Near-Eye Displays -

a Look into the Christmas Ball

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ISMAR 2008


Once upon a time, I broke some Christmas balls to try out concave mirrors for display glasses ...
It's all about hardware !

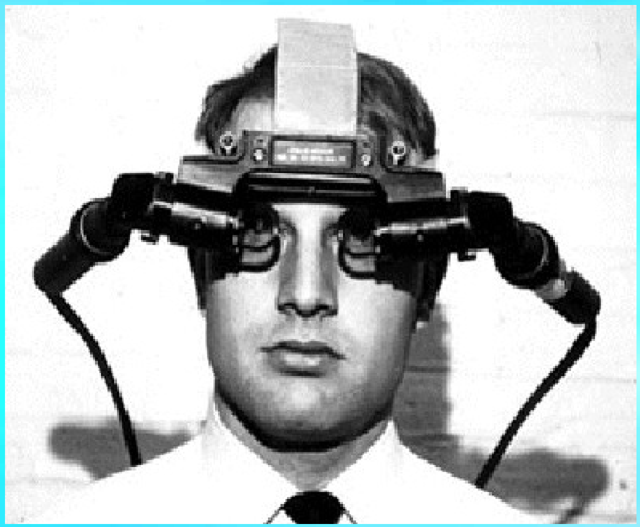
Present technology

The "laptop back"

John discovered these surgical telescope magnifiers as an ideal mobile phone accessory

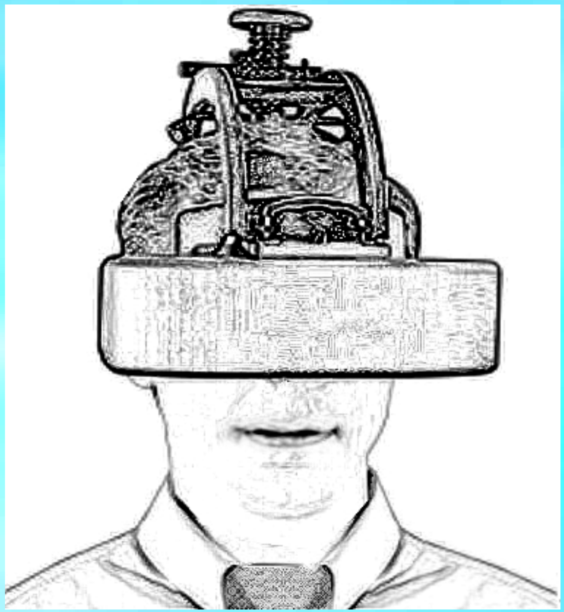
History

Hardware



1968

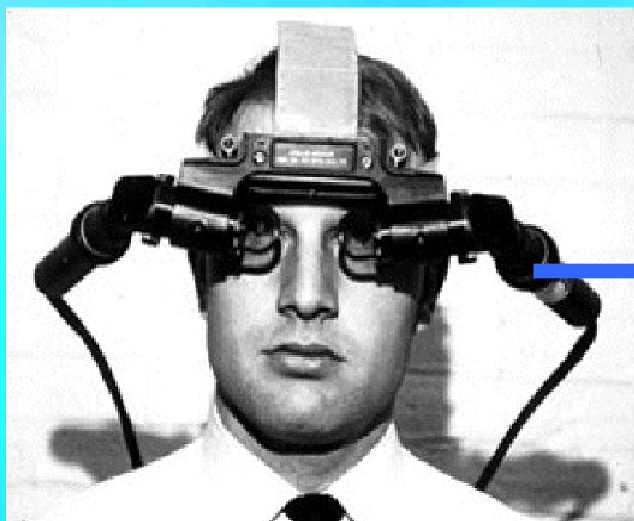
Ivan Sutherland,
Sun Microsystems



2008

?

History



1968

1993

HMD for out-of-cockpit view,
Tornado Simulator (CAE)

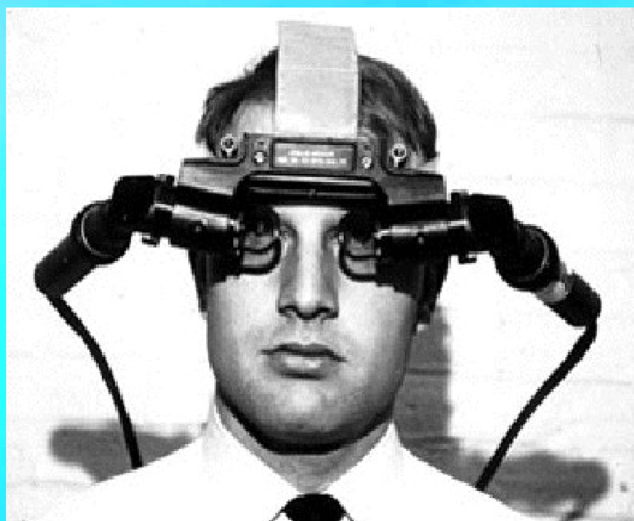
- Full eye and head tracking
- Perfect registration
- High resolution
- Extreme viewing angle

2008

NVIS

- Eye trackers optional

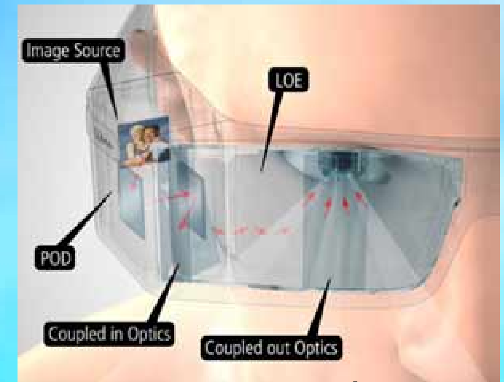
History



1968

Zeiss HOE glasses

2008



Lumus

Microvision (real application)

2003

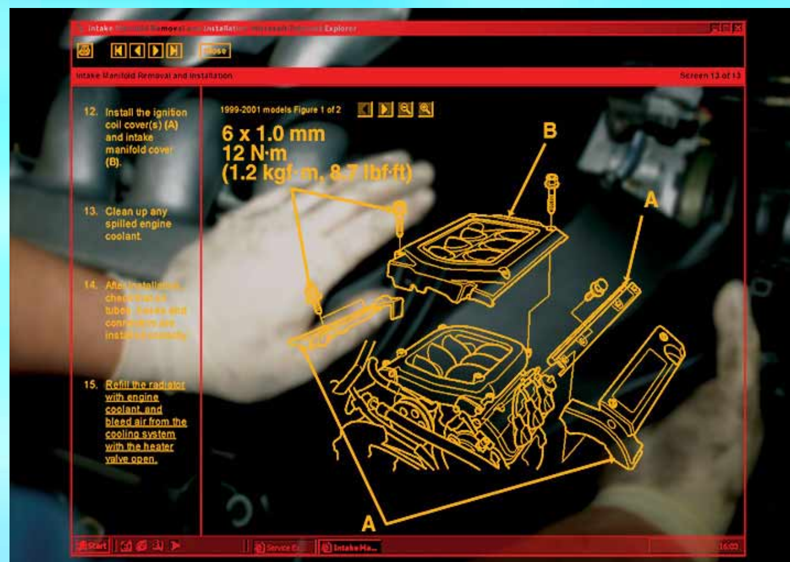
TheEndofHardware (vision)

2006

Microvision (vision)

2008

Commercial Applications ?



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1992

Wire tree Assembly (Boeing HUDset)

2007

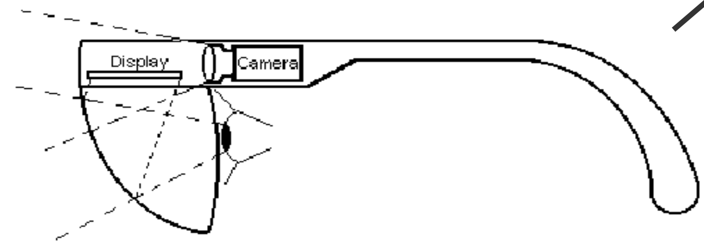
Car maintenance (Microvision)

Integrative 3D Visualization

Wiesbaden, Germany, 1994

the *Virtualware* concept

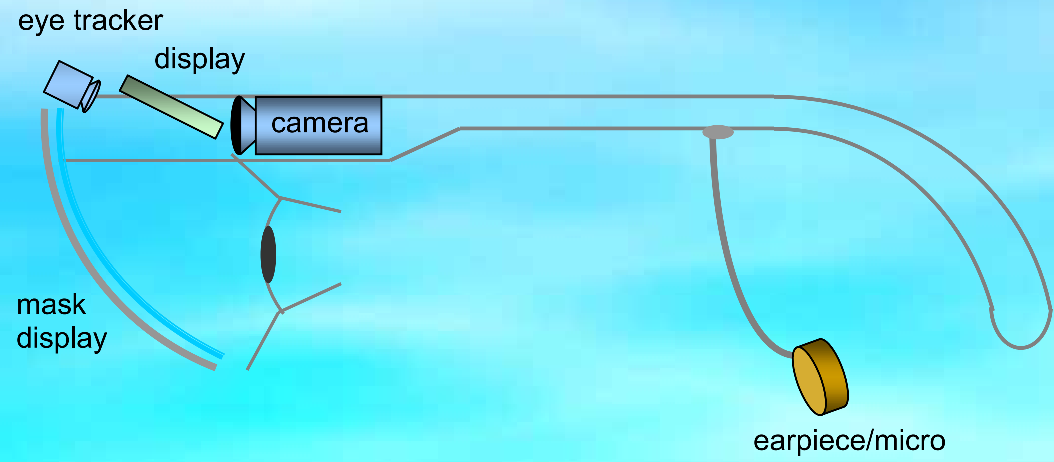
generation of virtual objects merged into real scenes,



- eye trackers and eye pointing
- camera based position sensing
- registration
- mask display
- holographic optics

1994

Elements of display glasses



Object display → **high resolution display glasses**

Object positioning → **Head position sensors: Conventional, Optical Acceleration, GPS, Camera, etc.**

Object insertion (Camera)
- → **Viewpoint recognition**
- → **Real scene acquisition**
- → **Masking techniques Mask Display**

Interaction detection (Camera) → **Finger, key pressing**

Adaptive Display/Rendering strategies (inlays etc.)
- **Dynamic focusing**

Fine positioning → **Eye tracking**

Audio **Microphone/Earpiece**

Misc. **Keys, Headlamps etc.**

Essential requirements

Eye tracker

Mask displays

Position cameras

Dynamic image generator

Dynamic fit and focus adaptation

No straps, no screws, no belts, no clamps

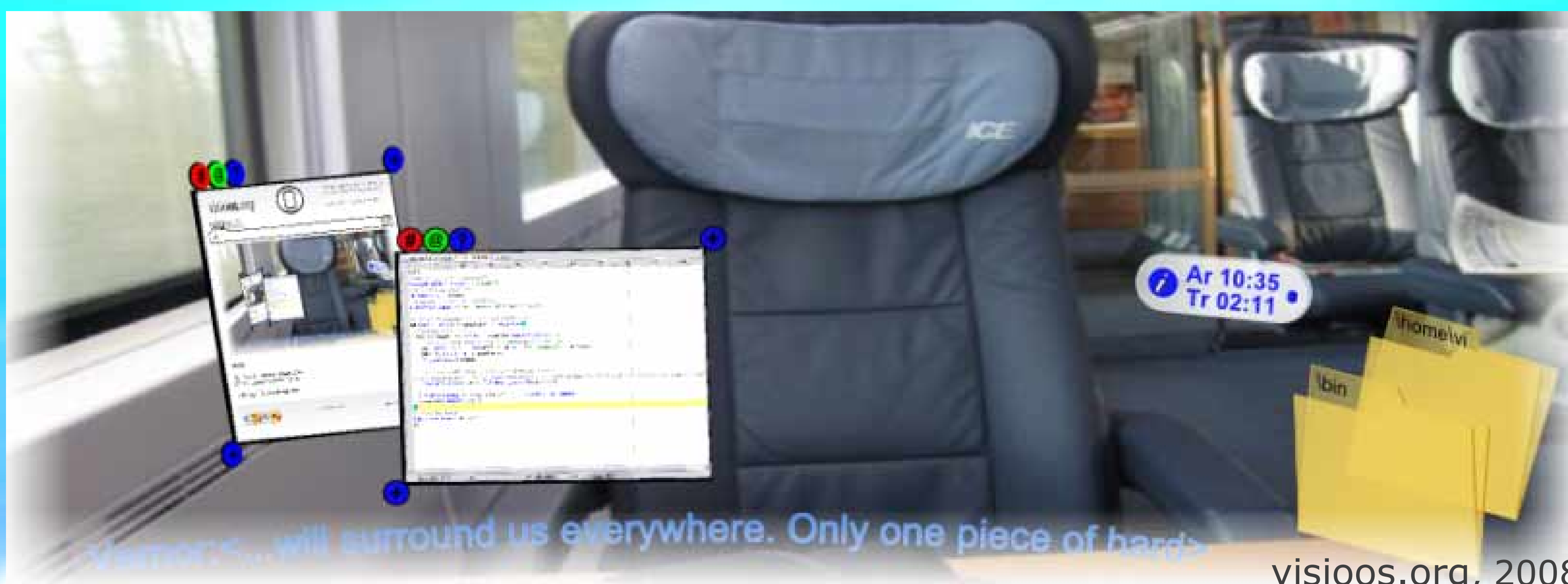
In current products, hardly anything is realized at all!

Future

The future: private use

- 'Professional' applications won't amortize this technology
- Only mass market applications can do
- The mass market is private
- **Who would be able to use a mobile phone if John Doe couldn't afford it ?**

The End of Hardware, 2006



visioos.org, 2008

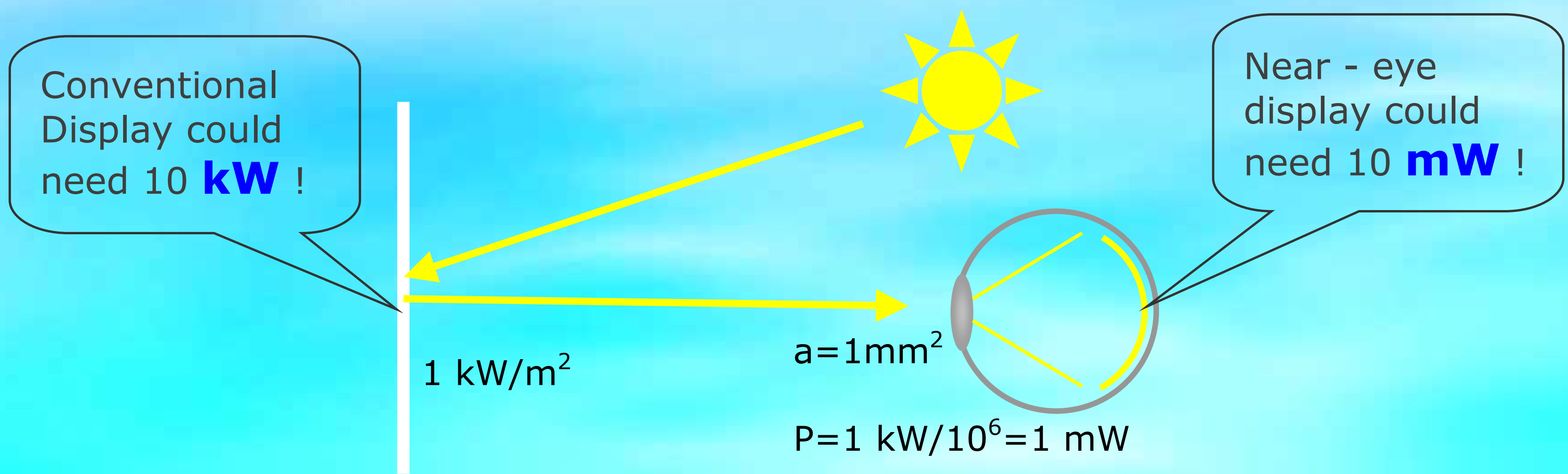
3D Operating systems ?

The desktop is not the only virtual computer world: Microsoft's BOB OS, 1995

3D ergonomics:
Windows Vista

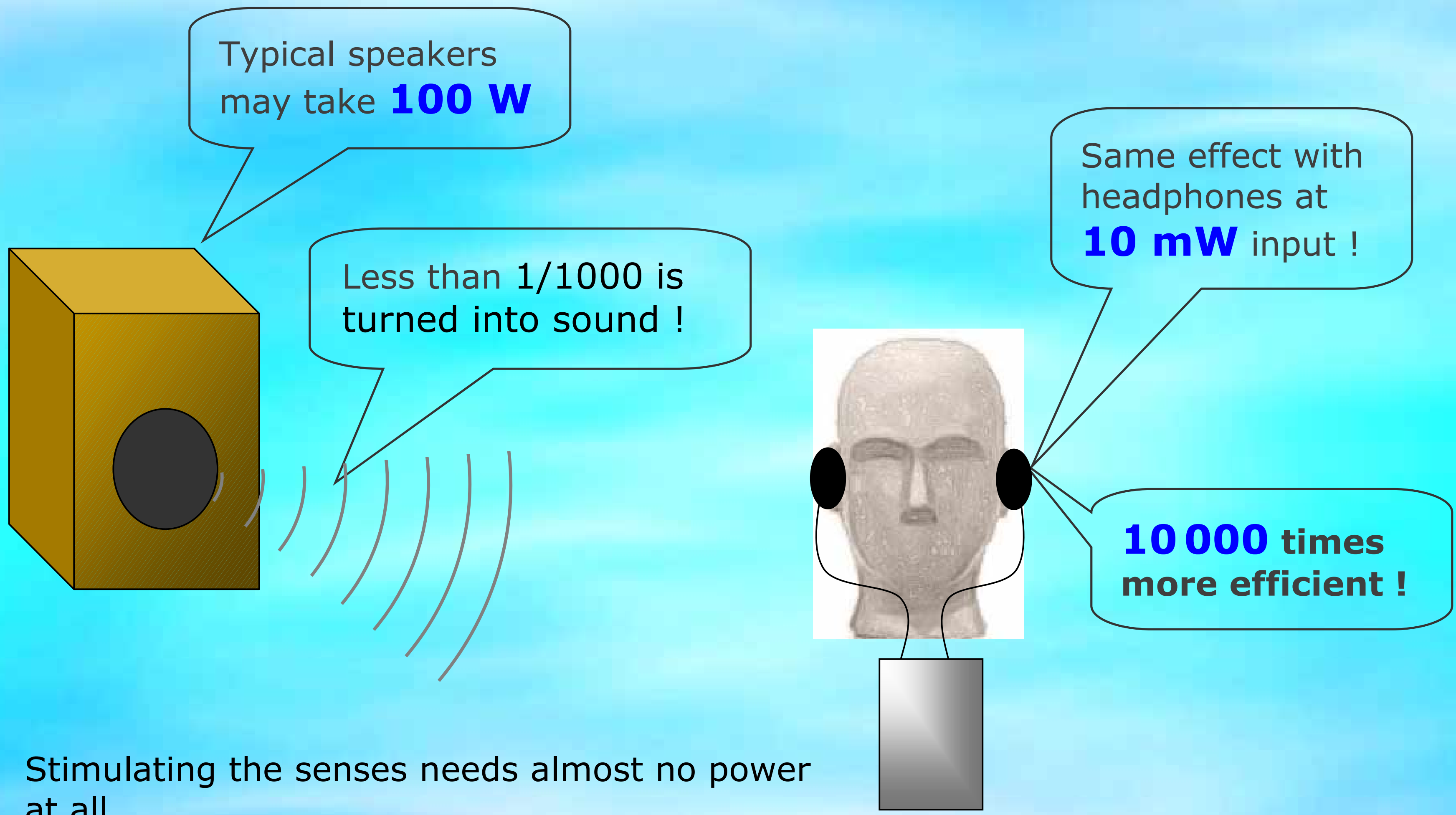
Microsoft future vision (2008)

Power consumption of display glasses



- Viewing a totally white scene in bright sunlight, only 1 mW of light enters the eye.
- Dynamically adaptive displays can guide almost 100% of light into the pupil.
- Practical viewing situations even require much less energy.
- Hence, near eye displays need very little energy for illumination.
- Piezo electric motors have efficiencies up to 30% and would only have to move micrograms in this application.
- Mask displays, sound add-ons etc. will only need a few milliwatts.

Sound



- ↳ Stimulating the senses needs almost no power at all.
- Most of the power consumption of advanced near eye displays will go into signal processing
- **Low power computing and signal processing will be an essential counterpart !**

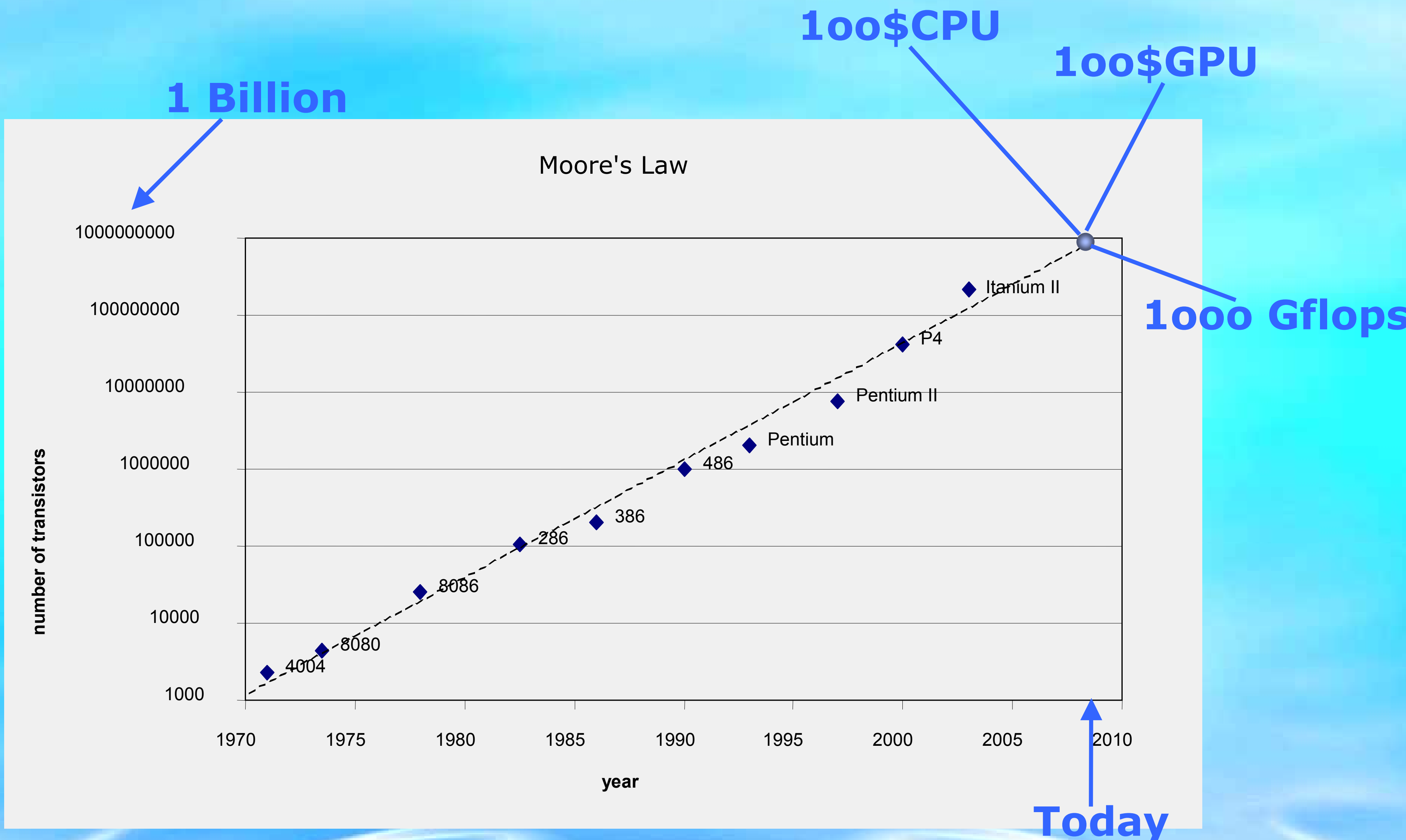
Economy and ecology

- **Near-eye-displays can be**
- ***1000*** **times lighter,**
- **draw *>>1000* times less power !**
- Today, fast changing technology obsoletes equipment every 2-5 years.
- Throwing away some 30 g of vision glasses is much better for the environment than throwing away a 30 kg large screen display.
- Virtual offices will become more feasible, saving office buildings.
- Any application will get **mobile**.
- One single device can replace hundreds of conventional screens and other hardware objects.
- Given these effects, and the even broader impact on everyday applications,
- **AR will be for the 21st century what the car was for the 20th.**

Markets

- AR technology can replace many kinds of hardware at a significant advantage in usability and considerably lower costs.
- It requires substantial investments to develop.
- ***Economics of scale:*** **Office and Home applications are the major markets for developments demanding this kind of major investment.**
- Other professional applications (military, medical, industrial, architectural etc.) will only create niche markets in comparison: these **Markets, 100 or 1000 times smaller might accept higher product costs, but not 100 or 1000 times as high.**
- The effect is even much stronger, as **diversity** (many producers, many developers) is a key ingredient of any complex innovation.
- **The current attitude to recognize AR as a technology just for professional niche applications is therefore shortsighted !**

Processing power: Right on target



The technology runaway

- ***Solutions calling for products***

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0.1 Lux, color

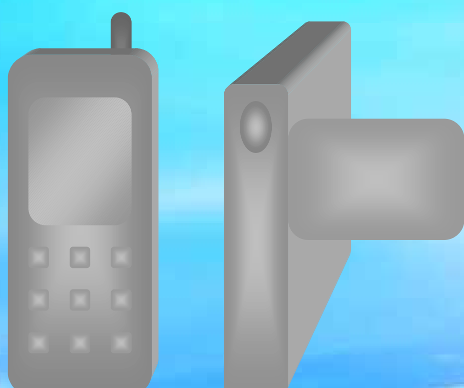
8 GB

20g

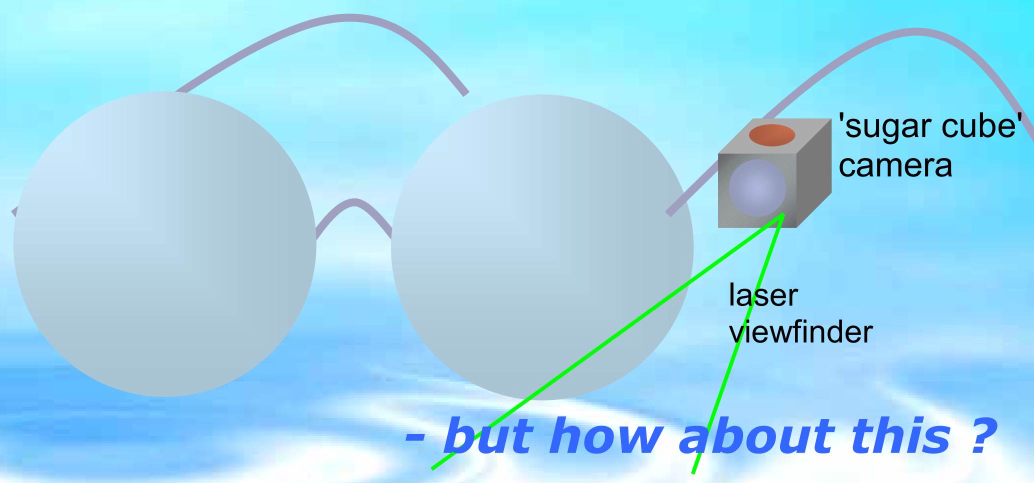
??

2008 !!

- *Applications lacking imagination*

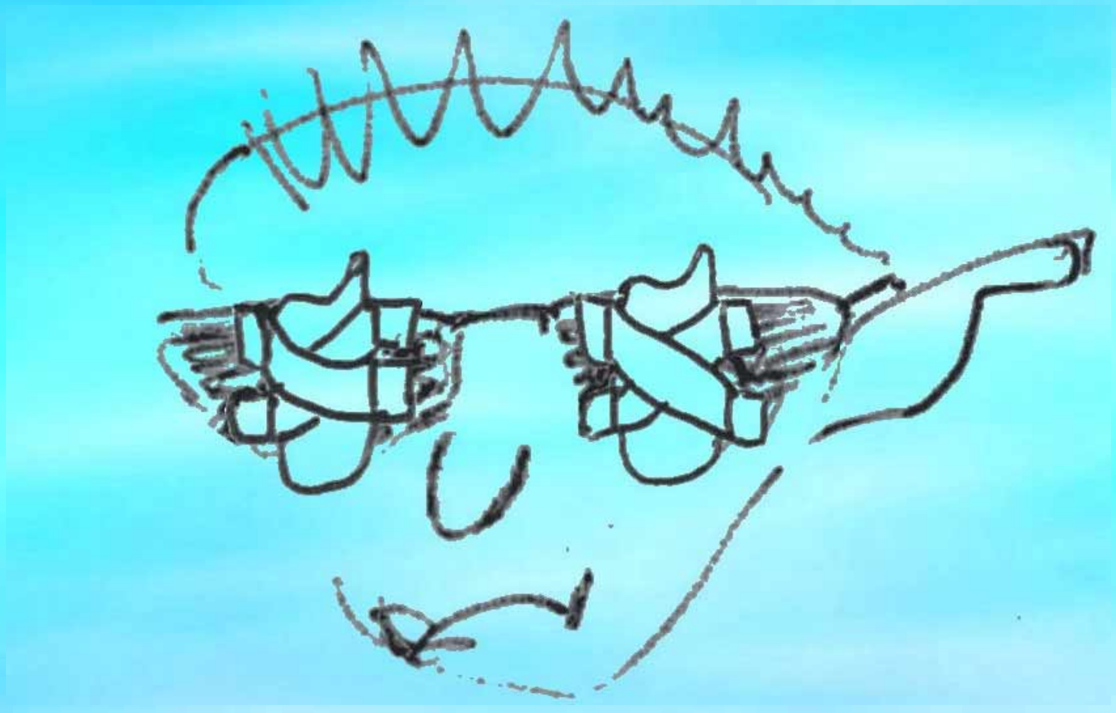


Some cheesy alternatives



- but how about this ?

