Capturing sound

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Driving forces to innovations

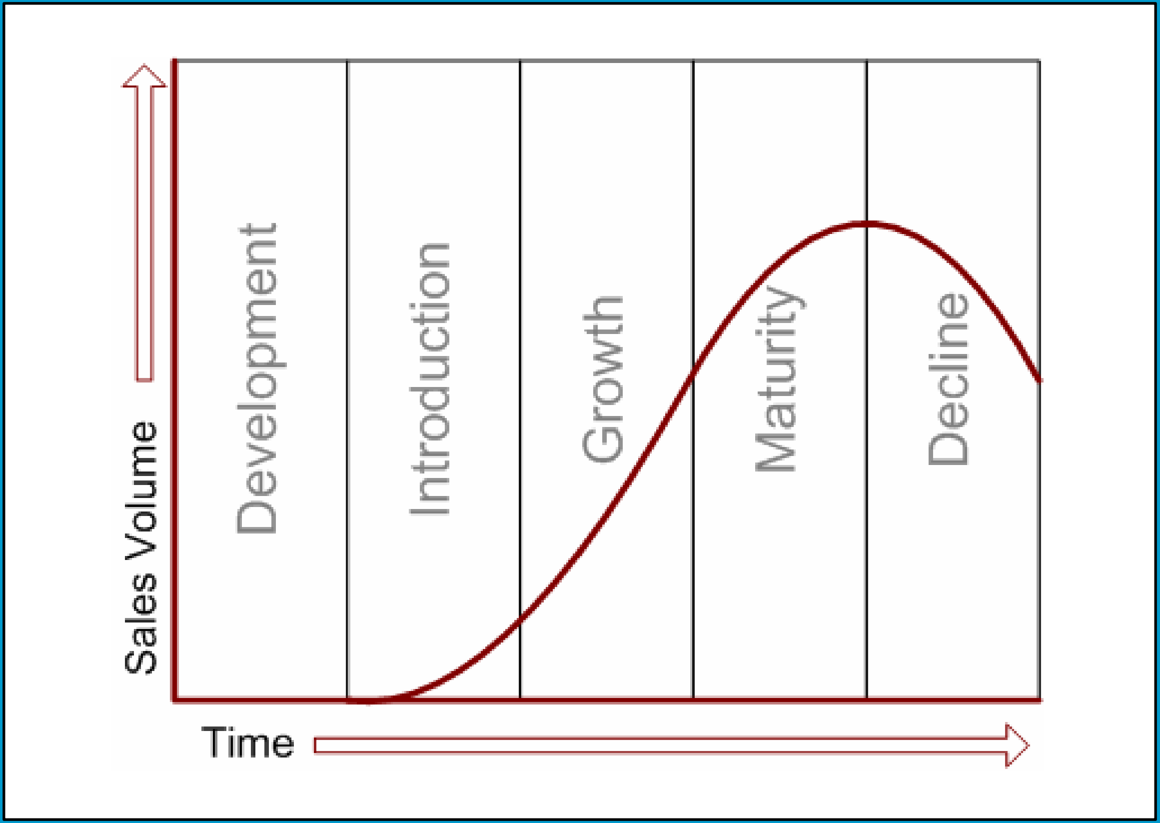
Human demands

- less work (effort)
- quicker (speed)
- better (quality)
- cheaper (cost)
- ......

Human curiosity

- progress in science

Life cycle of products



Capturing and storage of information

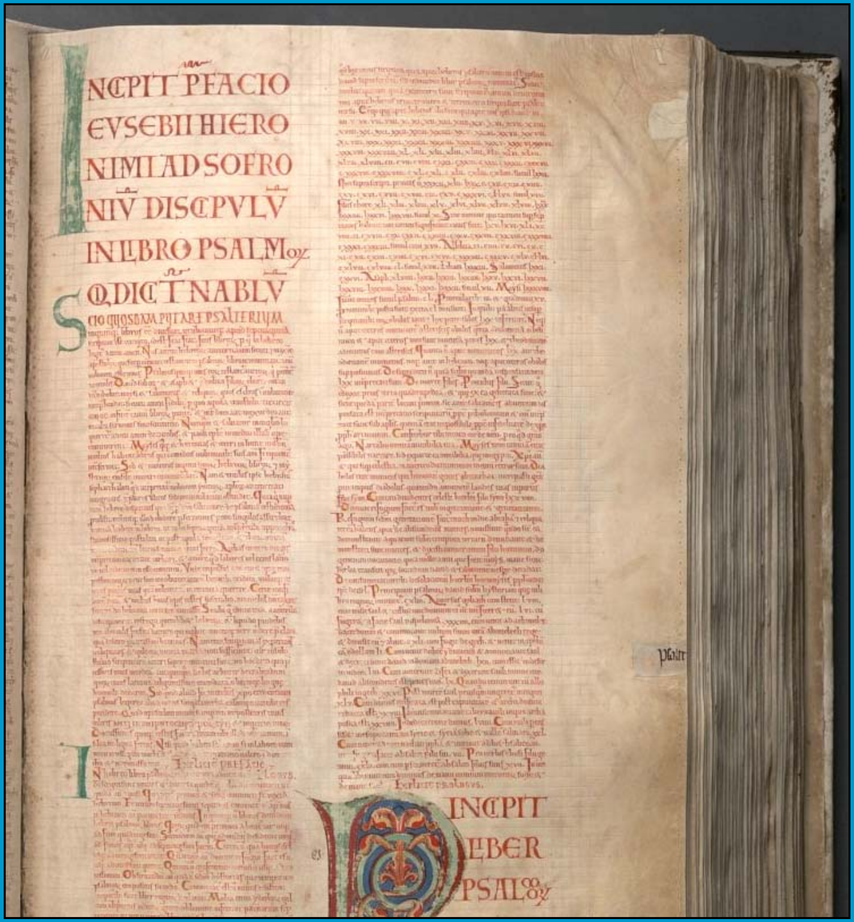
- written text
- audible waves
- still and movable pictures
- data

First storage of text

effort	--
speed	--
quality	+
cost	-

- cuneiform - ancient Middle East

Storage of text (medieval period)



- Codex Gigas
  - approx. year 1200
  - 300 pages
  - 900 x 500 mm

effort	--
speed	--
quality	+
cost	-

Information processing

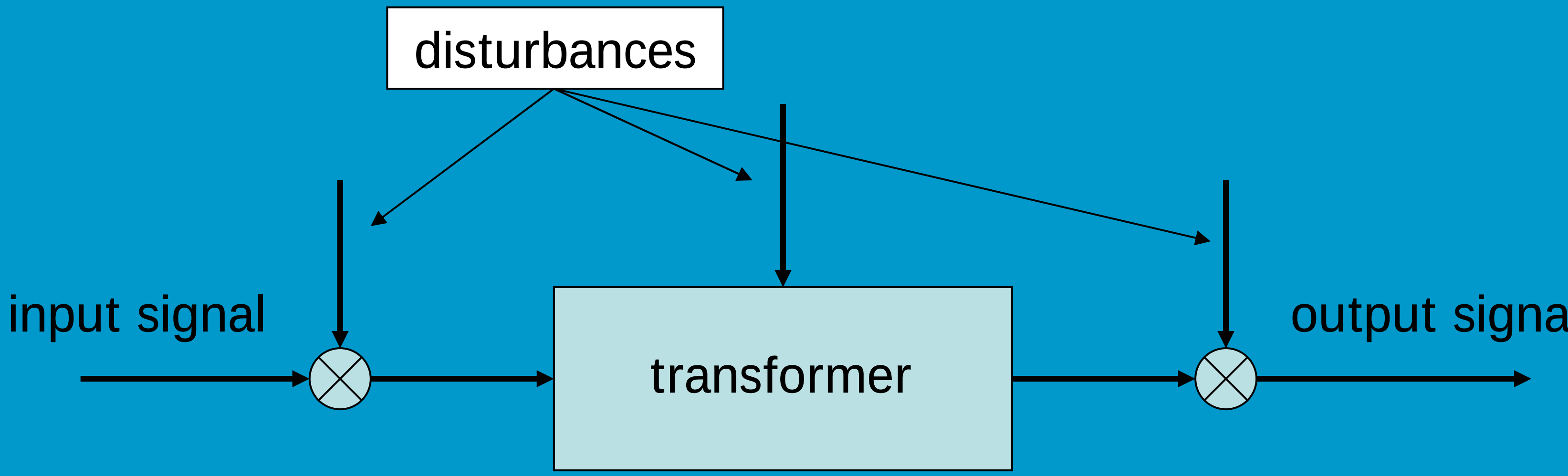
Purpose of information processing:

- make quantity X (better) observable to human senses
- make quantity X suitable for further processing (evaluation, storage, reproduction etc.)
- X to Y – usually transfer to another energy domain

Information processing

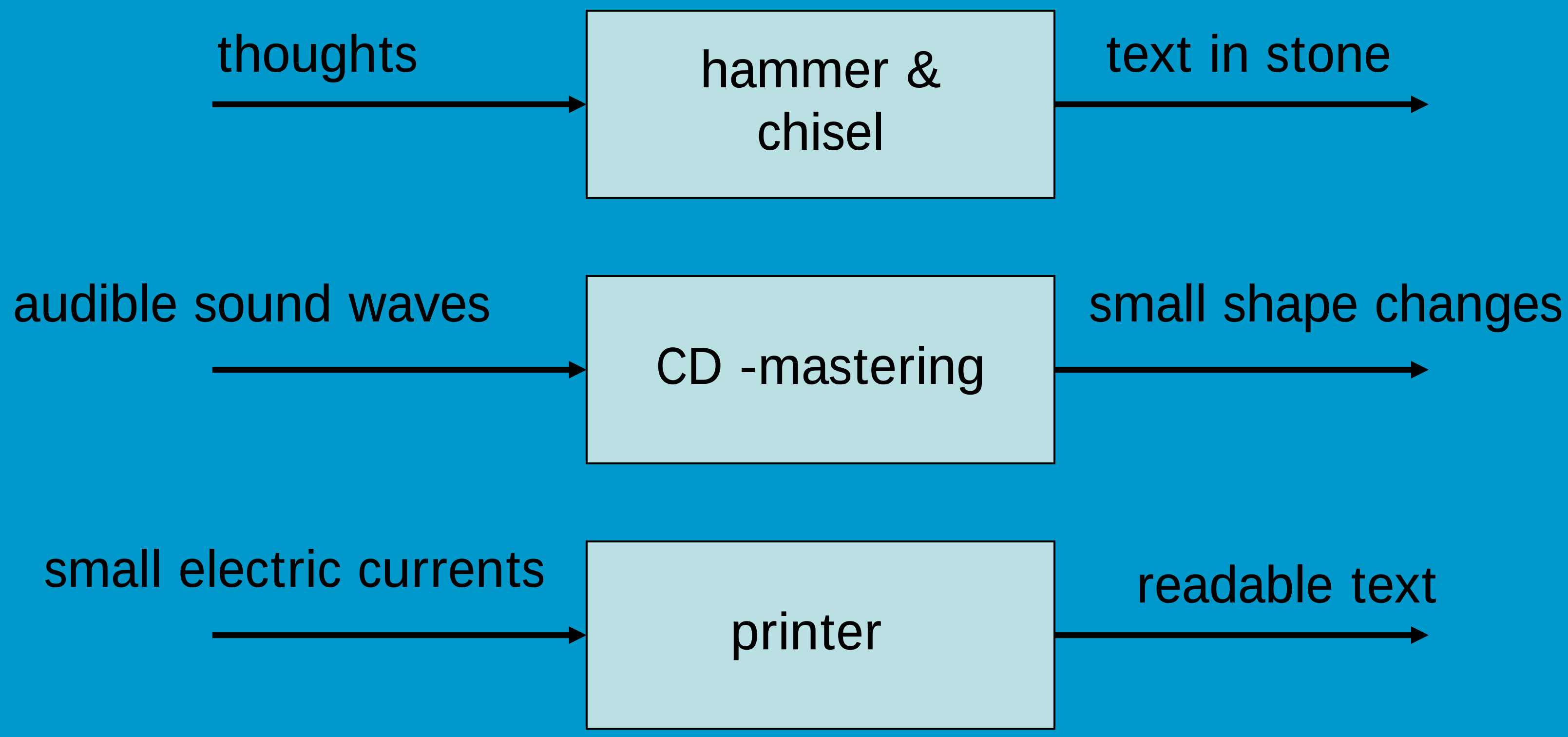
Demands on transformation transducers:

- accuracy of information transformation
- insensitive to external and internal disturbances



Information transducers

Examples:



Information transducers

Primary concern with transformation:

loading of the input source must be as low as possible

(in general the solution is minimizing mass of the components)

Sometimes additional energy necessary to support the transformation

Major trend:

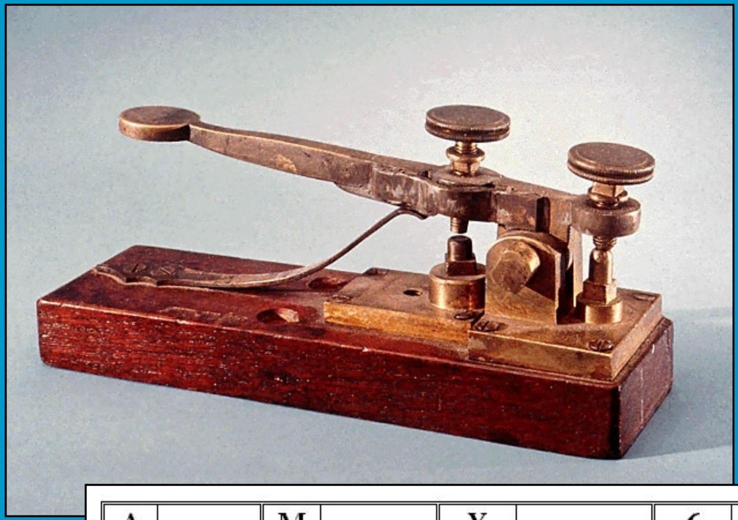
from pure mechanical transformation means toward mixed electro mechanical devices up to pure electronic solutions

Sound recording – storage of audio information

How it began?

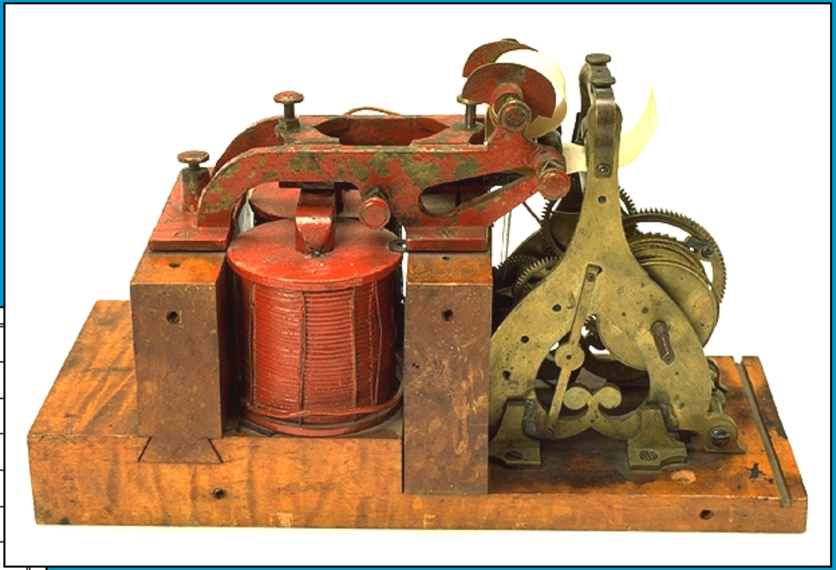
- invention of a telegraph and telephone
- need for recording messages and voices
- Thomas Edison was developing a machine that would transcribe telegraphic messages through indentation on paper tape
- in the same way speaking vibrations would made similar indentation in the paper (in a digital way !!)

Invention of a telegraph and telephone

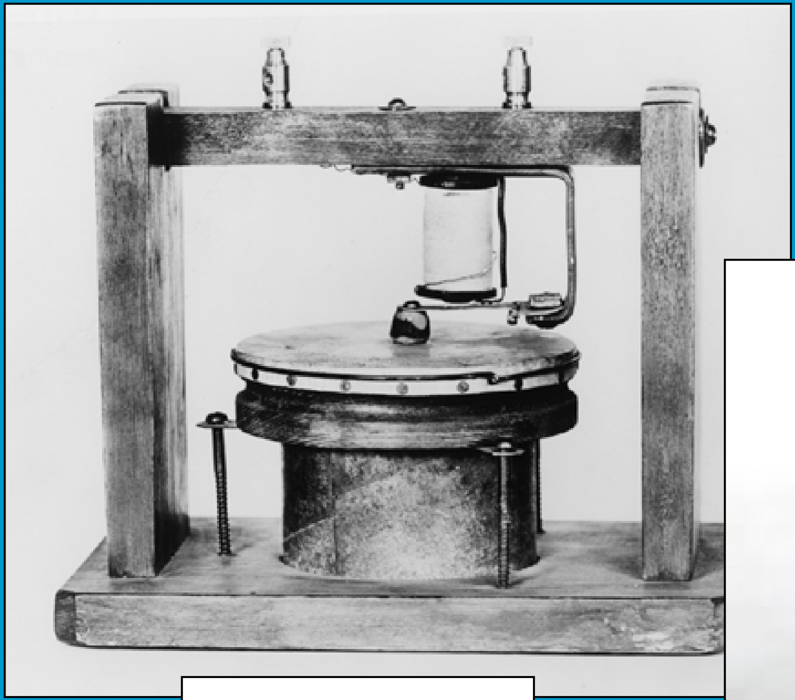


A	.-	M	--	Y	-.--	6	-....
B	-...	N	-.	Z	--..	7	--...
C	-.-.	O	---	Ä	.-.-	8	---..
D	-..	P	.--.	Ö	---.	9	----.
E	.	Q	--.-	Ü	..--	.	.-.-.-
F	..-.	R	.-.	Ch	----	,	--..--
G	--.	S	...	0	-----	?	..--..
H	....	T	-	1	.----	!	..--.
I	..	U	..-	2	..---	:	---...
J	.---	V	...-	3	...--	“	.-..-.
K	-.-	W	.--	4	....-	‘	.----.
L	.-..	X	-..-	5	.....	=	-...-

- Telegraph using Morse (digital) code



Invention of a telegraph and telephone



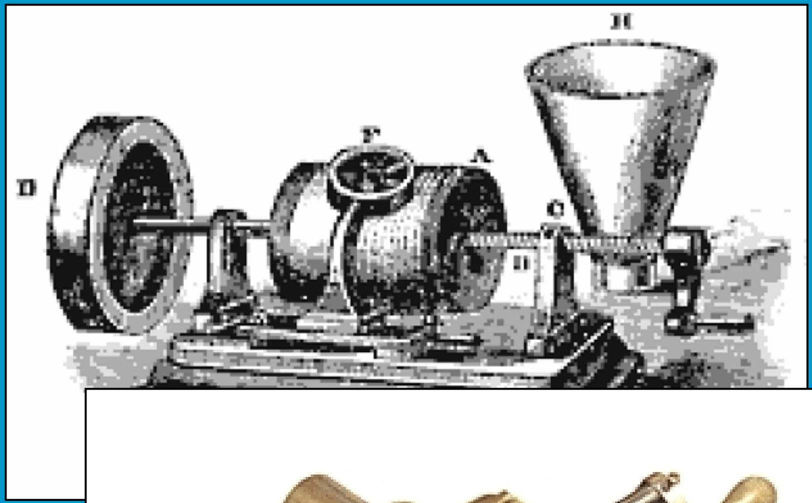
prototype

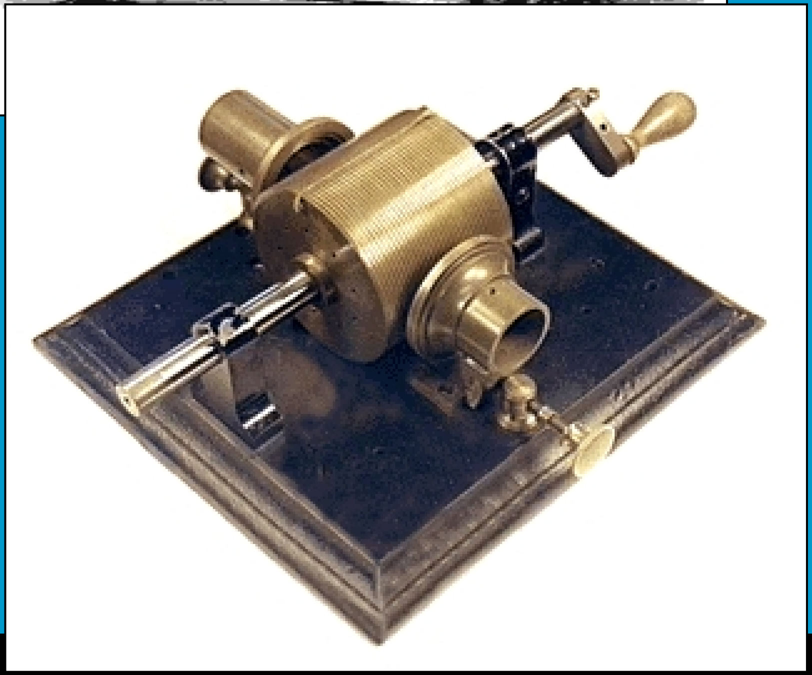
- Graham Bell's first telephone

Storage of audio information

- sound recording
  - variations of air pressure in time
  - need for time dependent storage medium
    - running paper tape
    - rotating drum
    - running wire
    - rotating disc

