Advanced Graphics & Image Processing

Display Technologies

Özgür Yöntem

Computer Laboratory, University of Cambridge

Hi, my name is Ozgur Yontem. I am a Senior Research Associate in Displays in Rainbow Research Group. I will give this lecture on Display Technologies as part of Advanced Graphics and Image Processing course.

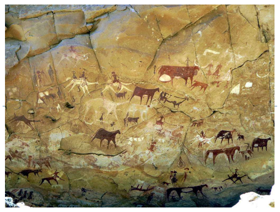
Overview

1. Display Components:
   - (Digital) Signal Processing
   - Optics / Electronics
2. 2D displays
   - Emissive
   - Transmissive
   - Reflective
   - Hybrid (MEMS)
3. 3D displays
   - Holography
   - Light Field
   - Volumetric
   - Augmented / Virtual / Mixed Reality Displays

This Lecture aims to give some insight about the current display technologies.

- It will address basic building blocks of displays in terms of signal processing, optics and electronics.
- We will cover some historical advancement of displays, the science and engineering behind them.
- We will focus on commonly used displays types in our daily lives.
- We will also look into more advanced displays, specific applications, and emerging technologies such as AR/VR/MR and 3D displays.

Displays



- Saharan rock art: 12000 years ago
- Mona Lisa by Leonardo Da Vinci
- *View from the Window at Le Gras* 1826 or 1827, (believed to be the earliest surviving camera photograph.)

- Maxwell's real image stereoscope (1856)
- Zoetrope (Maxwell's version 1861)

Displays are mediums to demonstrate visual information. Today, when we refer to displays, we immediately think of smartphone, TV or Laptop screens. However, early examples of displays can be considered as cave drawings, paintings, and analog photographs.

Some interesting analog displays are demonstrated by Maxwell. Maxwell has made his own versions of a stereoscope and a zoetrope which are available in the Cavendish Museum in the West Cambridge.

A real image stereoscope allows visualisation of stereoscopic image pairs.
A zoetrope is used to demonstrate hand drawn moving images. We can consider it as first examples of animations.

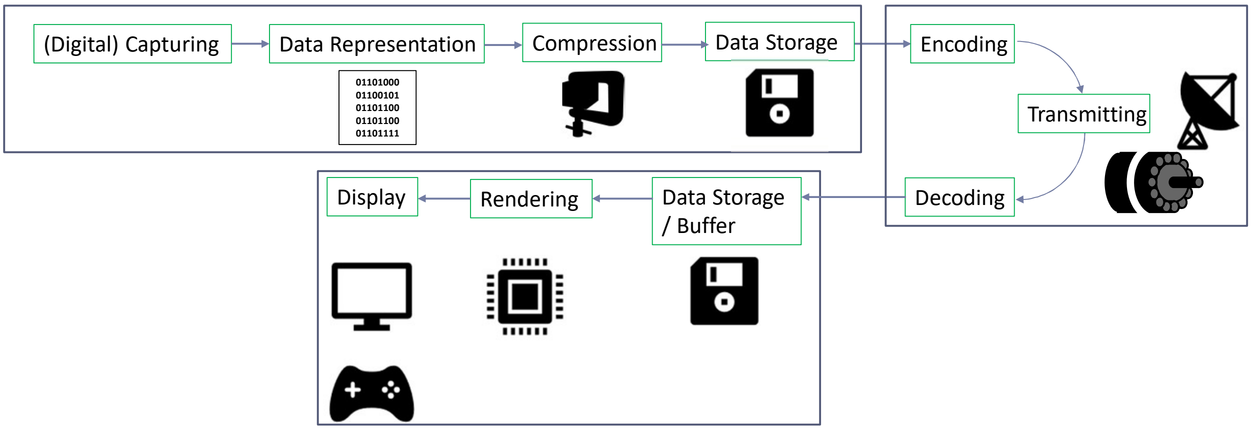
https://en.wikipedia.org/wiki/Saharan_rock_art
https://en.wikipedia.org/wiki/Mona_Lisa
https://en.wikipedia.org/wiki/History_of_photography
https://cudl.lib.cam.ac.uk/view/PH-CAVENDISH-P-00012/1
https://cudl.lib.cam.ac.uk/view/PH-CAVENDISH-P-00013/1

- Displays are the main interface in most of the (digital) machines and devices for visual feedback and interaction.
- Although cinema and TVs were the main display technologies we were familiar with in the not so distant past, we started to see the displays more commonly with the widespread use of PCs and smartphones. This became possible especially with the widespread use of LCD screen technology due to cheaper manufacturing costs and scalability of the technology.
- The variety of the displays and the technologies used are immense. We use them everywhere: laptops, tablets to smartwatches, digital signage, AR/VR head mounted displays, automotive and aircraft head-up displays, and so on.

Links to the images:
https://www.ictworks.org/mobile-phones-disaster-responders-humanitarian-aid/#.XvkBI8fPxhE
https://www.techradar.com/news/best-tablet
https://www.bicycling.com/bikes-gear/g20023538/9-great-smart-watches-for-cyclists/
https://www.cnet.com/news/top-25-battery-life-laptops/
https://metro.co.uk/2018/05/08/can-spot-camera-cash-machine-7530333/

https://www.avinteractive.com/news/products/lgs-showstopping-oled-falls-transparent-signage-reach-ise-06-02-2019/
https://www.gizmochina.com/2020/05/05/lg-has-released-worlds-largest-oled-tv-features-an-88-inch-8k-display/
https://homemcr.org/space/cinemas/
https://www.mes-insights.com/what-you-need-to-know-about-head-up-displays-huds-a-910391/
https://aerospaceamerica.aiaa.org/features/new-eyes-for-airline-pilots/

Display Components



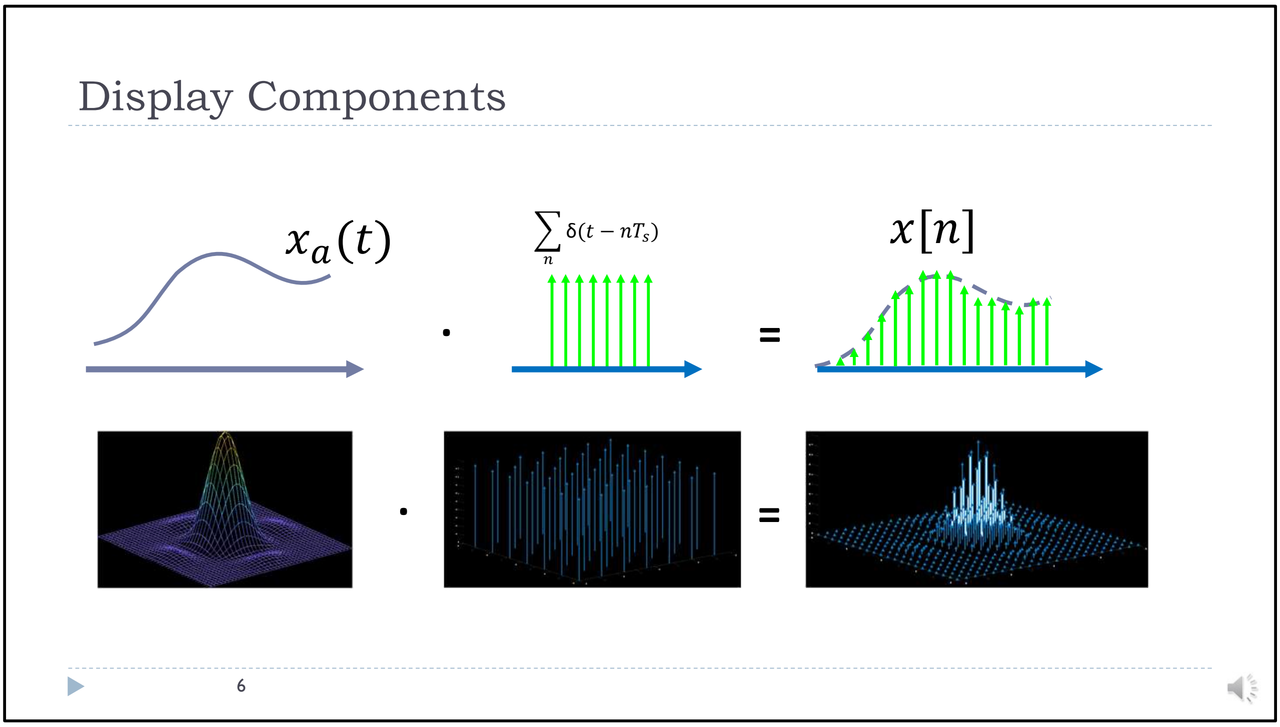
We can start this lecture by describing how I deliver the content to you visually. I will describe the pipeline briefly for the completeness of what is going on behind what you see on your LCD or OLED screen.

In order to display anything, first, we need to create the content. I am recording my slides for this lecture using my PC. We can assume that this is similar to video recording in a lecture theatre or using my webcam. Most of the current digital cameras have built in optical and electronic components to capture the light (analog-to-digital conversion), create a representation of the data, compress and store it. This data will then be encoded, transmitted, and decoded on your end.

Now, before you can see the video on your end this digital data needs to be stored on your device even if this were a live streaming. Since we are using causal systems we will need buffers to store some of the streamed data. This data then used for rendering the images by the GPUs of the devices you use and finally the signal is sent to your display and the display converts the digital signals to analog optical signals and you will observe me giving this lecture.

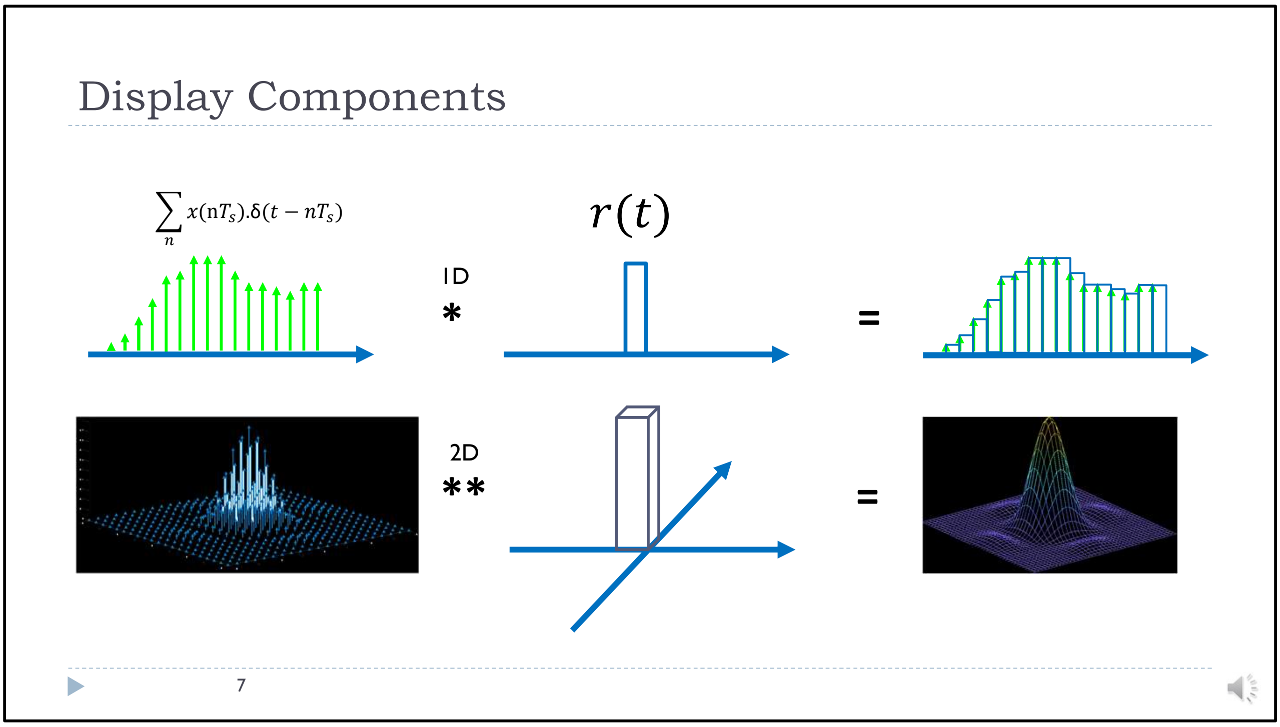
If you are playing an offline game or watching a pre recorded video, you will only be dealing with the last block.

Therefore, we can naively describe entire process as nothing but an A/D conversion, digital signal processing, and a D/A conversion.



Before we go into details of displays, let us refresh our minds about sampling theory. This lecture assumes you have previous knowledge from Digital Signal Processing course.

Digital processing of signals makes it more convenient for many applications. Since it is not possible to store analog signals as they are, we sample them and store their digital representations in memories. Mathematically speaking, we simply multiply an analog signal with so called an “impulse train” or a “comb function” and store the values as digital representation of the analog signal. For 1D signals like audio, we have a sequence of these over a certain time period. In real life, since we do not have hypothetical impulse trains, we use A/D converters which sample the analog signals. For 2D signals, we can imagine a 2D comb function. A practical example is a CMOS camera sensor. It simply converts the analog light intensity to digital data using a 2D grid-like sensing structure.

