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8.1. Application example of a multiprojector system with real-time, per-pixel geometry correction and radiometric compensation: Projecting onto the stage settings during live performance of the Karl May festival in Elspe, Germany. Image courtesy: **VIOSO** GmbH. . . . .
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8.13. Top: Basic principle of double modulation with transmissive or reflective matter: the illumination is premodulated by the projector, and is modulated a second time by being reflected, transmitted or absorbed by real matter. Bottom: Example of contrast enhancing a radiological paper print from less than 100:1 to over 60.000:1. [30]. . . . . .
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8.27. Regionally different mirror-flip frequencies and corresponding signal waves received by photosensors at different image areas. The overall image appears mostly uniform in intensity (top). Binary codes can be embedded into the first half of the exposure sequence while the second half can compensate the desired intensity (bottom) [154]. Image courtesy: Masahiko Kitamura, NTT Network Innovation Labs. . . . . .

9.1. Simple stereo displays require an almost fixed head position. . . . . .
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9.26. Principle of an active multilayer parallax barrier display. . . . . .

9.27. Compressive light-field prototype with three stacked layers of liquid crystal displays (left). Time-multiplexed patterns for the LCD layers (bottom right). Resulting left and right images (right). Image Courtesy: Gordon Wetzstein, Stanford University. . . . . .
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9.32. Multistripe lenticular display with overlapping exit beams. . . . . .
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9.34. Recording for multiperspective multistripe lenticular display. . . . . .
9.35. Multi-viewer perspective rendering with a multistripe lenslet display. . . . . .
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9.37. From left to right: LightSpaceTechnologies' DepthCube applying high-frequency switchable diffusers, Actuality Systems' PerspectaSpatial 3-D Display applying DLP-based micro display chips and relay optics to project RGB images onto a rotating screen from the side [83], Felix3D Volumetric Display [168] from High School Stade applying a helix shaped screen to support a projection from below, and Edwin Berlin's display (bottom-right) that generates volumetric imagery by illuminating LEDs mounted on a rotating panel ([18], US patent 4,160,973), and a photograph of the Solomon HoloDeck Volumetric Imager (top-right). Image courtesy (from left to right): **LightSpace Technologies**, Inc., Gregg Favalora, Knut Langhans, Gymnasium Staade, Edwin P. Berlin, LightSail Energy (bottom-right), and Dennis J. Solomon, **Holoverse**, Inc. (top-right). . . . . .
9.38. Rare earth doped heavy metal fluoride glass scanned with pairs of infrared lasers (left) [74], and laser-plasma scanning 3D display (right) [250]. Image courtesy: Elizabeth Downing, **3DTL** Inc. and **Burton** Inc. . . . . .
9.39. Light field recording and reconstruction principle: light rays just passing a window (left), light rays converted into pixel values on a tiny image sensor of a pinhole camera (center), light rays reproduced by a tiny projector being just an inverted pinhole camera (right). . . . . .
9.40. Principle of a light field display. . . . . .
9.41. Light field parameterization: two planes vs. polar ray coordinates. . . . . .
9.42. Turning light fields into holograms and back [310]. Image courtesy: Computer Graphics Laboratory, ETH Zurich. . . . . .
9.43. Light field focus correction for short-sighted (top) and long-sighted viewers. .
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9.45. Focus synthesis with pre-filtering and a denser lens raster. Source: [131]; Image Courtesy: Gordon Wetzstein, Stanford University. . . . . .
9.46. A 360° light field display: projection optics (left) and rendered 3D graphics example (right). Image courtesy: Paul Debevec, University of Southern California. . . . . .
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9.48. Adaptive light field display detail: while an observer moves laterally, he passes from beam to beam and simultaneously the displayed image is rendered for corresponding perspectives. . . . . .
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9.50. Holographic rendering with a volumetric raster expanding with distance. . . .
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9.54. Iterative fringelet optimization algorithm according to [181]. . . . . .
9.55. 20" adaptive holographic displays. Image courtesy: **SeeReal** Technologies GmbH. . . . . .
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9.57. Beam concentration by refraction index variation. . . . . .
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9.59. Principle fringe density variation. . . . . .
9.60. Pixel beam divergence and merging. . . . . .
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9.62. Intra pixel phase deviation. . . . . .
9.63. Interpixel phase stepping for perpendicular (left) and slanted beams (right). .
9.64. A basic encoding scheme for camera array recordings. . . . . .
9.65. Principle of multiview encoding adapted to current compression standards. .
9.66. Effective pattern size with virtual millimeter-wave hologram. . . . . .