Storage of audio information





- 1877 – the first prototype of a phonograph:
- instead of paper tape metal cylinder with tin foil around it
- when speaking into the mouthpiece, the sound vibrations were indented by the recording needle in a vertical (hill and dale) pattern

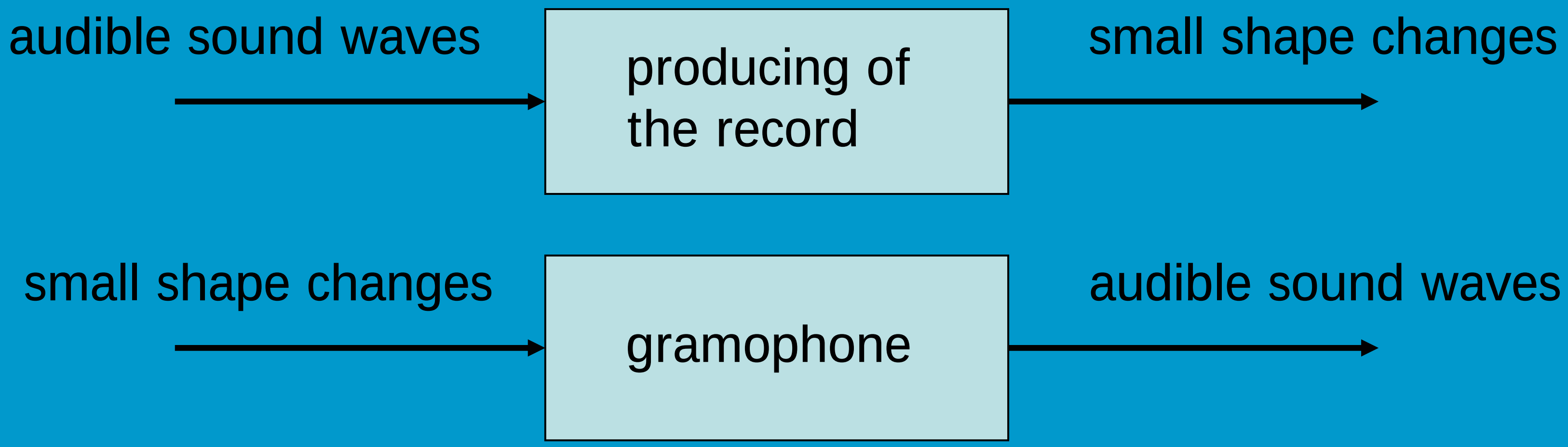
History of recording

Amazing speed of utilization of Edison’s invention

- December 4, 1887 – first sketch of the phonograph
- December 6, 1887 (30 hours later) – the first working prototype
- January 24, 1888 – establishment of Edison Speaking Phonograph Company
- February 19, 1888 – patent # 200.521 issued on this phonograph

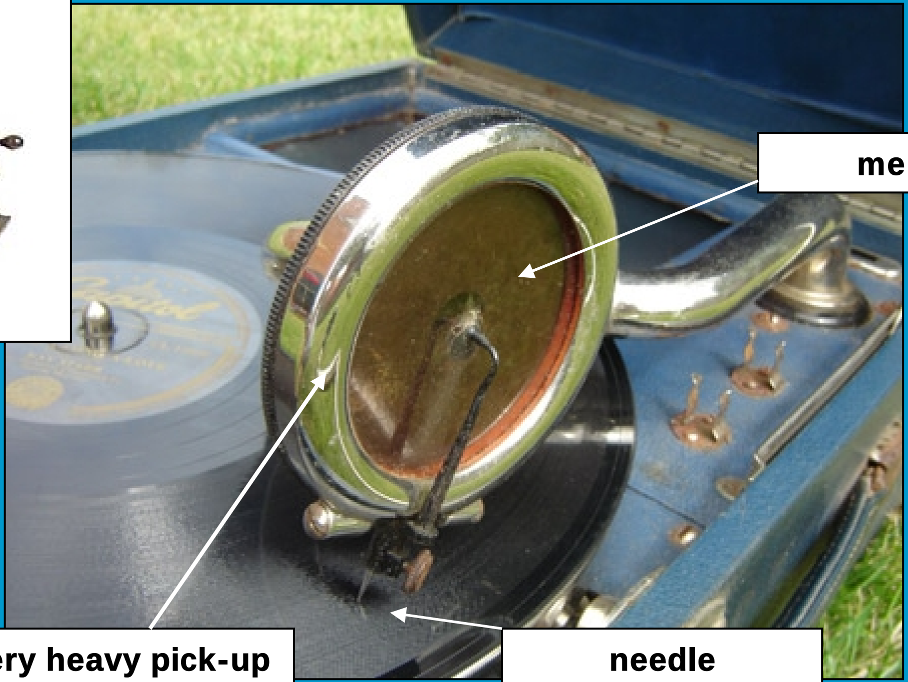
Audio recording and reproduction

- The heart of the transducer – a membrane (acting as a drumhead)
- Producing a record and reproduction of sound in pure mechanical way



Audio recording and reproduction

- In the beginning recording and reproduction in pure mechanical way



recording cylinder evolved in a disk
primary concern with this transformation:
loading of the input source was to high

Development of audio recording

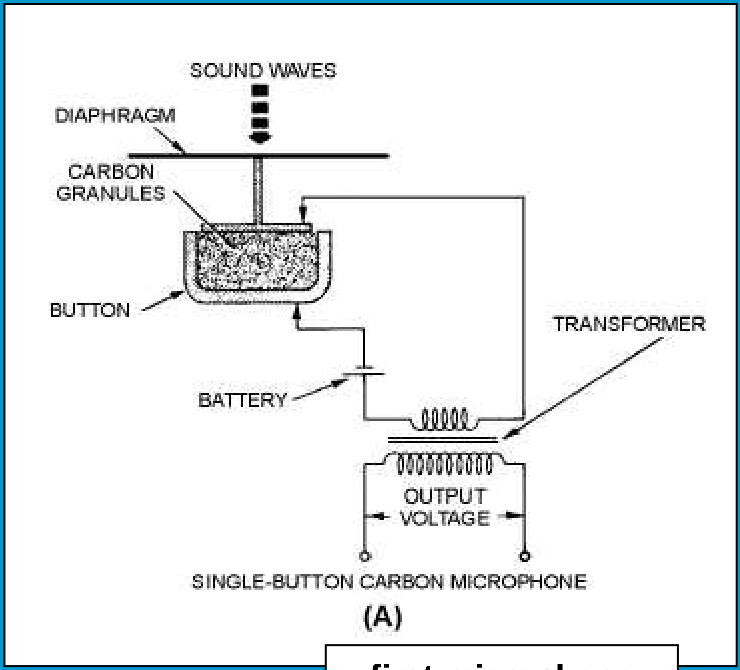
- recording cylinder evolved in a disk (storage and advantage) – year 1887 !!
- disk shape made it easier to produce copies of original recording
- loading of the source (large force pushing the needle into the groove) was to high (wear – degradation of the sound quality)

SOLUTION:

- get rid of the direct mechanical way of reproducing sound
- additional energy necessary to support the transformation
- minimizing mass of all moving components
- use of clever engineering solutions (gravity force compensation)

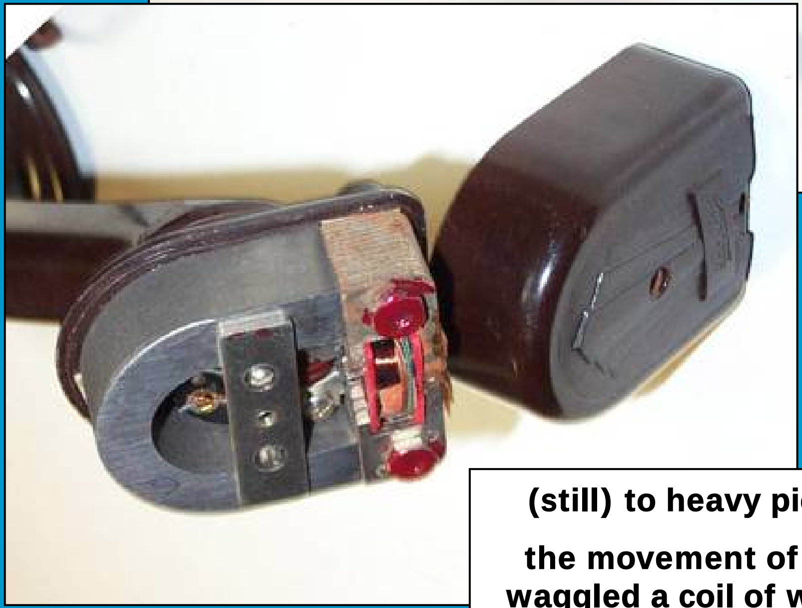
Audio recording and reproduction

- Big step – use of electrical transducers



first microphone

electrical pick-up



(still) to heavy pick up head

the movement of the needle waggled a coil of wire within a powerful magnet

Audio recording and reproduction - magnetic recording

it was almost impossible to make copies of the records

Poulsen Telegraphone, 1898,

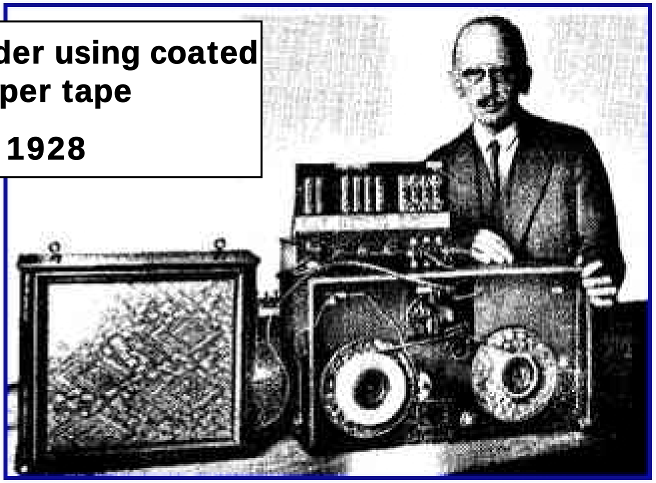
Poulsen Telegraphone, 1898,

answering machine using metal wire

1898

first recorder using coated paper tape

1928



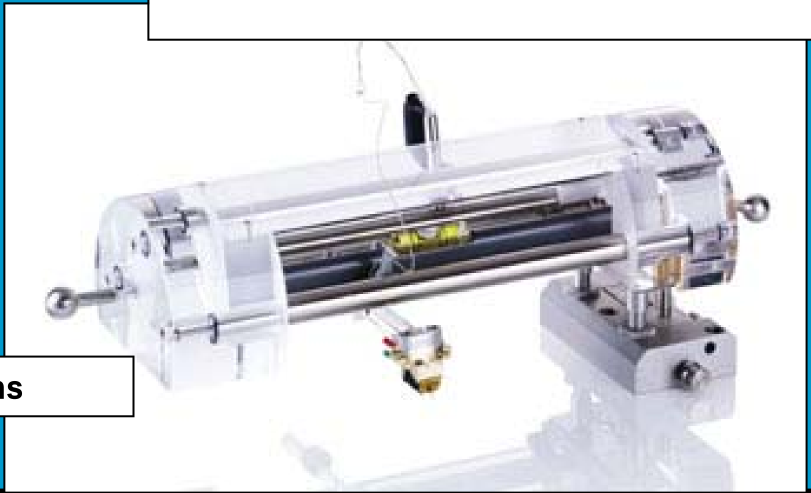
Fritz Pfleumer, ca. 1928

AEG Magnetophon, 1935,

Further development of audio recording

- brittle “shellac” disc records (78 rpm) replaced with vinyl LP (33 rpm)
- recording time rose from 3 min. to 25 min.
- increase in frequency response (from 168 - 2000 Hz to 20 Hz 45 kHz)
- first stereo two-channel records (1958)
- quadraphonic records in 1971
- high fidelity turntables and pick-up arms

Audio recording and reproduction – state of the art of analogue audio (year 2011!)



examples of modern pick-up arms

Audio recording and reproduction – state of the art of analogue audio (year 2011!)

analogue audio still very alive

There is room at the top of the market

digital versus analogue

€ 39

€ 120 000

There is a lot of room at the top of the market

digital versus analogue

€ 80

€ 120 000

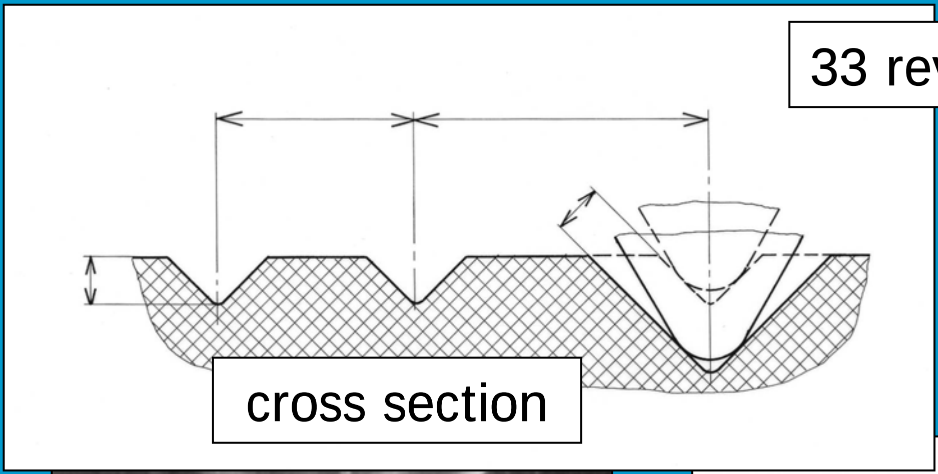
There is a lot of room at the top of the market

luxury analogue watches

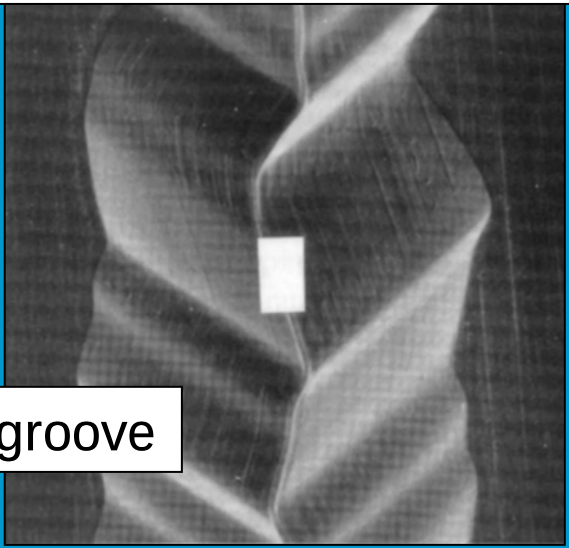
€ 250 000

Analogue recording - state of the art

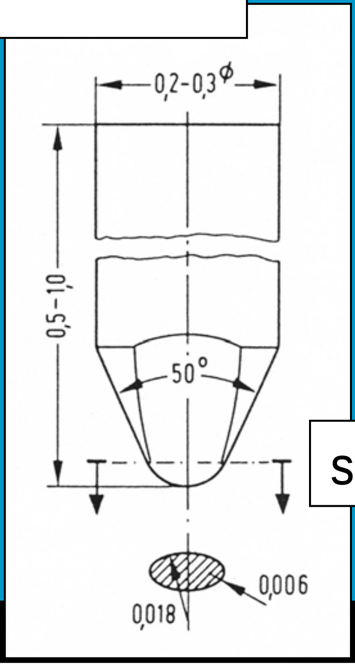
33 rev/min vinyl records



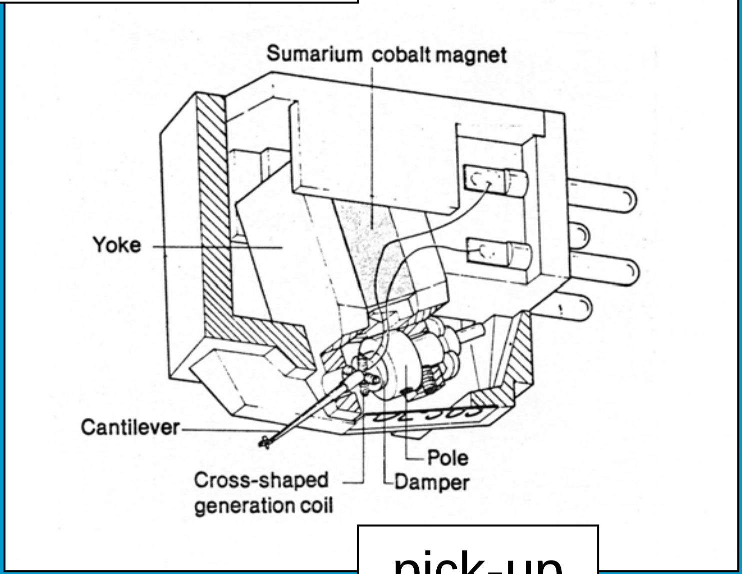
cross section



groove

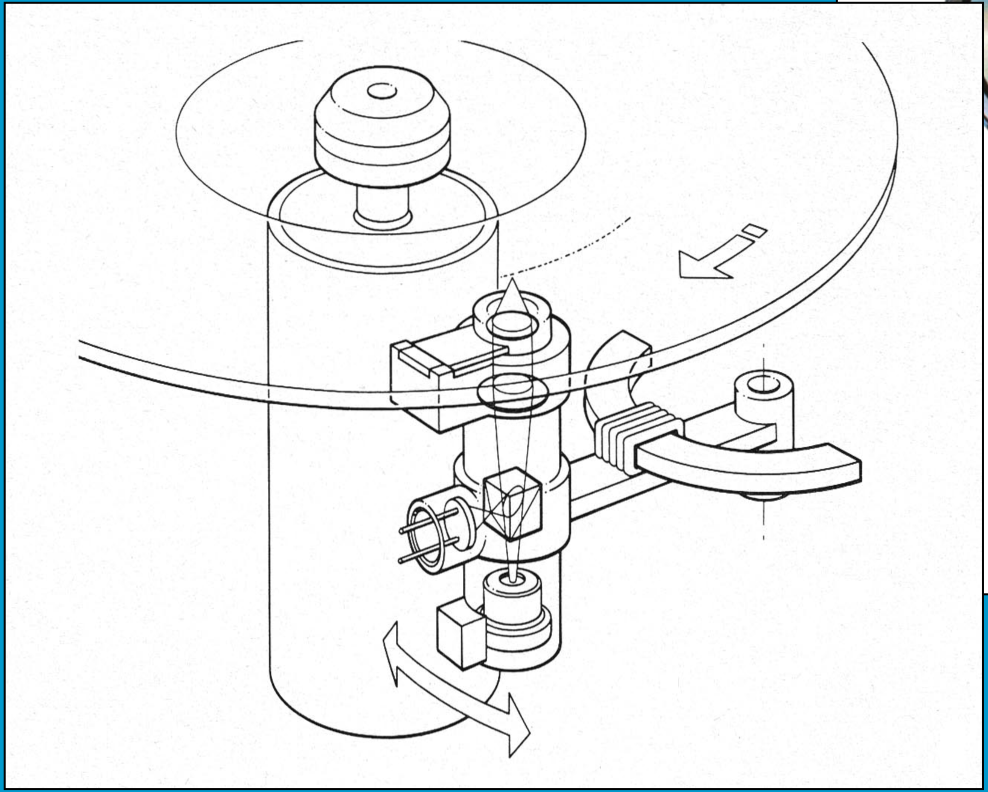


stylus



pick-up

Optical recording



Digital (optical) recording

Why there was a need for new ways of recording?

