Linux and High Dynamic Range (HDR) Display

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Linux and HDR Display

Disclaimer

- I am not a color expert.
- HDR is a broad topic.
- NVIDIA has not yet implemented HDR support in our Linux driver, though we have on Windows and Android.
- Goal today is to:
  - Give an overview of the building blocks of HDR from a window system perspective.
  - Raise awareness of some of the areas of the Linux ecosystem that may require updating for HDR.
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Ultra High Definition (UHD) Displays

Next generation displays aim to produce more realistic images.

- Higher pixel resolution ("4k" and "8k").
- Wider color gamut: express a wider range of colors than today.
- High Dynamic Range (HDR): express a wider range of luminance than today.
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Background: ITU-R BT.2020

- ITU-R BT.2020 (aka "Rec. 2020" or "BT.2020") recommends UHD parameters.
- This includes recommendations for:
  - Resolutions.
  - Refresh rates.
  - Chromaticity.
  - Signal formats (RGB 4:4:4, YCbCr 4:2:0, etc).
  - Digital representation (10- or 12-bit).
  - Transfer function.
- Often, when people say "BT.2020", they mean the BT.2020 color gamut.
- BT.2020’s color gamut is the goal; very few displays get close to that today.
- Current generation UHD displays are much closer to the DCI-P3 color gamut.
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Background: Chromaticity

• Different color spaces represent different sets of colors (color gamuts).
• CIE XYZ color space:
  • Color primaries X, Y, Z.
  • Y == luminance.
• CIE xy chromaticity diagram: 2D projection of 3D CIE XYZ color space.
• Other color spaces described by x,y coordinates within CIE xy chromaticity diagram:
  • x,y location of the red, green, and blue primaries.
  • x,y location of the “white point”.
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Background: Linear versus non-Linear Color Spaces

• Linear color space is a color representation where:
  • There is linear relationship between numbers stored and intensities they represent.
  • E.g., doubling the stored number doubles the represented intensity.
  • Always do graphics operations (blending, scaling, etc) in linear color space.
• However, human perception is not linear: more sensitive to darks than lights.
• Given finite discrete steps (e.g., 0-255), linear isn’t great:
  • Insufficient granularity in the darks; wasted precision in the lights.
  • So, generally recommended to store colors in non-linear color space.
  • The most ubiquitous non-linear color space is sRGB.
• Most (pre-HDR) monitors expect their input to be sRGB.
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What is HDR?

Informally:
• Brights are brighter; darks are darker.
• Details are more perceivable in both darks and brights.

More formally:
• HDR increases the range and granularity of luminance.
• Luminance is a measurement of intensity over area.
  • Unit is: candela per square meter (cd/m^2), aka "nit".
  • Standard Dynamic Range (SDR) (i.e., pre-HDR displays): max ~100 nits.
  • First generation HDR displays max ~1000 nits; HDR defines up to max 10000 nits.

HDR is about allowing highlights to be brighter, not making entire scene brighter.
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HDR Rendering is Not New

Many 3D graphics applications already use HDR for rendering.

• Create an FP16 (aka half-float, 16-bits per component) buffer.
• Render in FP16.
• At the end of the pipeline, “tone-map” from FP16 to lower-precision, lower luminance, e.g., RGBA8 SDR, for display.
• Now that we have more capable displays, we want to:
  • Give applications the information they need to tone map for the target HDR display.
  • Be able to pass the application’s higher-precision content through to the display.
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HDR Basic Flow

The basic flow for 3D applications to render and display HDR:

- Create FP16 buffer for rendering.
- Render to FP16, using scRGB color space.
- Tone map the scRGB FP16 content, for the target monitor’s capabilities.
- Provide metadata to be sent to monitor.
- Composite with SDR content.
- Receive scRGB FP16 image.
- Perform inverse EOTF to encode FP16 in display signal.
- Send encoded display signal and HDR InfoFrame to monitor.
- Receive HDR InfoFrame.
- Perform EOTF to decode digital signal into HDR content.
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scRGB

• Aka Canonical Compositing Color Space (CCCS).
• Has the same chromaticity coordinates as sRGB.
• Has a linear, FP16 encoding.
• (0.0, 1.0) corresponds to the traditional sRGB colors.
• Can have values outside of (0.0, 1.0).
• Values above or below (0.0, 1.0) extend the color range.
• Is absolute, rather than relative:
  • Relative: 0.0==darkest the monitor can display, 1.0==brightest the monitor can display.
  • Absolute: 1.0==80nits, 12.5==1000nits.

