AGENDA

- HDR Overview
- Human Perception
- Colorspaces
- Tone & Gamut Mapping
- ACES
- HDR Display Pipeline
- Best Practices
- Final Thoughts
- Q & A
WHAT IS HIGH DYNAMIC RANGE?

HDR is considered a combination of:

- Bright display: 750 cm/m$^2$ minimum, 1000-10,000 cd/m$^2$ highlights
- Deep blacks: Contrast of 50k:1 or better
- 4K or higher resolution
- Wide color gamut

What’s a nit?

A measure of light emitted per unit area.

1 nit (nt) = 1 candela / m$^2$
BENEFITS OF HDR

Improved Visuals

Richer colors
Realistic highlights
More contrast and detail in shadows
Reduces / Eliminates clipping and compression issues
HDR isn’t simply about making brighter images
HUNT EFFECT
Increasing the Luminance Increases the Colorfulness

- By increasing luminance it is possible to show highly saturated colors without using highly saturated RGB color primaries
- Note: you can easily see the effect but CIE xy values stay the same
STEPHEN EFFECT
Increased Spatial Resolution

More visual acuity with increased luminance. Simple experiment - look at book page indoors and then walk with a book into sunlight
HOW HDR IS DELIVERED TODAY

High-end professional color grading displays

- Dolby Pulsar (4000 nits), Dolby Maui, SONY X300 (1000 nit OLED)

UHD TVs

- LG, SONY, Samsung... (1000 nits, high contrast, UHD-10, Dolby Vision, etc)

Rec. 2020 UHDTV wide color gamut

SMPTE ST-2084 Dolby Perceptual Quantizer (PQ) Electro-Optical Transfer Function (EOTF)

SMPTE ST-2094 Dynamic metadata specification
### REAL WORLD VISIBLE LUMINANCE RANGE

Range of $10^{17}$ Luminance Levels

<table>
<thead>
<tr>
<th>Luminance Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7.0 \times 10^{10}$ cd/m²</td>
<td>Lightning flash</td>
</tr>
<tr>
<td>$3.2 \times 10^{9}$ cd/m²</td>
<td>Sun (zenith)</td>
</tr>
<tr>
<td>$4.3 \times 10^{5}$ cd/m²</td>
<td>Sun (horizon)</td>
</tr>
<tr>
<td>$1.2 \times 10^{5}$ cd/m²</td>
<td>60W incandescent light bulb</td>
</tr>
<tr>
<td>$3.0 \times 10^{4}$ cd/m²</td>
<td>White paper in noon sunlight</td>
</tr>
<tr>
<td>$1.3 \times 10^{4}$ cd/m²</td>
<td>Clear sky (horizon)</td>
</tr>
<tr>
<td>$4.2 \times 10^{3}$ cd/m²</td>
<td>Full moon</td>
</tr>
<tr>
<td>$3.6 \times 10^{3}$ cd/m²</td>
<td>White paper in daylight shade</td>
</tr>
<tr>
<td>$1.3 \times 10^{2}$ cd/m²</td>
<td>White paper under office light</td>
</tr>
<tr>
<td>$1.0 \times 10^{2}$ cd/m²</td>
<td>White of computer monitor or TV</td>
</tr>
<tr>
<td>$1.0 \times 10^{2}$ cd/m²</td>
<td>Wax candle flame</td>
</tr>
<tr>
<td>$1.0 \times 10^{2}$ cd/m²</td>
<td>Clear sky, twilight</td>
</tr>
<tr>
<td>$2.4 \times 10^{-1}$ cd/m²</td>
<td>Brightest star (Sirius)</td>
</tr>
<tr>
<td>$1.3 \times 10^{-3}$ cd/m²</td>
<td>Absolute threshold (single flash)</td>
</tr>
<tr>
<td>$4.0 \times 10^{-4}$ cd/m²</td>
<td>Starless night sky</td>
</tr>
<tr>
<td>$7.5 \times 10^{-7}$ cd/m²</td>
<td>Absolute threshold (steady light)</td>
</tr>
</tbody>
</table>
REAL WORLD VISIBLE LUMINANCE RANGE

Human Visual Response

- Limited to $10^5 - 10^6$ with a 95% contrast ratio of ~10000:1 (18 stops)
- Example: Full Moonlight - Can see details on the moon surface while simultaneously seeing details in the illuminated ground surface. (4200 cd/m2 to 0.012 cd/m2)
- Dark Adaptation
  - Slow, can take up to 30 minutes to see in the dark
- Light Adaptation
  - Fast, less that a second to a minute to adapt to bright light
- HDR displays should have a larger $10^7$ dynamic range
COLOR PRECISION
How do we avoid banding?
HUMAN PERCEPTION

