Holography

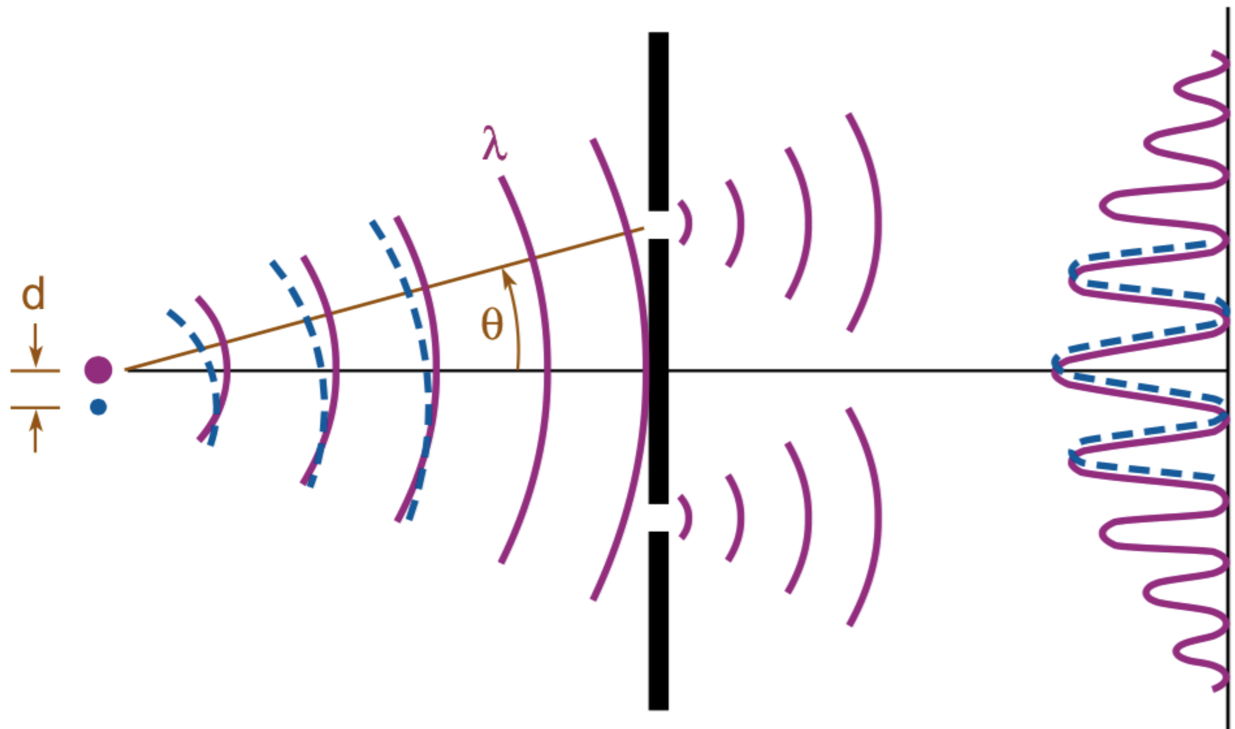
Ivan Bazarov

Cornell Physics Department / CLASSE

Outline

- **Coherence of light**
- **Holography**

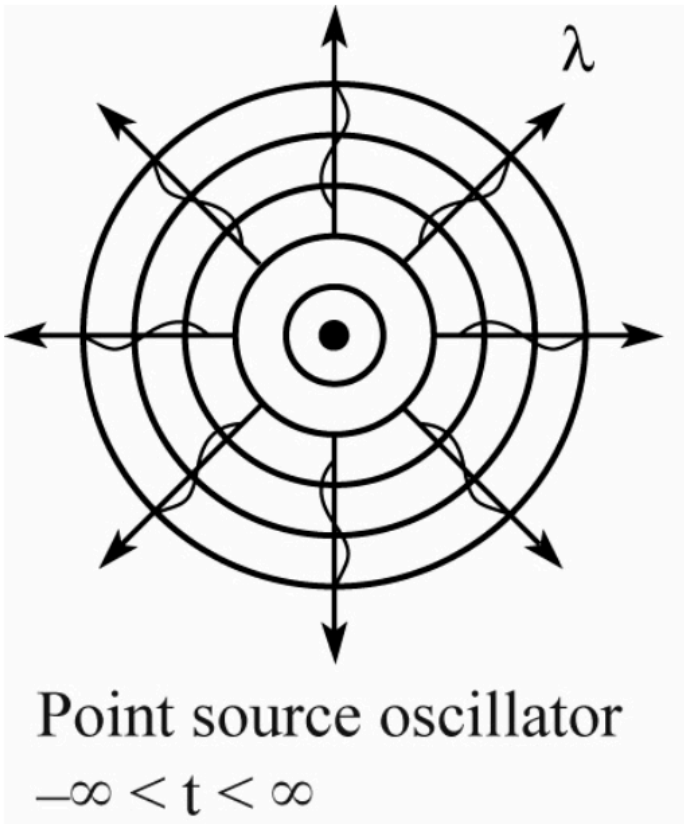
Young's double slits as a measure of coherence

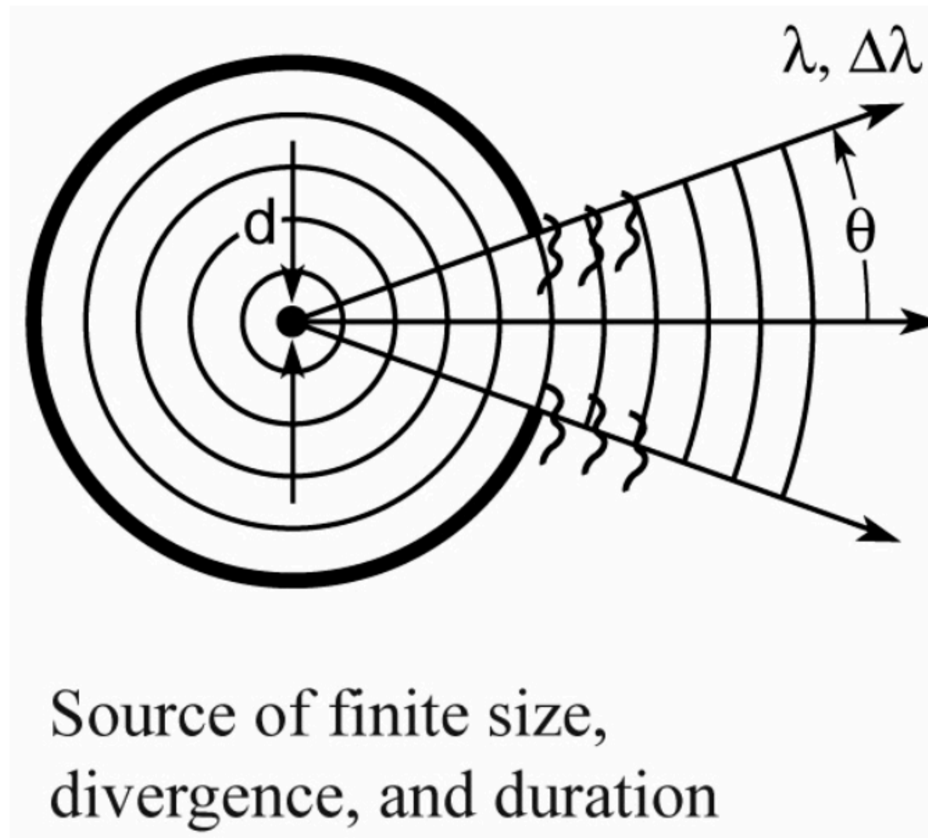


What happens to the fringes as the source grows from a point emitting monochromatic light to a finite size and bandwidth?

