THE VIRTUAL FRONTIER: COMPUTER GRAPHICS CHALLENGES IN VIRTUAL REALITY

Dr. Morgan McGuire | NVIDIA Research
NVIDIA RESEARCH

120 World-Class Ph.D. Researchers
Today, everyone is a high-performance computer user, with GPUs in phones, tablets, desktops, game consoles, and cars.
Power User Technology

VISION

Pervasive

FUTURE VR
1. Virtual reality will be the new interface to computing for everyone
2. Virtual reality requires a new graphics system
   sensors, algorithms, physics, rendering, AI, data structures, processors, optics, and displays
MODERN GRAPHICS SYSTEMS
VISUAL FIDELITY OF FILM CGI

Deadpool (Marvel)
FILM CGI: CONCEPT TO PHOTONS

Preproduction
Script
Characters
Costumes
Sets

Production
Performance
Modeling
Rigging
Animation
Texturing
Lighting
Simulation

Primitives
Particles
Triangles
Sub-D

Renderer
Path Tracer
Composite &
Color Grade
(Hours)

Display
Screen
24 Hz
9 Mpix
3D GAME SYSTEM

**Preparation**
- Script
- Characters
- Costumes
- Sets

**Production**
- Performance
- Modeling
- Rigging
- Animation
- Lighting simulation

**Primitives**
- Particles

**Renderer**
- Shadow Maps
- Rasterization
- AO
- Shade
- Post FX*

**Display**
- HDMI, Sync

* Includes depth of field, reflections, fog, color grading, motion blur, antialiasing

**User Input**
- Direction

**Primitives**
- Vectors
- Triangles

**AI**
- Network
- Simulation

**Display**
- 30Hz
- 2 MPix
3D GAME SYSTEM

* Includes depth of field, reflections, fog, color grading, motion blur, antialiasing
3D GAME SYSTEM

* Includes depth of field, reflections, fog, color grading, motion blur, antialiasing
3D GAME SYSTEM

* Includes depth of field, reflections, fog, color grading, motion blur, antialiasing
7X THROUGHPUT INCREASE

**3D GAME = 60 MPIX/S**
(1920 x 1080 @ MIN 30 FPS)

**MODERN VR = 450 MPIX/S**
(3024 x 1680* @ MIN 90 FPS)

* VR render resolution
3D GAME SYSTEM

*Includes depth of field, reflections, fog, color grading, motion blur, antialiasing*
3D GAME SYSTEM

* Includes depth of field, reflections, fog, color grading, motion blur, antialiasing
MODERN VR SYSTEM

User Input and Tracking

Primitives
Particles Triangles

Renderer
Shadow Maps Rasterization

Time Warp

HMD
HDMI, Sync
Display 90 Hz 5 MPix

Head Tracking

AI Network Simulation
LENS DISTORTION

- **Predistorted Image**
- **Optics**
- **User’s View**
MODERN VR SYSTEM

User Input and Tracking

Head Tracking

Renderer

HMD

HDMI, Sync

Display 90Hz

Time Warp + Lens Distortion

Rasterization

Shadow Maps

AI Network Simulation

Particles Triangles

Primitives
1. Virtual reality will be the new interface to computing for everyone

2. Virtual reality requires a new graphics system
   sensors, algorithms, data structures, processors, and displays

3. Pascal architecture upgrades the gaming system to modern VR
   warping, lens matched shading, multiprojection, stereo projection, variable resolution
FUTURE GRAPHICS SYSTEMS

The remainder of the talk describes active research, including new results not previously presented in public.

These are not products.
LIMITS OF HUMAN PERCEPTION

100,000x to 1Mx beyond modern VR

220° Horizontal
x 135° Vertical
x (120 pixels/degree)^2

≈ 400,000,000 pixels
= 200 x 1080p TVs
x 240 Hz

Future VR = 100,000 Mpix/s
Modern VR = 450 Mpix/s

+ High dynamic range (x2), photorealistic dynamic lighting (x10,000), ...
FOVEATED RENDERING
FOVEATED RENDERING

Conventional Approach: Aliasing
FOVEATED RENDERING
Our Approach: Perceptually Optimized
BEYOND TRIANGLES

