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Lecture Overview & Learning Objectives I

- **Lecture Unit:** Augmented Reality and Virtual Reality
- **Lecture Topic:** Virtual Reality Workflow and Core Components
- **Primary Objectives:**
  - Analyze the end-to-end operational workflow of Virtual Reality (VR) systems.
  - Deconstruct the four foundational components of VR: Virtual World, Immersion, Sensory Feedback, and Interactivity.
  - Understand hardware and software architectures supporting real-time synthetic environments.
  - Evaluate key performance metrics including Motion-to-Photon latency and spatial tracking.

Fundamentals of Virtual Reality (VR) I

- **Definition of VR:** A computer-generated, three-dimensional synthetic environment that surrounds the user and responds in real time to human actions.
- **Reality-Virtuality Continuum:**
  - Situated at the extreme right of Milgram's continuum (completely digital environment).
  - Distinct from Augmented Reality (AR) which overlays digital assets onto physical surroundings.
- **Core System Objectives:**
  - Replace physical sensory inputs with high-fidelity digital signals.
  - Provide continuous, low-latency interaction loops.
  - Create convincing perceptual illusions of spatial presence.

High-Level VR System Workflow I

- **1. User Tracking & Input Capture:**
  - Continuous tracking of head, hands, and body posture via 3DoF/6DoF sensors.
  - Capture of controller inputs, hand gestures, and gaze vectors.
- **2. Simulation Engine Processing:**
  - Physics engine updates object positions, collisions, and state changes.
  - Scene graph update based on world logic and user interactions.
- **3. Multi-Modal Rendering Pipeline:**
  - Visual rendering of left and right eye buffers (Stereoscopic view).
  - Spatial audio rendering via Head-Related Transfer Functions (HRTF).
  - Haptic wave-form generation for controllers and haptic gloves.
- **4. Sensory Output Display:**
  - Displaying rendered frames on HMD micro-displays or CAVE screens.

Component 1: The Virtual World I

- **Concept:** The digital content, spatial rules, and objects that populate the synthetic environment.
- **Key Elements of Virtual Worlds:**
  - **3D Assets & Geometry:** Polygonal meshes, procedural terrain, textures, and lighting maps.
  - **Behavioral Rules:** Physical laws (gravity, mass, velocity) and dynamic object behaviors.
  - **Scene Graph Structure:** Hierarchical spatial data organization representing spatial relationships.
- **Spatial Coordinate Systems:**
  - Continuous conversion between Object Space, World Space, Camera/Eye Space, and Clip Space.
  - Real-time matrix transformations for dynamic camera positioning.

Component 2: Immersion – Psychological & Technical Aspects I

- **Defining Immersion vs. Presence:**
  - **Immersion:** Objective, quantifiable measure of system technology (FOV, resolution, tracking accuracy).
  - **Presence:** Subjective psychological state of "being there" experienced by the user.
- **Determinants of Immersion:**
  - **Field of View (FOV):** Human horizontal FOV $\approx 200^\circ$; modern HMDs target $110^\circ - 180^\circ$.
  - **Display Quality:** High pixel density (PPD), minimal screen-door effect, high dynamic range.
  - **Degrees of Freedom (DoF):** 3DoF (orientation only) vs. 6DoF (orientation + translation).

Visual & Auditory Immersion Mechanisms I

- **Stereoscopic Depth Cues:**
  - **Binocular Parallax:** Displaying distinct images to left and right eyes to generate depth perception.
  - **Accommodation & Convergence:** Matching focal depth and eye convergence to prevent vergence-accommodation conflict.
- **Spatial Audio Immersion:**
  - **Binaural Audio:** Simulating sound arrival time differences (ITD) and level differences (ILD).
  - **HRTF Filtering:** Applying acoustic filters modeled on human ear geometry for 3D sound placement.
- **Physical Sensory Isolation:** Blocking ambient physical light and sound to eliminate real-world distractors.

Component 3: Sensory Feedback Systems I

- **Multimodal Feedback Integration:** Synchronizing visual, auditory, and tactile signals to create coherent realism.
- **Haptic Feedback Modalities:**
  - **Tactile Feedback:** Vibrations, surface textures, and temperature simulation via eccentric rotating mass (ERM) motors or linear resonant actuators (LRA).
  - **Kinesthetic Feedback:** Force feedback resisting user movement, simulating weight and physical boundaries using exoskeletons.
- **Vestibular & Somatosensory Feedback:**
  - Motion platforms for flight/driving simulation to stimulate inner-ear movement perception.

Component 4: Interactivity & User Engagement I

- **Definition of Interactivity:** The extent to which users can modify the form and content of the virtual environment in real time.
- **Core Interaction Metaphors:**
  - **Selection & Manipulation:** Ray-casting, direct virtual hand gripping, and distance grabbing.
  - **Navigation & Locomotion:** Continuous joystick movement, room-scale physical walking, and teleportation.
  - **System Control:** Diegetic spatial menus, hand-gesture triggers, and voice commands.
- **Natural User Interfaces (NUI):** Leveraging intuitive real-world movements to minimize cognitive load.

Hardware & Software Architecture I

- **Hardware Layer:**
  - **Sensors & Tracking:** Inertial Measurement Units (IMUs), infrared cameras, LiDAR, optical inside-out tracking.
  - **Displays & Optics:** OLED/Micro-LED panels, pancake and Fresnel lens optics.
- **Software Layer:**
  - **VR Engines:** Unity, Unreal Engine, WebXR standards.
  - **Runtime Middleware:** OpenXR API, SteamVR, Oculus SDK managing spatial anchor management and compositing.

Performance Metrics & Technical Challenges I

- **Motion-to-Photon (M2P) Latency:**
  - Time elapsed between physical head movement and updated pixel display on HMD.
  - Target threshold: < 20 ms to prevent visual lag and vestibular disorientation.
- **Cyber-sickness / Simulator Sickness:**
  - Caused by sensory conflict between visual movement cues and vestibular stillness.
  - Mitigation: High refresh rates (90–120 Hz), asynchronous timewarp/reprojection, fixed reference frames.
- **Rendering Optimization:** Foveated rendering using eye tracking to concentrate GPU compute on central vision.

Summary & Future Frontiers in VR Workflow I

- **Synthesis of Core Components:**
  - A successful VR system harmonizes the *Virtual World*, *Immersion*, *Sensory Feedback*, and *Interactivity* into a unified feedback loop.
- **Emerging Technological Frontiers:**
  - Photorealistic real-time neural rendering (NeRFs, Gaussian Splatting).
  - Advanced microfluidic haptic gloves for granular tactile sensations.
  - Direct Brain-Computer Interfaces (BCI) for intentional control and neural sensory injection.