Visibility of banding [Barten 1999]

Contrast Ratio (%) vs. Image luminance (cd/m²)

- Banding invisible
- Banding visible
COLOR PRECISION
sRGB

Contrast Ratio (%)

Image luminance (cd/m²)

sRGB 8b/color
sRGB 10b/color
COLOR PRECISION

Digital Cinema - 12bit, gamma 2.6, full white = 48 cd/m²
COLOR PRECISION

SMPTE ST-2084 - A new 12-bit HDR Transmission Standard

Contrast Ratio (%) vs. Image luminance (cd/m²)
COLOR PRECISION
FP16 - For GPU Rendering
REAL WORLD VISIBLE COLORS
Pointer’s Gamut of Naturally Occurring Colors

The CIE 1931 chart defines a coordinate system for all possible colors that the human eye can see [Pointer 1980] the colors of ‘real world’ objects.
COLORSPACES
Comparison of Common Colorspaces

Rec 2020
• UHDTV Standard
• 60% of visible colors
• 99% of Pointer’s Gamut

DCI-P3
• Digital cinema projectors

AdobeRGB (1998)
• Includes printable colors
• Same red and blue
• Purer green

scRGB (Vista)
• [-0.5, 7.5]
• (1,1,1) matches sRGB white

sRGB (1996)
• Designed around CRT
• Same primaries as Rec. 709
• 33% of visible colors
• 70% of Pointer’s Gamut
COLORSPACES
Impact on Rendering

Same colors can be represented in the different spaces, but...

- Modulus operations will yield different results based on the color primaries used
  - Material * Light is color space dependent
  - Purple in one color space will be brown in another
  - Issue is orthogonality of primaries in the other color space

- Rendering always implies a set of primaries
  - Important to keep colorspace consistent through development
  - Transform final result to different colorspace primaries
COLORSPACES
Challenges with Color Primaries

<table>
<thead>
<tr>
<th>*</th>
<th>sRGB</th>
<th>DCI</th>
<th>BT.2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Red</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Primaries in a color space are not orthogonal when transformed into another color space. This changes the results of modulation.
SCENE LINEAR VS OUTPUT LINEAR COLOR

Scene Referred (Scene Linear)
- Linear colors as they represent light in the scene
- Photons striking the virtual film

Output Referred (Output Linear or Display Referred)
- Linear colors as they are represented by the display
- Photos emitted by the display
- May have an EOTF applied.
TONE MAPPING
Conversion from Scene Referred to Output Referred

Compresses or clips the color data into the output range
Compresses shadows and high lights
Enhances mid-tone contrast
Irreversible, data is lost
TONE MAPPING
Why Tone Map for HDR?

HDR displays still limited (1000 nit max)

Real world luminance is much higher
  • Sun over 1000x more luminous
  • 100w bulb over 10x more luminous

Permits differentiation of luminance levels

No one true tone mapper, choice depends on the desired aesthetics

HDR adds complexities that could be ignored in LDR
TONE MAPPING

Linear

Scale and clip to [0,1]

Same general problems as in LDR

- Hard clip at the limit of the capabilities of the display
- Sun and light bulb likely to have same luminance on screen

Scene may look dull

Needs to account for the larger luminance range when scaling / clipping

- Otherwise, scene will just get brighter
TONE MAPPING

Reinhard

Classic $x/(x+1)$

No concept of output brightness
  - In HDR, images just get a lot brighter

Example: 0.18 will change from 12-45 nits to 150+ nits
  - 0.18 is often considered the color of asphalt after exposure
  - Result is a bright road

Limited control
TONE MAPPING
Drago

Algorithmic operator (similar to Reinhard)
Compressed range using an adaptive log scale
Provides argument for display output luminance
Better adapts to display brightness
TONE MAPPING

Filmic

S-curve in logarithmic space
Enhances mid-tones
Compresses shadows and highlight
Approximates the behavior of traditional film
GAMUT MAPPING
Mapping of Unrepresentable Colors to Representable Colors

Stretching or compressing one color space to fit within another.

