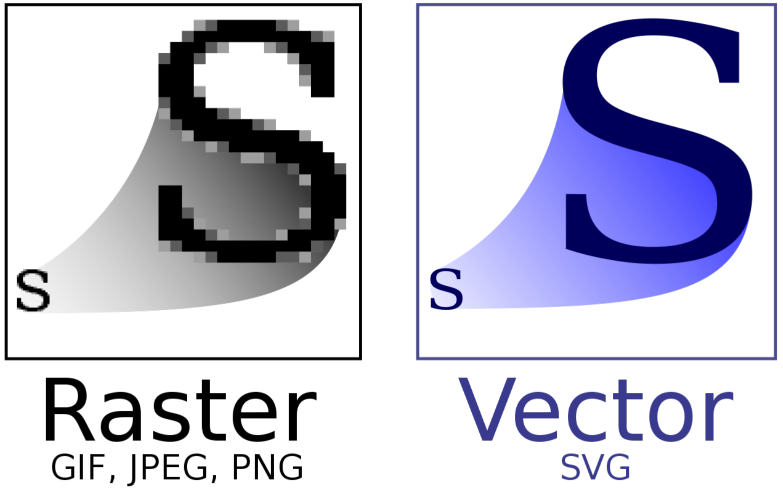
Cons:

- Heavier on complex images

- 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

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
  - To display an image, rendering is performed to evaluate analytically defines shapes on raster display



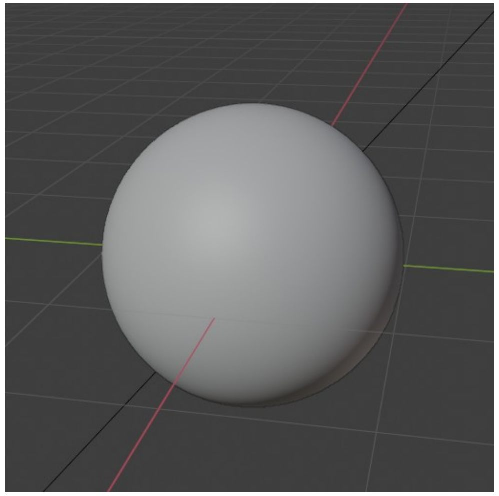
https://en.wikipedia.org/wiki/Vector_graphics

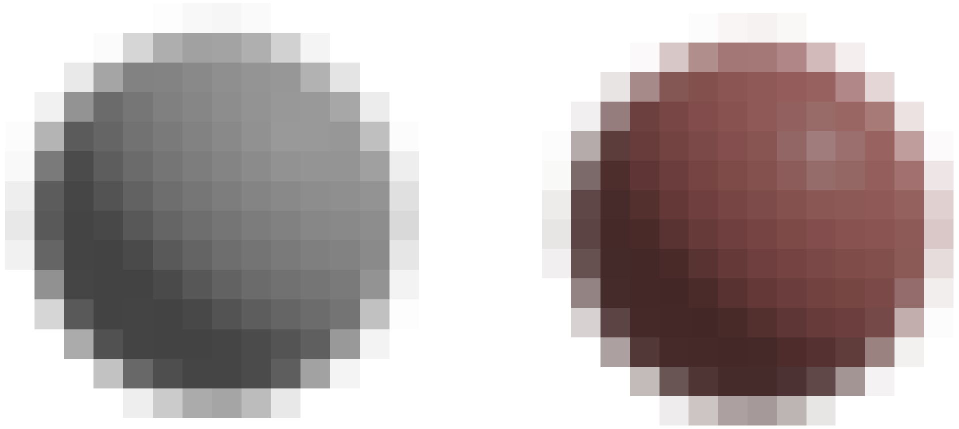
Aliasing and anti-aliasing

When continuous becomes discrete

Continuous and discrete

- Due to raster display devices, rendered images are also 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.



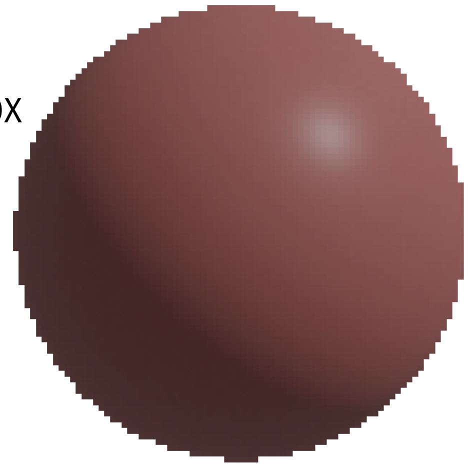


20x20px camera film plane

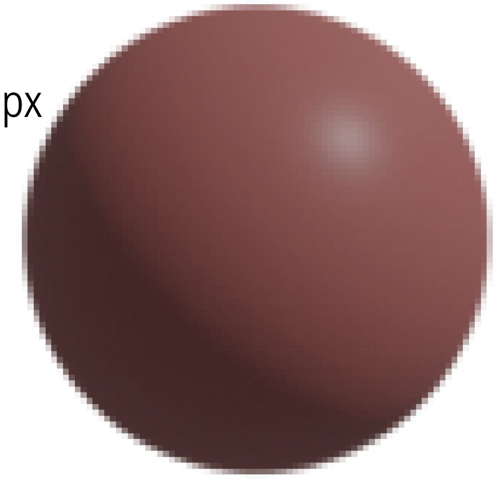
Discrete image

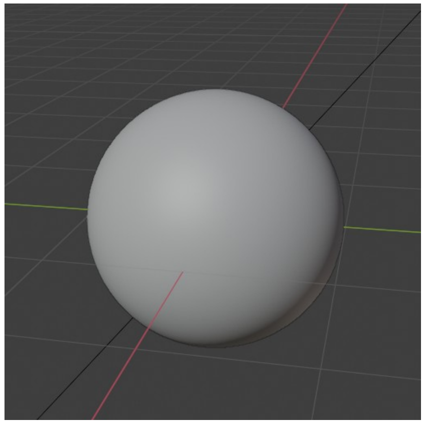
- Process of rendering images is inherently a sampling task
- Quality of final discrete 2D image is highly determined by:
  - How is the sampling of pixel performed
  - Methods which combine pixel samples in pixel color

