



FLOW VISUALIZATION

An introduction – I

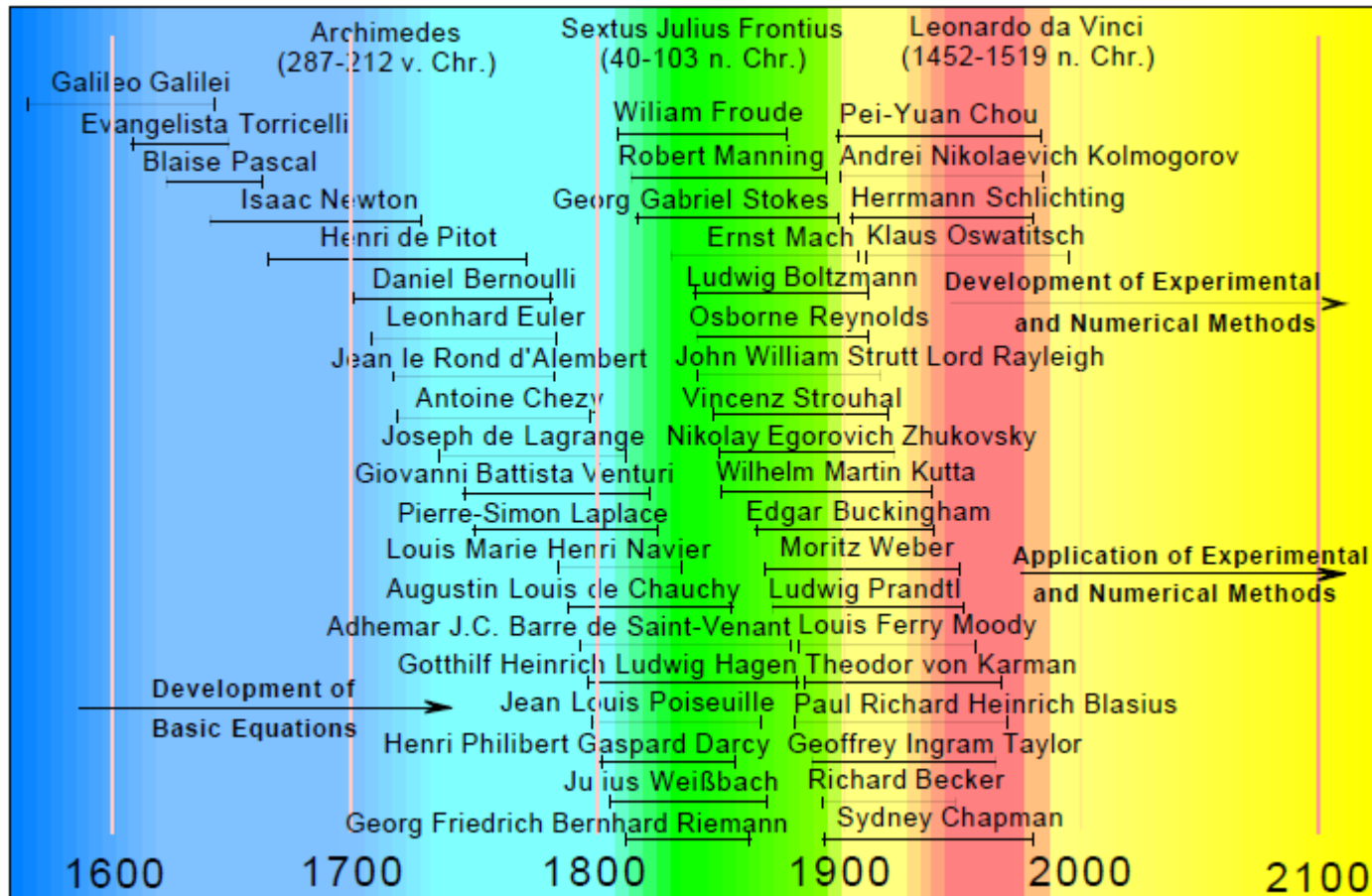
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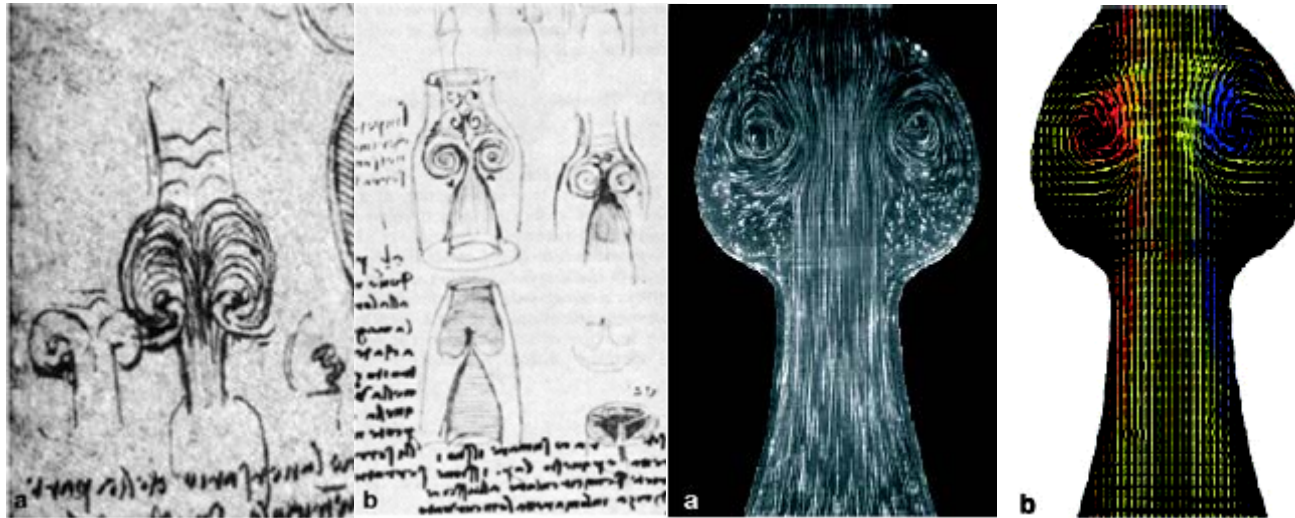
The first optical pyrometer (from *Heat and Temperature Measurement*, by R. L Weber, 1950)



Historical development of fluid mechanics (measurement techniques not covered).

F. Durst, *Fluid mechanics developments and advances in the 20th century*, Proc. 10th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, Lisbon (2000).

Leonardo's Vision of Flow in the Aortic Track



Flow visualization
using particles

Digital Particle
Image Velocimetry

M. Gharib, D. Kremers, M.M. Koochesfahani and M. Kemp, *Leonardo's Vision of flow visualization*, *Exp. Fluids*, vol.33, pp. 219-223, 2002

“Flow visualization is the art and science of obtaining a clear image of a physical flow field and the ability to capture it on sketch, photograph, or other video storage device for display or further processing.”

P. Freymuth, *Flow visualization in fluid mechanics*, Rev. Sci. Instrum., 64(1), Jan, 1993



Leonardo da Vinci's
illustration of the swirling
flow of turbulence.
(The Royal Collection © 2004,
Her Majesty Queen Elizabeth II)

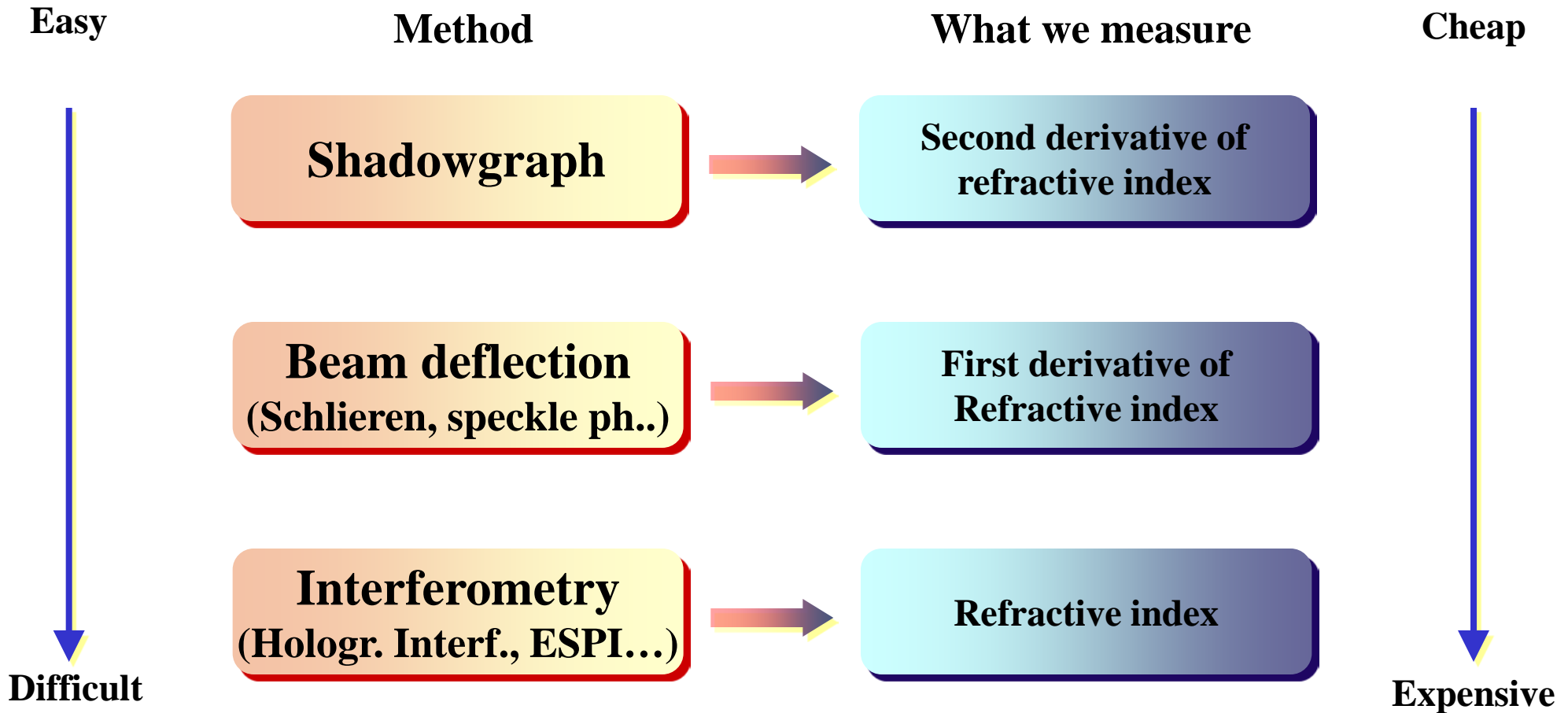
Our approach

Flow visualization is old, vast and complicated. In the following we shall use a very practical approach...

One can of course introduce almost any amount of mathematics into holography, but the essentials can be explained and understood from physical arguments.