Large number of disadvantages vinyl records:

- mechanical damage to the surface by stylus (source load)
- need for very accurate amplitude sensing (infinite number of levels)
- sensitivity to dust
- sensitivity to vibrations (external and internal)
- sensitivity to variations in rotational speed
- limited quality to due to large variations in linear velocity
- limited information capacity

Few advantages

- large frequency range (up to 80 kHz)
- still popular with audiophiles

Required properties of new technology

properties of analogue (mechanical) recording	what should offer the new technology (optical recording)
mechanical damage to the surface by stylus	contact less stylus (laser beam)
need for very accurate on-line amplitude sensing – analogue technology	sensing limited to only 2 levels (approx. “0” and approx. “1”) – digital technology
dust and mechanical damage	holding dust away from the information layer (thick window)
sensitivity to vibrations (external and internal)	off-line processing of information
sensitivity to variations of rotational speed	
large variations in linear velocity (due to constant angular velocity)	constant linear velocity (controlled by content of information buffer)
limited information capacity	smaller indents using micro engineering approach
large dimension – not suitable for portable applications	small dimensions due to high information density

Milestones that led to digital audio

1841 – A.L. Cauchy proposes a sampling theorem

1854 – G. Boole publishes "An Investigation into the Laws of Thought" – basis of digital circuit theory

1877 – T.A. Edison invents the phonograph while trying to invent a device that would record and repeat telegraphic signals (digital)

1887 – E. Berliner replaces Edison's wax cylinder with a audio disc

1928 – H. Nyquist introduces theory of sampling analogue signals

1937 – A. Reeves invents pulse code modulation

1947 – Magnetic tape recorder on the US-market

1948 – transistor invented, C.E. Shannon publishes :A Mathematical Theory of Communication"

1950 – R.W. Hamming publishes error detection/correction code

Milestones that led to digital audio

1958 – invention of the laser

1960 – I.S. Reed and G. Solomon develop error correction code

1969 – Sony introduces 13-bits PCM digital recorder (tape)

1970 – Compaan and Kramer at Philips complete a glass disc prototype of digital disc

1971 – first microprocessor

1978 – Philips releases the video disc player

1978 – technical standard for CD proposed by Philips and Sony

1983 – CD players introduced

1988 – CD recordable introduced

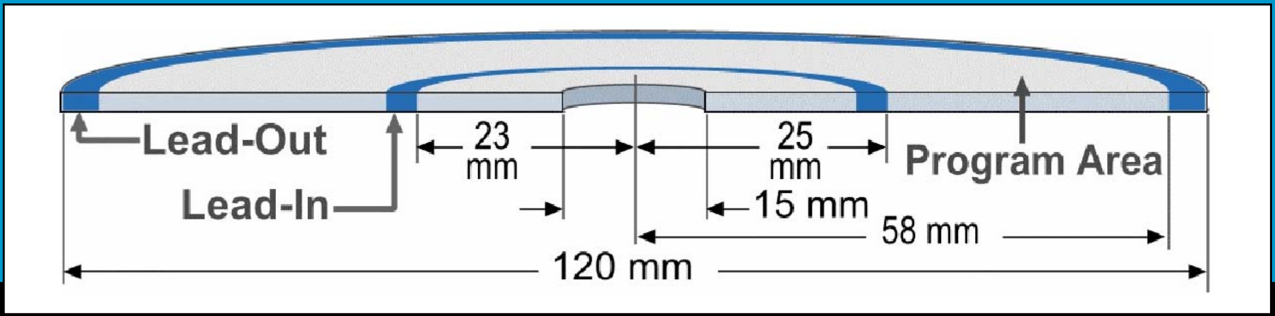
1996 – DVD technology introduced

1999 – DVD-video becomes main stream

2008 – Blue Ray available to consumer market

Optical recording – CD audio

- basic properties (agreement between Philips and Sony on Compact Disc technology)
  - digital technology based on A-D-A conversion
  - contact less reading using semiconductor laser beam
  - 60 minutes recording
  - frequency range limited to 20 – 20000 Hz
  - extended use of feedback control
  - information carrier – disk 120 mm diameter



Digitalization of analogue audio signal

Digitalization – key property of the new technology

Recording in “zeros” and ones”

- advantage of binary information
  - high intrinsic accuracy (only approximately “0” or “1” need to be detected)
  - almost insensible to number of processing steps
- Possibilities to record 0 and 1:
  - on/off
  - pit/land
  - reflective/non reflective
  - magnetized up/magnetized down
  - light/dark
  - charge/no charge

Restoring back of analogue audio signal

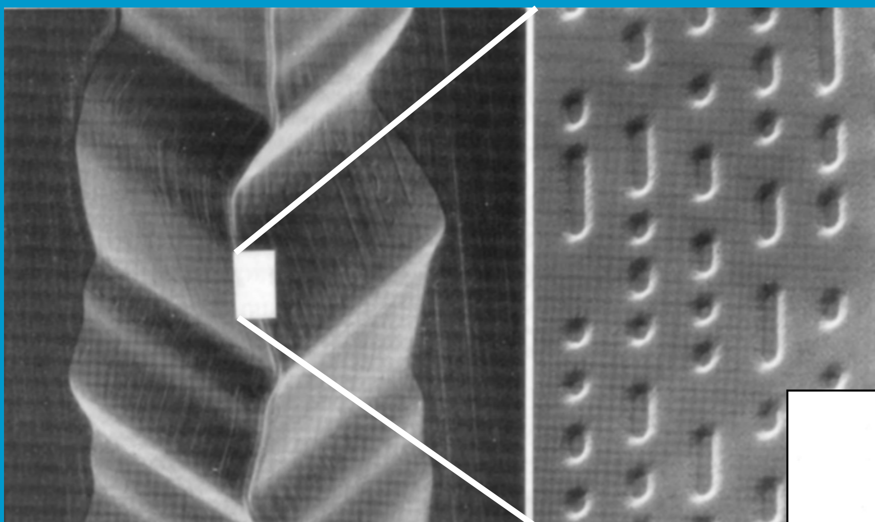
Reading of digital information ("zeros" and "ones")

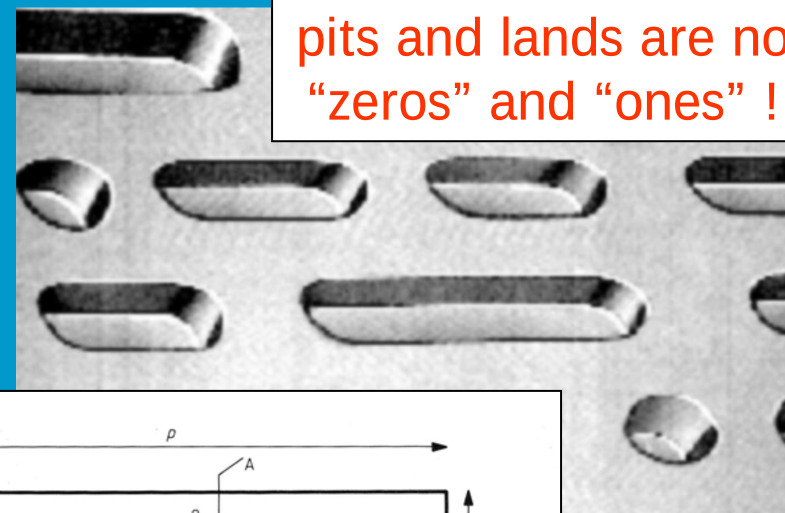
- reading speed can be independent of reproduction speed (of-line processing)
- processing in reverse order
- restoring in proper timely sequence
- obtaining of stepwise analogue signal
- processing with suitable filters
- reproduction

Digitalization of analogue audio signal

Original CD technology – “zeros” and “ones”on the disc

- using extreme small indentations (pits and lands)





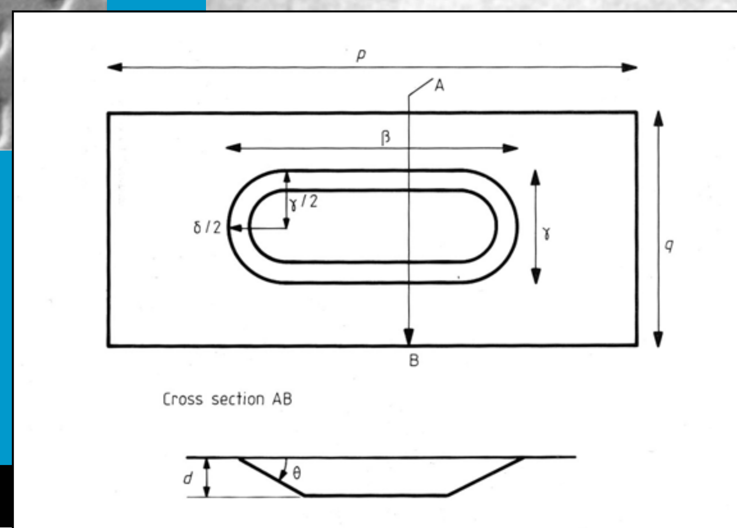
pits and lands are not “zeros” and “ones” !!

width – 0,6 μm

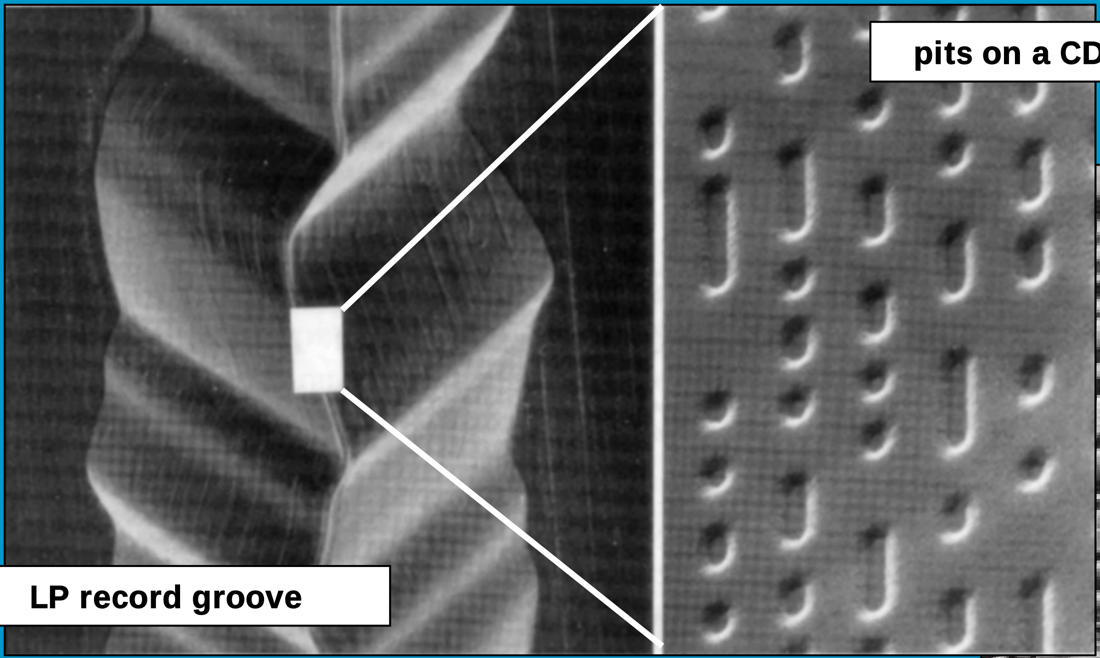
length – n*0,3 μm (3 ≤ n ≤ 11)

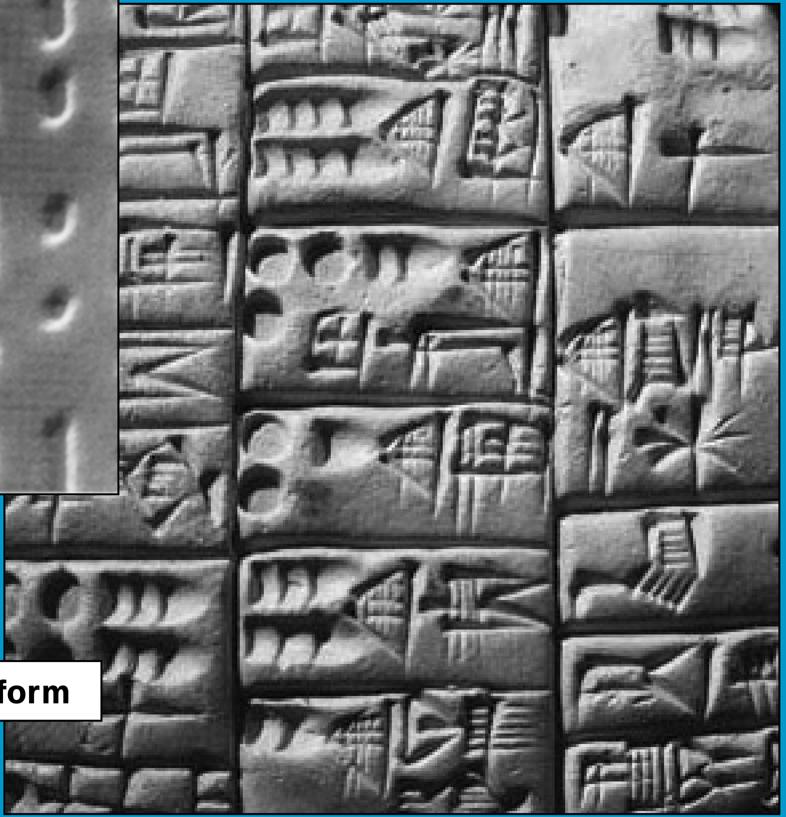
depth – 0,13 μm

track pitch – 1,6 μm



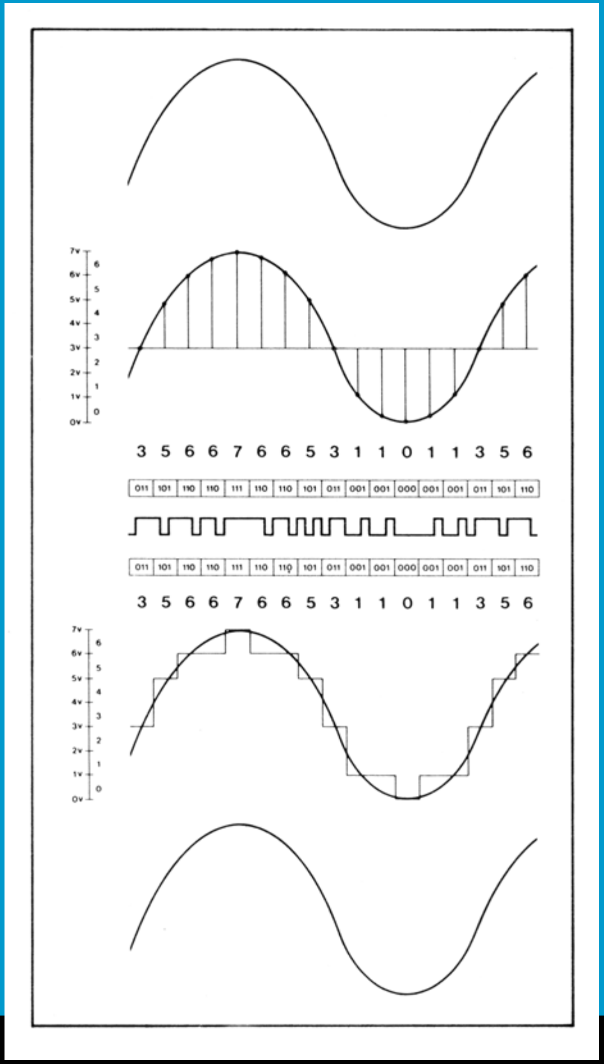
Nothing new under the sun





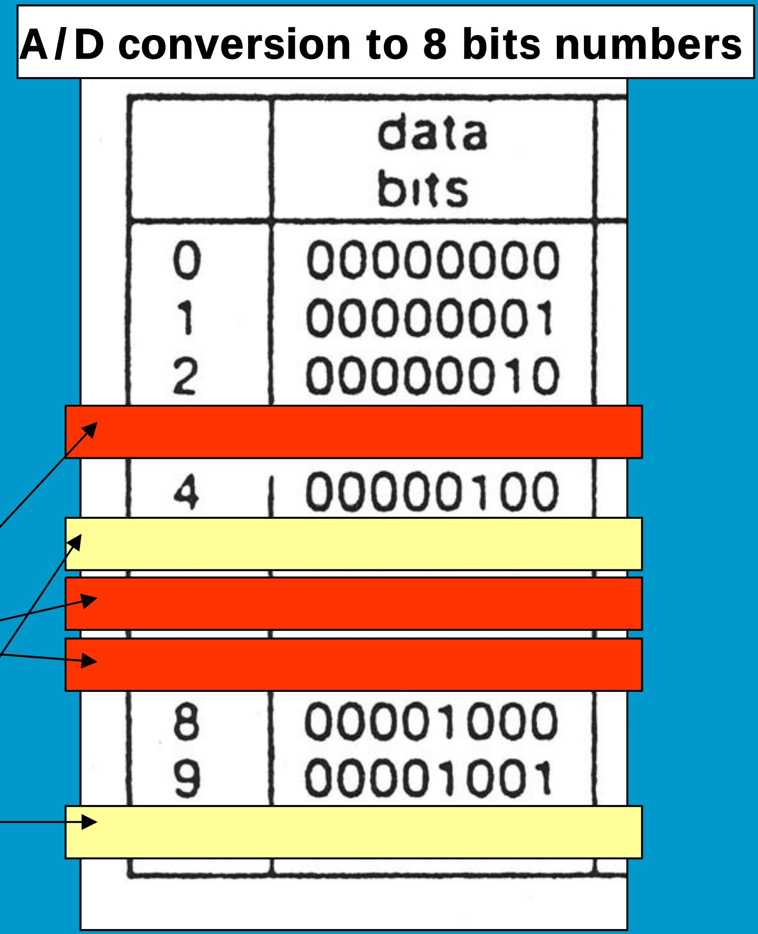
Digitalization of analogue audio signal

- sampling of amplitude levels using sampling frequency 44,1 kHz (for both, R and L channel)
- division of amplitude levels to 2^{16} (65536) steps (top - top)
- transformation of the levels into binary numbers (= 16 bits per channel)
- further transformation and error prevention coding
- transformation to a sequence “zeros” and “ones”



Recording of digitalized information

- indentation transitions ("ones") could not be very close to each other – they should be read separately
- the space between "ones" must be larger than the diameter of the laser spot