Interference pattern begins to disappear if there is ⩾λ/2 optical phase walk-off (=smear).

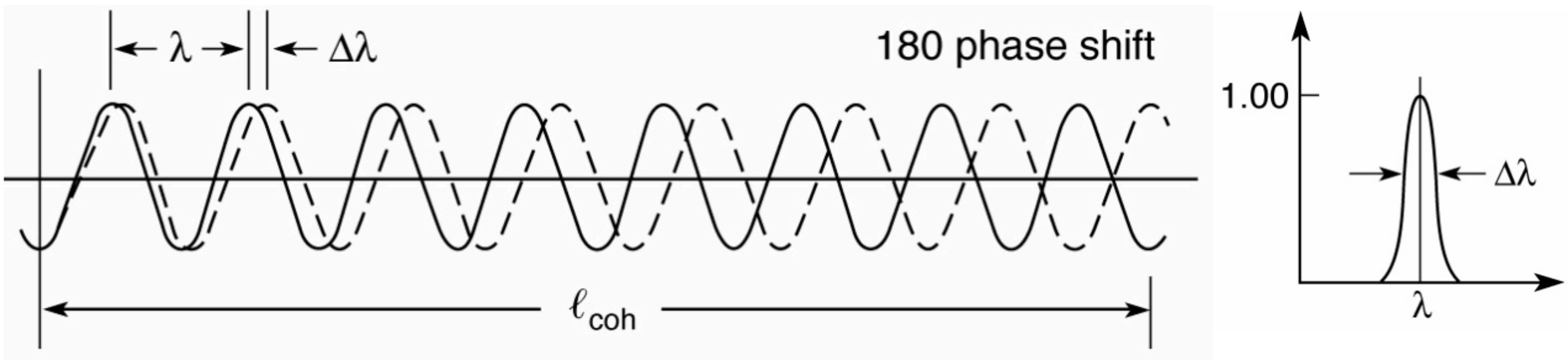
Coherence, partial coherence, and incoherence





Coherence length: marching in phase

Spectral bandwidth and longitudinal coherence length

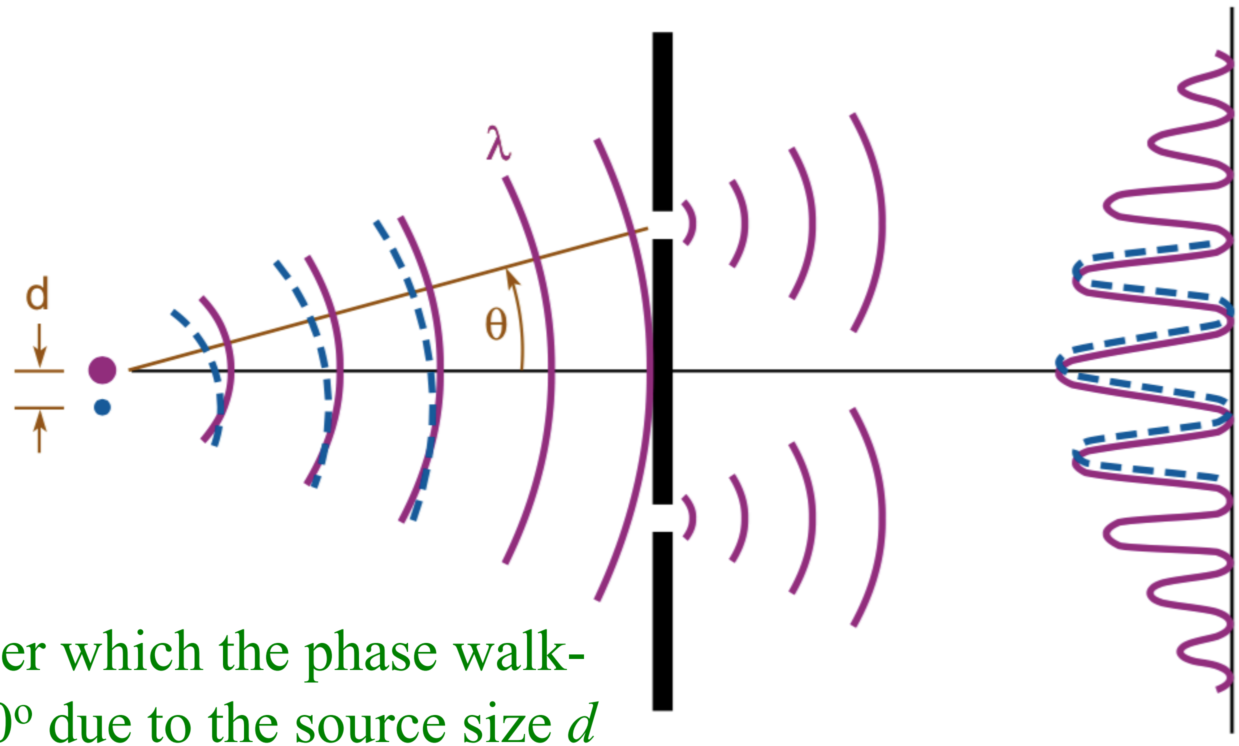


Longitudinal coherence length: defined as the length over which the optical phase "walks away" by 180°

$$\left.\begin{aligned} \ell_{coh} &= N\lambda \\ \ell_{coh} &= \left(N - \tfrac{1}{2}\right)(\lambda + \Delta\lambda) \end{aligned}\right\} \quad N = \lambda/2\Delta\lambda$$