D. Gabor – Nobel Lecture 1971

Index of refraction techniques

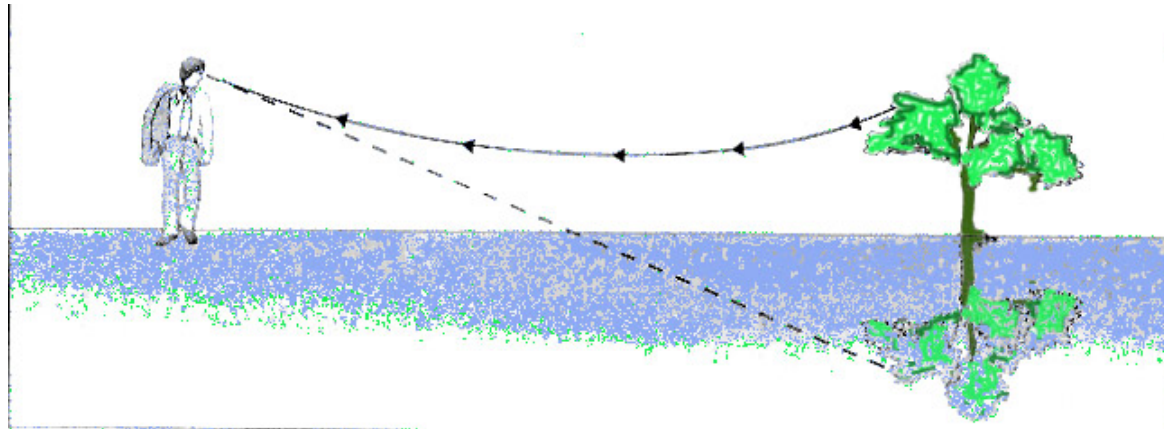


Back to basics 1:

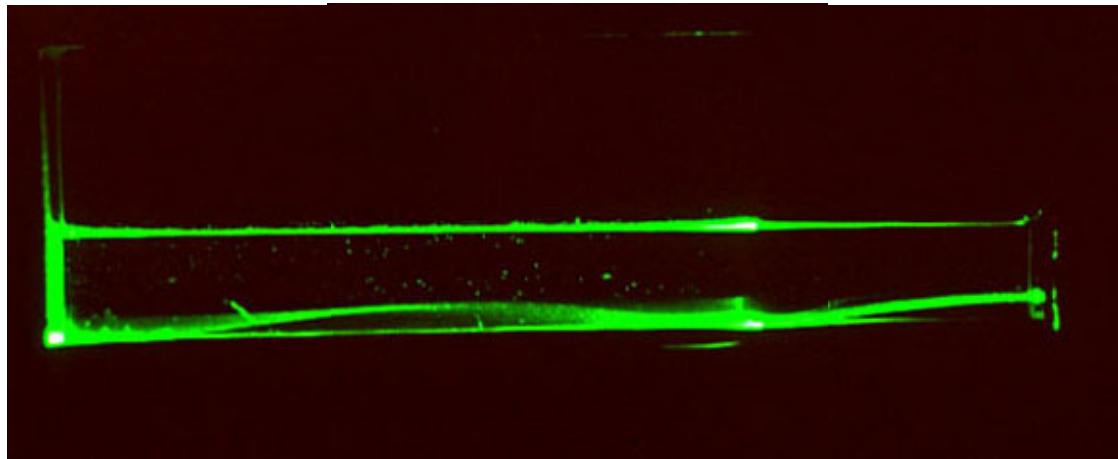
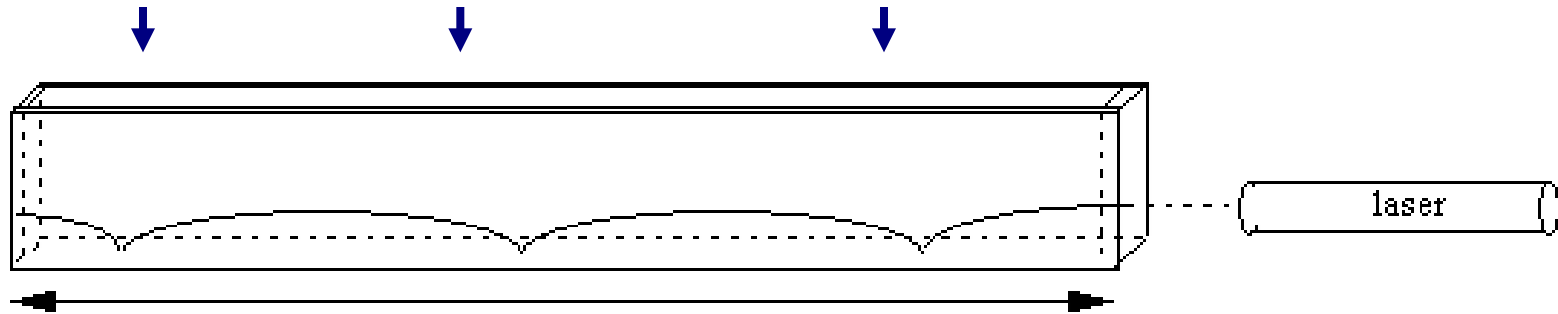
About a light beam traveling through a phase object

A medium characterized by refractive index gradients (called a phase object) has two effects on a traveling beam:

- A phase change (given by $kL\Delta n$)
- A beam deflection (such as in the mirage effect)



Tank filled with water: sugar cubes are added to the tank and allowed to dissolve undisturbed: a vertical gradient in concentration (i.e. in refractive index) is created.



W. M. Strouse, "*Bouncing Light Beam*" Am J Phys 40, 913 (1972); D. Ambrosini et al., "*Bouncing Light Beam and the Hamiltonian Analogy*" Eur. J Phys 18, 284 (1997).


Back to basics 2:

Transparent objects

In a fluid, the refractive index (n) and the density (ρ) are related by the Lorenz-Lorentz relation

$$\frac{1}{\rho} \frac{n^2 - 1}{n^2 + 2} = r(\lambda)$$

Specific refractivity



In a gas ($n \sim 1$) L.L. relation simplifies to the Gladstone-Dale equation

$$\frac{n - 1}{\rho} = \frac{3}{2} r(\lambda) = K_G$$

Gladstone-Dale constant



The Gladstone-Dale constant is a property of the gas. It is a weak function of λ and nearly independent of temperature and pressure (under moderate physical conditions). If the fluid can be considered an ideal gas, a relation between n and T is obtained

$$\frac{dn}{dT} = -0.961 \times 10^{-6} K^{-1}$$

Valid for air at 288 K, 0.1013 MPa and $\lambda = 632.8$ nm

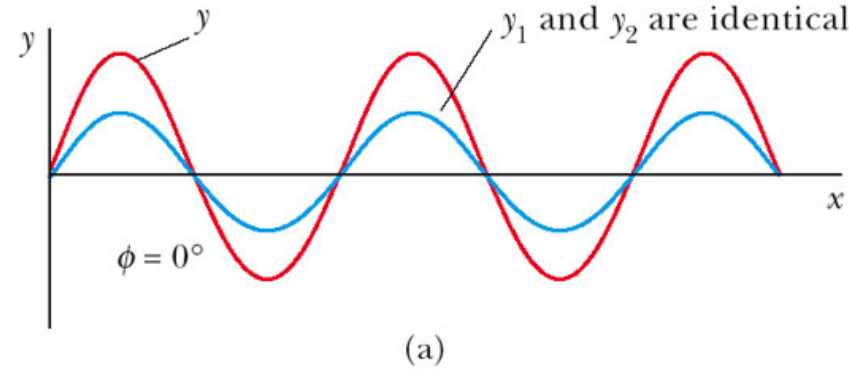
Many relations are available in literature for different fluids and λ .

Back to basics 3:

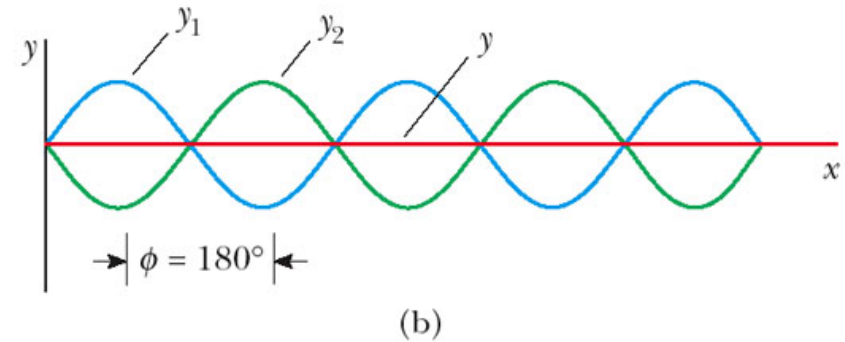
Interference

Interference result depends on the relative phase of the superposing waves.