128x128px
1spp



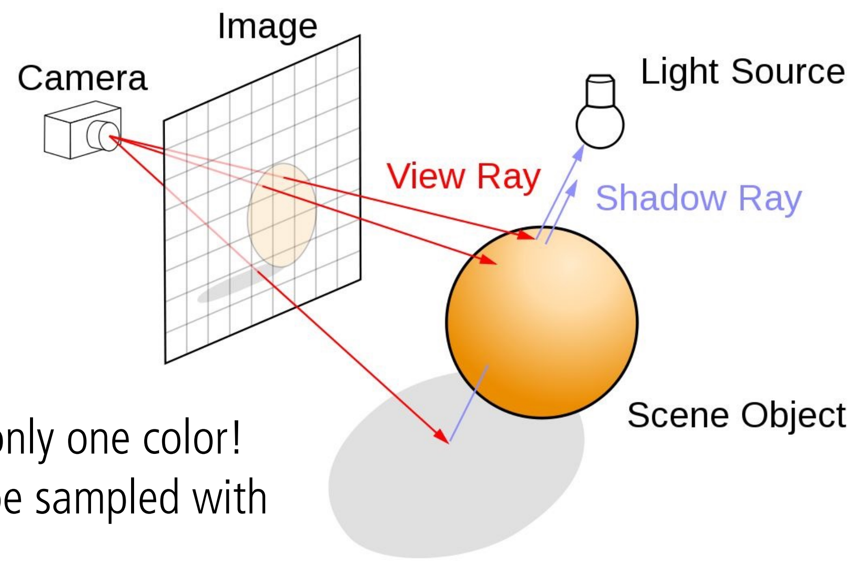
128x128px
64spp





Scene sampling and Image buffer

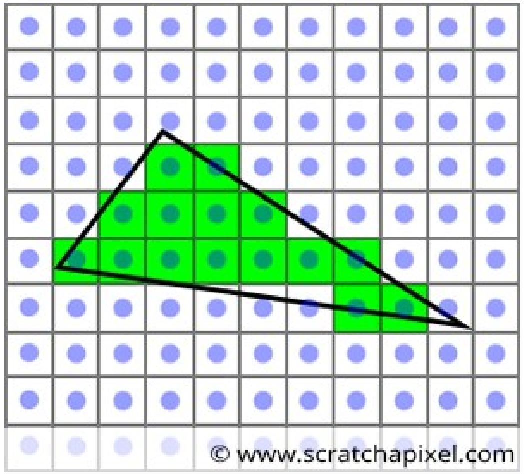
- Rendering is the process of sampling a 3D scene in order to obtain colors for each pixel in the image
  - Camera description is used to generate samples on film plane
  - For each sample, corresponding 3D scene sample is found and color is calculated
  - Color of each pixel for each sample is stored in **image buffer** – intermediate representation of image used by renderer
  - Final image is reconstructed from pixel samples



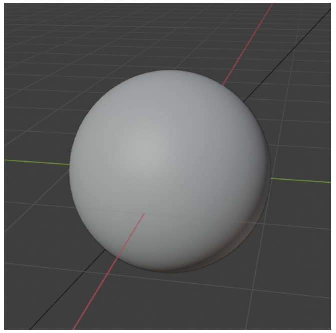
Note that pixel can have only one color!
Half covered pixels must be sampled with multiple rays.

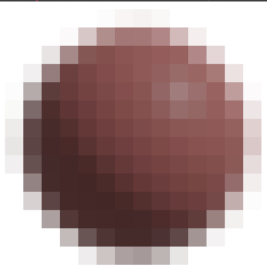
3D Scene discretization problems

- 3D scene is continuous description which must be discretized for display and may cause problems:
  - **Aliasing:** Jagged edges, flickering highlights (firelfys), Moiré pattern

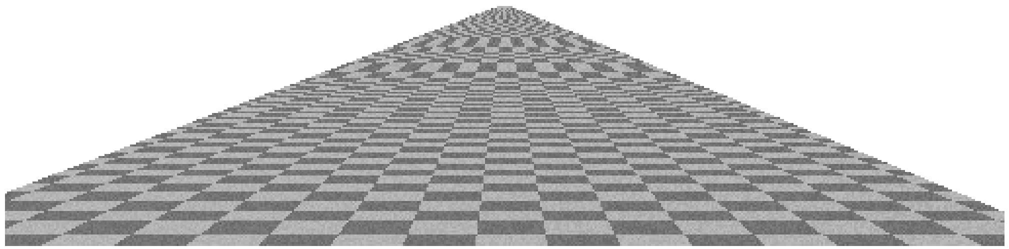


Jagged edges



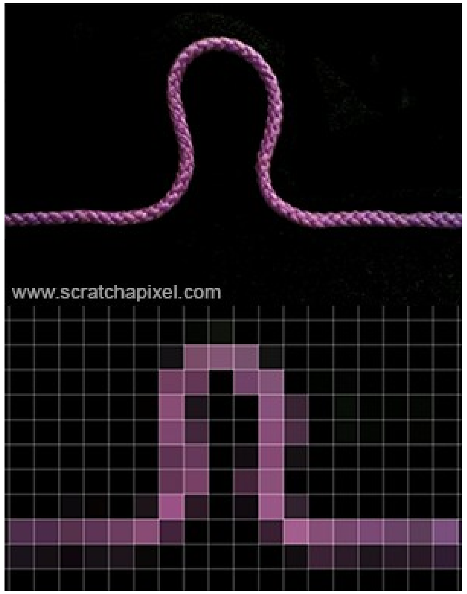


Moiré pattern

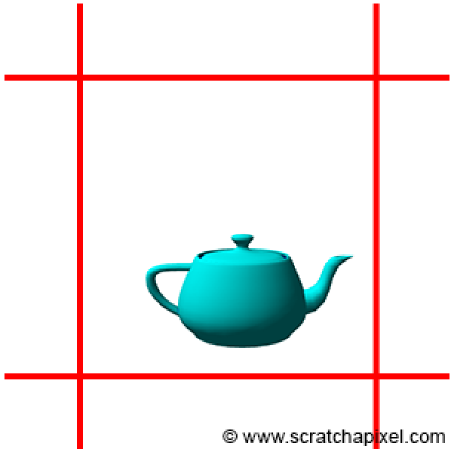


Aliasing: intuition

- Projecting pixel into 3D scene can cover larger portion of 3D scene which contain multiple objects and thus color variation.