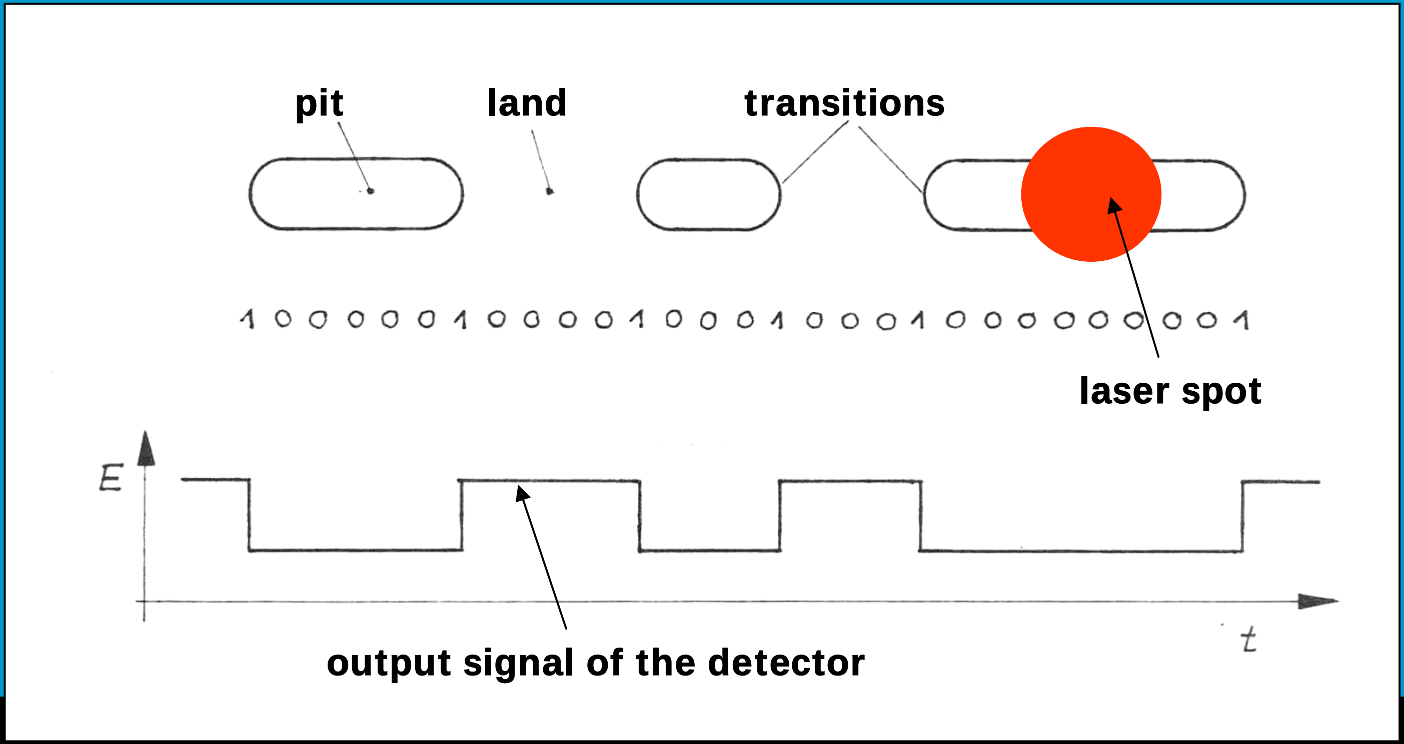


these "ones" are to close to each other

these "ones" are still to close

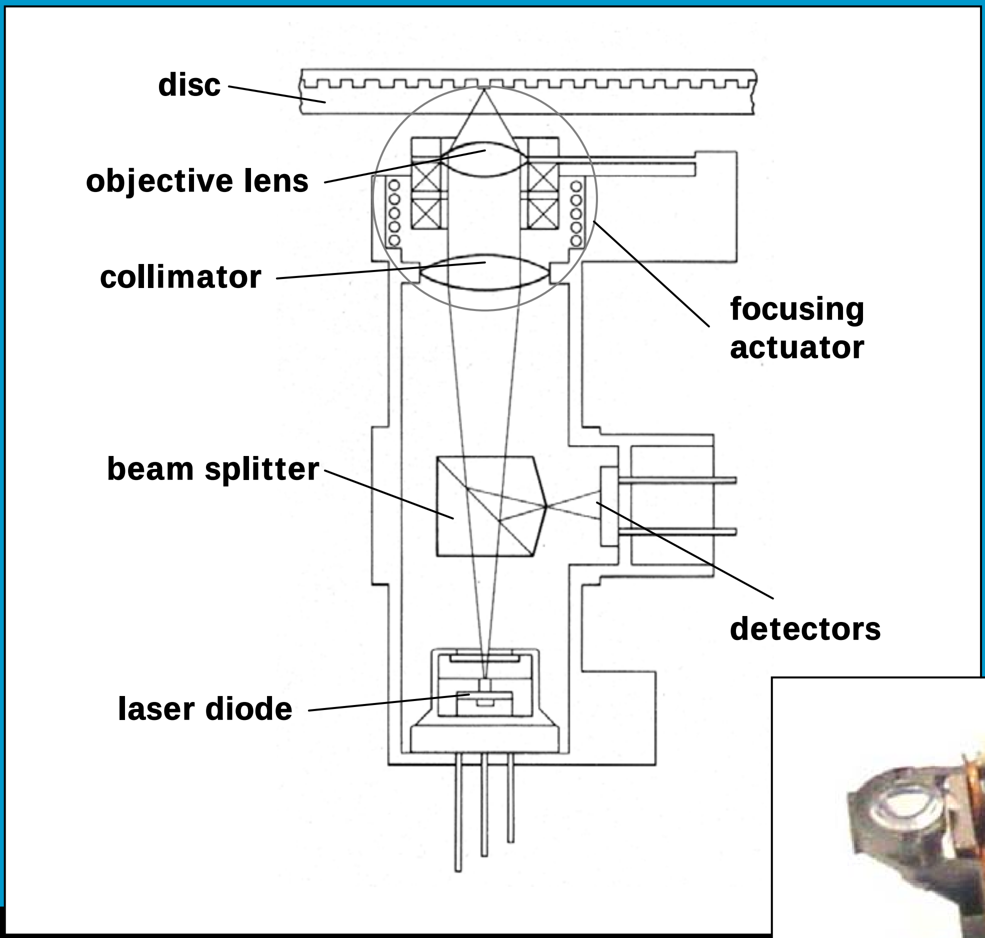
Digitalization of analogue audio signal

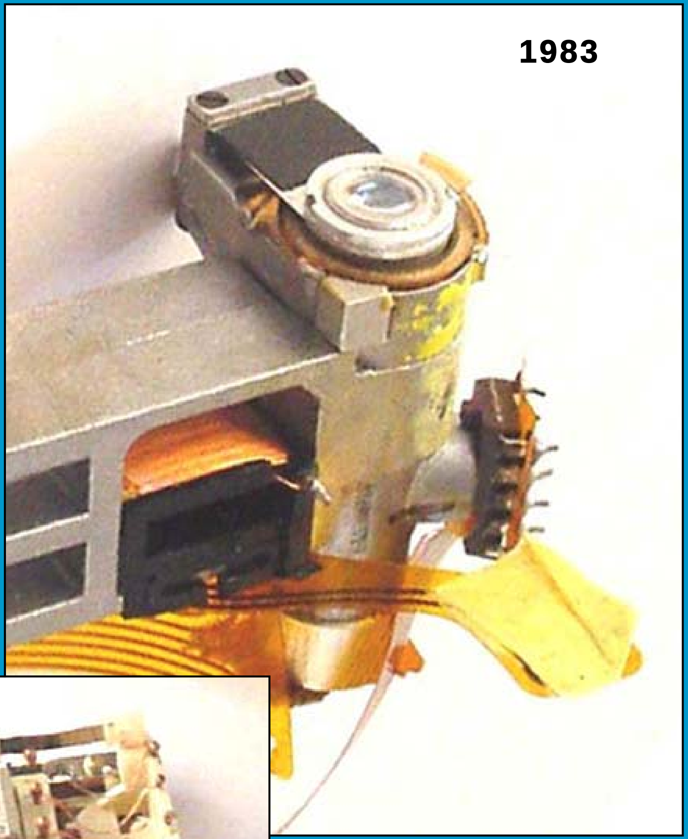
- only the transitions (from pit to land and from land to pit are relevant – these are the “1s”
- in this way the intrinsic accuracy is improved once more
- the “zeros” are filled in according to a time scale

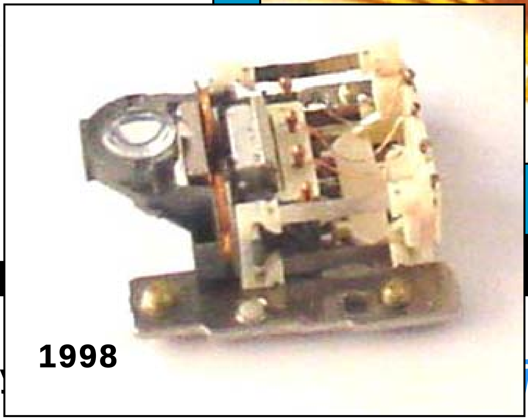


Reading information from the disc

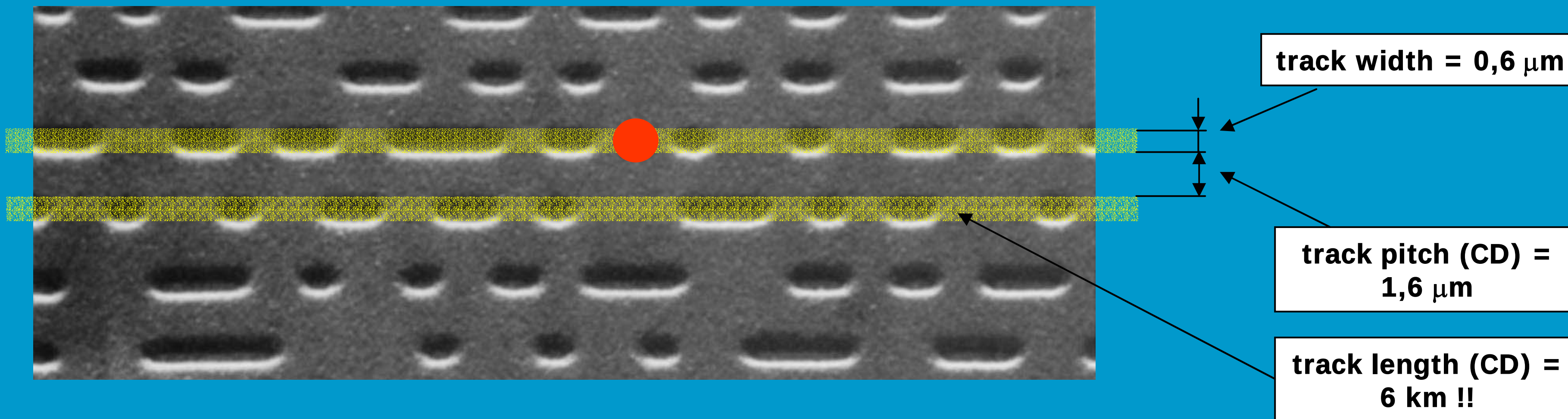
Basic configuration of the reading unit







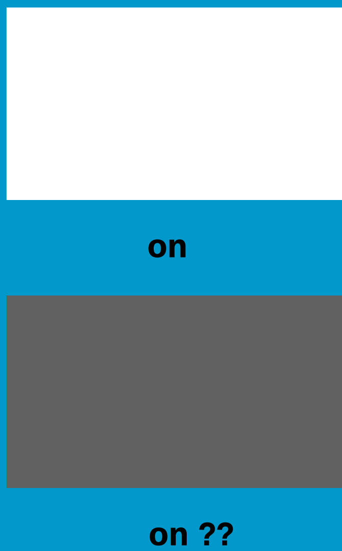
Reading information from the disc (without physical contact !!)



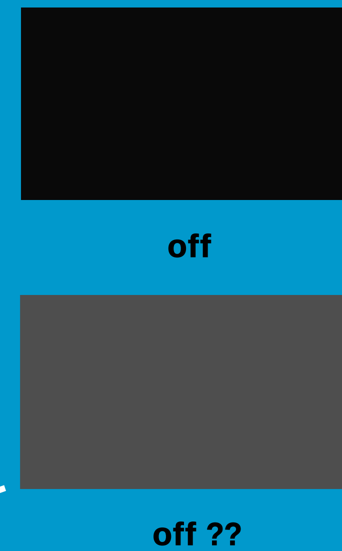
What are the necessary tasks in order to read information?

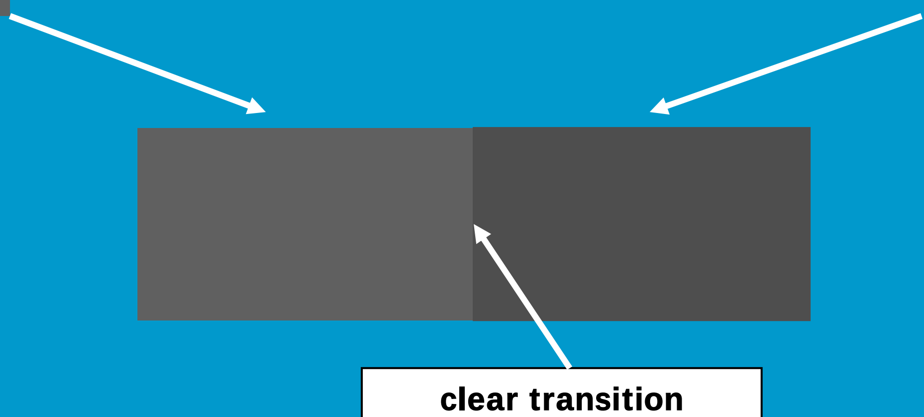
- keeping the laser spot on the track (tracking)
- keeping the spot diameter minimal (focusing)
- reading information with sufficient speed (controlling the rotational speed by checking the buffer content)

Why use of transitions ?



- exact “on” and “off” easy to distinguish
- technical imperfections can cause “on” and “off” being far from perfect – difficult to distinguish





Recording of digitalized information

In order to maintain high information density (information per unit area)

8 bit to 14 bit conversion (EFM) in a special scheme delivers the highest information density

in this scheme there are always at least two "zeros" between two "ones"

	data bits	channel bits
0	00000000	01001000100000
1	00000001	10000100000000
2	00000010	10010000100000
3	00000011	10001000100000
4	00000100	01000100000000
5	00000101	00000100010000
6		
7	00000111	00100100000000
8	00001000	01001001000000
9	00001001	10000001000000
10	00001010	10010001000000

Reading of digitalized information

- separate reading of frames (containing 588 bits)
- each frame will be divided to 588 windows of equal time duration
- the windows are then filled with “ones” at the corresponding time intervals
- the remaining windows not occupied by “ones” are then filled with “zeros”
- 8 bits numbers belonging to audio information are separated from the data stream
- using quartz clock each second 88200 numbers of 16 bits are sent to the D/A converter

Error correction measures

Previous description of restoring digital si[redacted]al was simplified – not taking account the [redacted]or correction measures

Recording and reading of the [redacted]ormation on the disc should be insensitive to [redacted]sturbances as dust, scratches, fingerpri[redacted]

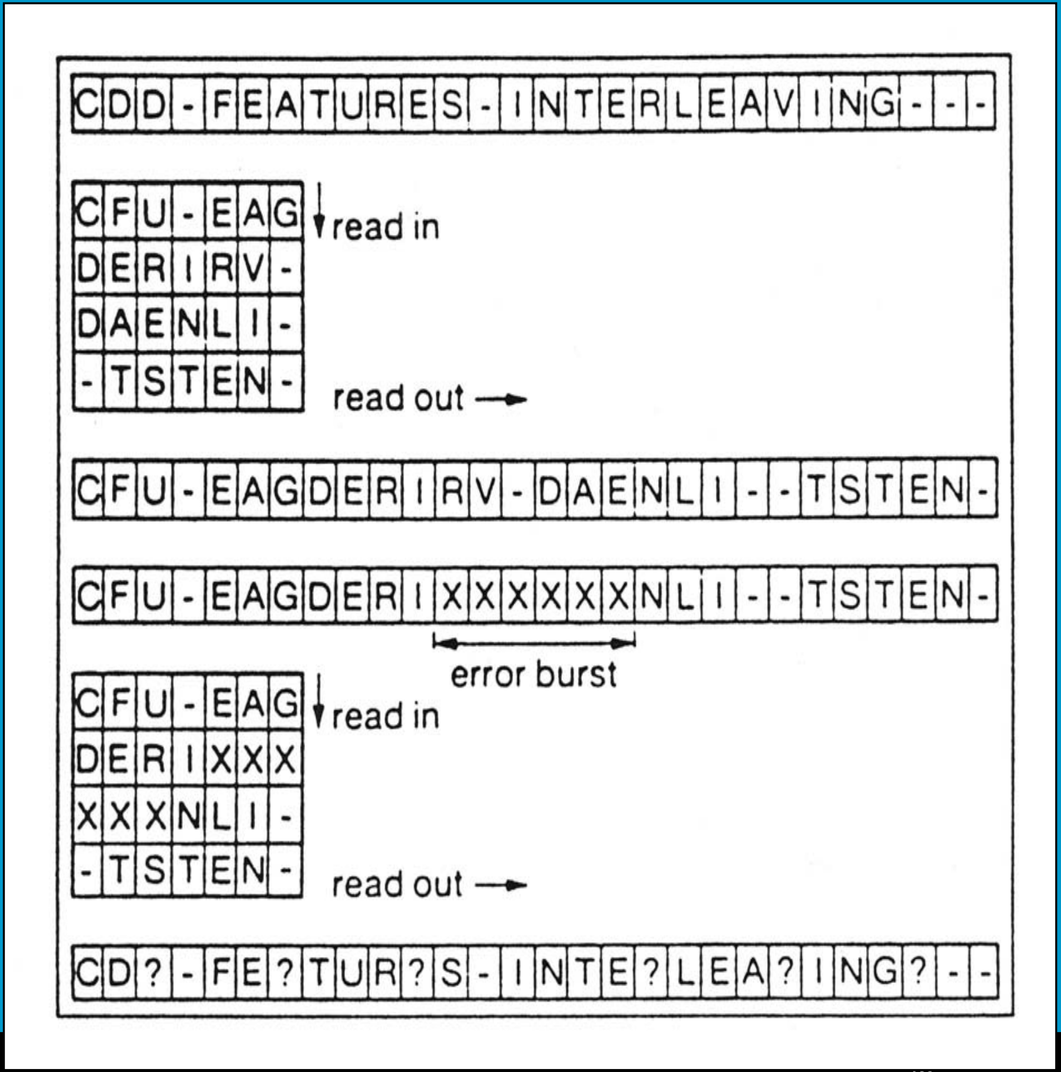
Complicated sche[redacted]es have been developed to fulfill the error preve[redacted]on requirements

Explanati[redacted] of these are beyond the scope of this course

large scratch along the information tracks

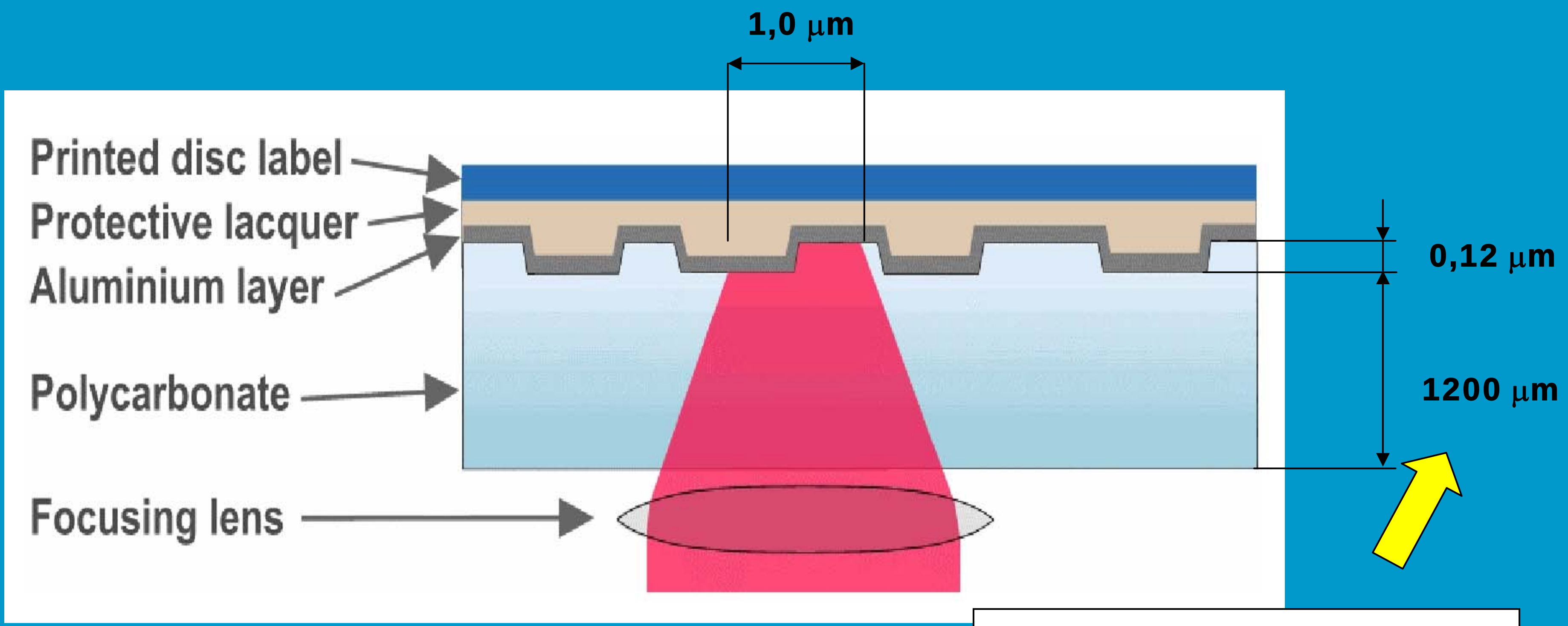
Error correction measures

Simplified representation of preventing errors due to surface damage (like scratches)