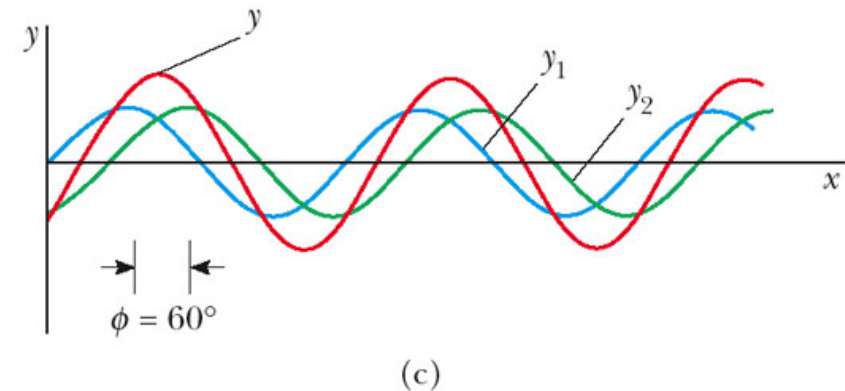
Constructive interference



Destructive interference



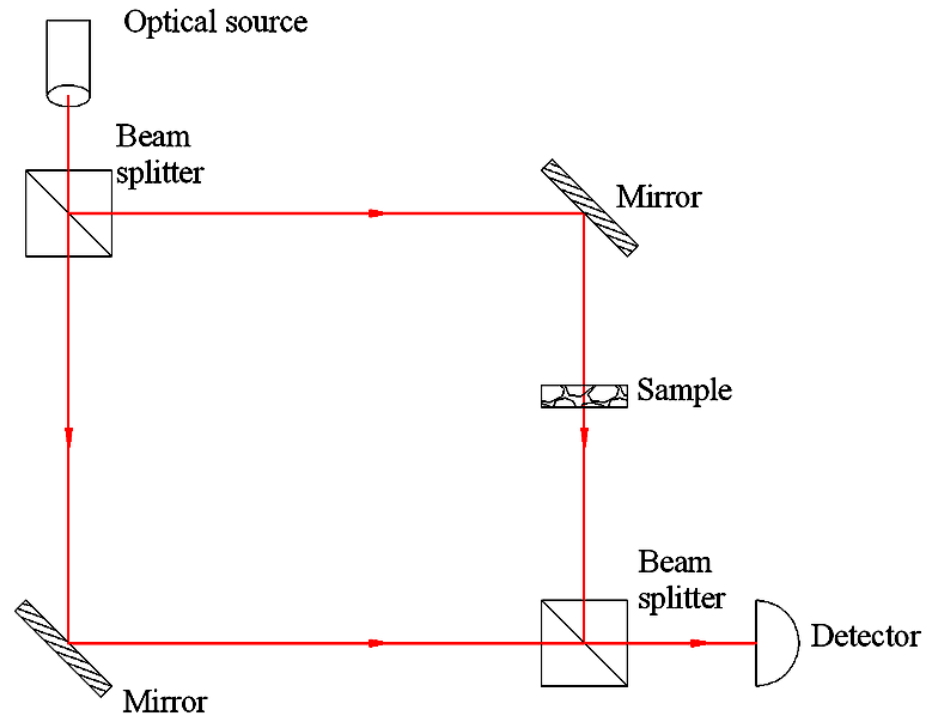
Normal interference



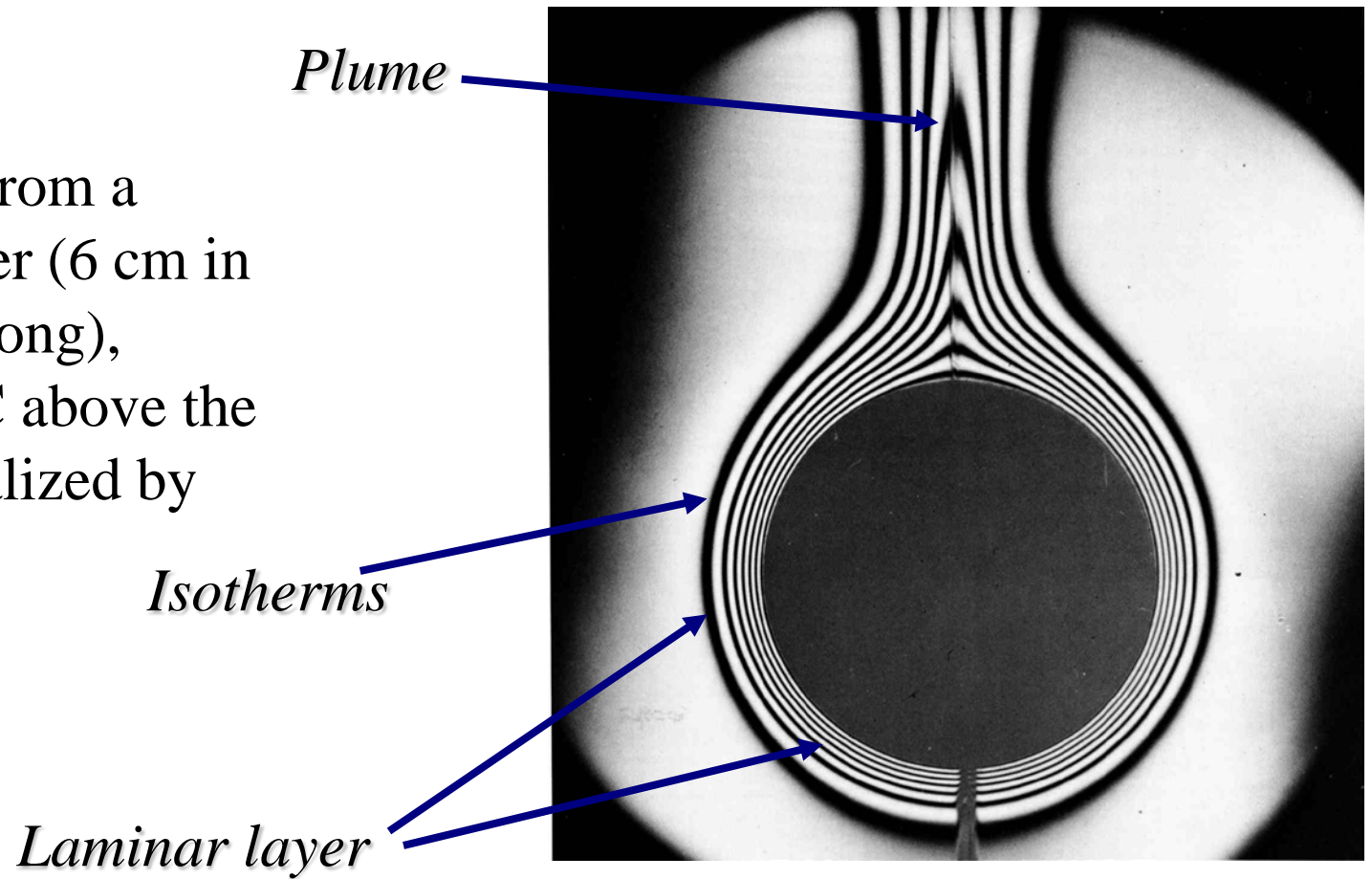
Interferometry

In interferometry, the superposition of waves allows to extract information about the waves themselves (e.g. their phase difference).

Mach-Zehnder interferometer (~1892) is widely used in flow visualization.



Free convection from a horizontal cylinder (6 cm in diameter, 60 cm long), heated about 9 °C above the ambient air, visualized by Mach-Zehnder interferometry.

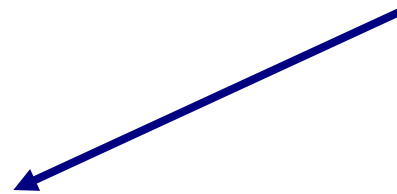
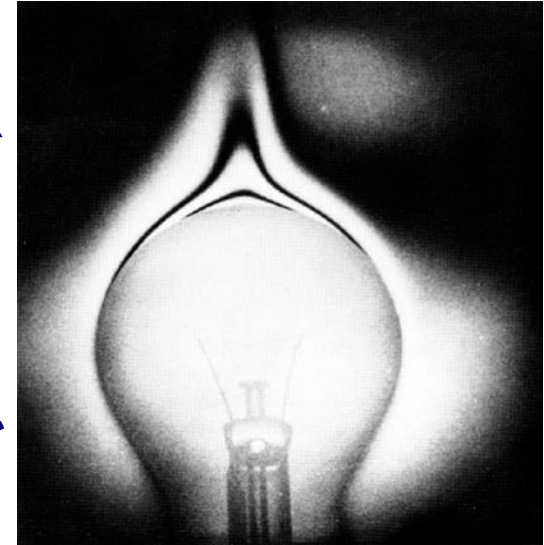


Pros & Cons

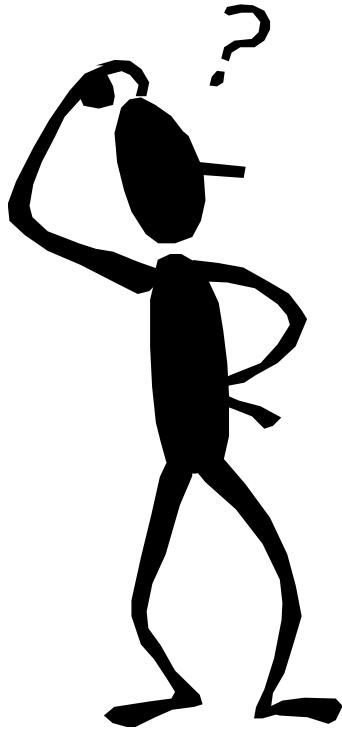
- High sensitivity, High quality image
- High precision mechanical performance required
- High quality of the components required



Very expensive instrument: costs grow rapidly with increasing diameter of the plates



High quality test section windows required: poor quality of the glass suppresses interference!



What is Holography??

*Holography (from the Greek, ὅλος-hòlòs whole + γραφή-grafè write) is the science of producing **holograms**; it is an advanced form of photography that allows an image to be recorded in three dimensions.*

(Wikipedia)

One giant leap and serendipity*

1947 – Holography is invented (“*too soon*”) by Dennis Gabor;

1960 – Laser invention: its pure, intense light, is ideal for holograms;

1962 – Off-axis holography introduced by Emmeth Leith e Juris Upatnieks. Holographic applications mushroomed all over the world.

1962 – Speckle (re)-discovery (Ridgen & Gordon);

1965 – Holographic Interferometry (R. Powell & K. Stetson);

1966 – Holographic Interferometry introduced in flow visualization (Heflinger *et al.*, Tanner);

1968 – Speckle photography invention (Burch & Tokarski);

1971 – Nobel Prize awarded to D. Gabor for inventing holography;

1971 – Electronic Speckle Pattern Interferometry (ESPI) is invented (Butters & Leendertz; Macovski *et al.*); first shearography (Butters & Leendertz).

1979 – A widely known single-authored book about Holographic interferometry published (Charles Vest);

1982 – Shearography (re)-invention (Hung).

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**Dennis Gabor himself defined his work about holography “an exercise in serendipity” and about the giant leap...*