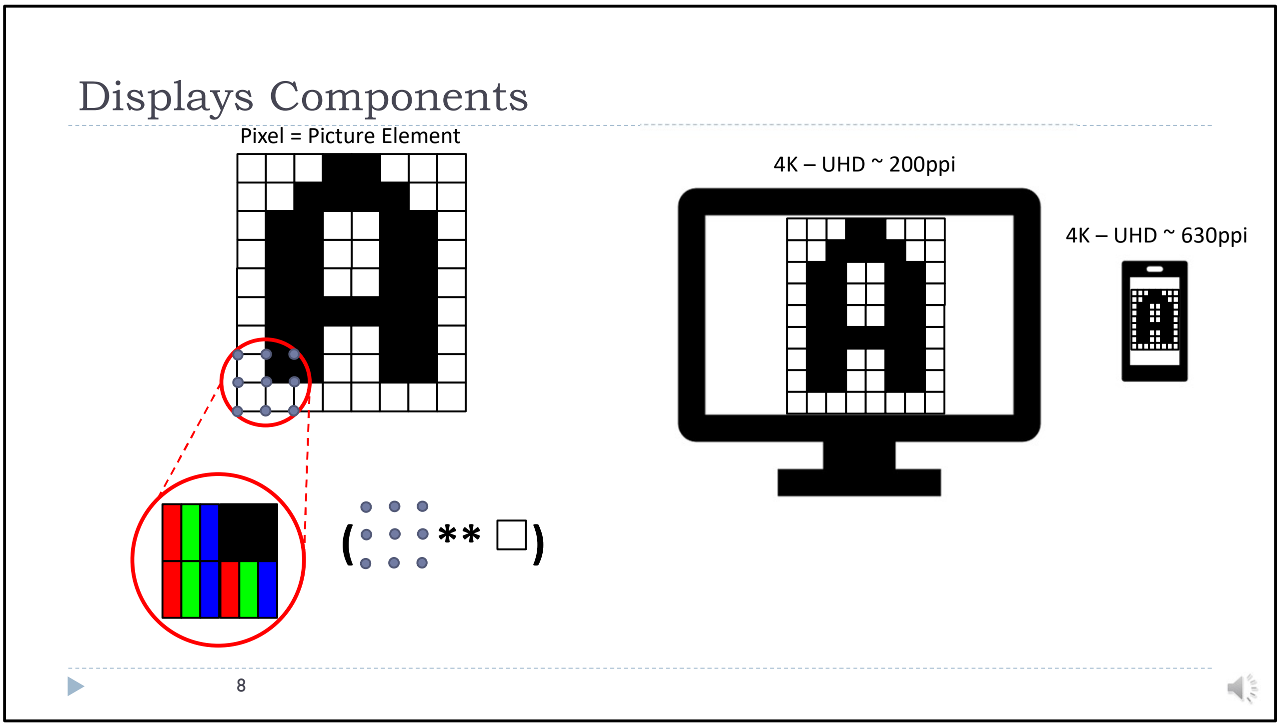


When we want to recover or reconstruct the original signal, we simply interpolate the samples using interpolation functions.
That is, we convolve the samples with an interpolation function.

In the case of 2D signals, we use a 2D convolution in both axes.

The most basic function is a rectangular function. Therefore, we perform a D/A conversion as a results.

In all of these, we assume we satisfy the Nyquist rate to avoid aliasing. We will not go into details of this in this lecture.



Pictures are comprised of "Picture Element"s so called "Pixels". Pixels are also comprised of sub-pixels of red, green and blue colours. We can represent pictures and display them with varying colours and intensities of these: e.g. all colours are visible = white pixels, all colours are blocked = black pixels. This is a D/A conversion where we observe the image as the analog optical signal while we are looking at the samples of the image.

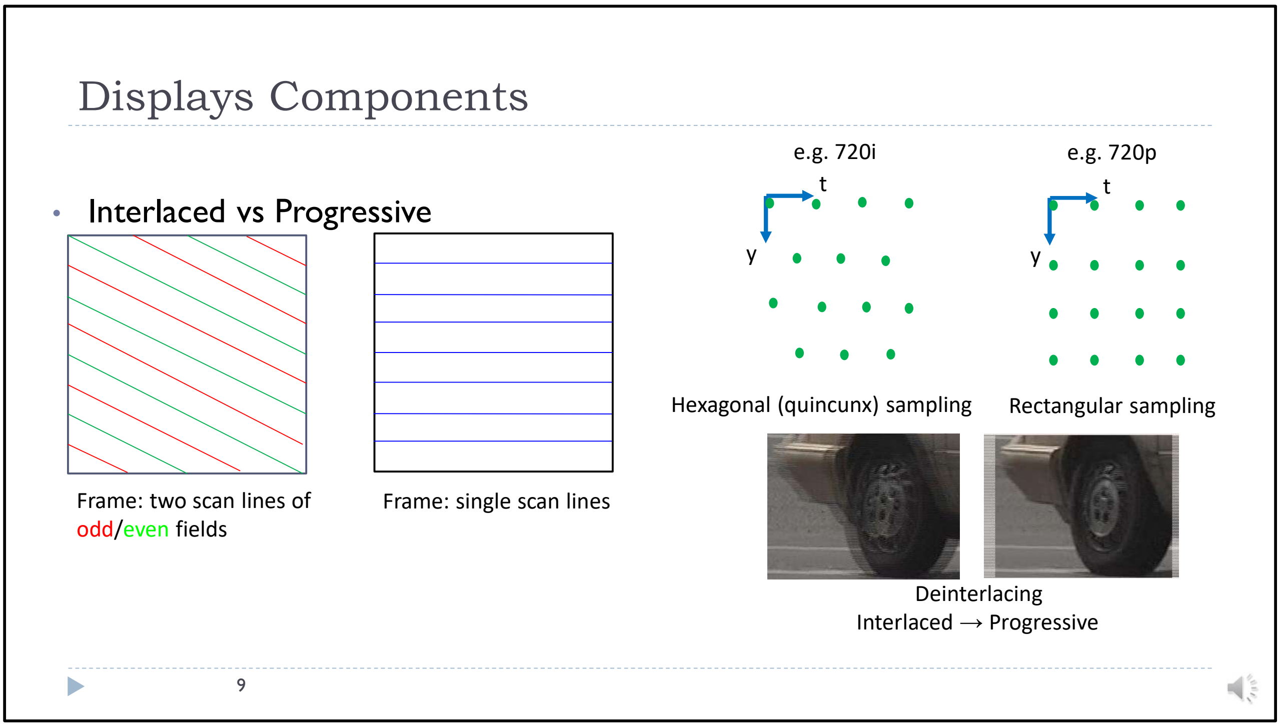
As you can see, we can assume the images have samples interpolated with rectangular reconstruction filter.

As the display technologies evolved, we see screens of larger sizes, higher pixel counts and varying pixel sizes in the order of tens of microns or hundreds of microns depending on the technology and the application.

The pixel count by itself does not enough to determine the resolution of a display. The pixel density "pixel per inch" is the standard to define the screen resolution. This also relates to visual acuity of the human eye.

Some special applications, such as 3D holographic displays, require pixel sizes in the order of 5-10microns in order to modulate illuminating light such that light can be treated as a wave. The pixels do not form the image but the interference of the light distribution at a certain distance reflected by these small pixels does. We will explain this later in this lecture.

https://en.wikipedia.org/wiki/PenTile_matrix_family
https://en.wikipedia.org/wiki/Pixel
https://enacademic.com/dic.nsf/enwiki/323901



For analog TV, the analog signals were used to create pictures. “interlaced” scanning creates a frame by two scan lines. Time sequential scanning of lines with so called “odd and even fields” are used. At every time either odd or even fields are scanned. This way the perceived frame rate is doubled without sacrificing extra bandwidth.

In progressive scanning, the frames are displayed by scanning a single scan line at every time. This type of signal became a standard for digital TVs.

You may have noticed that there are “i” or “p” added next to the resolution selection when you choose a source on your TV. The “i” represents interlaced video signal and “p” represents a progressive video signal.

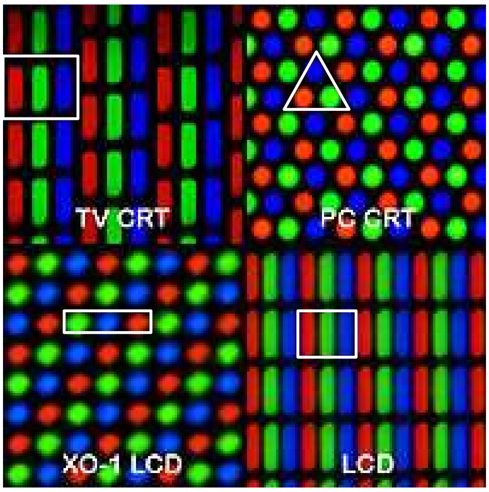
Interlaced video signal is still used for standard TV broadcasts and 1080i HD broadcasts. Digital screens like LCDs use progressive format.

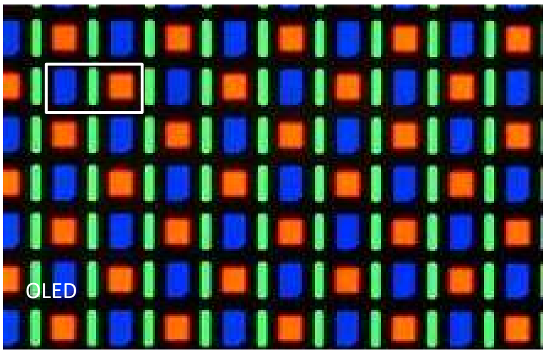
These signal formats use different sampling schemes. We observe a hexagonal sampling scheme in the interlaced video signals whereas a rectangular sampling scheme in the progressive displays.

If we directly feed the interlaced signal to a progressive type display, we will observe significant aliasing. If we convert the hexagonal sampling to a rectangular one, which is called “deinterlacing”, we can view the video properly with reduced artefacts. These are built-in for modern display electronics.

Images - https://en.wikipedia.org/wiki/Interlaced_video
https://www.sciencedirect.com/topics/engineering/interlaced-scanning

Display Components





Additional complexity of the displays come from the geometry of the pixels. Modern displays have a variety of pixel geometries. Each manufacturer has their own proprietary structure to overcome one drawback or the other, e.g. aliasing, colour uniformity, brightness uniformity, etc. However, they make sure that their devices are compatible with the standard signal types so that we do not observe any artefacts. All the processing of the signals are embedded in their device architectures.

2D Displays

- Transmissive
- Emissive
- Reflective
- MEMS – microelectromechanical systems
- Hybrid – e.g. HDR Display

The type and variety of displays are immense. Scientist and engineers are still improving the existing technology and also developing new ones. As new display types are developed, it is becoming difficult to categorise them.

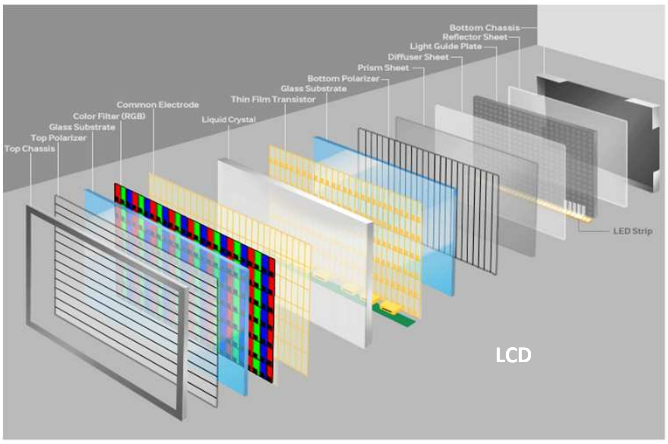
We will investigate different displays types based on the technology which is used to modulate the light:

The main ones are:
Transmissive, emissive, reflective and MEMS which is a variety of the reflective ones.

It is also possible to built hybrid displays by combining some of the above such as an HDR display.

Transmissive Displays

https://newvisiondisplay.com/brief-history-lcd-carrot-cholesterol-tfts-capacitive-touchscreens/



https://pid.samsungdisplay.com/en/learning-center/blog/lcd-structure

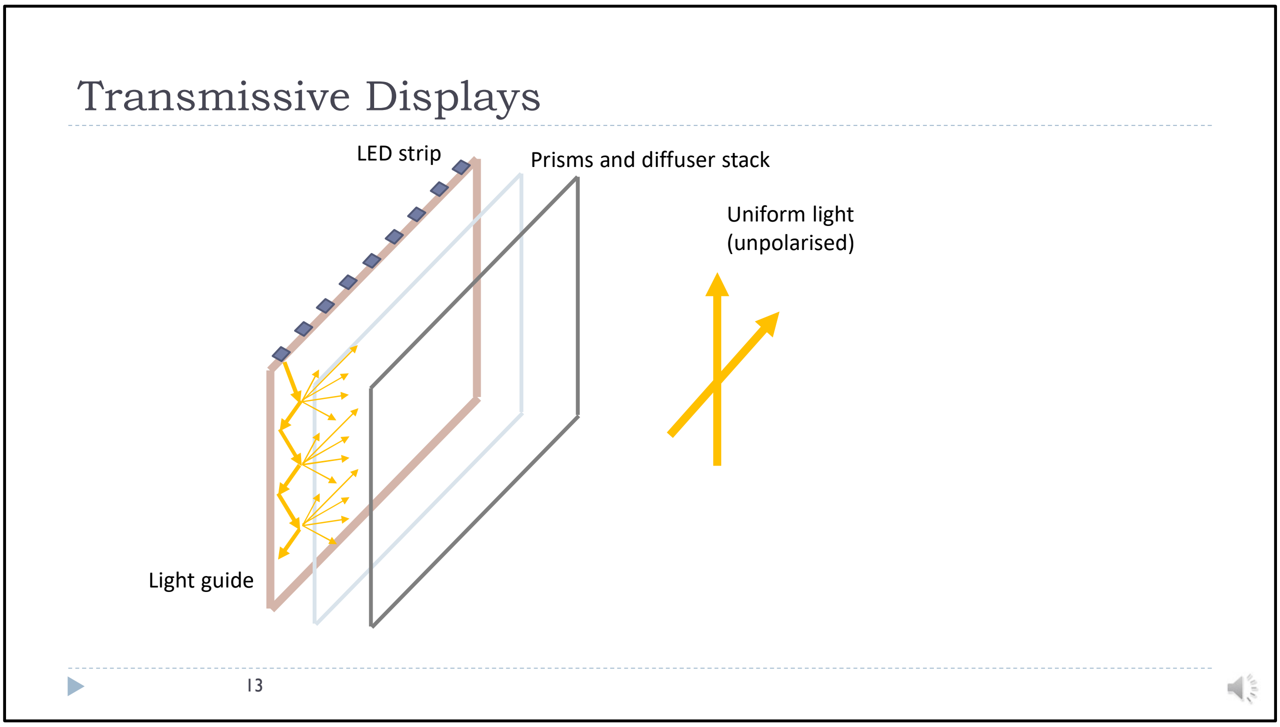
Transmissive type displays modulate the light that is passing through the display pixels. The most prominent one is the LCD technology.