10.1. Basic principle of a near-eye display: a miniature display and optics project directly into the eye, creating a virtual screen. Actual implementations use a large variety of different configurations and technologies, displaying multiple screens or objects, and merging them with the observer's view at the real world.
10.2. 1993: HMD for out-of-cockpit view, **Tornado** Simulator; quad LCD projectors coupled by fiber optics, head and eye tracking, high resolution inlays (equivalent resolution 4096 x 4096), field of view 82° x 66° per eye, 33° overlapping ([40]. Image courtesy: **CAE** Elektronik GmbH. . . . . .
10.3. 2015: **Microsoft Hololens** see-through HMD. Features advanced orientation hardware, sound, diffractive optics. Field of view 30° x 17.5°. Used with permission from **Microsoft** (source: https://news.microsoft.com/microsoft-hololens-press-materials/). . . . . .
10.4. Brightness of virtual displays. . . . . .
10.5. Calculation of light intensity on the retina. . . . . .
10.6. Simulation and registration of virtual display screens with distributed content sources. . . . . .
10.7. Closed head-attached display for virtual reality. . . . . .
10.8. **Oculus Rift** immersive NED. Images courtesy of: **Oculus VR**, LLC. . . . .
10.9. Semicovering head-attached display principle: these displays allow a view around the optics if necessary. The small image is either shown directly on a microdisplay (left), or is mirrored into the field of view (right). . . . . .
10.10Semi-immersive head-attached display example: **Vuzix Tac-Eye LT**, monocular, SVGA+(852x600) Color AMOLED, 30° horizontal field of view. Image courtesy: **Vuzix** Corporation. . . . . .
10.11Basic optical see-through designs. . . . . .
10.12Basic AR near-eye display assembly and its functions. . . . . .
10.13Combiner mirror for near-eye displays. . . . . .
10.14Principle dichroic filter curves. . . . . .
10.15Working principle of a holographic combiner. . . . . .

10.16Optical design principle of many current products. Display and optics may be positioned as shown, or beneath or below the eye. . . . . .
10.17HMD optics design with dual ellipsoid mirrors and asymmetric free-form correction lenses (top view). Image according to [303] . . . . . .
10.18Optical design with a prism and an optional 2nd prism claimed to reinstate see-through (US patent 6,049,429, **Canon** 1996). . . . . .
10.19Design study for a single-mirror display. . . . . .
10.20Collimated NED: object positions at infinity are independent of display position
10.21Automatic alignment of virtual images with collimated displays (HUD of a fighter jet, collimated NED, virtual viewfinder frame). . . . . .
10.22NED in collimated mode (image at infinity), with exit pupil shown. . . . . .
10.23Image formation in a near-eye display. . . . . .
10.24Principle of an ellipsoid mirror and display configuration [118] . . . . . .
10.25Left: ellipsoid design, cropped to the useful area for maximum vertical FOV. Right: resolution evaluation (top left: center; top right: 20° upward; bottom left: 20° left; bottom right: 20° down). The overlaid rectangles are 1 arcmin x 1 arcmin [118]. . . . . .
10.26Algorithm for incremental mirror synthesis [118]. . . . . .
10.27Principle of a spherical mirror and display configuration, using a transmissive display: schematic (left), greatly enlarged pixels (middle), matrix and layer detail (right) [118]. . . . . .
10.28Design study of a spherical concentric NED display [118] . . . . . .
10.29Resolution of the concentric sphere design: center (left), *peripheral resolution* at 20° (eye pointing straight ahead), and center resolution for a glasses displacement both 3 mm downward and forward (right). The markers are 1x1 arcmin wide. . . . . .
10.30Schematic and simulation of a planar transmissive NED display with dome-shaped mirrors. [118] . . . . . .
10.31Planar/dome display. From left to right: center resolution; astigmatism at 20° eye rotation; astigmatism compensated by focus change; and resulting resolution vs. eye rotation. [118] . . . . . .
10.32Simulation of a cylindrical transmissive NED display with barrel-shaped mirrors; left eye image of a 60°x120° FOV section (limited by the nose) [118]. . .
10.33Basic (non-functional) concept of a retinal laser scanner. . . . . .
10.34An early laser scanner design (virtual retinal display). . . . . .
10.35Virtual retina laser displays, VGA resolution. Image courtesy: **Microvision** Inc. . . . . .
10.36Basic adaptation of a laser unit. . . . . .
10.37Example of generating a large exit pupil with a laser scanner. . . . . .
10.38Keeping pupil contact by moving the scanner unit. . . . . .
10.39Eye resolution with respect to the visual field, and possible picture inlay sizes.
10.40Sub-resolution scheme for spatial displays. Left: block filling (here: in two steps). Right: deblocking. . . . . .
10.41Basic focus simulation. . . . . .
10.42Laser scanning display with a focus steering mirror. . . . . .
10.43A lens with segments of stepwise increasing curvature (a-d), resulting in multiple focus points. . . . . .
10.44Active selection and transparency rendering of layered virtual window elements by active accommodation steering. . . . . .