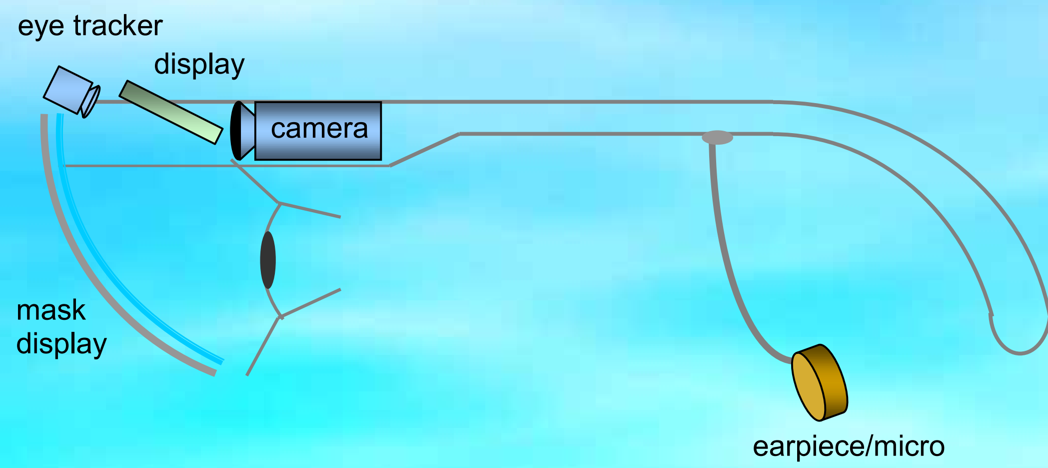
Just a matter of packaging ?



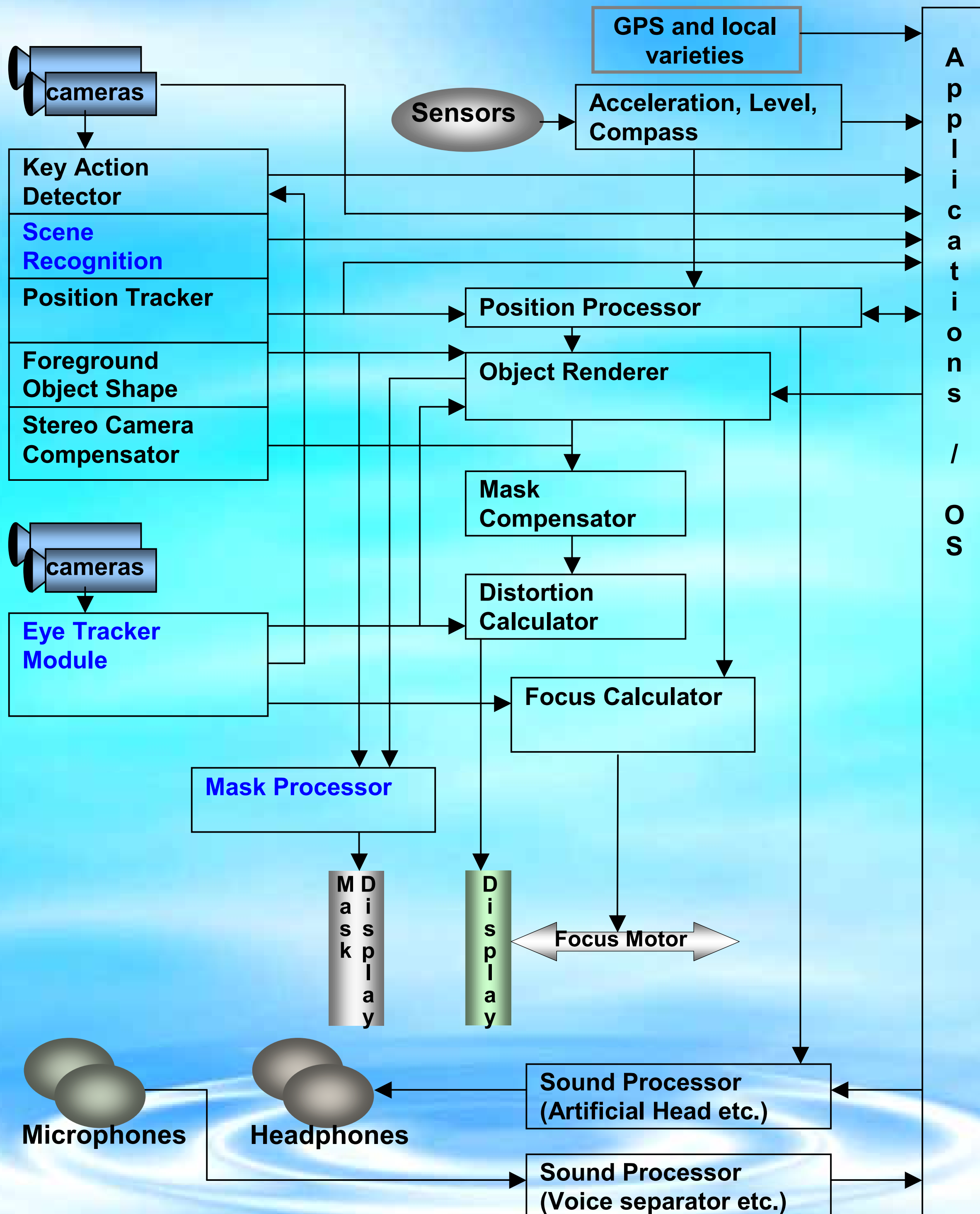
"During his sabbatical, John successfully demonstrated the feasibility of light weight display glasses"

Near-Eye Displays

Elements of display glasses

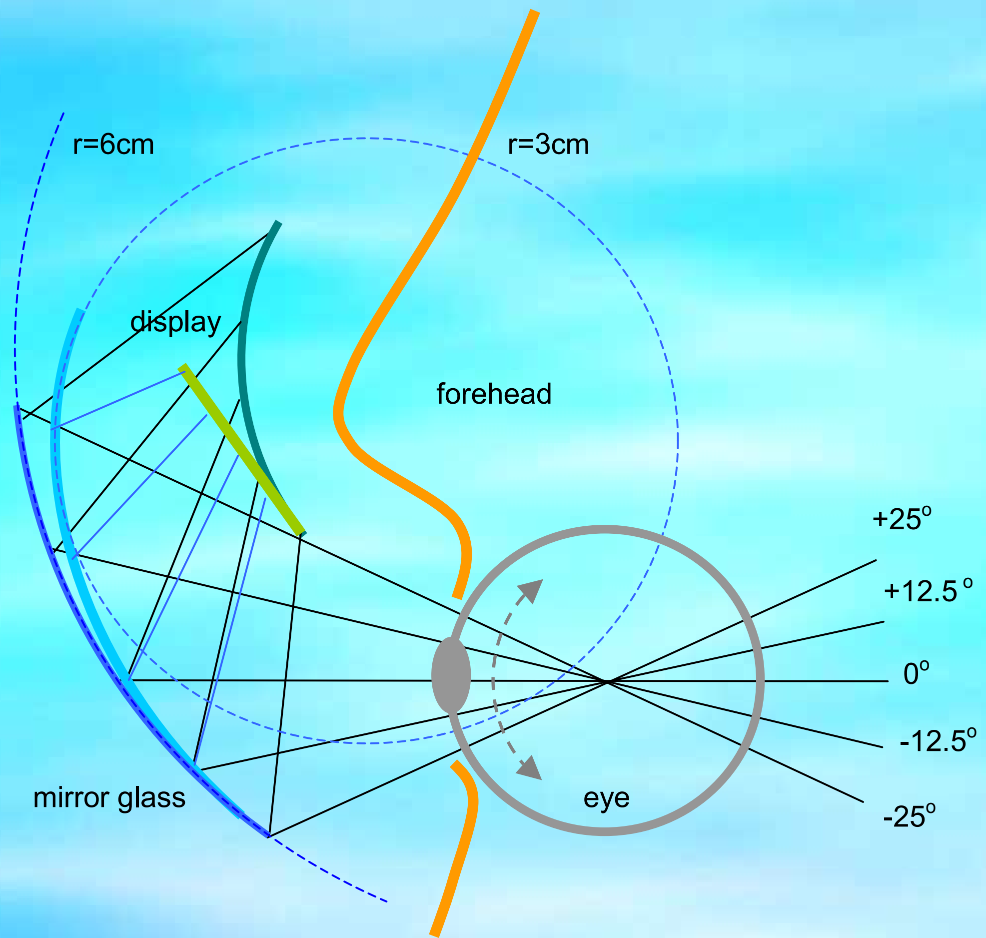


Object display	→	**high resolution display glasses**	**Interaction detection (Camera)**	→ **Finger, key pressing**
Object positioning	→	**Head position sensors: Conventional, Optical Acceleration, GPS, Camera, etc.**	**Adaptive Display/Rendering strategies (inlays etc.)**	
				Dynamic focusing
			Fine positioning	→ **Eye tracking**
Object insertion (Camera)	→	**Viewpoint recognition**	**Audio**	**Microphone/Earpiece**
	→	**Real scene acquisition**		
	→	**Masking techniques Mask Display**	**Misc.**	**Keys, Headlamps etc.**



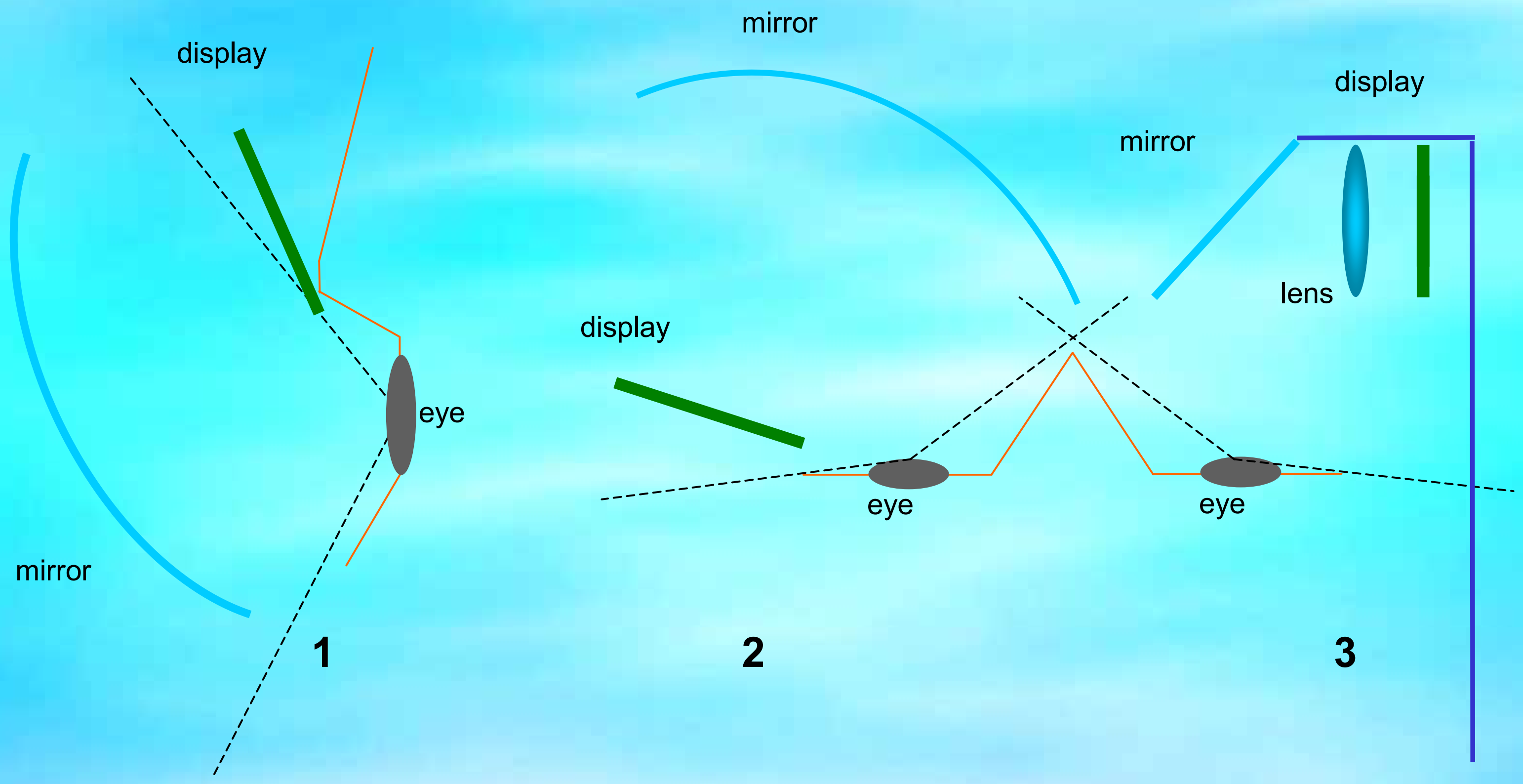
GPS and local varieties
cameras
Sensors
Acceleration, Level, Compass
Applications / OS
Key Action Detector
Scene Recognition
Position Tracker
Position Processor
Foreground Object Shape
Object Renderer
Stereo Camera Compensator
Mask Compensator
cameras
Distortion Calculator
Eye Tracker Module
Focus Calculator
Mask Processor
Mask Display
Display
Focus Motor
Microphones
Headphones
Sound Processor (Artificial Head etc.)
Sound Processor (Voice separator etc.)

Basic optics: the “Christmas ball” design



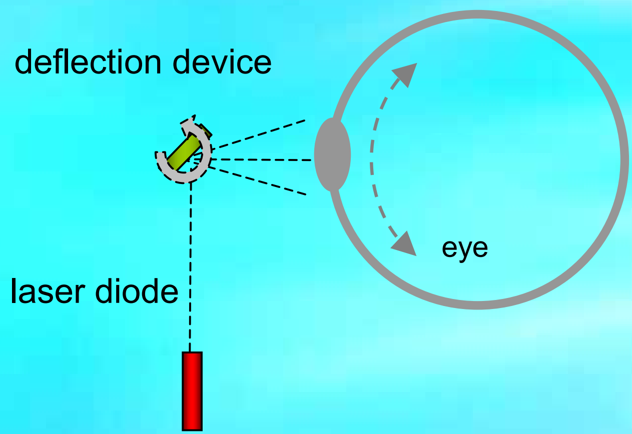
Basic concave mirror glasses design.

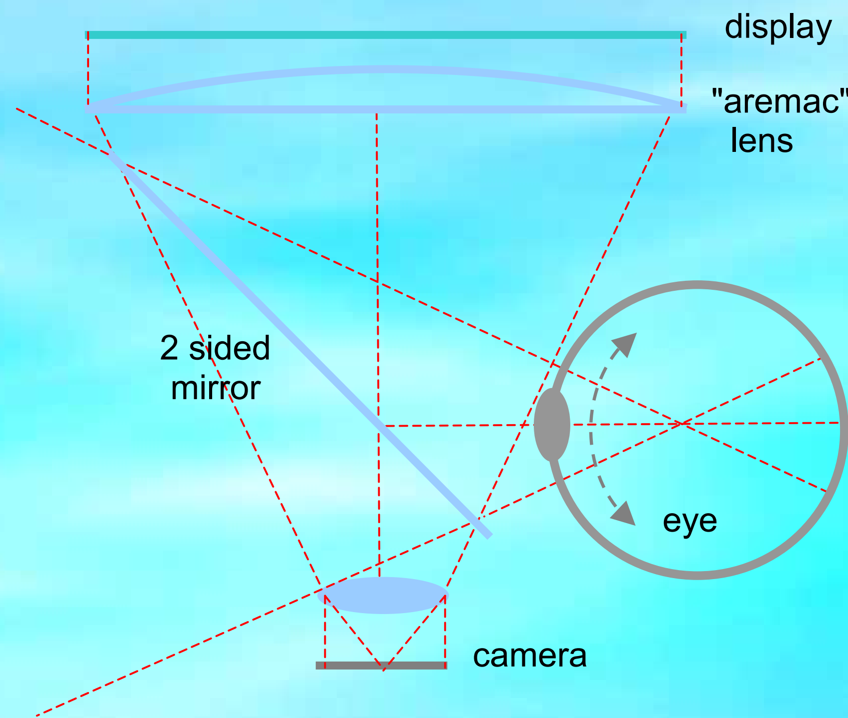
Some variations



Eyebrow display | Side display or projector | The usual primitive

Other Concepts ?

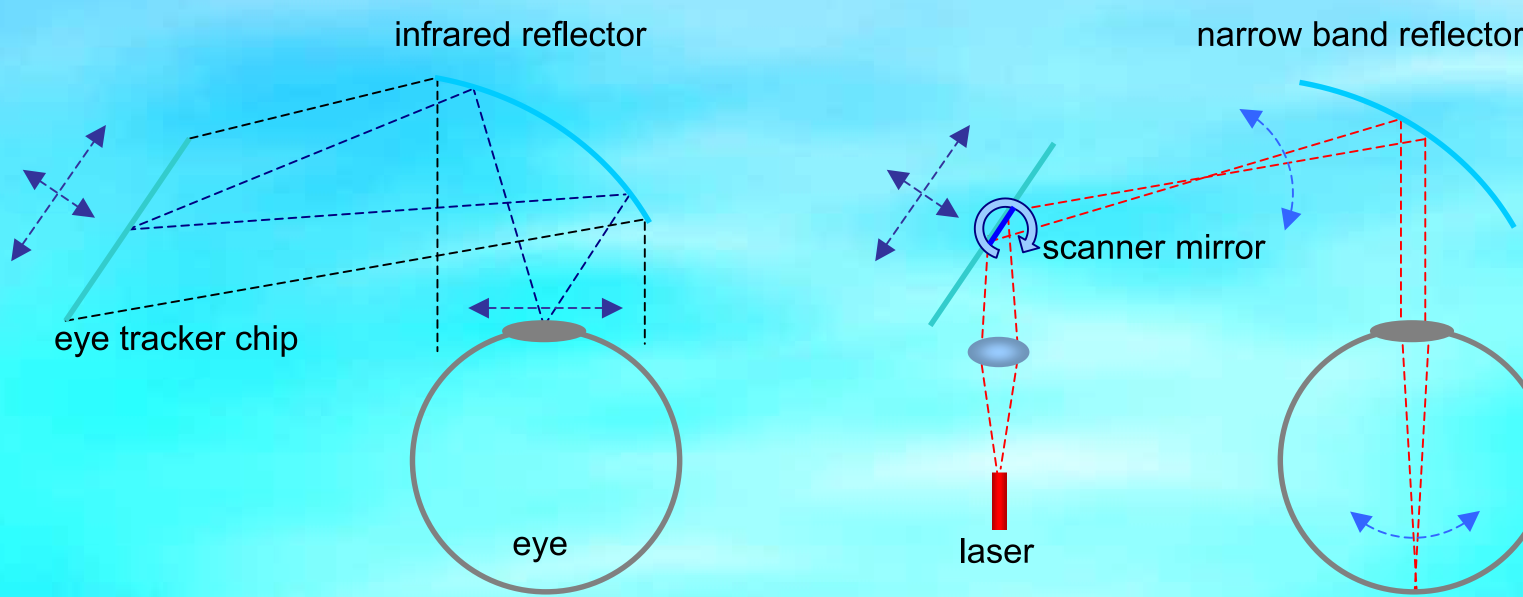




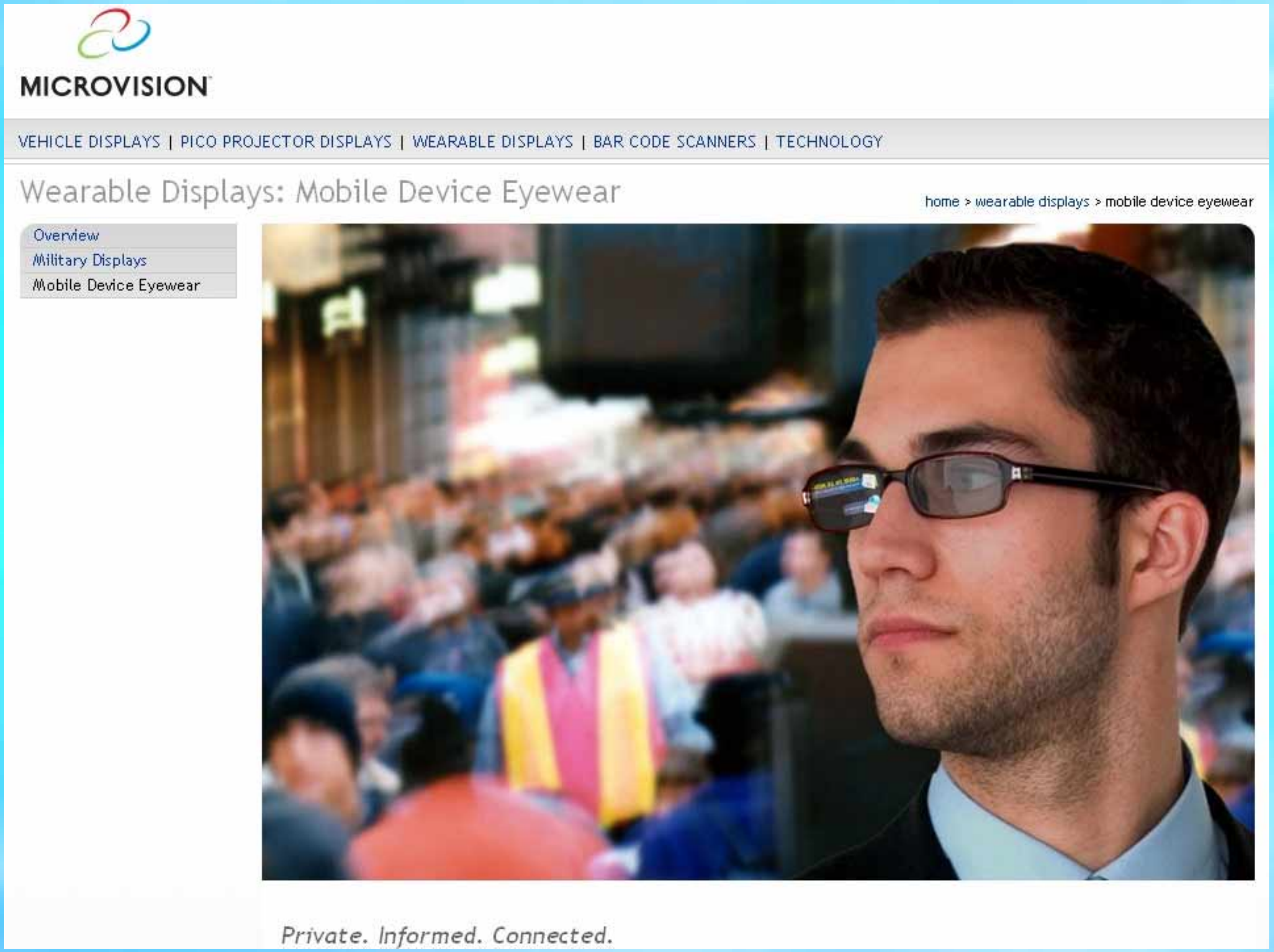
- Laser deflectors may be tiny, but this wouldn't work by any means...
- Not only would it occlude the view,
- Lasers also need focusing

- The Eyetap:
- Fine at a first glance, in spite of replacing the entire view by the camera picture.....
- But the eye is not a camera, it moves !

Future: eye operated cell phone – the KILLER application?



- We combine an eye tracker (left) and a laser unit (right) in the same optical path.
- The tiny scanner mirror is placed in the center of the eye tracker chip, hardly affecting its function.
- ***The entire assembly can be as light as a Christmas ball.***



2008: Microvision website promoting the possible use of laser displays in personal mobile devices

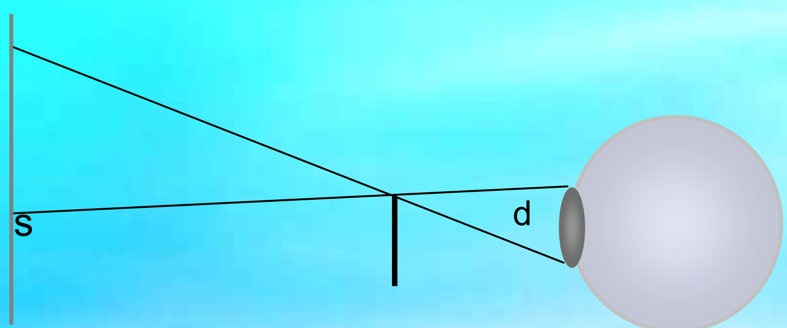
http://www.microvision.com/wearable_displays/mobile.html

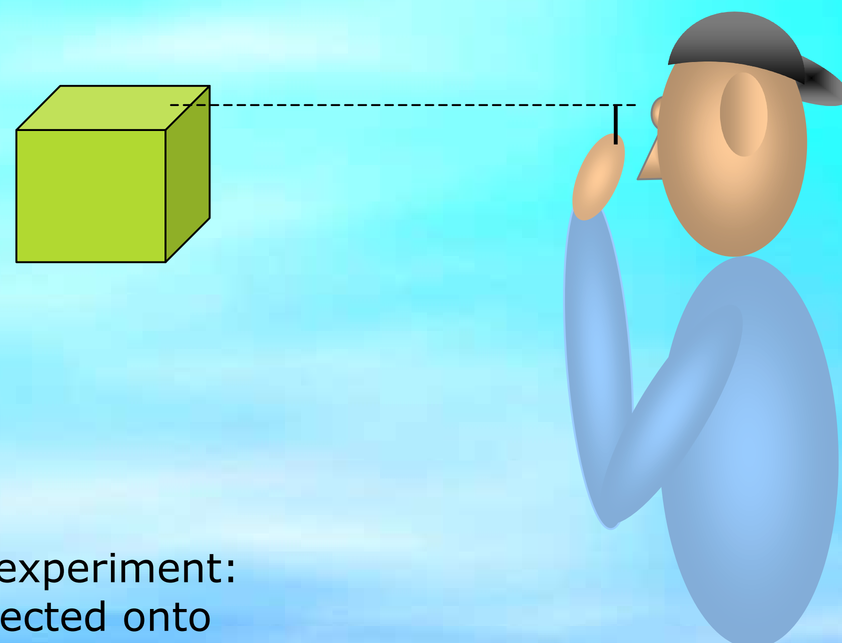
Essentials

The 'unsharp' mask display

- A 'gray card' reflecting 20% appears 50% bright
- Our brightness perception is logarithmic

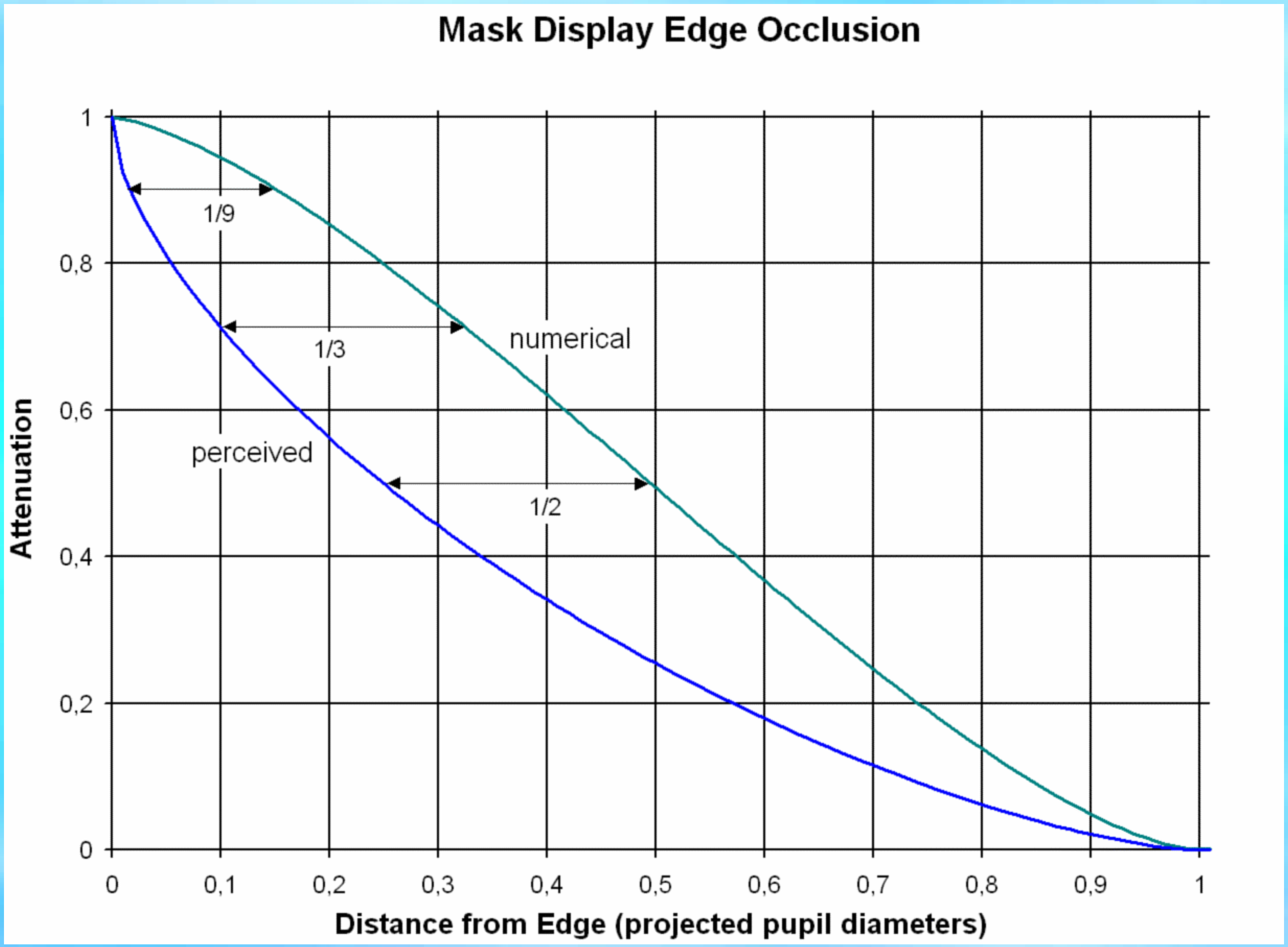
↳ perceived brightness: $B_p \approx 1 - A^{\ln 2 / \ln 5}$





Simple visual masking experiment:
Pupil diameter *d* is projected onto
object edge; sharp occlusion border at *s*

Perceived border width



⇨ An unsharp mask display close to the eye works much better than one would ever expect !