Thread contains large amount of details covered by only one pixel



One whole object in pixel footprint.

Aliasing

Sampling process might result in **aliasing** – an unwanted artifact in spatial or temporal domain (spatial vs temporal sampling)

- Aliasing happens if signal is sampled at too low frequency than the original and thus reconstruction can not be done correctly
- Sampling frequency must be twice the maximum frequency of signal which is sampled – **sampling theorem** – **Nyquist rate/limit**
- As maximum frequency must be present, signal must be band-limited

- **3D scenes are normally never band-limited** when rendering with point samples
  - Edges of triangles or shadow boundaries produce signal that changes discontinuously and produces frequencies which are infinite
  - Any rapid change of color can cause aliasing problems: specular highlights
  - Also, pixel footprint in the scene may contain lots of objects which are hard to sample even with dense number of samples per pixel
- Point sampling is almost always used and entirely avoiding aliasing is not possible
- At times, it is possible to know when the signal is band limited and then anti-aliasing is performed
  - Example is texture usage: frequrency of texture sampling can be compared to sampling rate of pixel and if texture sampling is higher then algorithms for band limiting the texture are used.
- Sampled signal must be reconstructed to recover original signal → **filtering** - final image is reconstructed from pixel samples

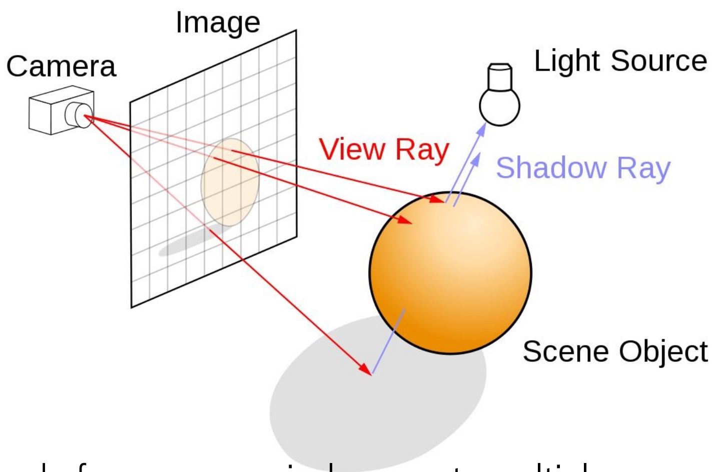
Aliasing

- Any kind of rapid (high-frequency) change in geometry edges, textures, shadows, highlights can cause aliasing.

https://www.crysis.com/

Anti-aliasing

- Different anti-aliasing methods:
  - Anti-aliasing can be applied on: geometry, textures, shadows, highlights, etc.
  - Trade-off between: quality, ability to capture sharp details or other phenomena, appearance, memory, speed and computing power
- Most common anti-aliasing method: **screen-based anti-aliasing**

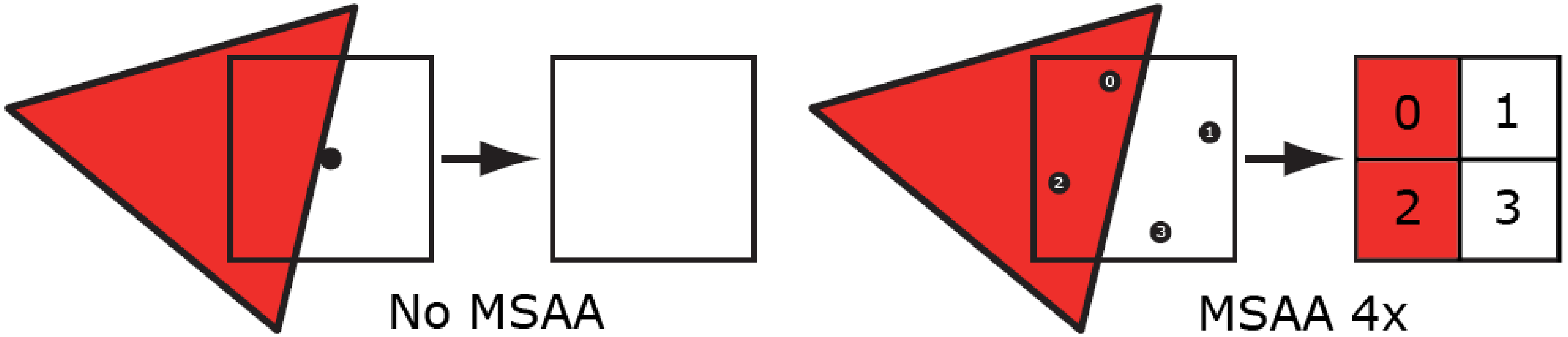


* In terms of signal processing this can be seen as sampling, filtering and reconstruction.