Remapping of the chromaticity values

Many different methods to remap the color space (clip, soft clip, scale, etc)

All methods have non-trivial caveats (hue shifts, memory colors, etc)
ACES
Academy Color Encoding System

Standard for digital post-production

Driven by the Academy of Motion Pictures

Provides framework for end-to-end processing and preservation of data

Defines reference transforms as part of the framework

  Tone mapping for different classes of displays

Open-source and available on GitHub

  Reference is written in Color Transform Language
ACES
Pipeline Components

Framebuffer

Input Device Transform

IDT
Convert to ACEScc

Look Modification Transform

LMT
Apply Look 3D LUT

Reference Rendering Transform

RRT
Device-Independent Tone Mapping

Output Device Transform

ODT
Device-Dependent Tone Mapping

Scene Referred / Linear Color Data

Display

GPU Technology Conference
ACES
Tone Mapper

Tone mapper is a filmic sigmoid-style-curve
Defined by segmented quadratic spline in reference implementation
  Two splines joined at middle gray
Operates per-channel in a wide color space
  Results in natural desaturation at the shoulder
Input middle gray is set at 0.18
Parameterized ODT developed by NVIDIA

Allows adaptation of the reference transforms to a wider set of uses

- Alter output middle gray level
- Alter input and output range of tone mapper
- Saturation adjustment
- Contrast adjustment
HDR DISPLAY PIPELINE
Practical Path to Utilizing Current UHD Displays

1) Create content with sRGB primaries as done today for LDR.
2) Render high-quality HDR using physically-based shading.
3) Post process in the scene referred space
4) Apply color grading to the rendered scene referred image
5) Tone map with a filmic ACES-derived tonemapper
6) Keep backbuffer in FP16 scRGB
7) Composite 8-bit sRGB referenced UI as normal
HDR DISPLAY PIPELINE

Logical Pipeline for HDR Output

- Linear Scene RGBA16F
- UI sRGB8
- Post-Process
- Color Grade
- Tone Map
- Composite & Encode EOTF
- Backbuffer FP16 or RGB10
DISPLAYING HDR ON WINDOWS

Quick Start Guide

Create backbuffer as R16G16B16A16_FLOAT/FP16 - Ensures enough color precision

DirectX: Create DXGI_FORMAT_R16G16B16A16_FLOAT swap chain

OpenGL: Specify WGL_PIXEL_TYPE_ARB = WGL_TYPE_RGBA_FLOAT_ARB
with color depth 16 (WGL_RED_BITS_ARB = 16,
WGL_GREEN_BITS_ARB = 16, WGL_BLUE_BITS_ARB = 16)

Make window fullscreen exclusive - Prevents OS compositor from destroying data

Query HDR capability from NVAPI

Call NVAPI to send HDR metadata and enable HDR

Output linear tonemapped scene to FP16 scRGB backbuffer in scRGB colorspace
DISPLAYING HDR ON WINDOWS
Use NVAPI to Enumerate GPUs and Connected Displays

// Enumerate GPUs and connected displays

NvPhysicalGpuHandle *nvGPUHandle = (NvPhysicalGpuHandle *)calloc(NVAPI_MAX_PHYSICAL_GPUS, sizeof(NvPhysicalGpuHandle));;
NvU32 nvGPUCount;
NvU32 *nvConnectedDisplayIdCount = (NvU32 *)calloc(NVAPI_MAX_DISPLAYS, sizeof(NvU32));
NV_GPU_DISPLAYIDS **nvConnectedDisplayIds =
    (NV_GPU_DISPLAYIDS **)calloc(NVAPI_MAX_PHYSICAL_GPUS, sizeof(NV_GPU_DISPLAYIDS));

if (EnumerateGPUsAndDisplays(nvGPUHandle, &nvGPUCount, nvConnectedDisplayIds, nvConnectedDisplayIdCount) != NVAPI_OK)
{
    MessageBox(NULL, TEXT("GPU and Display Enumeration Failed."), applicationTitle, MB_OK | MB_ICONINFORMATION);
    return 0;
}
DISPLAYING HDR ON WINDOWS
Query HDR Capabilities of Each Display from NVAPI

// On each GPU, get the HDR capabilities of each active display.
NvU32 gpu = 0;
NvU32 display = 0;
while (gpu < nvGPUCount)
{
    while (display < nvConnectedDisplayIdCount[gpu])
    {
        NV_HDR_CAPABILITIES hdrCapabilities;
        if (NvAPI_Disp_GetHdrCapabilities(display, &hdrCapabilities) != NVAPI_OK)
        {
            MessageBox(NULL, TEXT("NVAPI GetHdrCapabilities Failed."),
                        applicationTitle, MB_OK | MB_ICONINFORMATION);
            return 0;
        }