D. Gabor and his holographic portrait, realized to commemorate Nobel winning

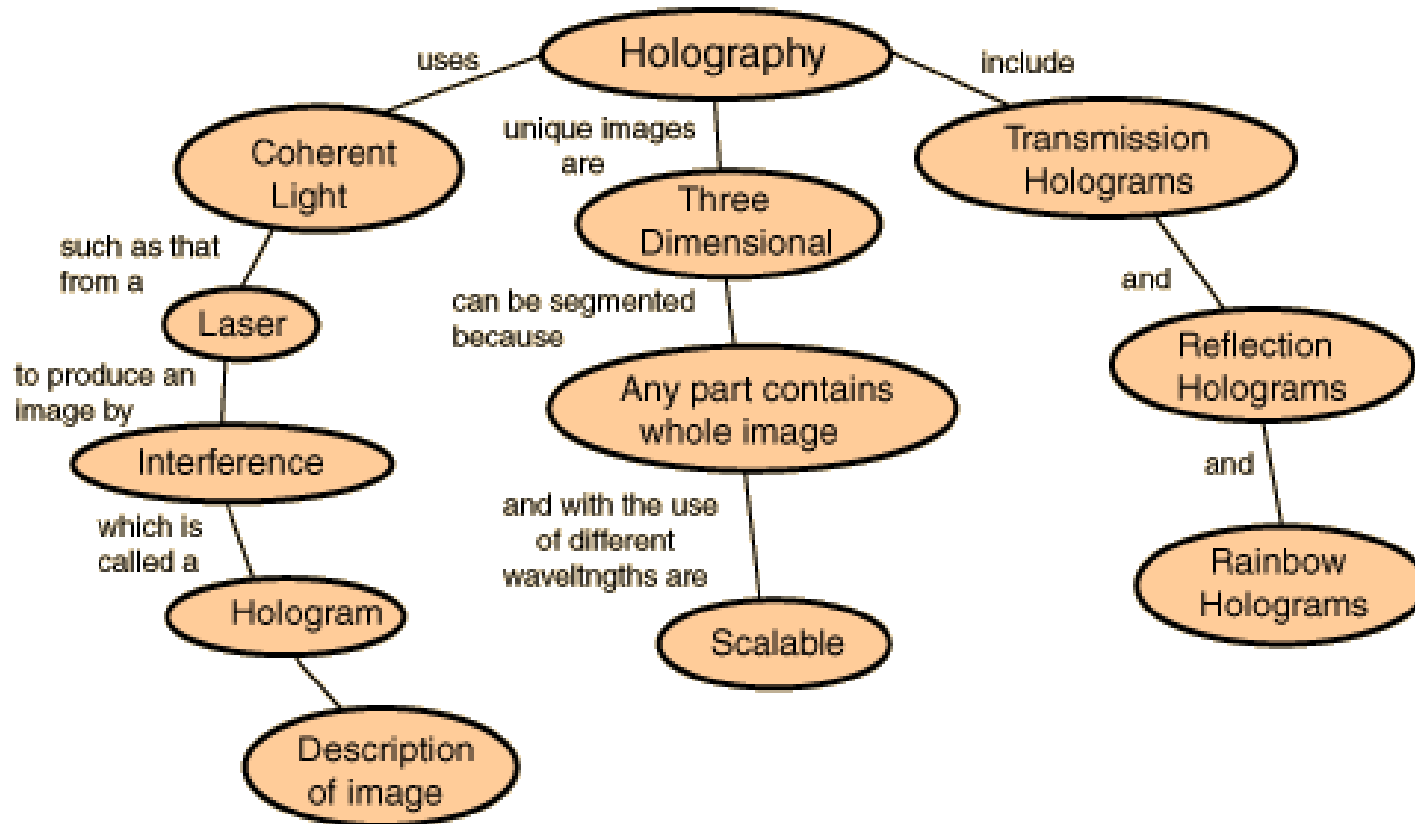


See <http://www.holophile.com/history.htm>

Holography vs. Photography

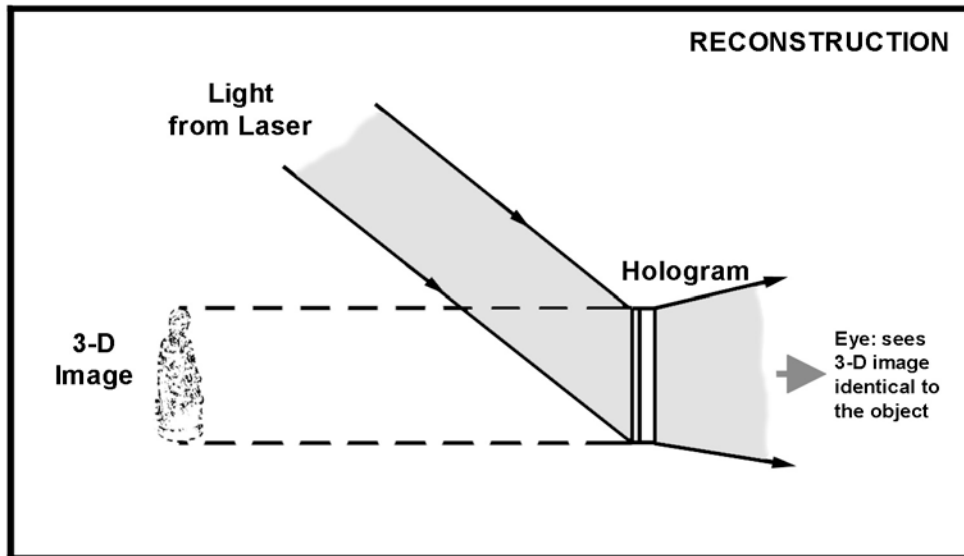
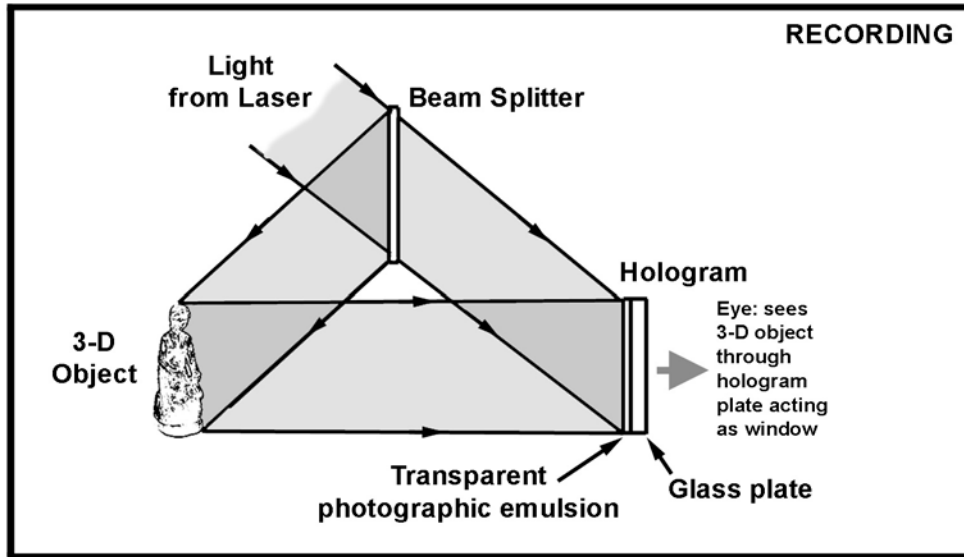
- Photography is a 2D version of a 3D scene;
 - Photography records intensity, phase information is lost;
 - Photography lacks depths perception.
-
- Holography is a 3D version of a 3D scene (“*wholewrite*”);
 - View what we would have seen looking at the original scene through the window defined by the hologram;
 - Holography maintains depths perception.

Holography concepts summarized



“A window with a memory”

Nils Abramsson



Holography is a two-step process:

1. Recording of holograms
2. Reconstruction (and viewing) of holograms

Redrawn from D. Gabor's Nobel Lecture

Holographic interferometry

Interferometry is the technique of superimposing two or more waves, to detect differences between them.

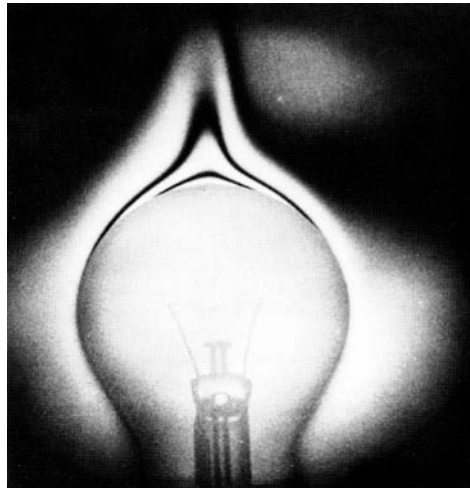
There are three basic methods of holographic interferometry:

1. Real time
2. Double exposure
3. Sandwich

Holographic interferometry can be used to compare objects in different times: If the object under study is changed or disturbed in some way during the hologram exposure or from one exposure to the next, then a pattern of “fringes” will appear on the image itself, making the object look striped. Fringes represent maps of the surface displacement and their deformation may locate defects.

Holographic Interferometry vs. Interferometry

- HI more flexible, more simple. A slight decrease in precision.
- Main advantage: relaxes the need for high optical quality elements!



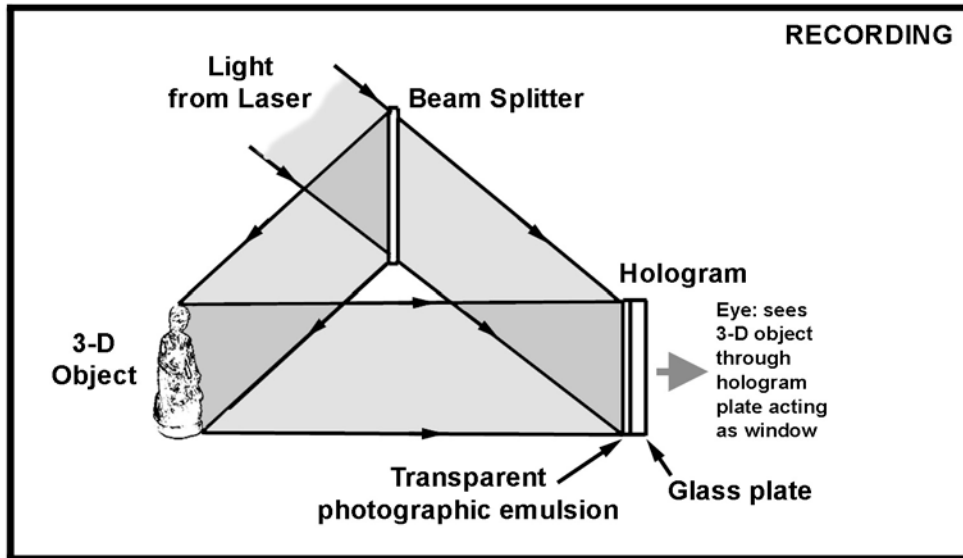
Mach-Zehnder



HI

Real time holographic interferometry

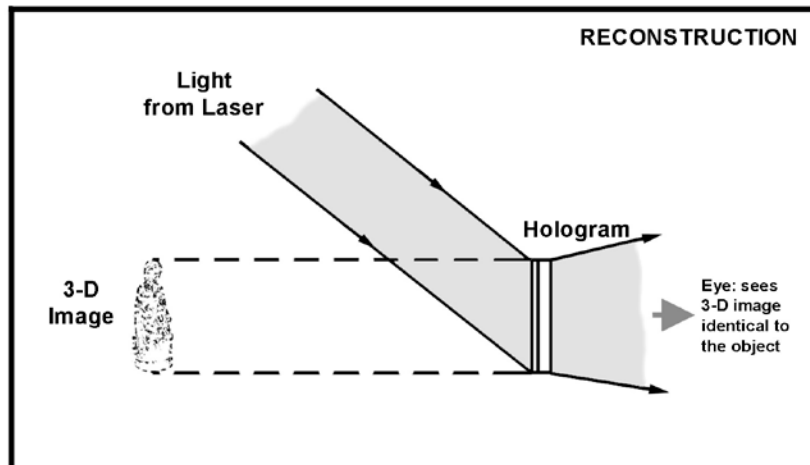
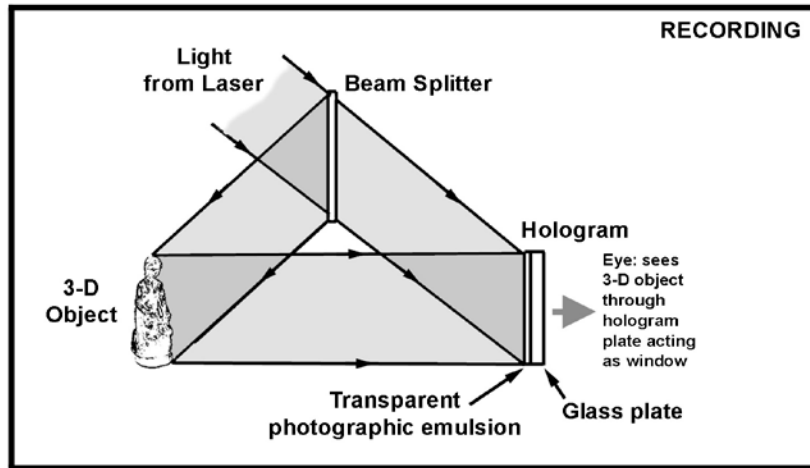
(“live-fringe”)



1. Make hologram
2. Develop hologram and replace hologram in original position
3. Illuminate with reference and object beam
4. If object is deformed interference fringes will be produced