Error correction measures

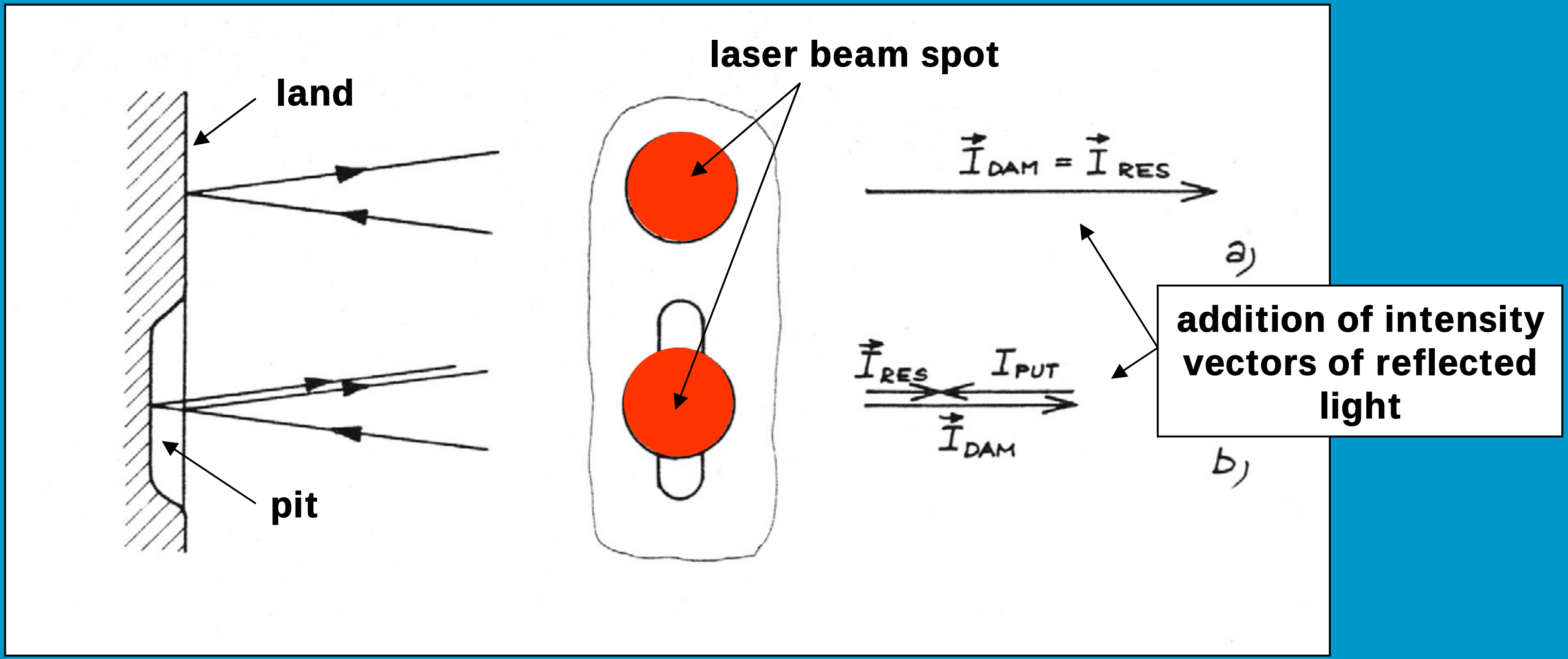
Prevention of disturbance by dust or fingerprints



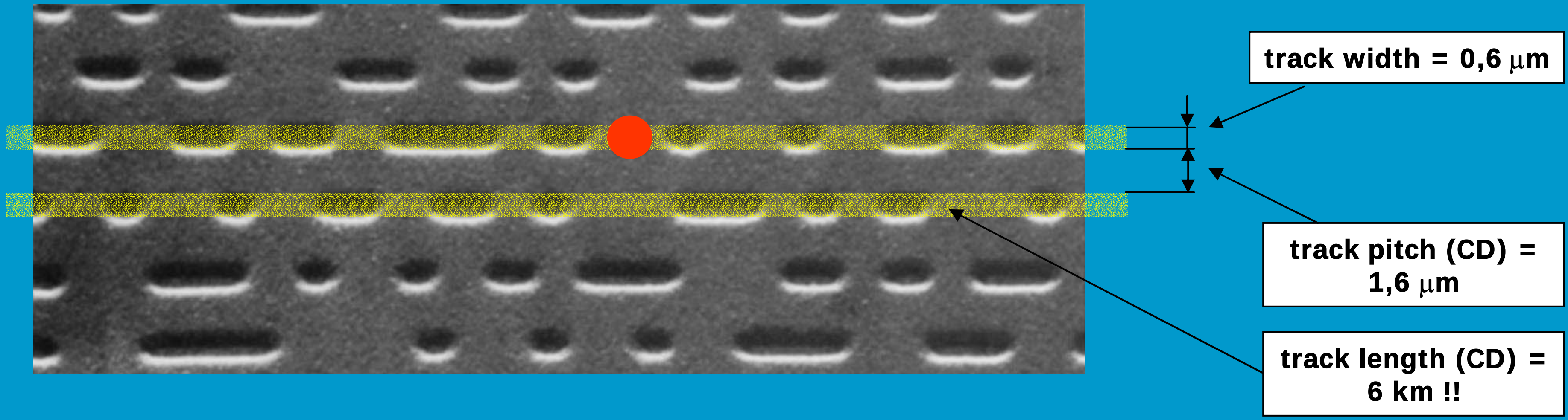
notice the huge difference in dimensions!!

Reading information from the disc

How the indentations are recognized by the reading laser beam?



Reading information from the disc (without physical contact !!)



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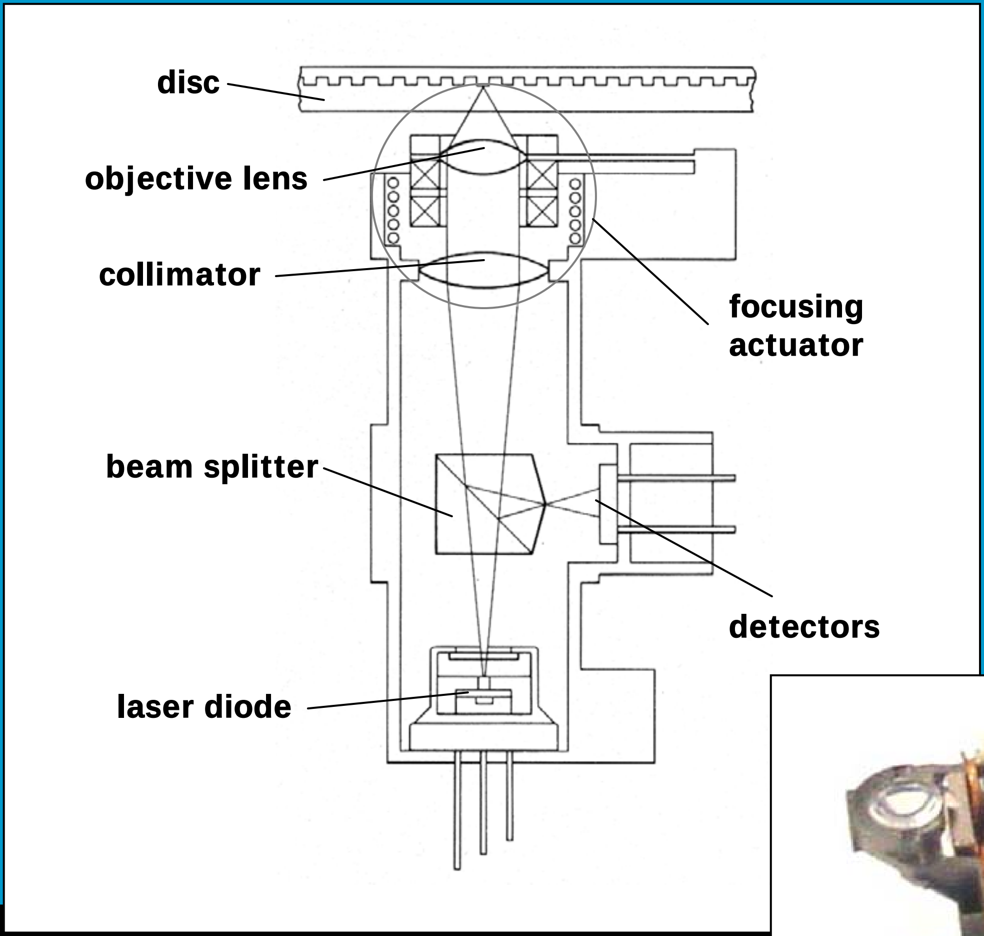
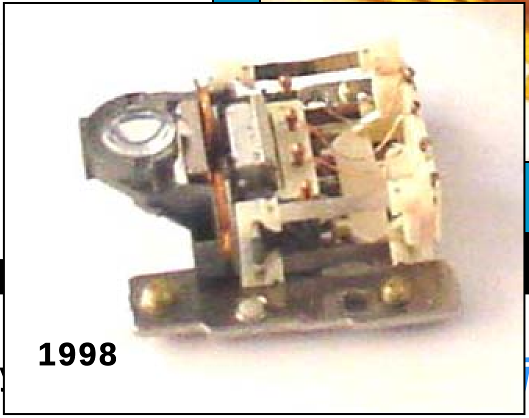
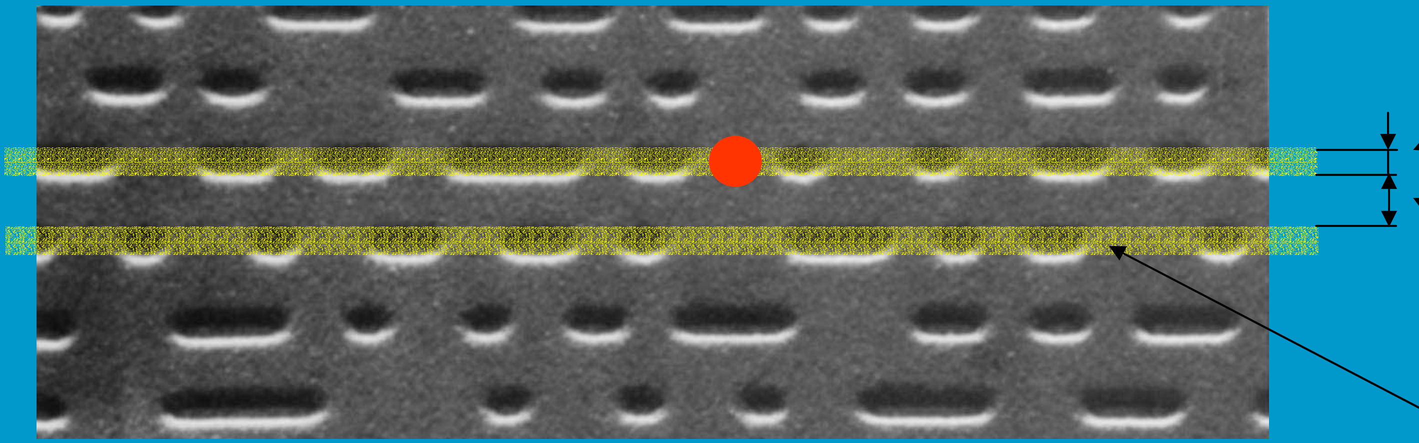
Reading information from the disc

Basic configuration of the reading unit





Requirements for reading information from the disc



tracking

- accuracy 0,1 µm at 1,25 m/s track speed (audio CD) or at 50 m/s track speed (CD-ROM)
- despite of the track eccentricity up to 200 µm/rev

focusing

- accuracy of spot positioning 1 µm
- despite of the swinging of the information layer up and down with a amplitude (top – top) up to 400 µm

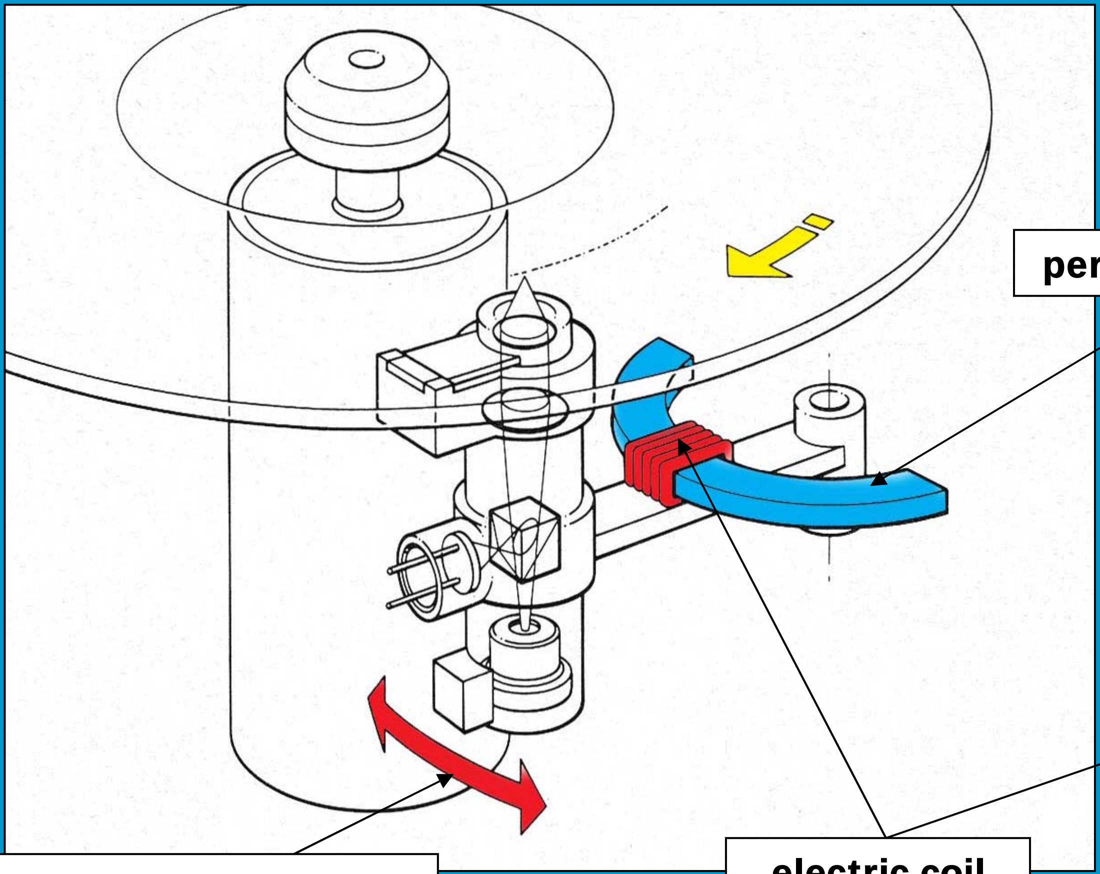
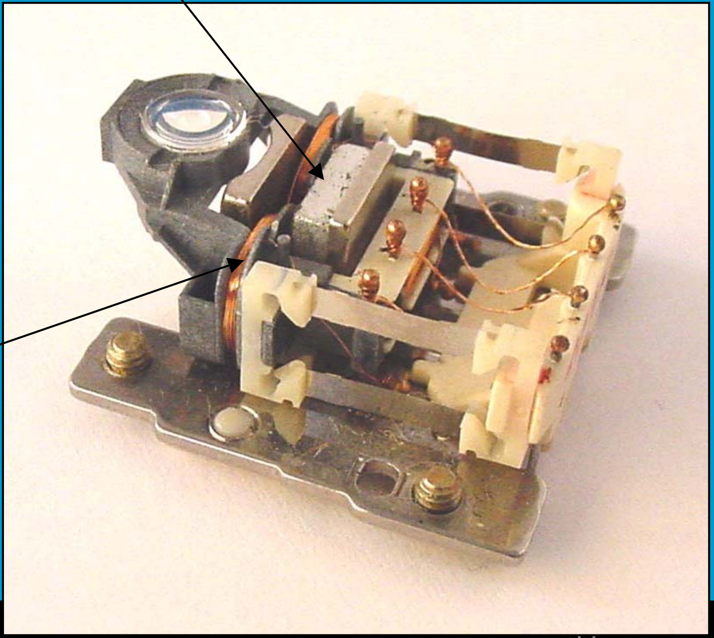
Reading information from the disc

To fulfill the requirements:

- extensive use of advanced feed back control
- therefore necessary:
  - sensing of errors (tracking and focusing) without any contact with the rotating disc
  - all information must be acquired from the returning reflected laser beam !!
  - corrections only possible by mechanical means – actuators to move the laser spot
    - to the correct position above the track
    - to the correct distance from the information layer

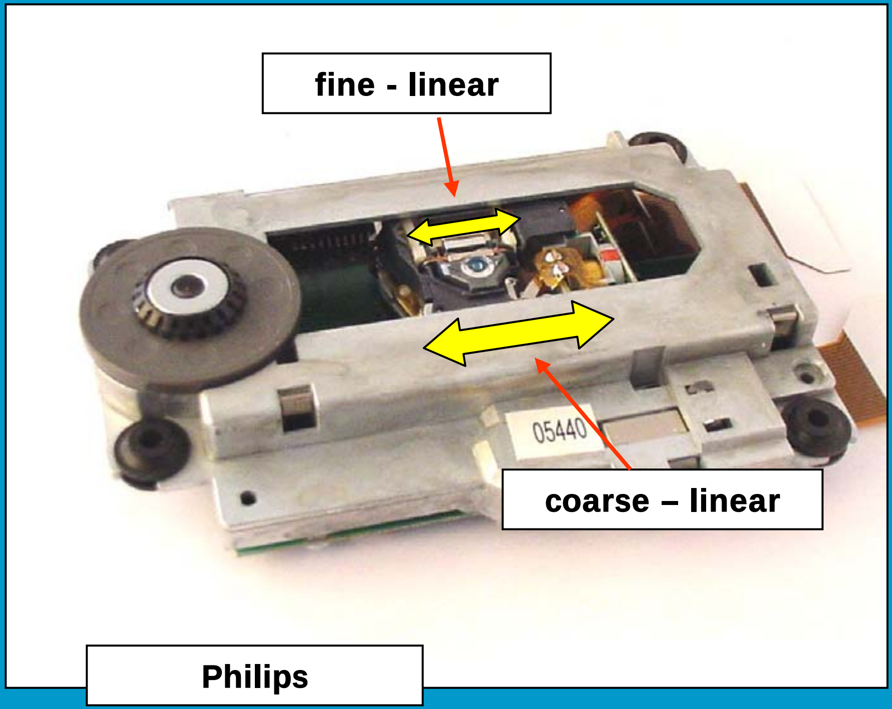
Track following

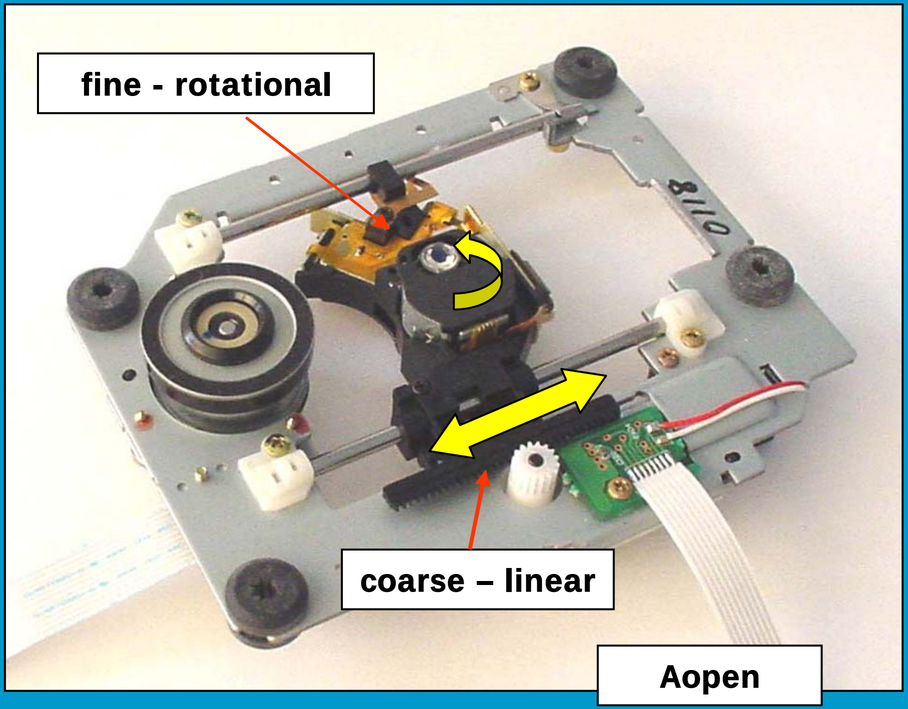
electromagnetic actuators (Lorentz type) - interaction between electric current and magnetic field