$$\boxed{l_{coh} = \frac{\lambda^2}{2\Delta\lambda}}$$

Spatial coherence

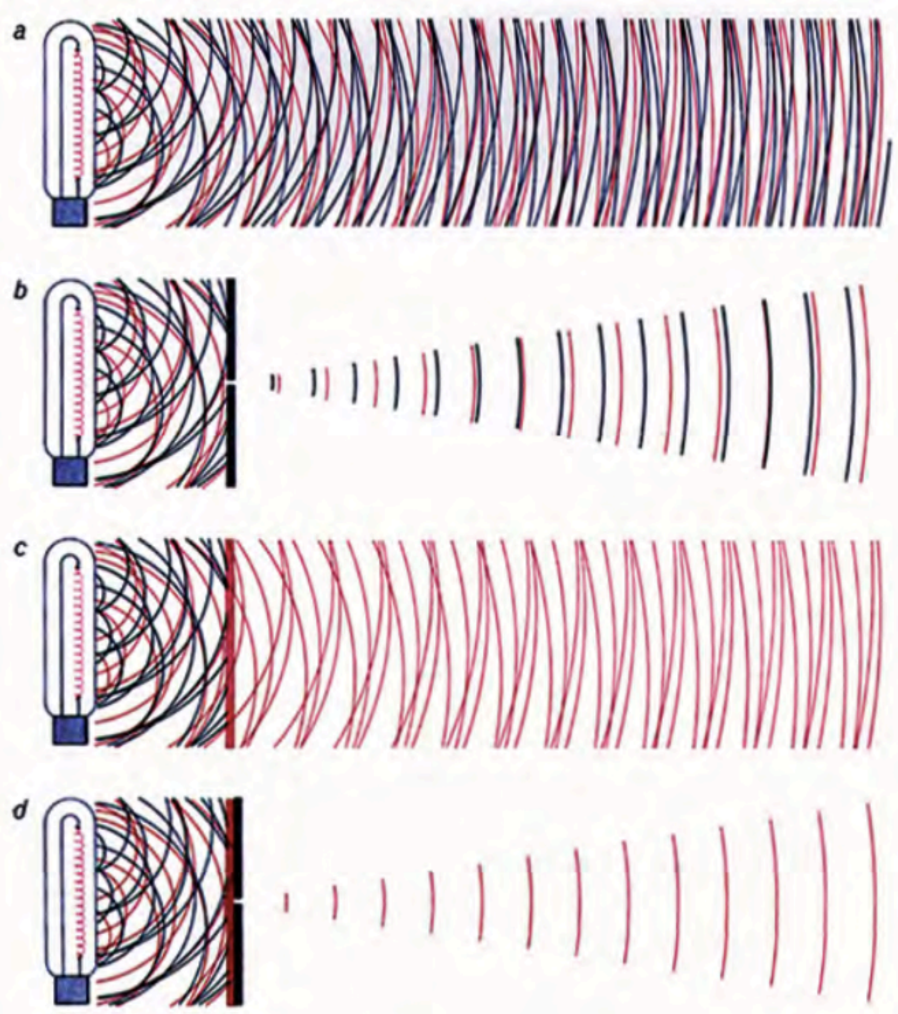


angle over which the phase walk-off is 180° due to the source size *d*

$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

Heisenberg may or may not have been here…

Spatial and spectral filtering to produce coherent radiation



Courtesy of A. Schawlow, Stanford.

Ordinary thermal light source, atoms radiate independently.

A pinhole can be used to obtain spatially coherent light, but at a great loss of power.

A color filter (or monochromator) can be used to obtain temporally coherent light, also at a great loss of power.

Pinhole and spectral filtering can be used to obtain light which is both spatially and temporally coherent but the power will be very small (tiny).

Conventional vs. holographic photography

- **Conventional:**
  - Records only intensity $|E_O|^2$;
  - 2-d version of a 3-d scene;
  - Photograph lacks depth perception or parallax;
  - Phase wavefront information is lost.

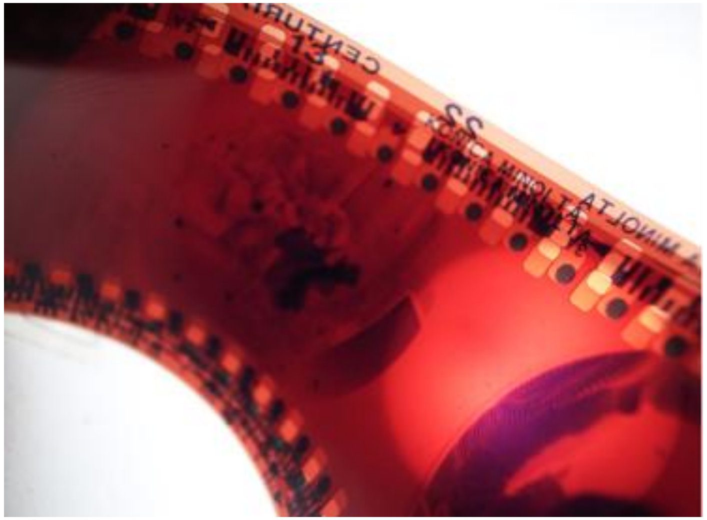


Image by live-14zawa
http://www.flickr.com/photos/livegym/306473531/

Conventional vs. holographic photography

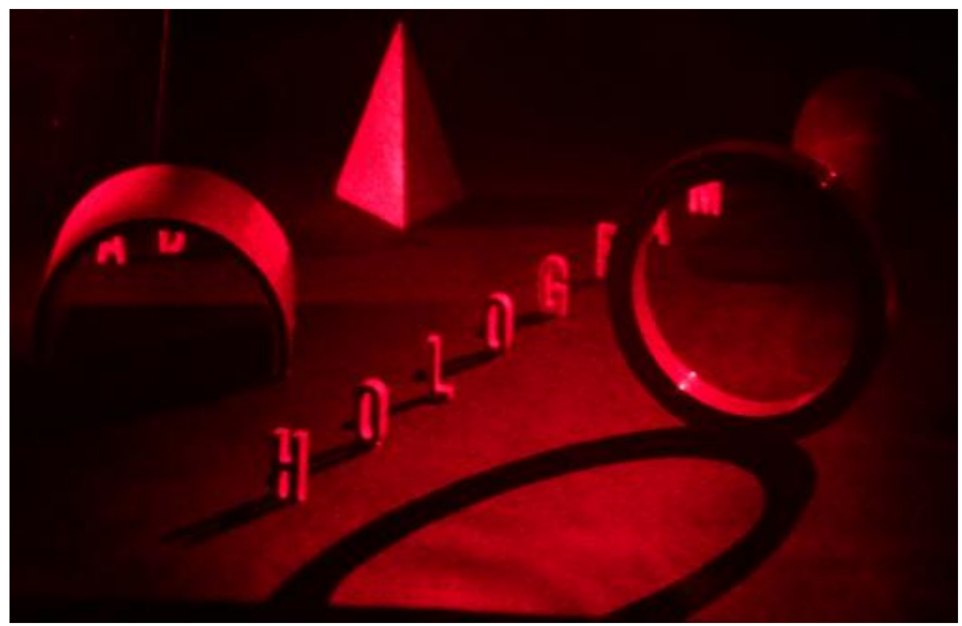
- **Hologram:**
  - Freezes the intricate wavefront of light that carries all the visual information of the scene including amplitude and phase;
  - To view a hologram, the wavefront is reconstructed;
  - View what we would have seen if present at the original scene through the window defined by the hologram;
  - Provides depth perception and parallax.