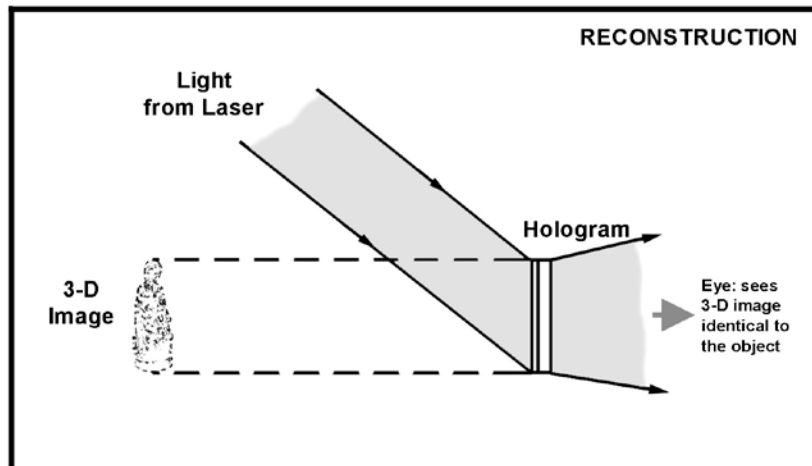
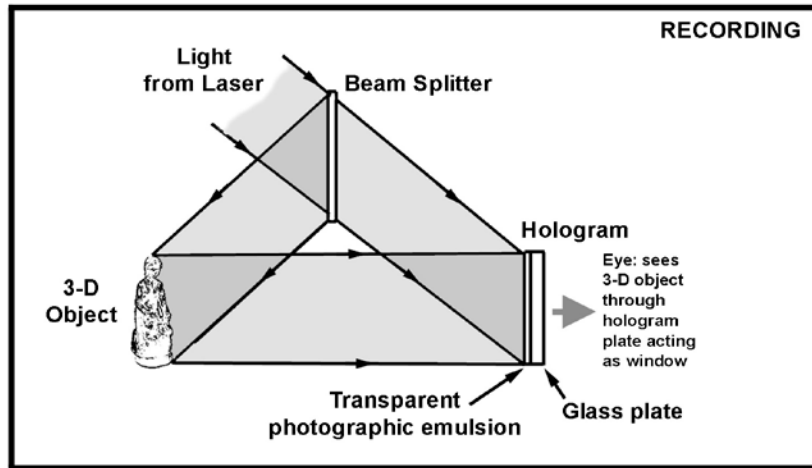
Double exposure holographic interferometry

(“frozen-fringe”)



1. Make hologram
2. [Make a second exposure on same plate](#)
3. Develop hologram and replace hologram in original position
4. [Illuminate with only reference beam](#)
5. If object is deformed between exposures, fringes will appear

Sandwich holographic interferometry



1. Make hologram
2. Make a second exposure [on a different plate](#)
3. Develop holograms and replace in original position
4. Illuminate together with only reference beam
5. If object is deformed between exposures, fringes will appear

Comparison

Real time

- Dynamic information provided (continuous comparison with initial state);
- Low contrast;
- Critical replacement of hologram after processing;
- Recording device needed.

Double exposure

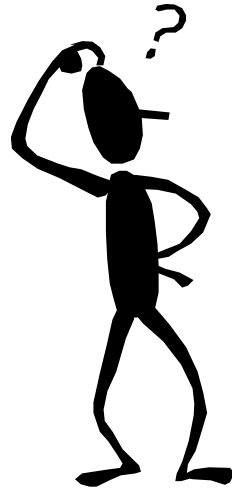
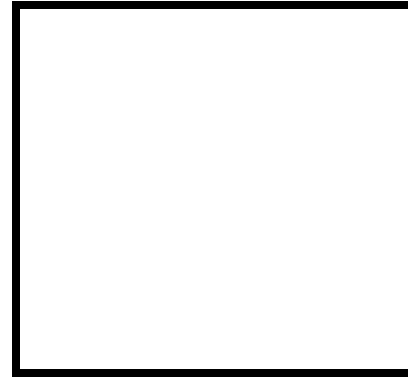
- No dynamic information provided (exposure states fixed);
- Good contrast;
- No critical replacement of hologram;
- Recording device not needed (interferogram freezed on plate).

Sandwich

- Dynamic information possible (using multiple plates);
- Good contrast;
- Fringes manipulation possible;
- Critical replacement of holograms (requires special holder);
- Recording device suggested.

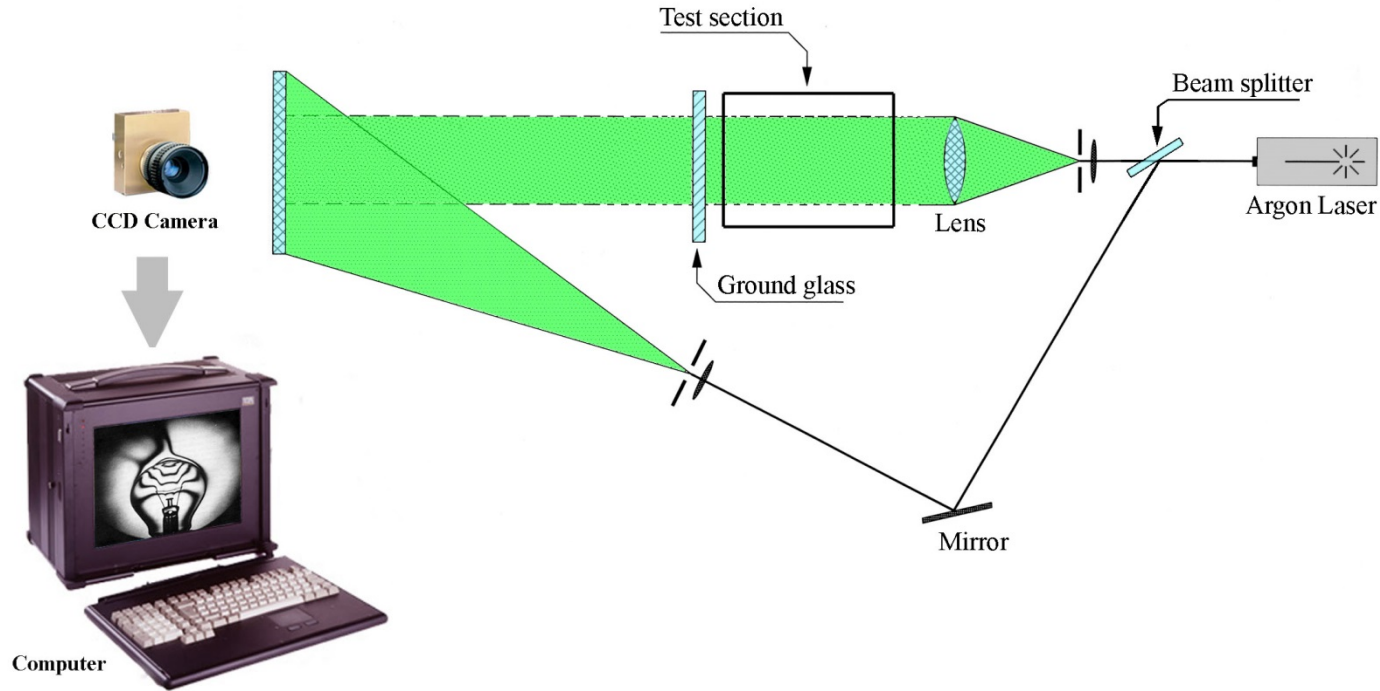
Flow Visualization:

The Art of Seeing the Invisible



Picasso: *The Invisible Man*

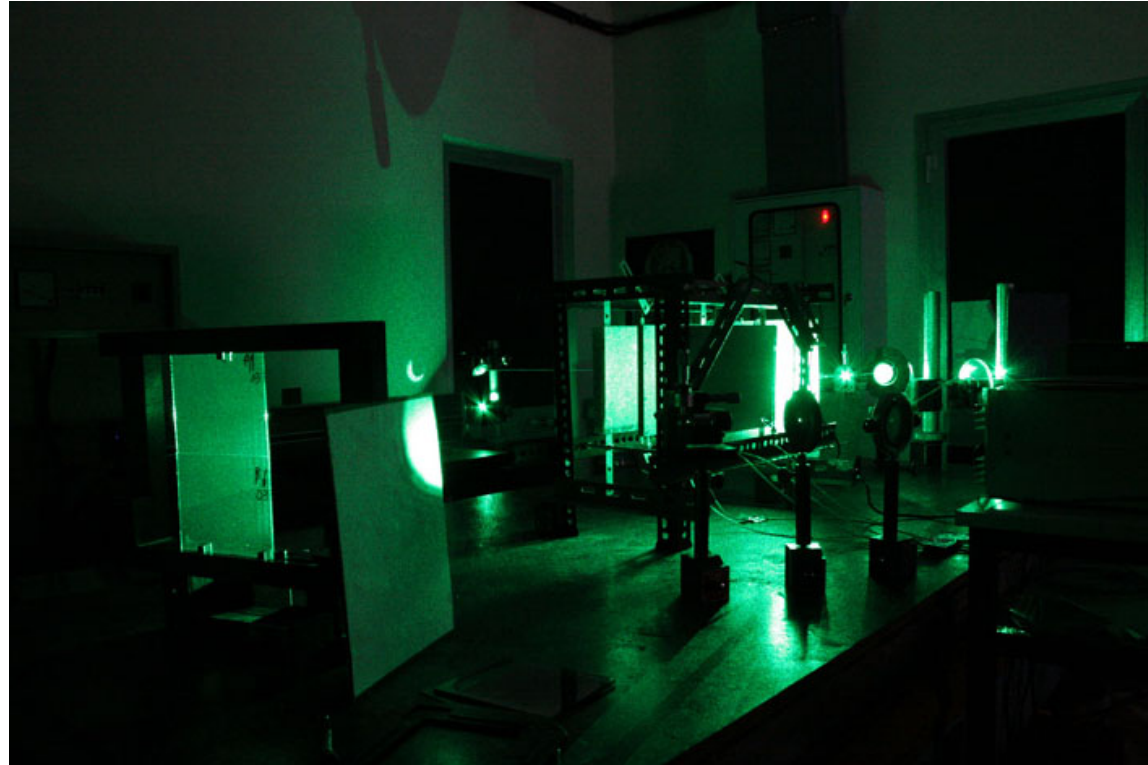
Holographic interferometry



Holographic interferometry maps the thermal field in terms of iso-temperature lines.