Simulated impressions

A rectangular mask with typical unsharp seen borders

A Virtual image has been inserted into the masked section.

With a natural background, the result is almost perfect

Typical border sizes:

- Virtual PC monitor - 2 mm
- Virtual large TV - 1.5 cm

Mask displays: crisper than thought

Currently, only LCD technology is conceivable for a mask display.

- It swallows 50% of the light, as it polarizes.
- Nevertheless, some people even wear sunglasses to the disco ...

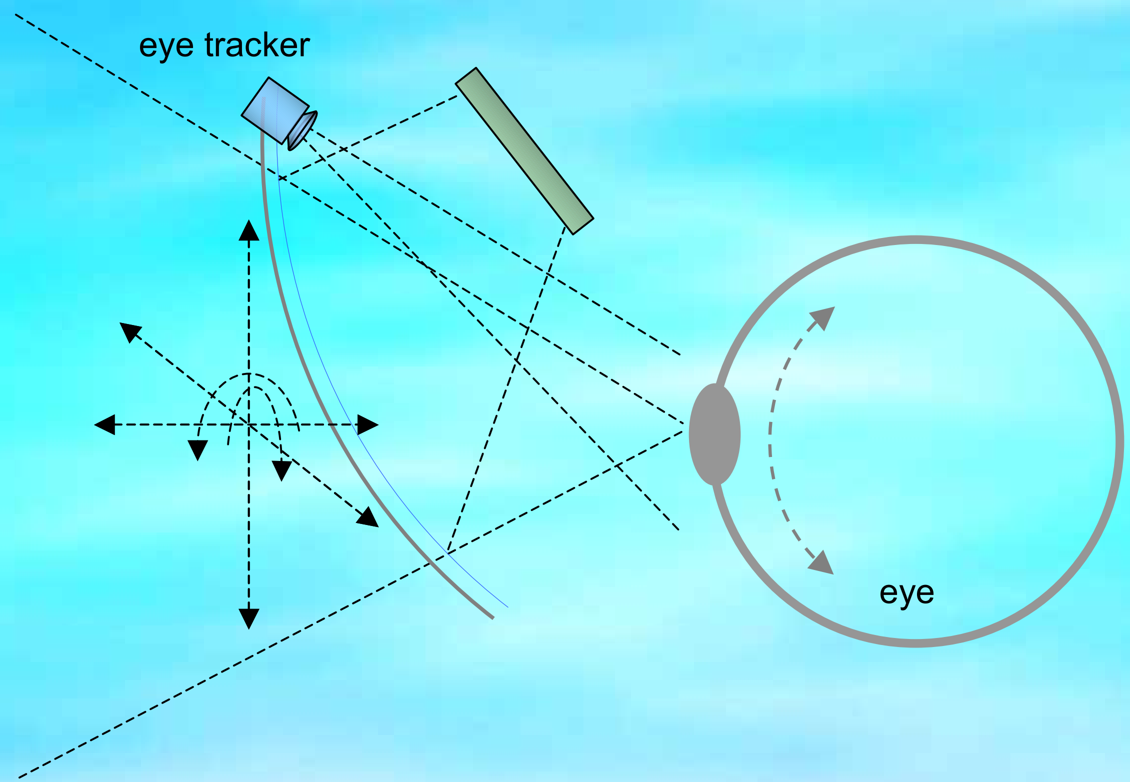
What we need is considerable resolution, hence a TFT driven device

- With borderless pixels
- and a transparent driver circuit

Driver technologies currently available:

- ZnO or SnO semiconductors
- Plastics with carbon nanotube additive

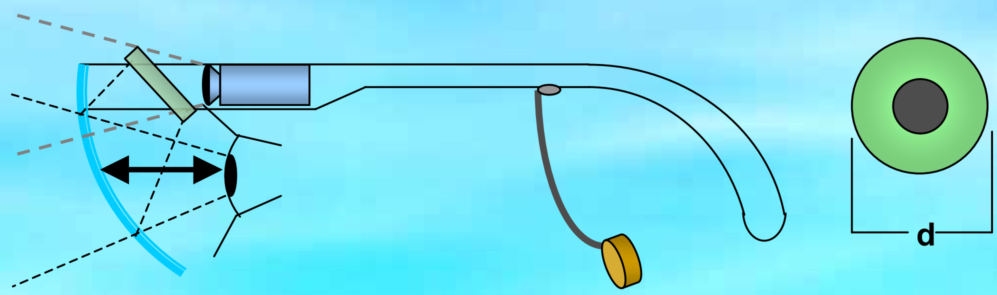
Eye tracking



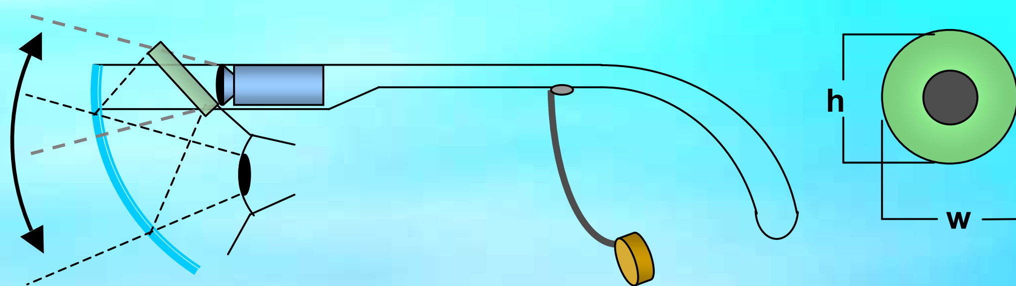
Example assembly with an eye tracker and usual degrees of freedom for conveniently wearable glasses

Eye trackers

- Eye trackers are not currently usual in virtual reality displays, but will be indispensable in the future.
- Eye trackers will help adjusting for misfit display glasses, guiding light into the eye, adapting the displays to the viewing direction (hi-res inlays, mask fitting etc.)
- The Hough transform enables Robust and accurate pupil detection.
- **'One-chip' eye trackers** integrating the algorithm in a low power parallel processing CMOS chip are already available.
- **CMOS** enables the integration even of light sensitive pixels with processing circuits (gate arrays on a single chip.



Sensing eye distance by Iris diameter

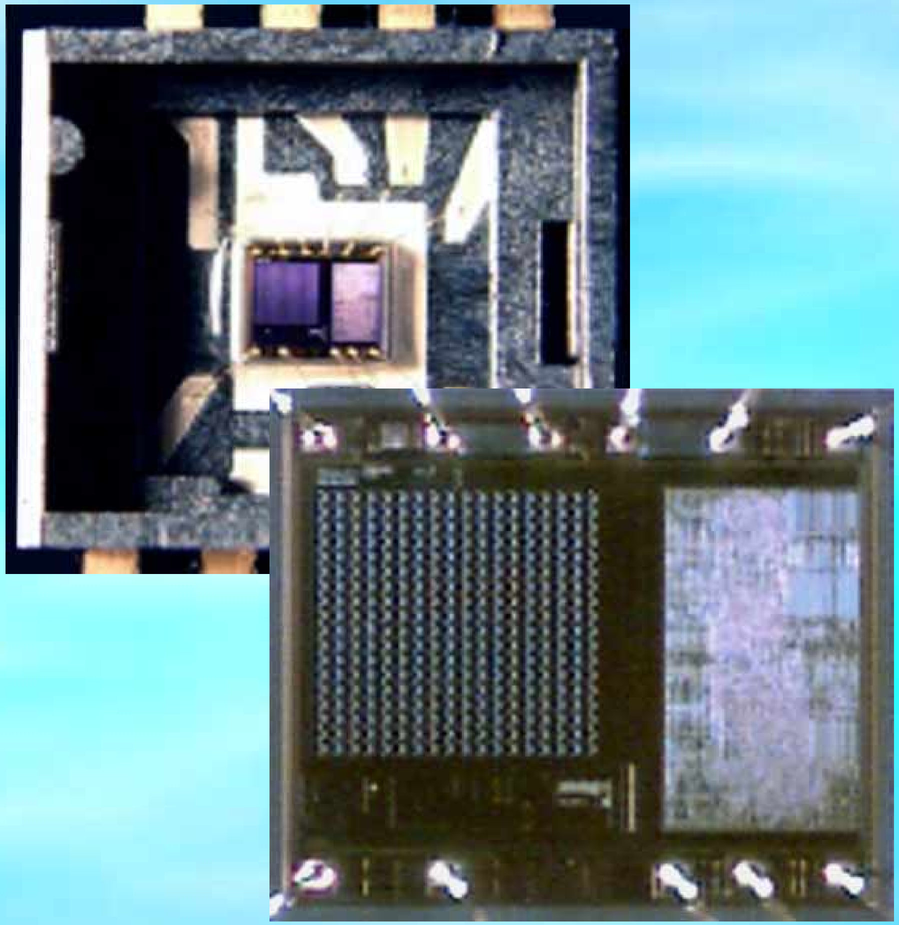


Detecting tilt by width/height comparison

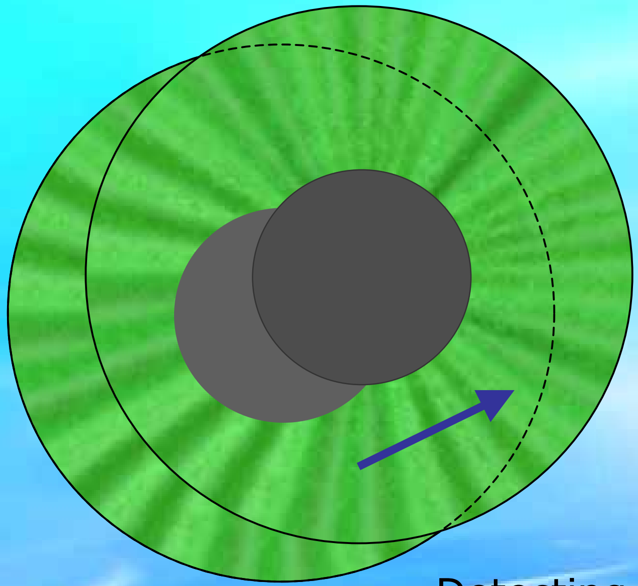
Visual Flow

- Robust and efficient detection of pattern motion ('**visual flow**'), as already implemented in optical computer mice, could detect iris motion in milliseconds with minimum effort and power drain.

  ⇨ Under the term "optical flow", already an issue in scene recognition.

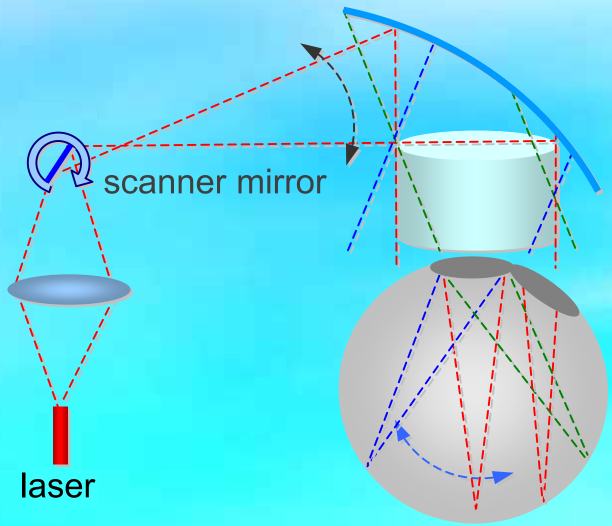


The 'heart' of an optical mouse: a single low-power CMOS chip carrying the sensor array together with the processing unit.

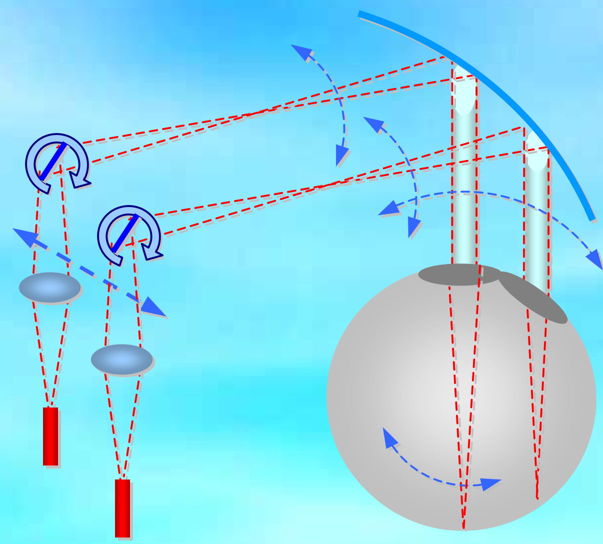


Detecting quick motion from iris pattern shifting

Aperture

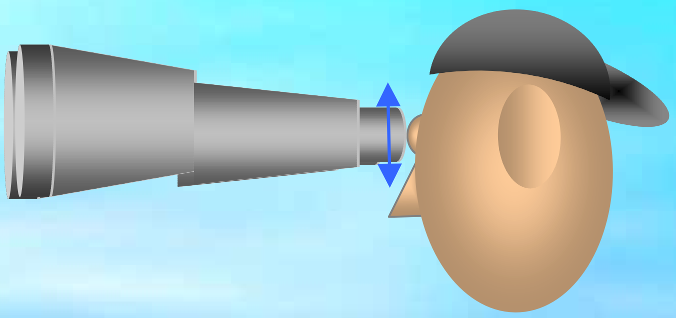


With laser scanners, wide beam apertures result in a wide range of tolerable eye movement, but significant loss of light.



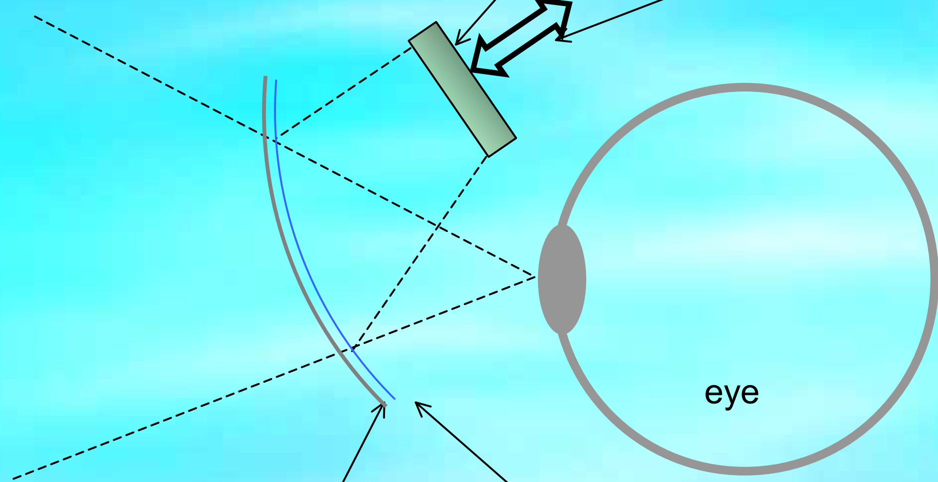
With narrow beams, all light can enter the eye, but eye motion is calling for compensation.

- **Aperture and other adaptation problems are best solved with a mechanical compensation.**
- **Electronic displacement and distortion compensation will also be necessary.**



With classical optics, large magnifications result in a small exit pupil, also calling for mechanical compensation of eye motion.

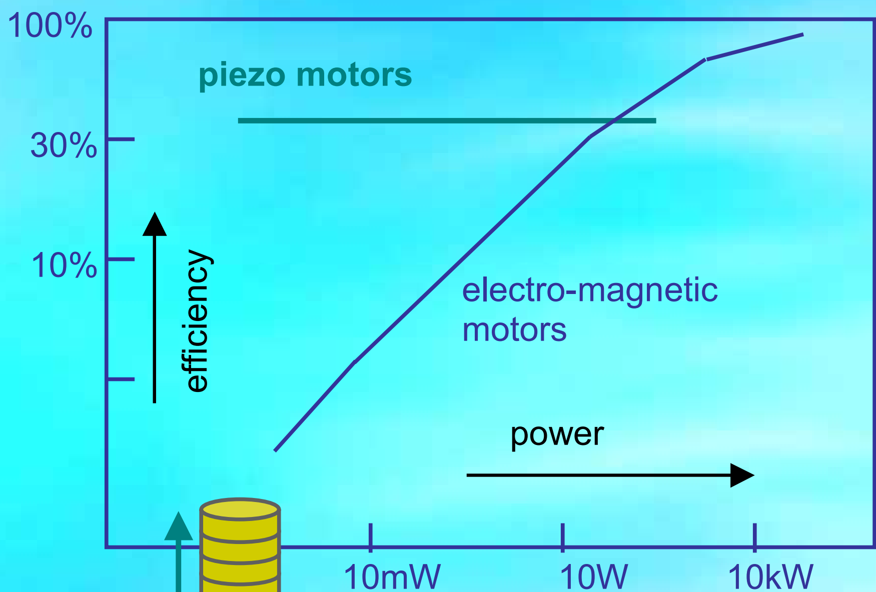
Focus synthesis

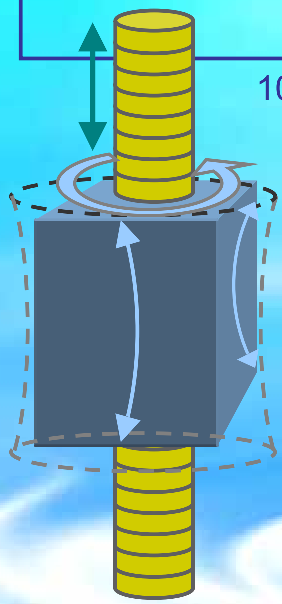


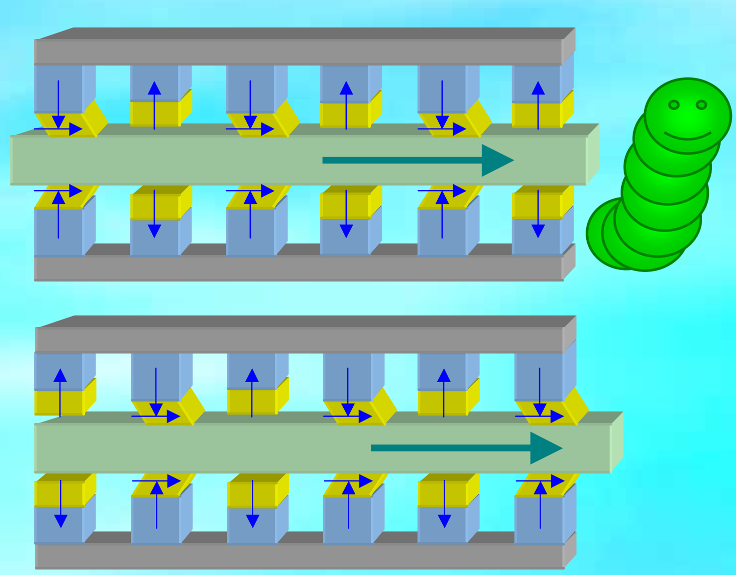
Mechanical focusing

Piezo electric micro motors

made stunning progress recently, and are now promising to solve for the high speed servo systems needed in display glasses, at incredibly low weight and energy.

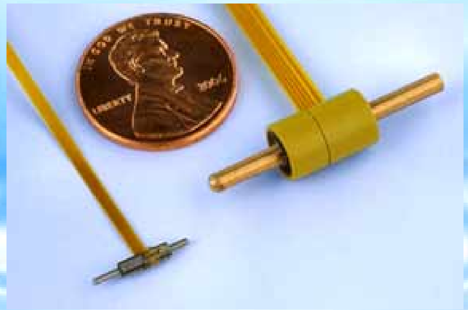






Piezo-Walk ®
(Physik Instrumente)

Squiggle ®
(New Scale Technologies)



Advanced eye control

Future concept: focus steered virtual objects

- Actively steering the rendering area by eye convergence tracking or focus accommodation sensing can also peel out the depth layer just in focus, by making details before and behind progressively blurred and transparent.

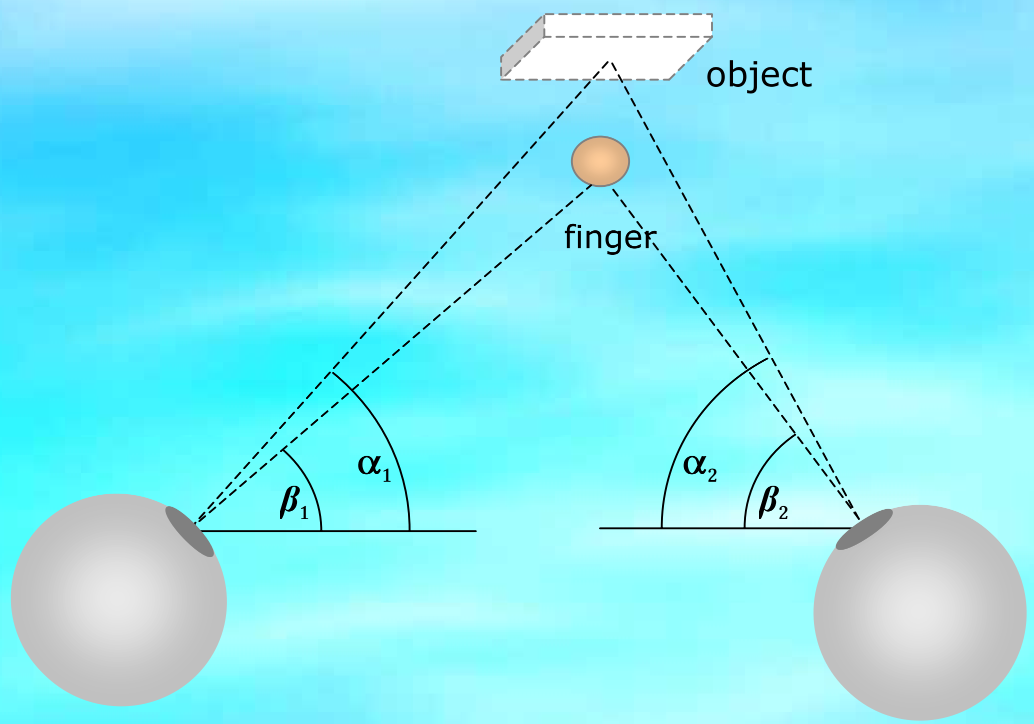
⇨ New applications: ***Ghost objects and devices***

Ghost objects and devices *(Vaporware?)*

New applications:

- gaze selecting among transparent 3D layered windows or objects
- simulated transparent views into real objects (engine service)
- 'seeing' through walls
- dissecting three dimensional structures
- moving virtual objects in all directions, by eye pointing
- creating really three-dimensional virtual objects (3D chess game)

Squint-and-touch



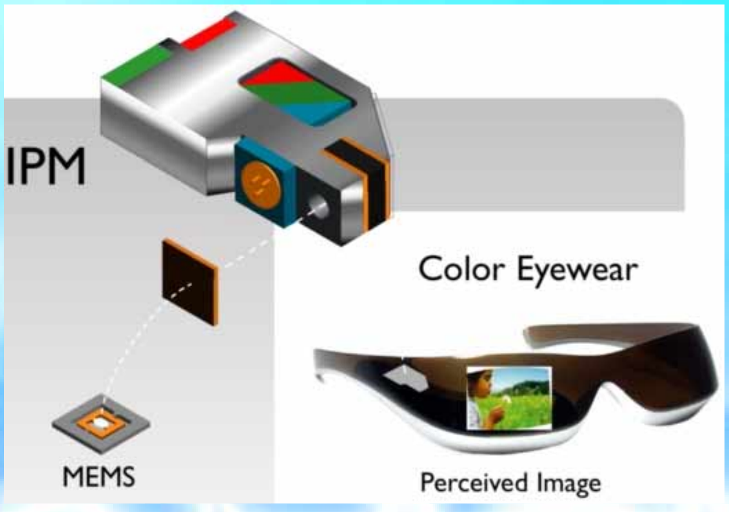
- We usually look where we want to hit
- The software only has to watch the area before the key, if a thing like a finger appears in the camera picture.
- Hence, the entire complexity of this approach is decisively lower than with the usual hand recognition schemes.
- Not only this: We could grab right into a complex 3D structure and pick out an element.

Laser Basics

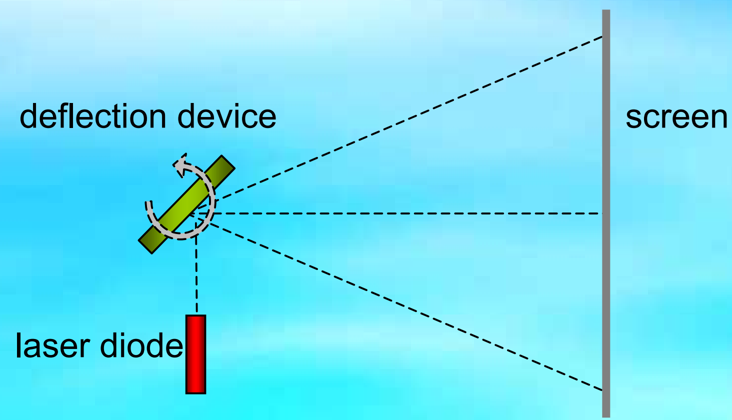
Laser displays

Microvision virtual retina laser displays
(monochrome, VGA resolution)

Announced Microvision
color laser assembly

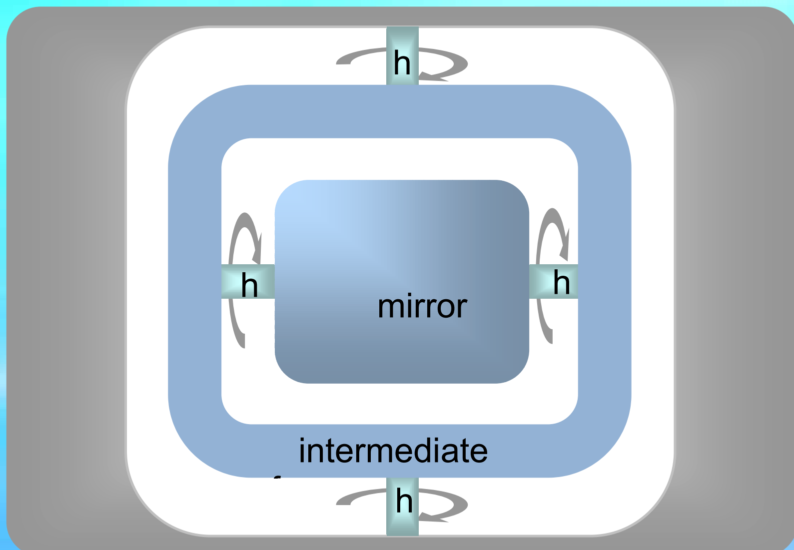


Working principle



Basic laser projection assembly

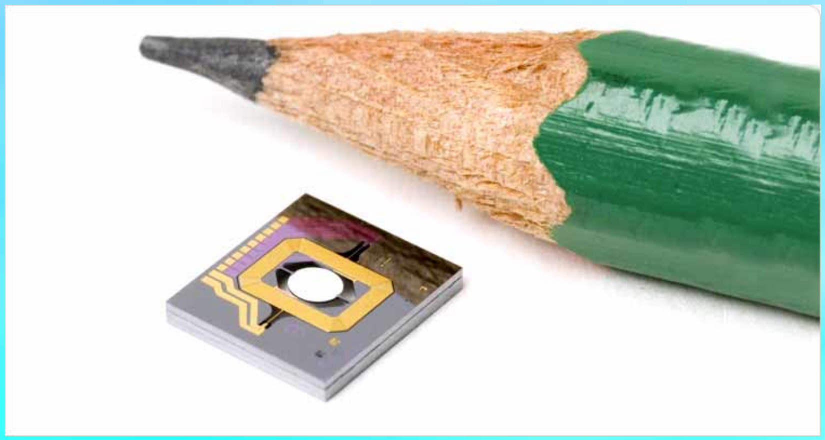
Super advantage of scanners: could follow eye movements immediately !