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

Antialiasing: sampling rate

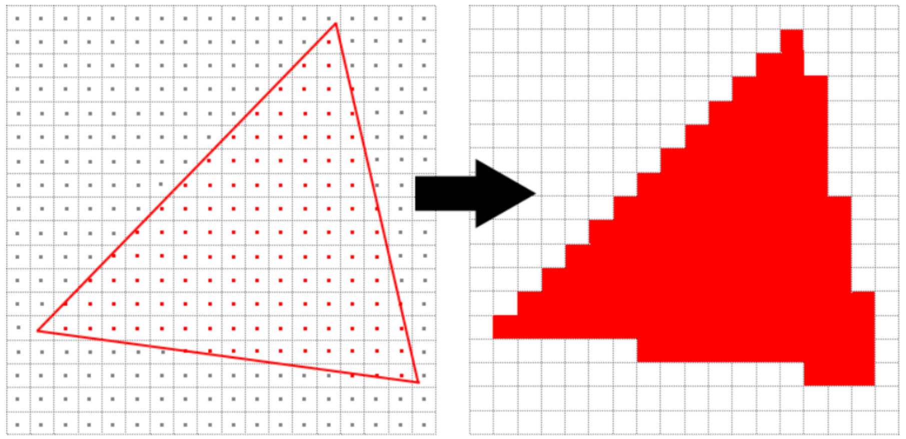
- Often problem causing aliasing is low pixel sampling rate

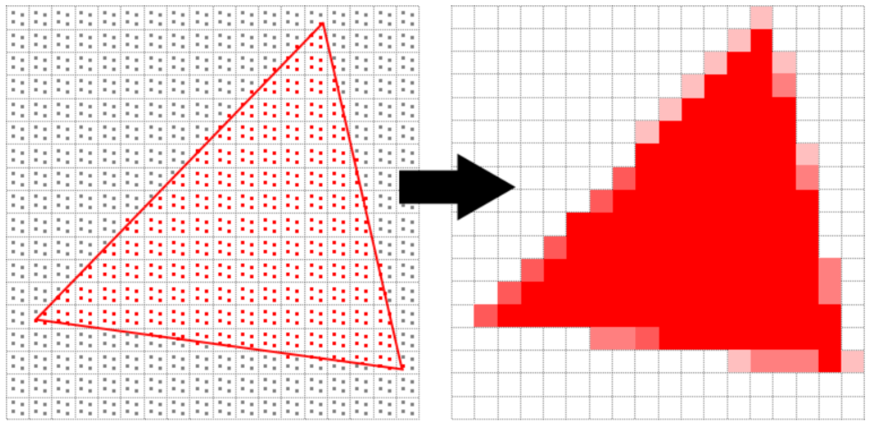


https://therealmjp.github.io/posts/msaa-overview/

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)



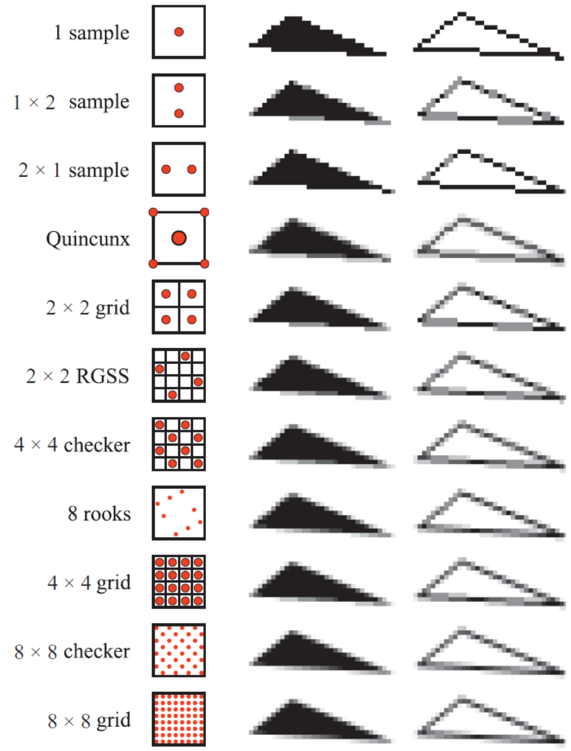


MSAAx4

https://vulkan-tutorial.com/Multisampling

Antialiasing: sampling rate

- By using more samples per pixel and blending those in some fashion a better pixel color can be computed
- Screen-based anti-aliasing schemes:
  - Sampling pattern is used for the screen
  - Samples are points samples
  - Pixel color is sum of weighted pixel samples



Limitations of display device

Limitation of display device

- **Display devices are limited** in:
  - Resolution (number of pixels)
  - Brightness (intensity)
  - Contrast
  - Color (gamut)
- Rendered images may contain values which can not be directly shown on display devices.

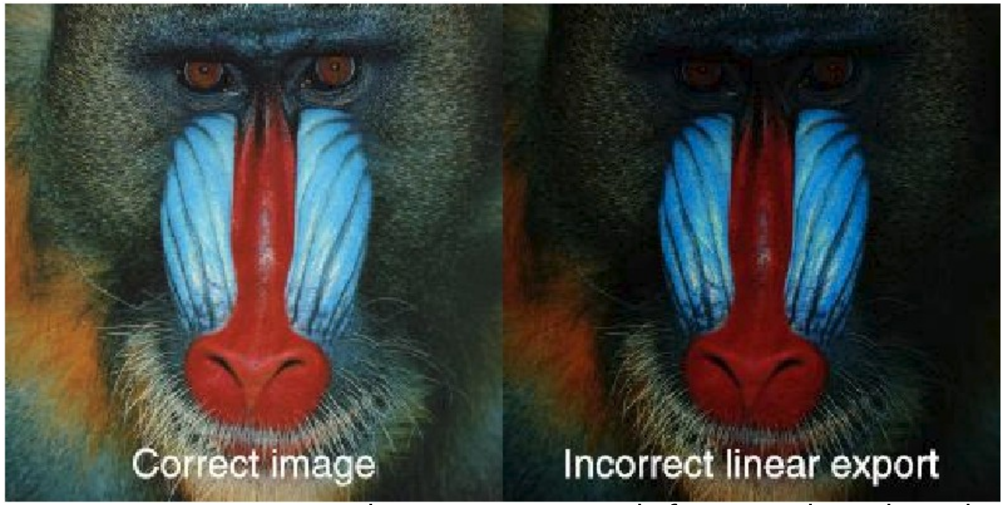
* also optical-electrical transfer function describe the other end of the process for image and video capture devices