You may not associate your PC's LCD screen to a carrot in the first instance but it has an interesting story that you can read from the given link. A brief history goes like this:

Liquid crystals are a class of molecular compounds which have one or more phases between the solid crystalline phase (like salt) and the isotropic liquid phase (like water). In 1888, the Austrian biologist [Friedrich Reinitzer] first discovered that certain derivatives of cholesterol extracted from carrots seemed to have two melting points: first I goes from solid crystal to milky fluid, then milky fluid to clear fluid.

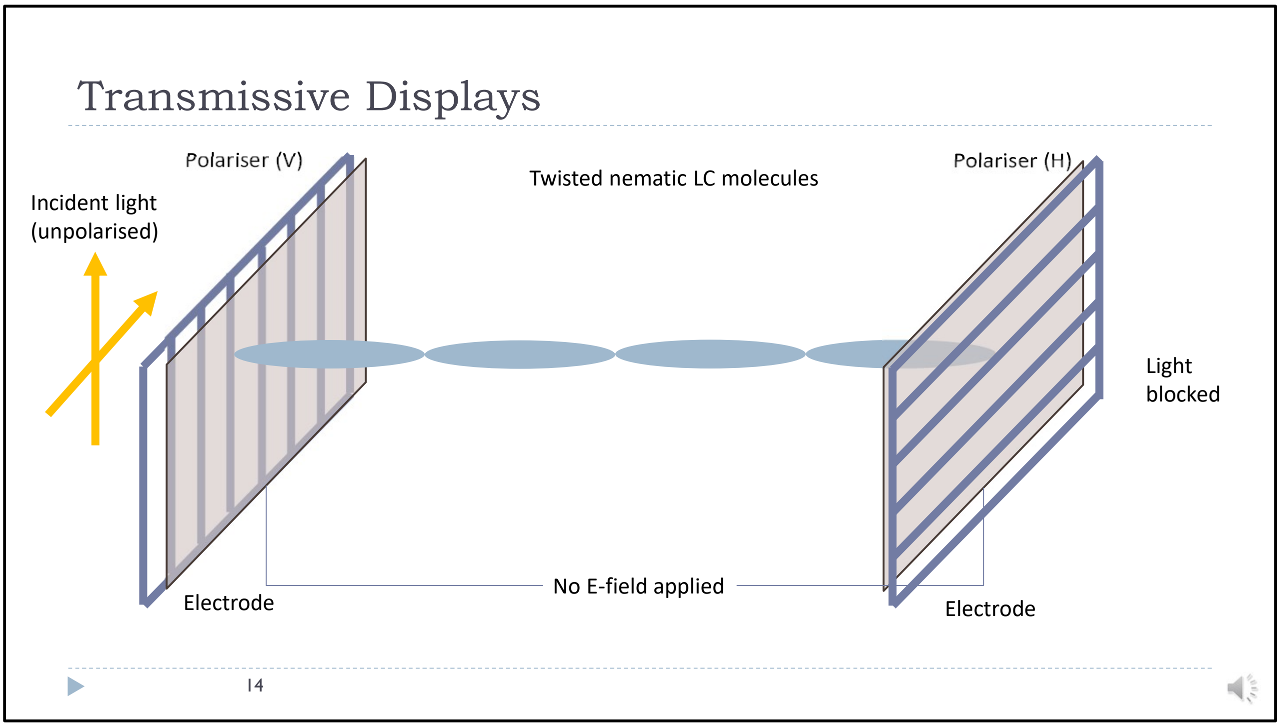
Together with the physicist Otto Lehman, Reinitzer concluded that the 'intermediate fluid' had crystalline characteristics. Following this discovery Vsevolod Frederiks first devised an electrically-switched light valve called the "Fréedericksz Transition" in 1927. This is the basic principle of all LCD (Liquid Crystal Display) technology.

In the GIF, an exploded diagram of an ordinary LCD panel is animated. As you can see, there are many layers that is built into the panel which creates the pictures.



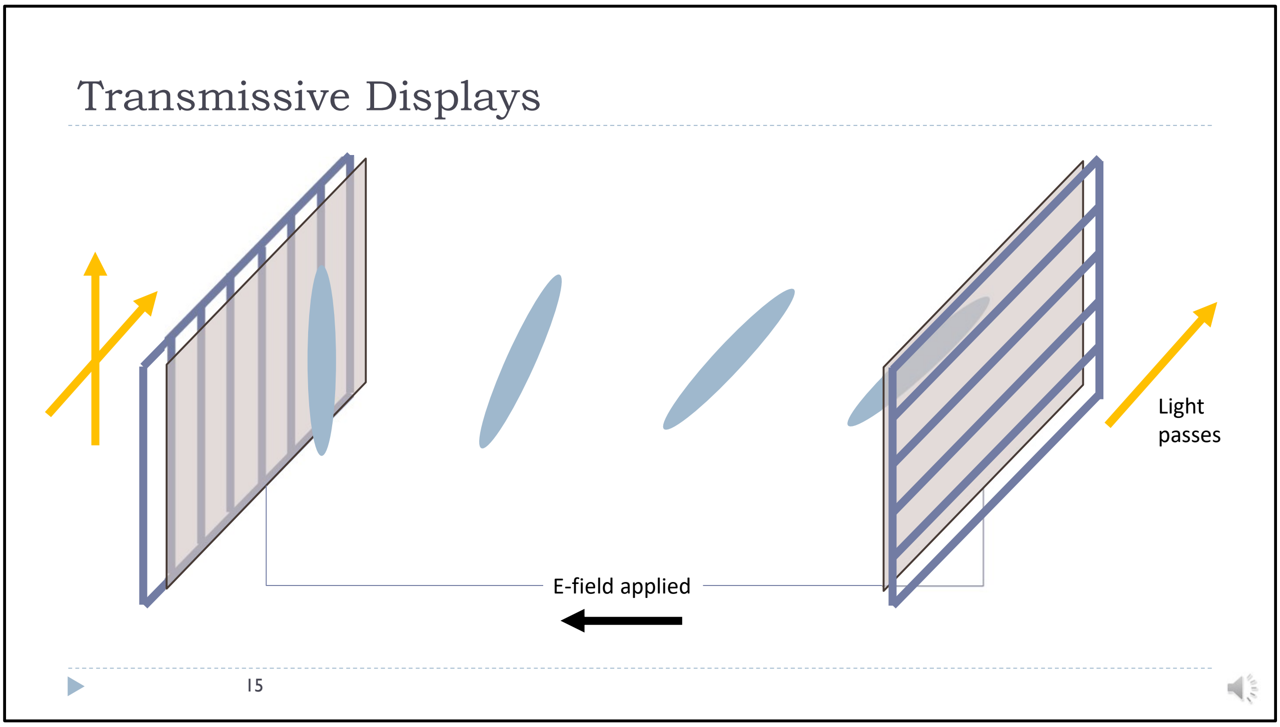
Basic working principle is as follows:
A backlighting LED strip uniformly illuminates the entire backplane of the display panel after passing through several optical prisms and diffusers.

First the light is coupled into a light guide and it travels inside it. Then it is decoupled over the entire surface of the light guide. Then, to create a uniform illumination, a stack of prism sheets and diffusers scatters the light where it is decoupled.

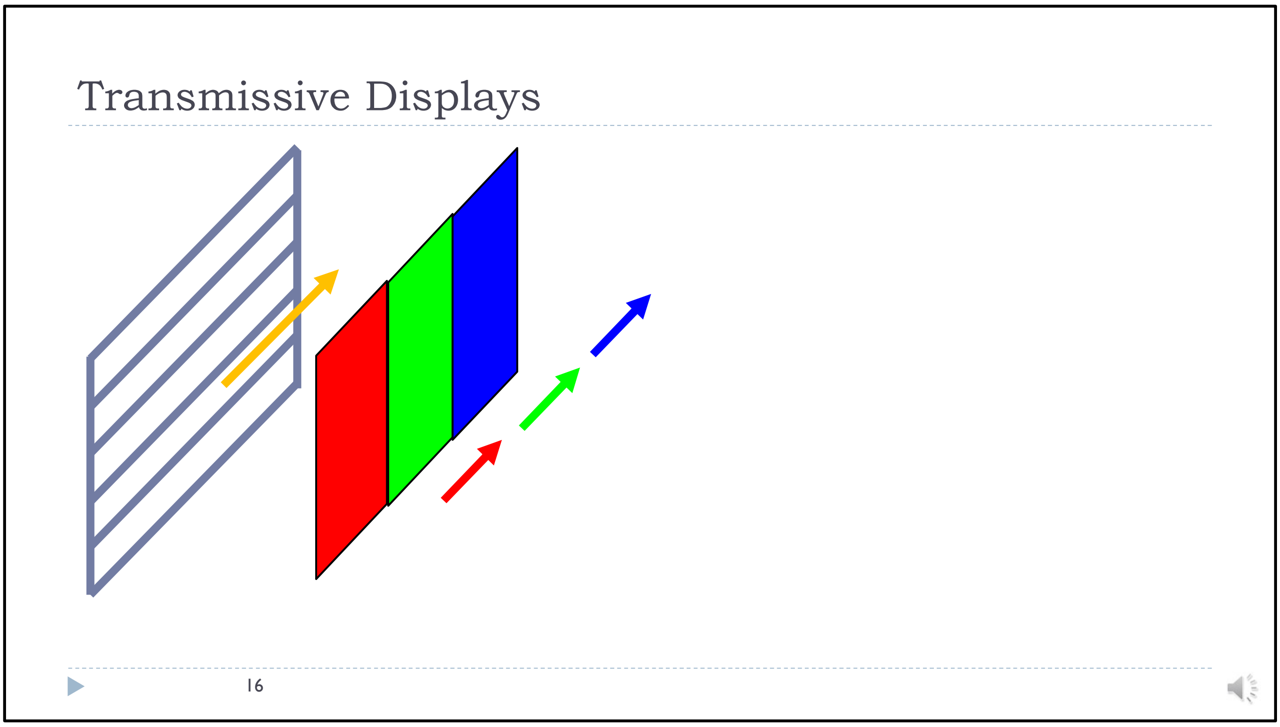


After the uniform but unpolarised light illuminates the back of the LCD, the light is modulated as follows:

- The LCD panel itself comprises of LC molecules sandwiched between two cross polarisers (one is horizontal and the other is vertical) and patterned electrodes.
    - The first polarizer faces the backlighting and aligns the illuminating light (vertically in this example).
    - The second one faces the other side of the panel horizontally.
    - When there is no E-field applied, the LC molecules do not allow the light pass through this structure. In this case, the panel will look black.



When an E-field is applied across the electrodes, the LC molecules twist and form a path to allow the light to pass through the structure. This can be imagined as a valve that adjusts the level of the light passing through each pixel.