10.45Reproducing focus by light fields requires multiple divergent beams approaching the pupil area. . . . .
10.46Lightfield stereoscope with two stacked LCD panels. Source: [129]. Image Courtesy: Gordon Wetzstein, Stanford University). . . . .
10.47Near-eye display with a Bragg mirror array. . . . .
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10.49Grating deflection mirror principle. . . . .
10.50Generating approximated phase values with raster displays. . . . .
10.51Raw scheme with CGH display (imaginary pixel positions visualized by sphere).
10.52Display module using a wave guide and holographic (diffractive) optical elements. See-through, viewing angle are design adjustable. Image courtesy: **Lumus** Inc. . . . .
10.53HOE based flat near-eye display optics (Lumus). . . . .
10.54**Microsoft Hololens** display, exploded view. Used with permission from **Microsoft** (source: https://news.microsoft.com/videos/b-roll-hololens/). . . . .
10.55**Q-Sight** display, helmet mounted. Image courtesy: **BAE Systems**. . . . .
10.56**Quantum Display**, principle. . . . .
10.57Left: principle of a rod type wave guide with straight mirrors, preserving the entrance angle. Center left: translating input angles to image point angles. Center right: defining image point distance by convex mirrors (example of an optional Fresnel mirror). Right: array combining multiple layers of wave guides with multiple 2D curved mirrors and a multiplexer wave guide. . . . .
10.58Contact Lens With Integrated Inorganic Semiconductor Devices. Image courtesy: Babak Parviz, University of Washington. . . . .
10.59Hypothetical contact lens displays with a moving mirror phased array scanner (left) or a Fourier Hologram (right), using a single coherent light source. . . .
10.60Left: a collimated micro projector embedded in a contact lens, being a close trade-off between size and resolution and also suffering from vignetting by the iris. Right: a display embedded into an artificial eye lens or implanted into the eyeball would have less restrictions. . . . .
10.61Example of a contact lens supported display. . . . .
10.62Example assembly of near-eye display with an eye tracker. . . . .
10.63**Viewpoint PC-60** eye tracker, mounted on glasses. Image courtesy: **Arrington Research**. . . . .
10.64Sensing eye distance by iris diameter. . . . .
10.65Detecting tilt by width/height comparison of the iris or pupil. . . . .
10.66Lateral tilt detection can be achieved by comparing the vertical eye positions. Here we exploit the fact that eyes usually don't move in opposite vertical directions. . . . .
10.67Finding the center of partially occluded iris or pupil from visible edge arcs. .
10.68Detecting very fast motion from simple pattern shifting (left), and the actual motion sensor chip of an optical mouse (right). . . . .
10.69Eye tracking in a DMD design. . . . .
10.70Coupling example of an eye tracking camera with a near-eye display. . . . .
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10.72Dual optical path eye tracker assembly (left) and retina tracker (right). . . .
10.73Retina tracking principle. . . . .
10.74Bi-directional display with OLED-on-CMOS technology (semiconductor structure cross-section). . . . .
10.75Efficiency of piezo vs. electromagnetic motors. . . . .

10.76 **Squiggle** piezo electric motor: principle (left), motor and driver chip (right). Image courtesy: **New Scale Technologies**. . . . . .

10.77 Principle of an eyetap display. . . . . .

10.78 Video-See-Through HMD: **Vuzix-Wrap920AR** with stereo color VGA resolution screens and cameras, 31° diagonal field of view. Image courtesy: **Vuzix** Corporation. . . . . .

10.79 Optics layout and assembly of an experimental masking display [156]. Image courtesy: Kiyoshi Kiyokawa, Osaka University. . . . . .

10.80 Simple experiment demonstrating properties of an out-of-focus mask display.

10.81 Original view of images inserted into sections covered by a mask, with typical unsharp borders (white and natural background). . . . . .

10.82 Left: circle in Cartesian coordinates (normalized for a circle area of one). Right: projected pupil area resulting in edge blurring. . . . . .

10.83 Calculated edge occlusion of a mask display: linear (Equation 10.1) and perceived (Equations 10.2) attenuations and resulting perceived vs. real border widths for selected attenuation levels. . . . . .