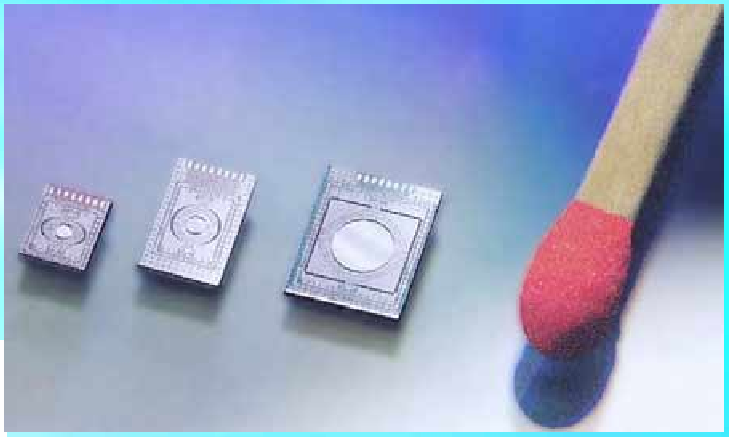
Basic deflection unit design (MEMS element)

While classical displays always have to draw entire frames, causing delay…

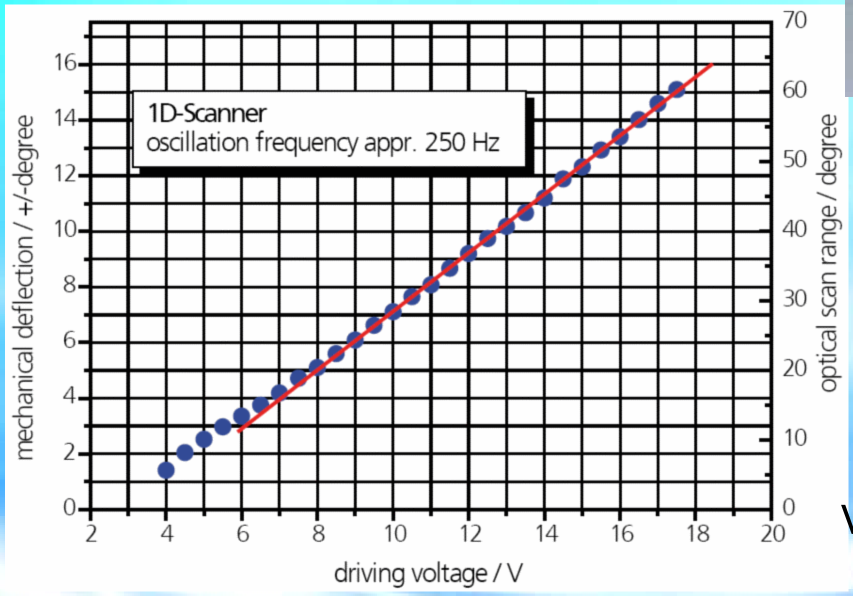
Current MEMS laser scanners



Microvision



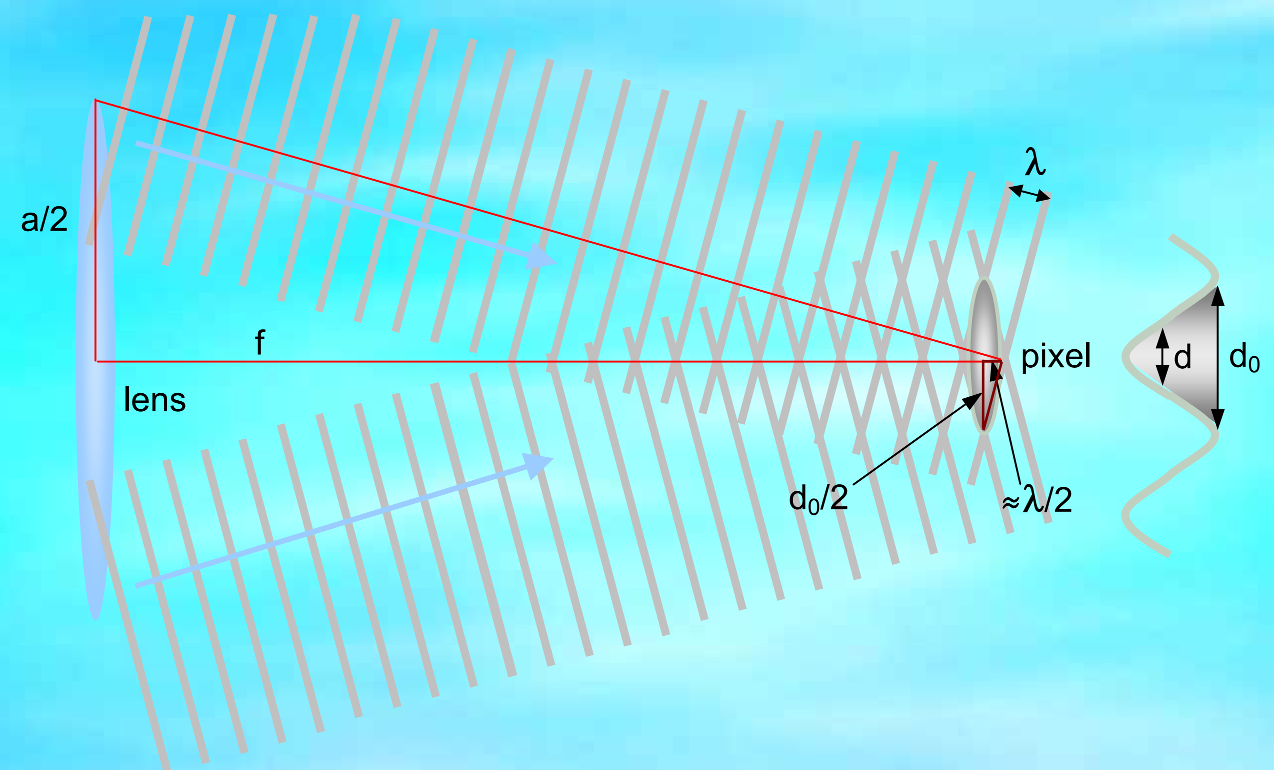
FhG-IPMS



Voltage vs. deflection (FhG-IPMS)

Laser beam deviation - a simple approach

- The resolution a lens can deliver, follows very simply from the actual pixel sizes light wavefronts from different parts of the lens are able to form:



- We can also use this formula to derive that it would take a lens or mirror almost a mile wide to see the remainders of lunar missions on the moon,
- or that an HDTV camera with optics could fit into a 1/8"(3mm) cube,
- or that the human eye can see crisp to 1 arcmin of angular resolution.

$$d \approx \lambda f/a$$

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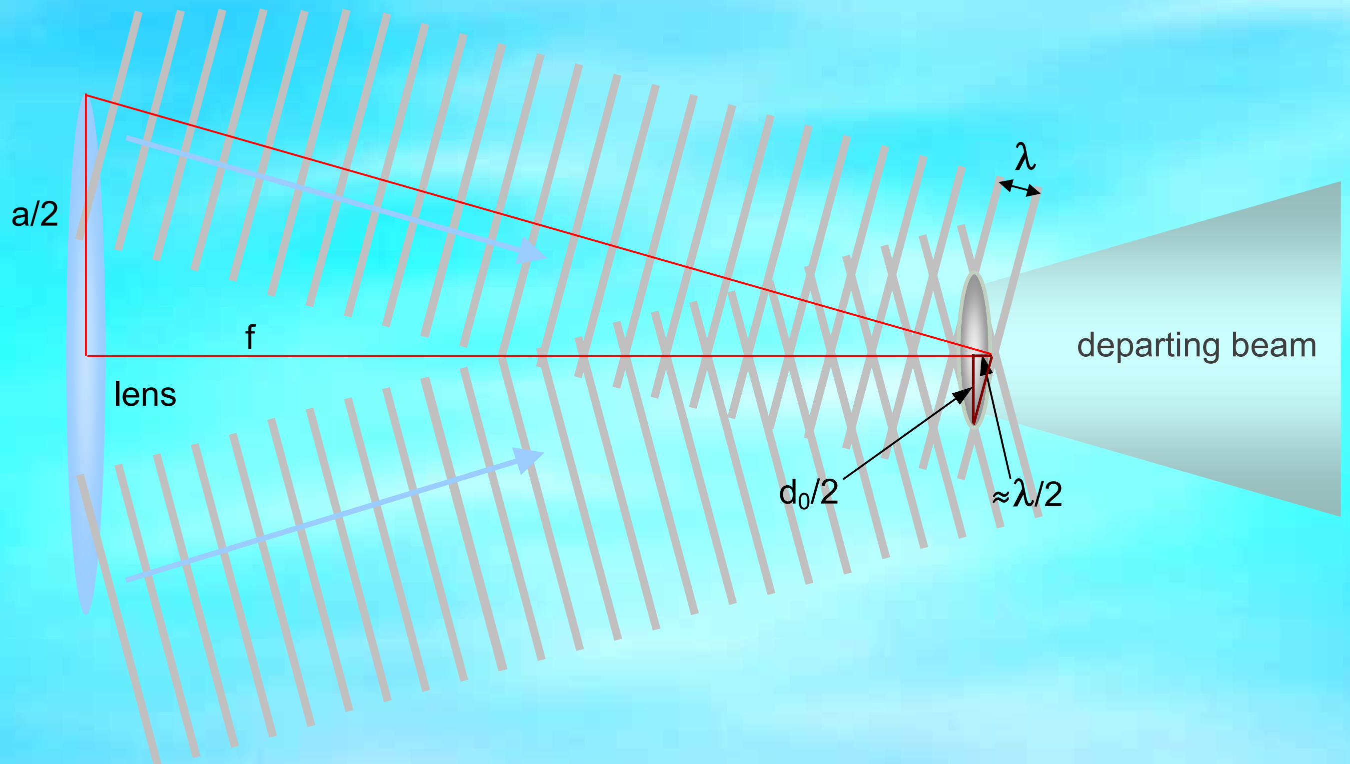
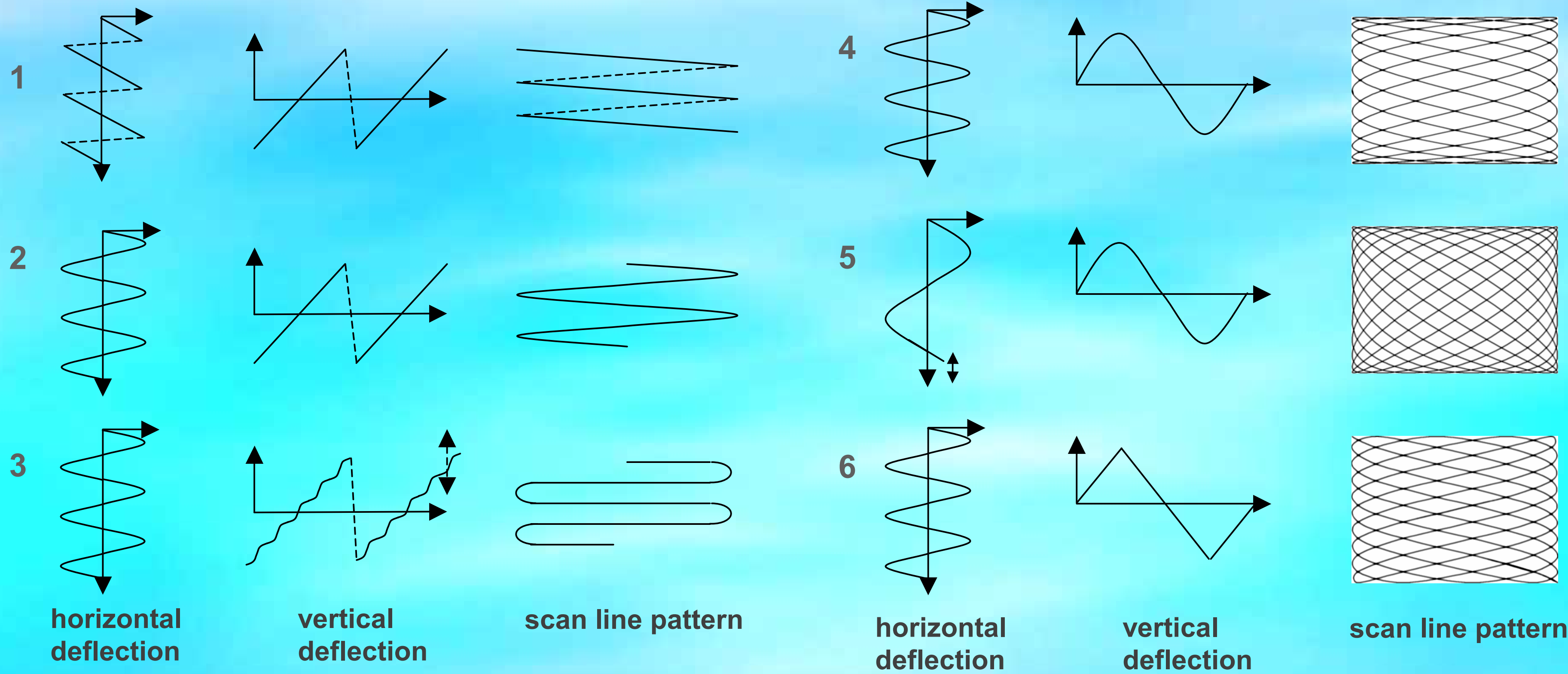


The focus point can also be interpreted as source of a typical laser beam

Beam deviation: $a \approx \lambda f/d$

Beam deflection: not really like a tube



- A beam deflection as in a TV tube (1) causes violent mirror accelerations.
- A sine wave for the faster (the horizontal) direction (2) avoids most of this. In example (3), the vertical deflection mirror is modulated with a small high frequency component, allowing for an even line raster even with a sine like horizontal scan.

Commonly in use currently are Lissajous patterns using sine waves only (4,5). They cause very smooth movements but highly uneven line distributions. Simply using a triangle for the slow axis would be much better.

The Laser dilemma: speed x resolution

- High resolution

=

- larger mirror

+

- faster mirror movements.

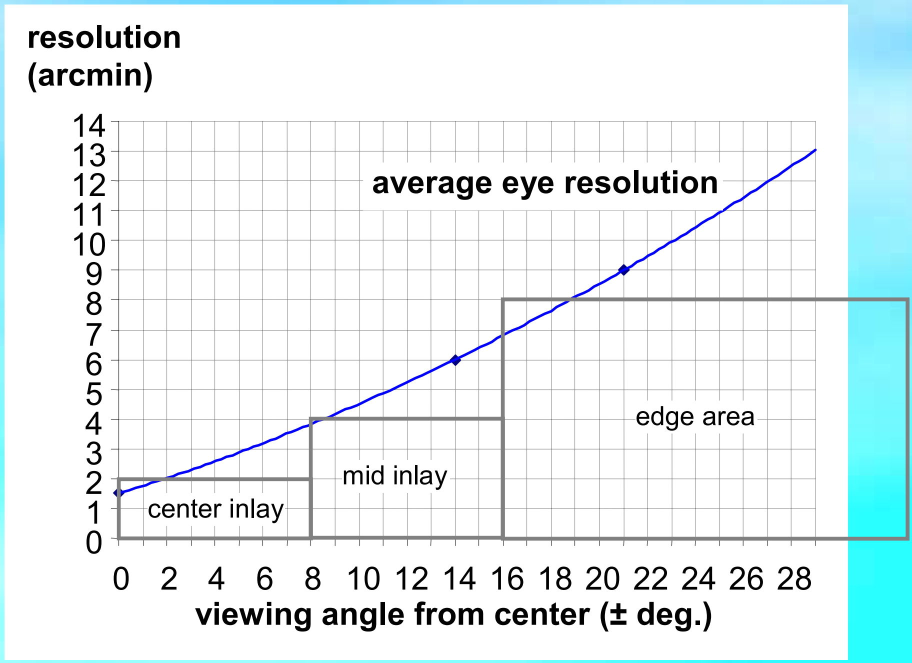
- Solution: high resolution dynamic inlays following the center of view

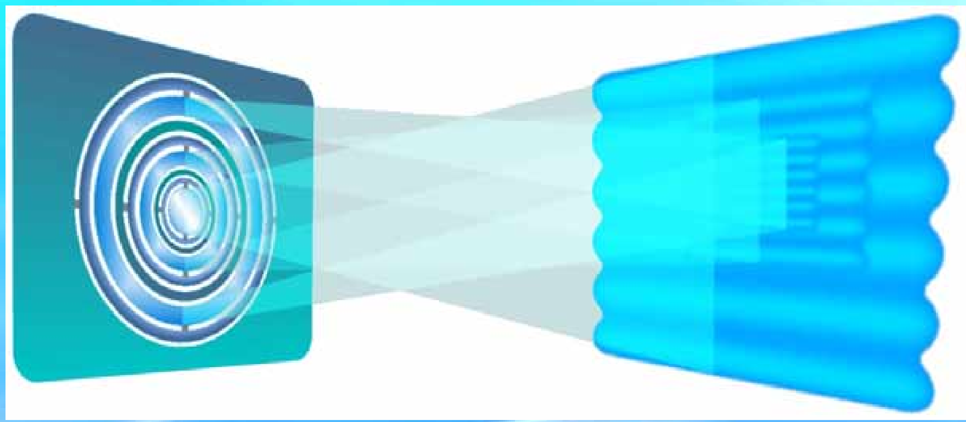
Picture:
only the center area is crisp; stare at it, and the edge blur goes unnoticed.

Suggestion: multi-inlay scanners

Hypothetical concentric 3-way beam deflector chip

real size

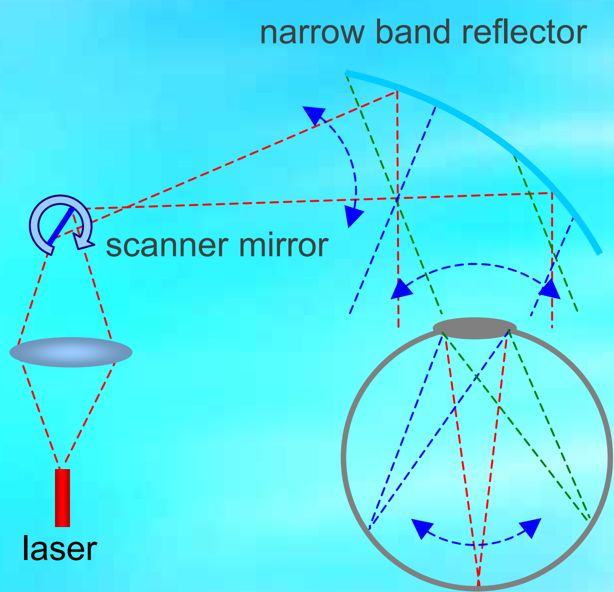


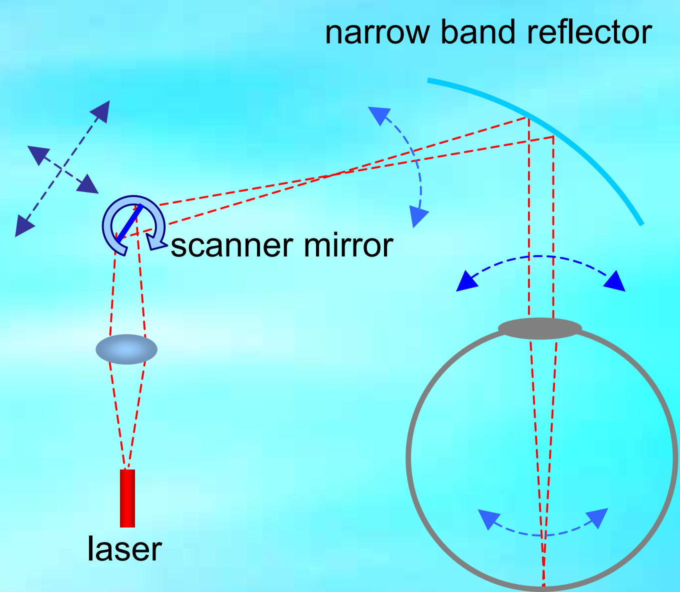


Deflection scheme for 3 staged inlays

- The best way combing mirrors of different size, speed and resolution would be in a coaxial assembly.
- Staged inlays sized 4:2:1 and with less than VGA resolution provide an ultra high resolution display.
- Color capable.
- Even interlacing is possible. Mirror frequencies and excitations would remain low (<10 kHz).

Laser phone optics: focusing the 'beam'



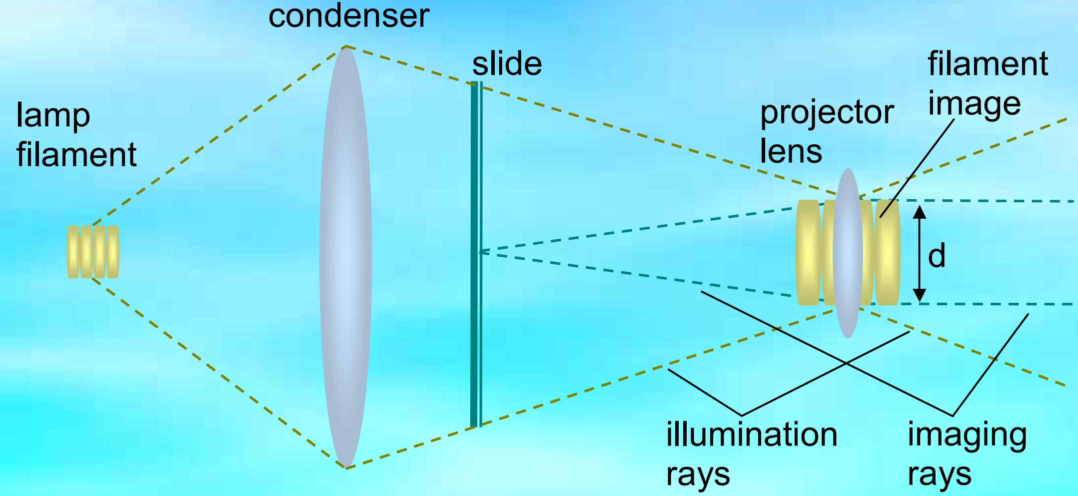


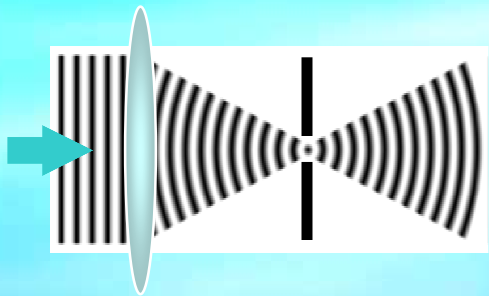
Enlarging the laser's exit pupil for safe eye coverage (right) is simple, but will waste most of the light.

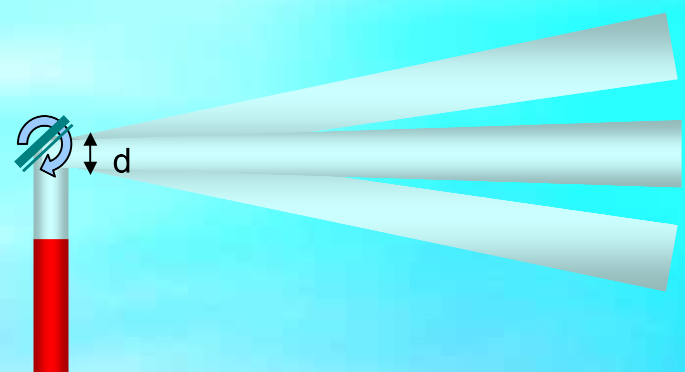
Moving the entire laser unit is a lot better, and can be very efficient, e.g. with piezo electric motors.

Depth of field

- In a beamer, an image of the lamp filament appears within the projection lens.
- A small light source delivers a narrow beam diameter, hence a large depth of field.
- Laser beams can be focused to form small virtual sources.
- With laser scanners, coherence, resolution and depth of field are determined by the size of the deflection mirror.







- **Depth of field does not depend on the choice of laser scanner or classical projector, but only on** the exit aperture of the system. This can be smaller (better) with a high spatial coherence or **the minimum focused size of the light source.**
- The exit aperture **d** cannot be chosen arbitrarily small if a certain resolution is required (equals beam deviation $2\varphi \approx \lambda/d$)

⇨ **Depends on the light source, no matter if projector or scanner !**

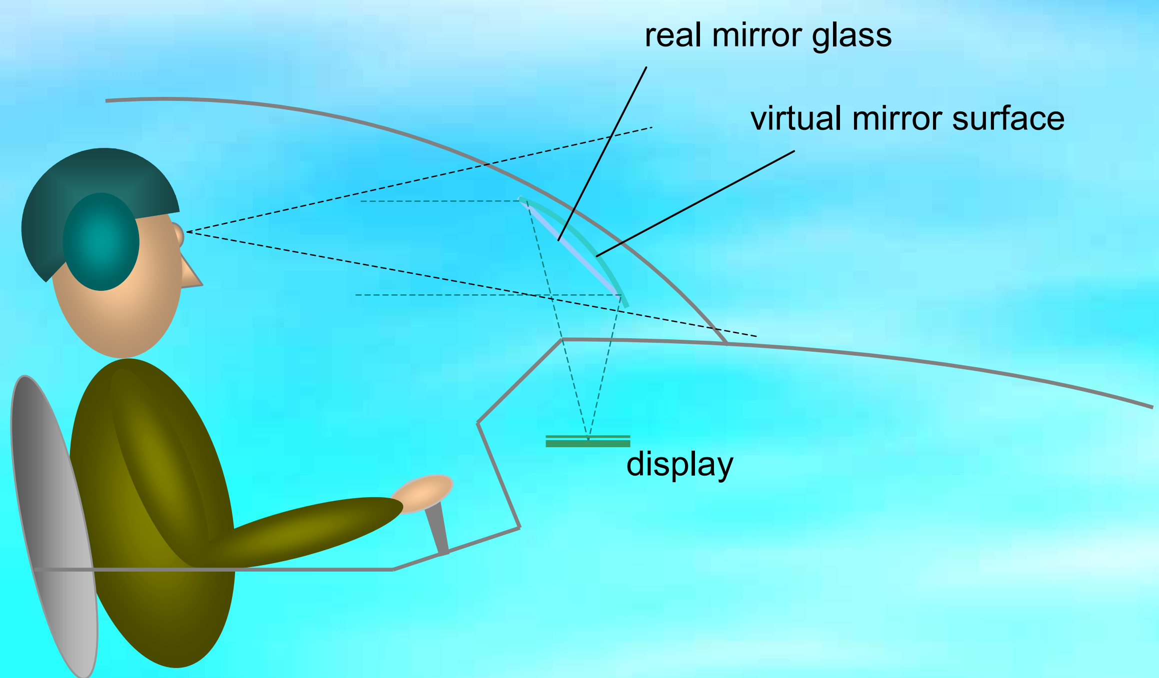
Holographic optics

Holographic optical elements (HOE)

headup display mirror (**THALES OPTICS**)

- Holographic patterns cannot only represent images, but also optical elements like lenses and mirrors. So called **volume holograms**, recording a wavefront in a thick film layer (several wavelengths thick) exhibit even more interesting properties.
- Usually such holograms are of course index holograms. The pattern after development is represented in **zones of different refraction index**.
- Volume holograms can be transparent to ordinary light and show their special behavior for **light of a certain wavelength only, coming in at a certain angle only** (constructive interference here has to comply with level and vertical patterns concurrently, which leaves only a few results).