Holographic interferometry in our Lab

- Holographic plates: Slavich VRP M; Chemicals Slavich and/or self-produced according to Slavich recipes
- Source: Nd-Yag laser, $\lambda = 532 \text{ nm}$, $P = 250 \text{ mW}$

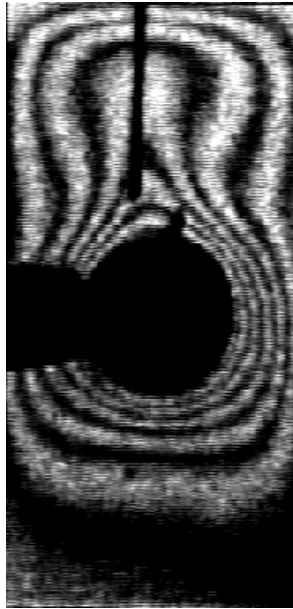


Mathematics

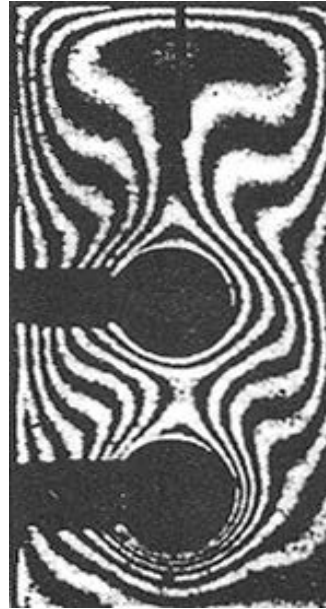
The classical way to analyze double-exposure holograms implies assigning a fixed temperature to each fringe as follows :

$$T_{i+1} = \left(\frac{1}{T_i} + \frac{\lambda}{LC} \right)^{-1}$$

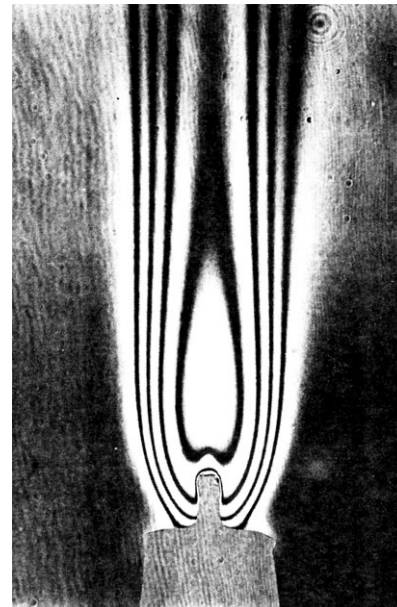
Fringes are counted by assigning number $i = 0$ to the large bright fringe in the undisturbed ambient. Subsequent bright fringes are assigned numbers $i = 1, 2, 3, \dots$ while the centres of all dark fringes are assigned numbers $i = 0.5, 1.5, 2.5, \dots$. The temperatures of undisturbed air ($i = 0$) and of the hot surface (maximum i) are known. The temperature distribution can be obtained by simply measuring the distance between successive fringes on the interferogram picture



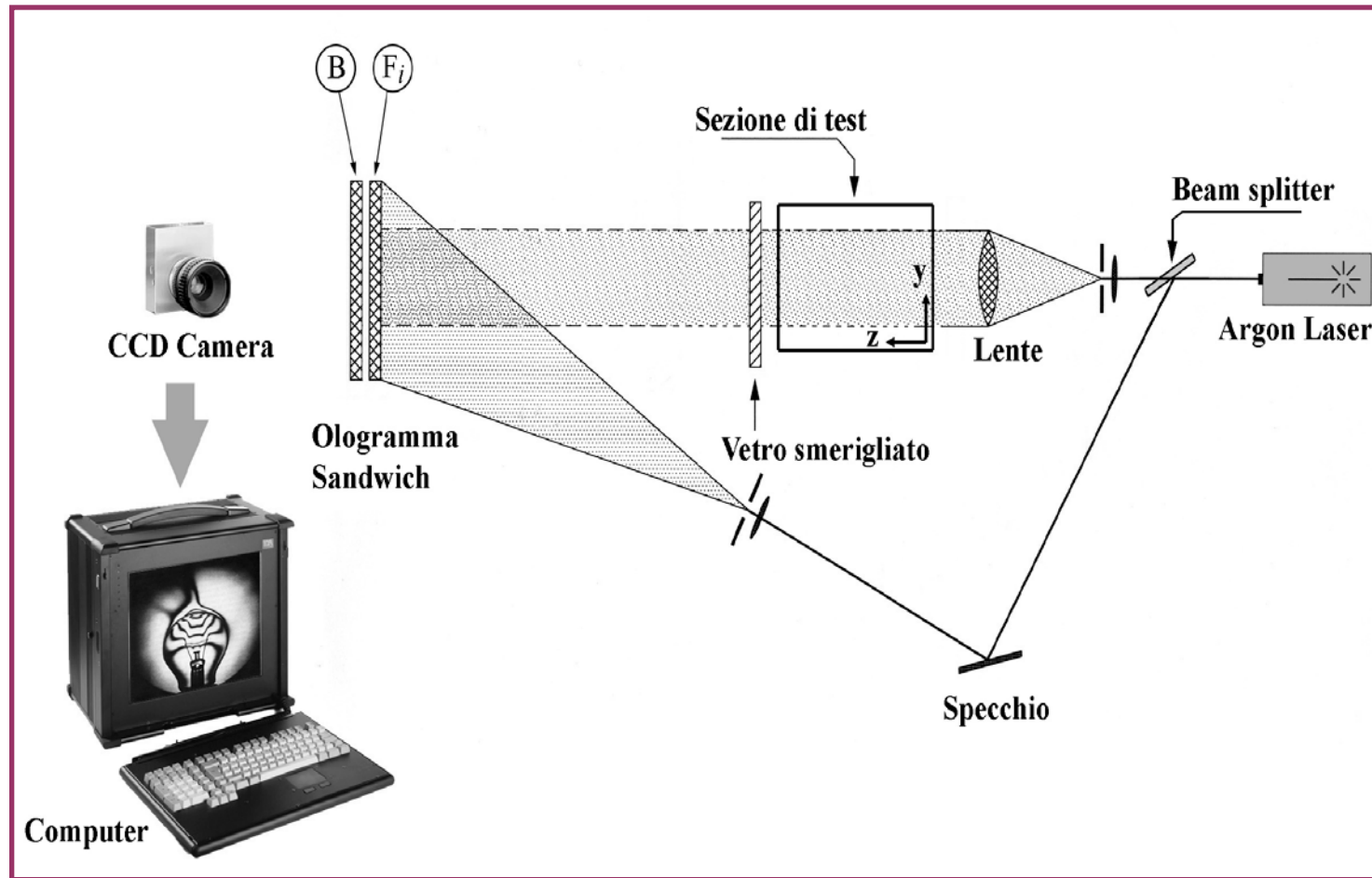
Cylinders in
enclosures
(Courtesy Prof
Cesini)



Candle



Sandwich holography



D. Ambrosini et al., *Sandwich holography for simultaneous temperature visualization and heat-transfer coefficient measurement*, *Optical Engineering* 40, 1274 – 1280 (2001)

Pros: a real-time / double exposure hybrid; fringes can be manipulated.

Cons: difficult technique: skilled operators and special holders needed.

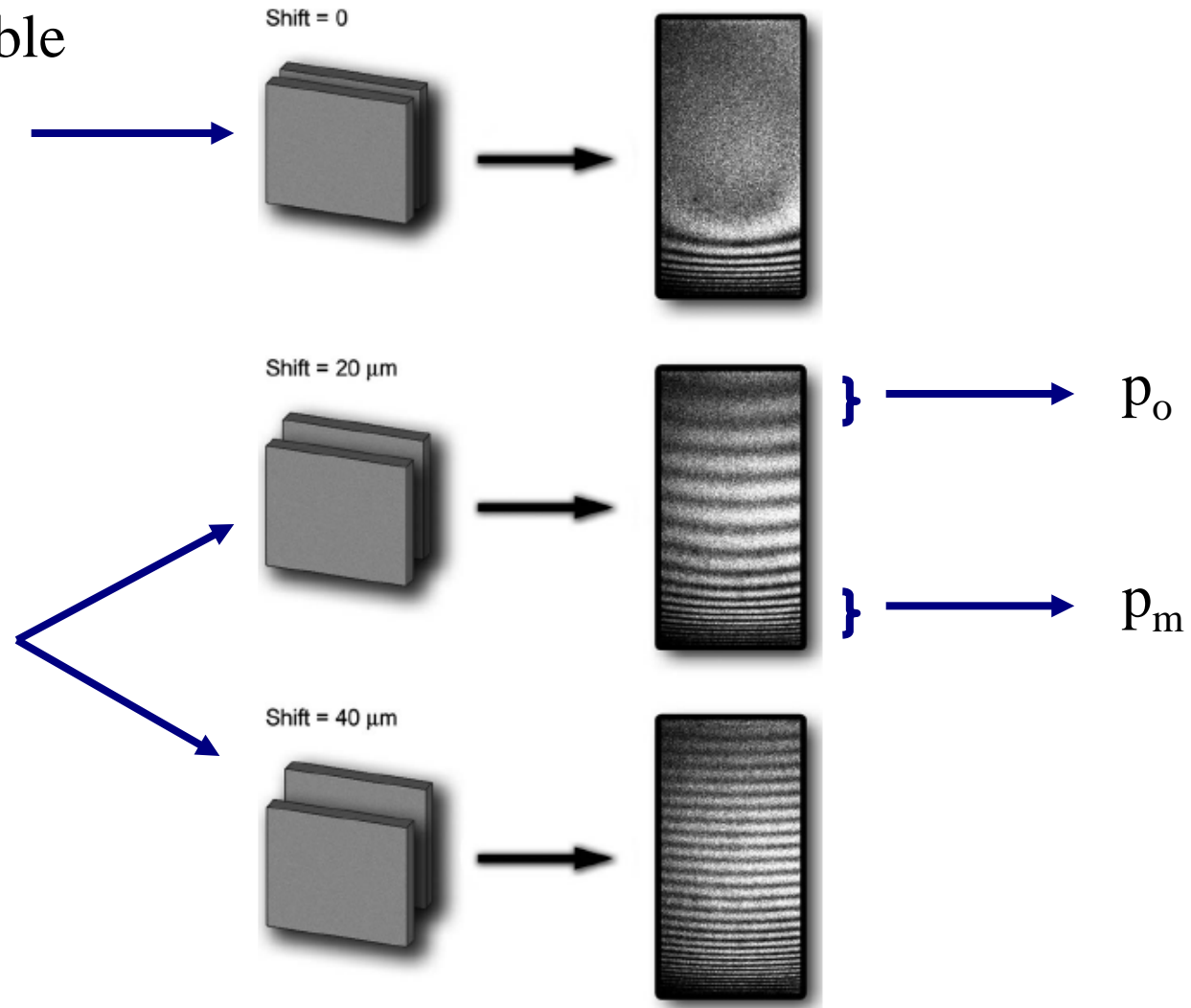
$$h = \frac{k}{T_p - T_a} \frac{\lambda}{L} \left[\frac{1.08559 \times 10^{-6}}{\left(1 + 0.369203 \times 10^{-2} T_p\right)^2} \right]^{-1} \left(\frac{1}{p_m} - \frac{1}{p_0} \right)$$