10.84 Real occlusion experiment using a black rod in front of a test pattern. Test pattern (left). Photo with central area covered by a slim stripe (right). . . . .

10.85 Construction of a mask image. . . . . .

11.1. Locations of subretinal and epiretinal implants within the retina. Image courtesy: Alfred Stett, NMI Universität Tübingen and Eberhart Zrenner, Center for Ophthalmology, University of Tübingen [315]. . . . . .

11.2. Example for subretinal implant. Image courtesy: Walter Wrobel, Universitäts-Augenklinik Tübingen. . . . . .

11.3. Example for epiretinal implant. Image courtesy: **IMI** Intelligent Medical Implants GmbH. . . . . .

11.4. Snail neuron grown on a CMOS chip with 128x128 transistors. The electrical activity of the neuron is recorded by the chip (chip fabricated by Infineon Technologies). Image courtesy: Max Planck Institute of Biochemistry. . . . .

11.5. The Utah Electrode Array (UEA) – 100 1.5 mm electrodes (separated by 0.4 mm) on a 0.2 mm thin carrier substrate (left). Thin and flexible electrode arrays printed onto silk films for recording brain activity (right). Image courtesy: Richard A. Normann, University of Utah, John Rogers, University of Illinois. . . . . .

A.1. Forward display model simulates the process of transforming digital pixel values into physical light on a display. An inverse display model provides the inverse mapping — it can determine what combination of pixel values is needed to produce a certain color. . . . . .

A.2. Comparison of gamma function with the sRGB non-linearity. The intensities are plotted using the linear scale on the left and the logarithmic scale on the right. The logarithmic scale is often used for plotting luminance as it better reflects perceived intensity of light. . . . . .

A.3. The relation between pixel values (luma — V) and emitted light (luminance — L) for several displays, as predicted by the GOG model from Equation A.6. The corresponding plots show the variation in ambient light, gamma, black level and peak luminance in the row-by-row order. The DR value in parenthesis is the display dynamic range as log-10 contrast ratio (equal to $\log_{10}(L_{max}/L_{min})$). The parameters not listed in the legend are as follows: L_{peak}=200 cd/m^2, L_{black}=0.5 cd/m^2, γ=2.2, E_{amb} = 50 lux, k = 1%. . . . . .
A.4. A chart that can be used to visually estimate the gamma exponent of a monitor. The task is to match the brightness of the patterned background to one of the uniform color patches with numbers. The numbers indicate the corresponding gamma values. The match is easier to make when a chart is seen from a large distance or when vision is not in focus (e.g. when looking on the thumb in front of a display plane instead of a display). Note that the chart needs to be enlarged so that the pixels in the pattern match the pixels on the screen, otherwise aliasing artefacts could make the match impossible. . . . . .
A.5. Half-tone patterns that could be used to recover the shape of a display transfer function. R is the ratio of "on" pixels to all pixels in a pattern. Row a) shows the pattern design and row b) shows how the pattern appears on a screen. The same pattern can be produced for red, green and blue primaries to recover individual transfer functions. . . . . .
A.6. A single step from a unique-hue selection task, used to color-calibrate a display without measuring instruments. The task for the user is to select one color that has the least amount of yellow or blue tint. A sequence of such selections will indicate the unique red color. . . . . .
A.7. Gabor patches of different spatial frequency, typically used in detection experiments. . . . . .
A.8. Contrast Sensitivity Function (CSF) plotted as the function of frequency (left) and luminance (right). Different line colors denote different background luminance (L_f), or spatial frequency (ρ). The plots are based on the model from [187] and data from [152]. . . . . .
A.9. The spatial contrast appearance chart. For very low contrast in the top rows, the perceived magnitude of contrast varies with spatial frequency. But the perceived contrast magnitude remains mostly the same for bottom rows containing large contrast. . . . . .
A.10. The smallest detectable difference in luminance across the luminance range. The plot is based on the data from [152]. . . . . .
A.11. The effect of quantization on a gradient of pixel values. Each column contains an image of different bit-depth, from 3 to 8 bits. The lower part of the gradient was generated using dithering to simulate higher bit-depth. . . . . .
A.12. Quantization errors on low dynamic range display (L_{peak}=500 cd/m^2, L_{black}=0.1 cd/m^2) for selected transfer functions. The errors are shown for 8-bit encoding in the plot on the left and for 10-bit encoding in the plot on the right. . . . . .
A.13. Quantization errors on high dynamic range display (L_{peak}=10 000 cd/m^2, L_{black}=0.005 cd/m^2) for selected transfer functions and 10-bit encoding. . . .
A.14. Perceptual transfer function compared with the brightness function (Stevens' law for brightness). . . . . .