Primitives
- Particles
- Triangles

Display
- 90Hz

AI
- Network
- Simulation

Points
- Text
- Voxels
- Light Fields

Renderer
- Shadow Maps
- Foveated Rasterization
- Time Warp + Lens Distortion

Head Tracking
- HDMI, Sync
- Display 90Hz

Head Tracking

Eye Tracking

User Input and Tracking

Primitives

HMD
McGuire et al., Real-time global illumination with light field probes, I3D 2017
COMPUTATIONAL DISPLAYS

- Primitives
  - Particles
  - Triangles
- Points
- Text
- Voxels
- Light Fields

- AI Network Simulation
- Shadow Maps
- Foveated Rasterization
- Time Warp
- HMD
- Varifocal Lens Distortion
- Display 90Hz

- Head Tracking
- Light Field
- Eye Tracking
- User Input and Tracking

- HDMI, Sync
COMPUTATIONAL DISPLAYS

Light Field Display

Display Prototype  GPU Output  Observed Image

Lanman and Luebke, Near-Eye Light Field Displays, SIGGRAPH Asia 2013
COMPUTATIONAL DISPLAYS
Varifocal Optics

Akşit et al., Varifocal Virtuality: A Novel Optical Layout for Near-Eye Display, SIGGRAPH 2017 Emerging Technologies
COMPUTATIONAL DISPLAYS

Varifocal Optics

Dunn et al., Wide field of view varifocal near-eye display using see-through deformable membrane mirrors, Proc. of IEEE VR 2017
PNEUMATIC HAPTICS

Primitives
- Particles
- Triangles
- Points
- Text
- 2½D Video
- Voxels
- Light Fields

AI Network Simulation

User Input and Tracking

HMD

Display 90Hz

HMD

Local Distortion
LOW LATENCY
Hierarchical Rendering

Primitives
- Particles
- Triangles
- Points
- Text
- 2½D Video
- Voxels
- Light Fields

AI Network Simulation

Renderer
- Remote GPU
- Shadow Maps
- Foveated Rasterization
- Time Warp

HMD
- Varifocal Lens Distortion
- Display 90Hz

User Input and Tracking
- Head Tracking
- Light Field
- Eye Tracking

Haptics
LOW LATENCY
Hierarchical Rendering

Crassin et al., CloudLight: A system for amortizing indirect lighting in real-time, JCGT 2015
LOW LATENCY
Hierarchical Rendering

Cloud GRID Platform
Tesla GPU

Local GeForce

Wearable Tegra

Crassin et al., CloudLight: A system for amortizing indirect lighting in real-time, JCGT 2015
LOW LATENCY
Hierarchical Rendering

Cloud GRID Platform
Tesla GPU

High speed network
Compressed lighting data

Wearable Tegra

*Crassin et al., CloudLight: A system for amortizing indirect lighting in real-time, JCGT 2015*
LOW LATENCY

Binary Frames

Primitives
- Particles
- Triangles
- Points
- Text
- 2½D Video
- Voxels
- Light Fields

Renderer
- Remote GPU
- Shadow Maps
- Foveated Rasterization

HMD
- Time Warp + Varifocal Lens Distortion
- Deep Focus Display 16000 Hz

User Input and Tracking

HMD

Head Tracking

Eye Tracking

Low Latency

Binary Frames

Remote GPU

Shadow Maps

Foveated Rasterization

HMR, Sync

Light Field

Haptics

AI

Network Simulation

Conventional Display: 60 Hz Source, No In-Display Offset Computation

Slow-Motion Playback Rate: 1/8 of Original

Our Algorithm: 60 Hz Source, 16 kHz In-Display Offset Computation
LOW LATENCY

Binary Frames

Motion Initiated

Data Received

Pixel Transmitted

Light Emitted

0.08 ms

Lincoln et al., From Motion to Photons in 80 Microseconds: Towards Minimal Latency for Virtual and Augmented Reality, IEEE VR 2016
LOW LATENCY
On-HMD Warping

Hardware Warping Prototype  Photographed in HMD  Warped Static Point Set
RAY & PATH TRACING