Headup Displays (HUD)



civil HUD

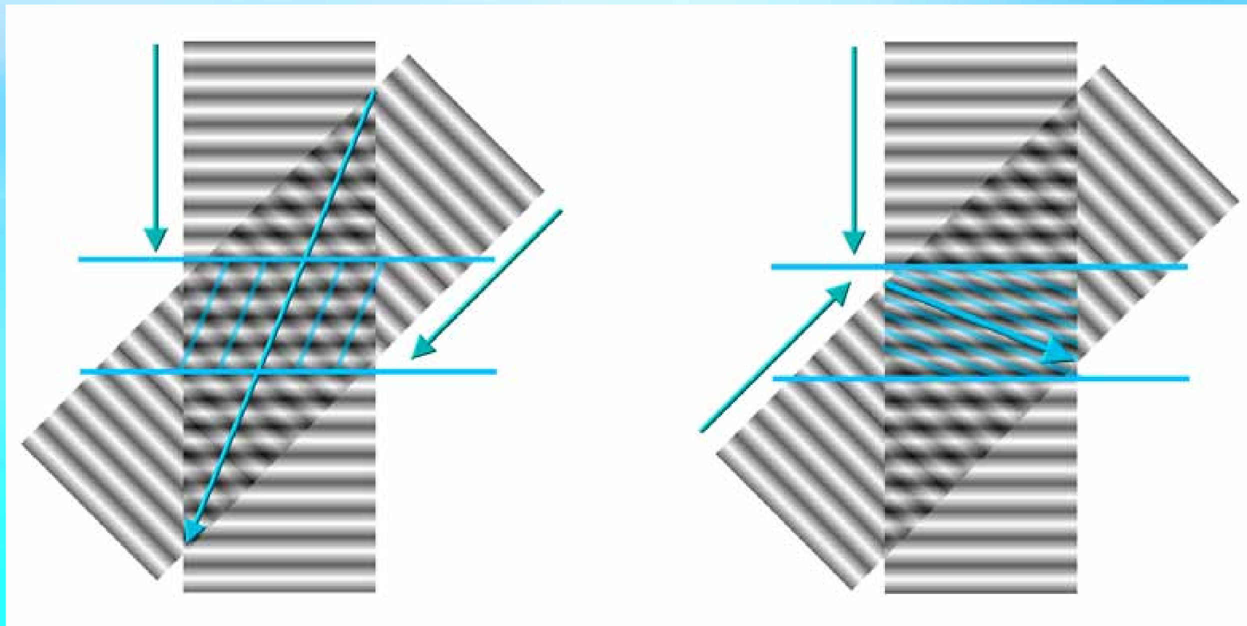
Headup display (HUD) in an airplane (principle)

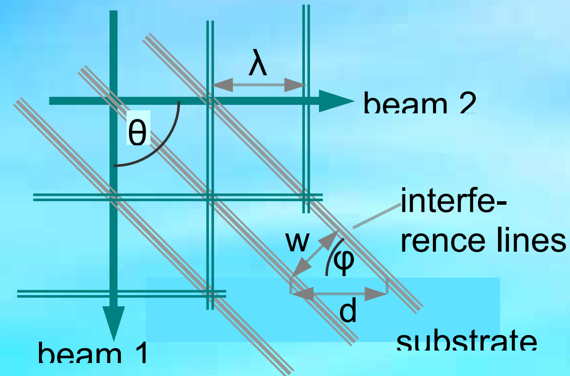
- Headup displays have been used in military aircraft **since 30 years**.
- Since a few years, they are slowly entering civil aviation as well.
- **No head tracking needed** because of angle invariance at infinity !!

Photos: THALES OPTICS

F-16 HUD

Volume gratings - construction





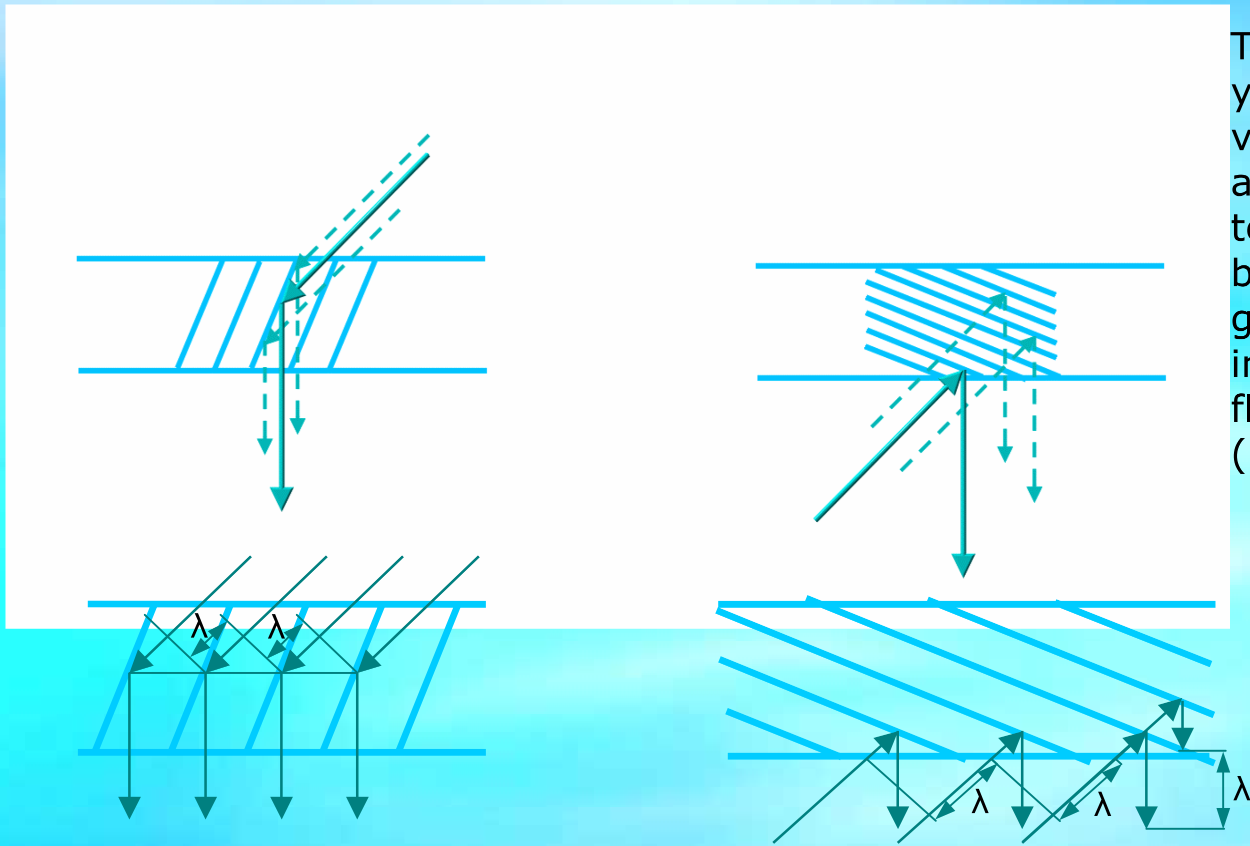
Resolution formulas:

$$w = \frac{\lambda}{2\ \sin\frac{\theta}{2}}$$

$$d = \frac{\lambda}{2\ \sin\varphi\ \sin\frac{\theta}{2}}$$

- A volume hologram contains the interference pattern of light waves as regions of different gray level or refraction index. Note that the light fronts are not standing, so the **interference patterns will travel** in a direction being just the vector average of the light front directions (blue arrows).
- Note that black and white in this picture mean negative and positive **maxima** of the sine waves, both exposing the film. Hence, straight lines are resulting (blue).
- Beams coming from the same side will form a **refractive** hologram, while beams coming from opposite sides will form a **reflective** hologram. It's actually the same thing happening (turn both beams and it's obvious).

Volume gratings - reconstruction



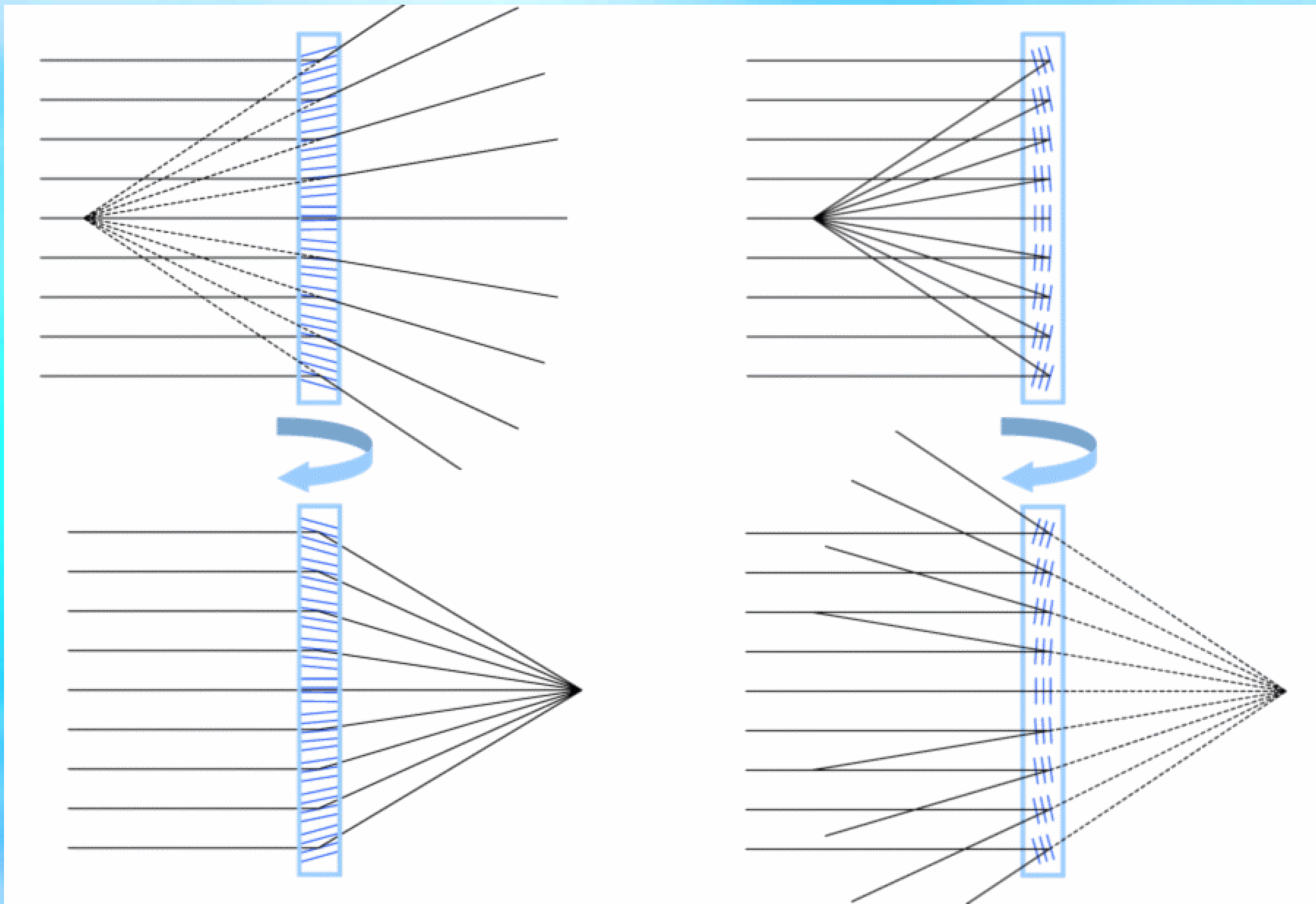
The resolution formulas also yield the pattern size and inverting them gives beam angles (beams generate pattern, pattern generates beams, the principle of holography). Simply setting nλ instead of λ, we get all reflected and diffracted modes (**Bragg's Law**):

$$d = \frac{n \ \lambda}{2 \ \sin \theta}$$

$$n \ \lambda = 2 \ d \sin \theta$$

- The 3D diffraction grating resulting, causes light to be refracted or reflected in the same angular proportions as the constructing beams. With **index** holograms, the effects of multiple layers add up (dashed lines).
- With sufficient thickness of the film, there is only one possibility for constructive interference, for **direction and wavelength** of the output as well as the input beam. Photographic holograms nearly always are several wavelengths thick, so they expose properties of a volume hologram. So even white light illumination can be possible.

Basic lens and mirror equivalents



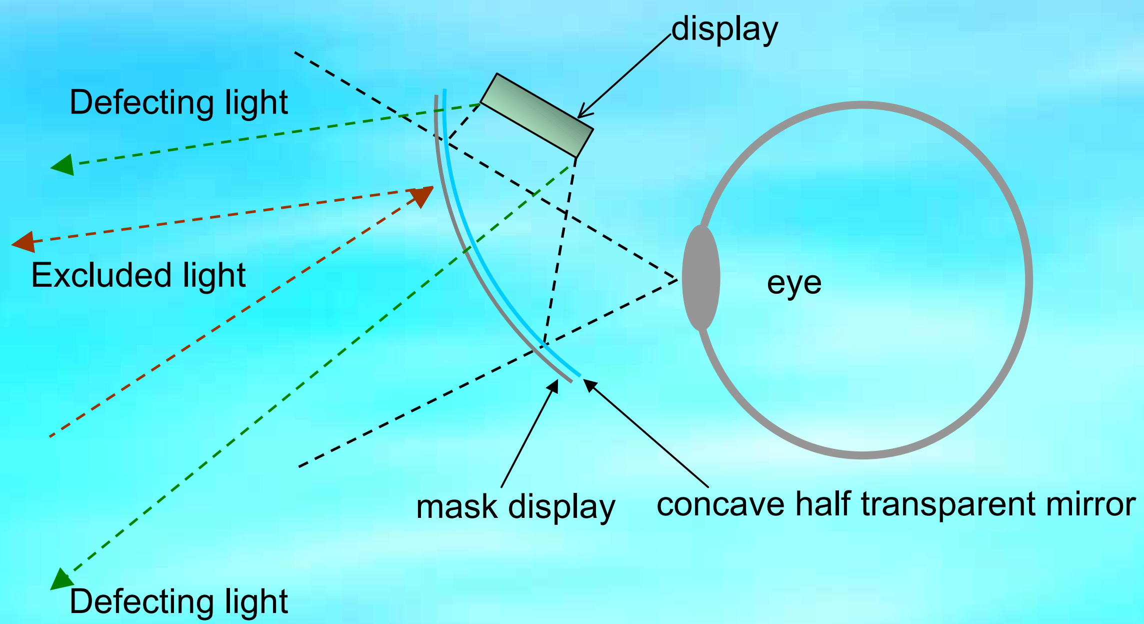
Flipping HOE's changes between diverting and collecting behavior.

Hologram effectiveness

Maximum diffraction effectiveness of various hologram types (%)						
Thickness	thin		thick			
Modus	transmission				reflection	
Type	amplitude	phase	amplitude	phase	amplitude	phase
Effectiveness	**6.25**	**33.9**	**3.7**	**100**	**7.2**	**100**

Source: Reinert: Holografie-Medium der Zukunft, 1986

Half transparent mirrors (combiners) for near eye displays



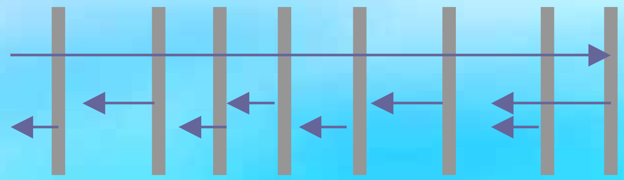
Simple half transparent silver coatings would just be primitive and inadequate.

Sophisticated combiner mirror types are:

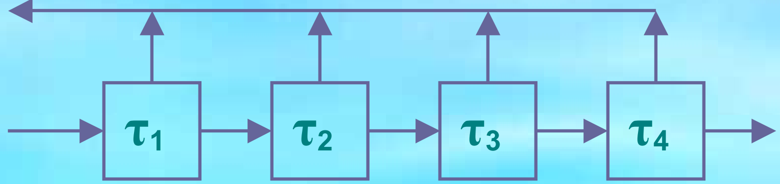
- directionally selective (e.g. **holographic**) mirrors
- spectrally selective mirrors (**dichroic** or holographic mirrors)

Dichroic filters/mirrors are produced by deploying **very thin coatings** (usually 20...40 layers) on glass. These filters work with interference of multiple partial reflections and can have a very narrow bandwidth, down to about 1 nm.

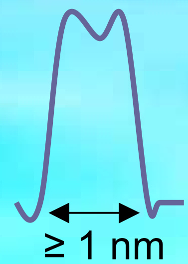
Dichroic mirrors



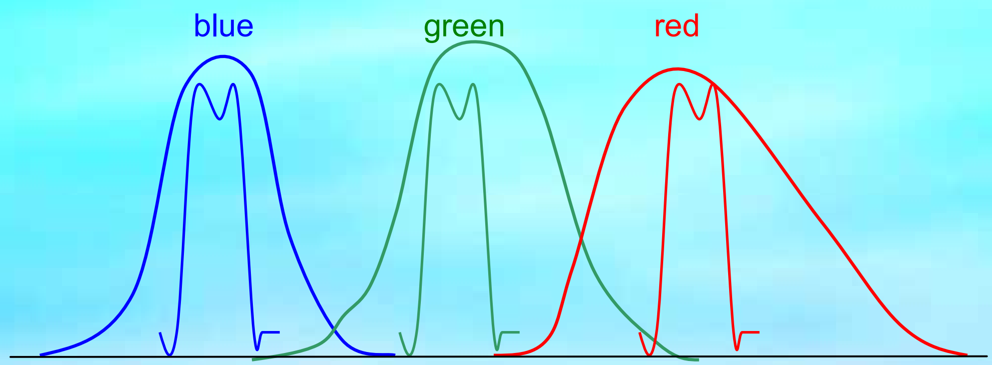
Fine tuned vacuum deployed layers of different refraction index, each reflecting part of the light.



Simplified filter equivalent (multiple back reflections excluded)



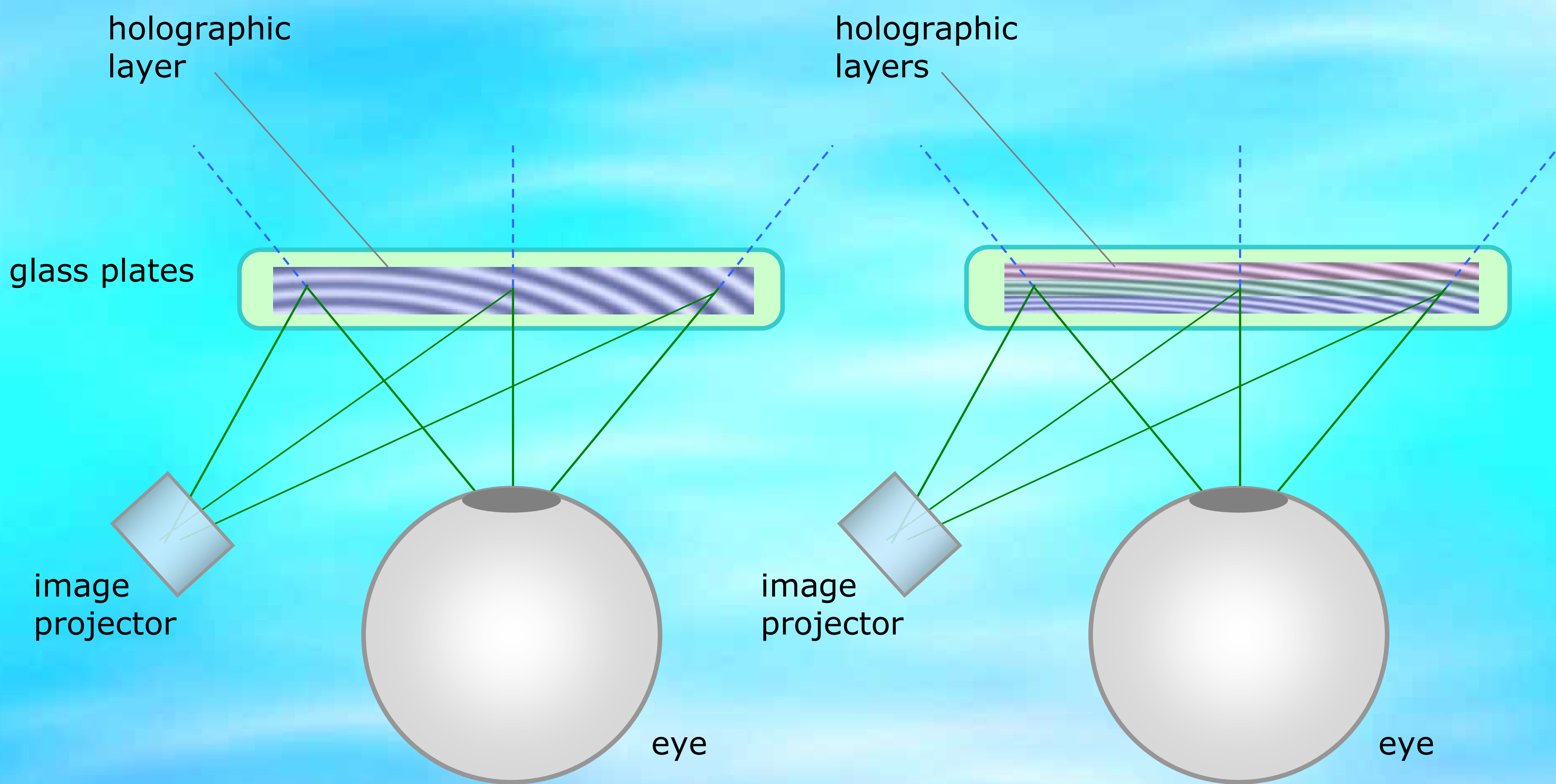
A typical dichroic filter curve



3 selective mirror bands vs. typical display emission curves

Dichroic filters/mirrors are produced by deploying very thin coatings (usually 20...40 layers) on glass. These filters can have a very narrow bandwidth, down to about 1 nm. They have extreme frequency selectivity but no directional component, unlike HOEs.

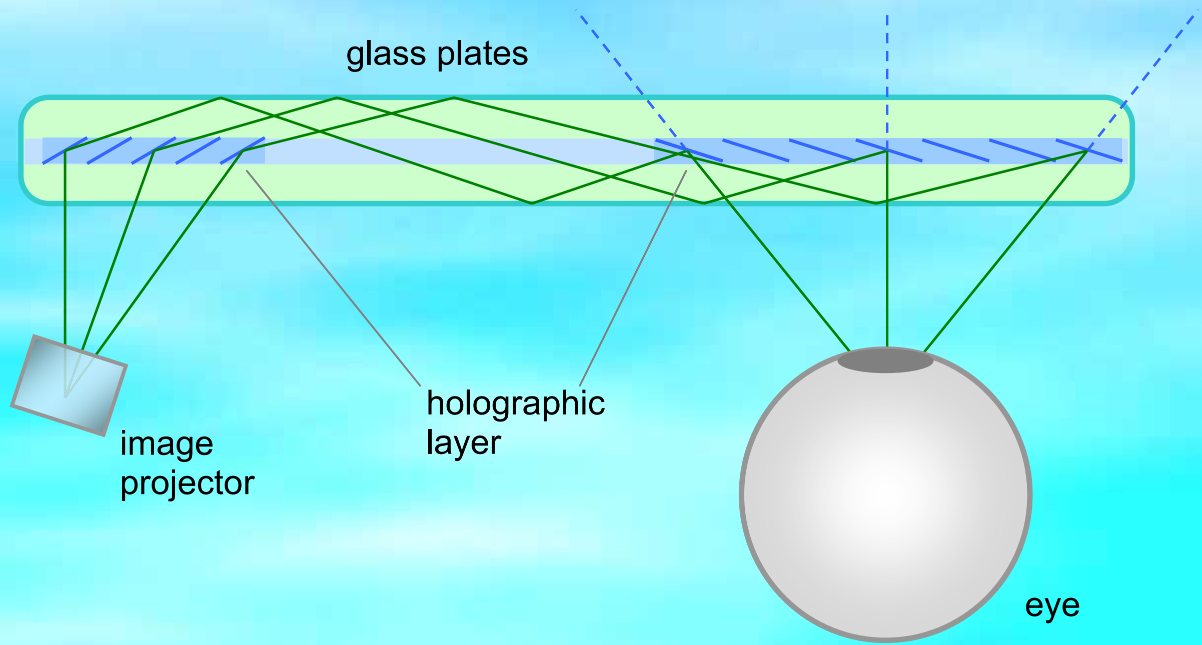
Basic holographic combiners

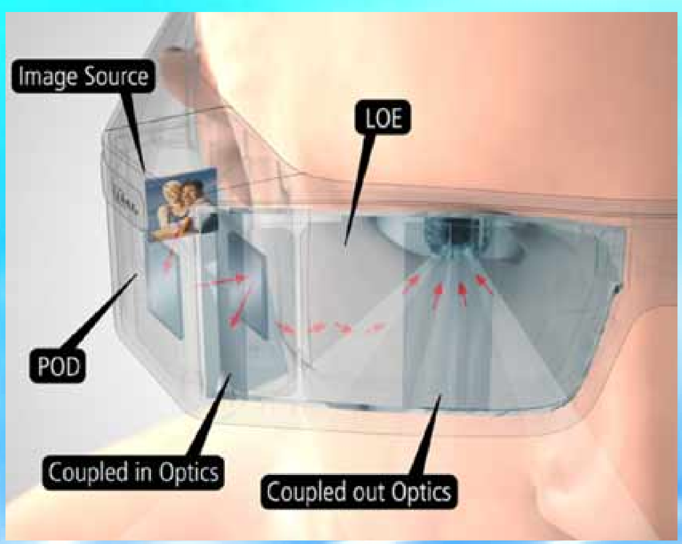


Monochrome (left) and 3-layered color version (right)

A more sophisticated holographic combiner*

- HOE's can be used to form very specialized mirror elements
- Here, a projector image is transformed into an extremely flat light bundle that is transported inside glass plates by total reflections
- A second HOE transforms the light bundle back into a concentric one





*Lumus Inc., www.lumus-optical.com

- Input and output beams may be shaped to almost any specifications
- Suited for Augmented Reality glasses with see-through capability
- Can be combined with laser sources (requires narrow bandwith sources anyway)
- The HOE's, usually consisting of gelatin, are well protected between glass and the assembly is kept simple (flat plates)
- The in-coupling element is relatively large, may cause obstructions in the field of view

Final remarks

Big Brother ante portas (or right inside)

- With everybody wearing cameras, anybody may be observed.
- Privacy will be a paramount issue.
- But a right to record one's own life has to be established.
- Copyright collides with the right to record our own life.
- Instead of DMCA for kindergarten stuff, we need privacy enforcement.
- Computers have become *mind extensions*.
- Enforcing communications for 'copyright' purposes is dangerous.
- Breaking into computers equals *thought control*.

"If privacy is outlawed, only outlaws will have privacy"

Phil Zimmermann

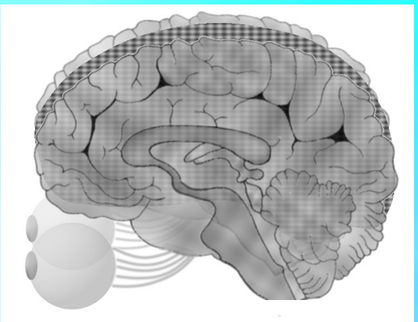
RESISTANCE IS FUTILE...

WE ARE BORG !

PC → **AR** → **Matrix**

1980 **2020** **2050...**

Picture. Microvision



Full-sized brain chip

2050 (*not 2525*)

- single chips will have a capacity like our brain
- but also be million times faster
- and will be implantable ...

Conclusion:

It can be done !

...and how do we get there ?

Advanced optics

MAJOR JOINT PROJECTS

MICRO MECHANICS

KILLER applications

DISPLAY TECHNOLOGY

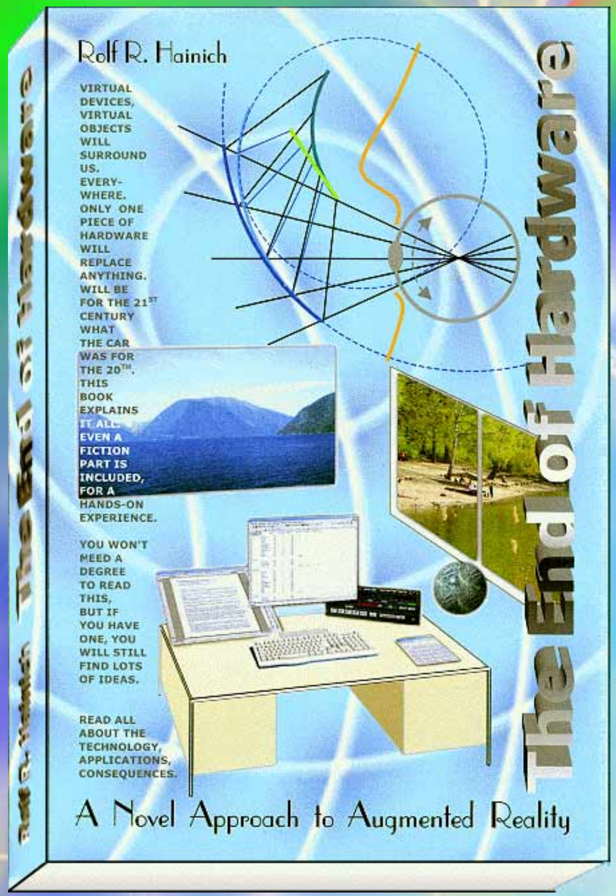
MICRO SYSTEM TECHNOLOGY

...and story-telling.


