Augmented Reality

Augmented Reality

- Augmented Reality (AR)
  - ➢ The enrichment of reality by artificial virtual content
  - ➢ Not static
    - Augmentation is continuous and adaptive to the viewpoint of the viewer

Fusing a real environment (left) with a virtual object (right) to achieve Augmented Reality (center). (Single images: © Tobias Schwandt, TU Ilmenau 2018. All rights reserved.)

Augmented Reality

- Requires
  - Video capturing (for VST)
    - A video stream of observer’s surroundings
    - Purpose is to capture reality, i.e. the real environment
    - Camera must be calibrated
  - Tracking
    - Estimation of position and pose/orientation
    - Continuous capture of observer/camera’s viewpoint
    - Many different techniques
      - Previously covered in Lecture 4
    - Results in a transformation
      - From user/camera coordinate system into coordinate system of real environment

Augmented Reality

- ➢ Registration
  - Anchoring or correct fitting of artificial virtual content into reality
  - Based on position and orientation from tracking
  - Virtual content appears firmly located (registered) in reality
  - Independent of changing viewpoint

Simple registration using a fiducial marker.

Augmented Reality

- **Visualisation**
  - Render virtual content based on registration and camera perspective
  - Virtual content superimposed on video image or optical overlay
  - Seamless superimposition affected by
    - Resolution, sharpness, colour range, contrast, etc.
- **Output**
  - Shown on display device
    - E.g., smartphone, AR glasses

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality, Springer, 2021

Perspective superimposition of an image used for tracking by a 3D object. (Image source: Jan Herling, TU Ilmenau.)

Augmented Reality

- Marker tracking
  1. Capturing image with known camera
  2. Search for quadrilaterals
  3. Pose estimation from homography
  4. Pose refinement
     - Minimise nonlinear projection error
  5. Use final pose

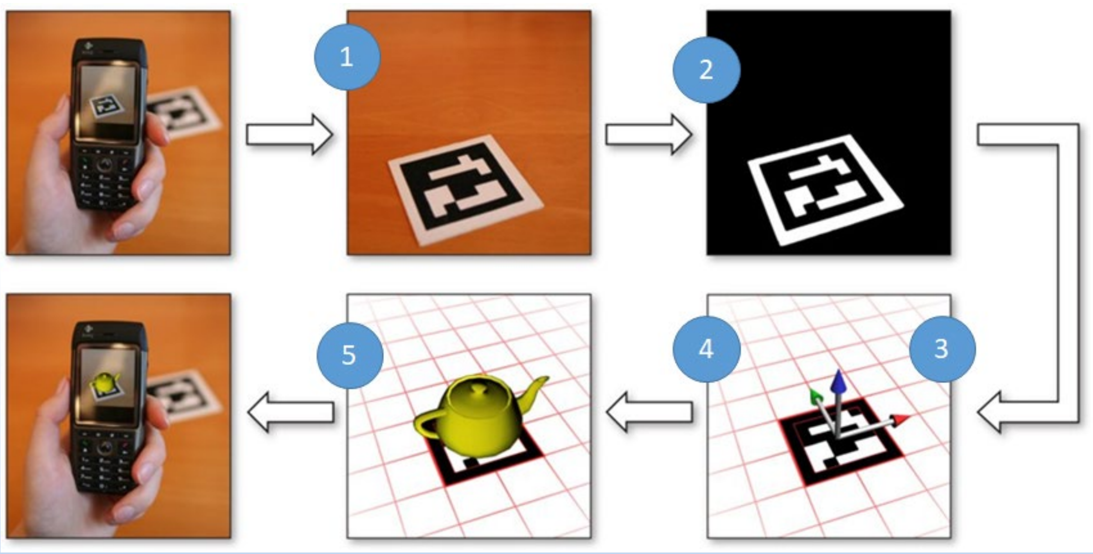


Image: Daniel Wagner

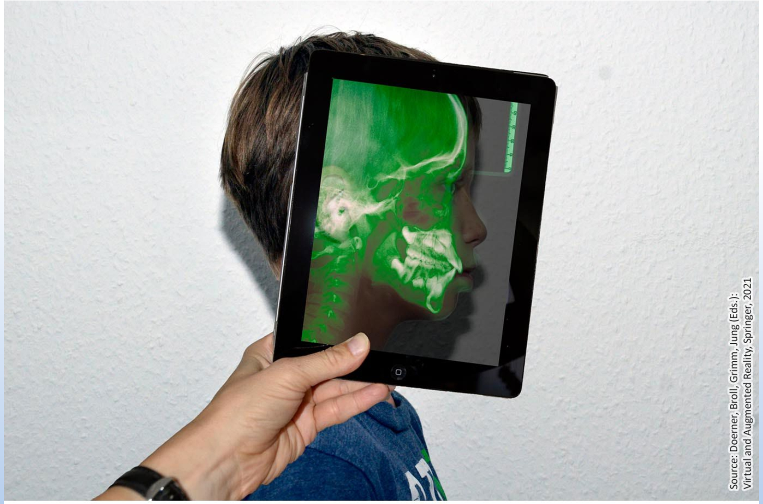
Augmented Reality

- Common to all types of AR
  - ➢ Perspective-correct projection of virtual content into the optical overlay/video image
  - ➢ Viewpoint and direction of view between real and virtual environment must be consistent
  - ➢ Virtual FOV must correspond to actual FOV of display
  - ➢ Scaling of virtual content must adapt to real environment

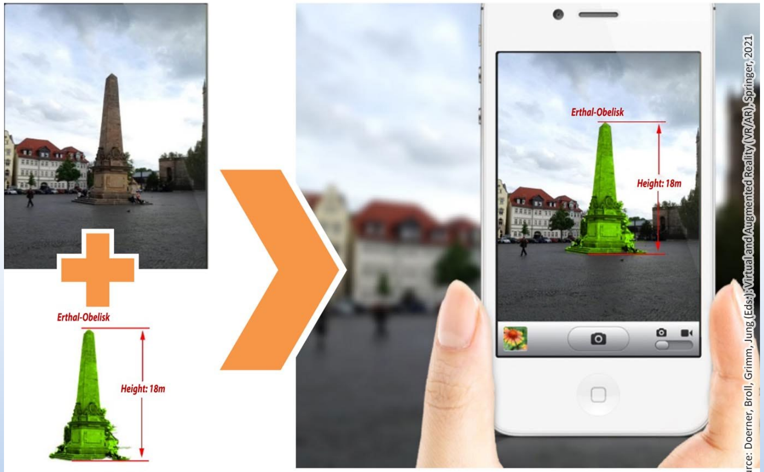
Output of an augmented video stream on a smartphone (here from the viewpoint of a second observer). (Image source: Jan Herling, TU Ilmenau.)

Augmented Reality

- Perspective
  - ➢ Ideally, perspective of captured image and the user should match
    - User get the impression that real environment really altered
  - ➢ Otherwise, viewer experiences decoupling between real environment and augmented environment observed



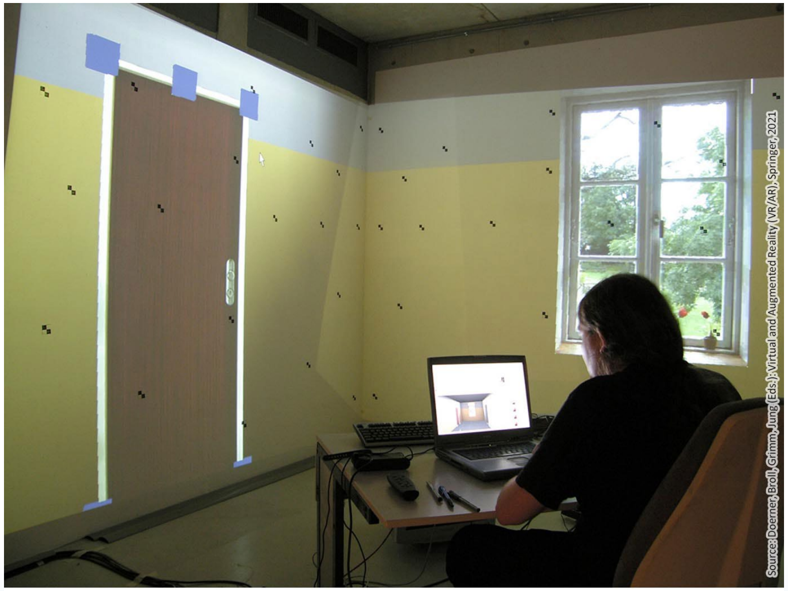
Example of a Magic Lens effect.



Perspectively correct superimposition of a camera image of the real environment by virtual content using video see-through AR – here on a smartphone.

AR Types

- Projection-base AR
  - ➢ Projecting virtual content onto objects in real environment
  - ➢ Does not allow creation of new spatial structures
  - ➢ Limited to
    - Manipulation of surface properties
      - – E.g. colour, texture
    - Additional information on the objects' surface
      - – E.g., explanations, highlights, symbols, etc.



Example of projection-based AR (virtual door, virtual color design of the wall). (© Oliver Bimber 2005. All rights reserved.)

AR Types

- Comparison between different AR types
  - Visibility of bright virtual content on different backgrounds

	On bright background	On dark background
Optical see-through	Partially visible, high transparency	Good visibility, low transparency
Video see-through	Good visibility	Good visibility
Projection	Partially visible	Good visibility

  - Visibility of dark virtual content on different backgrounds

	On light background	On dark background
Optical see-through	Not visible, almost complete transparency	Partially visible, high transparency
Video see-through	Good visibility	Good visibility
Projection	Not visible	Partially visible

AR Types

- OST AR
  - Dark virtual objects may appear transparent
  - Darkened perceive reality
- VST AR
  - Real background same optical quality and brightness

With the OST AR techniques, dark virtual objects sometimes appear transparent (here the less illuminated lower part of the red sphere).

Typical perception when using the optical see-through technique (left) compared to the video see-through technique (right)

AR Types

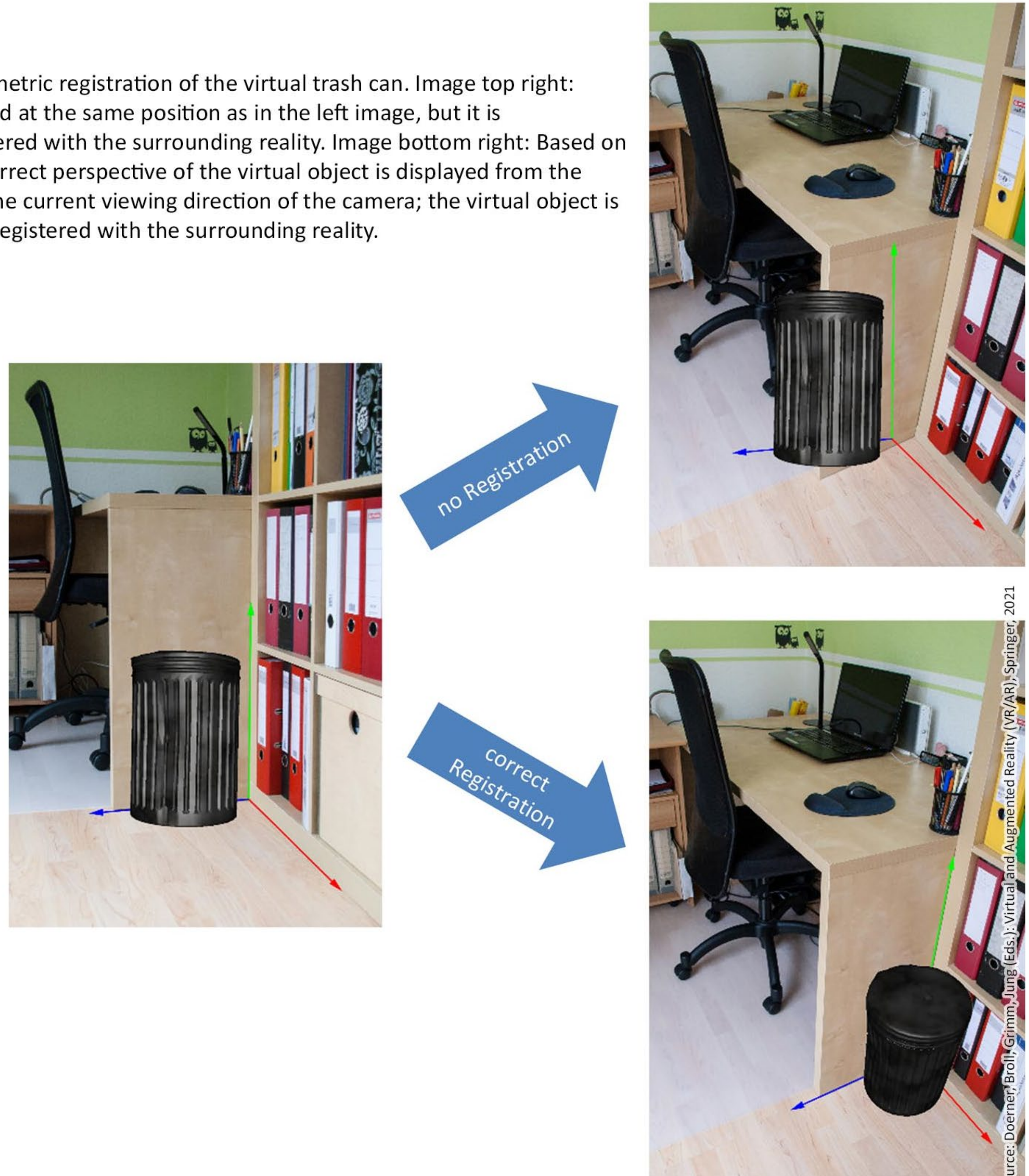
- Display of virtual shadows and virtual objects in space

	Virtual shadows	Universal object location
Optical see-through	Not possible	Possible
Video see-through	Possible	Possible
Projection	Not possible	Not possible/limited (on surfaces allowing for stereo projections)

Registration

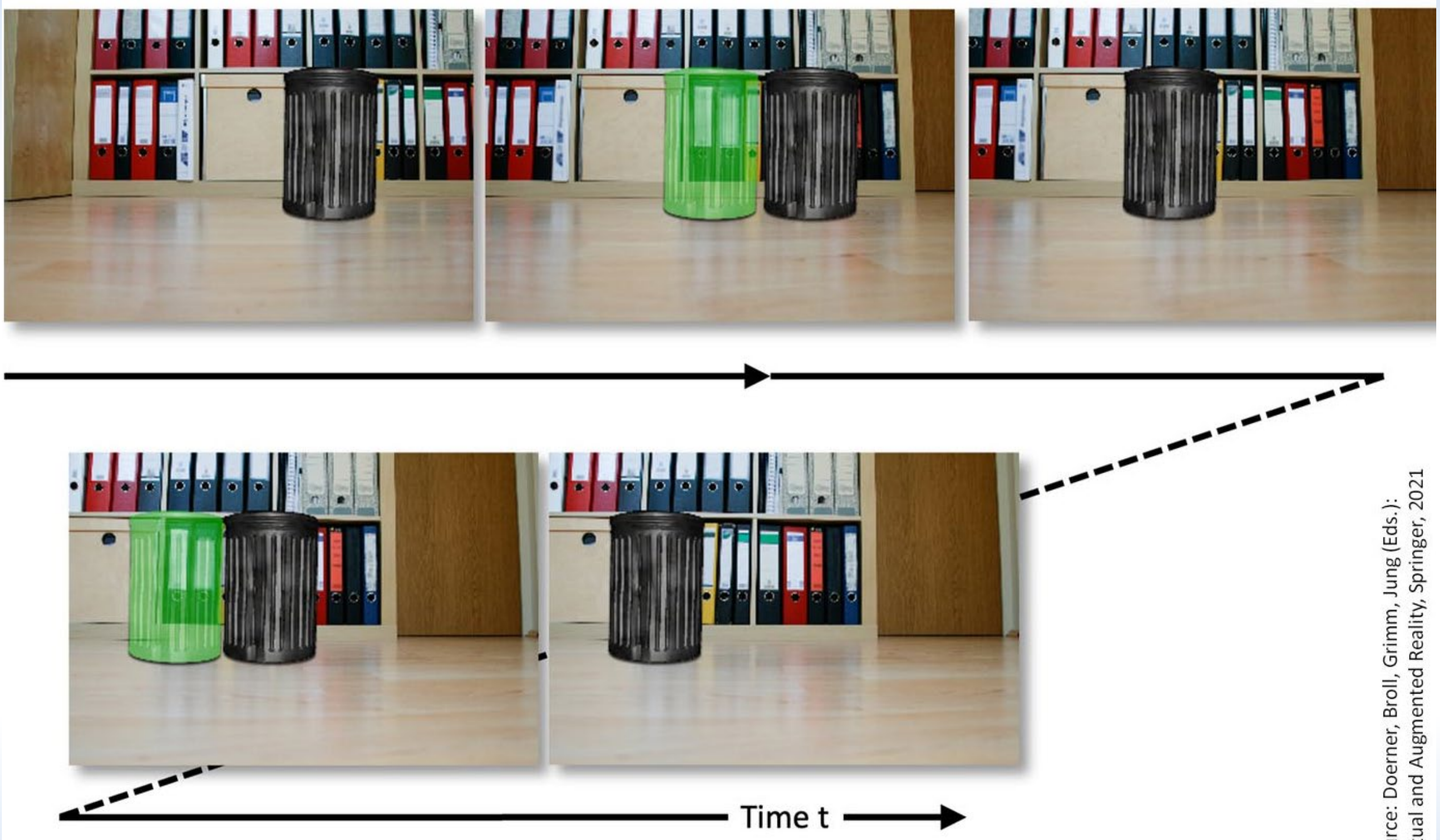
- Geometric registration
  - ➢ Virtual object appears to be in the same place in reality even if the camera perspective changes
  - ➢ Tracking provides basis for geometric registration
    - Quality of the tracking is crucial for visual quality of registration
    - Affected by tracking
      - – Update rate
      - – Latency
  - ➢ Update rate
    - Should ideally match frame rate, i.e. at least 60 fps
    - Otherwise, virtual objects will move when camera/head moves
      - – Then, jump or jerk back to the correct position

Left image: Correct geometric registration of the virtual trash can. Image top right: Virtual object is displayed at the same position as in the left image, but it is geometrically not registered with the surrounding reality. Image bottom right: Based on the tracking data, the correct perspective of the virtual object is displayed from the current viewpoint and the current viewing direction of the camera; the virtual object is geometrically correctly registered with the surrounding reality.



Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Registration



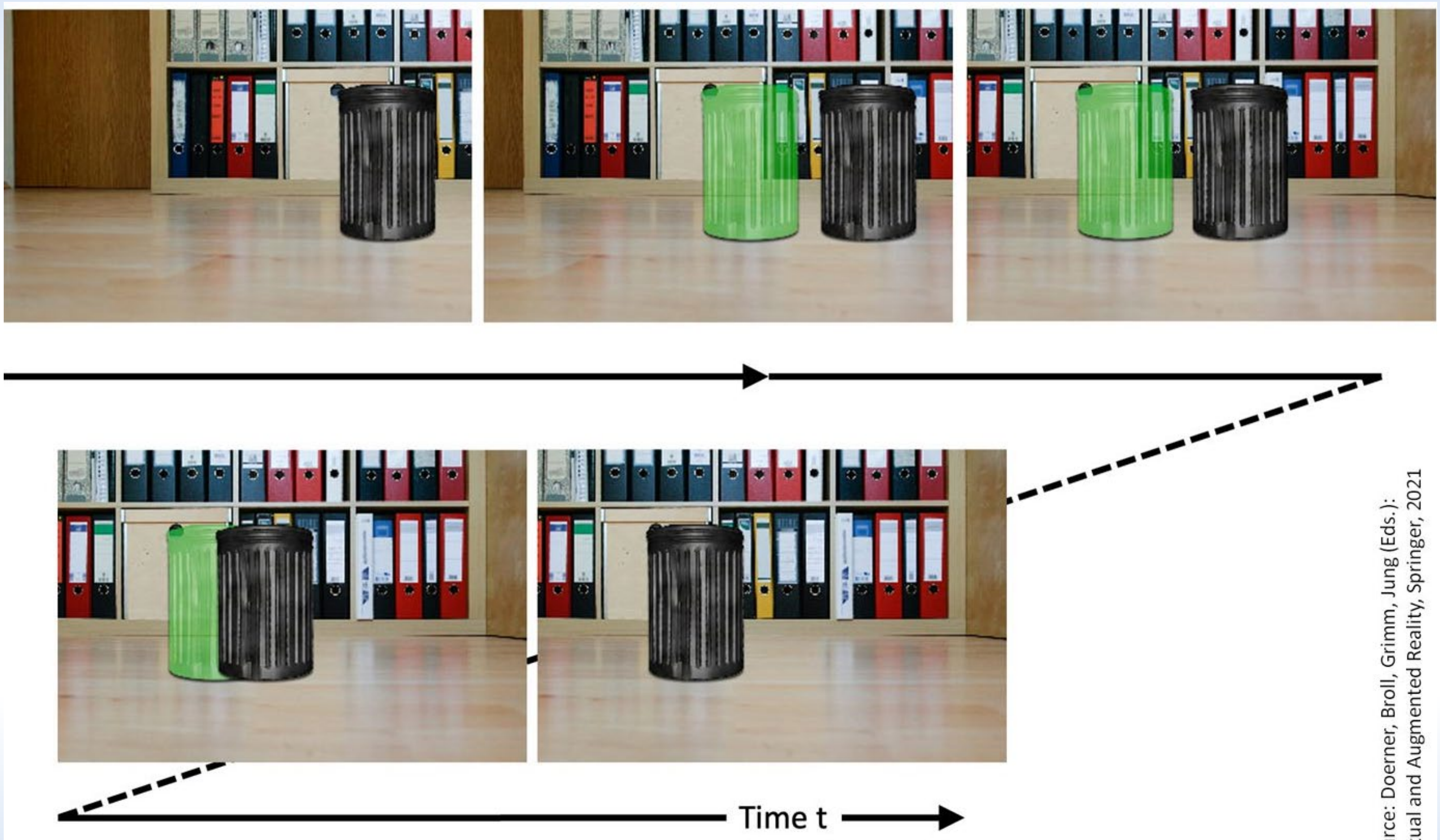
Incorrect geometric registration due to a too low tracking rate: the camera moves from left to right; due to missing tracking updates, the virtual object (the black bin) first moves along with the camera (second and fourth images) and then suddenly jumps to the correct position (third and fifth images) when new tracking data becomes available (actual correct positions shown in green).

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality, Springer, 2021

Registration

- Geometric registration
  - Latency
    - While symptoms similar to low update rate, actual problem is of a different nature
    - Delay between the moment of movement of camera/object and moment when resulting transformation of virtual object is observed
      - Time between measuring the position and orientation and applying it to the object transformation remains
      - The longer this time span, the more noticeable the resulting effect
    - The movement does not jump or jerk, but the object remains
      - Offset from correct position continues as long as movement continues

Registration



Incorrect geometric registration due to high tracking latency: the camera moves from left to right; the virtual object first moves with the camera for a short time and then mostly freezes at a wrong position; only after stopping the movement of the camera does the virtual object move to its correct position (correct positions in green).

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality, Springer, 2021

Registration

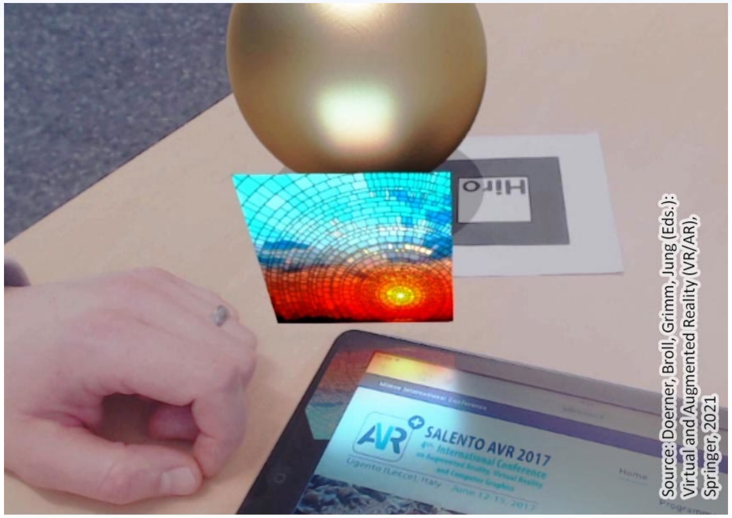
- Photometric registration
  - ➢ Geometric registration
    - A basic requirement of AR
  - ➢ Photometric registration of virtual objects
    - Only performed rudimentarily (if at all)
  - ➢ A correct adjustment of a virtual objects' appearance to its real environment
  - ➢ Need to capture the real lighting conditions
    - Light probes – reflective spheres placed in the scene
    - Not always possible/desirable to have light probes
    - Affects the surrounding illumination

Registration

- A mirroring sphere for glossy reflections

➢ Complete adaption of illumination

- Can only be done in VST
- OST, changes restricted to adding light
  - Shadows not possible



Illumination of virtual content influencing the real environment (virtual reflection on tablet computer). (© Tobias Schwandt, TU Ilmenau 2018. All rights reserved.)

Registration

- ➢ Augmentation of parts of reality is crucial
- ➢ Incomplete/incorrect photometric registration
    - Can quickly destroy illusion of seamless integration with reality

Comparison of an AR scene without and with photometric registration: in the right image, (real) light is reflected by the red sheet onto the virtual object; furthermore, light from the virtual object is reflected onto the background. (Picture source: Philipp Lensing, TU Ilmenau.)

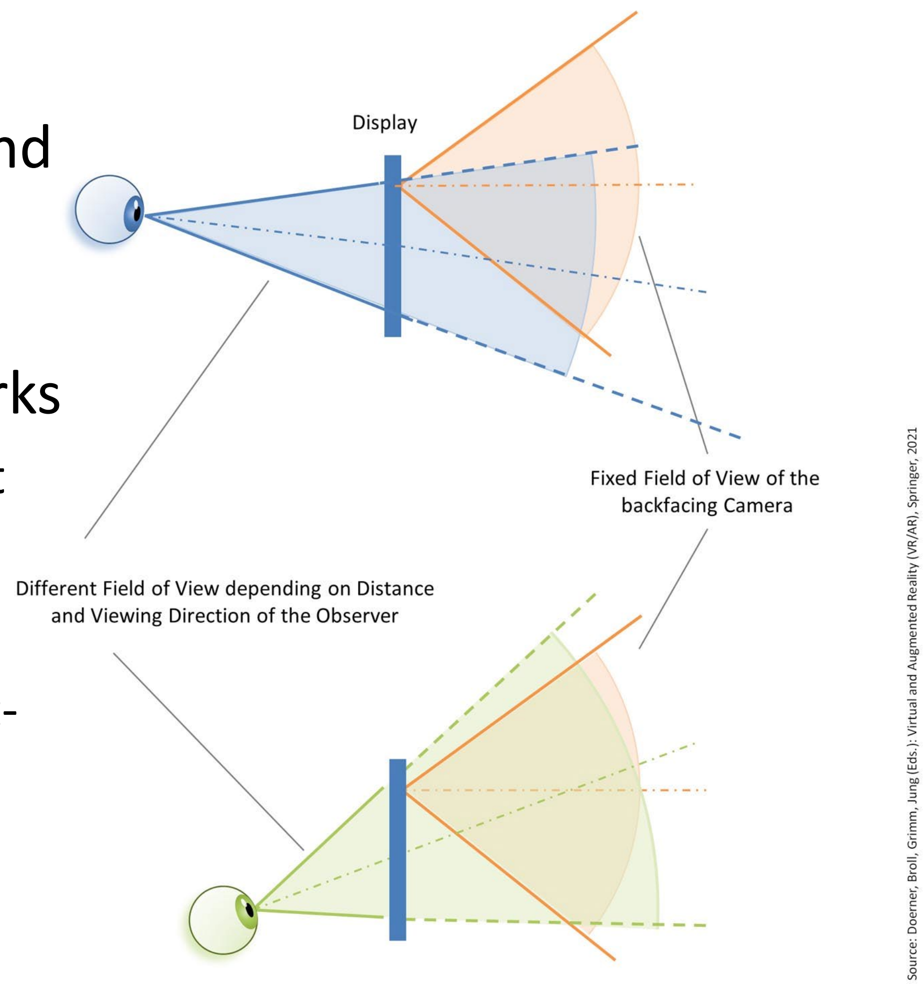
Registration

- Instead of reflective spheres, planar surfaces of the physical objects can be used

Reflective surfaces of virtual objects. (© TU Ilmenau 2018. All rights reserved.)

Visual Output

- Handheld devices
  - ➢ Currently most important and frequently used AR devices
  - ➢ Due to the availability of corresponding AR frameworks
    - ARCore for Android and ARKit for iOS
  - ➢ Analogous to VST
    - Augmentation usually correct-perspective, but not actual viewing point

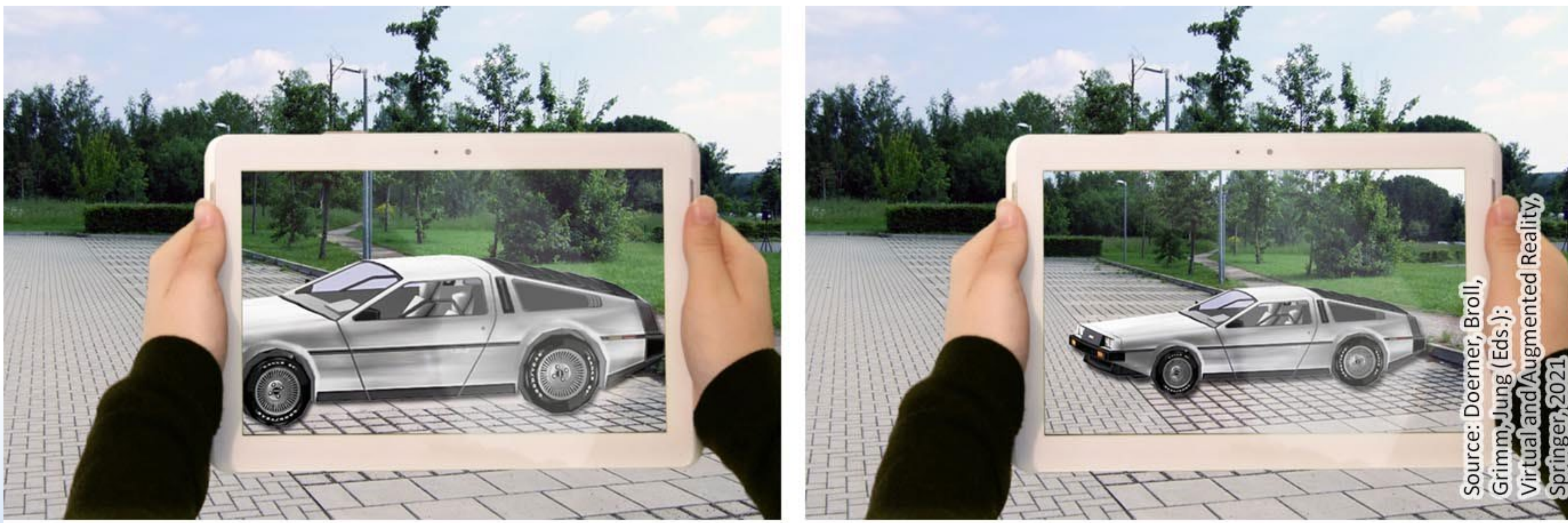


Different fields of view of viewer and camera in handheld AR.

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Visual Output

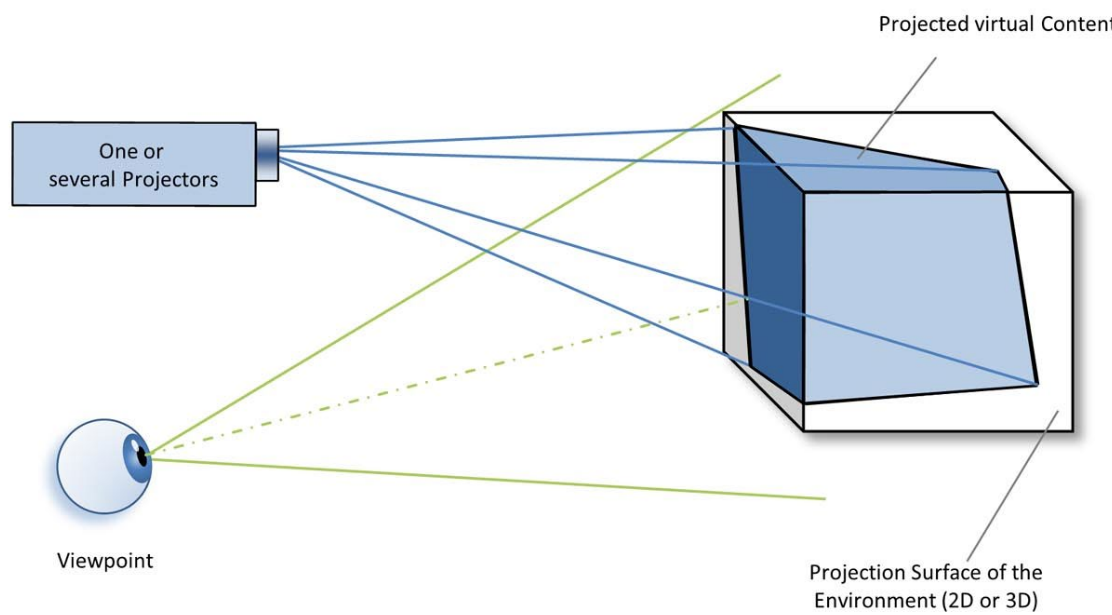
- FOV of camera is fixed in relation to the display
- The viewer's FOV depends on the respective viewpoint and the viewing direction in relation to the display



Left: Matching perspective between reality and augmented image (Magic Lens effect).
Right: Camera image and reality are perceived with a deviating perspective.