Primitives
- Particles
- Triangles

Points
- Text
- Voxels
- Light Fields

AI Network Simulation

Remote GPU
- Shadow Maps
- Foveated Rasterization

Renderer
- Light Field

Denoising
- Time Warp + Varifocal Lens Distortion

HMD
- Deep Focus Display 16000Hz

HMD
- HDMI, Sync

User Input and Tracking

Eye Tracking

Head Tracking

Haptics
10 rays/path

PATH TRACING

Deadpool (Marvel)
Visualization of path tracing noise

10 rays/path
1 path/pixel
10 rays/path
1000 paths/pixel
DENOISING PATH TRACING

Naïve Real-time Result

Chaitanya et al., Interactive reconstruction of Monte Carlo image sequences using a recurrent denoising autoencoder, SIGGRAPH 2017
Schied et al., Spatiotemporal variance guided filtering: real-time reconstruction for path tracing, High Performance Graphics 2017
Mara et al., An efficient denoising algorithm for global illumination, High Performance Graphics 2017
Chaitanya et al., Interactive reconstruction of Monte Carlo image sequences using a recurrent denoising autoencoder, SIGGRAPH 2017
Schied et al., Spatiotemporal variance guided filtering: real-time reconstruction for path tracing, High Performance Graphics 2017
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Mara et al., An efficient denoising algorithm for global illumination, High Performance Graphics 2017
AI GRAPHICS NVIDIA RESEARCH
SIGGRAPH 2017

AI Facial Animation

AI Anti-Aliasing

AI Denoising

AI Light Transport
MODERN VR SYSTEM

Primitives

Particles Triangles

AI Network Simulation

Shadow Maps

Rasterization

Time Warp + Lens Distortion

Renderer

HDMI, Sync

Display 90Hz

HMD

Head Tracking

User Input and Tracking

MODERN VR SYSTEM
FUTURE VR SYSTEM

Primitives
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Remote GPU

Denoising
- Time Warp + Varifocal Lens Distortion
- Deep Focus Display 16000Hz

HMD

Haptics

Points
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Light Field

Head Tracking

Eye Tracking

User Input and Tracking
1. Virtual reality will be the new interface to computing for everyone

2. Pascal architecture upgrades the gaming system to modern VR
   - GPU warping, lens matched shading, multiprojection, stereo projection, variable resolution

3. NVIDIA is innovating for a revolutionary new future VR system
   - Computational displays, varifocal optics, foveated & cloud rendering, light fields, binary frames, on-display warping, beam racing, haptics, path tracing, denoising
MODERN VR EXPERIENCES

Mechanics & Design
The Climb (Crytek)
SUPERHOT (Superhot Team)

Narrative & Characters
The Labs (Valve)

Simulation & Performance
NVIDIA VR Funhouse

Content
Google Earth VR

+Batman replacing Aperture
PROJECTOR-BASED DISPLAY
The Vanishing of Ethan Carter (The Astronauts)
CHALLENGE: FOCUS CUES

Vergence distance

Accommodation distance

Video from Narain et al., Optimal Presentation of Imagery with Focus Cues on Multi-Plane Displays, SIGGRAPH 2015
BEYOND TRIANGLES

Light Fields

McGuire et al., Real-time global illumination with light field probes, I3D 2017
NVIDIA AR/VR RESEARCH

Computational Displays
Light field displays and varifocal optics

Foveated Rendering
Perceptually-guided rendering for massive throughput

Ultra-Low Latency
Hierarchical & binary rendering, beam racing, near-display warp

Beyond Triangles
Points, voxels, light fields, and text

Path Tracing
Extending ray tracing leadership to cinematic quality rendering
NVIDIA VRWORKS SDK
BRINGING REALITY TO VR
NVIDIA HOLODECK HANDS-ON DEMO AT SIGGRAFP
NVIDIA PROJECT HOLODECK
# NVIDIA VRWORKS & PASCAL

Accelerating Modern VR

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VRWORKS & PASCAL
Hardware Acceleration for Modern VR

Lens Matched Shading & Multiprojection

Single-Pass Stereo

Preemption for Timewarp
VRWORKS & PASCAL

Hardware Acceleration for Modern VR

PhysX

Flex

VRWorks Audio

Hairworks

Flow

Cloth
FOVEATED RENDERING

High-fidelity foveal pixels

Low-fidelity peripheral pixels