ὅλος γραμμή

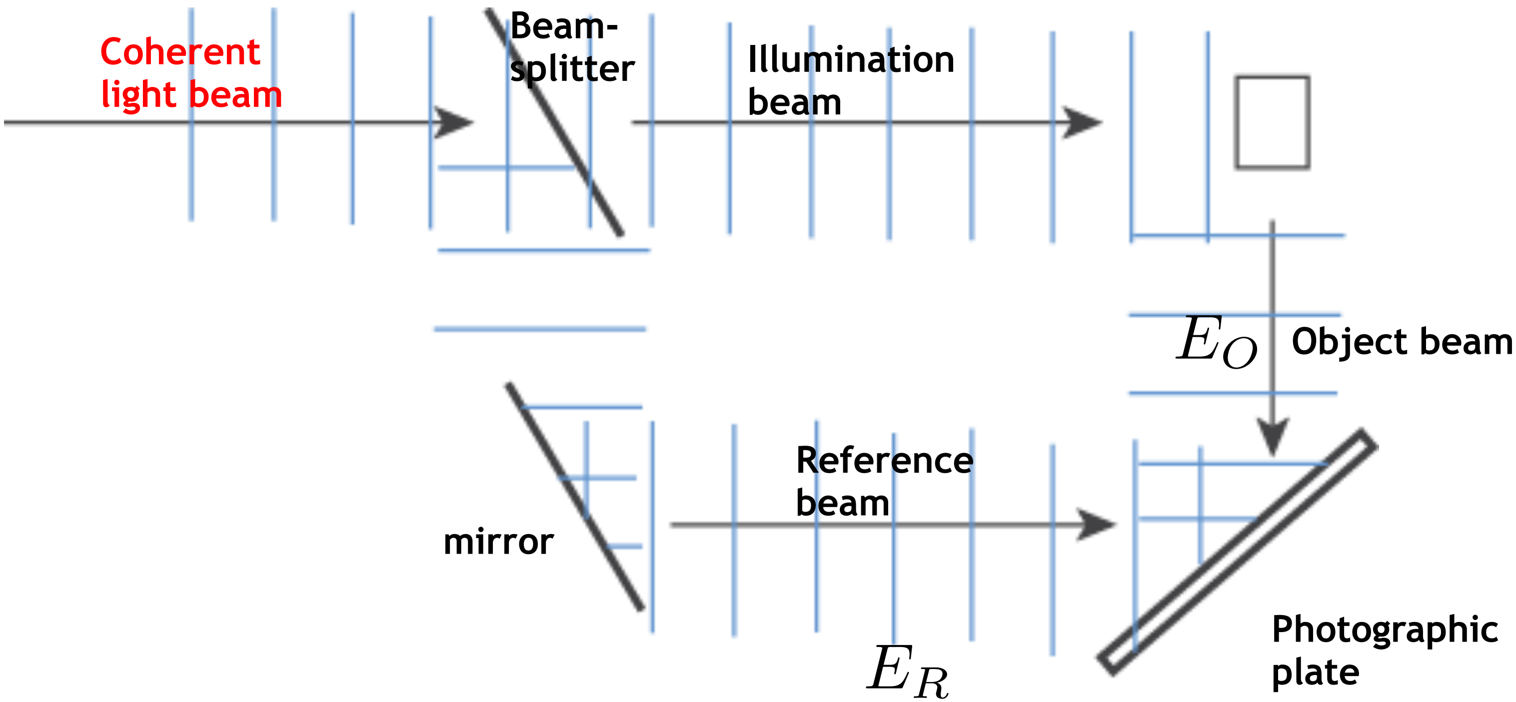
Holo **gram**

"whole" "writing"

Dennis Gabor, 1947



Holography: interference photography

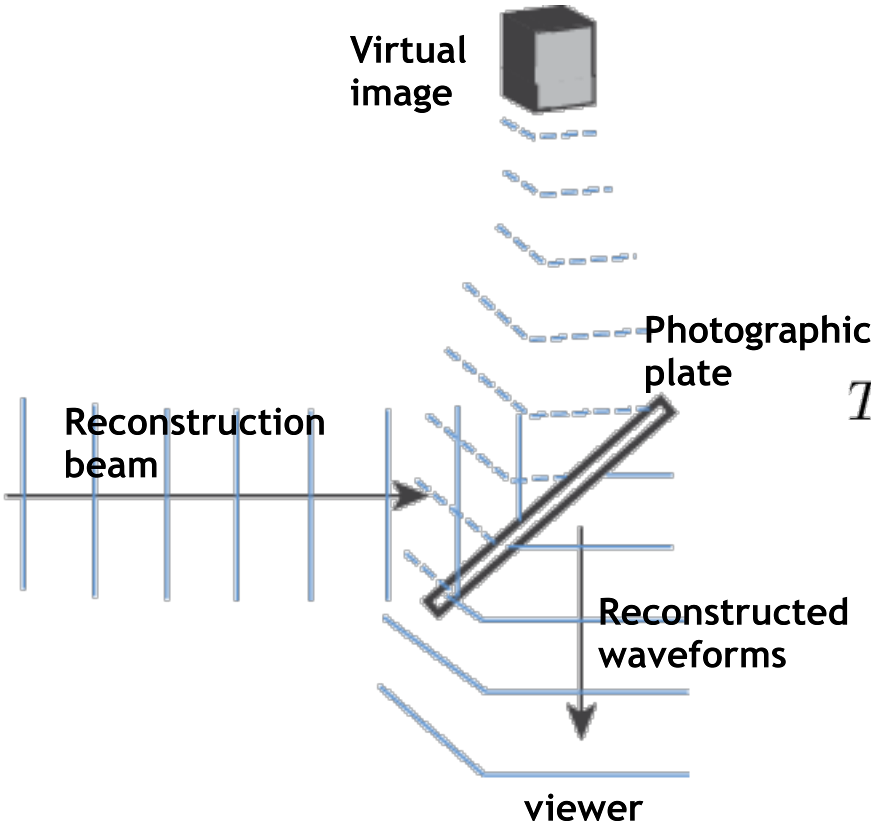


Important: the path difference must be within the coherence length!

Intensity of light on the photographic plate

$$|E_O + E_R|^2 = E_O E_R^* + |E_R|^2 + |E_O|^2 + E_O^* E_R$$

Holography: interference photography



If a photographic plate is exposed to the two beams, and then developed, its transmittance, T, is proportional to the light energy which was incident on the plate, and is given by

$$T = s[E_O E_R^* + |E_R|^2 + |E_O|^2 + E_O^* E_R]$$

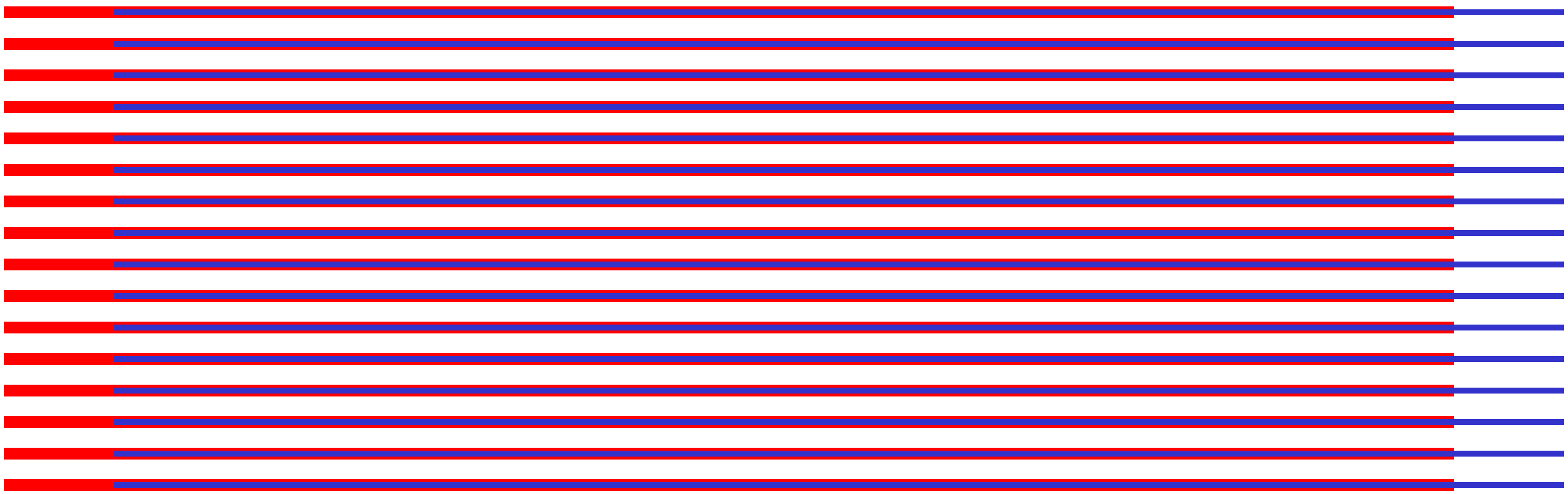
where s is a constant.