Visual Output

- Projection-based output
  - ➢ Illuminate surfaces of environment, such that perception of real objects changes
  - ➢ No free positioning of virtual contents in space is possible

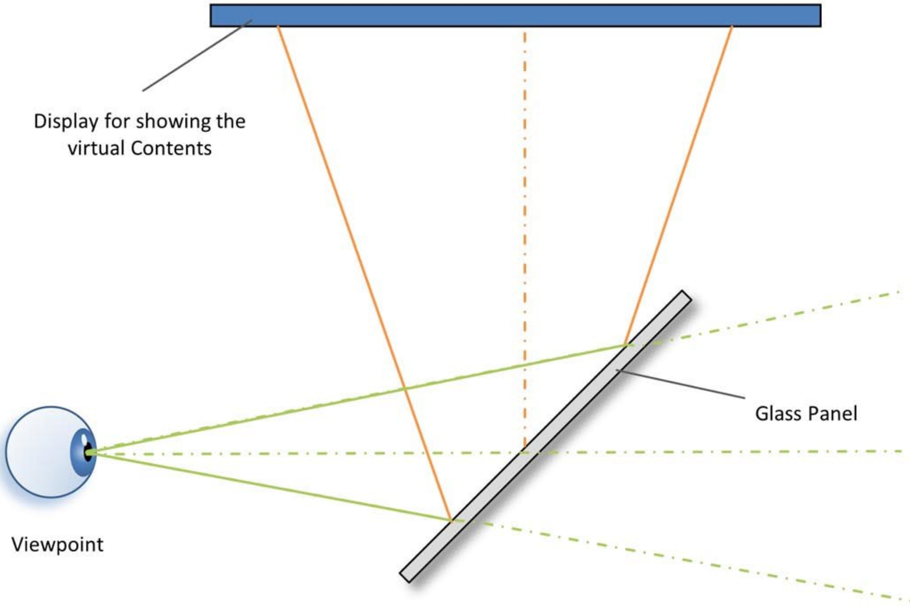


Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality, Springer, 2021

Schematic structure of a system for projection-based AR.

Visual Output

- Spatial AR
  - ➢ Often use glass plates/foils as mirrors
  - ➢ User looks through the glass at objects to be augmented
  - ➢ Glass is not perpendicular to viewing direction
    - Acts as a mirror
  - ➢ Results in OST AR



Spatial AR using a transparent, reflective surface.

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality, Springer, 2021

Visual Output

- For correct geometrical registration, head position must be tracked
- Range of movement of the user is limited
  - Only applications where user will only move head position to a small extent

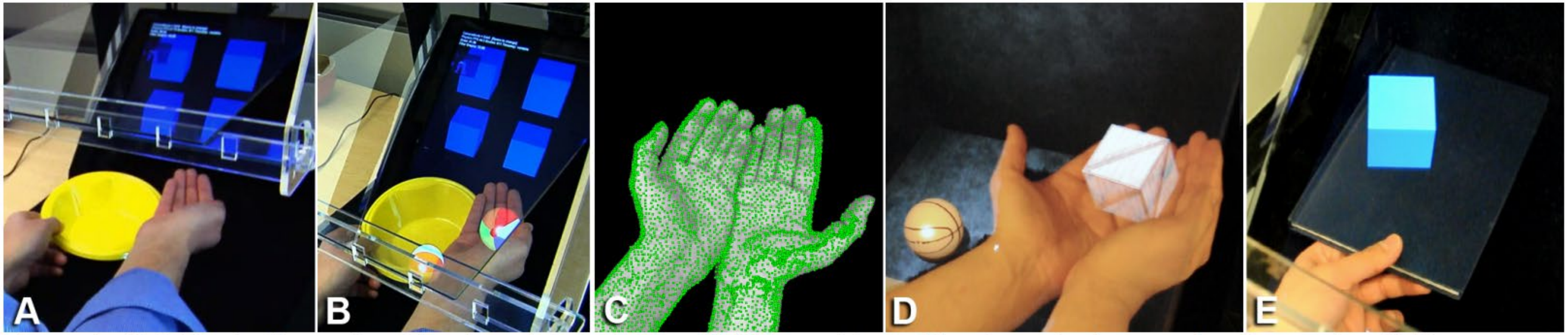


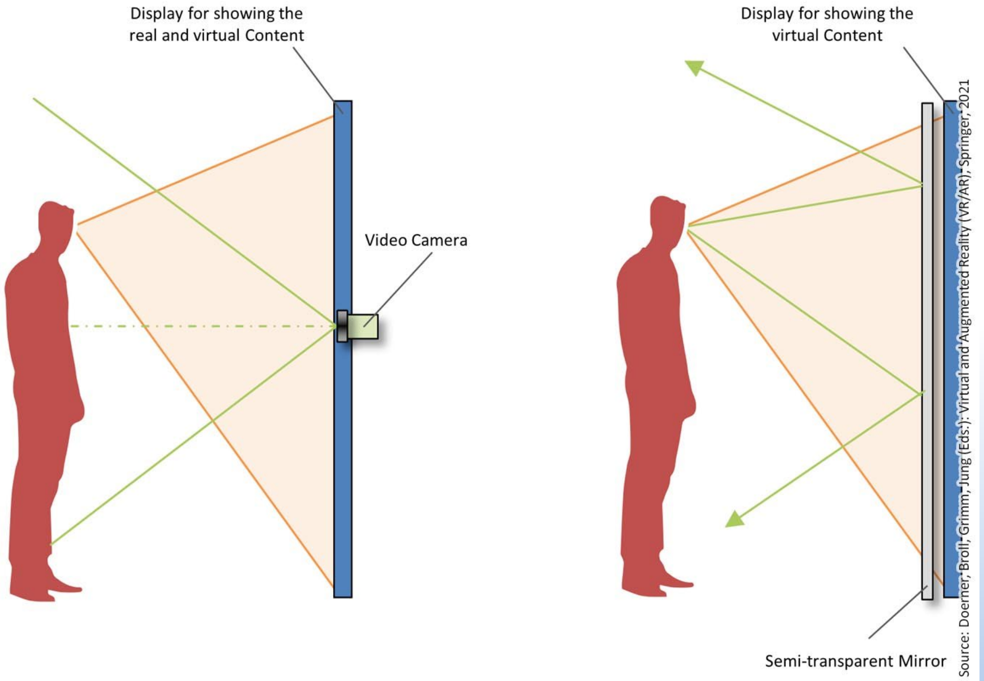
Figure 1: HoloDesk allows direct freeform interactions with 3D graphics, without any body-worn hardware. A + B) User sees a virtual image of a 3D scene through a half silvered mirror. Scene is corrected for the viewer's perspective. User can freely and directly reach into the 3D scene to interact with it. C + D) A novel algorithm is presented that allows diverse and unscripted whole-hand 3D interactions e.g scooping and grasping. E) Other real objects beyond hands can be used for interaction.

https://www.microsoft.com/en-us/research/wp-content/uploads/2012/05/p2421-hilliges.pdf

Visual Output

- AR mirrors
  - ➢ Particular popular to simulate the fitting of clothes
  - ➢ Viewer sees themselves and their surroundings in a mirror
    - The mirror image is enriched by virtual content
  - ➢ Can be VST or OST

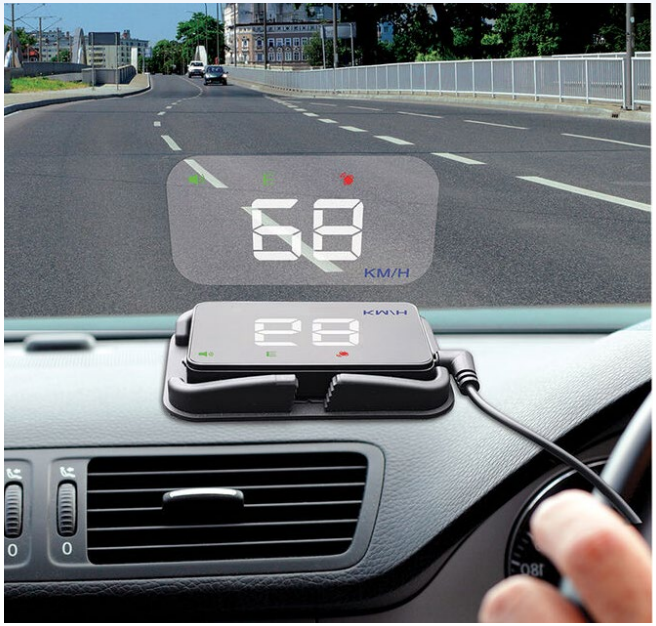
https://www.trendhunter.com/trends/fx-gear



VST vs. OST AR mirrors.

Special AR Techniques

- Head-up content
  - Sometimes called a dashboard
  - Content displayed regardless of position and orientation of the viewing direction
- Occlusions and phantom objects
  - When real objects are closer to the user than virtual objects
  - Perception and behaviour of virtual object doesn’t match



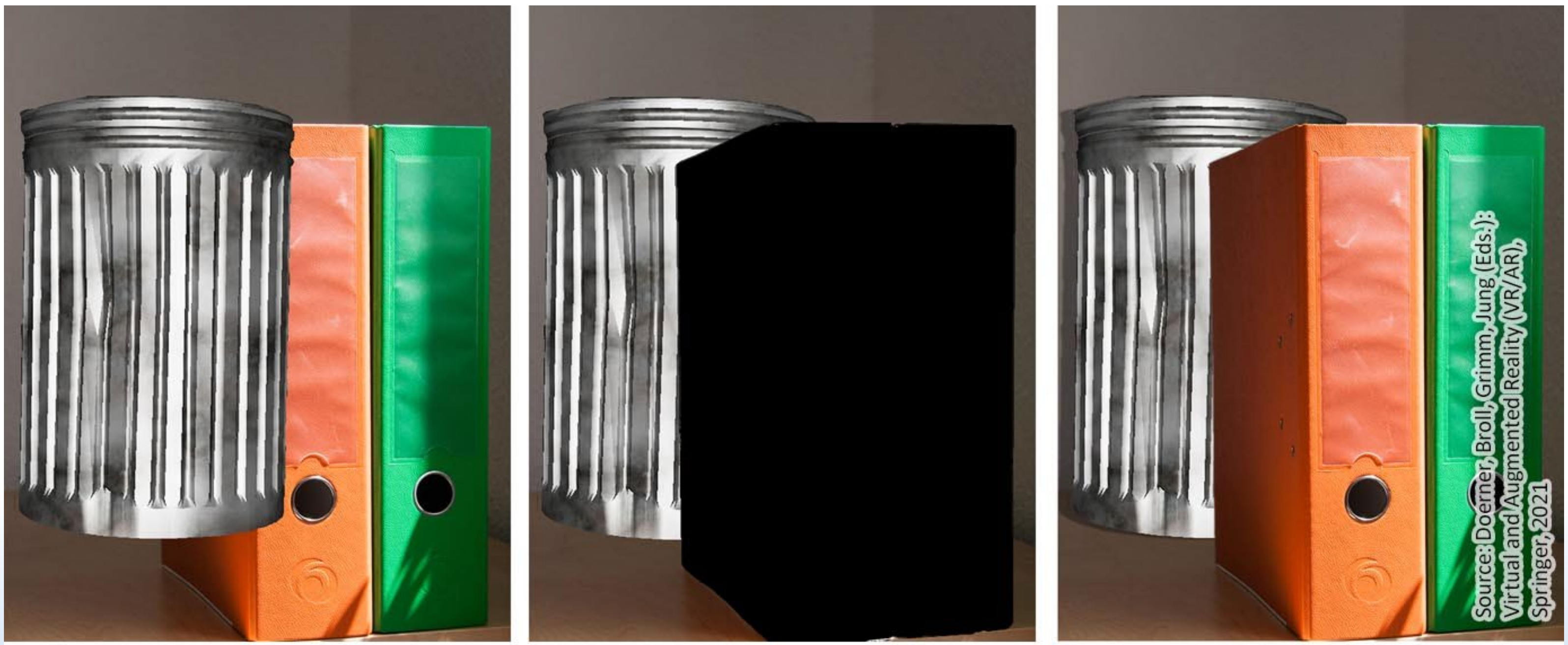
https://www.supercheapauto.com.au/p/sca-sca-gps-heads-up-display/621741.html?gclid=Cj0KCQjwgLOiBhC7ARIsAIeetVDb9aBI2uzvTEnRe0Mn2PDkQzyIQIKnwgD7IpQL5R3tImxspX14hWEaAo-YEALw_wcB&gclsrc=aw.ds

Special AR Techniques

- Virtual content always visible in OST or superimposed in VST
  - Conflict for the observer
    - Cannot resolve which object is actually closer
- Occluders need to be identified
  - i.e., real objects, with respect to the image areas covered by them
  - Allows for proper masking and removal of those virtual object areas
- Phantom objects
  - Virtual objects that should not be rendered, but serve to correctly occlude other virtual content
  - In OST, rendered as black and unlit to appear transparent
  - In VST, rendered into depth buffer, so virtual objects behind won’t appear

Special AR Techniques

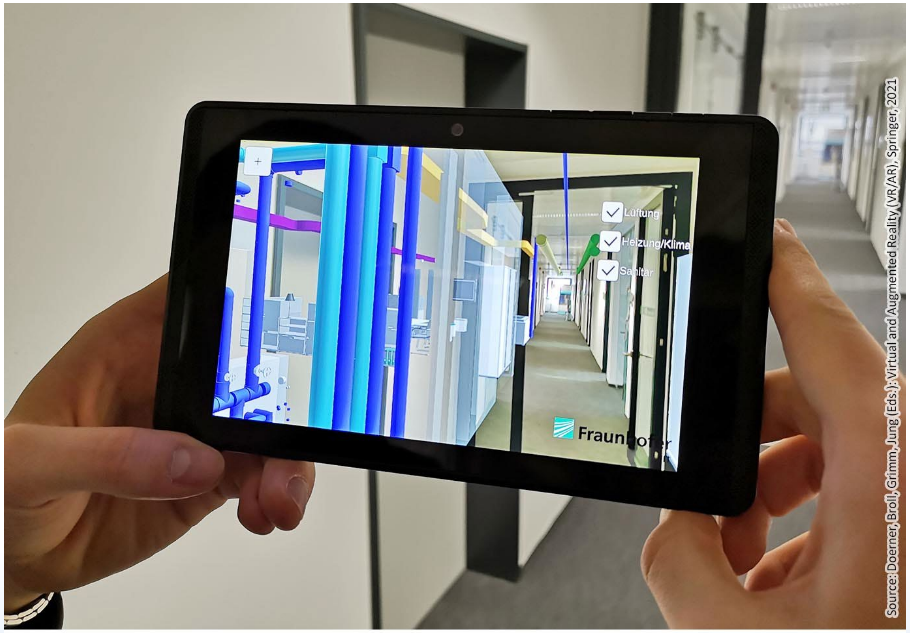
- One way to obtain depth information is to use depth cameras



Phantom objects enable correct mutual occlusion between real and virtual objects. Without a phantom object, the virtual object seems to float in front of the real objects, whereas with correct masking by the phantom object it seems to be behind the real objects.

Special AR Techniques

- X-ray vision
  - ➢ AR can be used to see through solid objects
  - ➢ Occlusion is a problem when fusing reality with virtuality
    - Can use phantom objects
    - Alternatively, reproduce real surfaces using partially transparent virtual objects



Pipes and cables behind a cover and in the wall are made visible using AR for X-ray vision. (© Leif Oppermann, Fraunhofer FIT 2018. All rights reserved.)

Use of SAR to represent hidden parts of reality.

Special AR Interaction Techniques

- Most interactions in VR can be used in AR
  - ➢ Can use some special interactions in AR
- Gaze-based interaction
  - ➢ Requires eye-tracking
    - Integration of sensors into AR glasses, e.g., HoloLens2
    - Use of backward pointing camera of smartphones/tablets
  - ➢ Selection mechanism can use orientation of the head or camera (for handheld devices)
    - Select object in centre of FOV, just needs trigger action
      - – Dwell time can be used as trigger, but prevents fast operation

Special AR Interaction Techniques

- Tangible user interfaces
  - Real objects linked with virtual objects
  - Real object (placeholder object or proxy) is mapped to the state of the virtual object
  - Physical properties of real object correspond to those of virtual object

Tangible User Interfaces: a real proxy object is used to interact with a virtual object.