Thank You!

Rolf R. Hainich

Some materials presented originate from the Book

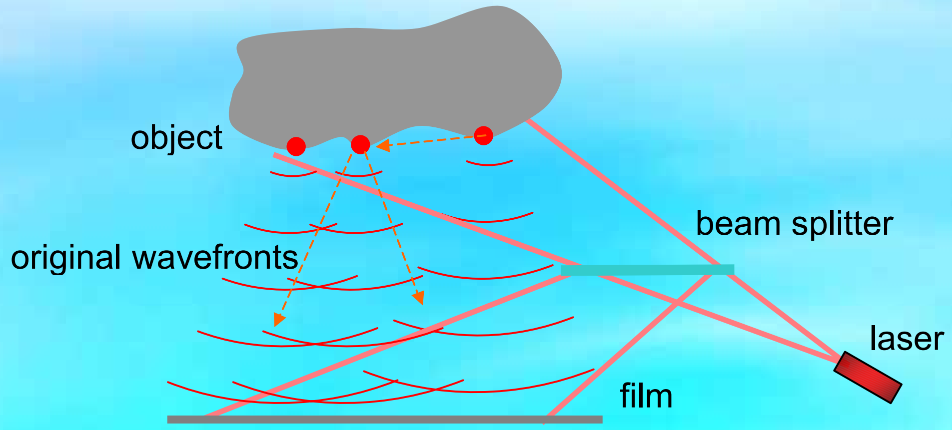


(3rd edition due Christmas '08)
and from it's website
http://www.theendofhardware.com

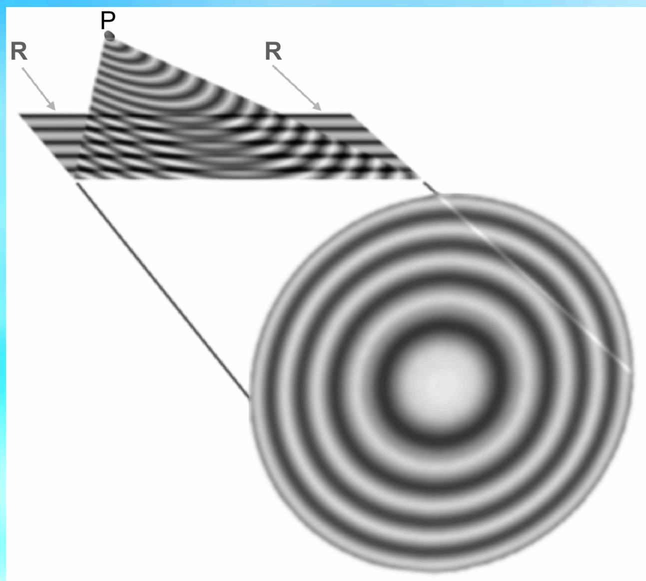
Appendix

notes and details

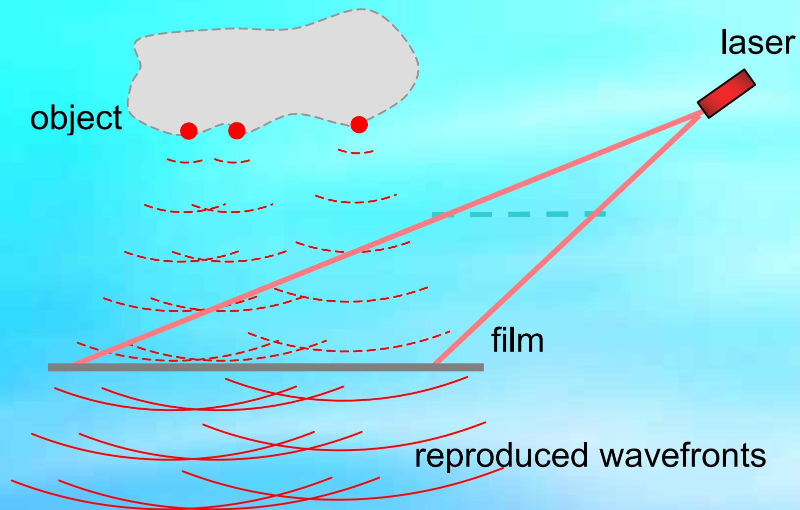
Holography basics



Simplified hologram photography assembly



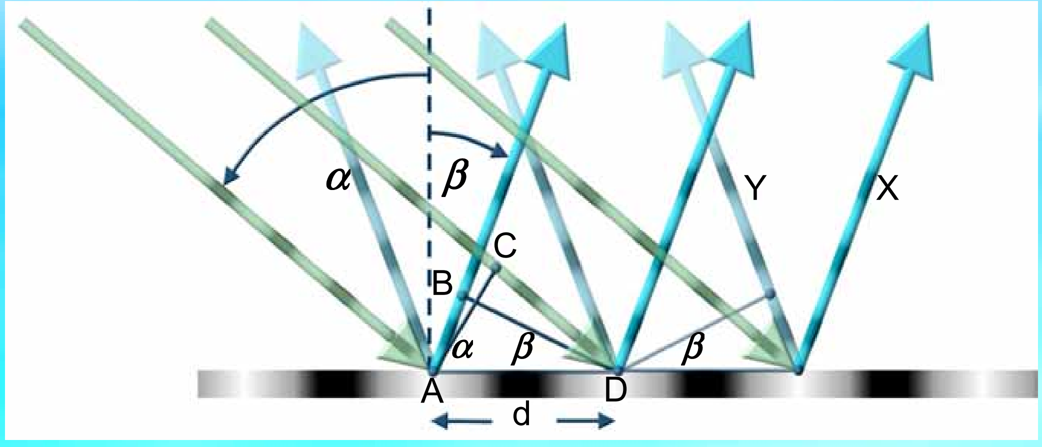
As simple as it gets: Concentric wavefronts from single pixels result in 'zone plate' fringe patterns, these in turn result in concentric wavefronts (virtual pixels) when illuminated.



⇨ Many 'zone plate' patterns superimposed can form a picture.

Reproduction: A laser of the same wavelength and position reproduces the reference beam and illuminates the holographic pattern on the developed film, the hologram pattern converts it into the same wavefronts as if the object points were still there.

The Grating equation



With a **reflective hologram** as depicted above, it can easily be seen that '**constructive interference**' of waves from the different wave origins (the bright parts of the pattern) occurs when

$$\underline{CD} \pm \underline{AB} = n\,\lambda$$

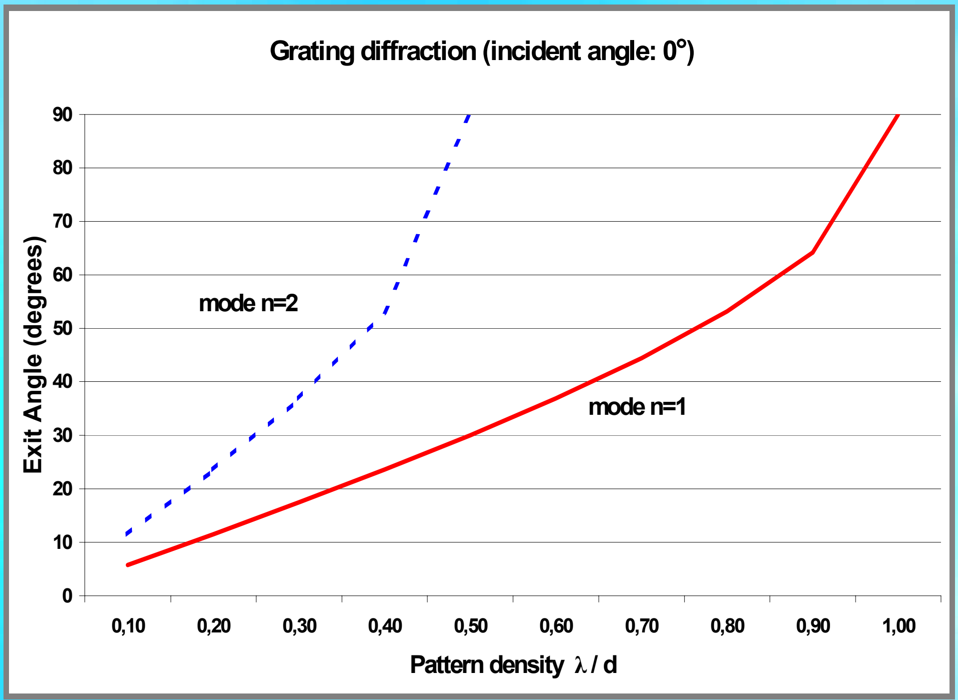
(the underlinings denote distances). So actually two 'conjugated' departing wavefronts X and Y are generated.
Hence, $n\,\lambda = d \sin \alpha \pm d \sin \beta$, the '**grating equation**'

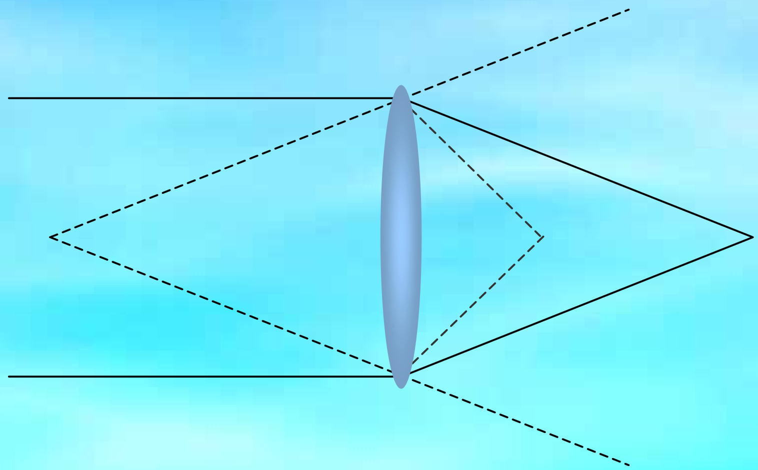
$$\boldsymbol{\beta = \pm \arcsin (n\,\lambda / d - \sin \alpha)}$$

$$\boldsymbol{\beta = f\,(d)}$$

The ambiguous zone plate

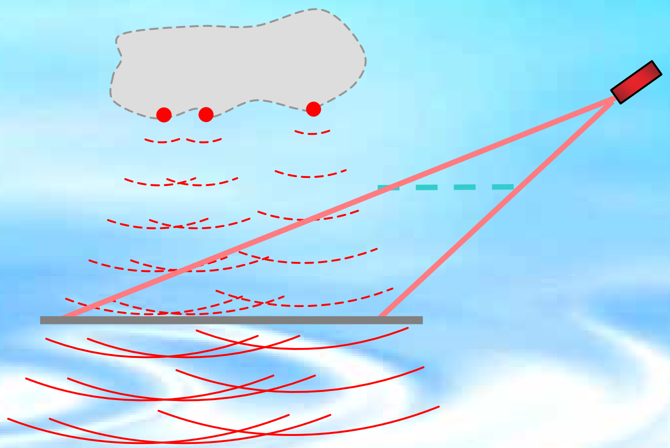
- **Incident angles around zero deliver several unwanted modes (n>1)**





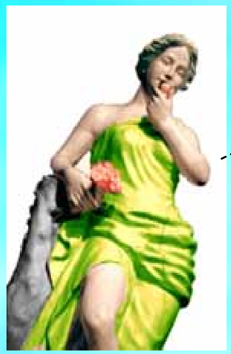
- Exit angles are ambiguous (+ or -)
- A plain vanilla zone plate shows ghost images and is collecting and diverting lens in one

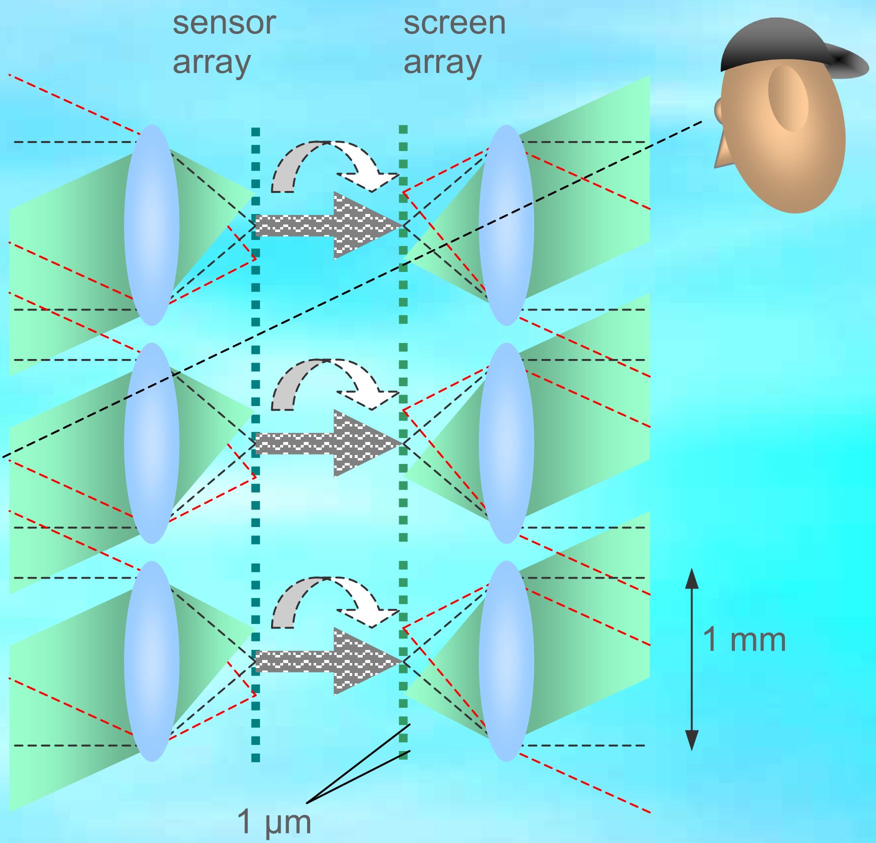
⇨ For practical applications it is better to use **slanted** setups (like in our initial example), canceling unwanted beams out into uncritical areas.



The other way round: light fields

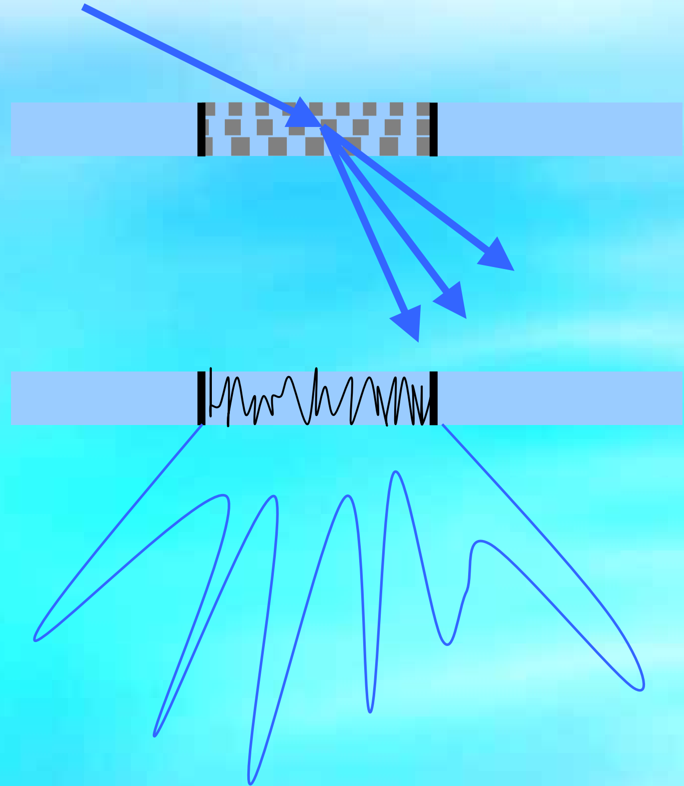
- Arrays of micro cameras could **record all light beams** hitting a recording window: angle, position and intensity.
- Each camera **converts angle to position** on its image sensor.
- An equivalent array of micro projectors could **reproduce all beams** with high accuracy.
- Signal transmission could use raw data (n^4 pixels!), compressed light field data, synthetic holographic data.



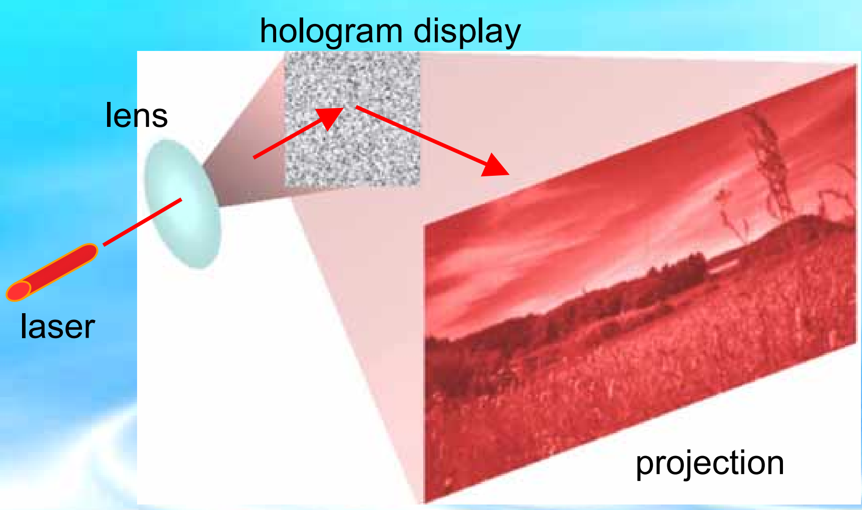


- Each camera/projector pair acts like a camera obscura, hence a small hole, and **many small pinholes are simply forming a window**.
- Physically, the approach is possible (1mm camera size, 1 µm pixel size are in the achievable range and well fit for large screens).

Holographic light field rendering (Fourier holograms)

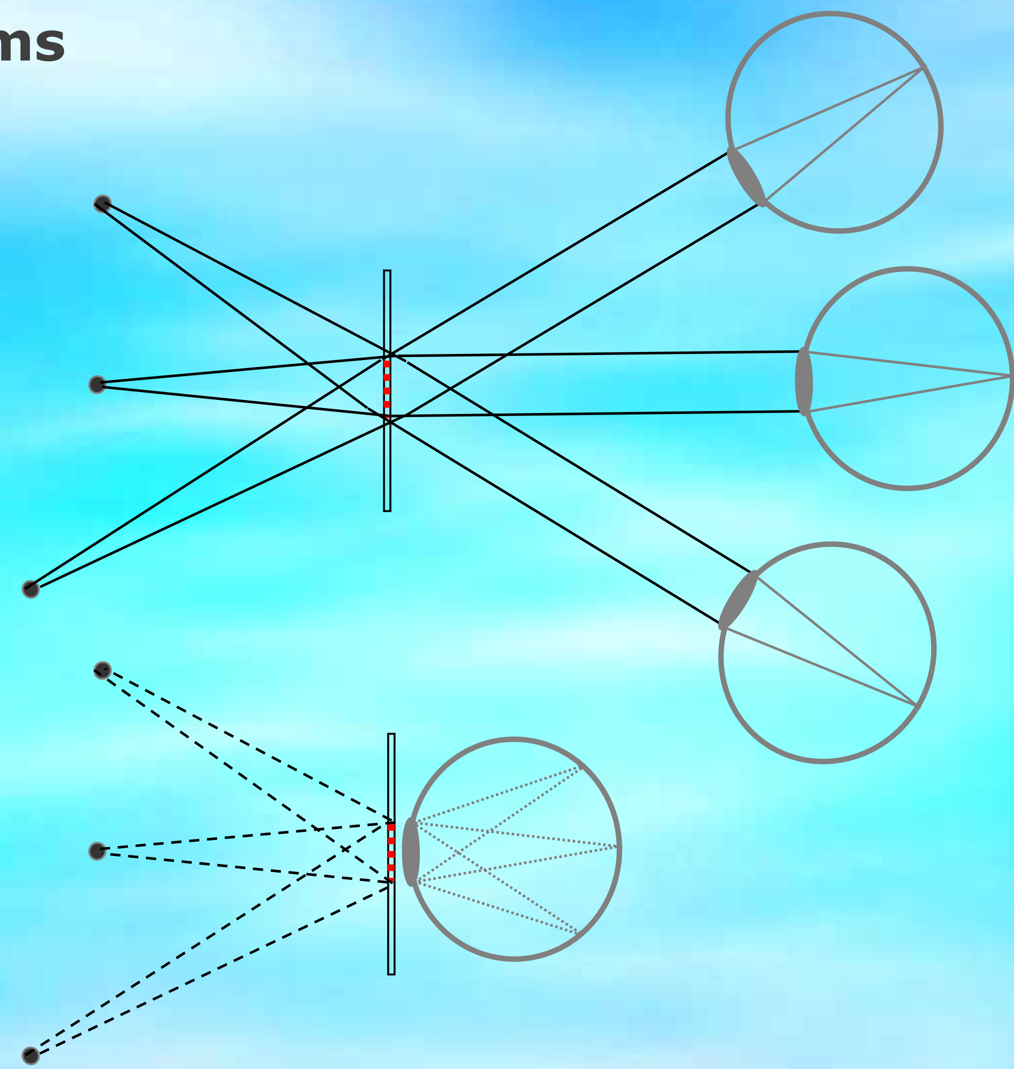


- A laser beam hitting a line pattern at an angle is deflected according to the pattern frequency (^grating equation).
- Overlaying several patterns of different frequencies results in several exit beams at different angles.
- An entire line spectrum results in a complete angle/intensity distribution, hence a light field. The angular distribution equals the **Fourier transform** of this spectrum.
- A display stripe containing such a spectrum is the perfect equivalent of a micro lens with micro display stripes behind it. Simplified holographic displays have been built this way (Lucente 1994).



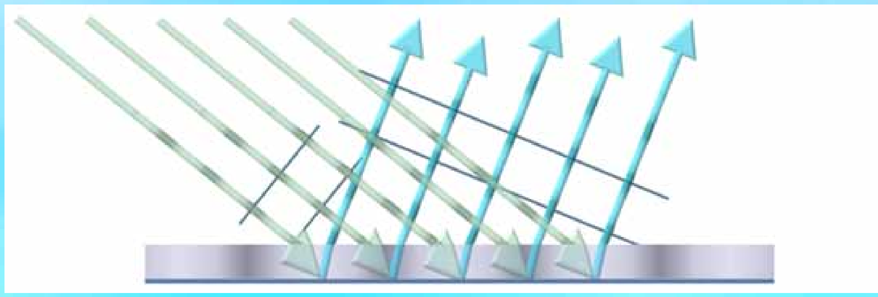
- Principle of an holography based projection display (Light Blue Optics), generating 2D projection pictures on a remote screen.
- A **2D Fourier transform** renders an angle/intensity pattern, i.e. a light field causing the projected image. With the small angles involved, an LCOS display of 13 µm pixel size is already adequate here.

Keyhole Holograms



- The same hologram sniplet has to deliver the information for many viewing angles at once, even for the entire image, as it can be regarded from any angle (within the eye aperture range).
- This implies that the entire scene can be seen through an arbitrary small area of the hologram ('**keyhole hologram**').

Index holograms



- Simple gray tone holograms will inevitably absorb *at least* 50% of the light.
- Specially developed photo emulsions and certain plastic films can record light as **variations of refraction index**.
- Index variations do not absorb light, so these holograms are a lot more efficient.
- As these index variations also change the speed, and therefore shift the phase of light they can do the same things as gray value patterns.

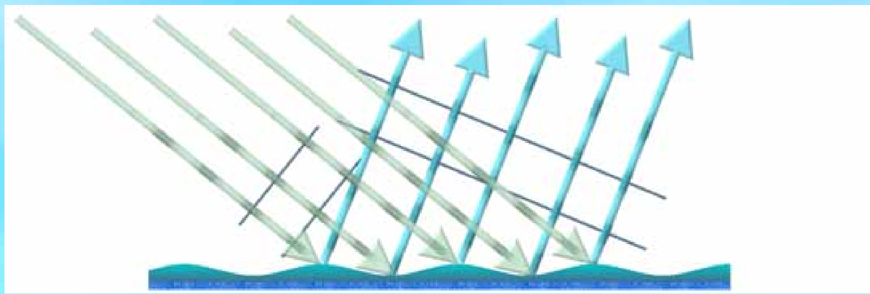
Simply replace 'black' by a phase shift of λ/2

- Index holograms can be thicker than a wavelength, allowing for 3-dimensional patterns that can be selective to certain incident angles and colors and define exit angles with an effectiveness of nearly 100% (more later).

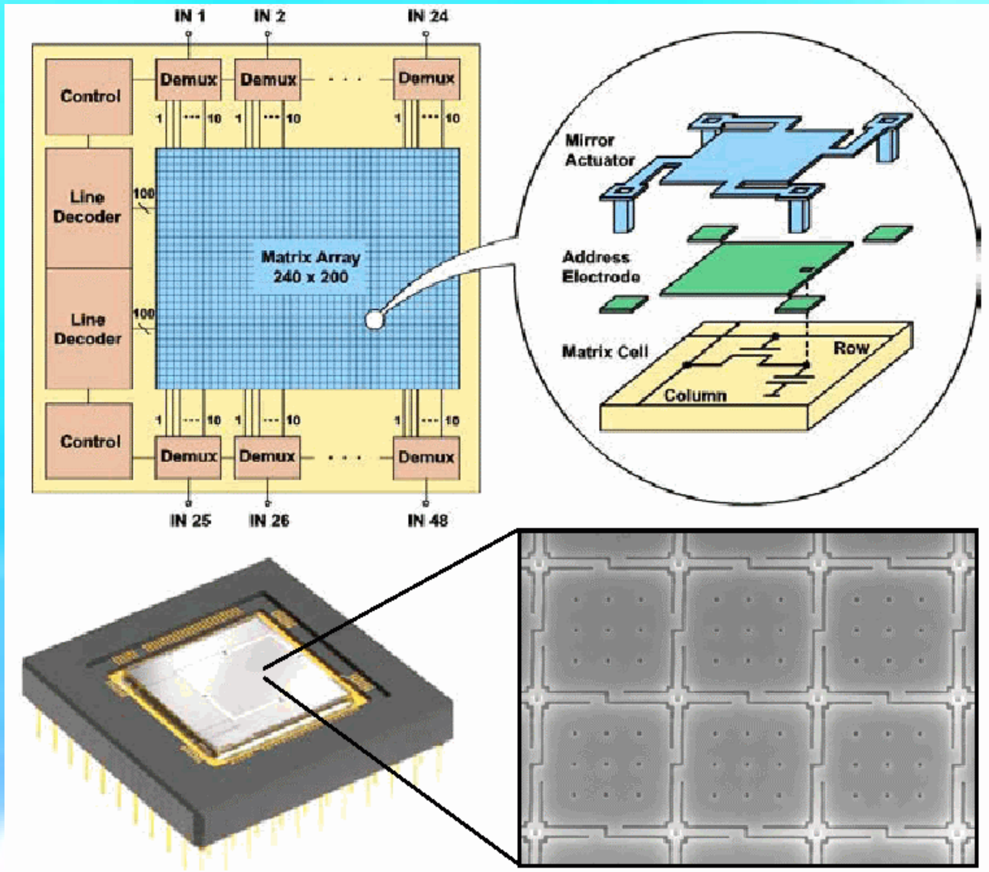
Most display holograms are 'thick' index holograms

(Photographic films usually are thicker than a wavelength anyway)

Embossed holograms



- Phase shifts can also be achieved by engravements in a reflective surface.
- Light sensitive lacquer can provide such structures in a photographic way.
- **Micro mechanical chips** can be used to show dynamic embossed holograms.