When the developed plate is illuminated by the reference beam, the light transmitted through the plate, $E_{VIEWER} = T^* E_R$ is:

$$E_{Viewer} = E_R T = s[E_O E_R^* + |E_R|^2 + |E_O|^2 + E_O^* E_R] E_R$$

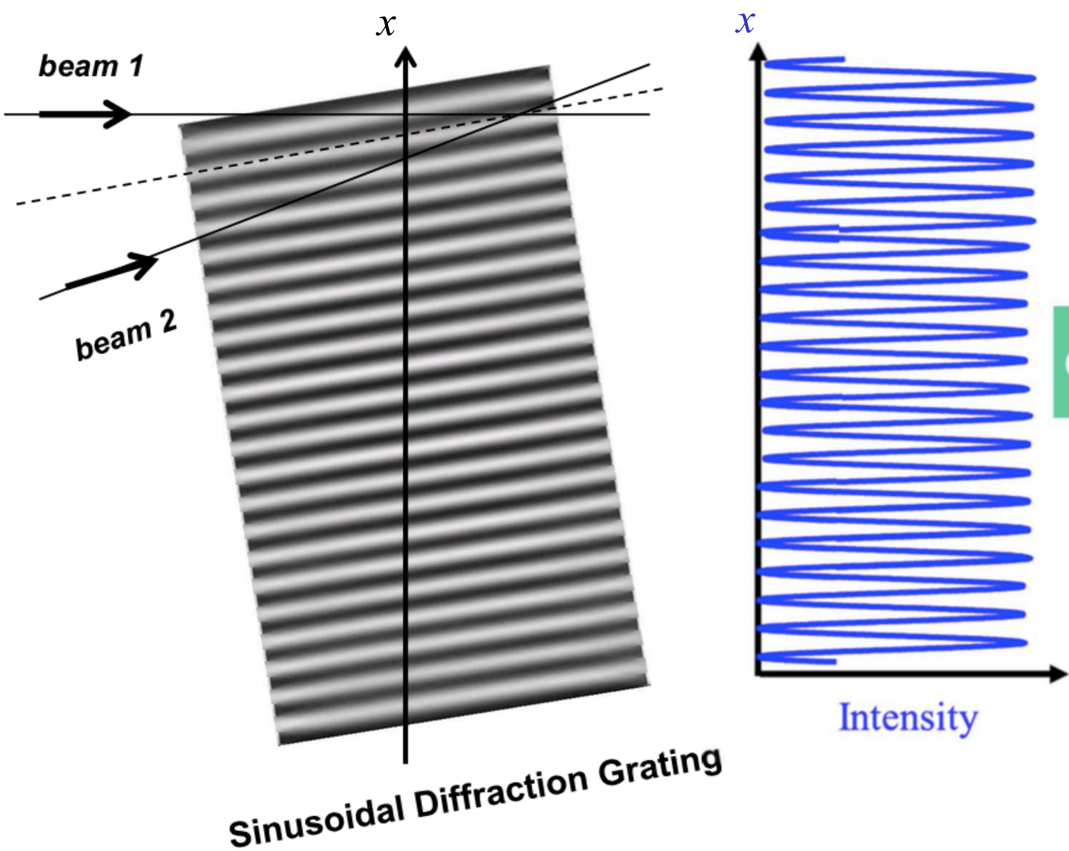
The simplest hologram

Reference and object beams at an angle



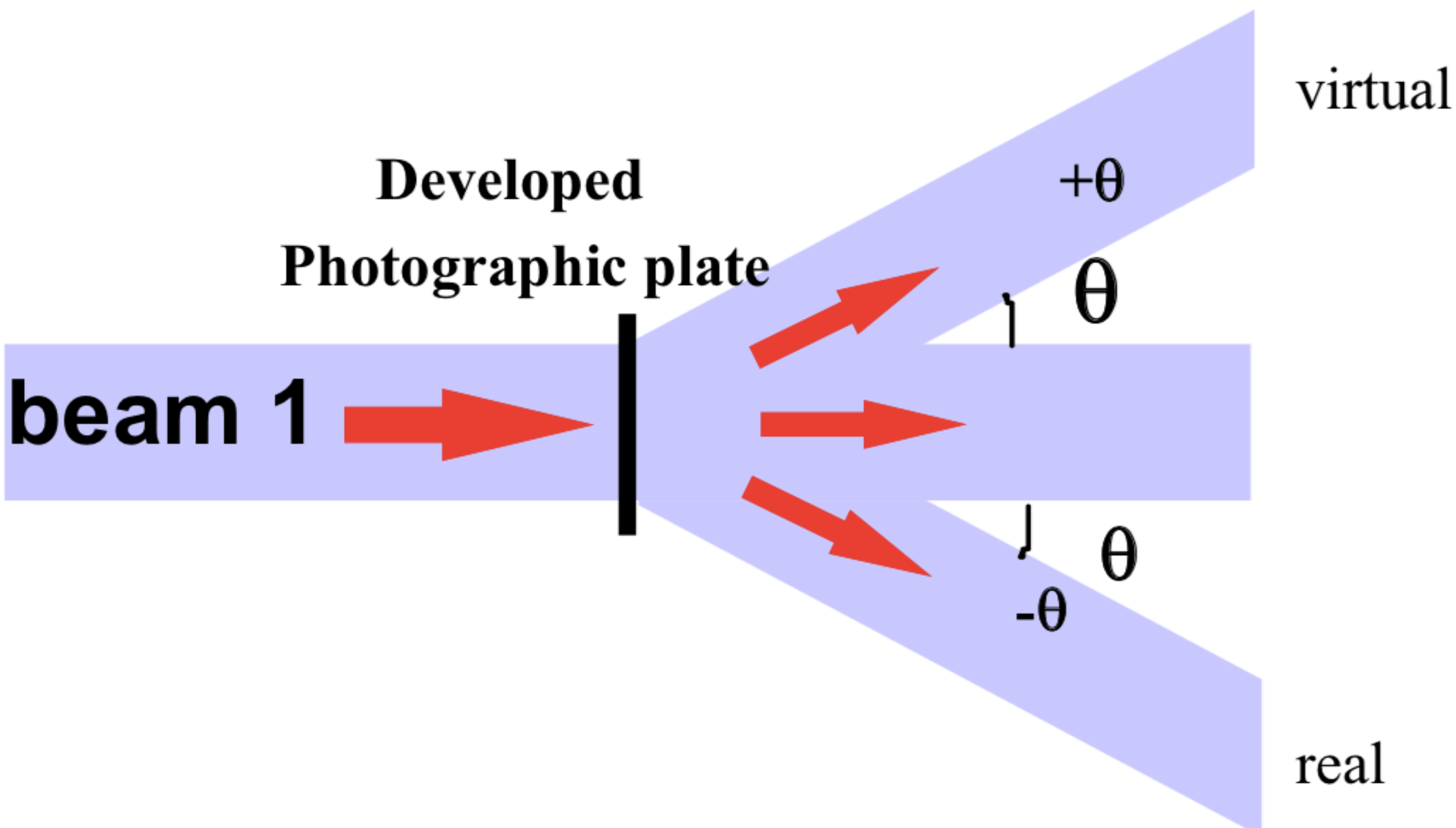
The simplest hologram

- After film is developed (sinusoidal) lines appear on film;
- Feature size can be very small (e.g. ~10 μm).