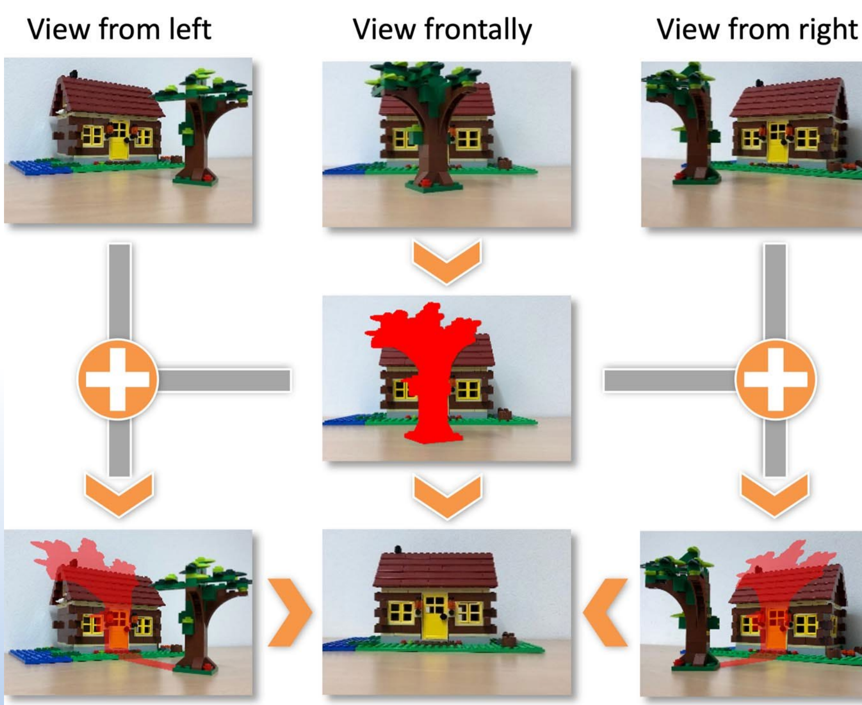
Diminished Reality

- Diminished reality
  - Not AR
    - Removal of parts of reality
  - Two types
    - Attempt to reconstruct the actual real background
    - Merely create a plausible overall impression
      - i.e., showing some alternative content for removed object
  - Retrospective removal of persons from pictures has long tradition

Example of Diminished Reality: The sink drain is removed from the live video stream in real time. (© TU Ilmenau 2018. All rights reserved.)

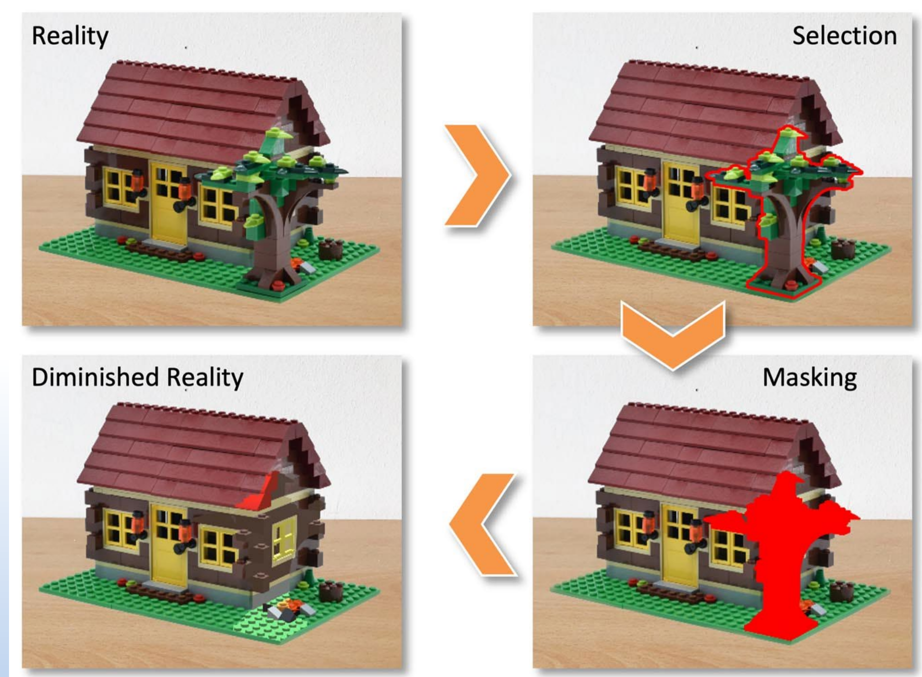
Diminished Reality

- Removal of AR tracking markers
- Can reconstruct background from other views or just plausible one



Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Reconstruction of the real background using several camera views. (Individual images: © TU Ilmenau 2018. All rights reserved)

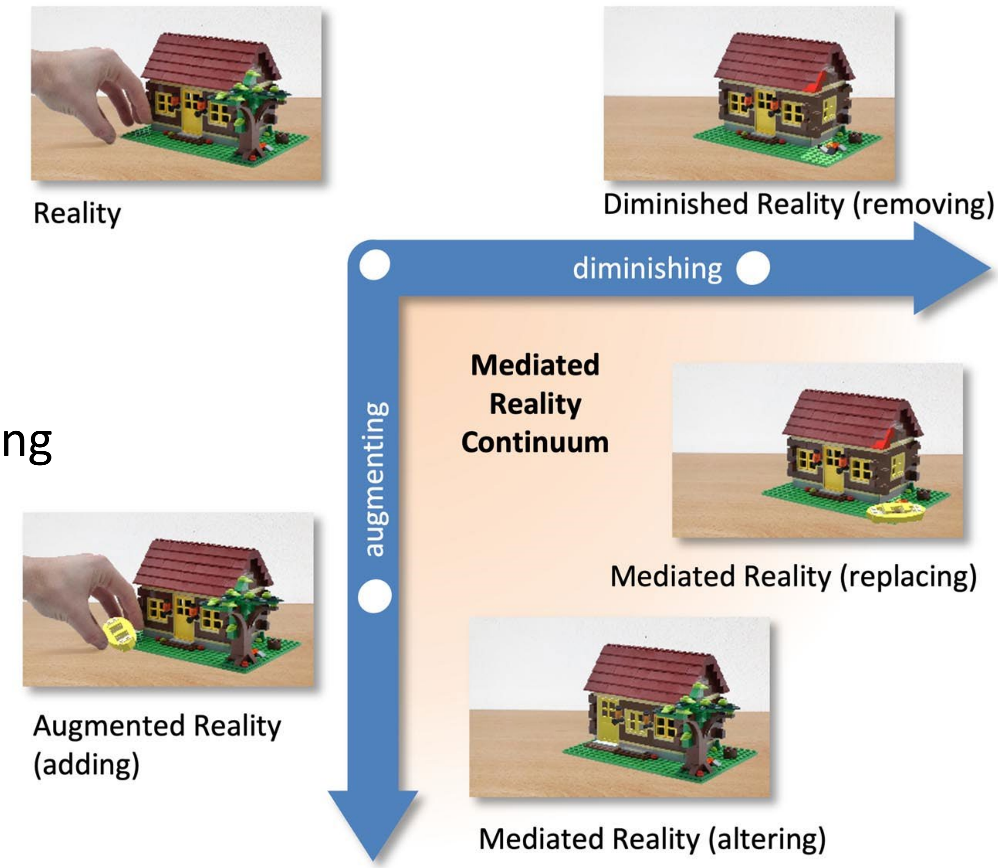


Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Diminished reality by masking and context sensitive filling. (Individual images: © Tobias Schwandt, TU Ilmenau 2018. All rights reserved.)

Mediated Reality

- Mediated reality
  - ➢ Both AR and DR are partial aspects
    - Adding and removing parts of reality
    - Even replacing or altering parts of reality



The Mediated Reality continuum: reality may be augmented (AR) by adding virtual content as well as diminished (DR) by removing real content. In combination, this allows both the replacement of real content with virtual content as well as its modification (Mediated Reality). (Still images: © Tobias Schwandt, TU Ilmenau 2018. All rights reserved.)

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Mediated Reality

- Can combine AR with DR
  - Remove some part and insert something else

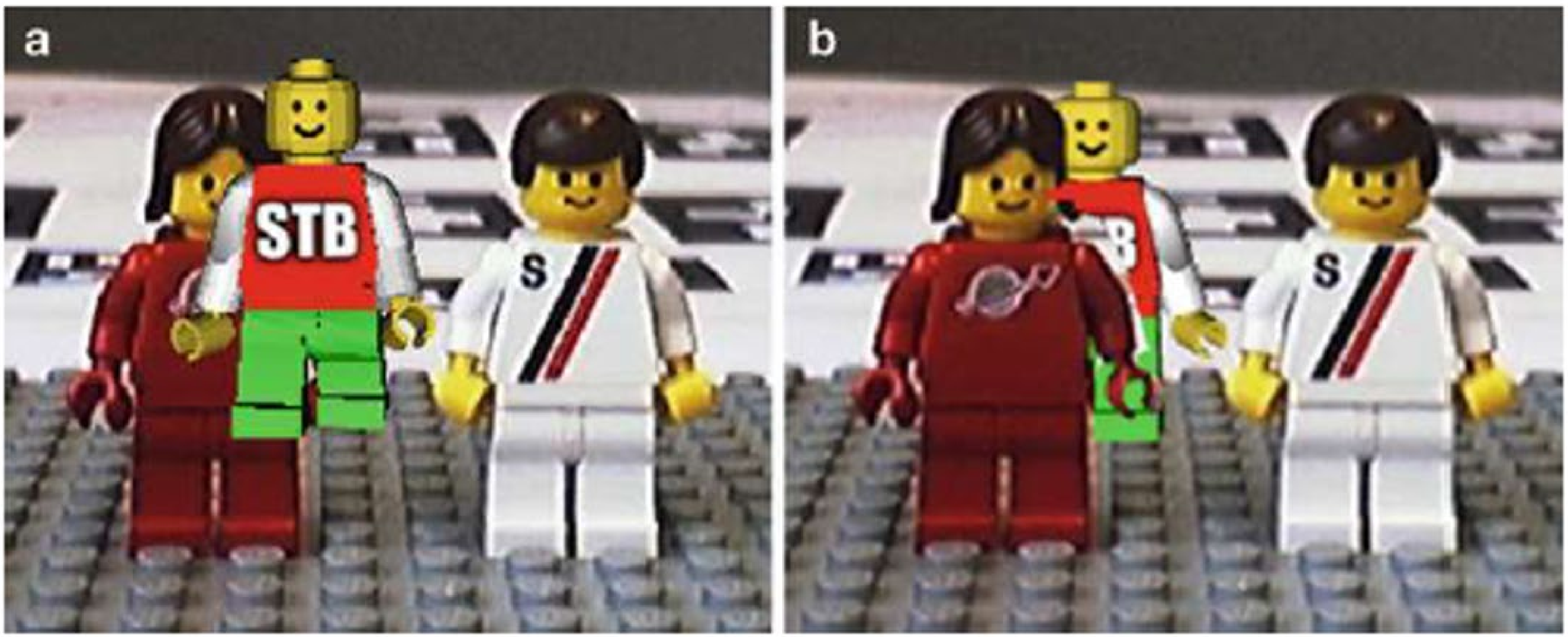
Combining Dimished Reality and AR. (© Christian Kunert, TU Ilmenau 2018. All rights reserved.)

Visual Coherence

- Occlusion
  - One of the strongest depth cues
  - Simply drawing computer graphics objects on top of a video background with a registered camera
    - Not sufficient to create impression where real and virtual coexist
  - Virtual in front of real
    - Draw augmentation on top of video background
  - Virtual behind real
    - Need strategy to distinguish visible from occluded augmentations
    - Failure to consider occlusion
      - Leads to a composition that is irritating and not effective in conveying the 3D position of a virtual object

Visual Coherence

- Occlusion example
  - Lack of appropriate depth cues

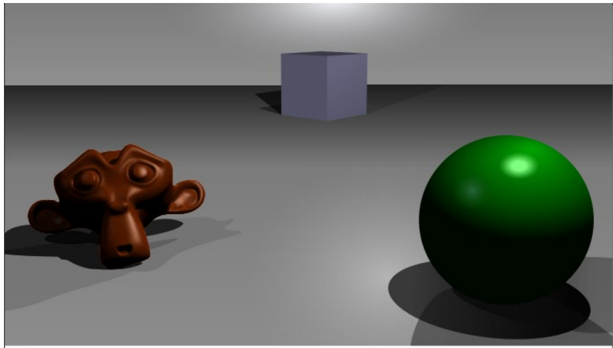


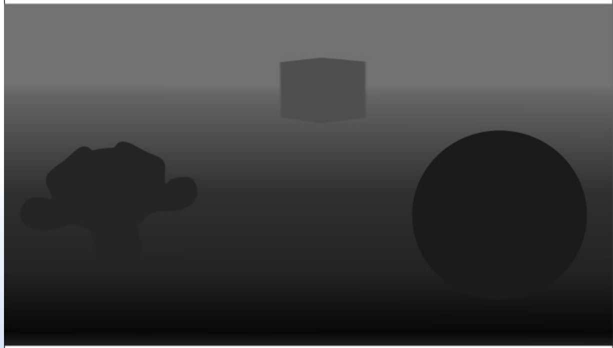
The virtual character is placed at the correct position, but occlusion by the physical character is not considered

Correct occlusion rendering creates a much more realistic impression without conflicting cues

Visual Coherence

- Phantoms
  - Virtual representation of a real object, rendered invisibly
  - Occlusions handled by graphics hardware
    - Requires the z-buffer (depth buffer)
    - Phantom only rendered in the depth buffer
    - Establishes correct depth values for real object visible
    - Will occlude virtual objects


A simple three-dimensional scene


Z-buffer representation

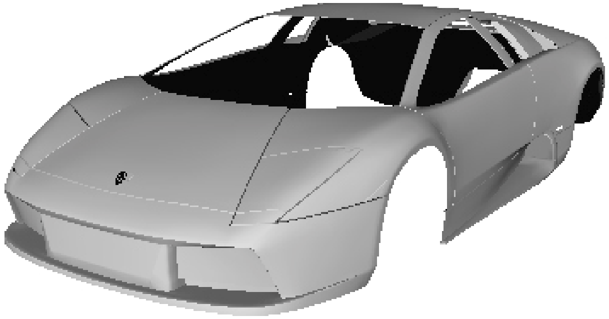
-Zeus-, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Visual Coherence

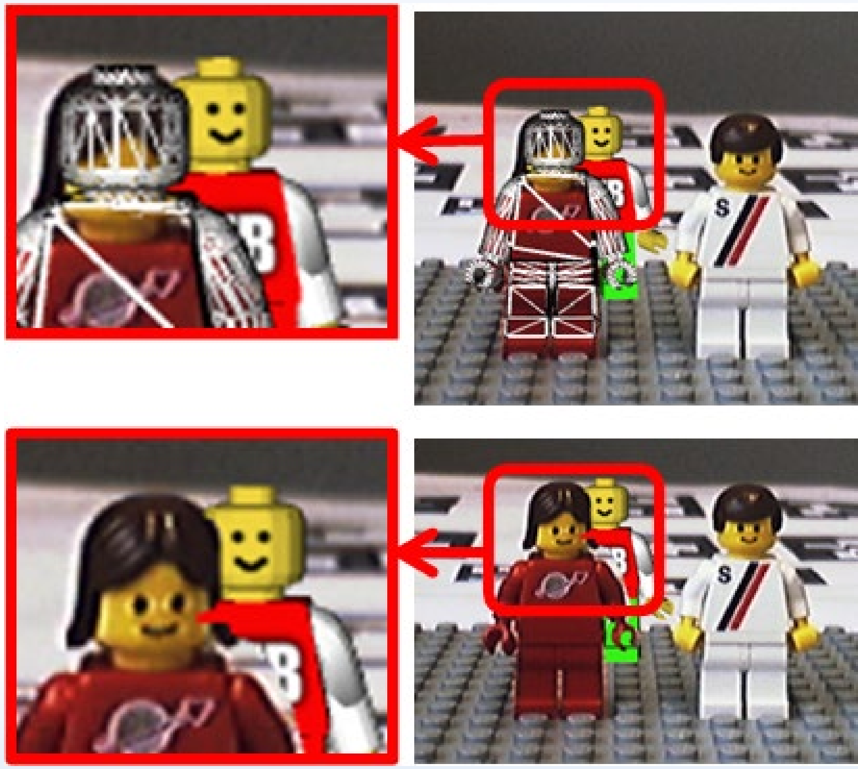
- Phantom rendering

  Pseudocode

  1. Draw video
  2. Disable writing to colour buffer
  3. Render phantoms
     - Only sets values in depth buffer
  4. Enable writing to colour buffer
  5. Draw virtual objects