Track following

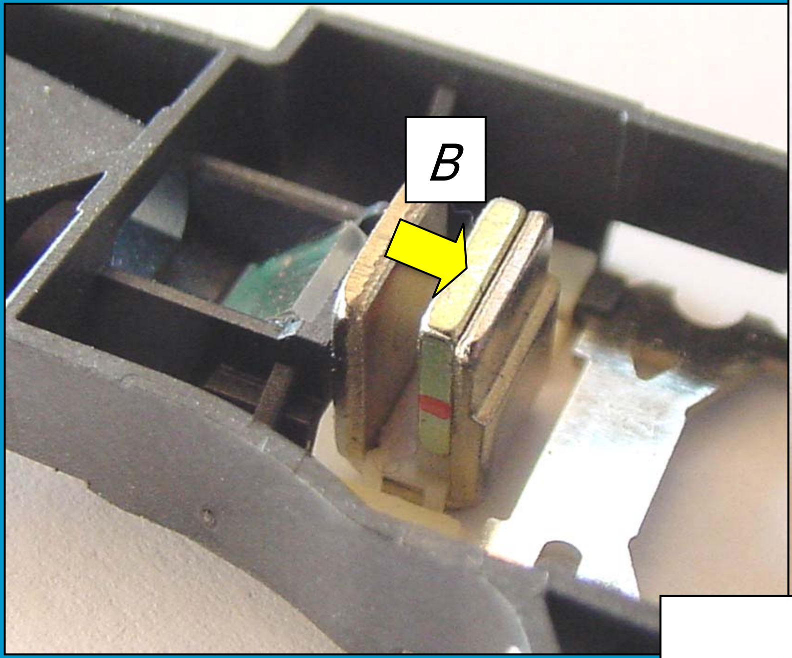
- Double stage actuators
  - 1st stage - coarse linear movement along the entire track
  - 2nd stage - fine correction adjustment (linear or rotational)

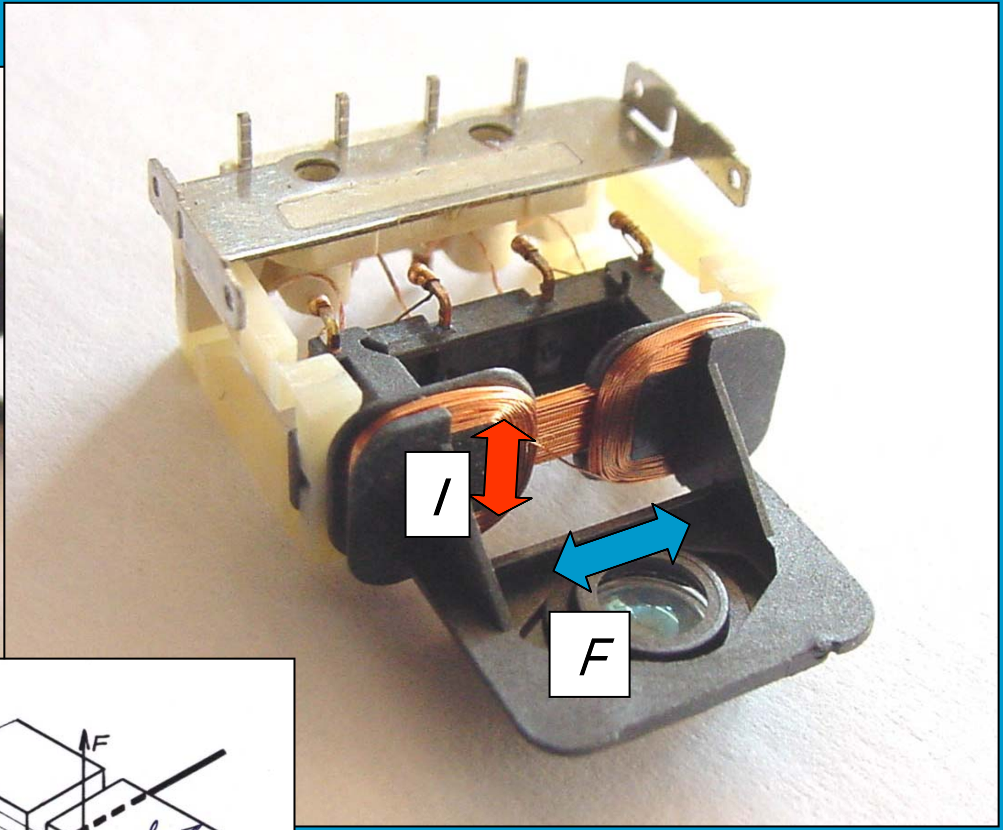


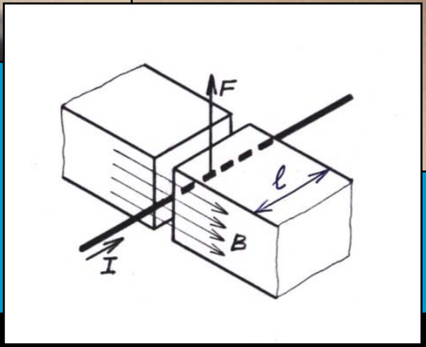


Electro-mechanical actuators– design

Track following

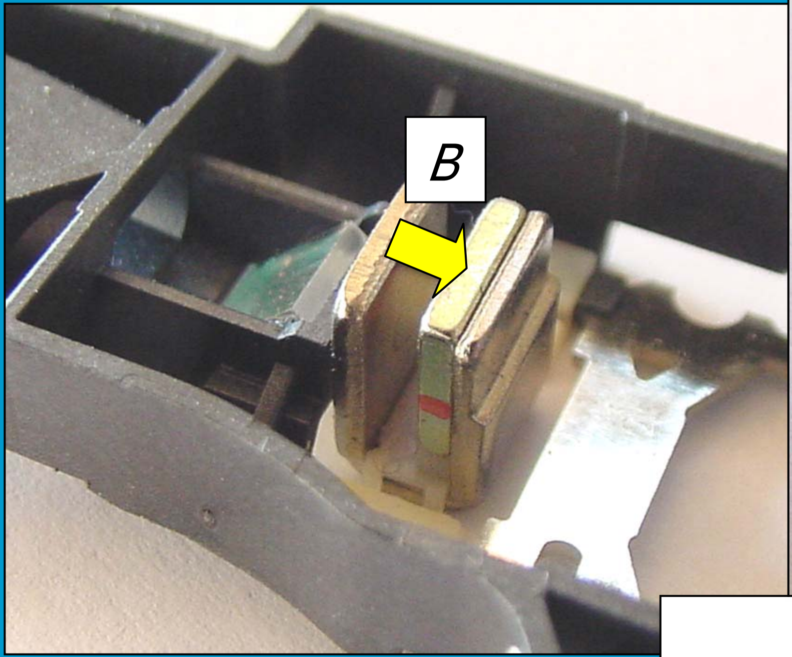


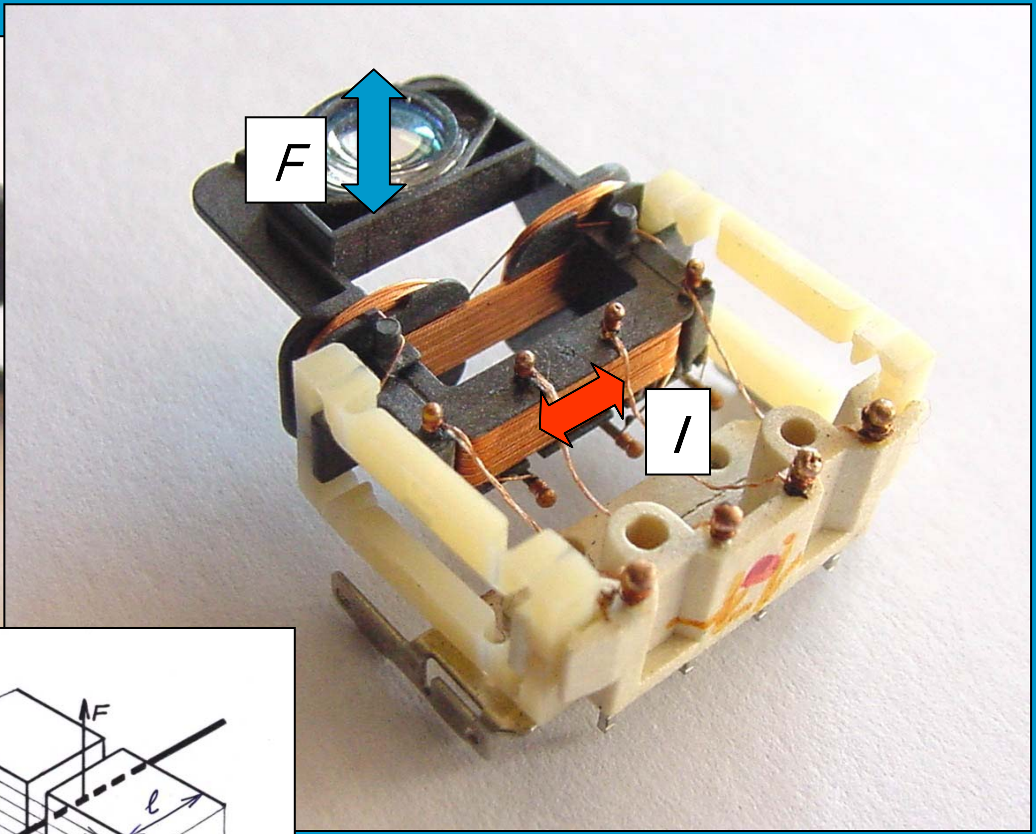


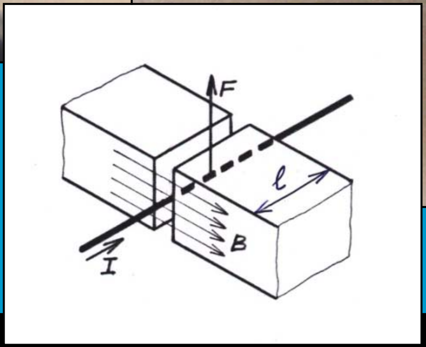


Electro-mechanical actuators– design

Focusing

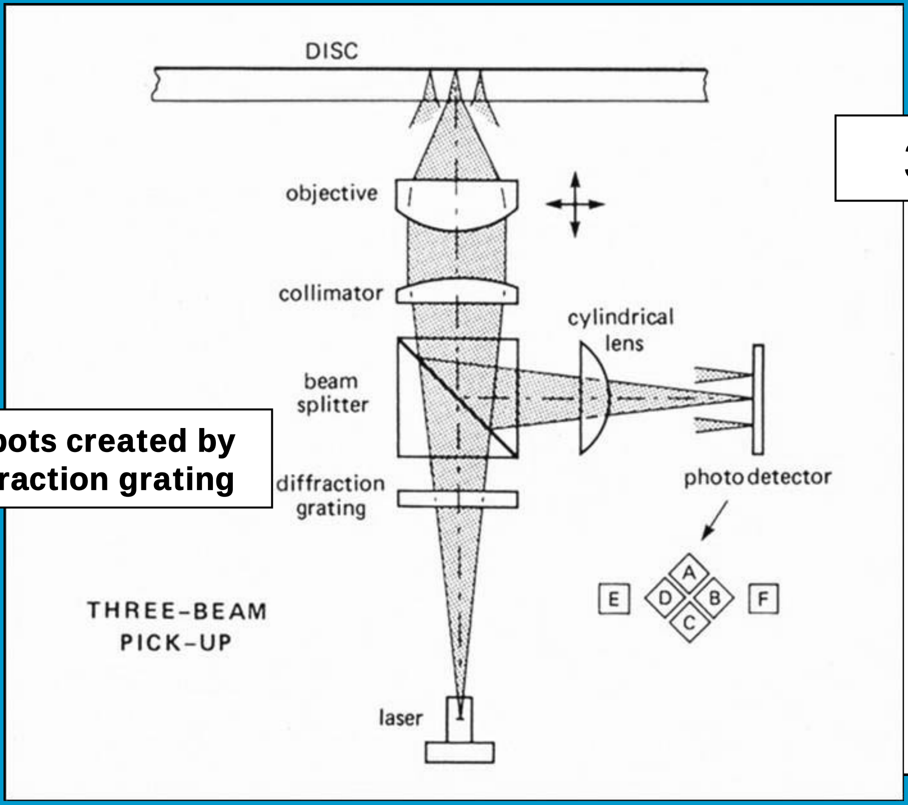






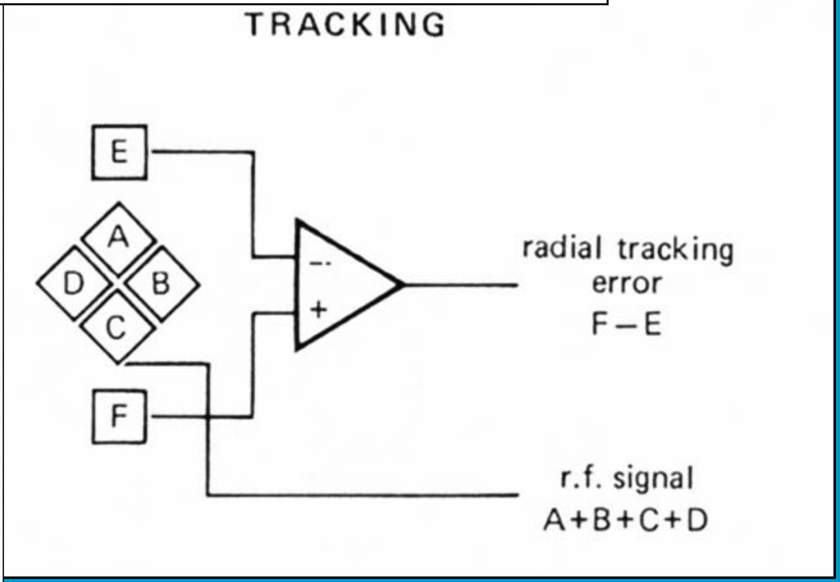
Track following

How to obtain the error of laser spot position relative to the track?



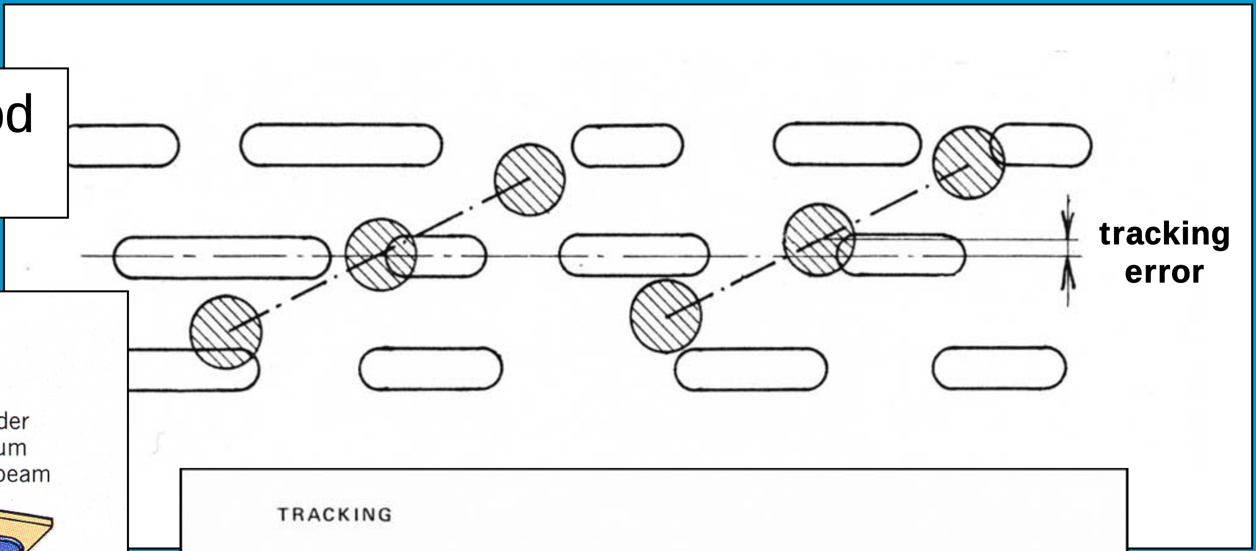
3 spots created by diffraction grating

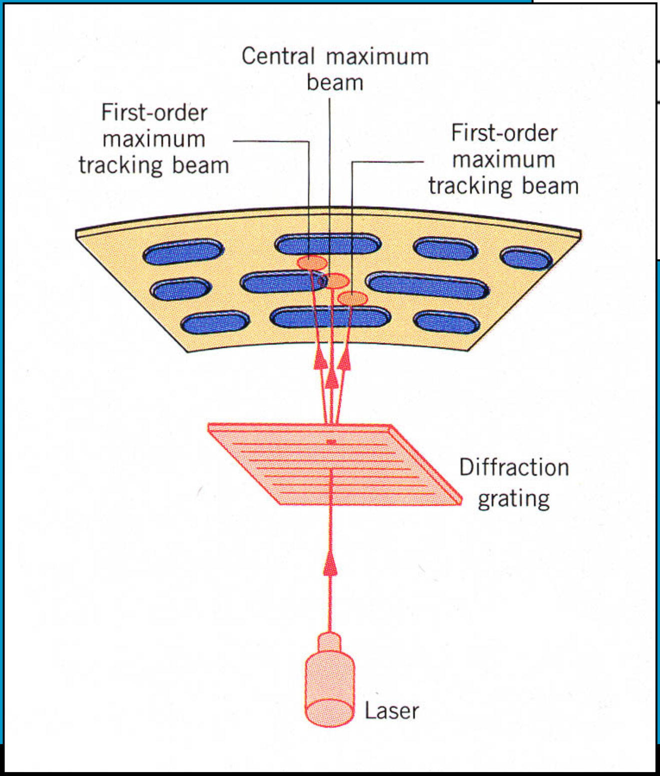
3 spots method (Sony)