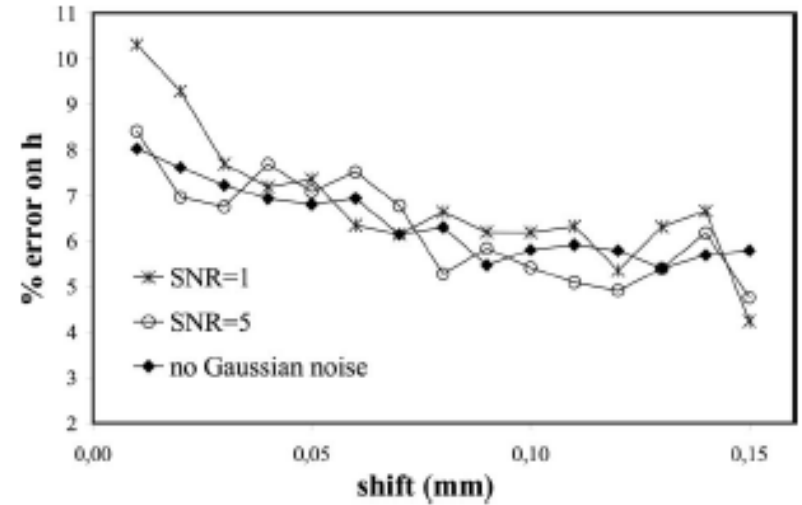
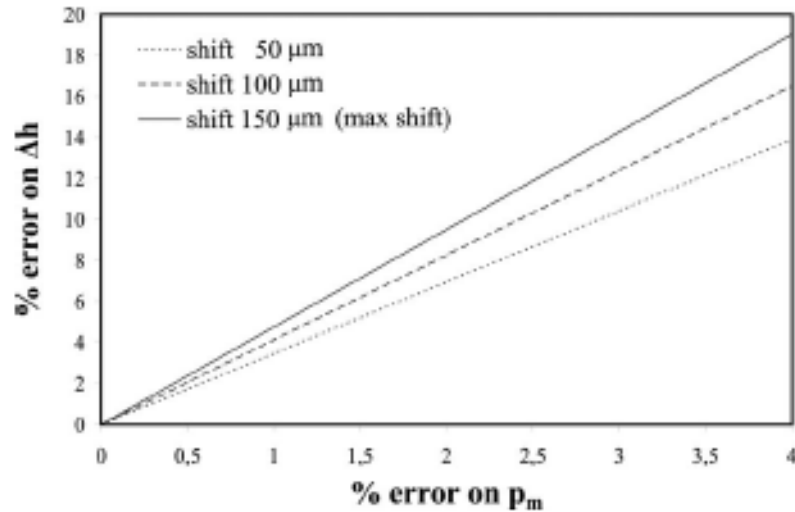
The convective coefficient h can be deduced from geometrical parameters. Air at T_p (in °C), $\lambda = 514.5$ nm, p_0 e p_m suitable fringe spacings.

Free convection in water from a colder plate surface (temperature difference ~ 1.5 K).

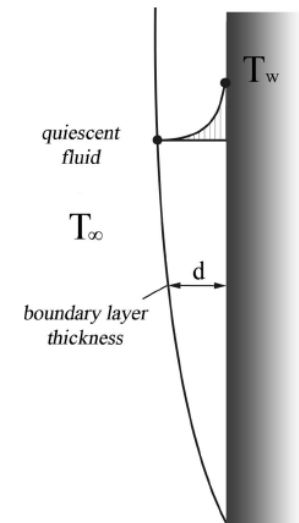
Equivalent to a double exposure hologram: fringes maps the thermal field.

Fringes no more directly related to the thermal field: can be elaborated to obtain h .

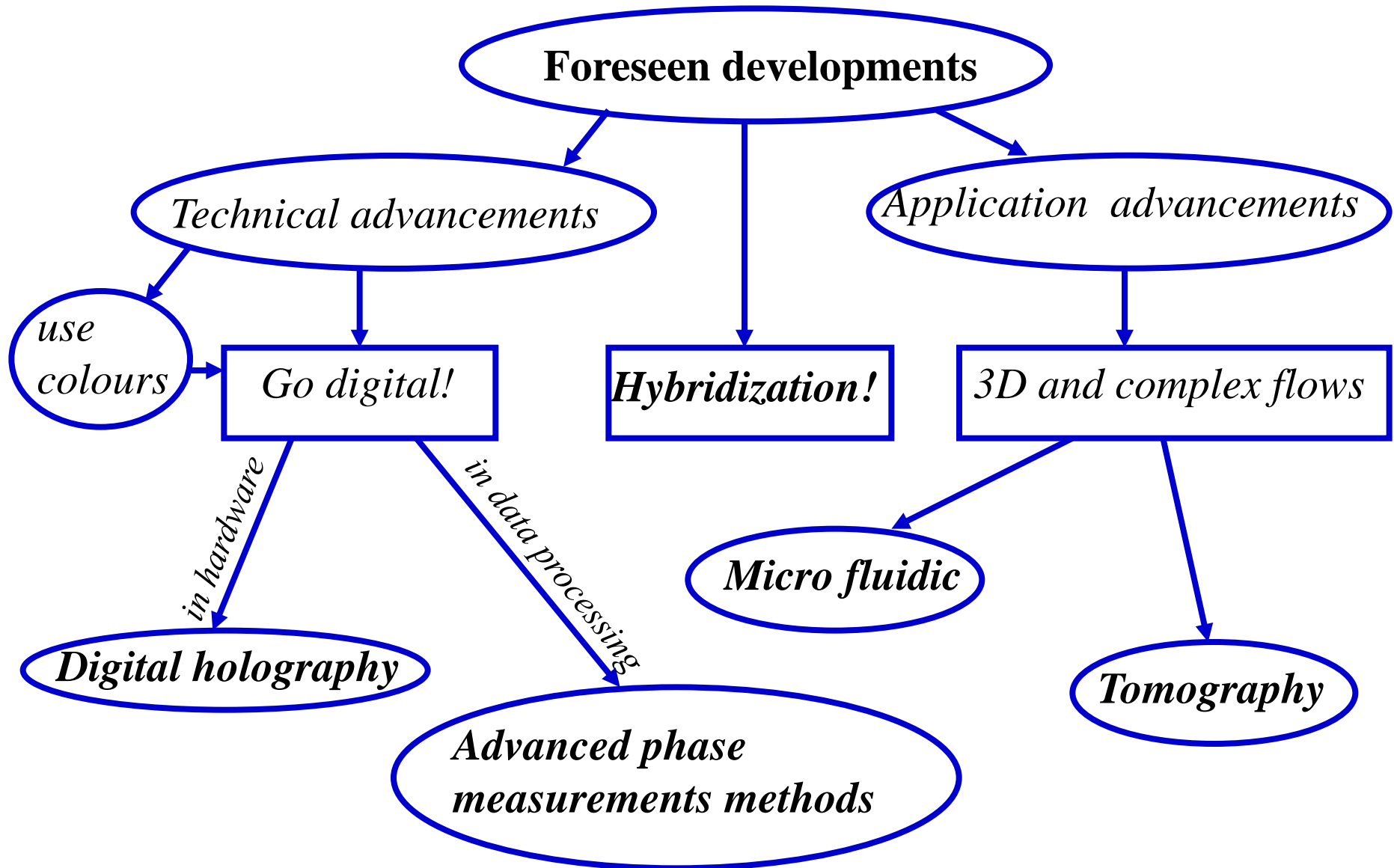




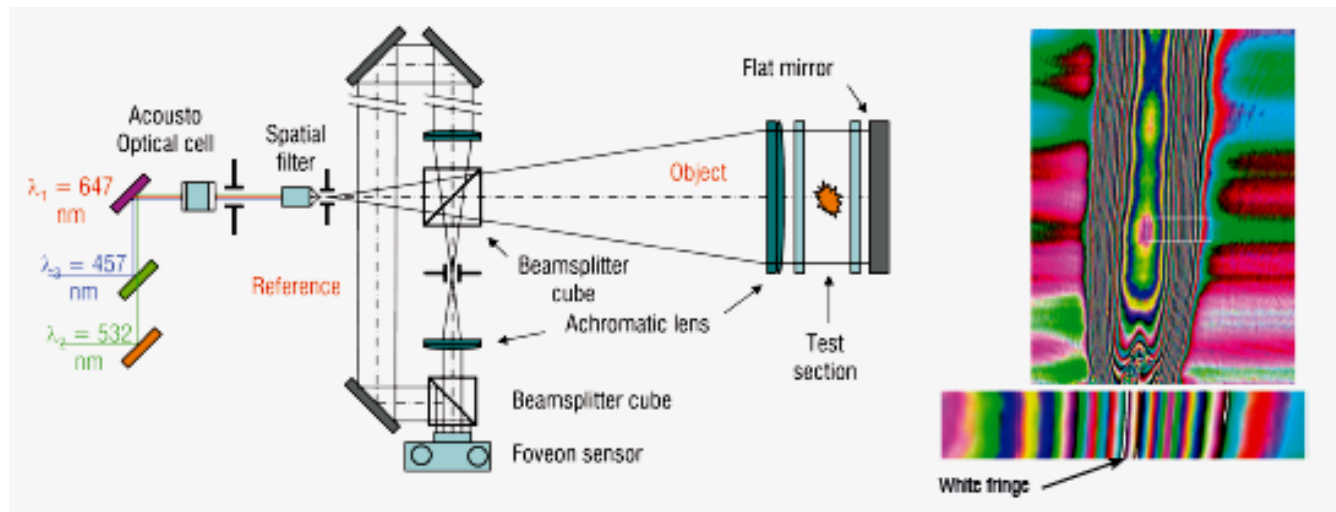
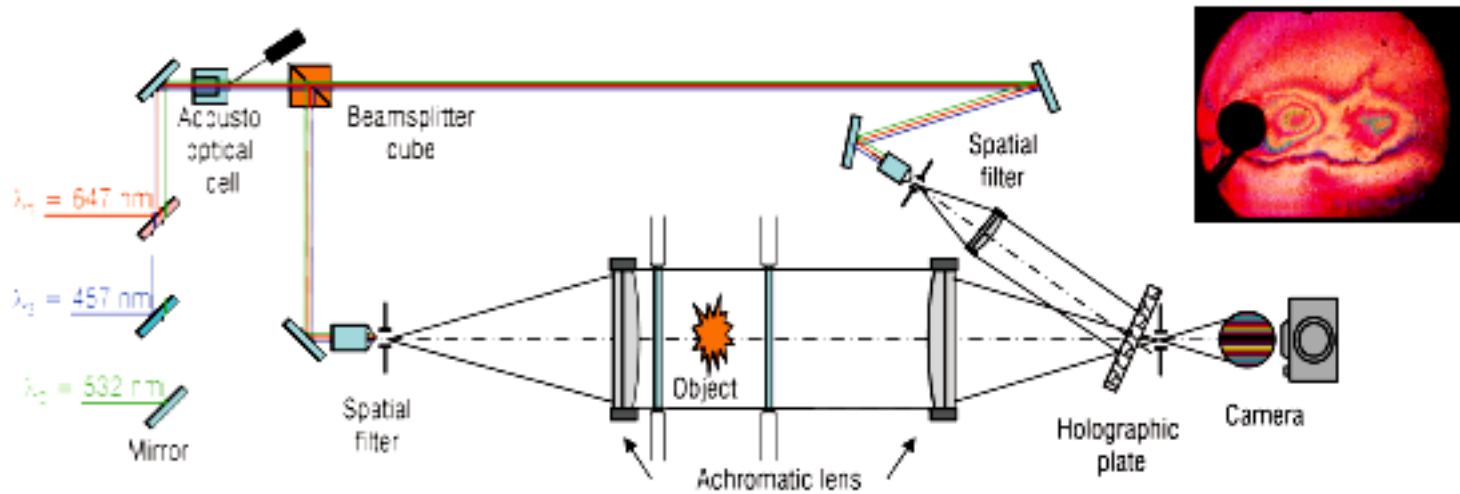
Overall uncertainty for the present technique of h measurement is estimated on the order of 7 to 8%.