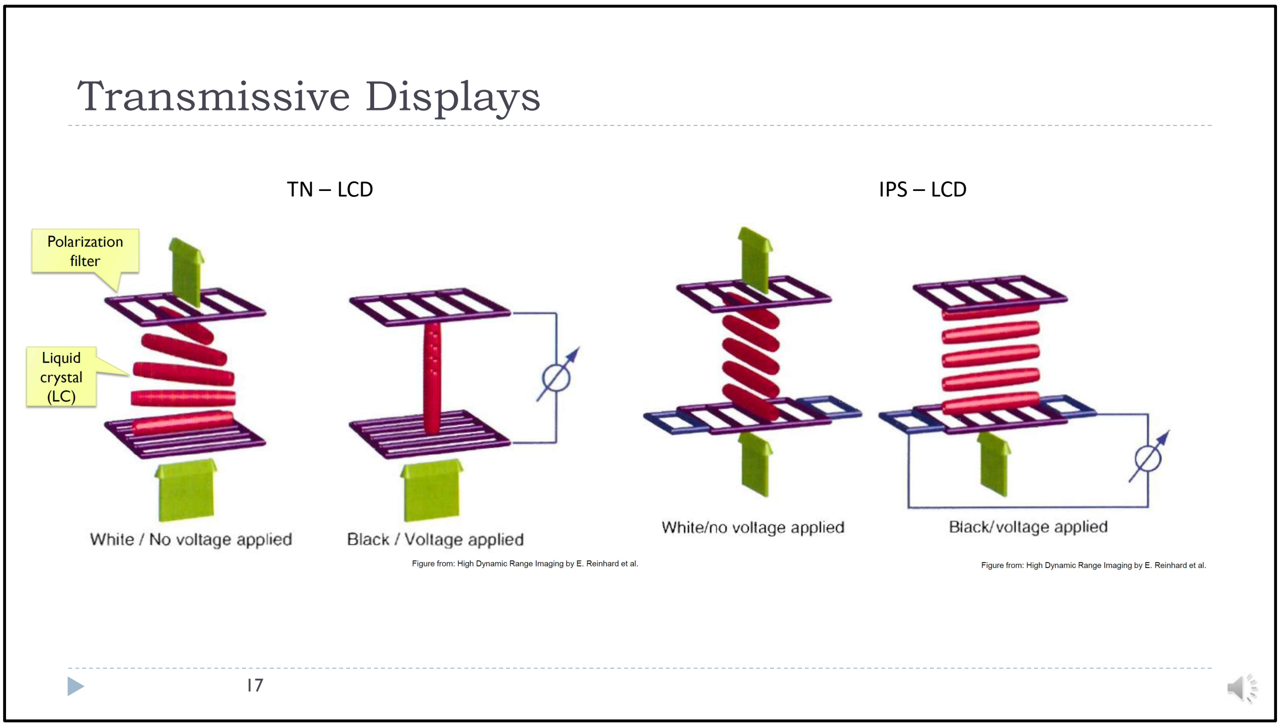


The vertically polarised light at the input of the LCD panel is twisted and turned into a horizontally polarised light.

At the final stage, we have colour filters on the subpixel that we discussed earlier. Together with the amount of light we allow and the pixel we turn on, we can create images.

One major drawback is that we can never achieve a fully “off-state” in the LCD technology and there is always a ”light leak” which disturbs the black levels by creating blueish black look. This reduces the contrast levels significantly. Also, the luminance levels are limited by this configuration which also limits the dynamic range of the display, i.e. the maximum brightness that can be produced and the black levels that can be achieved.

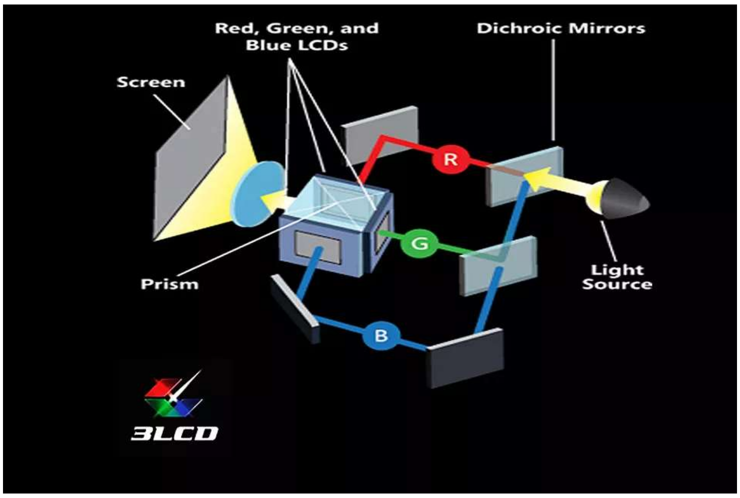
(There is a short video of “How to make LCD display” in the (MIT courseware): https://www.youtube.com/watch?v=rWqHLR5aSXM for those who are interested in DIY stuff.)



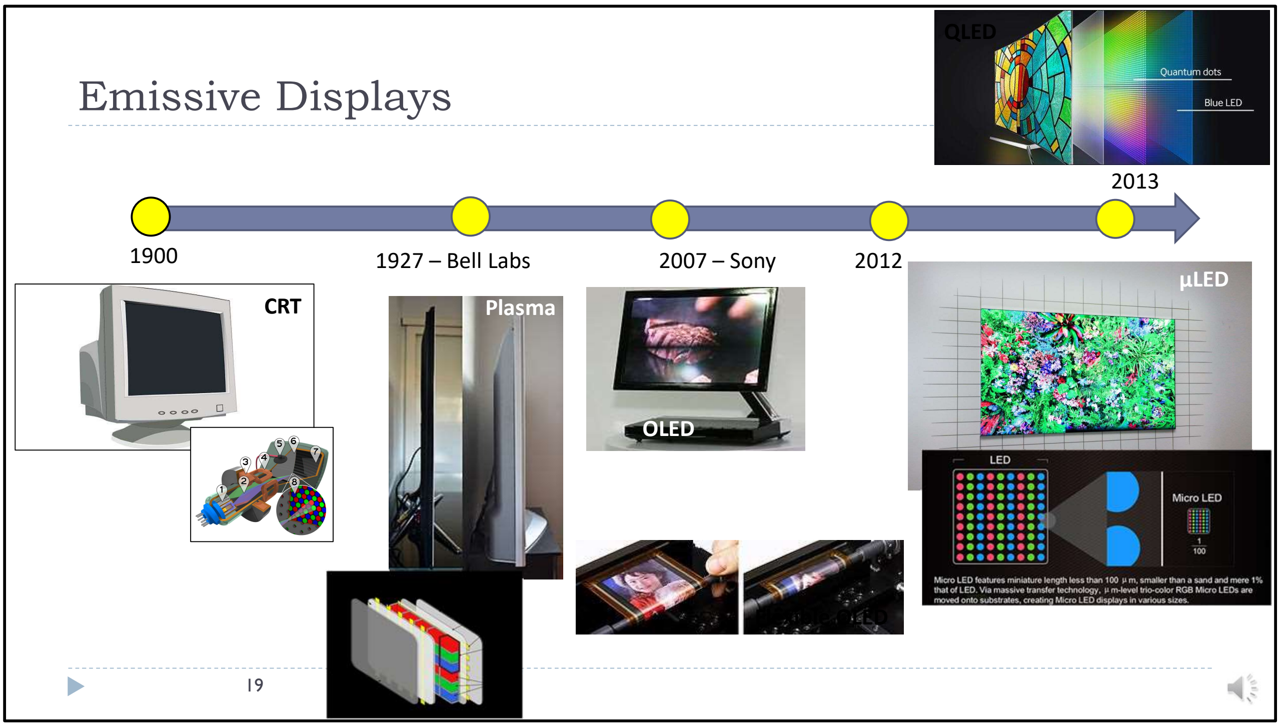
There are different types of LCD configurations. We saw one version of the "Twisted Nematic" configuration where the display looks black in the idle state like your monitor when it is turned off. It is possible to configure this the opposite way depending on the application.

Another LCD configuration is called "In Plane Switching" or IPS. In this type, the switching is done using electrodes only on one side of the LCD panel. This increases the transparency of the screen. It reproduces better colours. However, the response time is slower and requires higher power consumption compared to TN configurations.

Transmissive Displays



This display technology revolutionised the entire display market by offering cheaper and scalable manufacturing and dominating the market. For example: we have very large TVs and very small displays like in the projectors. Some projectors use LCD technology as the picture generation device. Like in the figure, the light is generated by a halogen lamp, and filtered through dichroic mirrors and RGB colours are produced. Each different colour illuminates the corresponding LCD and then they are combined into one image using a special prism. This way, each coloured pixel comes on top of each other optically so that we do not have shifted subpixels. Moreover, the brightness levels are significantly higher than standard LCD screens. Unfortunately, although it is possible to use these in projectors with higher brightness levels, the black levels are still limited in these devices.



The emissive type displays generate their own light for each pixel.

The technology for Cathode ray tube based monitors developed in the early 20th century. Electrons are generated and fired at the back of a vacuum tube, and they are deflected using electromagnetic field. When the electrons hit the florescent screen at the front, it creates pictures. It found a widespread use. However, they were not practical for large screen applications and had potential risks.

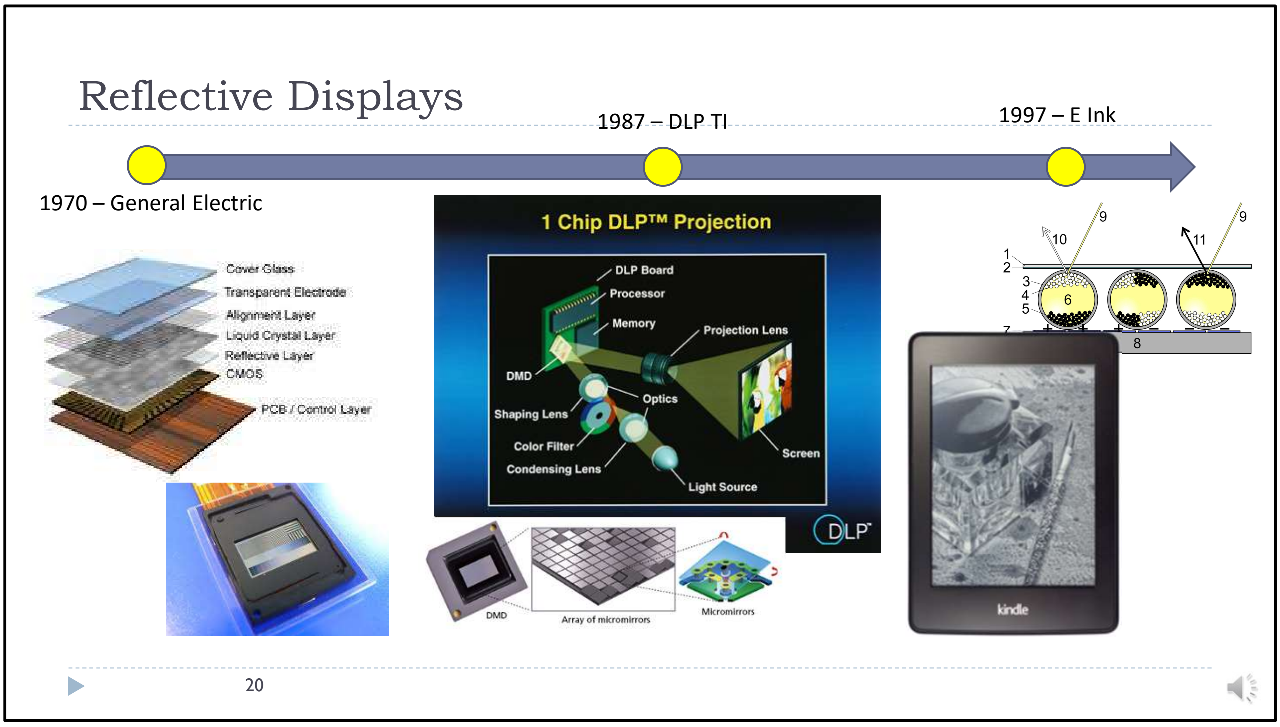
Plasma TVs dominated the large screen market for a long time. Again the technology was developed in early 20th century. It produces light by a chemical process. A noble gas or mercury gas is trapped in the cells/pixels and turned into a plasma by applying a high voltage. In a chain of events a UV emission is achieved which hits the florescent paint inside the cells/pixels creating images. However, these were expensive for consumer market, contained some hazardous materials and requires high power consumption.

Another revolution came with the OLEDs or Organic LEDs. In this technology, each individual pixel generates light like an ordinary LED but some organic compounds are used in the making of them. Although, it is scalable like LCDs, its manufacturing is expensive. There are a couple of main manufacturers of this technology. Main advantages are: they can be manufactured on a very thin substrate, it has true black levels as individual pixels can be turned off completely achieving virtually infinite contrast ratios. They can even be manufactured on flexible substrates. However, the brightness levels are limited and high levels of brightness may damage the display.

Alternative technologies like Quantum-Dot is introduced as a competitor. A blue backlight is tuned to different wavelengths by quantum dot based colour filters creating a large colour gamut.

The developing micro-LED technology aims to get very high brightness level on top of the pure black levels, and pure colour generation. This type of display will comprise of a few micron size LEDs individually placed over the entire display panel. However, this is very nascent and expensive technology at the moment.

Images
- http://clipart-library.com/clip-art/186-1862592_computer-monitor-clipart-old-computer-monitor-clip-monitor.htm
- https://en.wikipedia.org/wiki/Cathode-ray_tube
- https://en.wikipedia.org/wiki/Plasma_display
- https://en.wikipedia.org/wiki/OLED
- https://www.stuff.tv/my/features/oled-tv-vs-qled-tv-Malaysia
- https://www.cnet.com/news/samsung-tv-the-wall-biggest-screen-weve-ever-seen/



It is also an alternative method to modulate light by reflecting the light source illuminating the display. In this case, images are created by deflecting a uniformly illuminating light by physically changing individual pixels. This type of displays are mainly used in projectors or holographic applications.