Display limitations

- Display devices have **nonlinear relationship between input voltage and display amount of light**
  - Early display devices: cathode-ray tube (CRT).
    - As energy level applied to pixel is increased, the amount of light emitted doesn’t grow linearly but according to power law.
    - E.g., Pixel set to 50% will emit 0.5^2 amount of light → **nonlinear relationship**
  - LCDs and other display devices mimic the CRT response, although have different intrinsic tone response curves.
  - Relationship between digital values in image buffer and amount of light emitted from the display is described with **electrical-optical transfer function** (EOTF)*

Problem

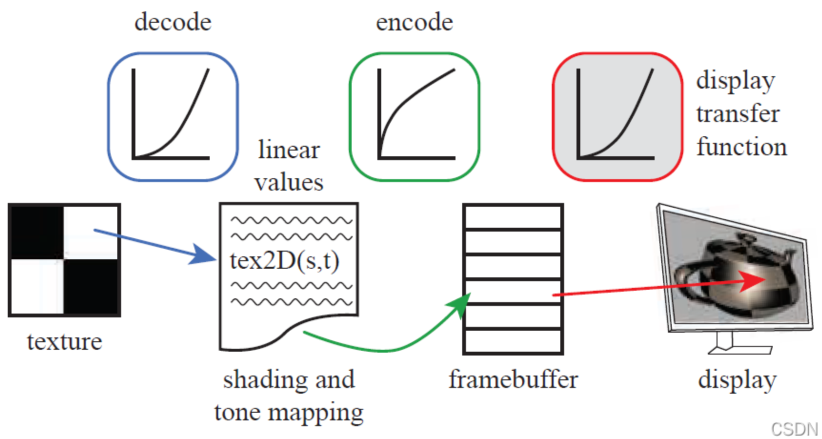
- Image which is rendered is in **linear color space** and will not display correctly if shown directly
  - Linear values will appear too dim on the screen



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

Solution: display encoding

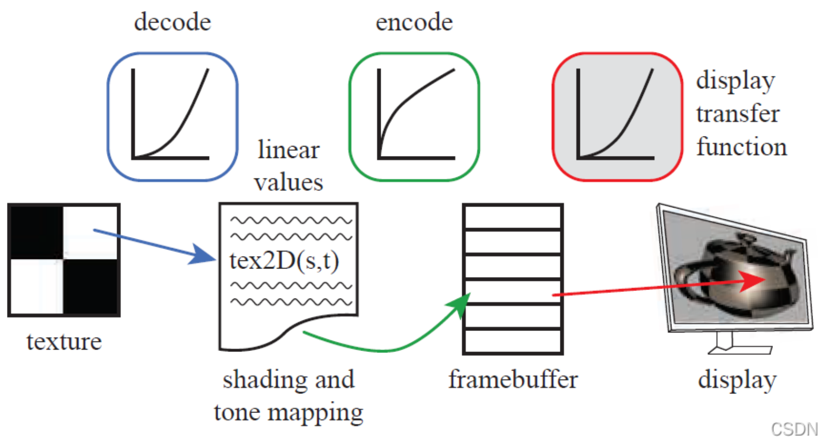
- When encoding linear color values for display, the goal is to cancel out the effect of display transfer function: inverse of display transfer function (EOTF) is applied to color values in image buffer – **gamma correction**
  - Standard transfer function for personal computer display is called **sRGB**



https://www.realtimerendering.com/

Gamma correction

- Gamma correction can be seen as 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 (y) the following formula is applied to all color values:
    - $y = x^{1 / gamma}$, where $gamma = 2.2$



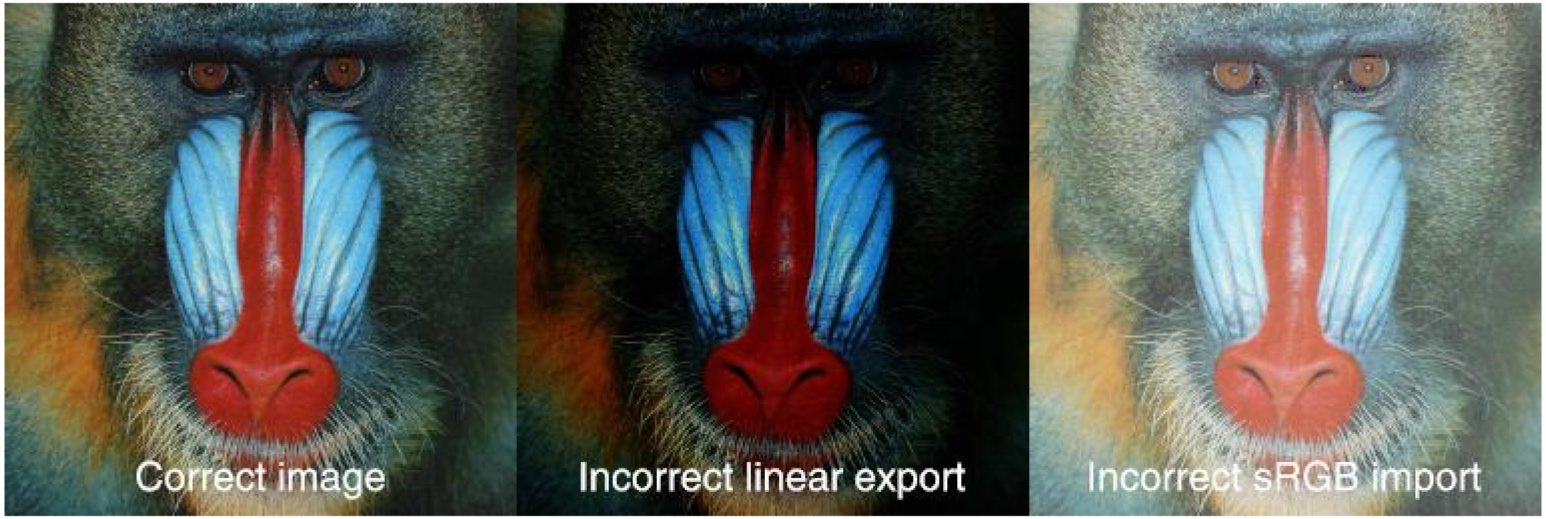
Modeling and rendering requirements

- All input values (e.g., texture image) for rendering and all values during rendering must be in **linear** colorspace.
  - Linear values are needed for correct addition and multiplication operations
  - Working with linear color gives more accurate arithmetical results
  - Makes color faster and easier for the computer to deal with.
  - Doubling the numeric values of a color in linear color space doubles the intensity and has no loss of precision