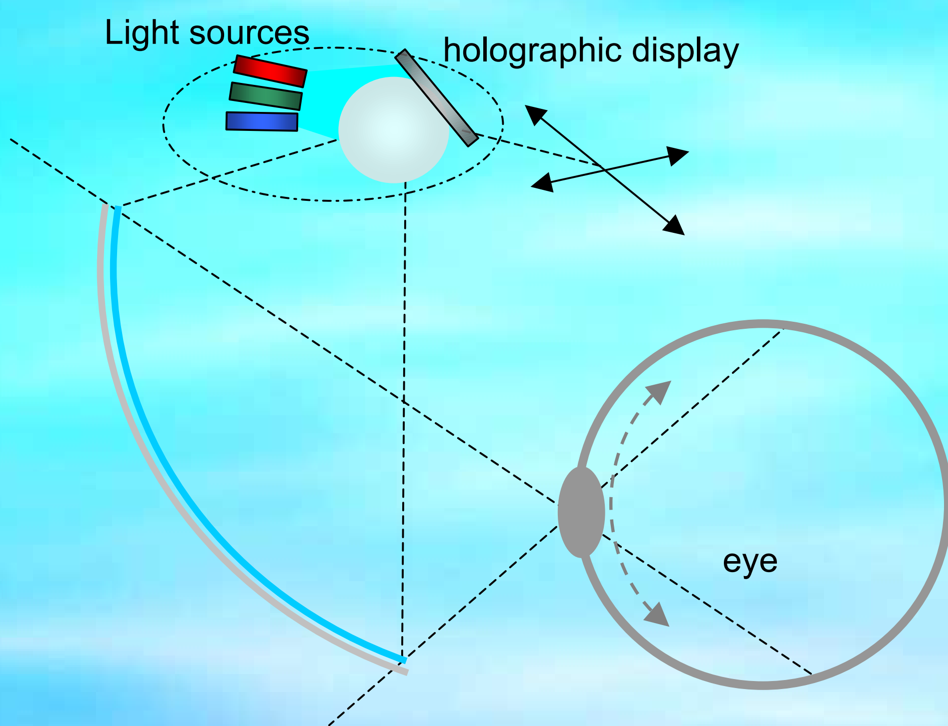


Piston type moving micro mirror display (FhG-IPMS)

Micro holgram / light field displays ?

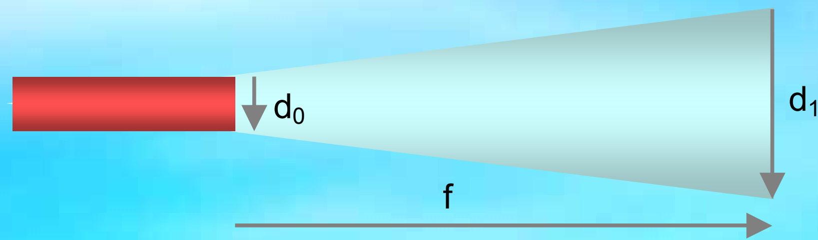
Piston displays or micro lens arrays may enable holographic or light field characteristics.

Dynamic focusing or special optical constructions could be potential applications.



Raw scheme with synthetic holography display
(imaginary pixel positions visualized by sphere)

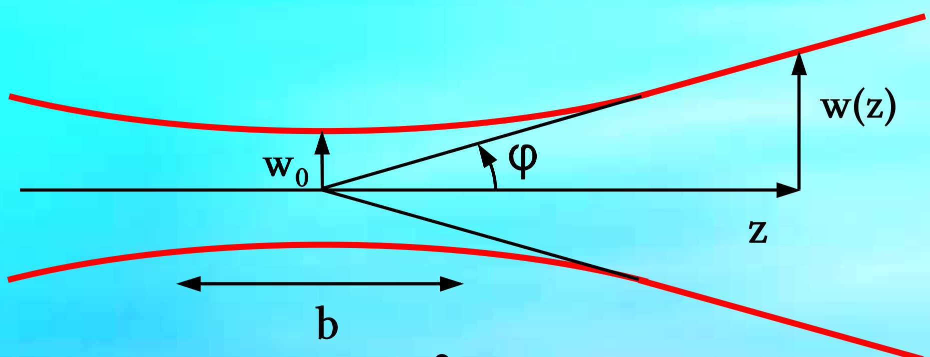
Laser beam deviation



Deviation of a laser beam with source diameter d_0

Electromagnetic field equation (real part):

$$I(r,z) = I_0\left(\frac{w_0}{w(z)}\right)\exp\left(\frac{-2r^2}{w^2(z)}\right)$$



$$b = \frac{2\pi\ w_0^2}{\lambda}$$

Rayleigh depth-of-field

$$w(z) = \frac{\pi\ w_0^2}{\lambda}$$

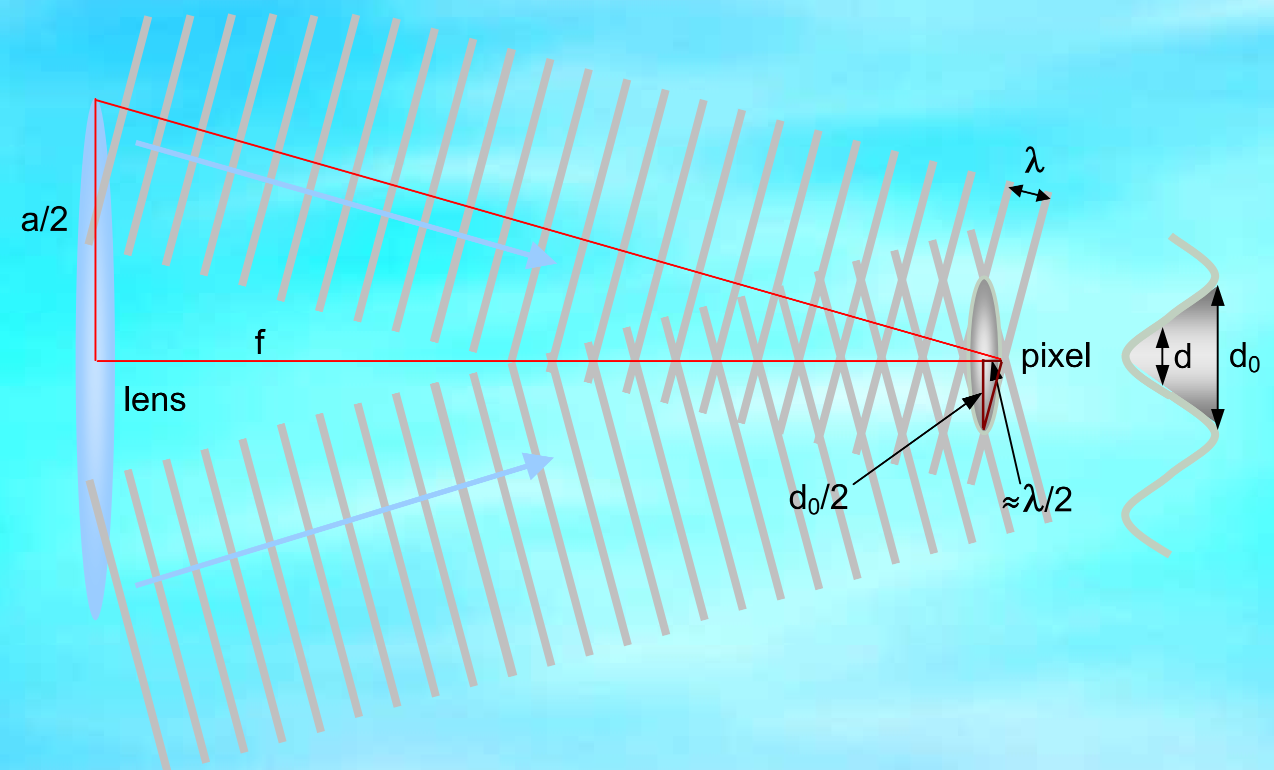
$$\varphi = \frac{\lambda}{\pi\ w_0}$$

Beam deviation angle

'Exact' solution: The Gaussian Beam
(edge amplitude:= $1/e$)

A simpler derivation, via lens resolution

- The resolution a lens can deliver, follows very simply from the actual pixel sizes light wavefronts from different parts of the lens are able to form:

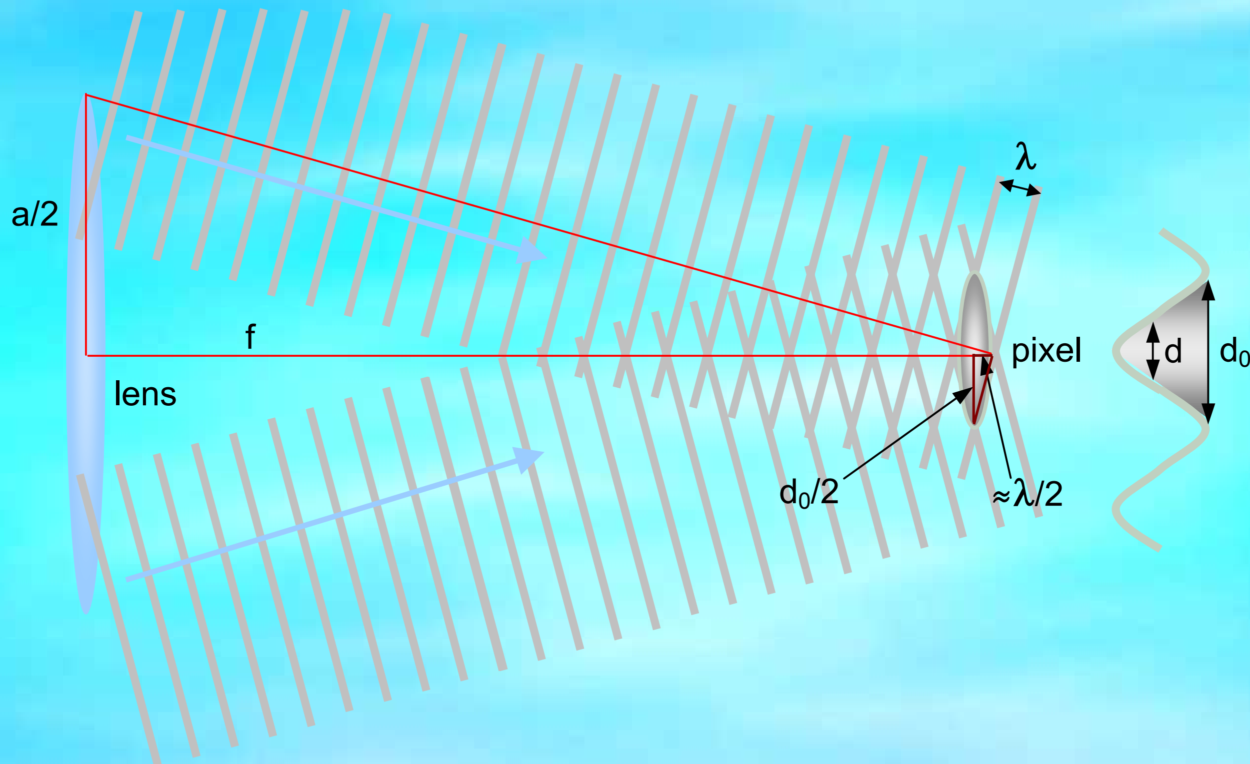


- For small angles *(x ≈ tan x)*, we simply get $\frac{a}{2} / f \approx \frac{\lambda}{2} / \frac{d_0}{2}$, hence **$d_0 \approx 2\lambda f/a$**.
- As d_0 only denotes the rims of a sinusoidal intensity distribution, the actual pixel diameter is smaller, depending on the contrast values we require, e.g.

$$d \approx \lambda f/a$$

A simpler derivation, via lens resolution

- The resolution a lens can deliver, follows very simply from the actual pixel sizes light wavefronts from different parts of the lens are able to form:

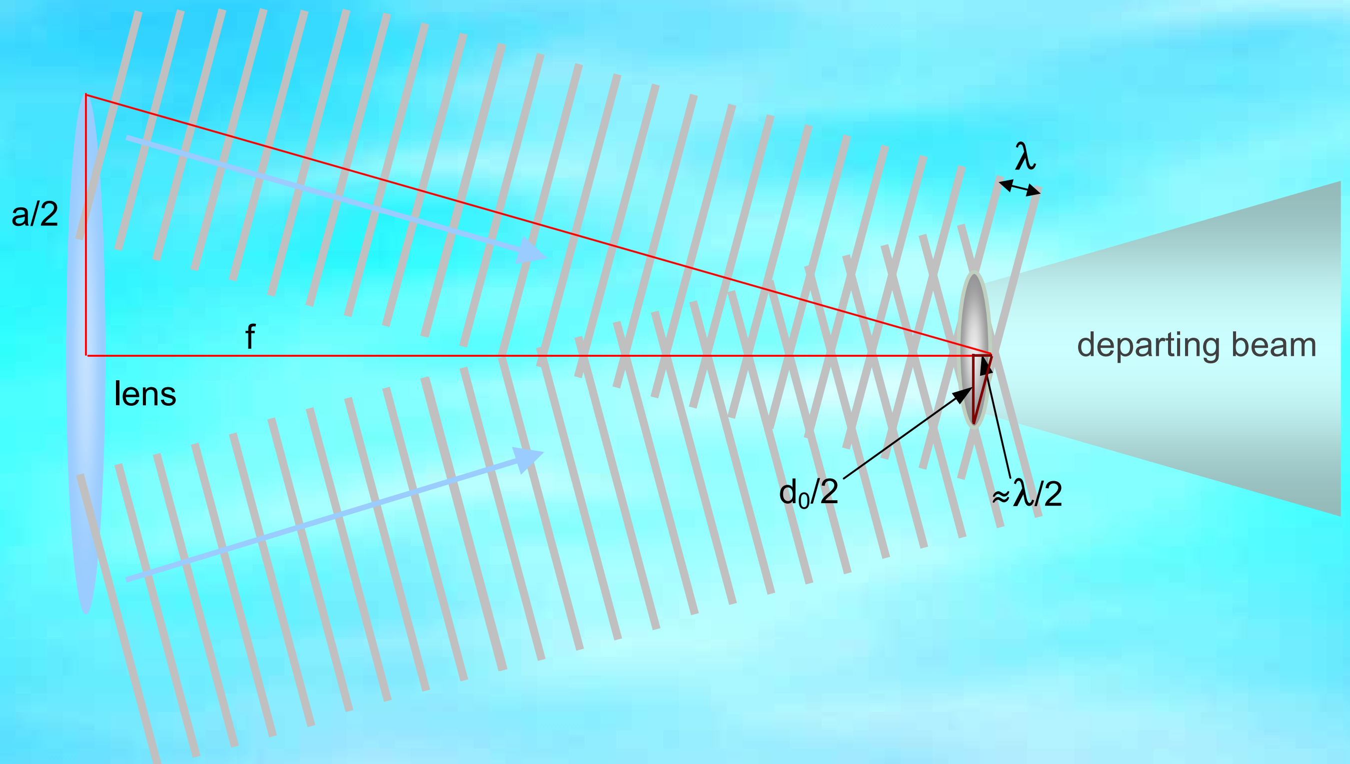


- We can also use this formula to derive that it would take a lens or mirror almost a mile wide to see the remainders of lunar missions on the moon,
- or that an HDTV camera with optics could fit into a 1/8"(3mm) cube,
- or that the human eye can see crisp to 1 arcmin of angular resolution.

$$\mathbf{d \approx \lambda\, f/a}$$

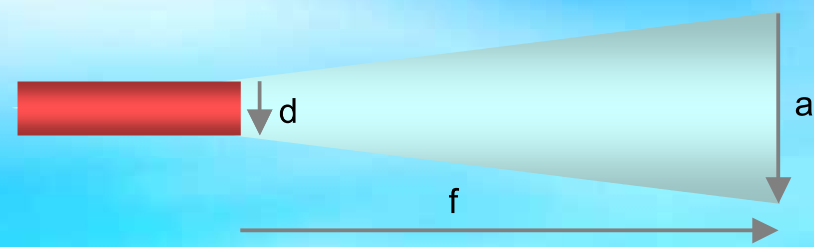
A simpler derivation, via lens resolution

- The resolution a lens can deliver, follows very simply from the actual pixel sizes light wavefronts from different parts of the lens are able to form:



The focus point can also be interpreted as source of a typical laser beam

Results:

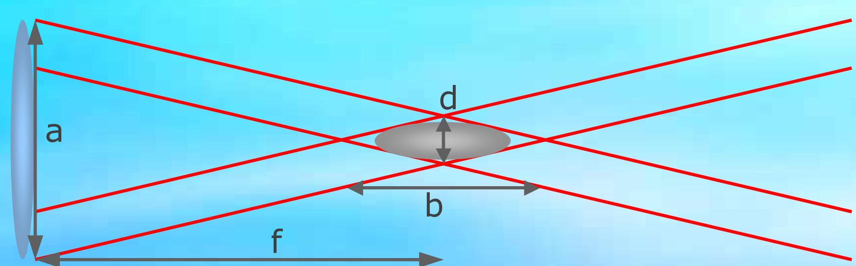


Beam deviation: $a \approx \lambda f/d$

The Gaussian beam solution would be $a \approx \frac{4}{\pi}\lambda\, f/d$, a matter of contrast definition !

Beam deviation angle: $a/f \approx 2\varphi \approx \lambda/d$

The Gaussian beam solution as shown above, would have been $2\varphi \approx \frac{4}{\pi}\lambda/d$



Depth of field (max.):

$b \approx 2d\, f/a \approx 2\lambda f^2/a^2$

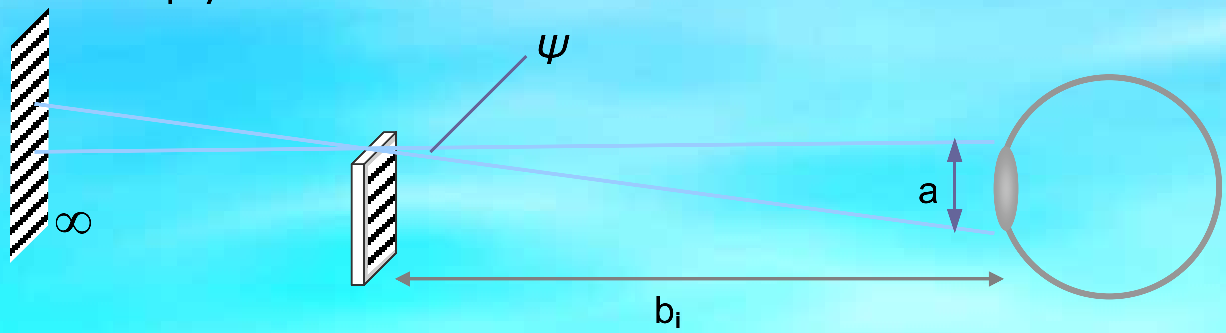
Gauss/Rayleigh: $b \approx \frac{8}{\pi}\lambda\, f^2/a^2$

In case of limited camera resolution : $b \approx 2\lambda f^2/(a_o a)$ for $a_o < a$

where a_o is the aperture corresponding to this resolution (for the eye: $a_o \approx 2$mm).

Depth of field to infinity

- In line with our former calculations, a closest distance b_i, for a depth of field from b_i to infinity we could simply derive as follows:



$b_i = a/\Psi$ $\qquad\qquad$ $\Psi = \lambda / a_o$

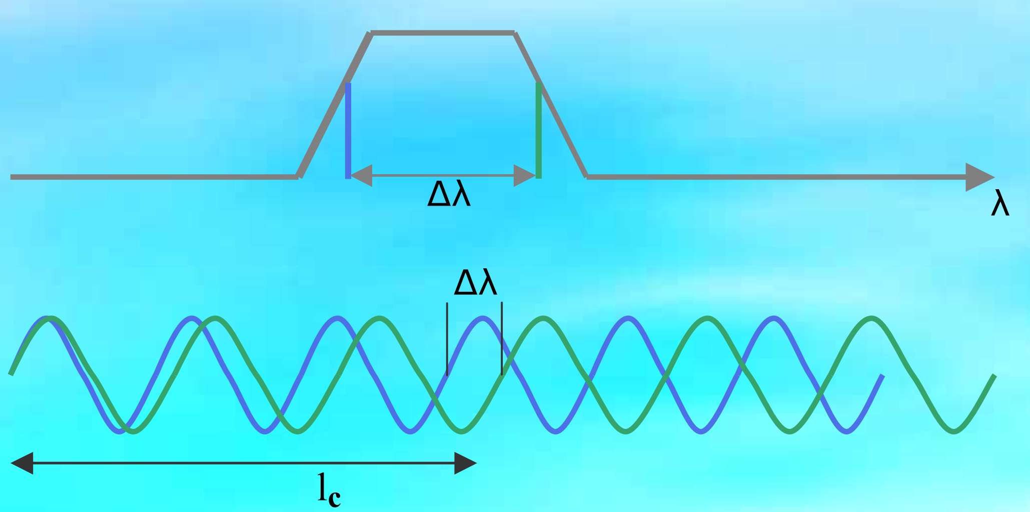
- Assume eye focusing to distance b_i. Towards infinity, the rays should not deviate by more than an angle Ψ, that should equal b_i/a and also the eye resolution given by λ/a_o (1 arcmin at best). As the same deviation can be allowed before b_i, a factor of 2 has to be introduced for the full depth of field:

$$\mathbf{b_i \approx (a_o a)/2\,\lambda} \quad \text{if } a_o < a$$

$$\mathbf{b_i \approx a^2/2\,\lambda} \quad \text{otherwise}$$

- One solution would be a lens size of a=1mm, hence a field depth of $b_i \approx$1m to infinity, probably good enough for a basic light field recording, and an angular resolution of 2 arcmin, yielding ≈ 2000 pixels at 60 degrees image width.
- This could for example be implemented with somewhere between 4x4 and 16x16 standard resolution pinhole cameras, for a target resolution of 1..2x HDTV.

Illumination and coherence



$l_c \approx \lambda^2/\pi\Delta\lambda$ (for $\Delta\varphi = 360^0/\pi$)

$\Delta\lambda \approx \lambda^2/\pi l_c$

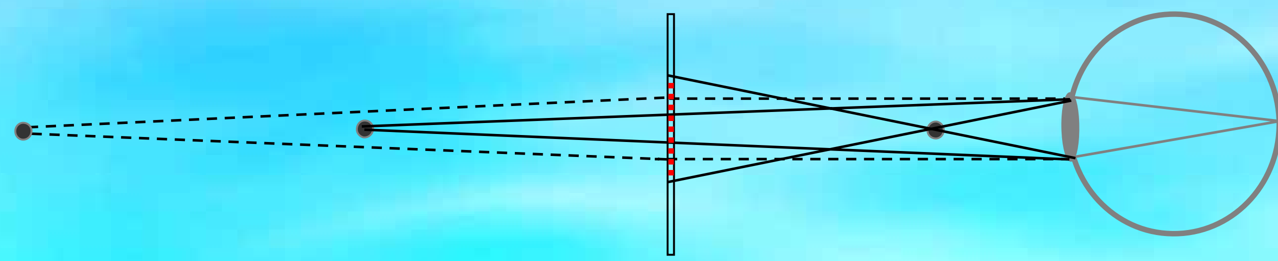
Δλ is the *bandwidth*, for convenience (some optics texts use this for *half* bandwidth)

- Consider a small light source with a bandwidth Δλ (we use wavelength instead of frequency, as usual with light). After a certain distance, two signals at the band edges will erase each other. Going further, the entire signal get irregular and lose its phase information.

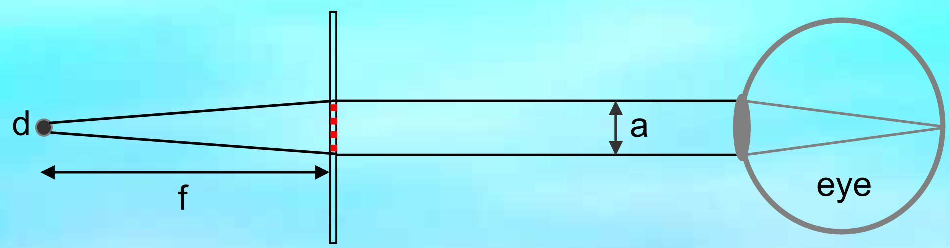
- We can define a coherence length l_c (as above) up to where the signal is sufficiently in phase. A usual, haphazard assumption is a phase difference of $360^0/\pi$. Anything using constructive interference will only work within approx. the coherence length.

- For hologram **photography**, the coherence length limits the useful distance range. Therefore huge coherence lengths are desirable (laser light).

For **hologram reconstruction**, we only need a coherence length just allowing constructive interference from the contributing fringes.

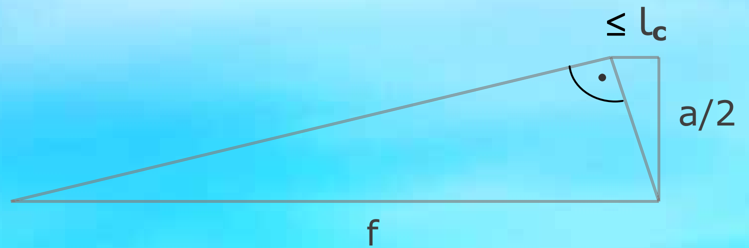


- A certain image pixel (d) can only be represented by an area, actually a tiny zone plate. In case of a pixel at infinity, this zone plate cannot be bigger than the pupil. For nearer pixels, it becomes smaller, and for virtual image pixels before the hologram plane it can also be bigger.



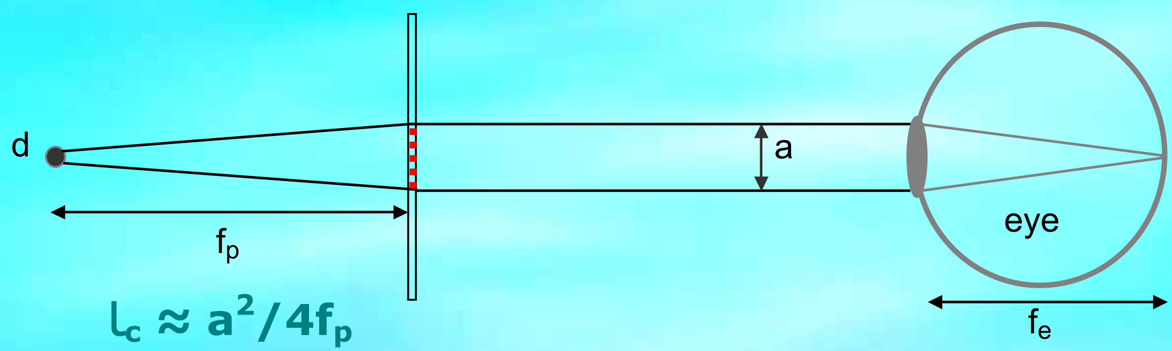
- For general considerations we can simply assume the contributing fringe pattern or 'zone plate' to be just as big as the pupil

- Calculating the influence of timely coherence, hence we need the size of the fringe pattern forming a pixel, and the distance of the pixel from the fringe.



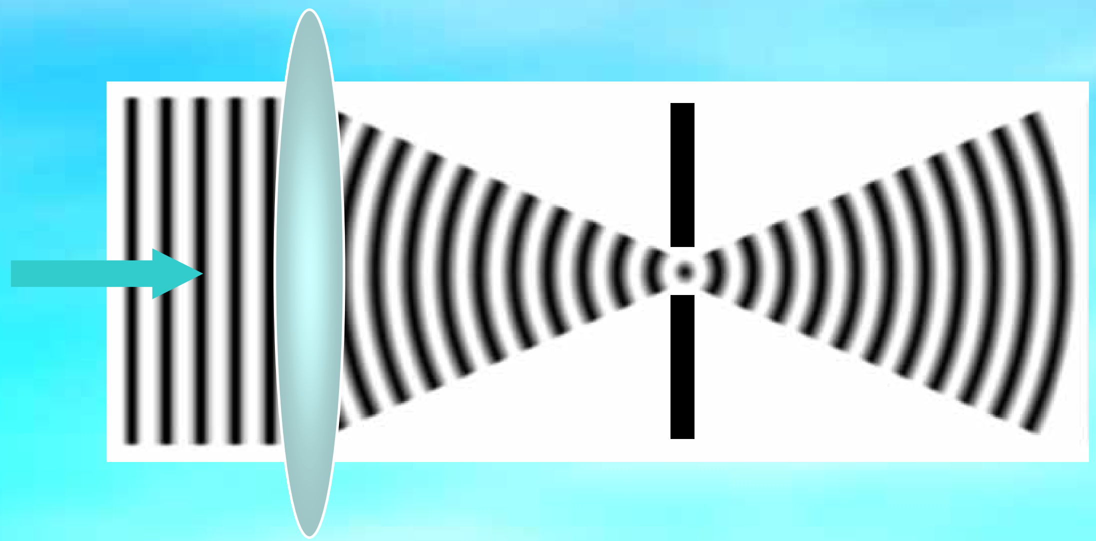
$$lc \Big/ \frac{a}{2} \approx \frac{a}{2} \Big/ f$$

$$l_c \approx a^2/4f$$

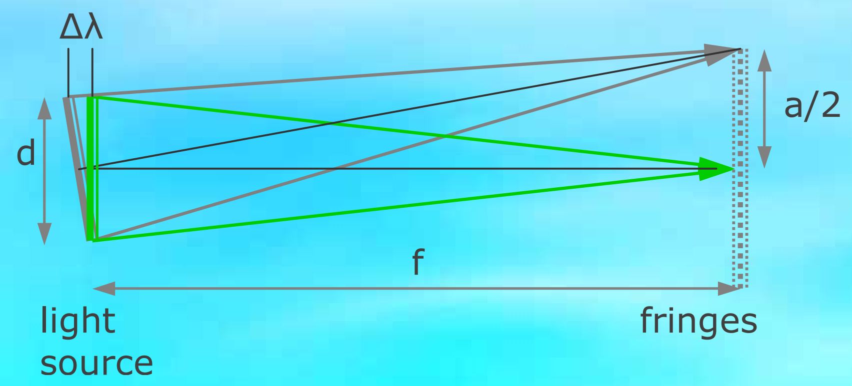


- The viewer's eye has a lens that delays the inner part of the beam, there we have no problem. The differences occur at the source pixel. Hence, we take f= f_p.
- With f_p=200mm and a=2mm, we get $l_c \approx 5$ µm. With λ=0.5µm, **Δλ is 16 nm**.
- Hence, as any display hologram must define any pixel only within a pattern size as big as the viewer's eye aperture, a light source with e.g. 16 nm bandwidth whould be sufficiently coherent in many cases !