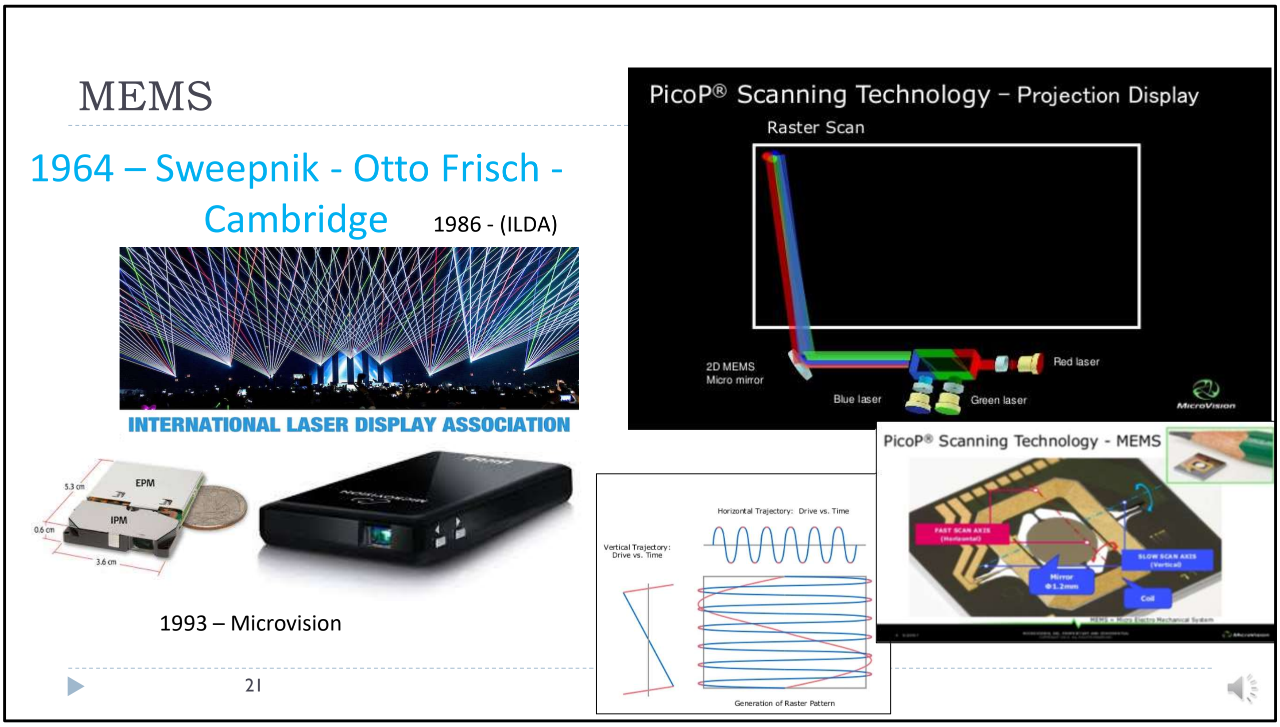
LC on silicon technology is developed to modulate light at a small size. The size of these displays are normally 0.7”. Pixels in the order of few micros can be achieved. LC technology is used in combination with CMOS technology. The amplitude or the phase of the light can be controlled this way.

Digital micromirror device chips comprise of micron sized mirrors. The common size of these displays are around 0.4”-0.7”. Texas Instruments developed this technology. They control light using so called digital light processing. Individual mirrors deflect the oncoming light to a specific angle. By time sequential control of the light, grey levels are obtained. Moreover, a “colour wheel” which runs synchronously with the DMD chip can create full colours. These chips run at very high frequencies. Therefore, this is possible.

Another reflective type display technology is E-ink. This type of display normally invented to work with external light sources like when you read a paper. It was intended to use them as e-papers. However, it found market as Kindles. The working principle is as follows: it contains tiny spheres with some sort of oil as well as trapped black and white pigments. When an E-field is applied the orientation of the spheres change and different levels of black and white are displayed. This way it is possible to observe images on the screen with external illumination.

Images

- https://electronics.howstuffworks.com/lcos1.htm
- https://www.ledsmagazine.com/leds-ssl-design/microcontrollers/article/16695785/digital-micromirror-devices-enable-dynamic-stage-lighting-magazine
- https://holoeye.com/lcos-microdisplays/
- https://www.tradeindia.com/fp3944033/Color-LCOS-Microdisplay.html
- https://en.wikipedia.org/wiki/E_Ink



MEMS stands for micro electro-mechanical structure. In the display context, we will refer to the projector technology which uses tiny mirrors (1-2mm in diameter) scanning in two axes and deflecting a laser beam.

In fact, the scanning beam idea came from Physics Lab here in Cambridge. Although initial use was different, the technology later evolved to be used as displays. International Laser Display Association has standards for scanning laser based displays.

A company called Microvision aimed to commercialise the technology by integrating these into mobile phones. However, due to power consumption levels and the size of the units, it was not successful.

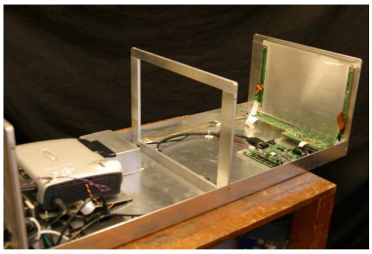
The main working principle is combining three independently controlled laser light beam to create the colours and tracing the beam on a surface using a MEMS mirror. Theoretically, it has a high contrast ratio as there is no light present when the beam is not illuminating a single point. However, due to persistence of vision the contrast levels decrease.

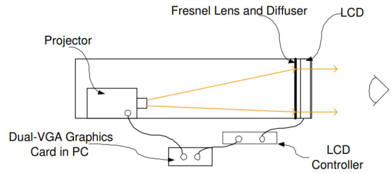
Images

- https://pghardy.net/lsl/lsl_history.html
- http://www.cambridgephysics.org/sweepnik/sweepnik6_1.htm
- https://hothardware.com/news/showwx-pico-projector-takes-mobile-content-beyond-the-small-screen
- https://www.slideshare.net/MicroVision/laser-beam-scanning-short-throw-displays-an-exploration-of-laserbased-virtual-touchscreens
- https://en.wikipedia.org/wiki/International_Laser_Display_Association

HDR Displays

Prototype HDR display





From [Seetzen et al. SIGGRAPH 2004]

The displays demonstrated until now so called standard dynamic range displays. They cannot reproduce very low brightness and very high brightness in the same image simultaneously, e.g. LCD displays. Even if they achieve high contrast values, the maximum brightness levels can be limited, e.g. OLED displays.

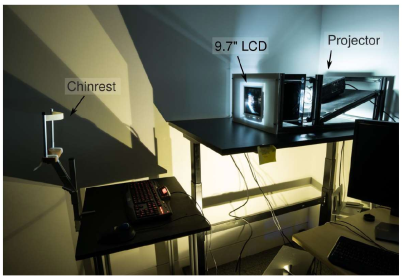
Although there are efforts to improve intrinsic bottlenecks of these technologies, they are fundamentally limited. Therefore, hybrid configurations of these technologies are being developed to overcome these issues. A high dynamic range display can achieve very high contrast and brightness levels.

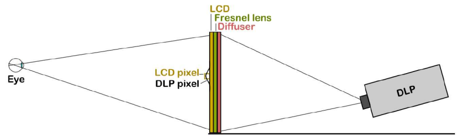
A prototype HDR display was demonstrated in SIGGRAPH 2004. It uses a DMD based projector to generate the back illumination replacing the fixed back lighting of an LCD panel. The projector achieves very high brightness grayscale levels when colour wheel is removed, and the LCD modulates the colour and increases the contrast by reducing the leaking light from the projector.

HDR Displays

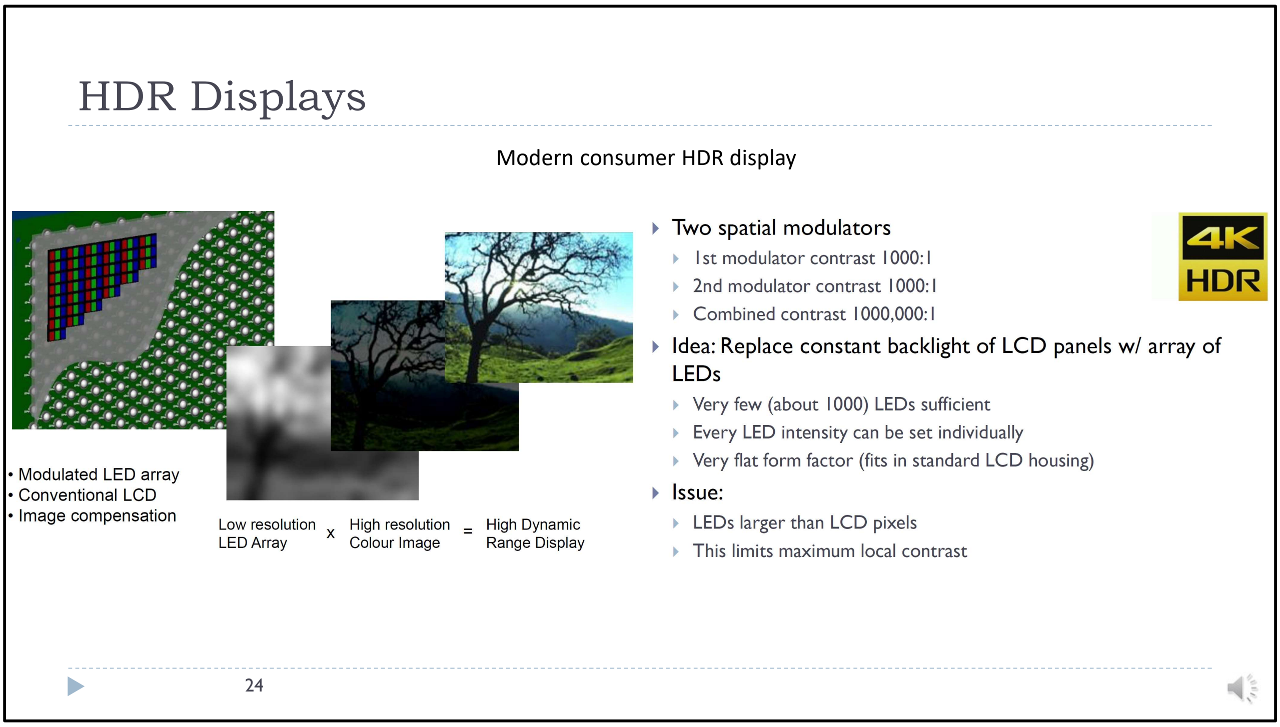
Cambridge experimental HDR display

- 15,000 cd/m^2 peak luminance
- 0.01 cd/m^2 black level
- LCD resolution: 2048x1536
- Backlight (DLP) resolution: 1024x768
- Geometric-calibration with a DSLR camera
- Display uniformity compensation
- Bit-depth of DLP and LCD extended to 10 bits using spatio-temporal dithering

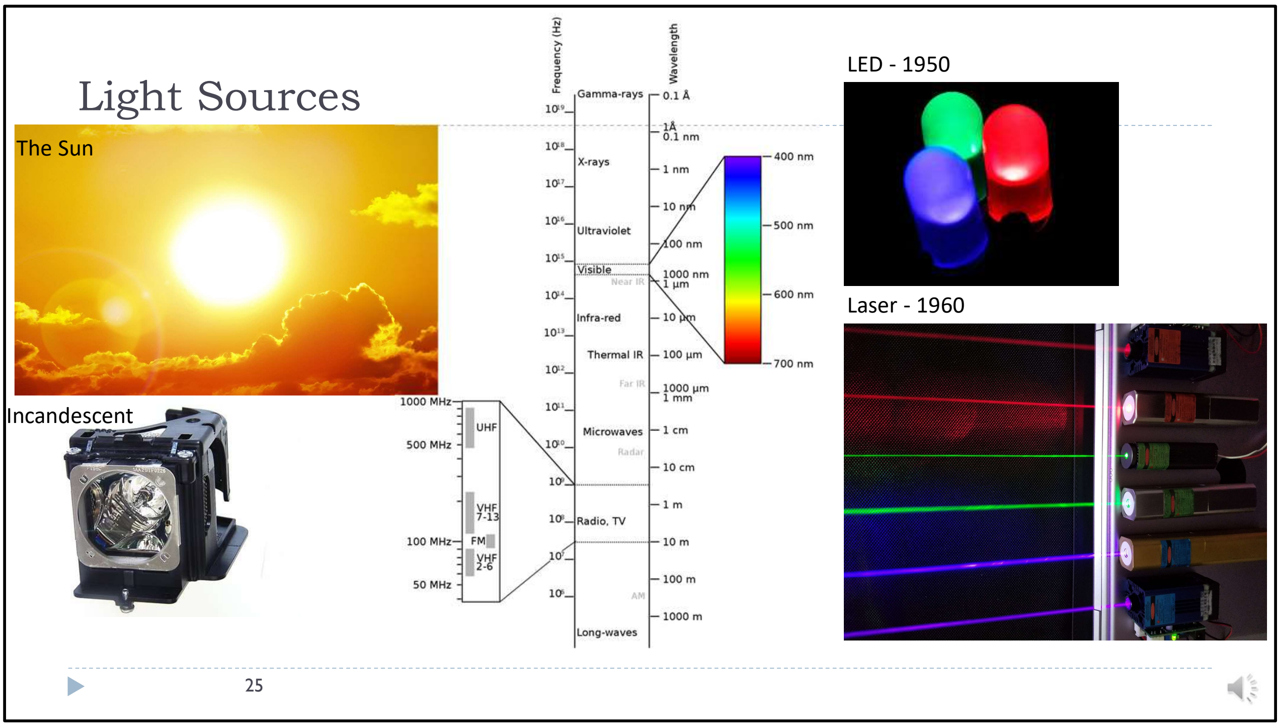




Here at the Computer Labs, an experimental HDR display was built which can achieve significant brightness and contrast levels which can simulate a sunny day outside or dark shades of enclosed spaces.