$$\cos^2\left(\tfrac{1}{2} kz \sin\theta\right)$$

Recreating “image” from the simplest hologram

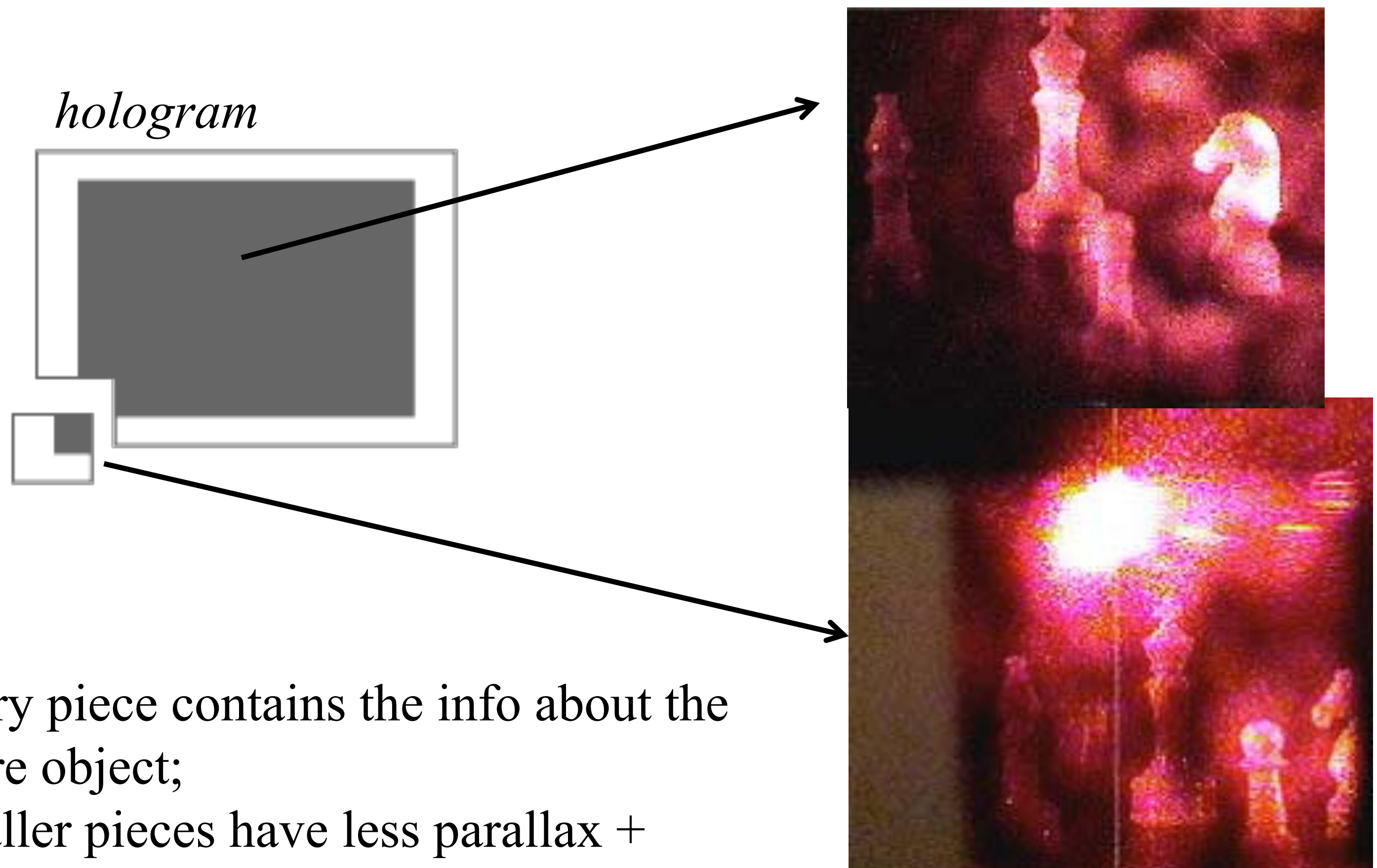


Parallax in holograms

- The entire wavefront is captured;
- Can refocus, change the perspective (within limits) – 3D!

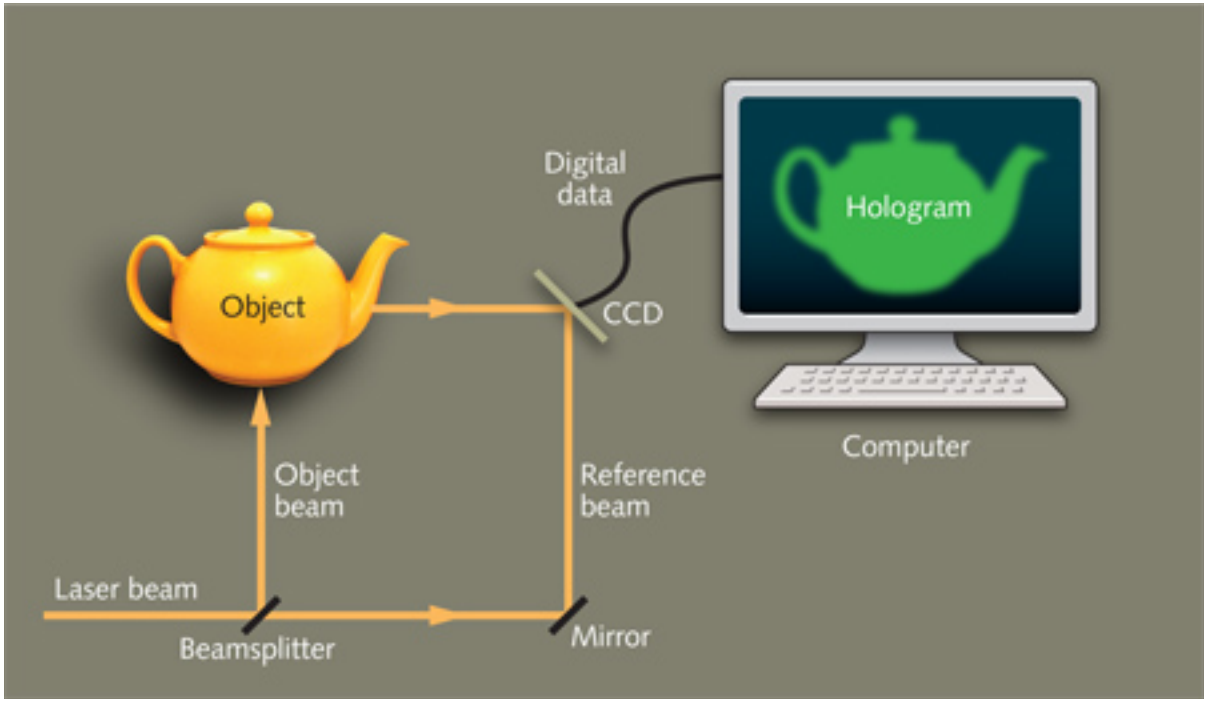
When a piece is the whole…

http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/holog.html



- Every piece contains the info about the entire object;
- Smaller pieces have less parallax + poorer resolution.

Digital holography



- Use CCD to record hologram;
- Use computer to display the object (e.g. at different depths of focus) + much more.