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

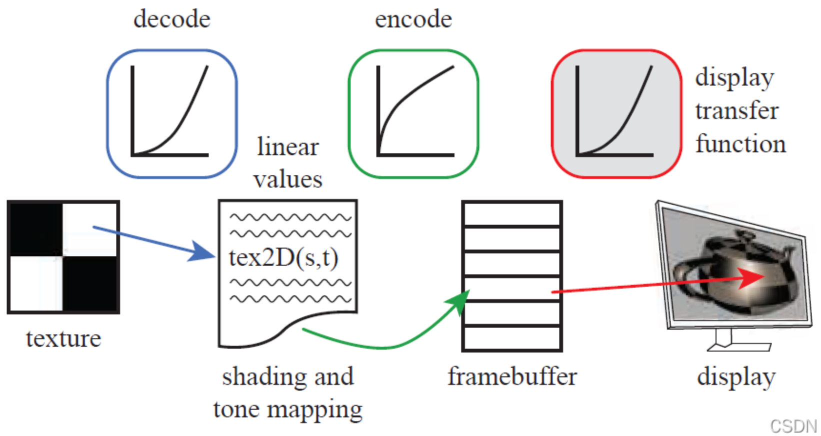
Problem

- 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 $gamma = 2.2$



Advanced display encoding

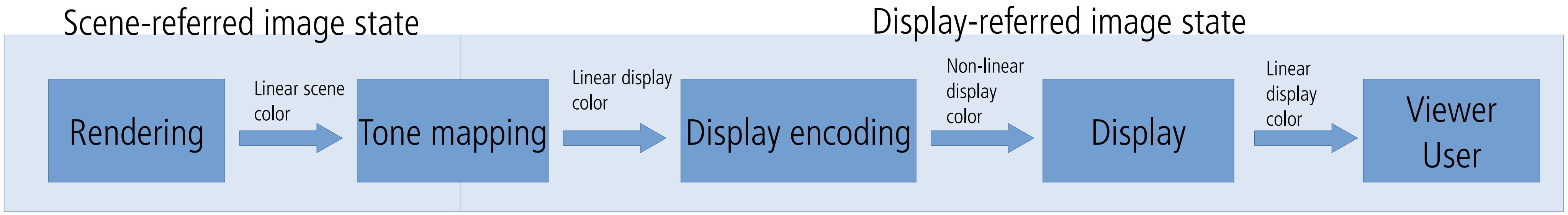
- We discussed display encoding for standard dynamic range monitors (SDR) which use sRGB display standard
- High dynamic range (HDR) displays and different display devices used other display standards which must be applied accordingly.

Tone mapping

- **Rendering:** calculating image color based on 3D scene description.
  - The results are pixel values in display buffer – display results still needs to be determined.
- **Display encoding** is process in which linear color (radiance) values are converted to nonlinear values for display hardware.
- Between rendering and display encoding there is **tone mapping step.**
- **Imaging pipeline** describes color handling from initial rendering to final display.

Imaging pipeline

- Tone mapping is step between following **image states***:
  - **Scene-referred**
    - Defined in reference to scene color (radiance) values.
    - Physically-based rendering computations are correct for this state
  - **Display-referred**
    - Defined in reference to display color (radiance) values.



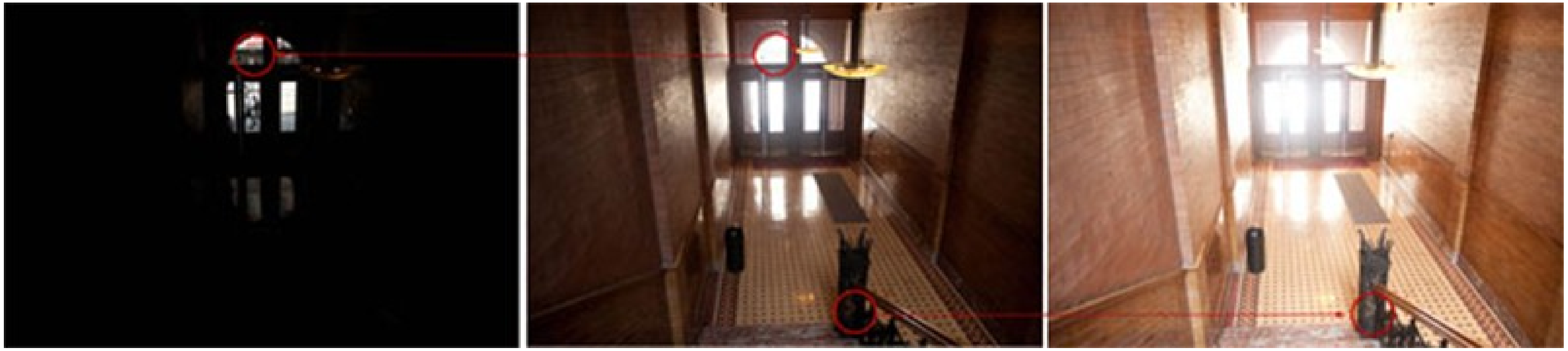
* Display limitations require non-linear transform between two states

Tone mapping

- Tone mapping (end-to-end or scene-to-screen transfer) is about converting scene color values to display color (radiance) values
  - Goal 1: **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.
  - Goal 2: **preferred image reproduction** – create display-referred image that looks better (to some criteria) than original scene.