Modern consumer level HDR displays have modulated LED array directly behind the LCD panel. You can think of this LED array as a very coarse sampling of the picture in grayscale. The colour image again is obtained by the high resolution LCD panel. On top of this, local dimming and lighting schemes are introduced in these displays to dynamically adjust the backlighting. Also, by constantly measuring the ambient lighting, the backlight is adjusted to compensate for these external changes. Therefore, it is possible to achieve very high equivalent contrast ratios.



Our main natural light source is the Sun. Light is another electromagnetic radiation in the entire spectrum. Different animals developed different receptors in their eyes which are sensitive to different wavelengths of the light. The wavelengths approximately between 400nm and 700nm are defined as the visible range for human eyes.

There are many artificial light sources used in the displays.

Incandescent light sources such as halogen bulbs are used in projectors. These light sources are high power and high throughput sources. They are not energy efficient but provides a wide illumination spectrum.

LEDs are mainly used in LCD, OLED, microLED, displays and also recent low cost projectors. LEDs are low cost and energy efficient alternative to incandescent light sources. They can have relatively narrow spectrum so that they can be used to generate individual colours with high accuracy if required. Or, they can create white light in other configurations.

Lasers can be used in MEMS scanning and some high end projectors. Lasers have very narrow bandwidth in the visible spectrum. Therefore, they can generate pure colours. This is especially useful for wide colour gamut generation. They are also essential for holographic imaging. However, they also produce intrinsic random noise called “speckle” which is due to the light generation mechanism of lasers.

As E-ink does not require a light source, it uses the light coming from the Sun or some other light sources depending on the environment.

Images
- https://en.wikipedia.org/wiki/Visible_spectrum
- https://en.wikipedia.org/wiki/Electromagnetic_spectrum
- https://physicsworld.com/a/better-blue-and-green-lasers/
- https://en.wikipedia.org/wiki/Light-emitting_diode
- https://www.avpartsmaster.co.uk/p-9306-original-inside-lamp-for-epson-eb-x72-projector-original-lamp-in-compatible-housing.aspx?pk_cid=1&pk_keyword=9306&pk_medium=multifeeds&pk_campaign=Google&pk_source=Google&pk_content=ElectronicsVideoVideoAccessoriesProjectorAccessoriesProjectorReplacementLamps&utm_source=Google&gclid=Cj0KCQjwoub3BRC6ARIsABGhnyZkxZF65QNGy9xMXTEzGjmeLbPlstZbTj64PFEA3VS_Xxdu9sTRMRMaAnJYEALw_wcB

Holography

- Dennis Gabor – A new microscopic principle, 1948.
- "Holos" (whole) + "grafe" (writing) = entire information (i.e. amplitude and phase)
  - Coherent (monochromatic) light, i.e. lasers
  - Invention of lasers, 1960.
- Yuri Denisyuk – white light holography, 1958.

Holography is a "true 3D" image acquisition and display method. Theoretically, we can capture and reproduce all the depth cues with this.

It was first proposed by Dennis Gabor as a new image acquisition method for microscopy.
The name comes from the combination of "Holos" (whole) + "grafe" (writing). These relate to the recording of the entire information, in this case the amplitude and phase of the light distribution. Remember that, we only record the intensity of the scene when we take an ordinary picture.

It was only possible to demonstrate holographic method after the invention of lasers. Although this is the case, a Russian scientist Yuri Denisyuk demonstrated his method of white light holography in 1958.

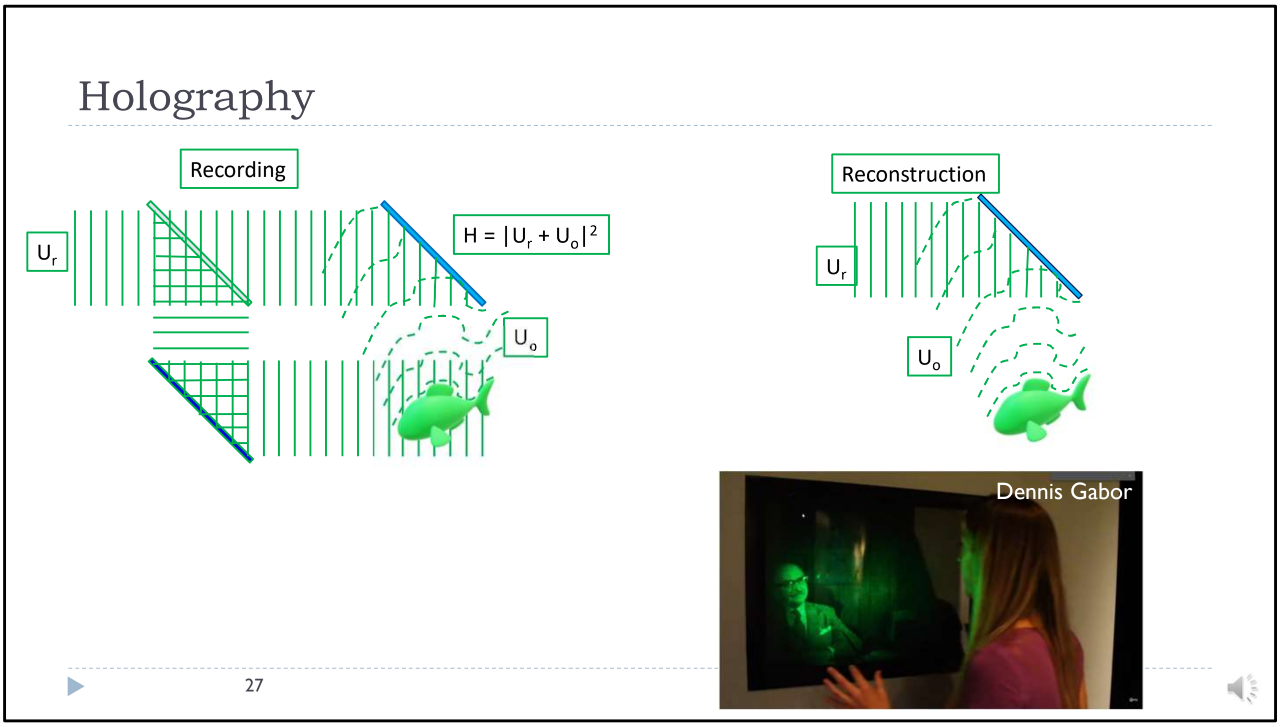
Like capturing of analog photographs and developing them, analog holograms are prepared using a special chemical process.

Ref to GIF:
https://www.pinterest.com/pin/158822324345609605/

https://www.youtube.com/watch?v=0ics3RVSn9w – Dennis Gabor

If anyone interested, you may check the detailed video on Youtube.

How to make Dichromated Gelatine Hologram (Holocreators):
https://www.youtube.com/watch?v=5IszBMYJ5Ks



We can briefly describe the recording and display processes as follows:
Here the recording setup has a beamsplitter, a mirror, a 3D object, and a recording medium or holographic plate. We illuminate the setup with a reference beam which is chosen as plane wave here. It is split into two paths by the beam splitter.

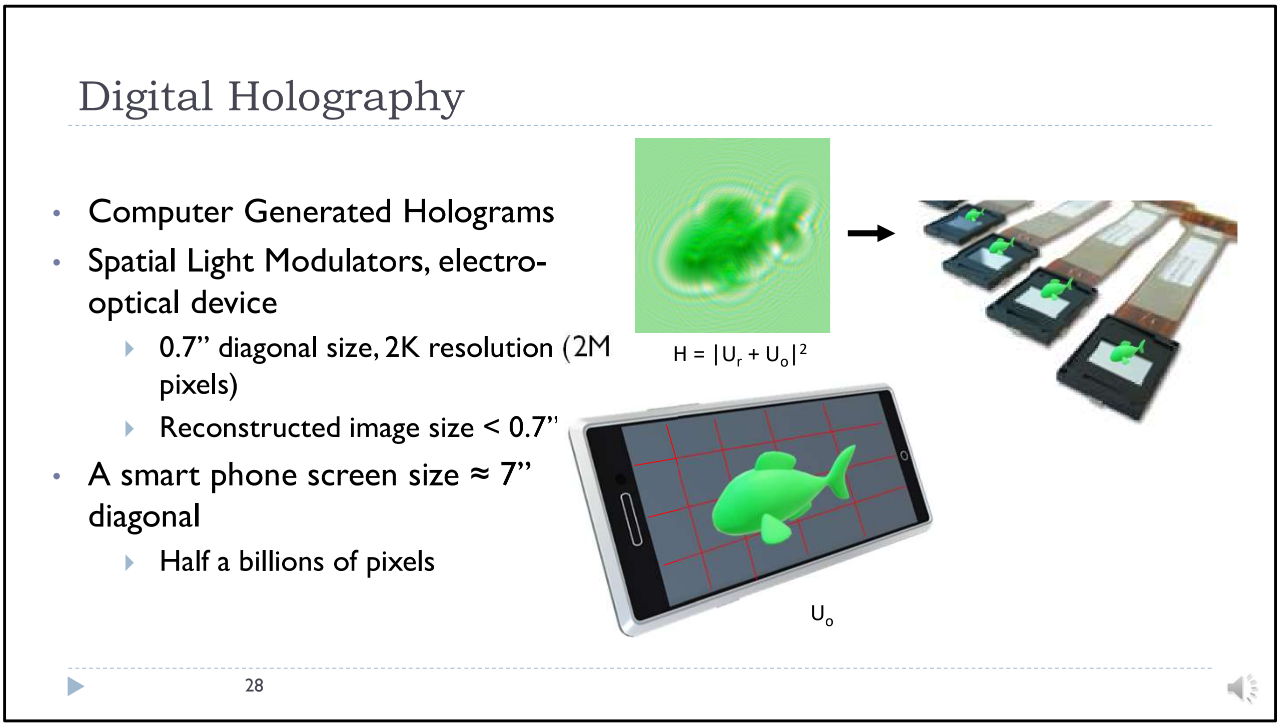
One path is used to illuminate the 3D object. The light scattered from the object reaches the hologram plane. On the other side, half of the beam directly reaches to the recording medium. When the reference and the object beam reach hologram plane, they create an interference pattern and the intensity of this recorded as the hologram. This way the information proportionate to the phase is intrinsically recorded. This carries the 3D information.

When we want to display the hologram as a 3D image, we simply illuminate the hologram by the same reference beam. This way the object waves will be created and they will create an interference pattern and reconstruct the 3D image. In the video you see Dennis Gabor's hologram recording.

Ref to GIF:
https://www.pinterest.com/pin/158822324345609605/

https://www.youtube.com/watch?v=0ics3RVSn9w – Dennis Gabor

If anyone interested, you may check the detailed video on Youtube.
How to make Dichromated Gelatine Hologram (Holocreators):
https://www.youtube.com/watch?v=5IszBMYJ5Ks



It is difficult to capture and prepare analog holograms because capturing is a phase sensitive process and development is chemical process. Of course, it is not reconfigurable.

First Computer Generated Hologram was demonstrated by Lohmann in 1969 as binary holograms. At the time, there were no displays to view these 3D images so high resolution prints were used.

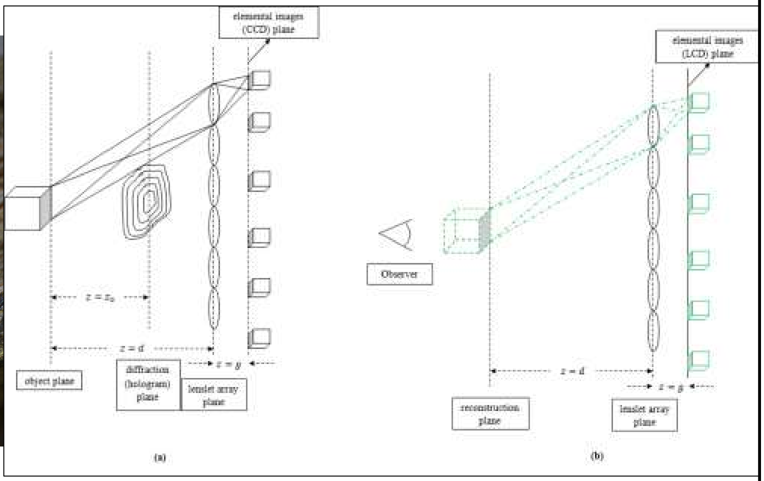
Today, we use Spatial Light Modulators to display digital holograms. The pixel sizes for these devices are in the order of 3-8 microns whereas the pixel counts are in the range of 2M-8M, hence the device size is only about 0.7". Typical 3D image sizes displayed by these are about the size of the SLM.

If we want to achieve a decent size 3D image, we need to increase the size of the display to a size let's say of a mobile screen. Even in this case, we will need half a billion pixels which means that many samples. For a full colour video hologram the data size will be immense. Also if we want to display a dynamic hologram, we will need to compute this at least 25 times per second to achieve video rates.

These are some of the fundamental problems of Digital Holography.

B. R. Brown, A. Lohmann, Computer generated binary holograms, IMB J. Res. Dev., v. 13, No. 2, 160-168 (1969).

Integral Imaging



If we look at the nature, we will observe that some insects like flies or dragon-flies, have multiple lenses on their eyes. That is one mechanism helping them to detect the danger coming from behind.