        // If HDR is supported, break
        if (hdrCapabilities.isST2084EotfSupported)
            break;

        display++;
    }
    gpu++
}
DISPLAYING HDR ON WINDOWS

Call NVAPI To Send HDR Meta Data and Enable HDR

// If HDR is supported, enable it
if (hdrCapabilities.isST2084EotfSupported) {
    NV_HDR_COLOR_DATA hdrColorData = {};  
    memset(&hdrColorData, 0, sizeof(hdrColorData));

    hdrColorData.version = NV_HDR_COLOR_DATA_VER;
    hdrColorData.cmd = NV_HDR_CMD_SET;
    hdrColorData.static_metadata_descriptor_id = NV_STATIC_METADATA_TYPE_1;
    hdrColorData.hdrMode = NV_HDR_MODE_UHDA;

    if (NvAPI_Disp_HdrColorControl(display, &hdrColorData) != NVAPI_OK) {
        MessageBox(NULL, TEXT("NVAPI HdrColorControl Failed."), applicationTitle,  
                   MB_OK | MB_ICONINFORMATION);
        return 0;
    }
}
DISPLAYING HDR ON LINUX
DISPLAYING HDR ON LINUX
Not Possible Today Due to Lack of Infrastructure

32-bit XServer prevents color deeper than R10G10B10A2.

No infrastructure for metadata transfer

Will be discussed at XDC 2016 Conference September 21-23 in Helsinki, Finland
**HDR BEST PRACTICES**

Physically-Based Rendering

Makes light interactions more correct / plausible.
- Results in proper highlights, not just a hack that looks good in LDR

Creates values on a scale consistent with the real world
- [0,1] brightness level doesn’t make sense in an HDR world
- Will need to make compromises (FP16 won’t represent the brightest sun)
HDR BEST PRACTICES

Colorspace

Keep using sRGB primaries.

Keeps consistency with the present art pipeline

- No surprises for artists
- No gamut mapping problems on LDR displays

Will still reap the benefits of brightness and brighter saturated colors

Starting point. Plan to be more aggressive in the future.
HDR BEST PRACTICES
Gamut Remapping

Stretches rendering done with sRGB primaries to more extreme ones.

- Produces richer / more saturated colors
- May work OK for some applications, not so much for others

Will present challenges with existing artwork

- Unnatural skin tones
- Hue shifting
- Memory color
HDR BEST PRACTICES

Luminous Effects

Make things that glow, glow at a level consistent with the light source

- Emissive level and light source should be correlated

Looks odd when a specular high light outshines a light source
HDR BEST PRACTICES
Scene Referred Post-FX

Perform operations that require linear lighting prior to tone mapping.

- Bloom
- Motion blur
- Depth of field

Operating scene-referred maintains consistency

- Same operation for HDR and LDR
HDR BEST PRACTICES

Color Grading

Ideally done in scene-referred space

- Makes operations consistent LDR/HDR
- Avoids tone mapping “fix-ups”
HDR BEST PRACTICES
Luminance-Aware Tone Mapping

Many operators designed to work within a generic [0-1] space.

- How bright is 1.0?
  - Scaling to a 1000 nit display would display asphalt at 100 nits

Need an operator that understands the output luminance

- Middle gray stays at a reasonable level
  - Colors only compressed where they need to be

Use ACES or Drago
HDR BEST PRACTICES

UI Compositing

UI typically authored in straight RGB

- Need to composite properly into the color space of the HDR scene

Using scRGB backbuffer provides simple solution

- Same sRGB primaries with (1, 1, 1) as the brightness level for white
- Blending just works.
HDR BEST PRACTICES
UI Blending Challenges

UI may look dimmer / duller than intended
- Due to adaptation of the eye to the brighter colors of the HDR display
- Scale up the UI luminance to counteract this

Transparent elements may suffer glow throw effects
- Example: 1000 nit highlight behind a transparent dialog with white text
- Solution: Clip / Apply simple LDR tone map to scene elements underneath
HDR SDK
HDR Display Sample Code

Simple app demonstrating ACES tone mappers + HDR display
Allows setting HDR metadata to enable HDR on UHD TVs
Offers standard ACES tone mappers + customized ACES tone mappers
Provides EXR and HDR file format loading to visualize HDR data
Offers exposure scaling and range ‘enhancement’ tools

http://developer.nvidia.com/high-dynamic-range-display-development/
HDMI 2.0a is required.

- On Quadro GPUs will need an active DP 1.2 -> HDMI 2.0a dongle.
THINGS TO COME
Support for HDR is Evolving

Native OS Support for HDR

- Will remove requirement for full-screen exclusive window
- Include support for HDR10/UDH metadata transmission replacing NVAPI functions.

GPU Hardware support

DP 1.4 metadata support
MORE INFORMATION

http://developer.nvidia.com/high-dynamic-range-display-development

- White Paper
- SDK


Q & A
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