Spatial coherence



- A laser source delivers waves in phase for all of its surface. If we want to use a different source, such as an LED, any part of its surface emits its own light phase.
- A laser beam can be focused down to about wavelength. This defines a fully coherent wavefront as we require for good holography.
- A light source that cannot be focused this tight, is spatially less coherent. We could use a pinhole to enforce coherence, but we may lose a lot of light this way.
- What remains, defining a measure for spatial coherence and calculating how spatially coherent a light source has to be for certain applications.



$$a/2f \approx \Delta\lambda / d$$

$$\Delta\lambda < \lambda/2\pi \quad \textit{(definition*)}$$

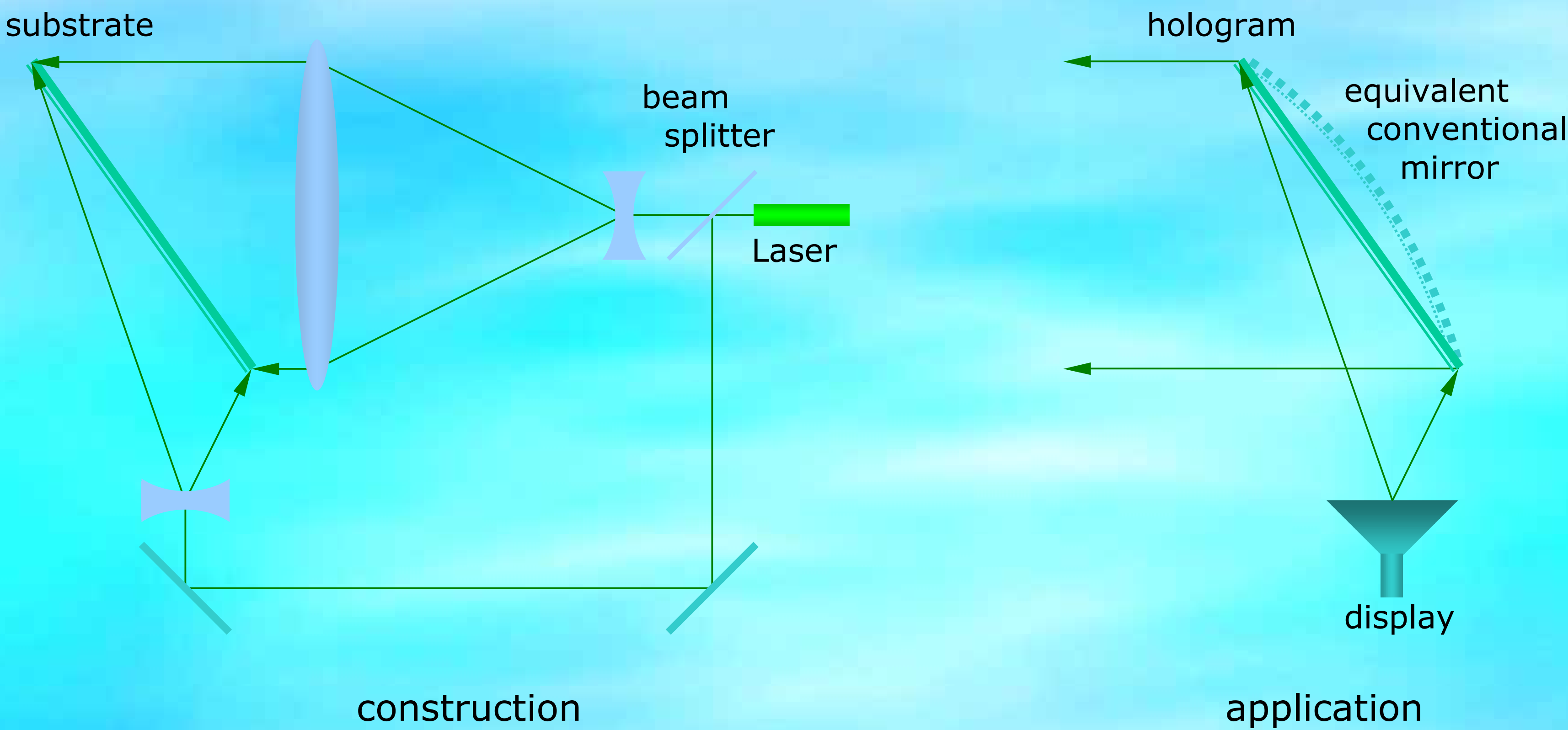
$$\rightarrow \; d < f\lambda/\pi a$$

- Consider a light source of diameter d illuminating a fringe pattern of diameter a from distance f. Beams from the edges of the light sources travel the same distance to the center of the fringes but different distances to their edges.
- This difference Δλ should be smaller than one wavelength, otherwise we get destructive interference. We define $\Delta\lambda<\lambda/2\pi$* or ≈$60^{0}$, which over the full pattern width a results in ≈120^{0} or a max. amplitude loss of ≈0.5.

We get: **$d < f\lambda/\pi a$**

*some sources allow only half as much, but we try to stay consistent with timely coherence.

Construction of an Holographic Optical Element for HUD



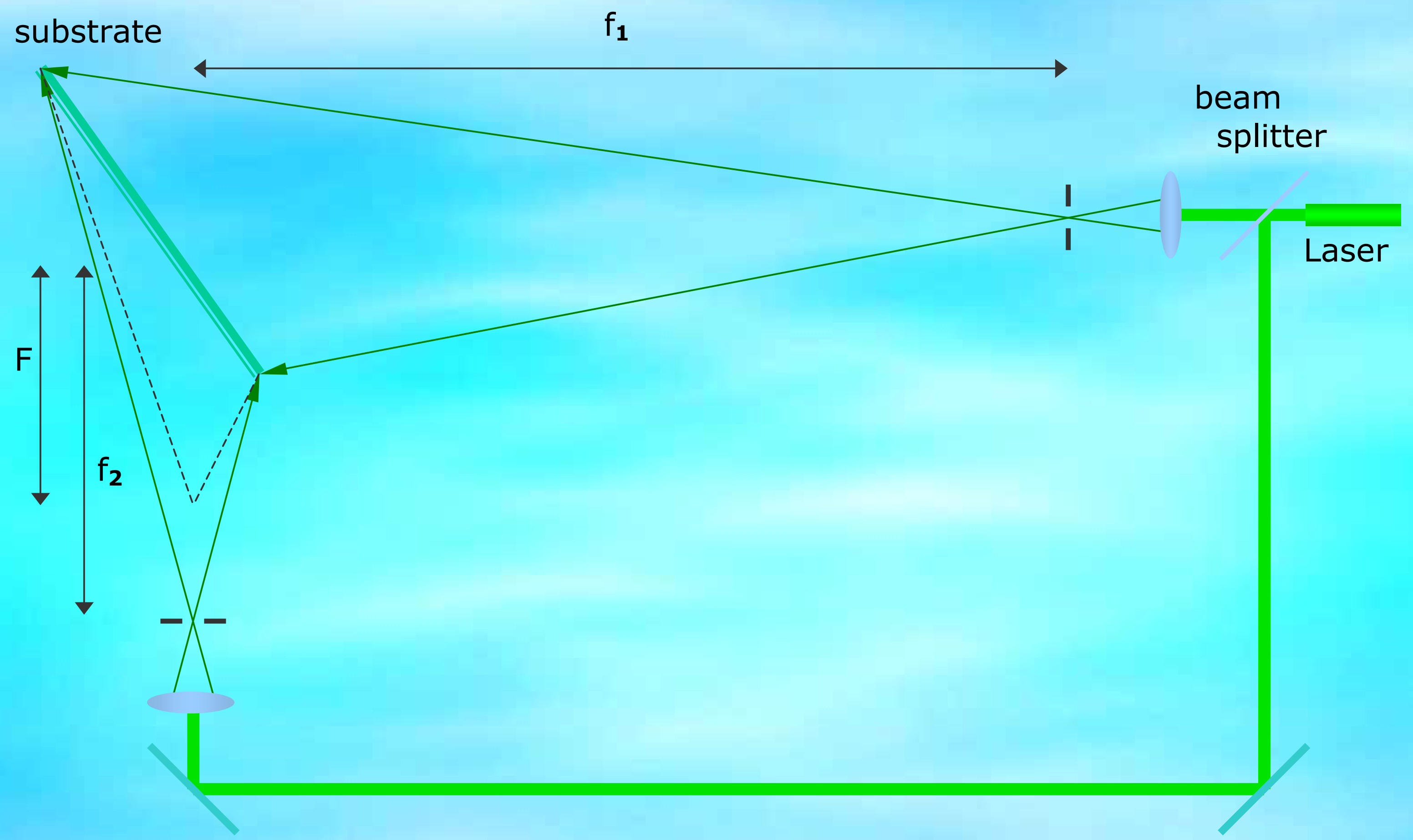
Construction:

Shaped beams from the same Laser source are forming a holographic volume pattern in a light sensitive substrate.

Application:

The pattern has been developed into a volumetric refraction index hologram that will convert parallel into concentric beams and vice versa, just like a parabolic mirror.

A more practical construction setup



- Real laser beams are 'thick', so we use crossover concentrating lenses to form point like sources, and some hole blinds to clean off stray light.
- A huge lens to imitate infinity is unpractical, so we use the lens equation

$$1/F=1/f_1+1/f_2$$

to form an equivalent holographic mirror from finite focus points.

Making of HOE's

Method 1 : Film

Film

Exposure

Developing: Silver halide (black)

Bleaching: Silver Bromine (refractive)

Method 2: Gelatin

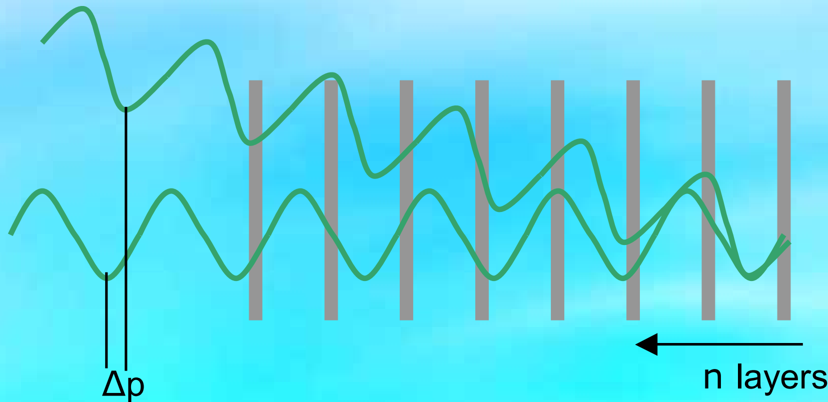
Gelatin on glass

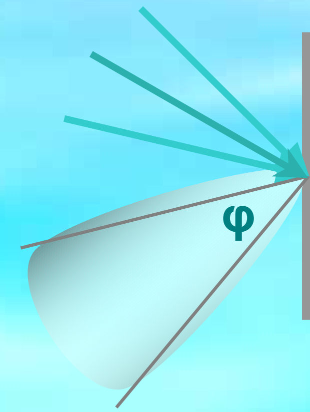
Exposure

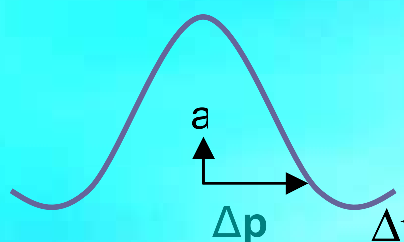
Developing: refractive fringes

Laminating with a second glass plate

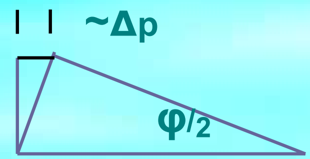
HOE characteristics: Angle







$$\Delta p \sim n/\sqrt{\Delta\varphi}$$

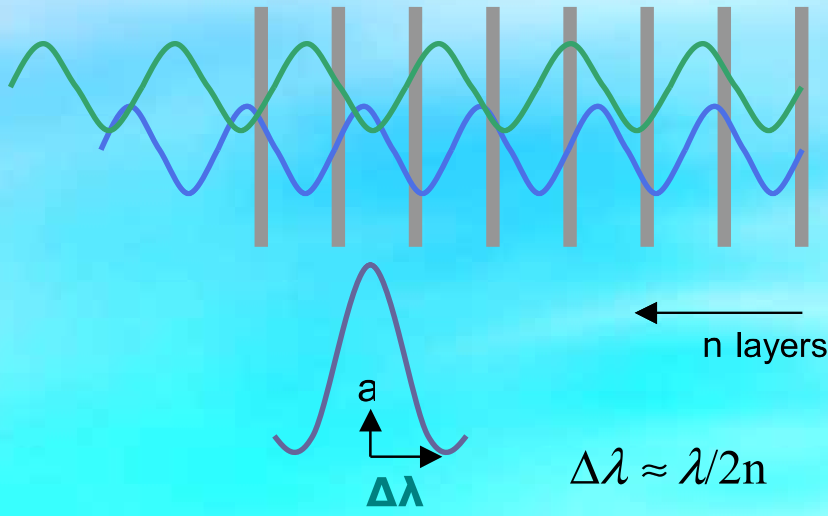


Smaller angle variations result in minor phase variations (1-cosφ or ≈ Pythagorean,
⇨ **square root of φ**, relatively wide !).

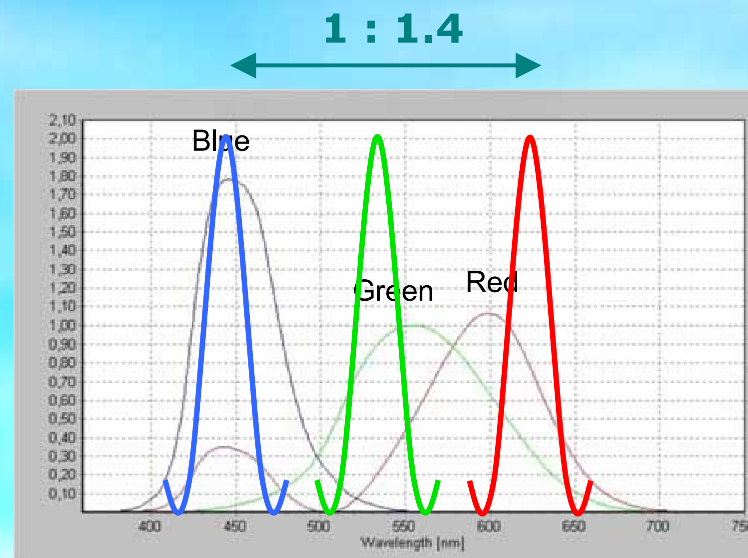
Example: ≈ 10 effective layers ⇨ **Δφ ≈ 15°**.

Higher orders are less likely in near eye displays because of limited angular range for possible beams from the display to the eye (but some effects with environmental light may still be possible).

HOE characteristics: Frequency



$\Delta\lambda \approx \lambda/2n$



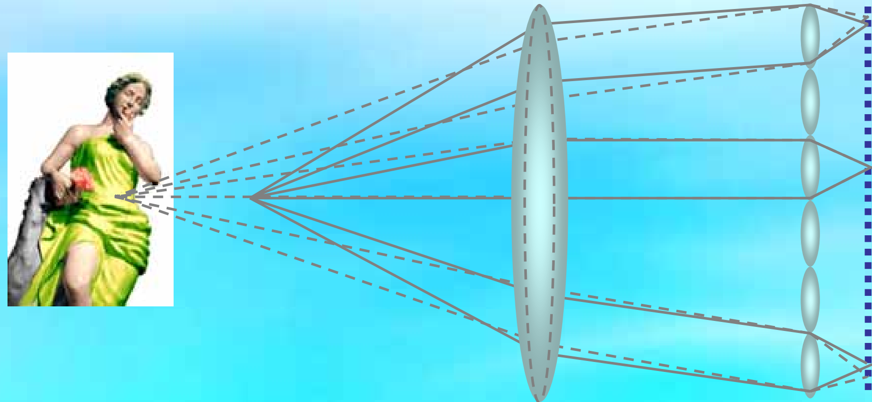
Example: Approx. 10 effective layers,
λ=500nm ⇨ **Δλ ≈ 25nm**

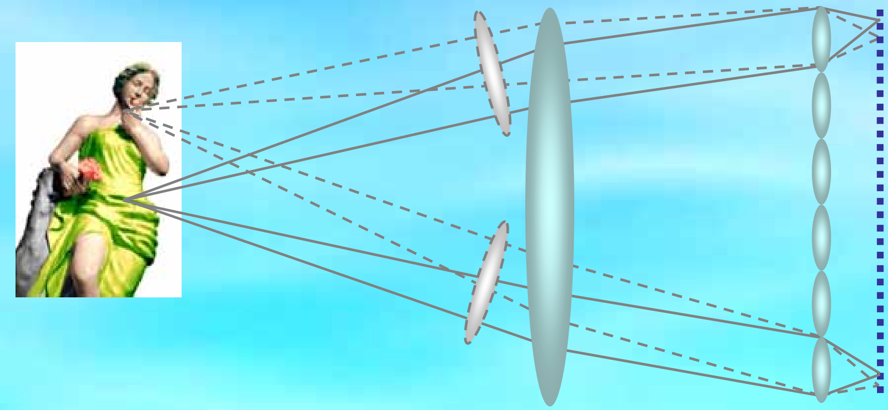
Base color range << 2
⇨ higher orders unlikely to occur

More sophisticated characteristics:
Subtle layer variations would allow for custom tailored characteristics.

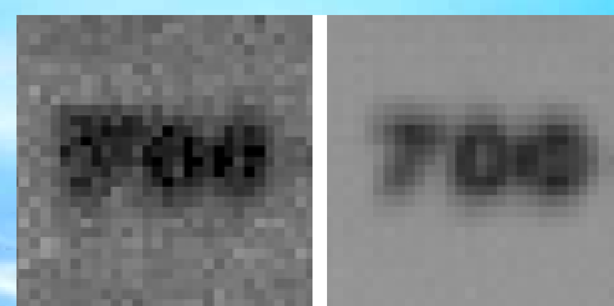
⇨ Could this be accomplished, e.g. using several wavelengths in construction?

The light field camera*





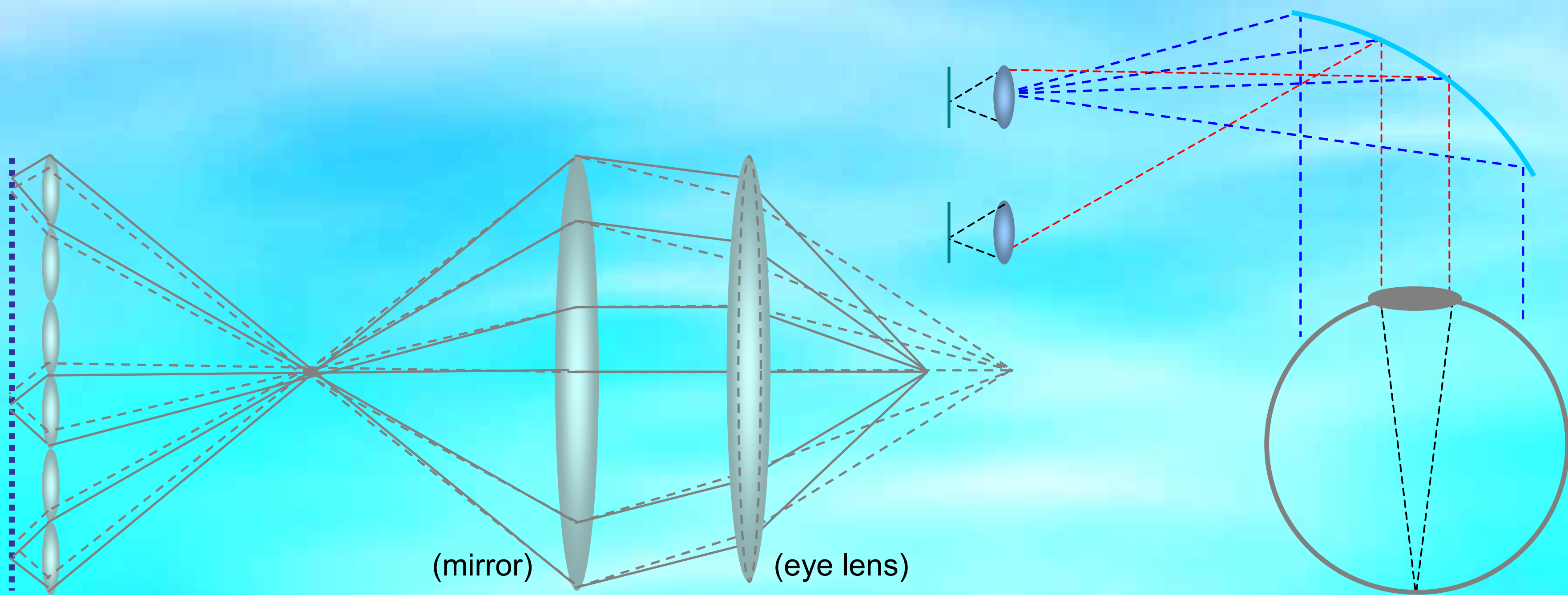
- Replacing any pixel of a conventional camera by a small lens, addressing many tiny sub pixels behind it - a tiny camera of its own - allows to select certain rays out of the image from the large lens by selecting the appropriate sub pixels.
- Any sub pixel together with its lens selects rays as if seen through a pinhole camera located at a certain position on the main lens.
- Sub pixels may be selected to collect light rays as if we had focused the main lens nearer or farther.
- Sub pixels may as well be selected to form sub images seen from different points on the main lens, hence different perspectives.
- The selection rules may be combined to render and entirely crisp 2D or 3D image, or a 2D or 3D image with almost any focus distance and depth of field desired.
- Most important advantage: with a conventional camera, the depth of field **b** for optimum aperture (a_0=a) depends on the object pixel size **d** only: **$b \approx 2d^2/\lambda$**. The light field camera overcomes this restriction.



f22 conventional   f4 refocused light field*

*(Ng, Duval et al., Stanford Tech Report CTSR 2005-02)

Depth pointing : monocular if you like



Suggestion: measuring eye focus by the light field camera principle:

- Observing the retina through the pupil with an autofocus camera would be obvious.
- Taking pixel displacements between several sub camera images might work as well.
- Just a few small sub cameras at sample positions should be enough.

Any sub camera however can only deliver useful pixels where it sees (through) the pupil.

Masking of objects: current status

This is research, obviously not for everyday use:

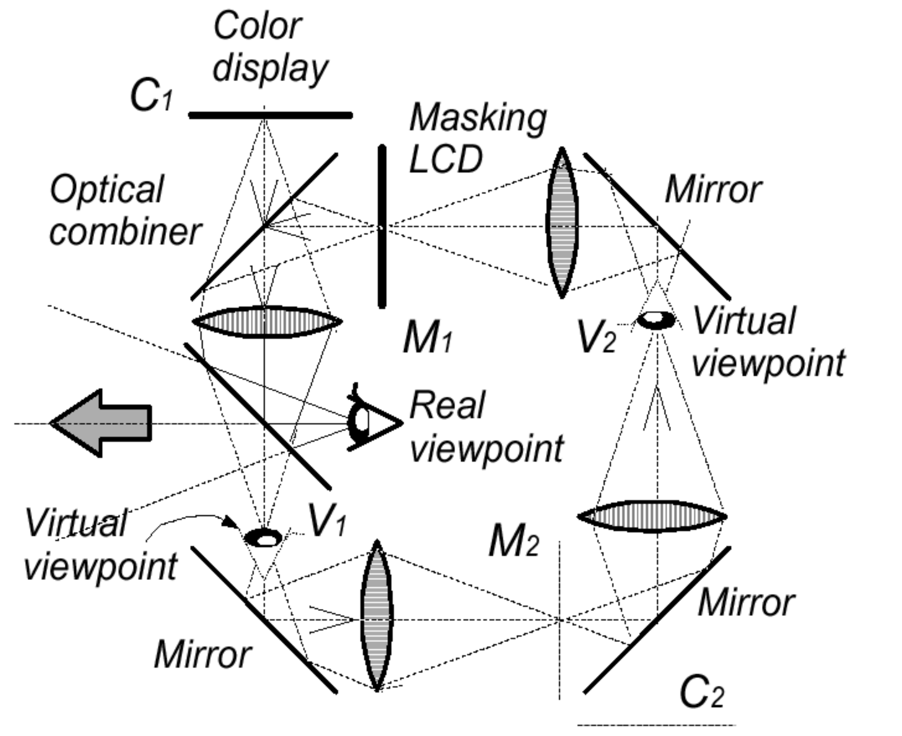


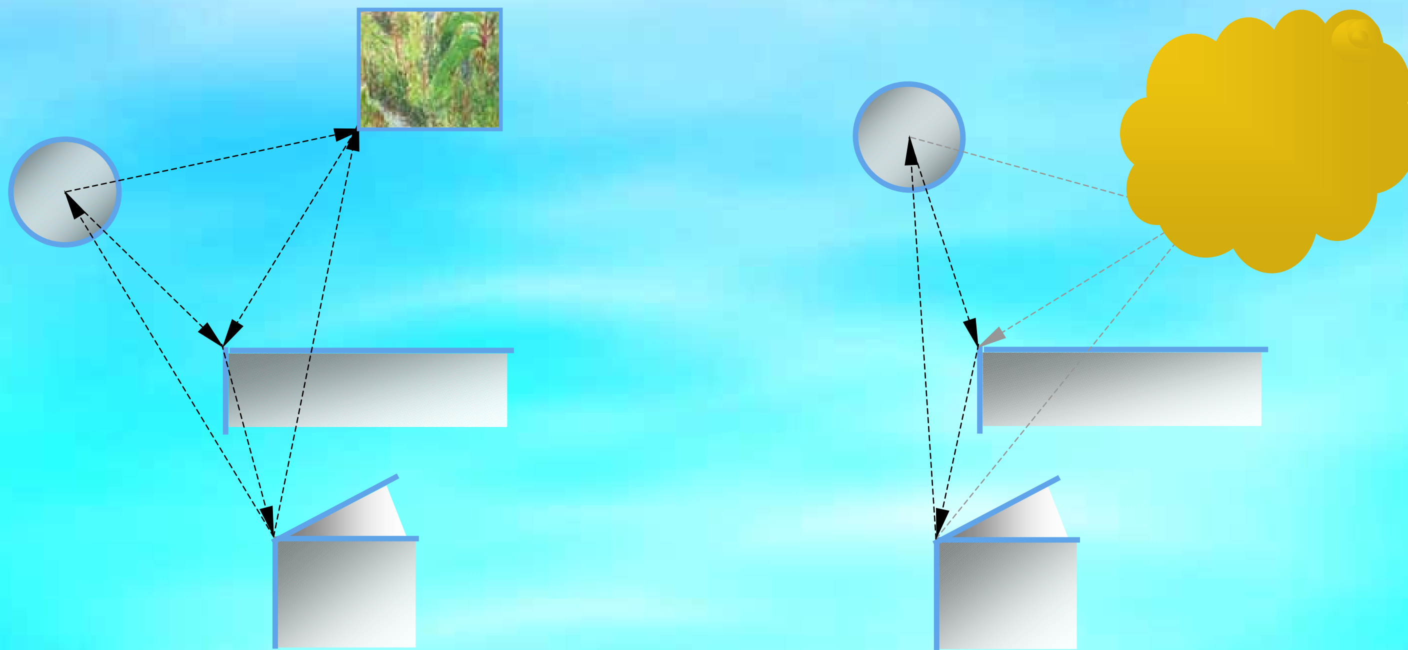
Figure 8. A simplified ELMO-4 optics.

Figure 10. Close-up of ELMO-4 in use.

Optics layout and assembly of an experimental masking display for research.

(Kiyoshi Kiyokawa et al. 2003)

Scene tracking and orientation - a suggestion



- Suggestion: ***normalized geometric primitives*** from position camera scenes,
- arranged in pointer structured database.
- A two-dimensional ***distance matrix*** can represent any number of dimensions.
- ***Rotation invariant*** by nature.
- Perspective and sense independent, ***'stupid' recognition*** of structure.

⇨ This is software - not our topic here; more in "The End of Hardware"

Keynote talk held at ISMAR 2008 in Cambridge

http://www.theendofhardware.com