Inspired by this, there are camera and display systems which can record 3D information and display 3D images with microlens array optics.

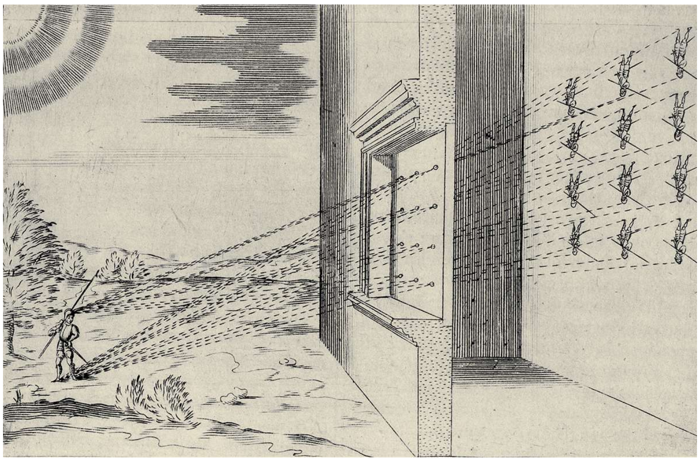
Gabriel Lippmann developed a photographic method called Integral Photography in 1908. He proposed capturing light from 3D objects or scenes using an array of lenses like the fly's eye! When the captured sub-images are observed through the same lens array it was possible to observe the 3D images of the real objects. This technique is also called Integral Imaging.

The diagram depicts the recording and display steps. On the left hand side, a 3D cube is being imaged by an array of lenses at a fixed imaging distance on an image sensor. The captured small perspective images are called elemental images. On the right hand side, we display these images on an LCD panel, place the same lens array at the same imaging distance and look at the setup. We can observe a 3D reconstruction of the image of the 3D cube at the same distance.

This is a non-holographic method which captures and displays the intensity of the light. Integral Imaging can be thought as a generalisation of stereo capturing and display where we have an array of cameras.

A. Ö. Yöntem and L. Onural, "Integral imaging based 3D display of holographic data," Opt. Express 20, 24175-24195 (2012).
Image – Dr Ali Ozgur Yontem

Light field[1]



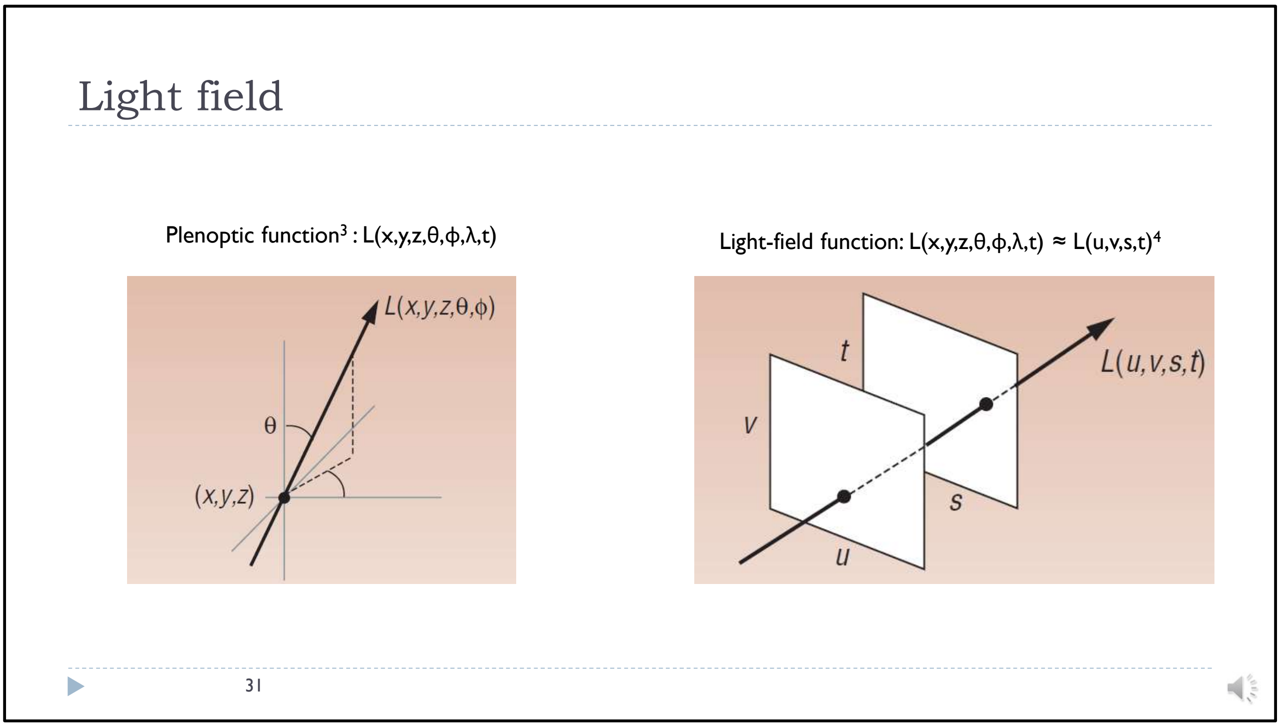
30

Light field is first coined by Andrey Gershun while he was working on radiometry. He defined the light as a field transported in the free space.

In order to capture the light field we can use Integral Photography.

Although Lippmann proposed his photographic method in 1908, there are drawings of Mario Bettini, who is an Italian mathematician and astronomer, imaging 3D objects through small holes on a wall. This in fact resembles capturing with pinhole array cameras which is a common method used in light field rendering.

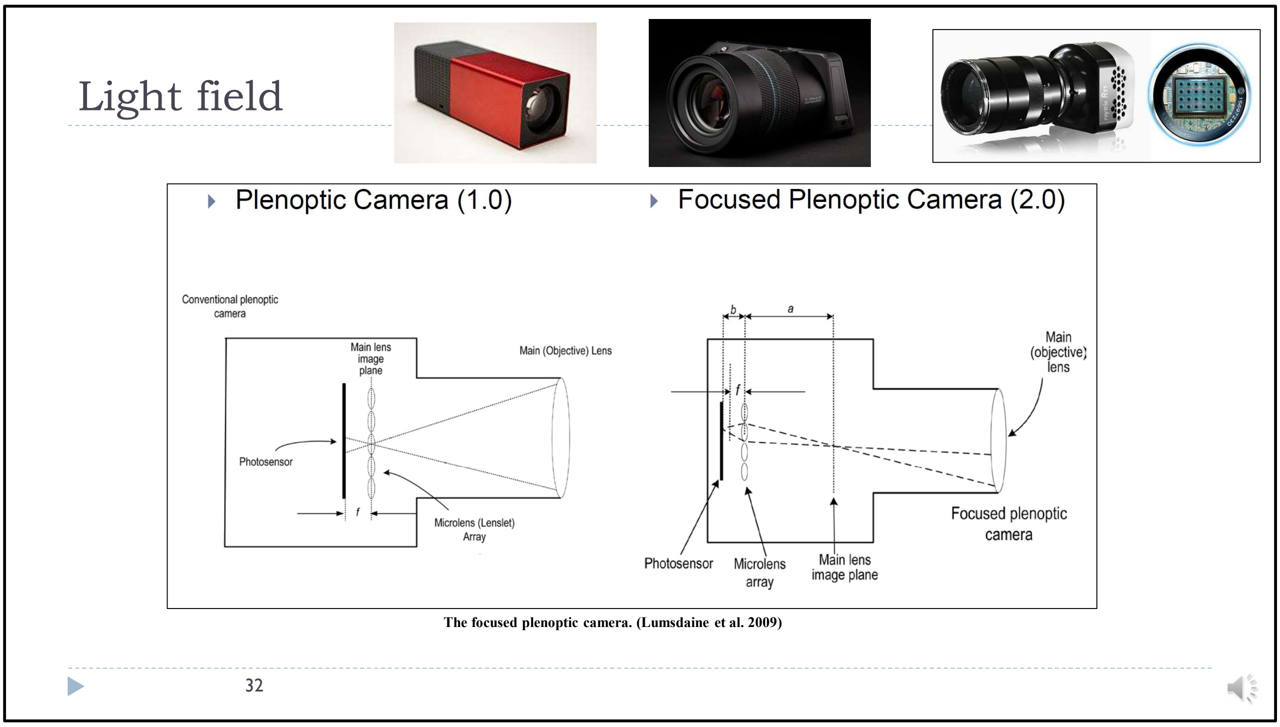
[1] The Light-field, (A. A. Gershun, 1936)
[2] https://commons.wikimedia.org/wiki/File:1642_Mario_Bettini_-_Apiaria_universae_philosophiae_mathematica.jpg
[7] G. Lippmann, “La photographie integrale,” C.R. Hebd. Seances Acad. Sci. 146, 446–451 (1908).



The Plenoptic function is defined by Adelson and Bergen to describe a light as a ray passing through a point in space. It has position and angular information as well as wavelength and time.

However, this is a very complicated way to define the light in space. Later, Levoy and Hanrahan defined the Light field as a 4D function by a ray defined by "L" as a function of four variables passing through two parallel planes defined by (u,v) and (s,t). This simplifies the 7D plenoptic function significantly. However, processing of light field function is still challenging.

[3] The plenoptic function and the elements of early vision. (Adelson and Bergen, 1991)
[4] Light-field rendering. (Levoy and Hanrahan, 1996)



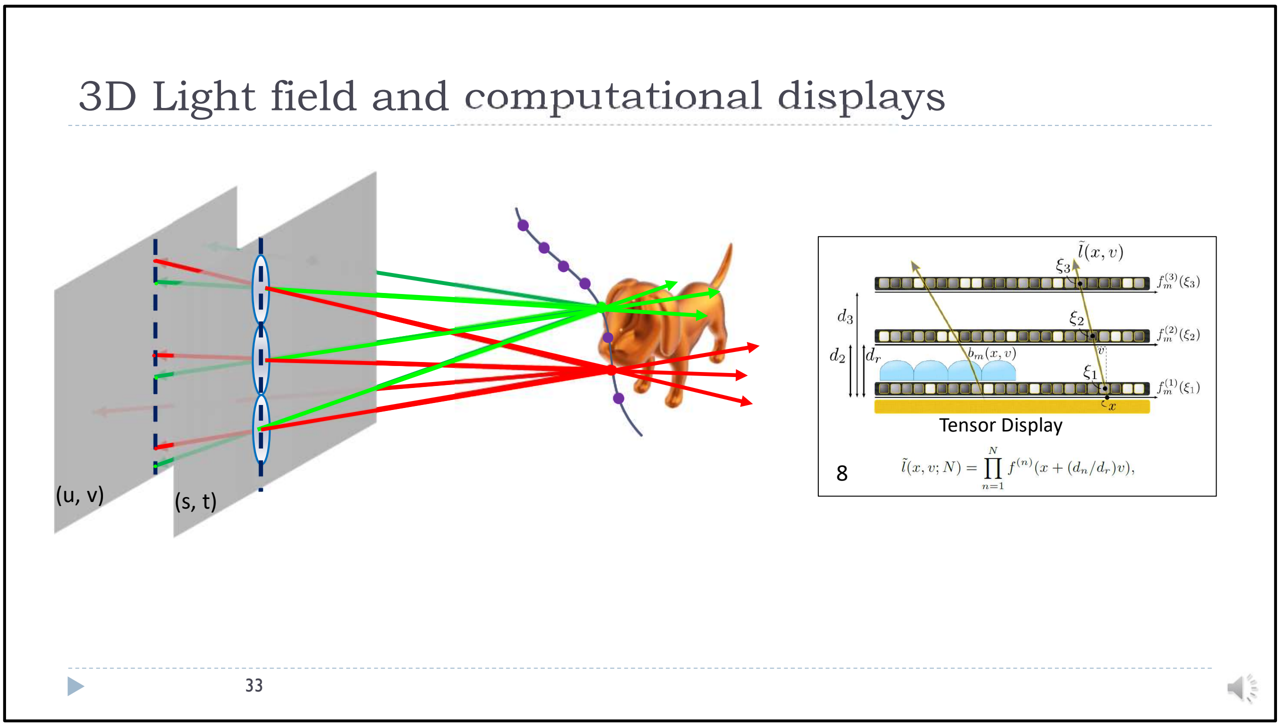
In order to capture the light field, plenoptic cameras, which was proposed by Lumsdaine, are used . A plenoptic camera is like an ordinary DSLR camera but with a lens array introduced between the sensor and the main lens.

In the first version, the images are focused on the lens array plane. This allowed to have a larger field of view but reduced resolution.

A second version is later proposed where the outside world is imaged in an intermediate imaging volume and then reimaged by a lens array. The advantage of this configuration is having a higher resolution in exchange of reduced field of view.

There are some commercially available cameras Raytrix. Raytrix cameras are mainly for industrial applications like defect detection, etc. Lytro introduced first consumer level light field cameras but it lacked the interest from consumers. The company eventually acquired by Google.

[5] The focused plenoptic camera. (Lumsdaine et al. 2009)



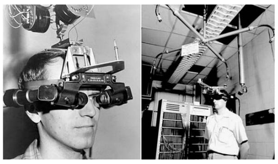
A Light-field display is a non-holographic display type and can be considered as an autostereoscopic variety. Unfortunately, to capture, represent and store the entire light-field, is as difficult as holographic methods. Fortunately, we can impose certain restriction while capturing the data. In fact, light-field will be equivalent to integral imaging where lens arrays are used to capture and display 3D information.