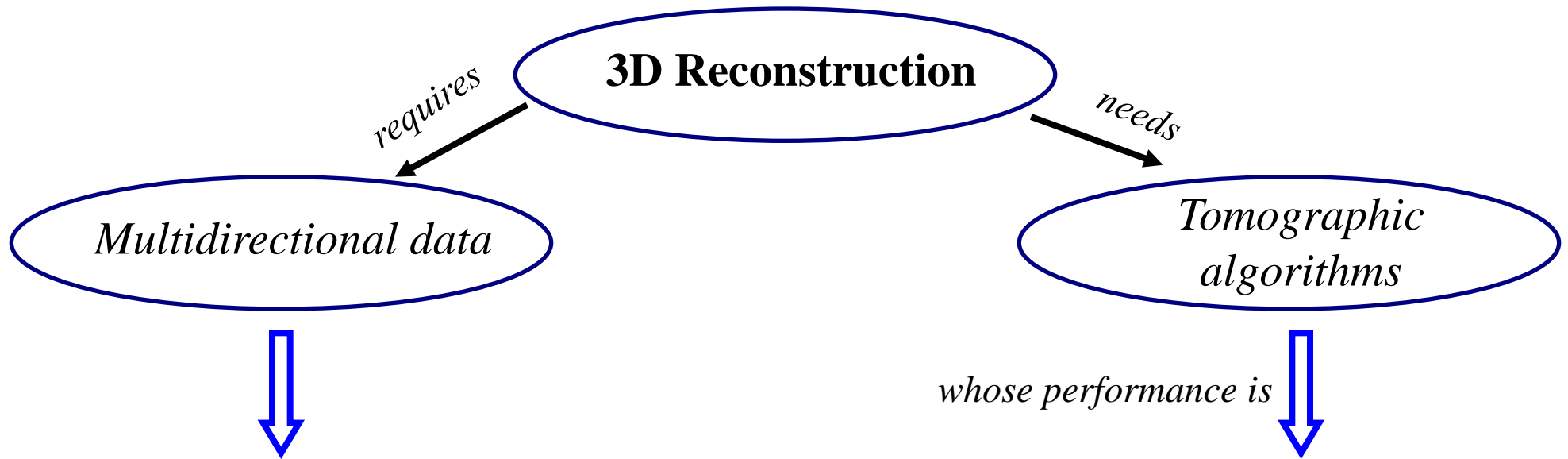
Issues for the future



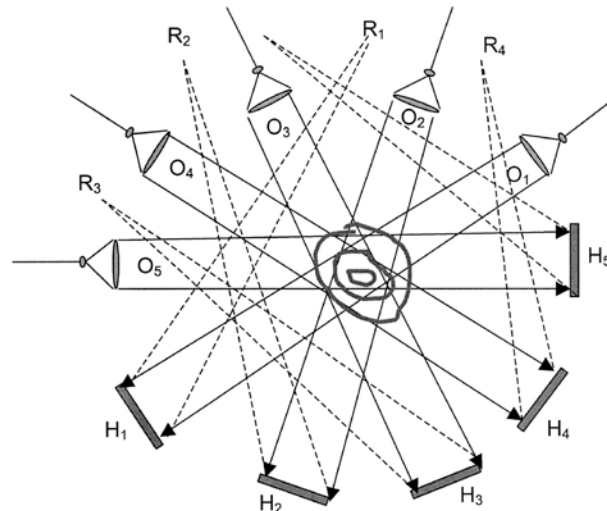
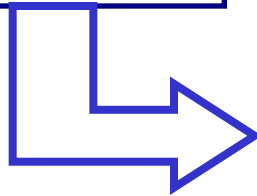
Colour Holography (also digital)



Tomography



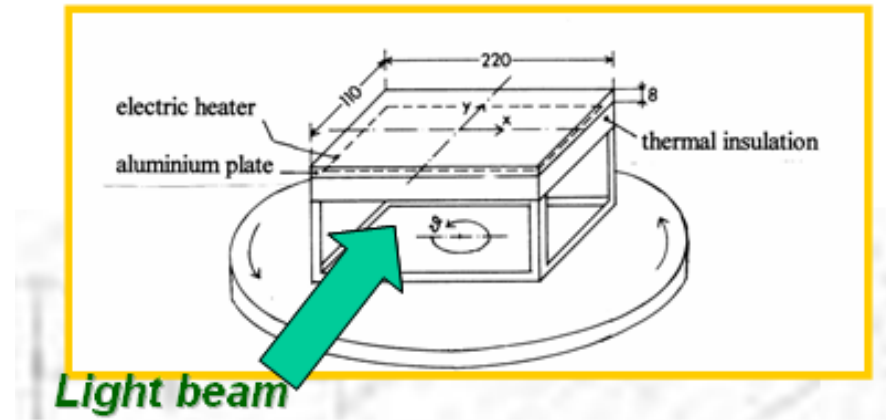
High experimental complexity



- *Data dependent*
- *Application dependent*

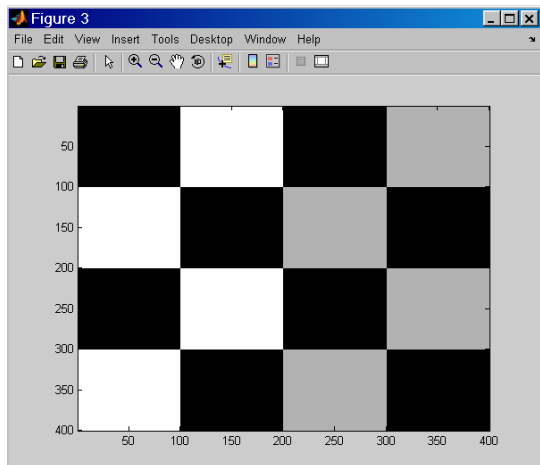
A possible solution

Measuring along one line
only and rotating the test cell

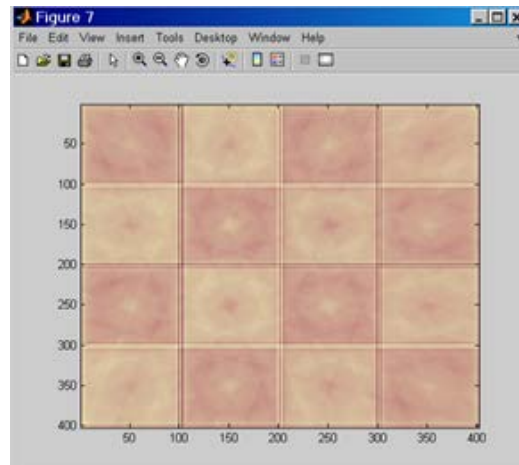


Choose the reconstruction algorithm which suits best:

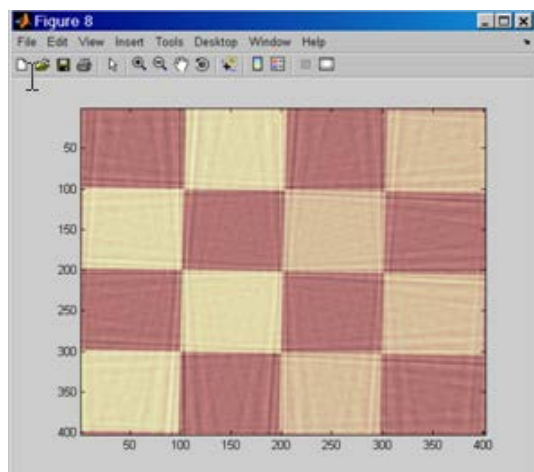
Tomography is largely used in medicine (therefore useful algorithms could be borrowed from it) but in medicine, usually, a large number of projections are used.



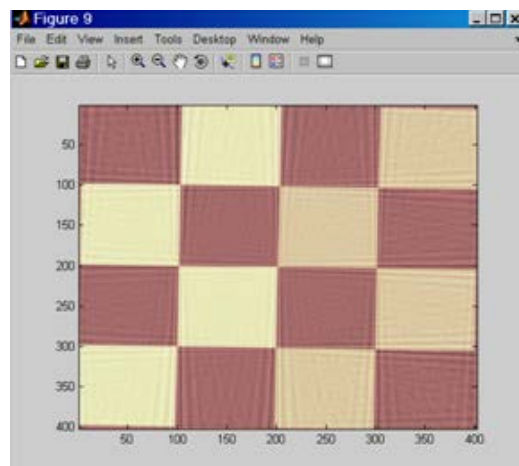
original



10 projections

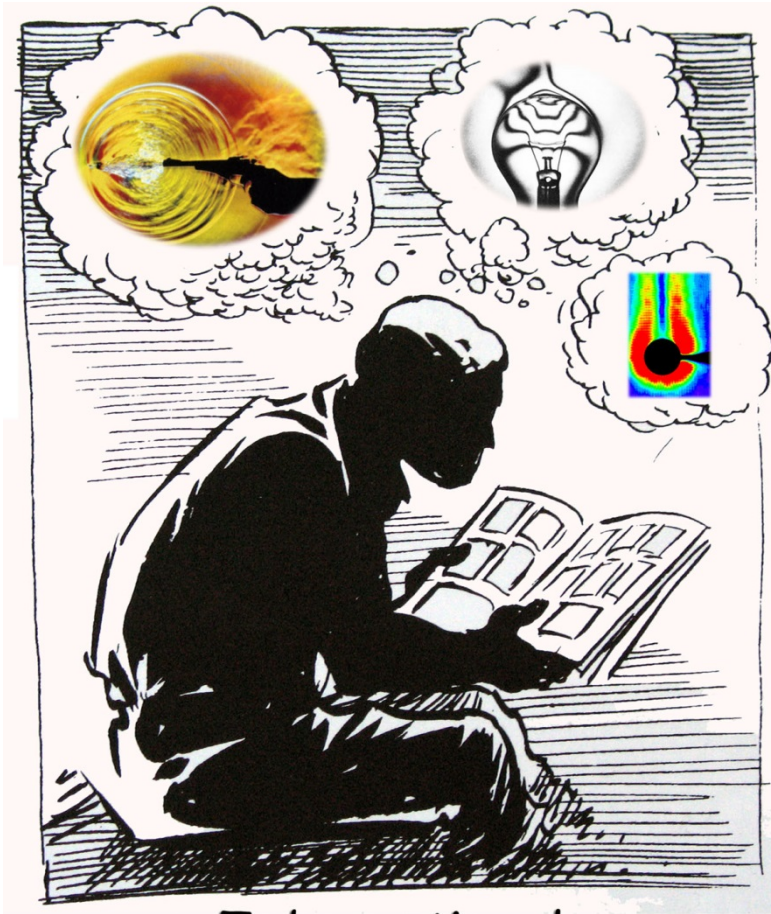


60 projections



90 projections

Simulation realized using the free Matlab tool *Image reconstruction Demo*, by H.H. Muhammed, Royal Institute of Technology, Sweden



To be continued