Math for data processing

Intensity of interference pattern on CCD:

$$I(x,y) = |E_O(x,y) + E_R(x,y)|^2$$

object (E_O) reference (E_R)

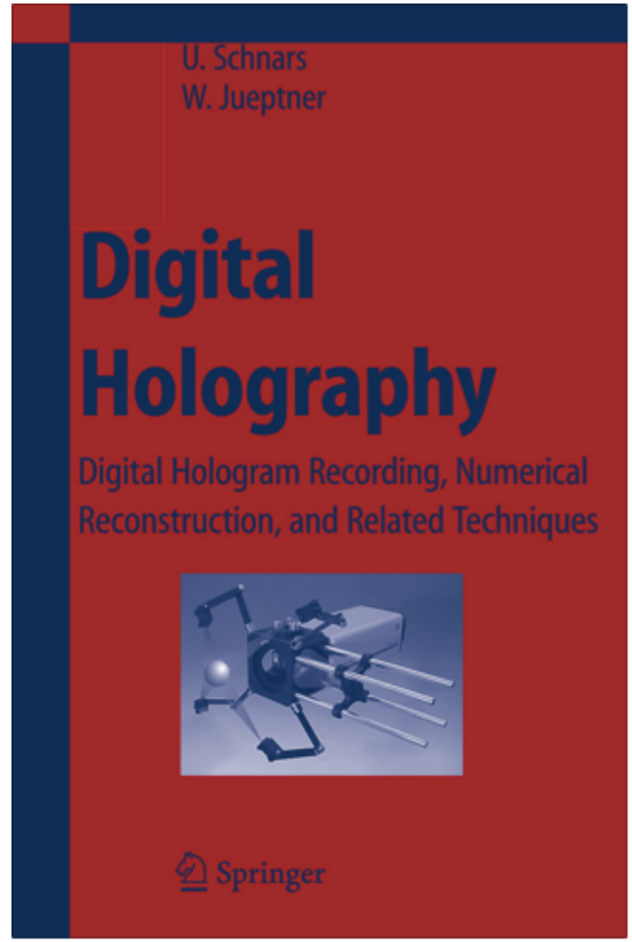
'Object' at a distance *d*:

$$\Psi(x',y') = \underbrace{e^{i\pi\frac{x'^2+y'^2}{d\lambda}}}_{\text{spherical wavefront of a lens}} \underbrace{\mathrm{FT}^{-1}\left\{I(x,y)\right\}}_{\text{like Fraunhofer diffraction}}$$

Final image:

$$\mathrm{Abs}\left\{\Psi(x',y')\right\}$$

Refer to Section 3.2 in Schnars & Jueptner.



Available for free for Cornellians at http://link.springer.com

Spatial frequency requirements

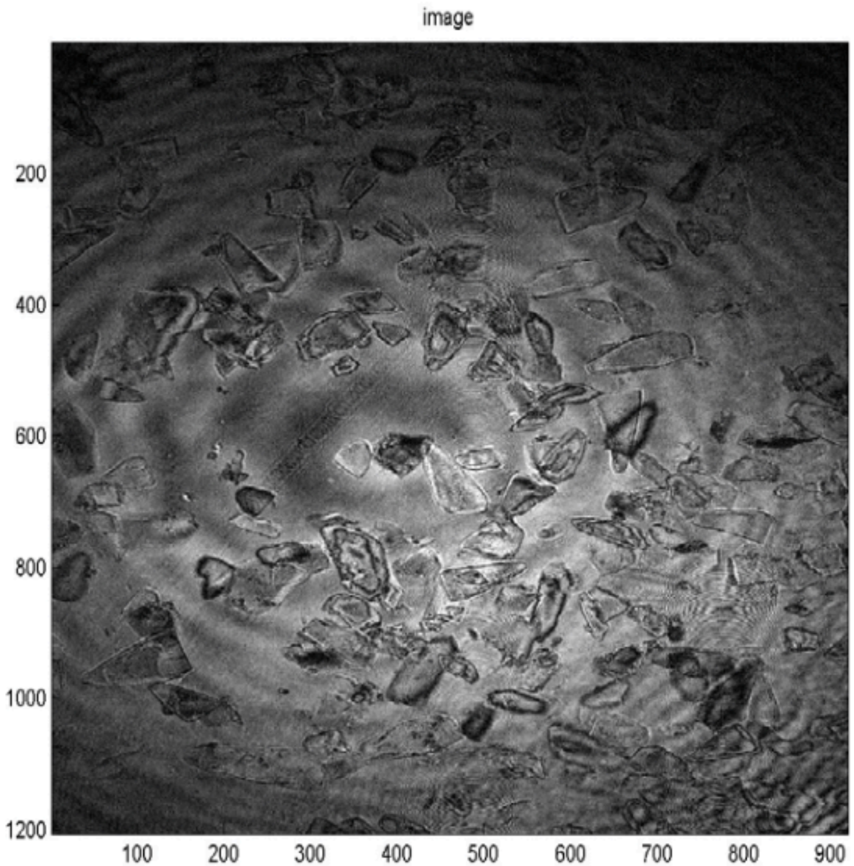
Max spatial frequency to be resolved

Max angle between waves (object & reference)

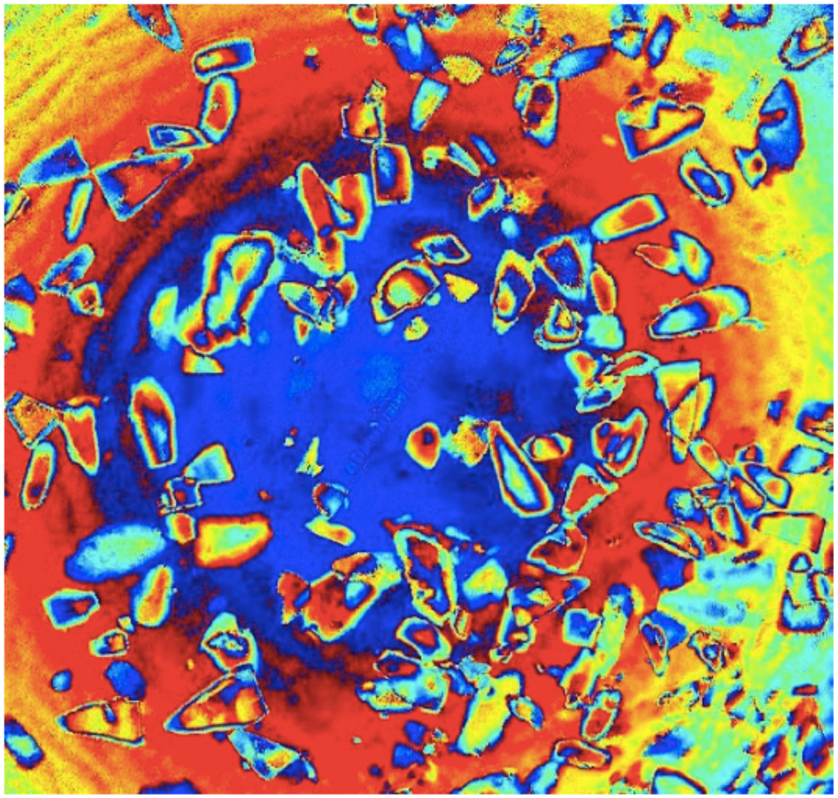
$$f_{max} = \frac{2}{\lambda} \sin \frac{\theta_{max}}{2} = \frac{1}{2\Delta x}$$

Spacing between CCD pixels (~10-20 μm)

Lots of cool tricks can be played!