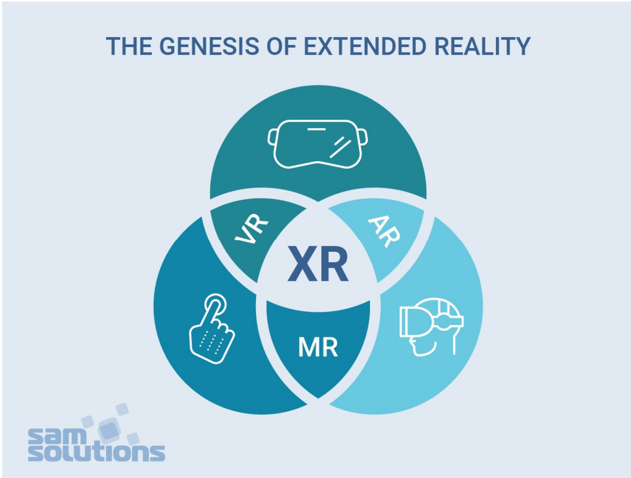
Another method to create the light rays are using computational displays. A stack of LCD panels are used as active masks to define the path of rays of a light field. This way we can create the light field partially. By creating individual rays it is possible to demonstrate a 3D image. These type of displays are called Tensor displays.

[8] G. Wetzstein, et al. “Tensor Displays: Compressive Light Field Synthesis using Multilayer Displays with Directional

Immersive technologies: AR/VR/MR/XR/…

- AR - “Character marker” – L. Frank Baum, 1901.
- VR - "Experience Theatre“, Sensorama – Morton Heilig, 1950.
- MR - “Virtual Fixtures platform” - Armstrong Laboratories, USAF, 1992.





Immersive technologies are defined for a common theme for creating visual, audial and touch sensation stimulation. This is like HoloDeck from StarTrek.
What we heave today as Augmented Reality, Virtual Reality, Mixed Reality, Extended Reality, this may not stop here, are technologies invented or proposed within the past century but only be made accessible in the consumer level within the past decade.

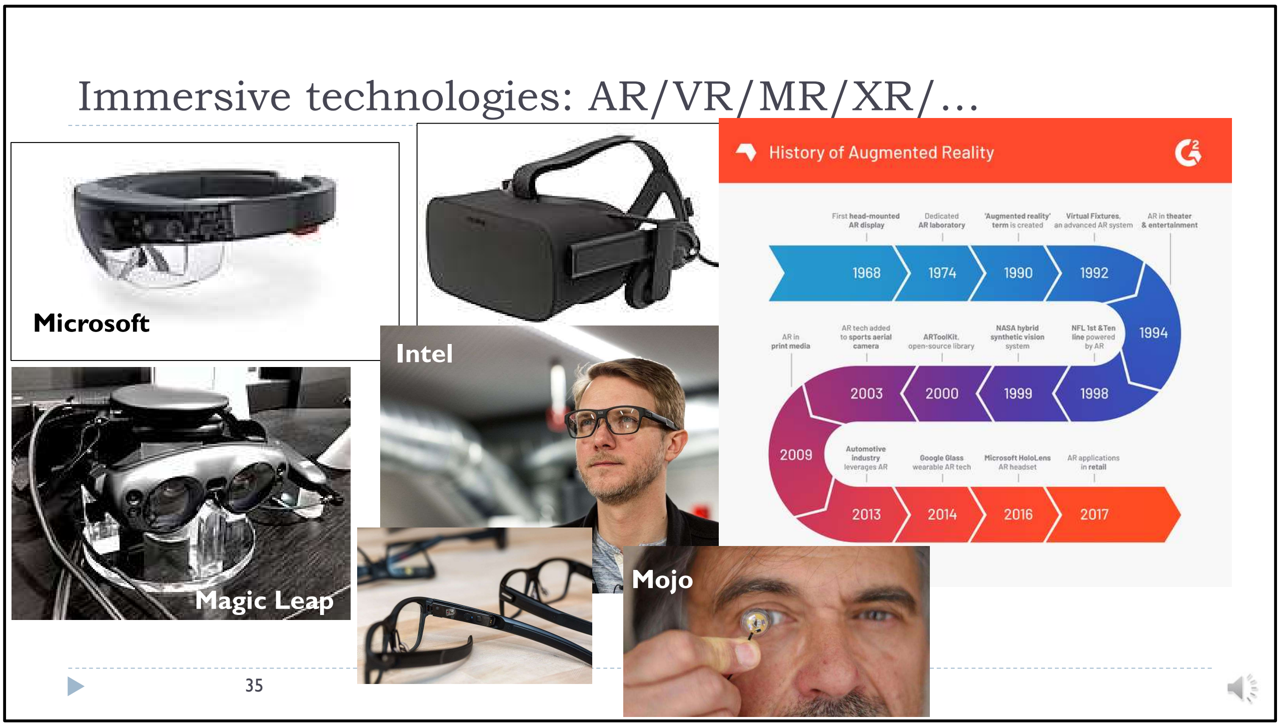
For AR, we overlay virtual images over the real objects and display the combination of this by a see-through device.
A sci-fi writer Frank Baum, defined what we can accept as AR today, in his in book in 1901 as a “Character Marker”. The device was described as a tiara worn on the head and it was showing the true nature of people by a mark appearing over them only visible to the wearer.

VR is a closed system that the wearer can observe an entirely new virtual environment. There are no physical objects present although controls and wearables can help to add physical experience. For VR, it was first demonstrated as an arcade machine in 1950 – Sensoroma.

MR is mainly an AR platform with additional interactions. It is based on sensing the

environment and displaying a dynamic interactive virtual overlay.
MR was first introduced as a military application.

Images
- https://medium.com/desn325-emergentdesign/vr-ar-mr-xr-whats-the-difference-889373f37497
- https://virtualspeech.com/blog/history-of-vr



Virtual Reality is a standalone concept and less demanding compared to Augmented and Mixed Reality.

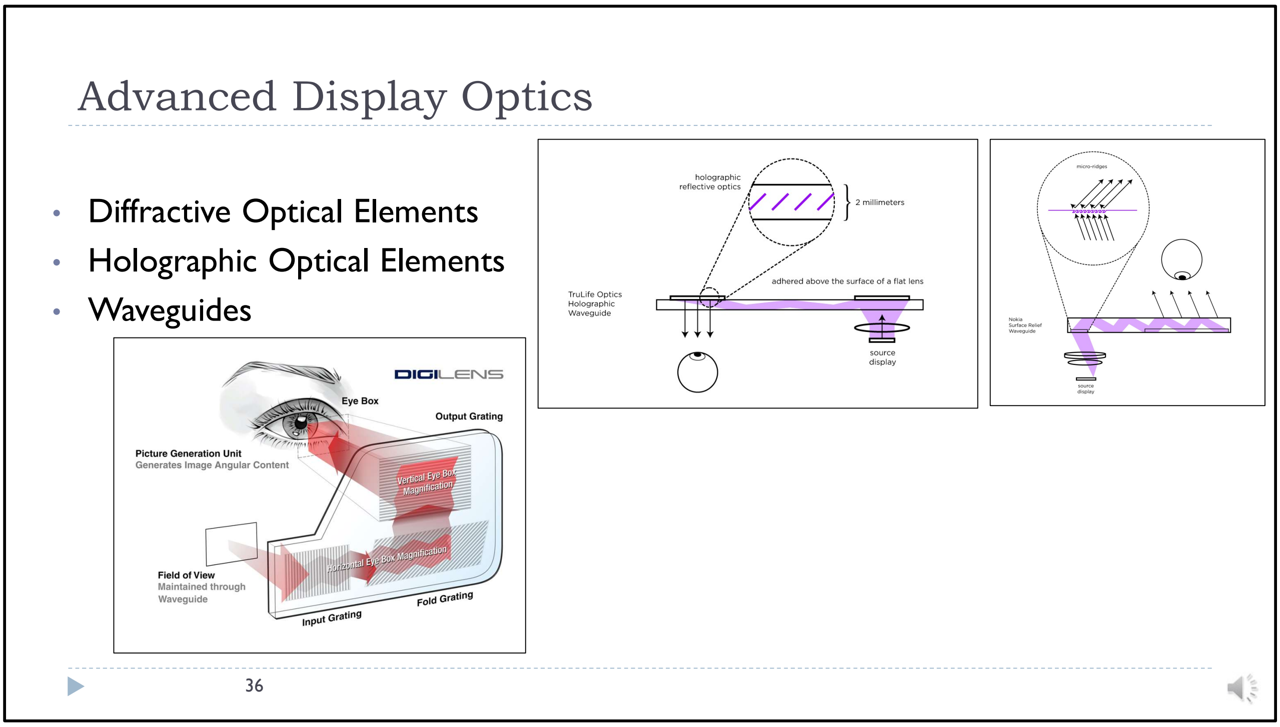
Augmented Reality has a long history starting from the first demonstrated headset in 1968. The main challenges with AR is the form factor (i.e. size of the device) and the experience that the platform can deliver with that form factor. It is the dream to have AR glasses with a size of ordinary spectacles.

Maybe even like a contact lens.

However, current available state of the art are Microsoft Hololens and Magic Leap Leap One. Even though they have acceptable sizes, they are in fact high performance computers with multiple sensors, cameras and displays.

Images
- https://www.theverge.com/2018/2/5/16966530/intel-vaunt-smart-glasses-announced-ar-video
- https://en.wikipedia.org/wiki/Oculus_VR
- https://en.wikipedia.org/wiki/Magic_Leap

- https://en.wikipedia.org/wiki/Microsoft_HoloLens
- https://learn.g2.com/history-of-augmented-reality
- https://skarredghost.com/2019/05/09/smart-ar-contact-lens-battery/



For AR/VR/MR applications, the conventional type displays are not suitable again due to the practicality and size. Just recall the images of the displays we discussed earlier.

In the state of the art AR devices, advanced display optics are used such as diffractive and holographic elements and waveguides.

In essence, a waveguide is a piece of glass that traps light and lets it travel inside using total internal reflection phenomena. (Just like optical fibres carry light.)

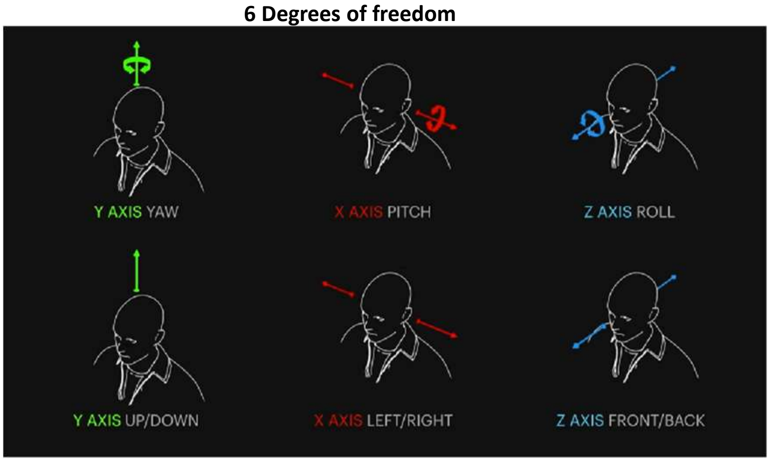
This way it is easier to reduce the size of these devices. Current waveguide market is huge due its potential and the current demand.

Diffractive and holographic elements are also crucial. They are used to steer the light, to couple light into or out of the waveguides.

The images are generated by means of other methods we learned earlier like small projectors, SLMs, scanning lasers, etc.

6DOF and SLAM

6 Degrees of freedom



Earlier, we briefly mentioned what Mixed Reality requires in order to create the interactive experience. For these advanced displays, we cannot rely on conventional human-computer interfaces either. We need much more complicated sensing and feedback mechanisms. For that reason, a 6DoF device and Simultaneous Localisation and Mapping, SLAM in short, should be embedded in the device, for example, like they did in Microsoft Hololens.

There are 6 basic movements of the users’ head: yaw/pitch/roll, translation in x/y/z. If the device can sense this information, then it will be possible to freely move with the device on the head.

https://en.wikipedia.org/wiki/Six_degrees_of_freedom
https://ivrpa.org/news/degrees-of-freedom/

6DOF and SLAM

- Simultaneous Localisation And Mapping
  - Single camera
  - Multi cameras
  - ToF (time of flight) cameras – LiDAR
  - RBG-Depth cameras

https://medium.com/maxst/slam-core-technology-of-ar-what-is-it-e6c9ae4839b4

On top of this, we need to know the world coordinates in order to “lock” the virtual coordinates of the virtual objects. This can be done by depth sensing cameras, multi camera configurations, gyro, etc.

SLAM was first introduced at the International Symposium on Robotics Research in 1995. After a mathematical definition was made at the IEEE Robotics and Automation Conference in 1986, studies using statistical theory and navigation devices have been carried out.

In 1998, at the European Conference on Computer Vision, **Davison presented a method of using only camera without any other sensors.** This has led to the development of vision-based SLAM that uses camera as a three-dimensional position detector.

https://www.techrepublic.com/article/augmented-reality-for-business-cheat-sheet/

Thank you

- All the captions and references of this lecture are available in the lecture slide notes.
- Please get it touch via email for any questions.
- Thank you.