Visual Coherence



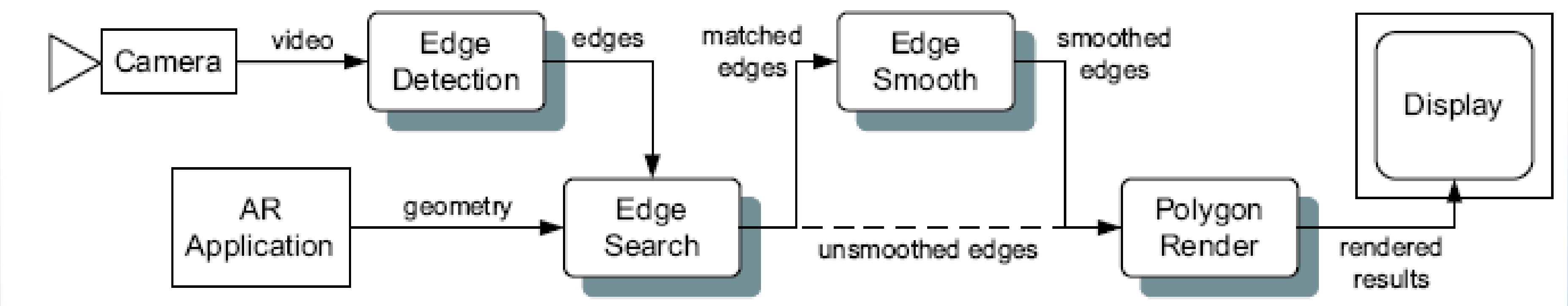
- Phantoms often defined using conventional polygon models
  - Can readily be rendered using standard graphics hardware
- Phantom rendering problems
  - Requires accurate
    - Model
    - Tracking data
    - Registration
  - Models that do not faithfully represent real object cannot produce correct occlusion masks
  - Incorrect tracking or registration, phantom rendered at wrong location

Visual Coherence

- Occlusion refinement
  - ➢ Humans quite good at detecting inconsistencies
  - ➢ Only silhouettes of a phantom object must be accurate
    - Only edges of polygonal model that form the silhouette must be correct
  - ➢ Correction can be estimated in image space
    - Search video image for corresponding nearby edge representing true occlusion boundary
    - Polygon adjusted to match the edge found in the image
    - Transparency gradient applied to blur edges
      - – Makes inaccuracies less obvious

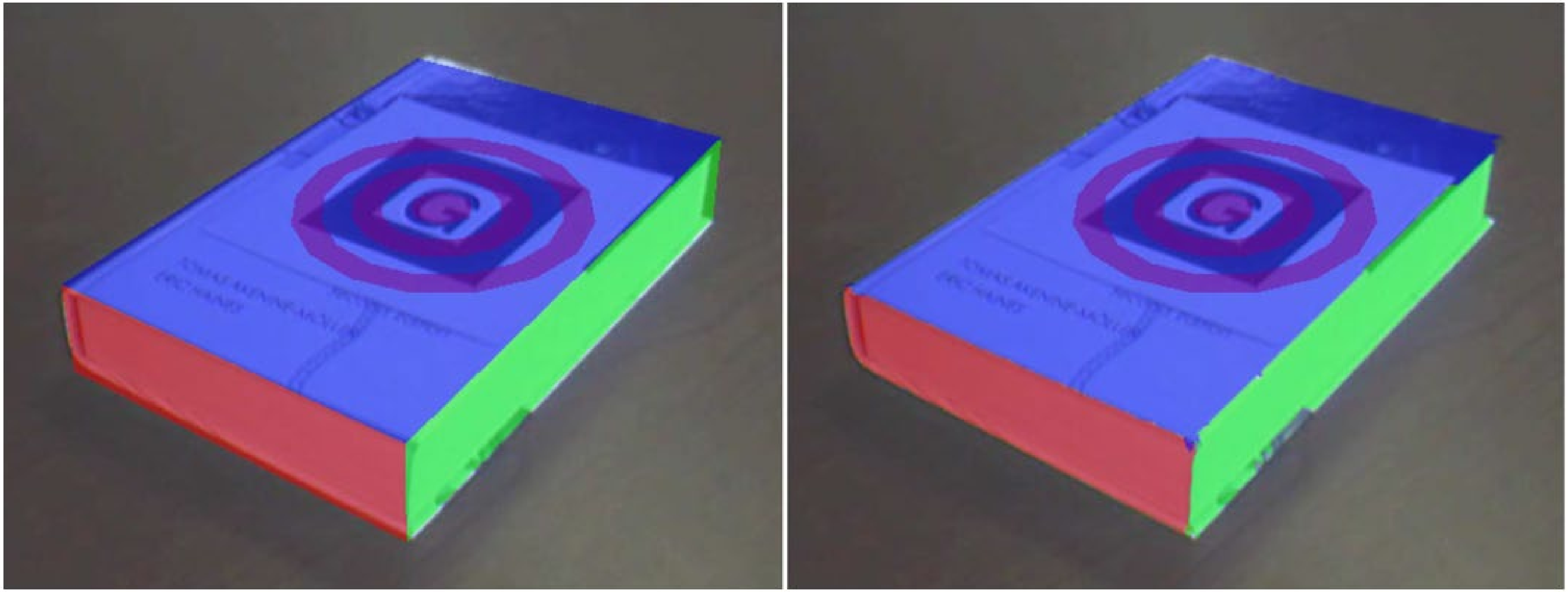
Visual Coherence

- Edge occlusion pipeline
  - Possible approach for occlusion refinement performed purely on the GPU
  - First, edges are detected in video image and matched with edges of virtual models
  - Corrected edges then superimposed with alpha blending on top of polygon from which they were derived



Visual Coherence

- Edge occlusion example

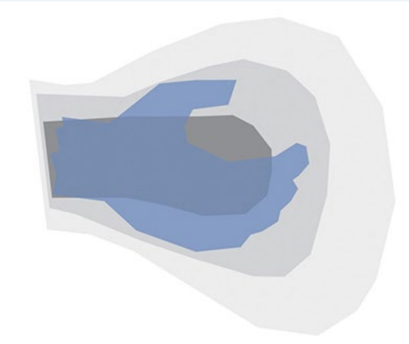


Search near the projected edge of a phantom object for the true edge of the corresponding real objects

→ correct occlusion boundaries

Visual Coherence

- Probablistic occlusion
  - Phantom rendering of dynamically moving limbs
    - Tracking uses motion capturing system
  - Probabilistic model used where tracking is not precise
    - E.g., human hands
  - Multiple nested transparent surfaces
    - More transparent from innermost to outermost shell
    - Compensate for tracking and registration error by reducing occluder's transparency depending on the probability of occlusion

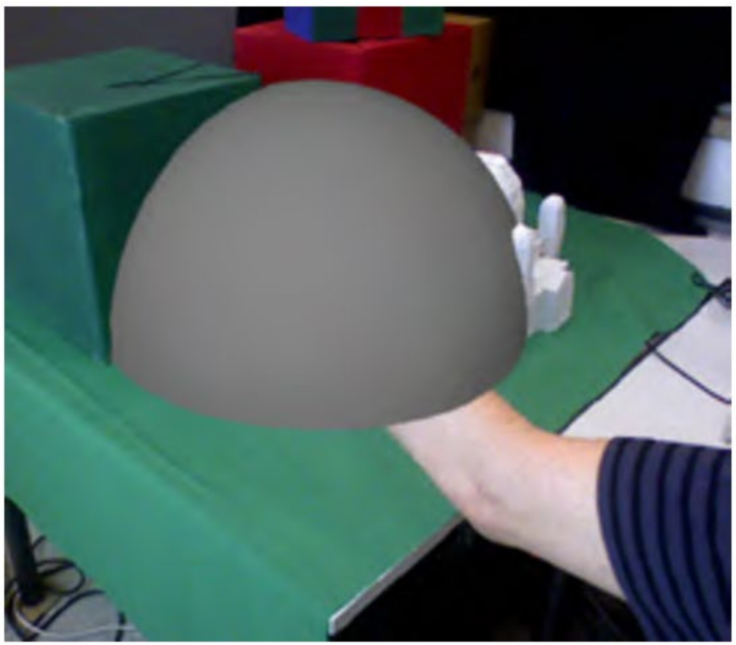


Visual Coherence

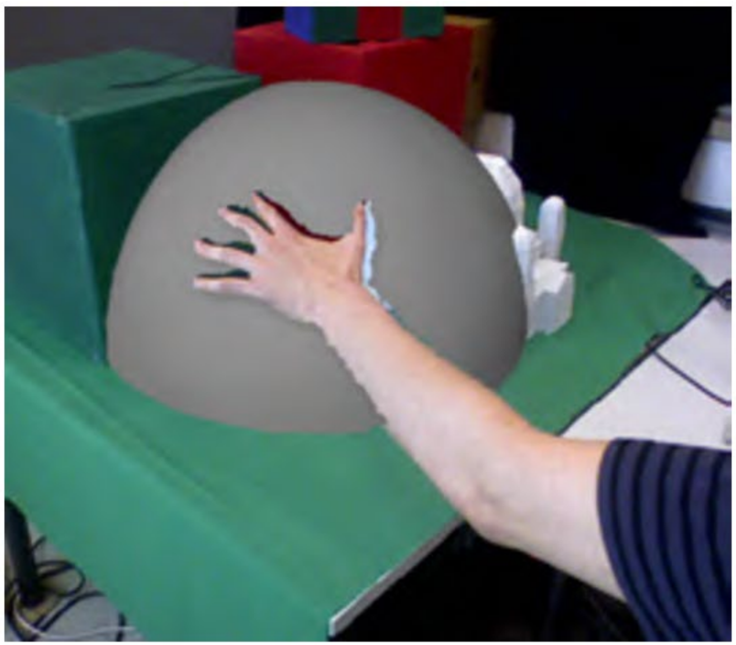
- Model-free occlusion
  - ➢ Not always possible to obtain phantom objects beforehand
  - ➢ Instead of tracking and registering phantom model
    - Construct depth map from video
      - – From computer vision
      - – Stereo, shading, structured light, etc.
    - Must consider performance
  - ➢ One method
    - User manually selects a foreground object
      - – System tracks the contour of this object in successive frames to derive correct occlusions
      - – No explicit 3D model required

Visual Coherence

- Dedicated depth sensor
  - Depth maps obtained fully automatically in real-time
  - Depth image must be reprojected into camera's view space



The hand is incorrectly occluded by the virtual object



A depth sensor provides a simple way to resolve depth with real-world objects for every pixel at frame rate

Visual Coherence

- Virtual studio occlusion
  - A priori knowledge of the scene layout
    - Foreground and background structure already known
  - Foreground separated by illumination
    - Imperceptible flash keying
    - Foreground illuminated by flashlight alternating frames at 60Hz
    - Synch. with camera

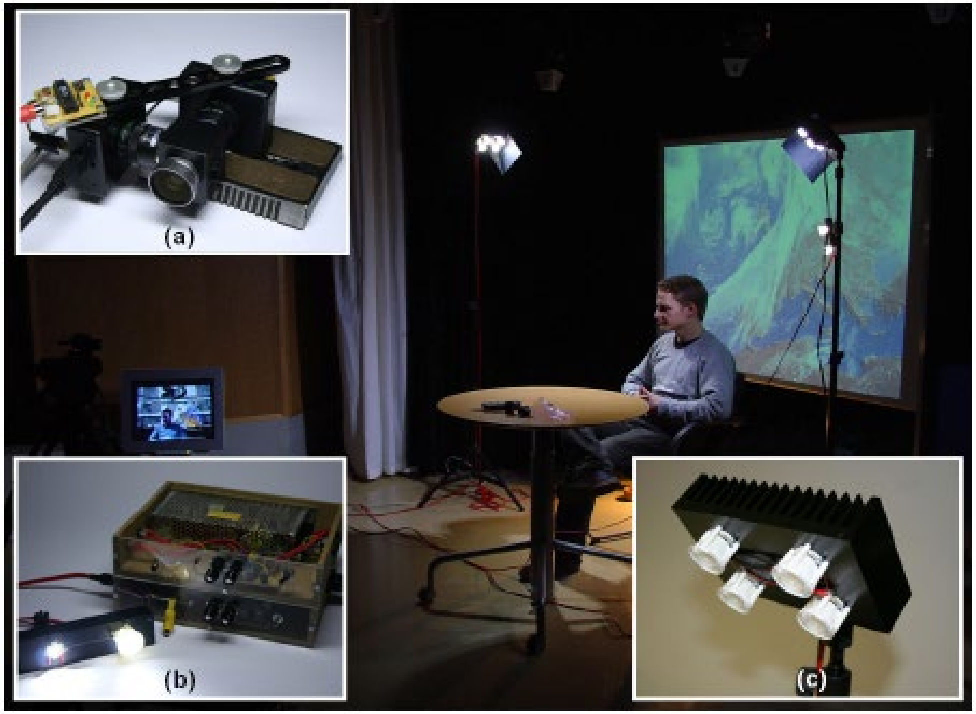


Image: Oliver Bimber

Visual Coherence

- Virtual studio occlusion

A speaker in a virtual studio in front of a live background

Using structured light, the speaker in the foreground can be segmented in real time

Image: Oliver Bimber

Visual Coherence

- Detecting certain objects
  - Large body of work on hand detection
  - Assumption that hand is the foreground object that occludes any virtual objects
  - Burn AR example
    - User's hands are segmented based on skin colour
      - The detected hands are virtually ignited

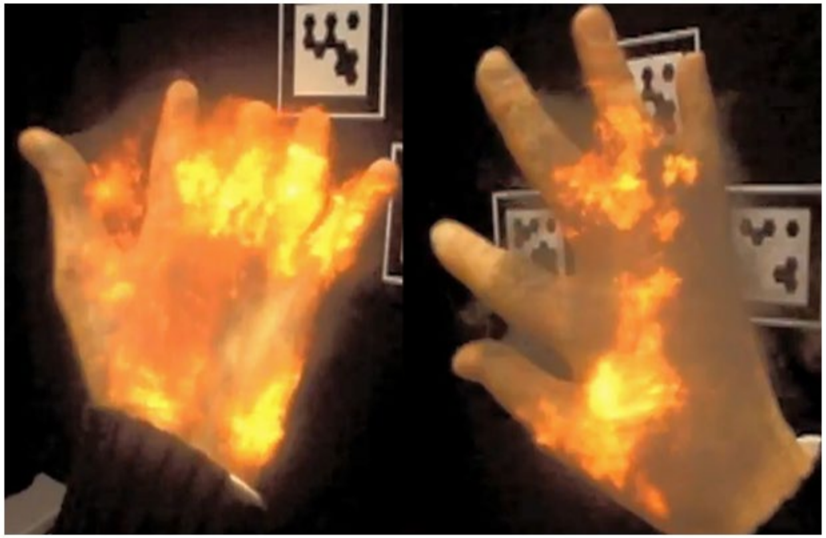
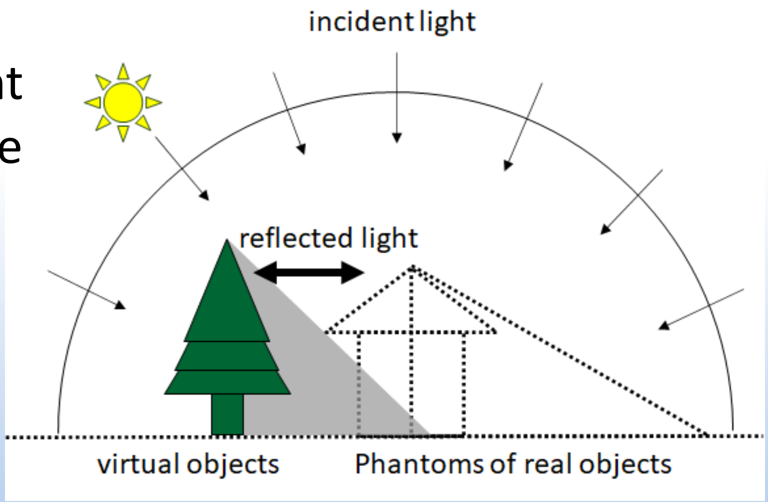


Image: Gerhard Reitmayr

    - Colour-based segmentation works without additional hardware
      - Not robust, easily fail in challenging lighting conditions

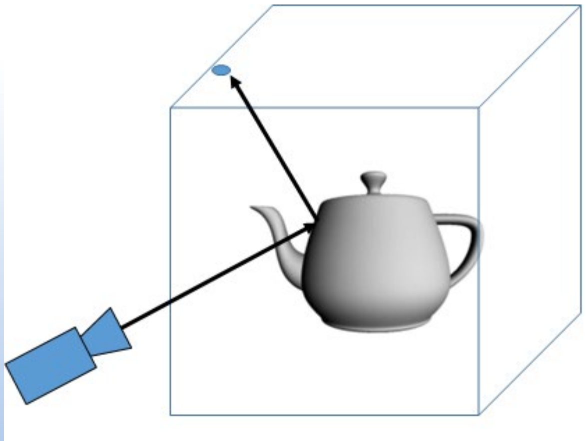
Visual Coherence

- Photometric registration
  - ➢ Occlusion between real and virtual not sufficient to produce realistic AR images
  - ➢ Consistent illumination of virtual objects
  - ➢ Need to consider incident illumination
  - ➢ For small AR workspaces
    - Limit complexity by assuming all light sources distant and external to scene
    - Only sun/ceiling lights
      - – No local sources, e.g., desk lamps, candles