Tone mapping: image reproduction

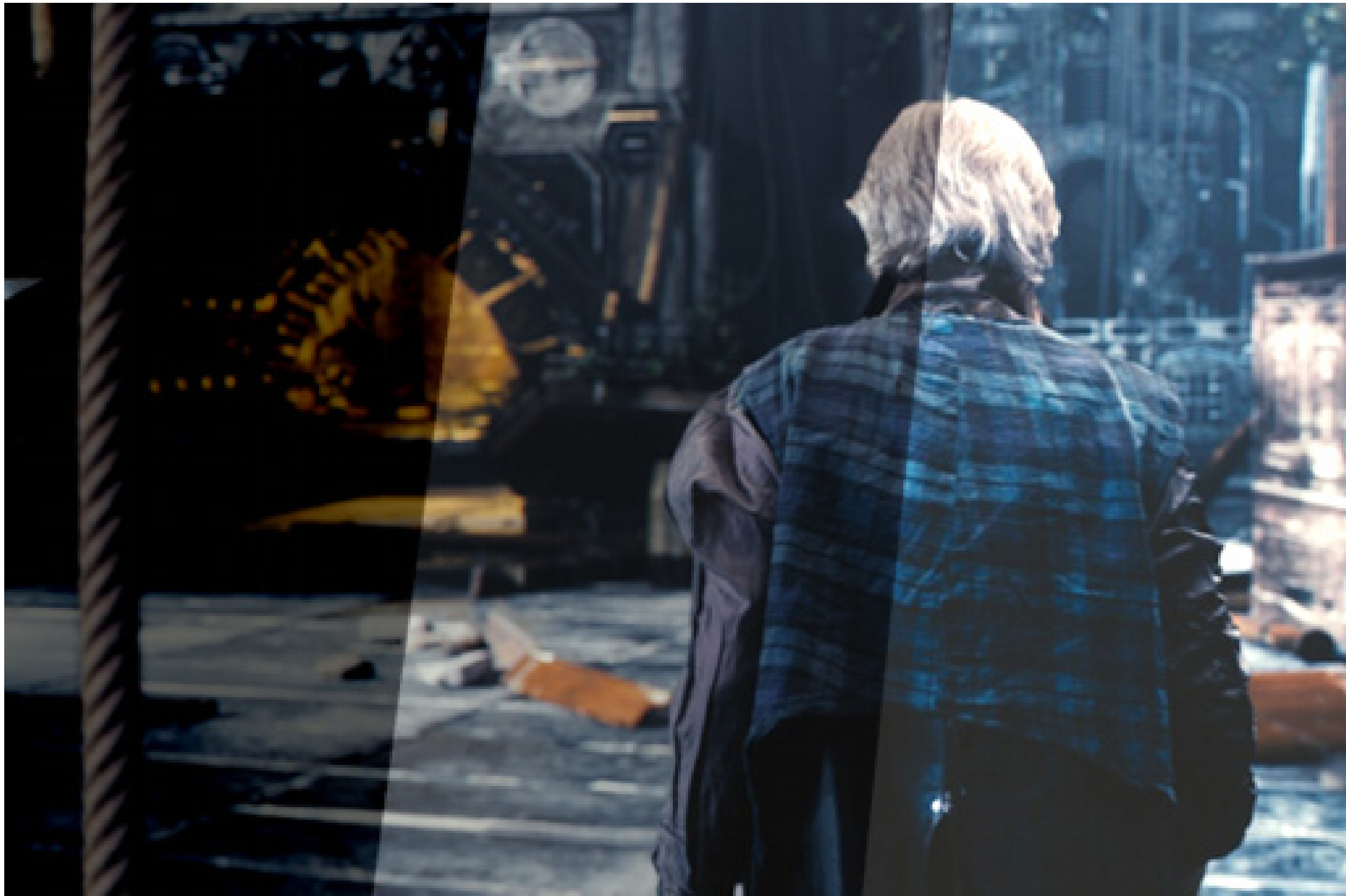
- Reproduce a similar perceptual impression as the original scene, problems:
  - Original scene **luminance** exceeds display capabilities
  - **Saturation** (purity) of original scene also exceeds display capabilities
- **Exposure** is critical to image reproduction
  - Exposure in photography refers 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 mapping is applied.



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

Tone mapping: image reproduction

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



Tone mapping: image reproduction

- Process of transforming floating point color values to the expected [0,1] range for LDR without loosing too much detail
- **Global tone mapping:**
  - Scale by exposure
  - Applying tone reproduction transform
- Local tone mapping:
  - Different mapping pixel-to-pixel based on surrounding pixels and other factors

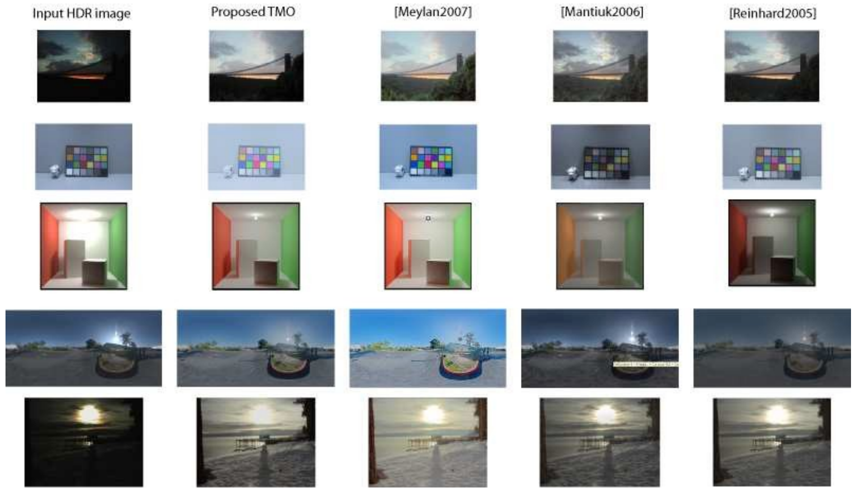
Global tone mapping: Exposure scaling

- Commonly used method from computing exposure is to compute average of pixel brightness of rendered image – **Reinhard method**

Global tone mapping: tone reproduction transform

- **Reinhard tone reproduction operator**
  - Early method for tone mapping
  - Leaves dark values unchanged and bright values asymptotically to white
- ACES tone mapping
  - Standard for tone managing for motion picture and television
  - Emerging in real-time applications: Unity and Unreal
- Other tone reproduction operators:
  - Drago, Duiker, Day, etc.