These properties make scRGB good for representing HDR content, and also good for compositing HDR content with SDR content.
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HDR Metadata: SMPTE 2086

SMPTE 2086 defines HDR-related metadata passed between GPU and monitor:

- $x,y$ chromaticity coordinates for color primaries and white point (i.e., color gamut).
- Maximum luminance (in cd/m$^2$).
- Minimum luminance (in cd/m$^2$).

The GPU needs this metadata from monitor, to know how to render image.
The monitor needs this metadata from GPU, to know how to interpret signal.

CEA-861-3 defines how HDR metadata is transferred:

- Encoded in EDID (Display => GPU).
- Encoded in InfoFrame (GPU => Display).
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HDR Transfer Functions

Electro-Optical Transfer Function (EOTF):
- Defines how display should convert non-linear digital signal to linear light values.
- Optimized for bandwidth: compress signal into as few bits as possible, sacrificing precision where it won’t be missed.
- sRGB is the defacto EOTF for SDR.

Two common HDR EOTFs:
- SMPTE 2084: Perceptual Quantizer (PQ).
- Hybrid-Log (HLG).

To create digital signal, GPU needs to do inverse of EOTF (aka “OETF”).
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HDR Basic Flow (again)

The basic flow for 3D applications to render and display HDR:

Application
- Create FP16 buffer for rendering.
- Render to FP16, using scRGB color space.
- Tone map the scRGB FP16 content, for the target monitor’s capabilities.
- Provide metadata to be sent to monitor.

Driver (or composite manager)
- Composite with SDR content.
- Receive scRGB FP16 image.

Driver/GPU
- Perform inverse EOTF to encode FP16 in display signal.
- Send encoded display signal and HDR InfoFrame to monitor.

Monitor
- Receive HDR InfoFrame.
- Perform EOTF to decode digital signal into HDR content.
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Missing Pieces on Linux: HDR Metadata

- An API for getting HDR metadata from display.
  - Maybe this should just be client-side library that parses the EDID.
  - Maybe this should be reported by drivers... depends on whether drivers will need to influence the metadata.
  - Potentially composite managers would need to influence metadata, too?

- An API for applications to express the HDR metadata for the buffers they present.
  - Consider arbitration: multiple applications could provide input that influences metadata.
  - Perhaps composite managers would be involved in metadata arbitration?
Missing Pieces on Linux: Displaying FP16

- Submitting FP16 to display engine.
  - Eventually display hardware will do FP16 => digital signal (using inverse EOTF).
  - Until then, use shader.

- Would be nice if current SDR RGBA8 windows can coexist in the same desktop as FP16 HDR windows.
  - scRGB defines a good way for the two to be composited together.
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Missing Pieces on Linux: Displaying FP16 In Wayland

- Wayland compositors will need to be FP16-aware.
- Be able to accept FP16 buffers from clients.
- Be able to composite SDR RGBA8 with HDR FP16 into an FP16 buffer.
- Be able to flip to FP16 buffer.
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Missing Pieces on Linux: Displaying FP16 In X11

• Primary producers of HDR content will be:
  • 3D APIs (OpenGL, Vulkan).
  • Video APIs (VDPAU, VAAP).
• Don’t need X rendering to FP16, but easier to prohibit or allow?
• Or make FP16 look like SDR RGBA8 to X rendering (hiding RGBA8/FP16 conversions in drivers)?
• Should we allow the root window to be FP16?
• Or add an FP16 overlay visual (like traditional 8-bit color index overlay)?
  • When FP16 window is unredirected, driver’s job to composite HDR FP16 with SDR RGBA8.
  • When FP16 window is redirected, composite manager’s job to composite HDR FP16 with SDR RGBA8.
  • Composite managers create FP16 child window of Composite Overlay Window to display HDR FP16.
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Conclusion

• Hopefully these slides give context to help understand HDR documentation.
• There are several open design questions for enabling HDR on Linux.
• Over coming months, we’ll try to make more concrete strawman proposals.
• Questions or feedback: aritger ‘at’ nvidia.com
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Links, Further Reading

HDR:
- [https://developer.nvidia.com/high-dynamic-range-display-development](https://developer.nvidia.com/high-dynamic-range-display-development)

Linear RGB vs sRGB:
- [http://www.4p8.com/eric.brasseur/gamma.html](http://www.4p8.com/eric.brasseur/gamma.html)
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Specifications

- **ITU-R BT.2020**
  - Defines numerous UHD parameters.

- **SMPTE 2086**
  - Defines HDR metadata.

- **SMPTE 2084**
  - Defines the Perceptual Quantizer (PQ), a particular EOTF that is particularly efficient at encoding HDR content.

- **CEA-861-3**
  - Defines how SMPTE 2086-defined metadata should be encoded in EDID and InfoFrame.