Visual Coherence

- Distant light sources
  - Can be modeled as directional light stored in an environment map
  - An environment map is an efficient representation of illumination an object receives from its surroundings
    - Purely index by direction, not position
  - Light leaving the scene and being reflected, not considered
  - Limited to low frequencies
    - Hard shadows are rare



Visual Coherence

- Image-based lighting
  - Radiance map
    - An environment map that represents incoming light from the point of view of the observer
  - Can use radiance map to apply image-based lighting to virtual objects
  - Programmable texture mapping on GPUs allows interactive use of image-based lighting

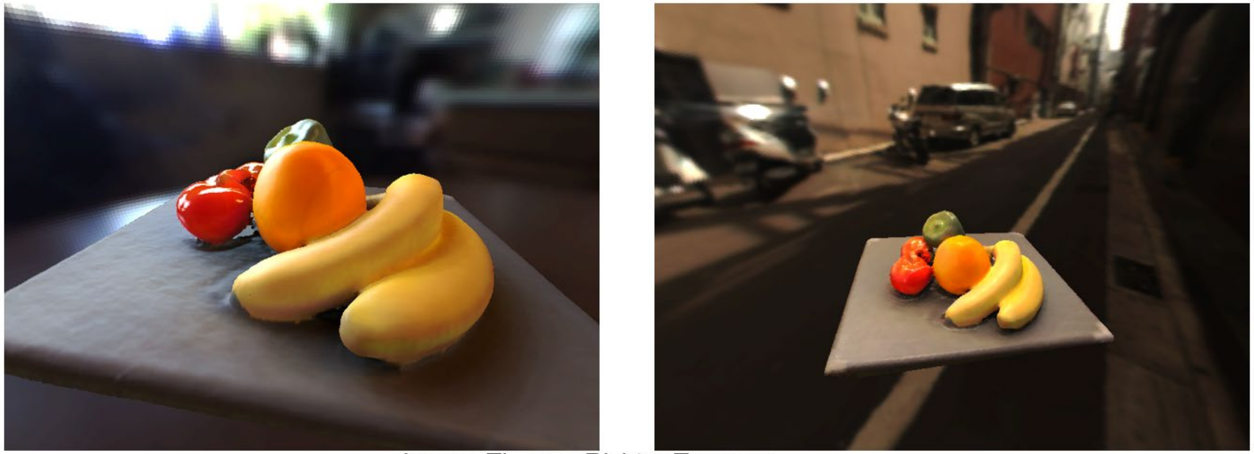
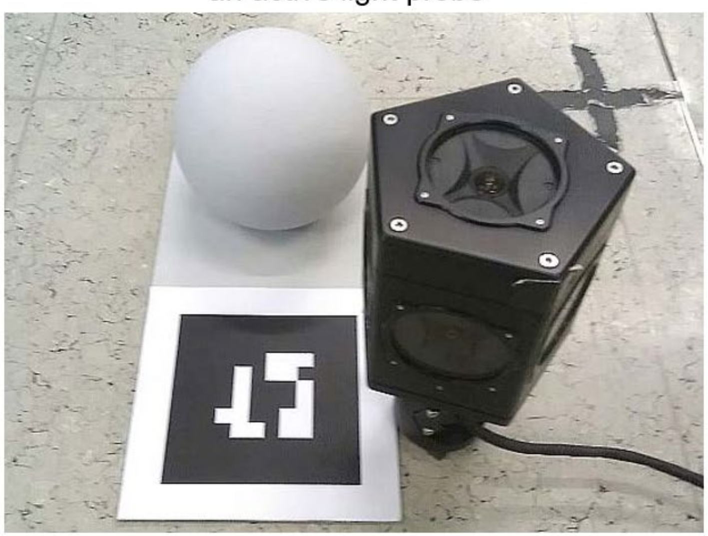


Image: Thomas Richter-Trummer

Visual Coherence

- Light probes
  - Can be used to effectively acquire a radiance map
  - Can be passive (reflective object) or active (camera)
  - Should be omnidirectional
    - Cameras require fish-eye lens

An omnidirectional camera can serve as an active light probe



A light probe in the form of a diffuse sphere and mirror sphere captures the real-world illumination

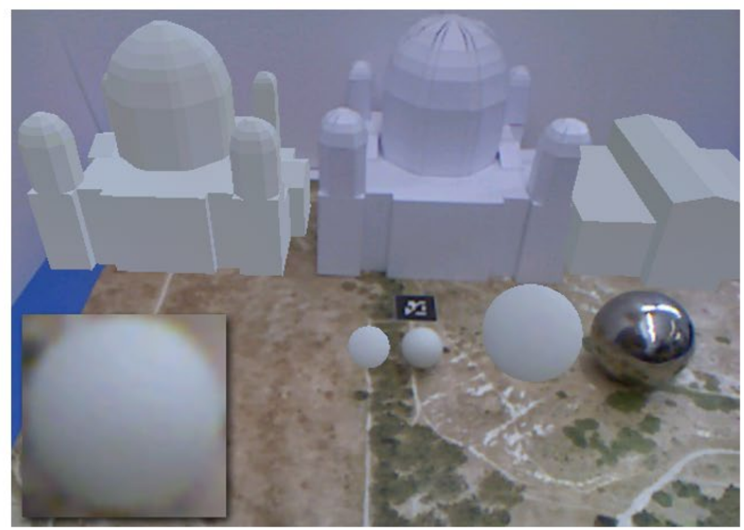


Image: Lukas Gruber

Visual Coherence

- Light probe and environment maps
  - Shiny chrome sphere

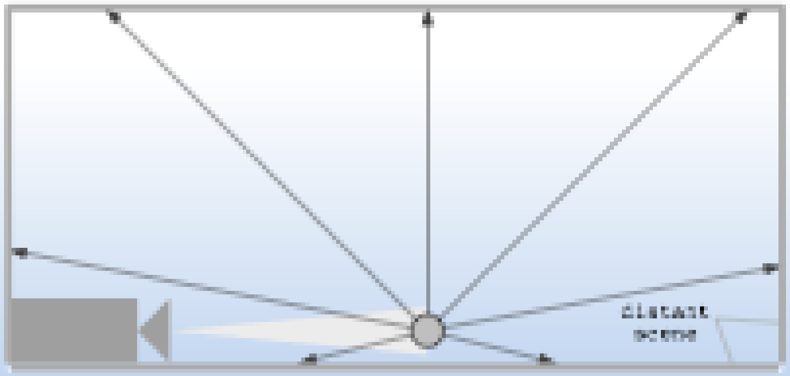


Image: Paul Devebec

Visual Coherence

- Textured target as light probe
  - Flat objects as diffusely reflecting light probes
    - A planar tracking target
      - E.g., a textured rectangle with known texture
  - Simple light probe to estimate the dominant lighting direction
  - A virtual object can have realistic shading and cast a shadow

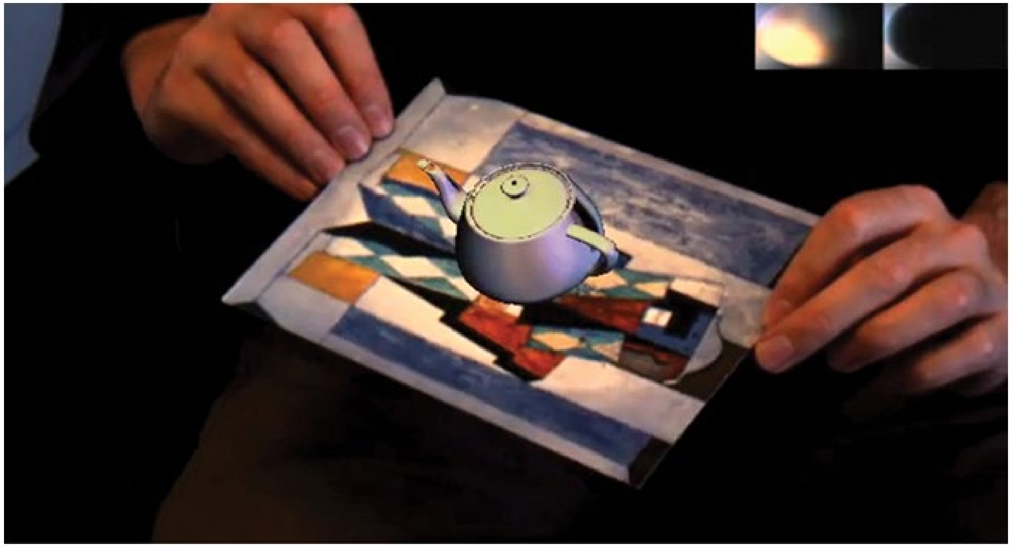


Image: Julien Pilet, Andreas Geiger, Pascal Lagger, Vincent Lepetit and Pascal Fua

Visual Coherence

- Diffuse reflections
  - Directional light can be estimated from diffuse objects and applied to a virtual object
  - Estimated incident light represented as a cube map
  - Change in the strongest lighting direction
    - Indicated by the red dot in the environment map
    - Corresponds to movement of white highlight on the dome

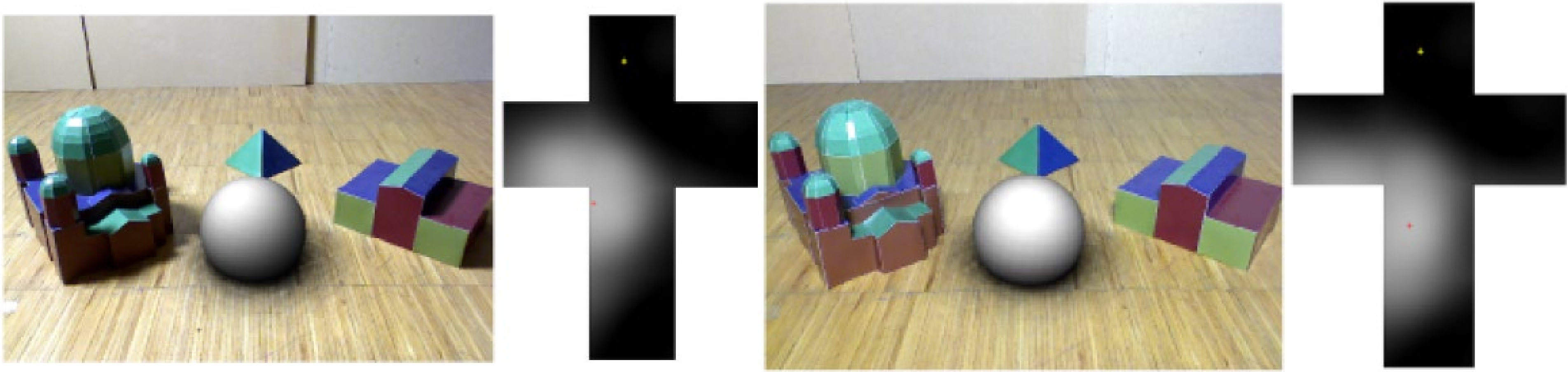
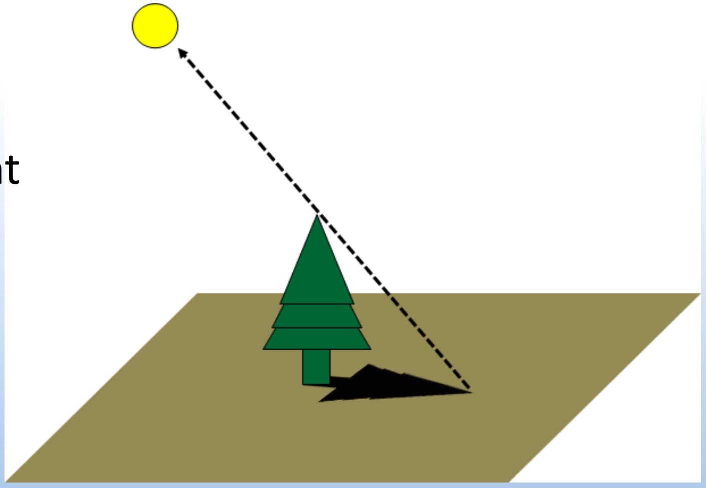


Image: Lukas Gruber

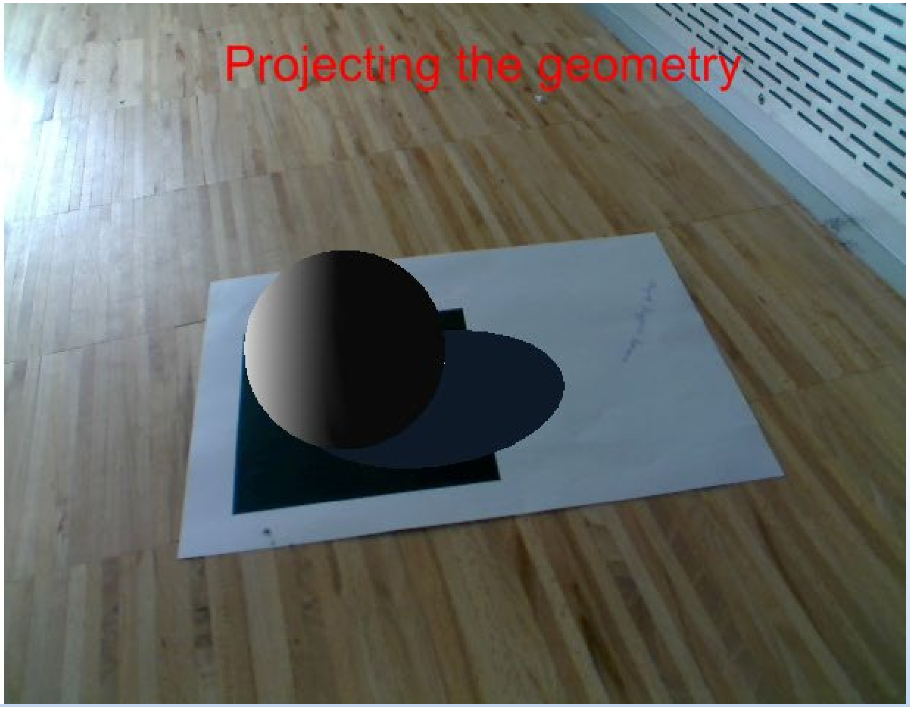
Visual Coherence

- Shadows
  - Important for
    - Depth perception
    - Scene interpretation
  - Shadows in an image are a method of estimating light sources
  - Based on
    - Knowledge of shadow caster's geometry
    - Correct classification and measurement of shadow
  - Detect shadow and contour
    - Direction of light source estimated by forming a ray from a unique point in a shadow's contour to the corresponding surface point on the shadow caster



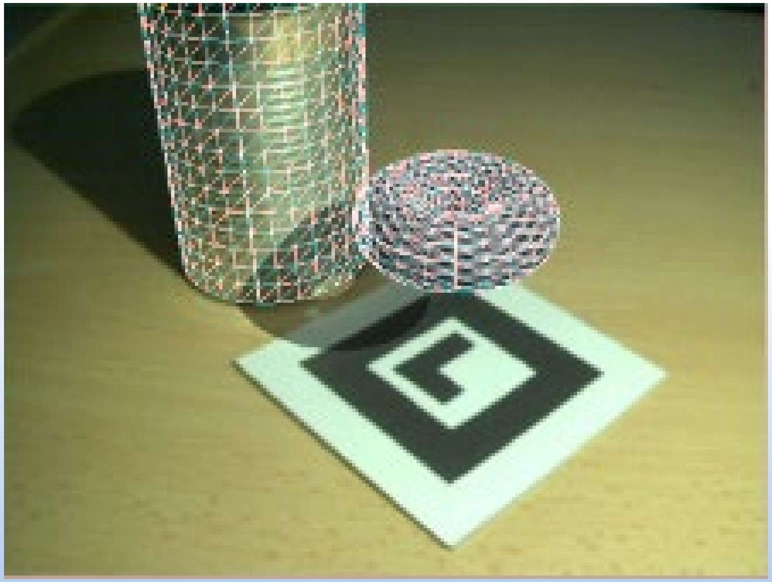
Visual Coherence

- Shadow on plane
  - Simple scene geometry
  - Only virtual shadows



Visual Coherence

- Scene model requirements
  - Virtual objects
  - Phantoms of real objects
  - Light sources
    - Represented in shading
    - Used to shadow casting