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

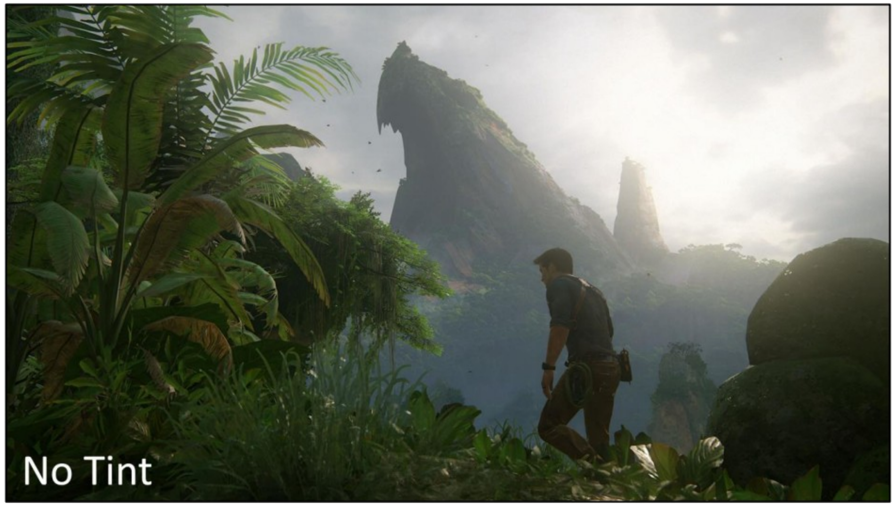


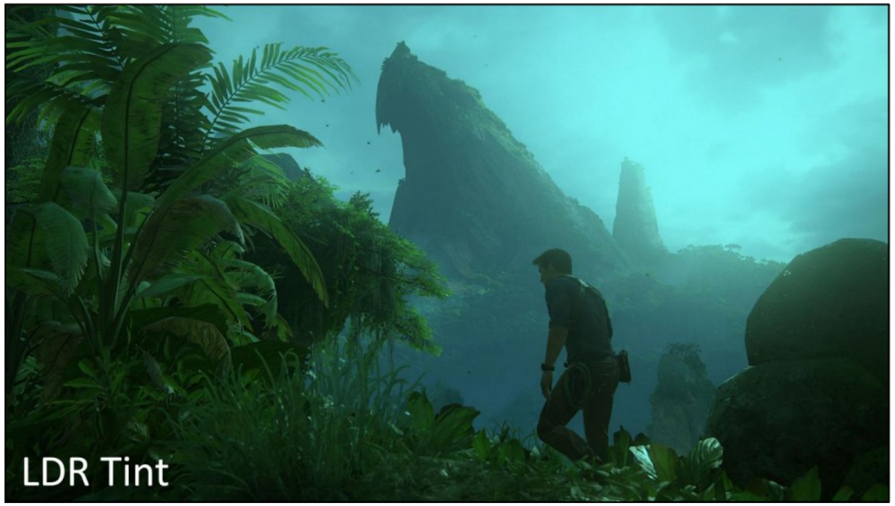
https://www.researchgate.net/publication/221039985_Spatio-temporal_Tone_Mapping_Operator_Based_on_a_Retina_Model

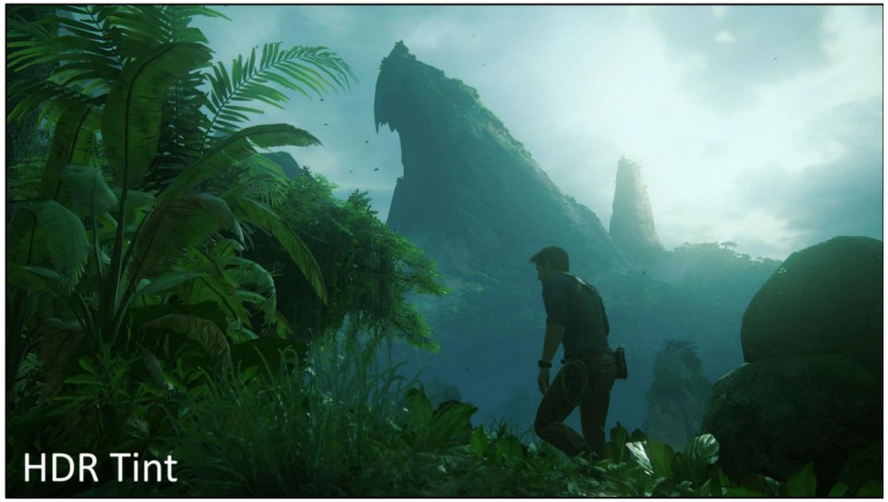
Tone mapping: preferred image reproduction

- Creative manipulation of image colors to obtain image desired artistic “look” - is called **color grading**.
- **Grading look up tables** (LUTs) contain desired color transformations which are applied on image
  - e.g., baked color curves
- Color grading is possible on:
  - Scene-referred images: produce hi-fi results
  - Display-referred images: easier to set-up

Color grading







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

To remember

- Raster images and file formats
- Aliasing
- Screen-based anti-aliasing
- Gamma correction
- Tone mapping: exposure and color-grading

More into topic

- https://developer.nvidia.com/sites/default/files/akamai/gameworks/hdr/UHDColorForGames.pdf
- Color grading:
  - http://filmicworlds.com/blog/minimal-color-grading-tools/
  - https://docs.unrealengine.com/4.27/en-US/RenderingAndGraphics/PostProcessEffects/ColorGrading/
- https://cinematiccolor.org/