Original image

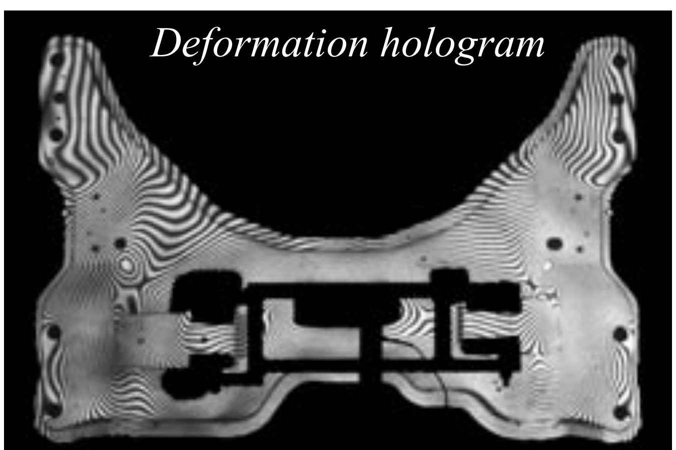


Color coded phase shift

Refer to Schnars & Jueptner for details.

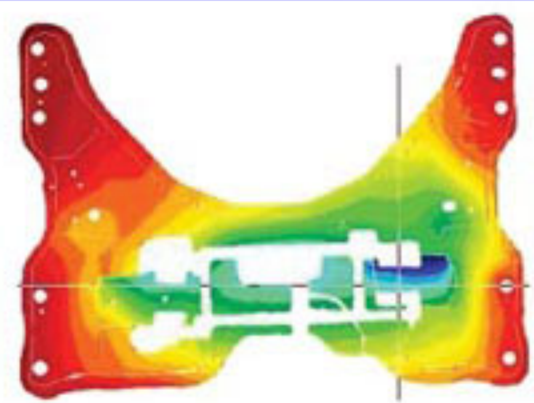
Applications of holography

- **Artistic creations**
- **Holographic interferometry**
  - Strain analysis of objects;
  - Measuring shapes of objects;
- **Data storage**
  - Contain large amount of visual information;
  - Same technique can be used for data storage.



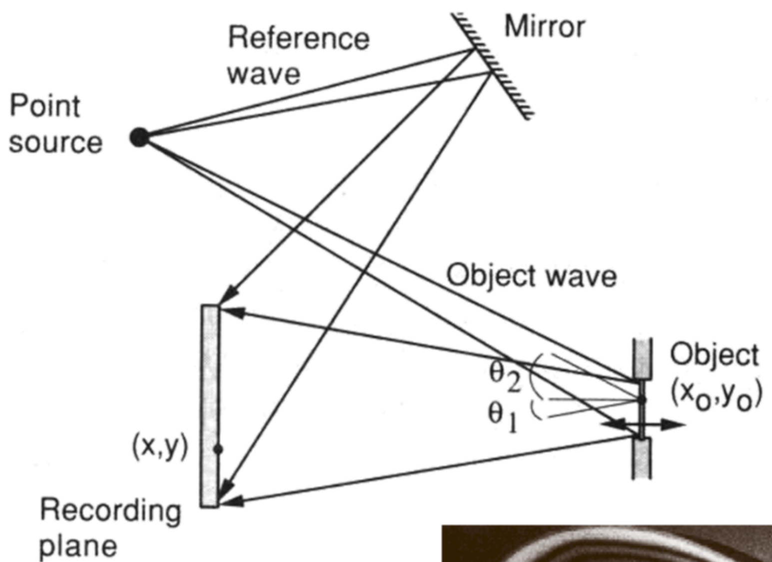
http://www.photonics.com/Article.aspx?AID=19434

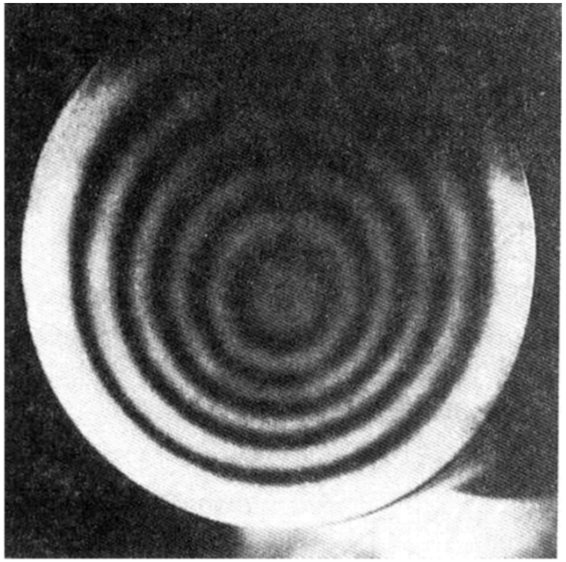
Deformation map after data processing →

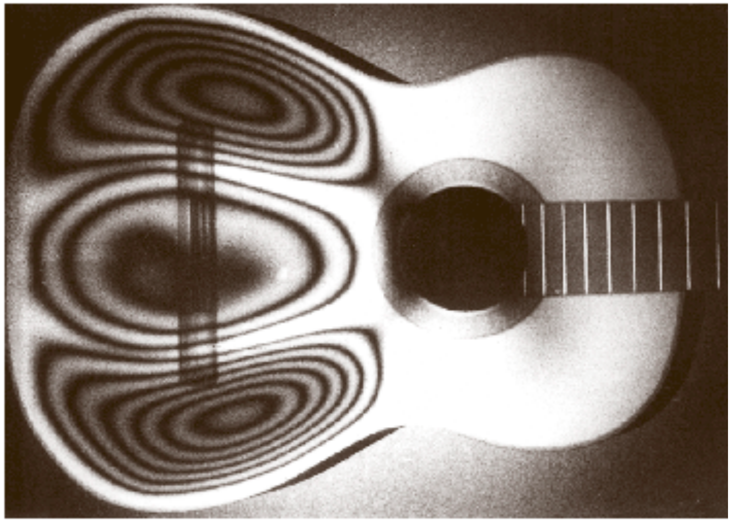


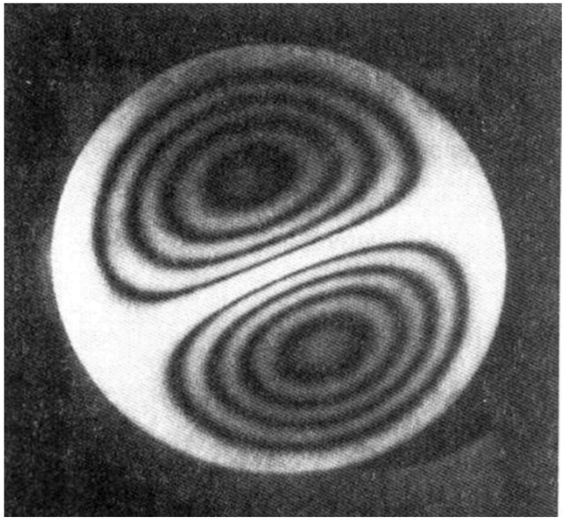
Vibration analysis

Doubly exposed hologram in sequence









Links/references

Ulf Schnars and Werner Jueptner, *Digital holography: digital hologram recording, numerical reconstruction and related techniques,* Springer 2005 (full ebook text available through Cornell library)

http://optics.hanyang.ac.kr/~shsong/16-Holography.pdf

http://www.es.lth.se/cccd/images/cccd03holography-Viktor.pdf

http://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-007-electromagnetic-energy-from-motors-to-lasers-spring-2011/lecture-notes/MIT6_007S11_lec28.pdf

http://ast.coe.berkeley.edu/sxr2009/lecnotes/12_SpatialTempCoh_CohUndRad_2009.pdf