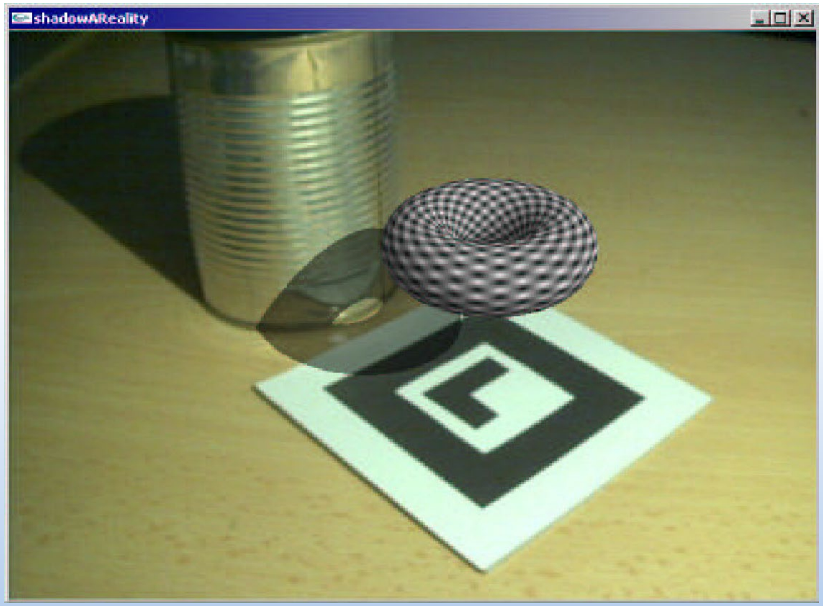
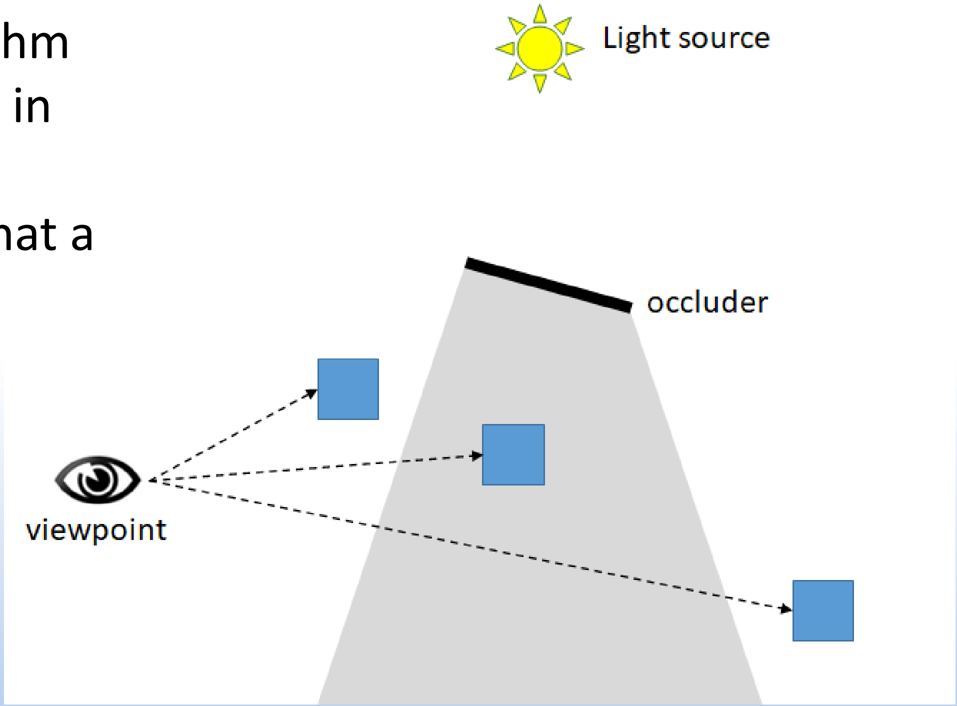


Image: Michael Haller

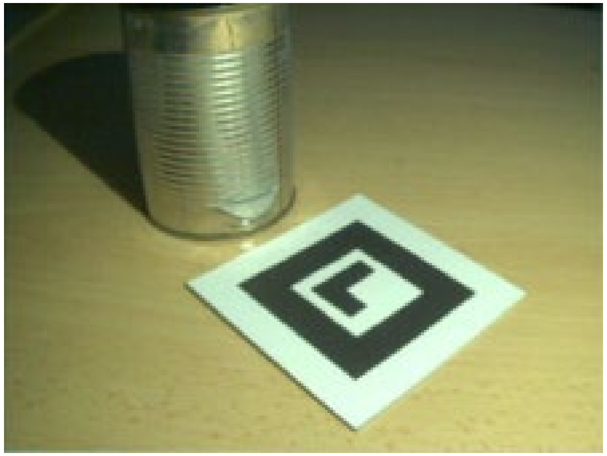
Visual Coherence

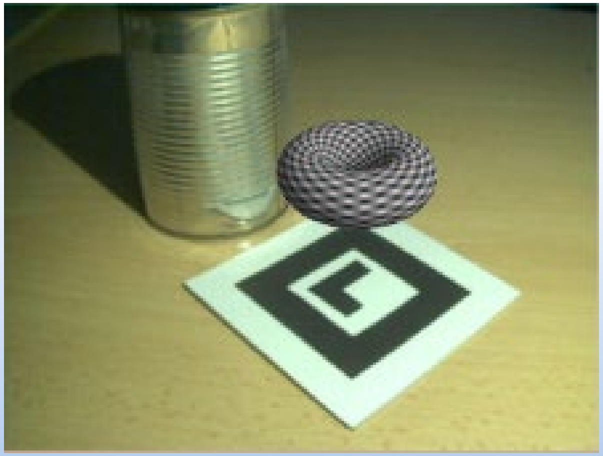
- Shadow volume
  - A frustum that encloses objects that lie in shadow with respect to
    - A given shadow-casting polygon and a light source
  - Requires stencil buffer
  - The shadow volume algorithm determines an object to be in shadow by calculating, via stencil buffer operations, that a view ray entered a shadow volume but did not exit it



Visual Coherence

- Multi-pass shadow volume
  1. Draw scene without illumination
  2. Rasterising front-facing shadow volume polygons increments stencil buffer
  3. Rasterising back-facing shadow volume polygons decrements stencil buffer
  4. Scene drawn again, stencil buffer value of zero not in shadow





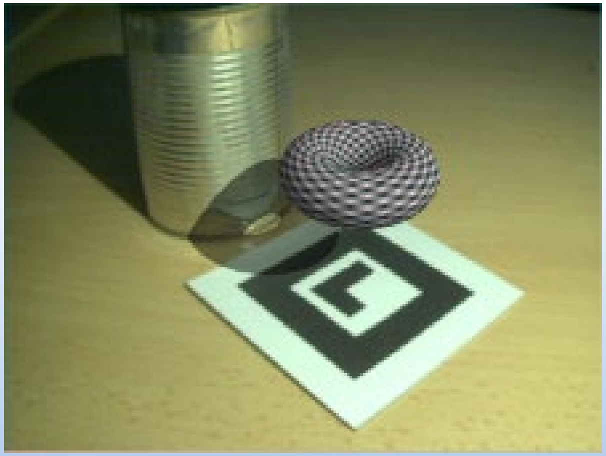


Image: Michael Haller

Visual Coherence

- Shadow mapping
  - Two-pass technique
    - First pass: render to depth buffer from perspective of a light source
    - Second pass: scene rendered from observer's viewpoint, determine whether fragment occluded from point of light source

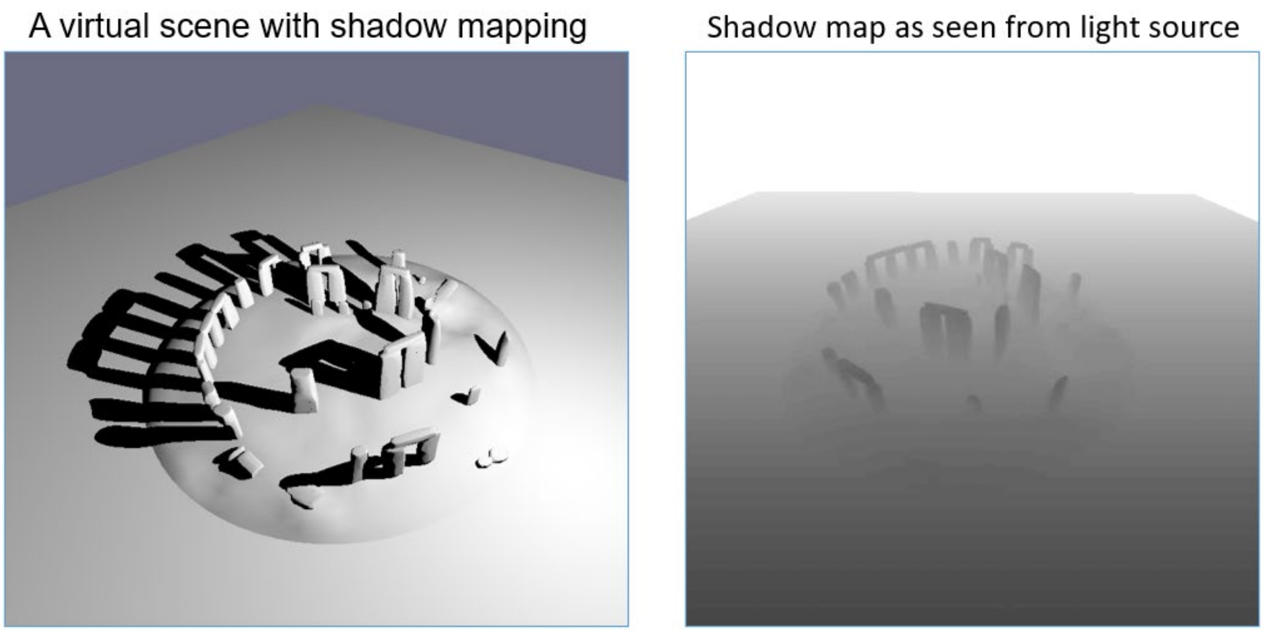


Image: Michael Kenzel

Visual Coherence

- Reconstructing explicit light sources
  - Can be estimated by subdividing an environment map into regions of equal radiance
  - Determine a representative point in each region
  - For high-resolution radiance map, number of light sources can be excessive

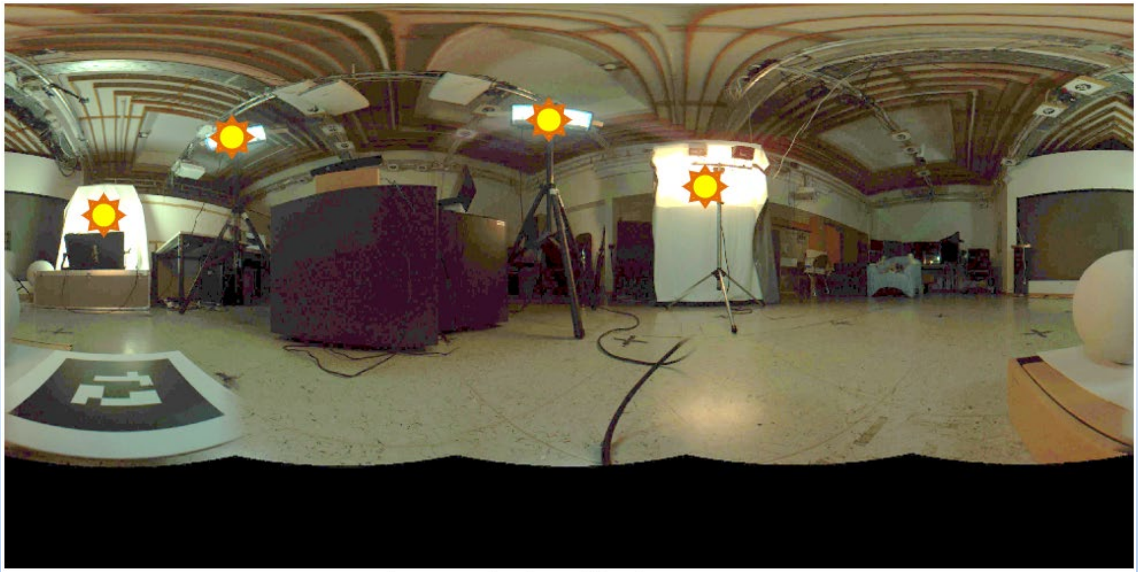


Image: Lukas Gruber

Visual Coherence

- Differential rendering
  - Given geometry and material of the scene and parameters of the camera and light sources
    - Can compute L_R, original scene without any virtual objects
  - After inserting virtual objects, can compute L_{R+V}
  - The difference $L_{R+V} - L_R$ represents how the illumination changed by adding the virtual object
  - Can be added as a correction term to the camera image L_C
    - Pixels showing virtual objects: $L_{final} = L_{R+V}$
    - Pixels showing real objects: $L_{final} = L_C + L_{R+V} - L_R$
  - More difficult if there are changes to light sources

Visual Coherence

- Differential rendering combines the light contributions
  - of newly added virtual objects, as calculated against a virtual representation of the physical scene L_R
  - and the live video input

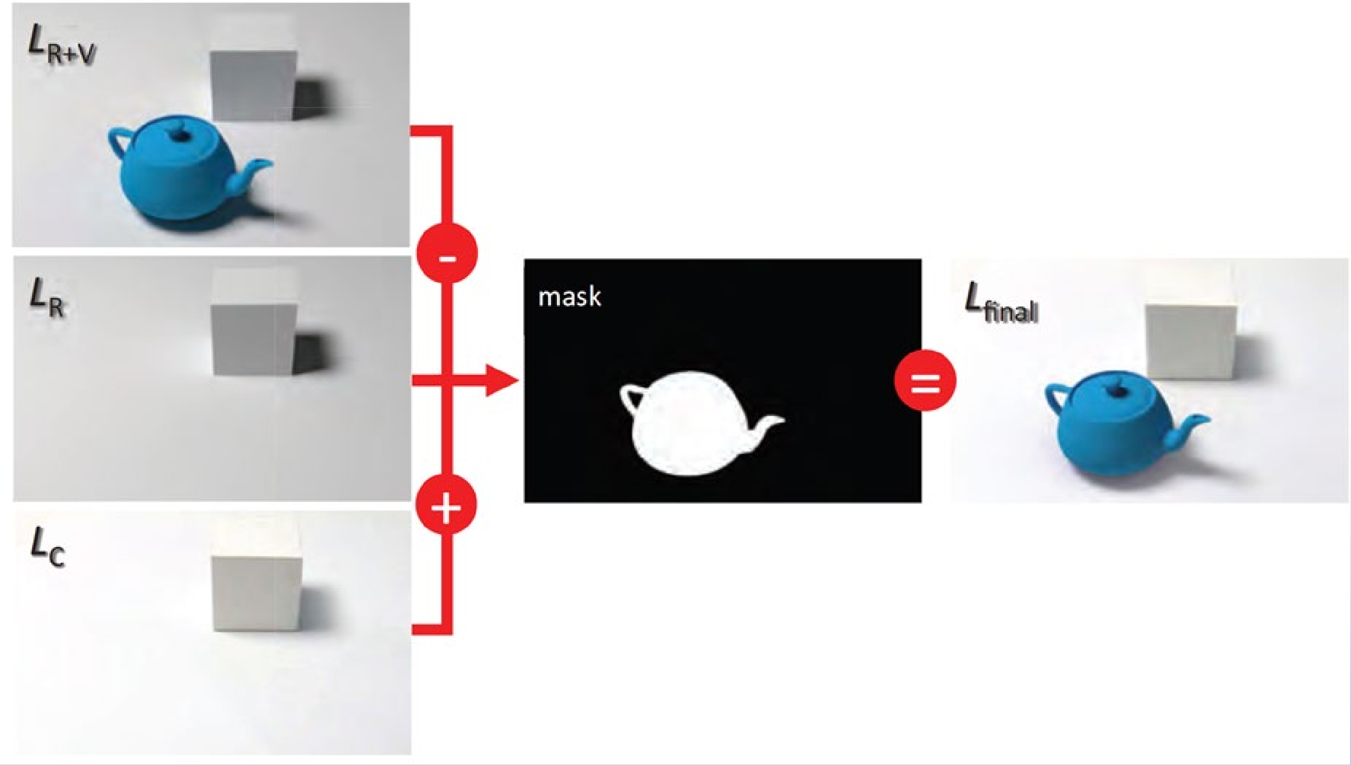


Image: Peter Kán

Visual Coherence

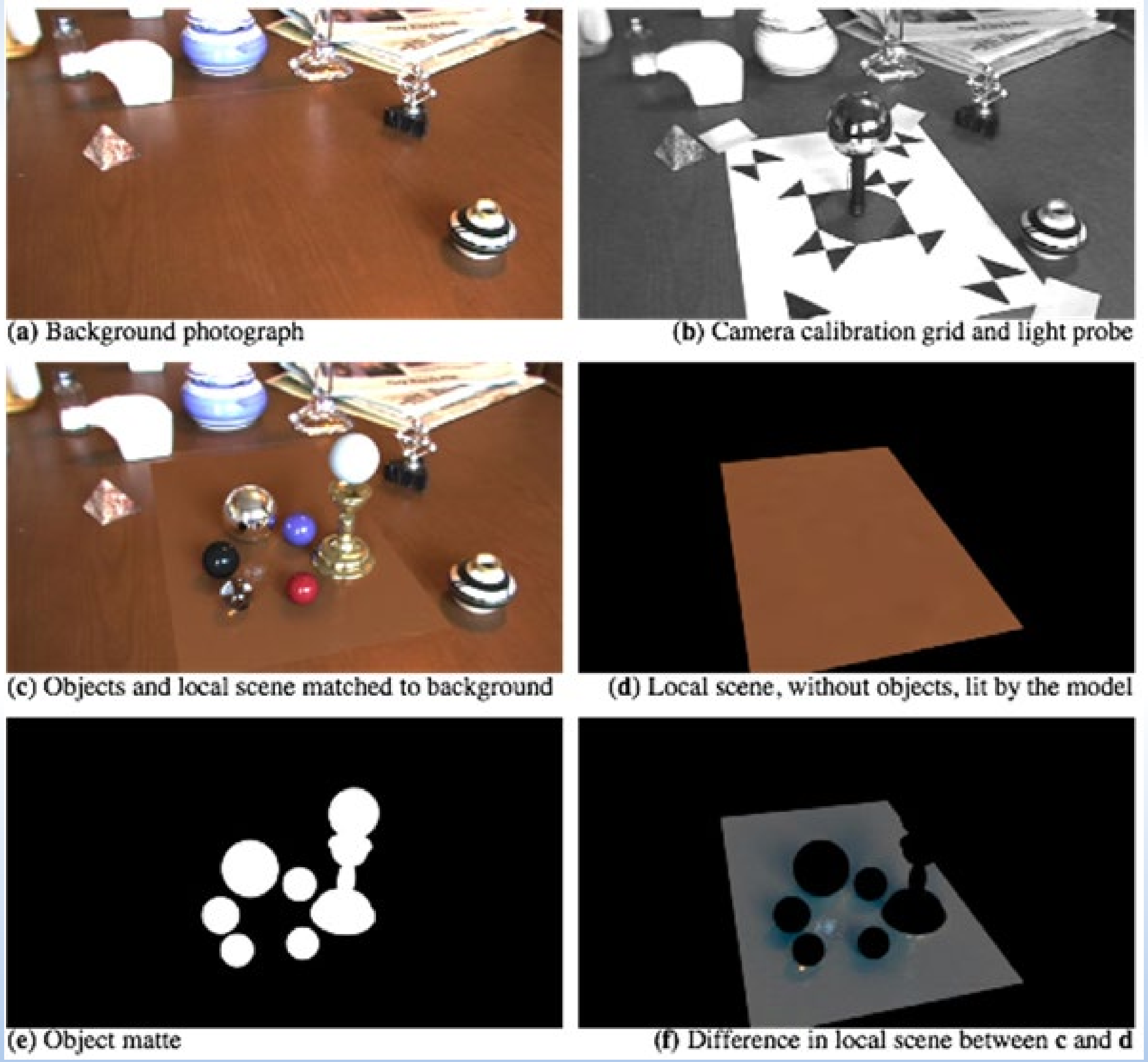


Image: Paul Debevec

Visual Coherence

- Differential rendering results

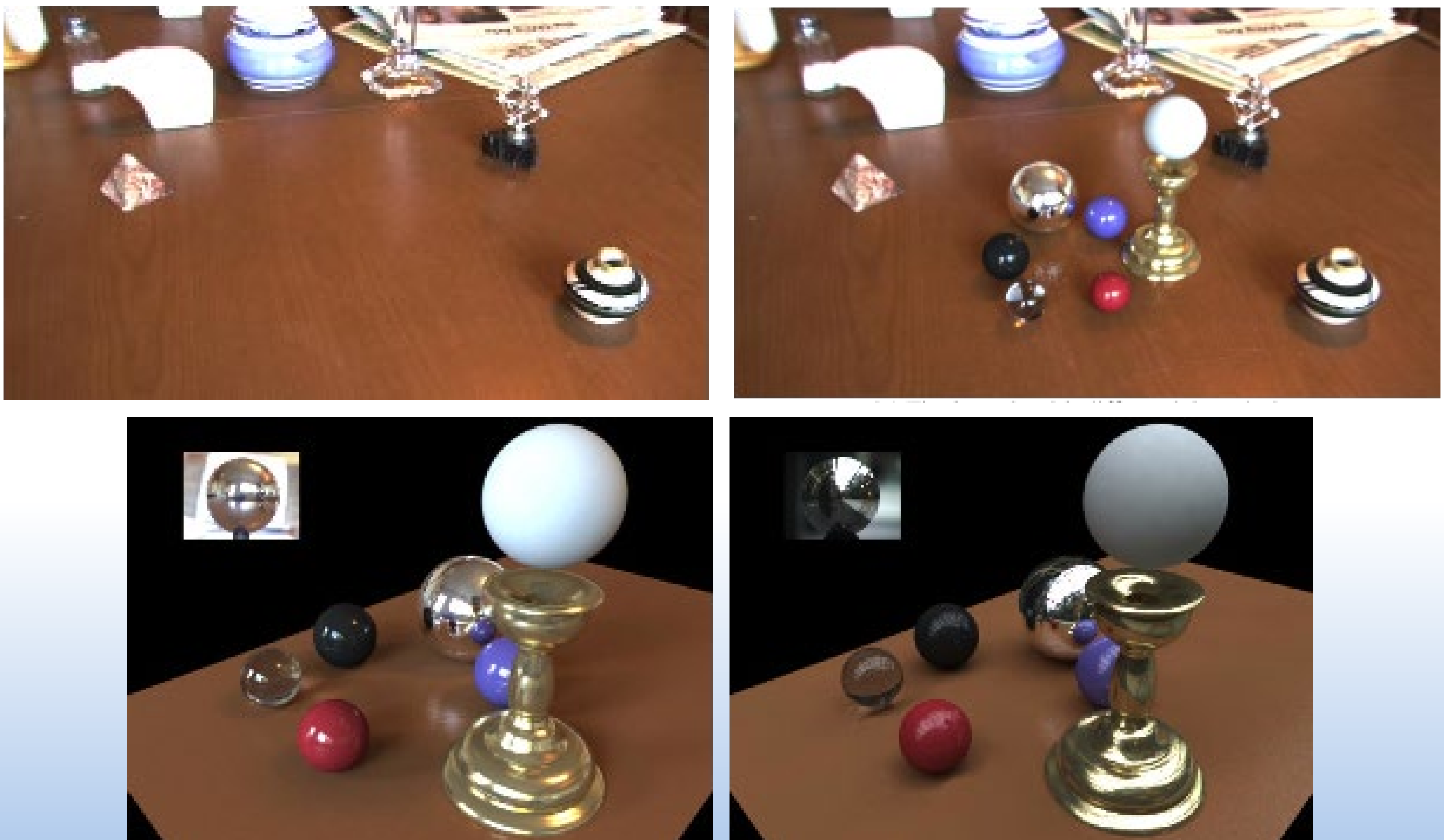


Image: Paul Debevec

Visual Coherence

- Differential path tracing
  - Real-time path tracing enables realistic global illumination effects
  - Local illumination (left) and global illumination (right) rendering for augmented reality

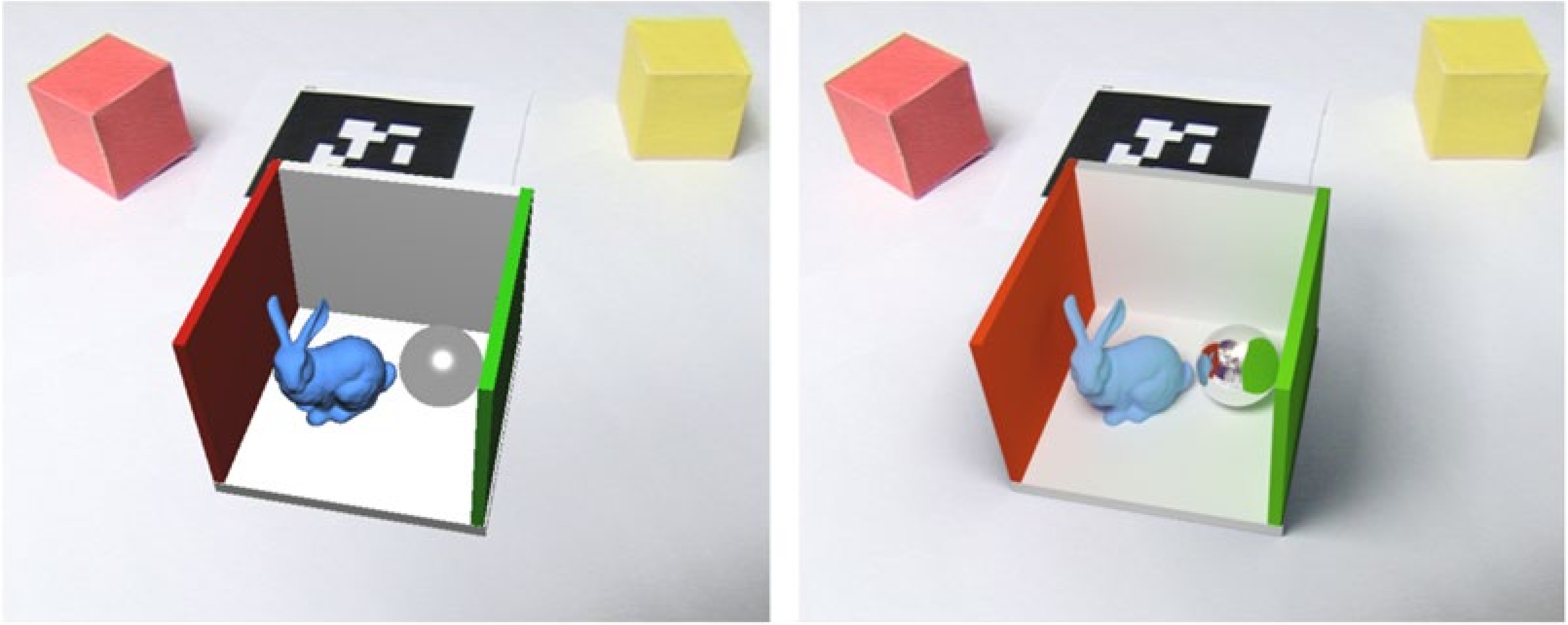
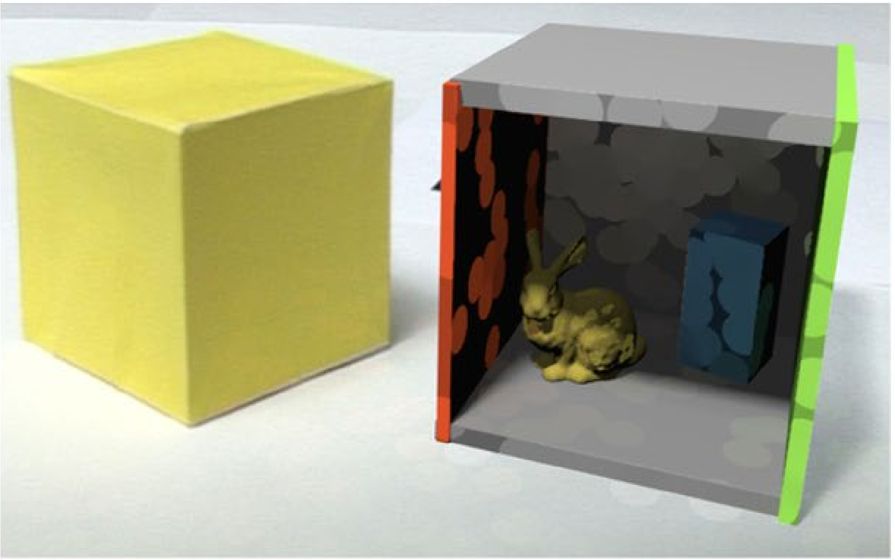


Image: Peter Kán

Visual Coherence

- Differential photon mapping

Visualization of raw photon map



Converged global illumination solution

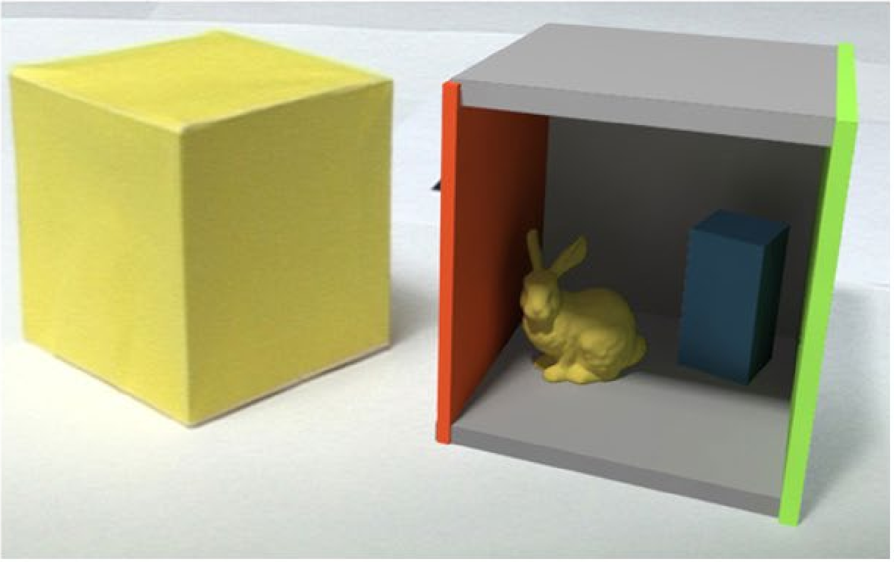
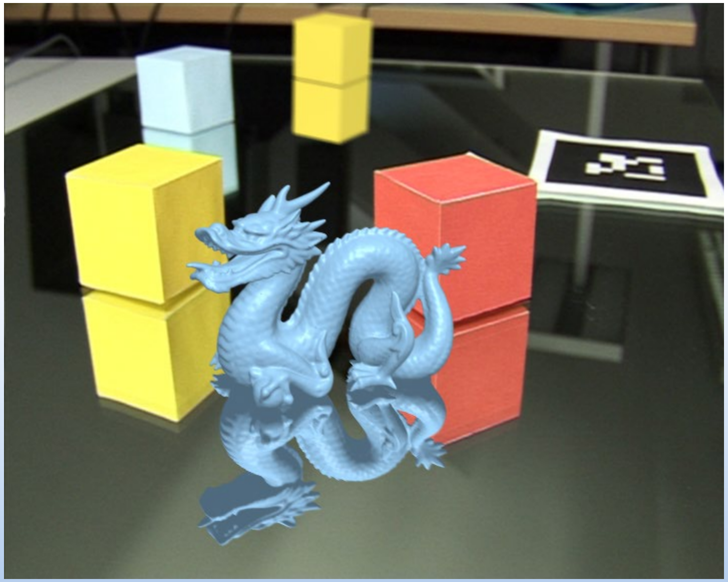


Image: Peter Kán

Visual Coherence

- Reflections
  - Specular reflections of virtual and real objects in a real mirror table surface, produced with real-time ray-tracing
- Refractions
  - Refractions computed with real-time ray-tracing let the user's hand appear realistically through the virtual glass



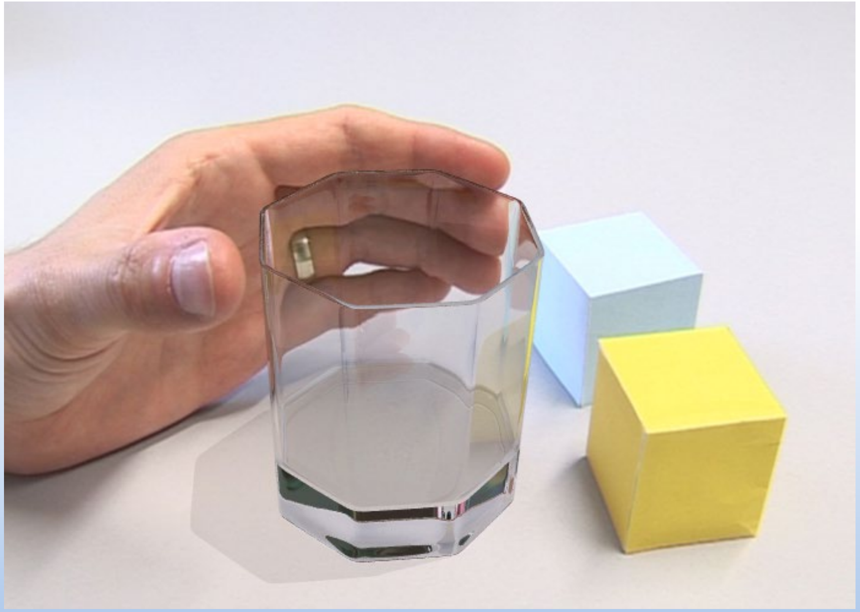


Image: Peter Kán

References

- Among others, material sourced from
  - ➢ D. Schmalstieg and T. Hollerer, Augmented Reality: Principles and Practice, Addison-Wesley
    - www.augmentedrealitybook.org
  - ➢ R. Doerner, W. Broll, P. Grimm, B. Jung, Virtual and Augmented Reality: Foundations and Methods of Extended Realities, Springer
  - ➢ http://en.wikipedia.org/wiki/