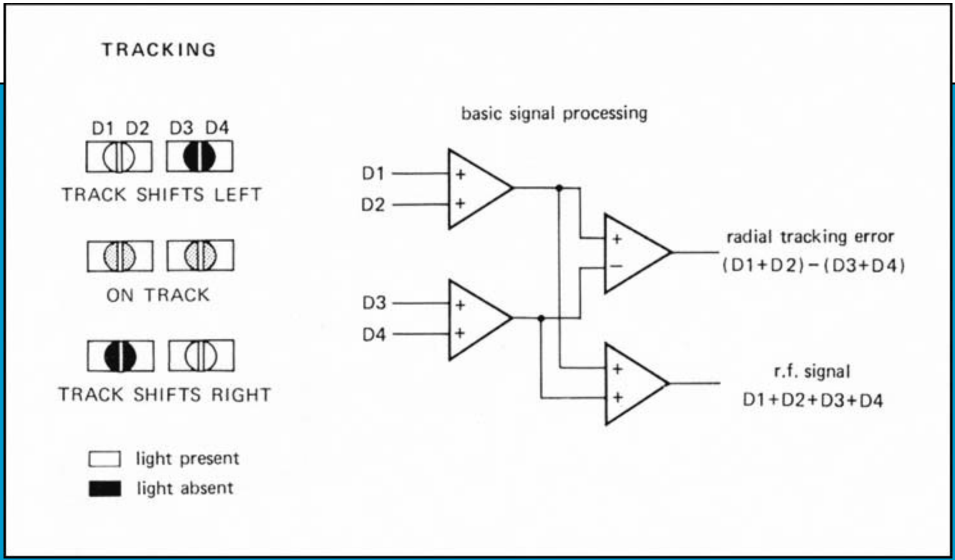


Track following

3 spots method (Sony)

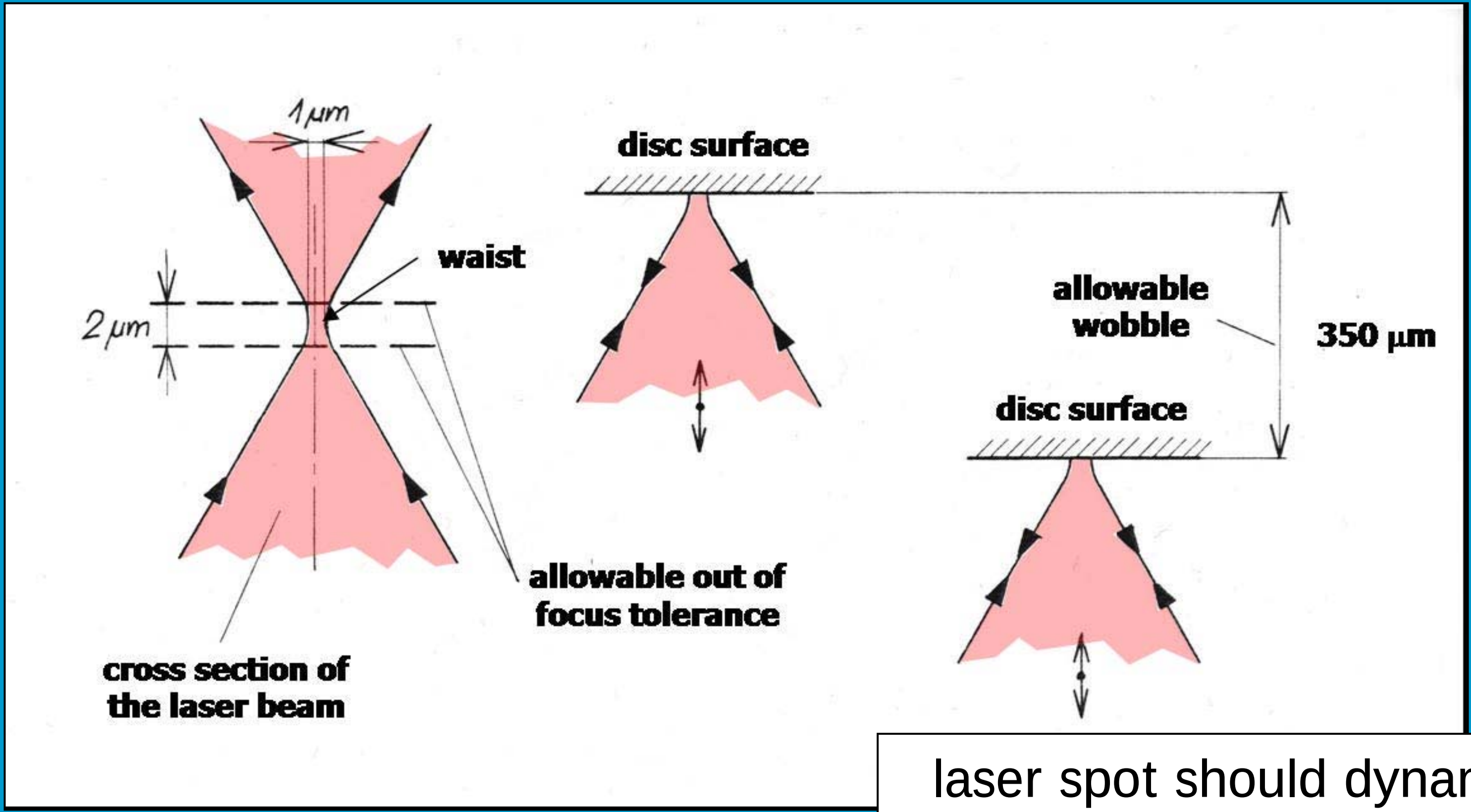






Focusing of the laser spot

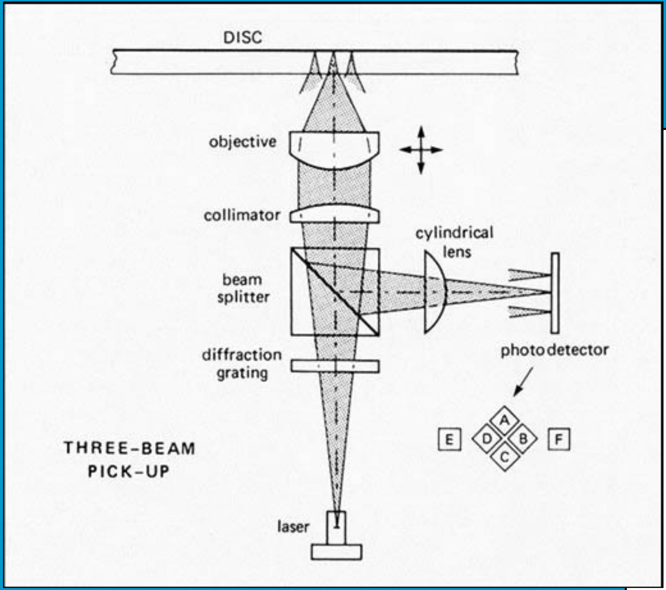
What is needed to accomplish?



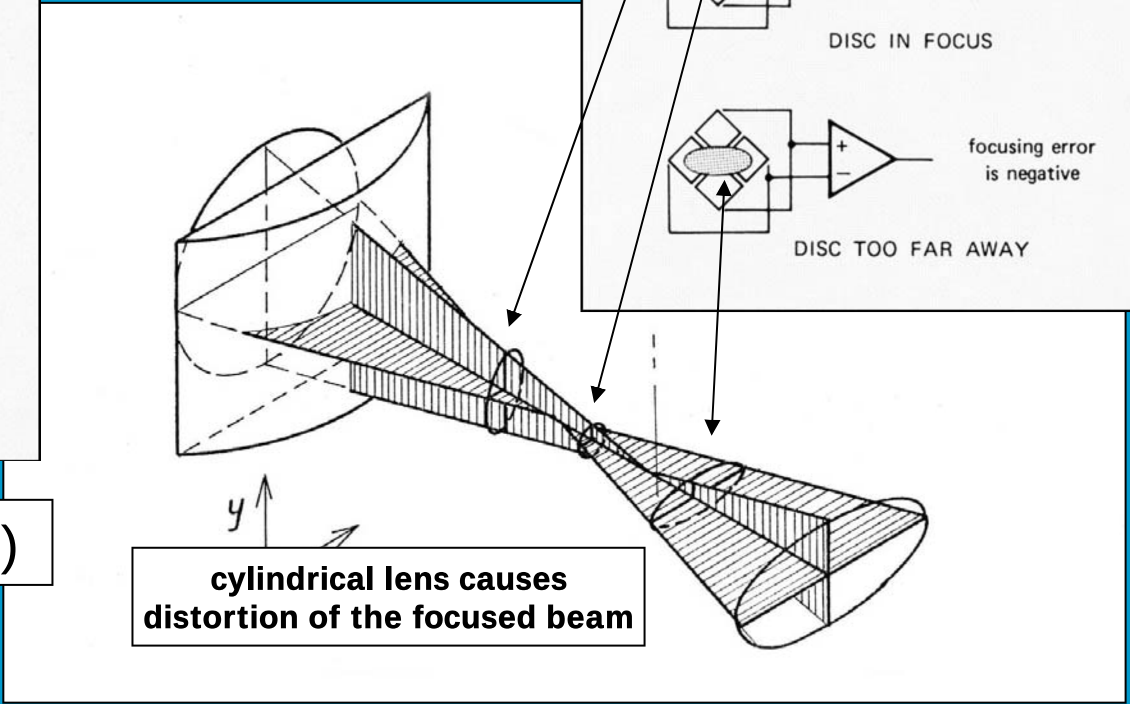
laser spot should dynamically follow the disc surface

Focusing of the laser spot

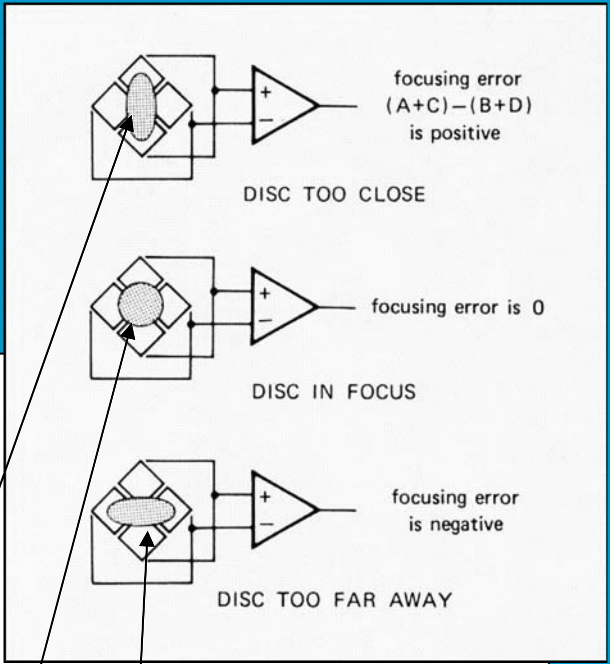
How to obtain the focusing error of the laser spot in contact less manner?



astigmatic method (Sony)

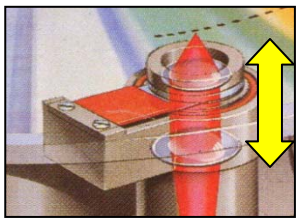


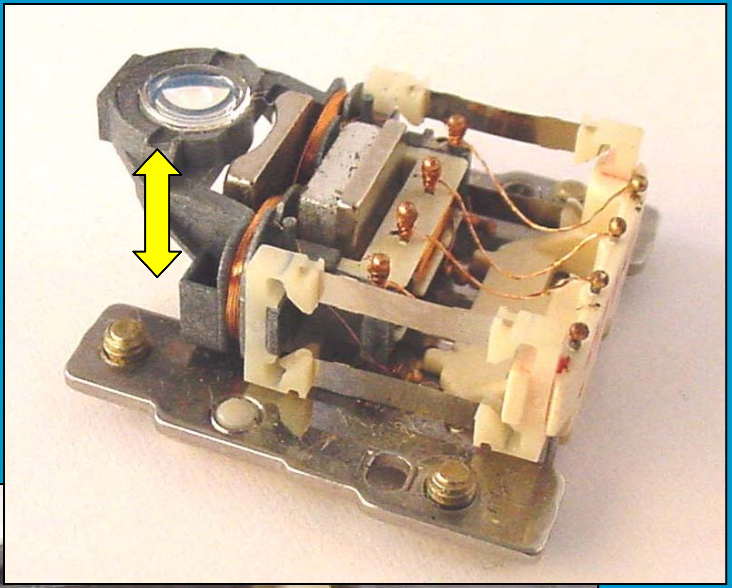
cylindrical lens causes distortion of the focused beam

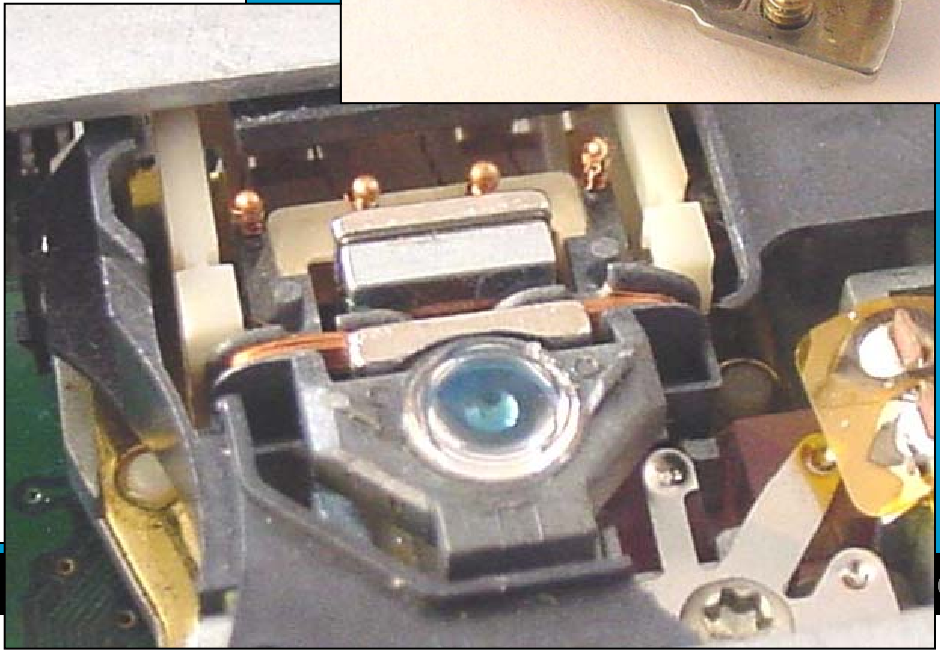


Focusing of the laser spot

Focusing actuators (Philips)

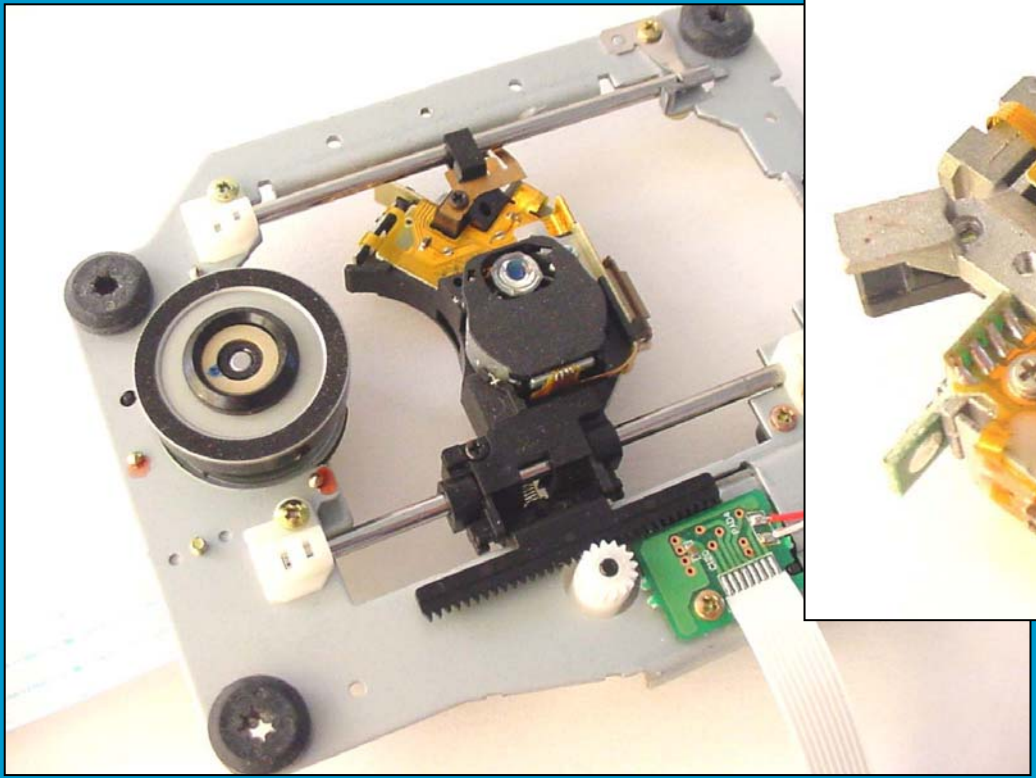


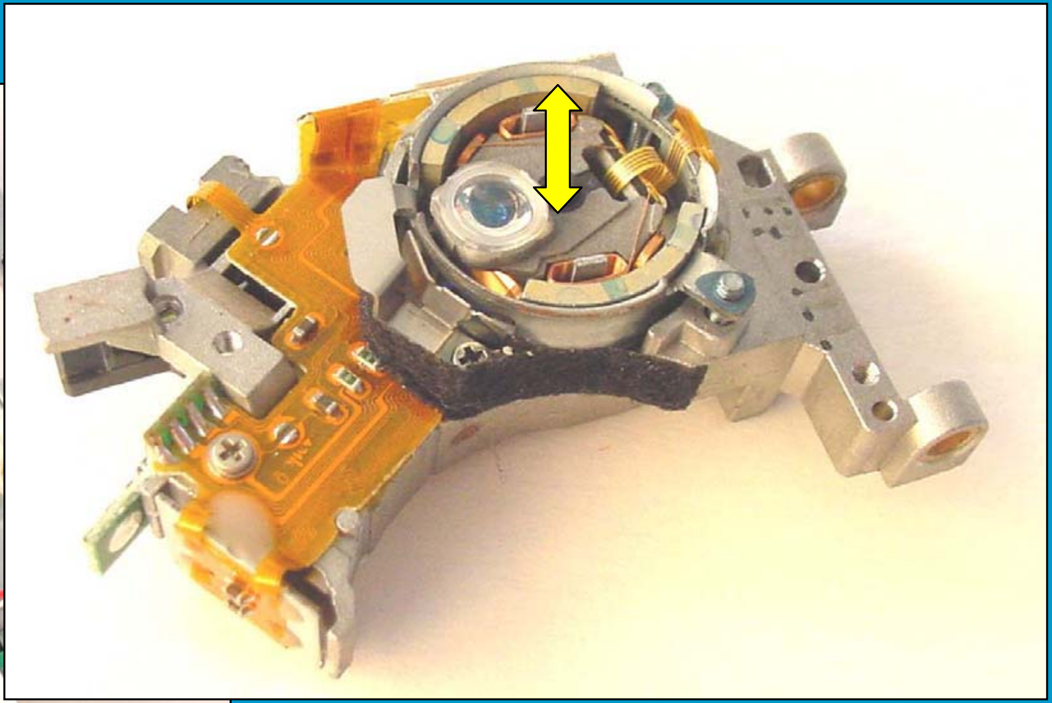




Focusing of the laser spot

Focusing actuators (Aopen)





Rotating of disc

Main task:

- movement of long track along the laser spot
- reading information with sufficient speed (controlling the rotational speed by checking the buffer content)

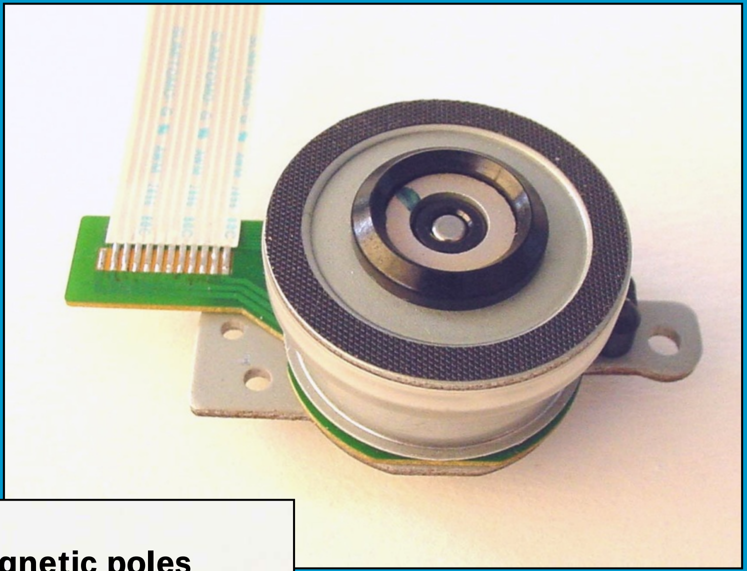
Basic properties:

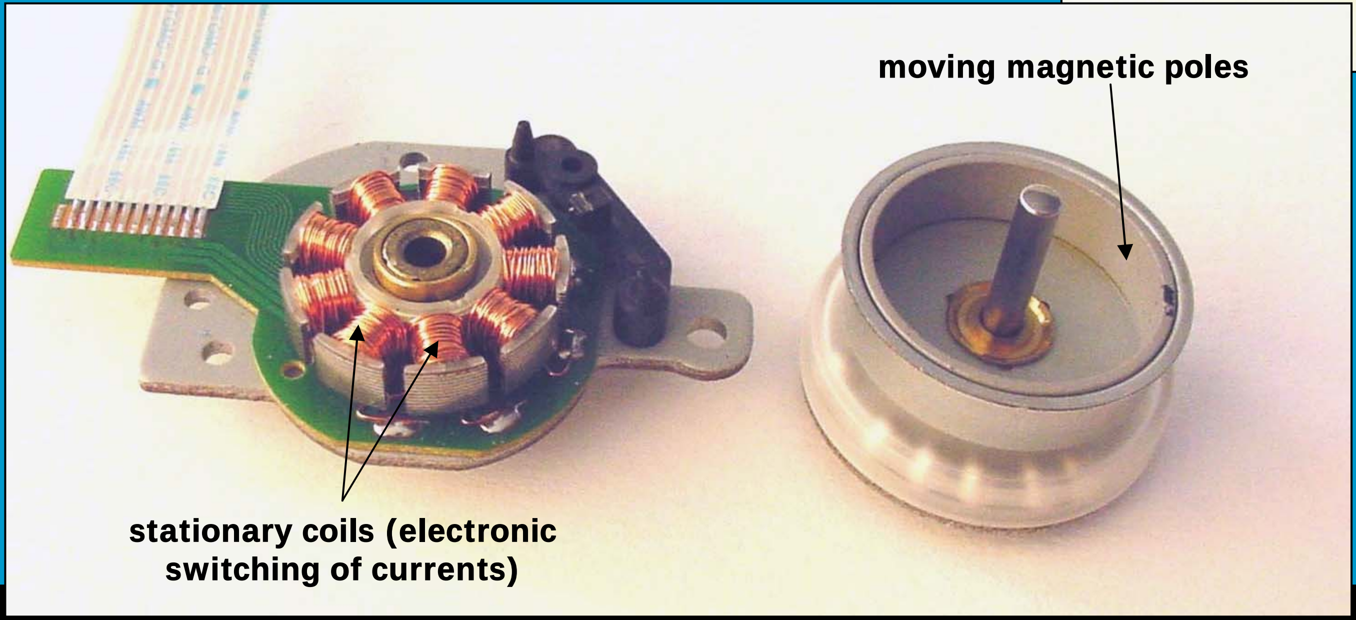
- constant linear velocity of the track for CD-audio (1,25 m/s)
- reading starts at the inner radius of the disc (WHY?)
- variable speeds with all other applications
  - up to 50 times average reading speed compare to audio CD (linear rotating speed slightly less due to caching technology – but still up to 8000 rev/min max. rotating speed)

Rotating of disc

Disc table actuators

- very thin (flat) configuration
- maintenance free
  - electronic commutation
  - spiral groove bearings (no wear)

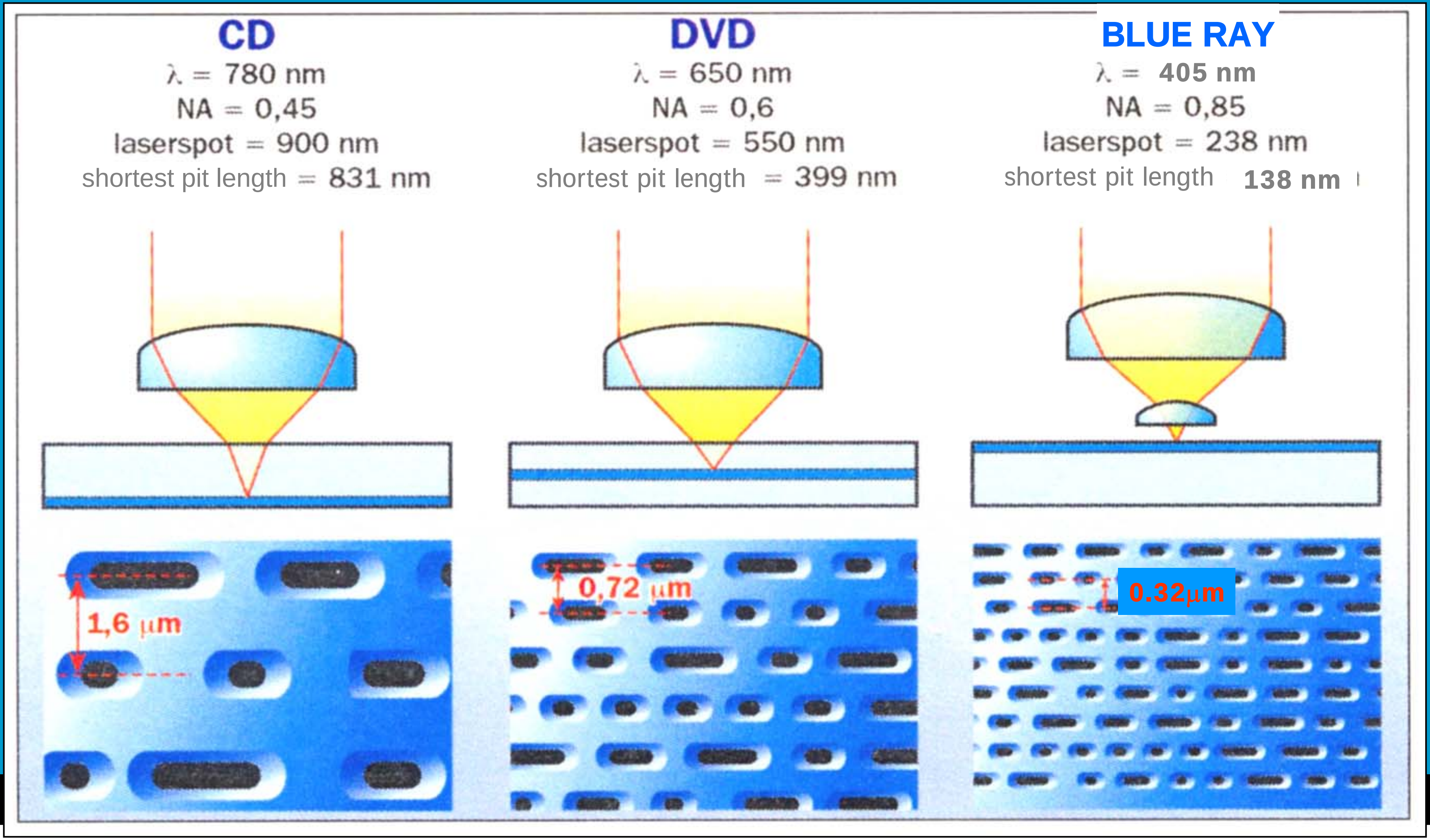




Continuing development to higher performances

- higher information density
  - CD (800 Mb) -> DVD (4,7 Gb – 18 Gb) -> Blue Ray (up to 100 Gb)
- higher reading speeds
  - (up to 50 times audio speed)
- demand for individual writing on discs
  - CD-R, Mini Disc, CD-RW, DVD-R, DVD-RW
- compatibility of formats
  - players and writers should be able to process all formats

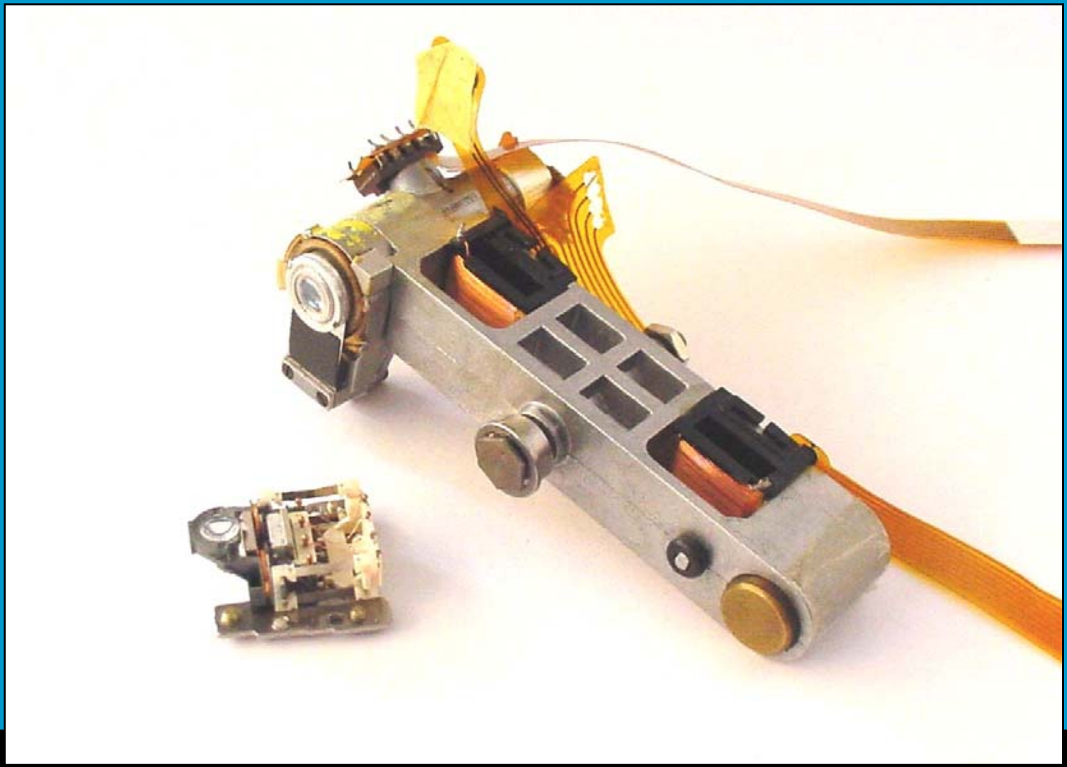
Continuing development to higher information density



Continuing development to higher processing speeds

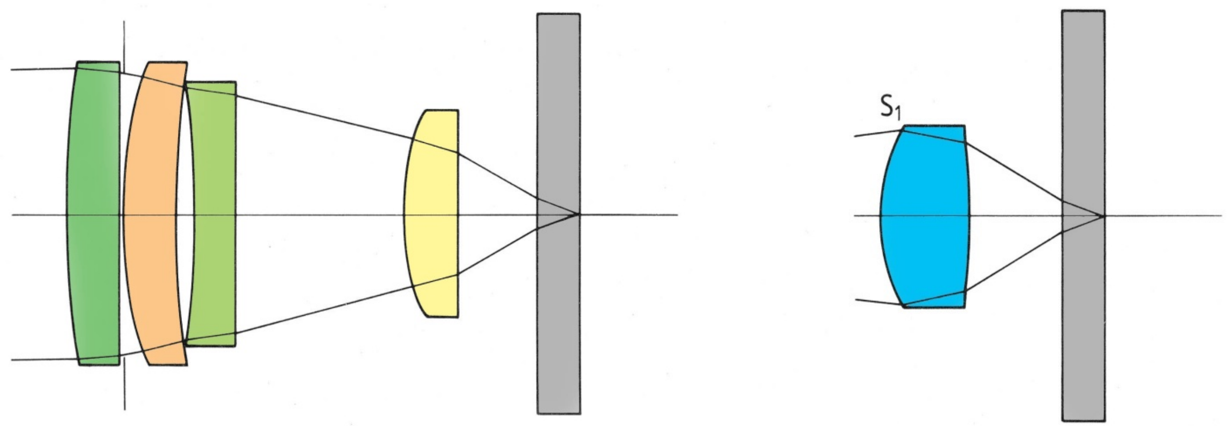
Conflicting demands – high speed + low energy consumption

Solutions: far reaching miniaturization of moving components



Continuing development to higher processing speeds

Miniaturization of optical elements



multiple spherical lens glass objective (mass > 2 g)

single aspherical lens plastic objective (mass < 0,2 g)

CD(DVD)-R and CD(DVD)-RW technology

The next design question was:

- Would it be possible to write or even erase the information on the disc on individual basis (by the end user himself)?

Solution:

- using the same principle of sequence of “zeros” and “ones” placed a long spiral track
- applying sensitive layers on the track which can change their reflectivity under influence of heat (thermal energy from the laser spot)

CD(DVD)-R and CD(DVD)-RW technology

Raw discs are already equipped with the continuous track indentation

- (this spiral groove serves for servo guidance, absolute time information and other data)
- the track pitch and the decoding technology is identical with the mass produced discs which already contain information

CD (DVD)-R technology:

- the reflectivity of the sensitive layer can be change only once (it is not reversible)

CD (DVD)-RW technology:

- the reflectivity of the sensitive layer can be change many times (it is full reversible)

CD(DVD)-R and CD(DVD)-RW technology

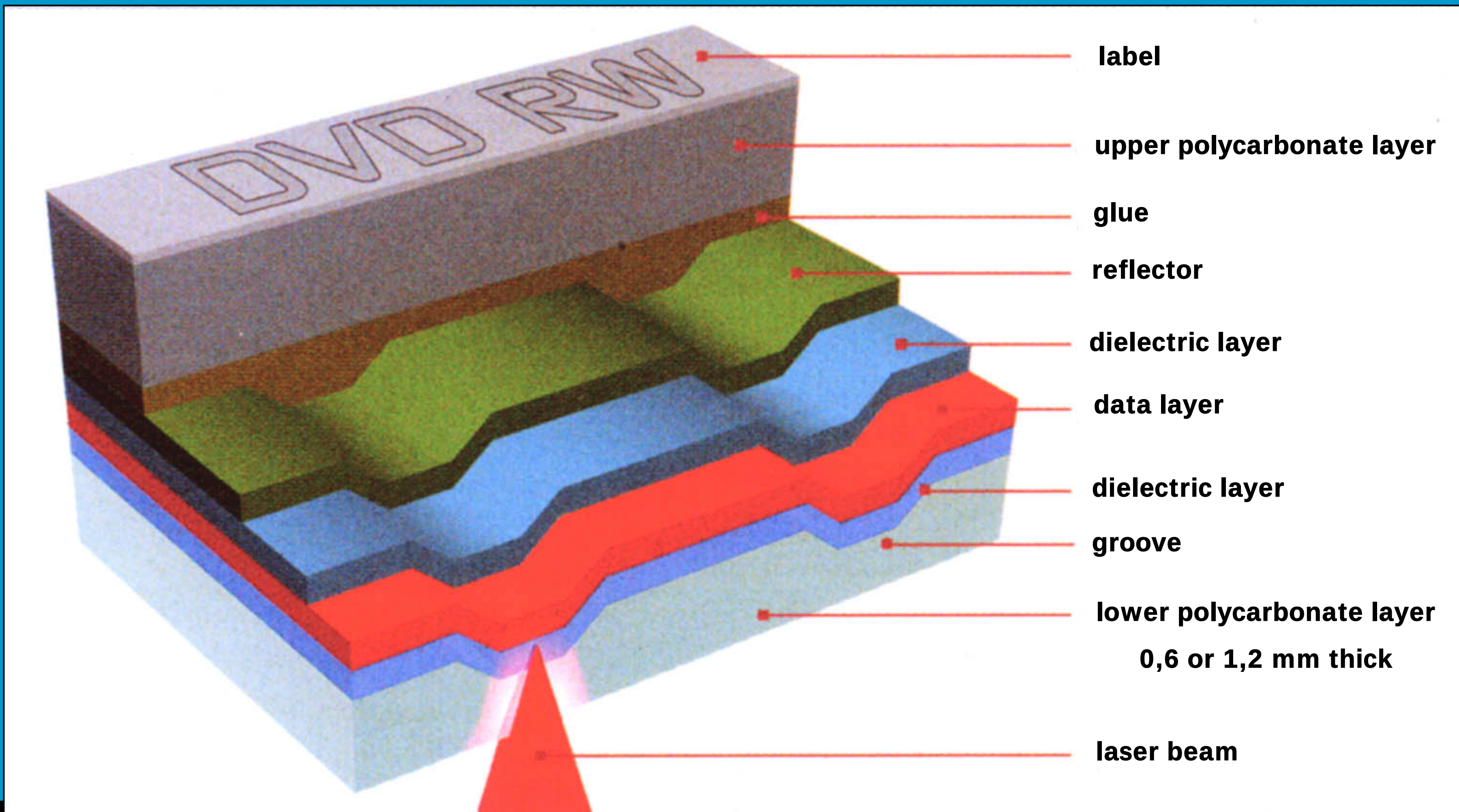
The key player is the “dye” layer:

- the heated areas of the dye, heated beyond a critical temperature (slightly above 200 C) are “burned” – they become opaque (or absorptive) and reflect less light then the unaffected areas

Dye materials differ in:

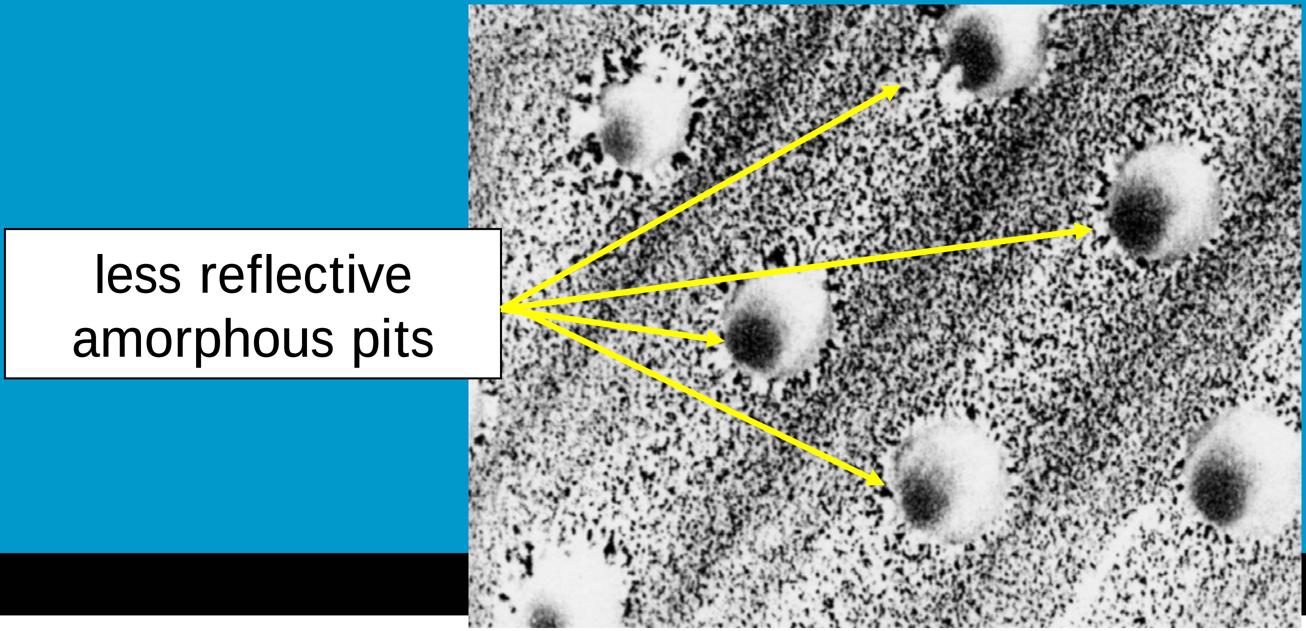
- chemical definition
- reflective properties
- longevity (10 to 200 years at room temperature)
  - storing in daylight (UV-light) or exposing to temperatures above 80 C is fatal !!

CD(DVD)-R and CD(DVD)-RW technology



CD(DVD)-RW technology

- The sensitive layer consists of an alloy from silver, indium, antimony and tellurium
- In original state (no information written) – material in polycrystalline state (high reflective)
- Under heat it undergoes optical phase change (becomes amorphous – less reflective)

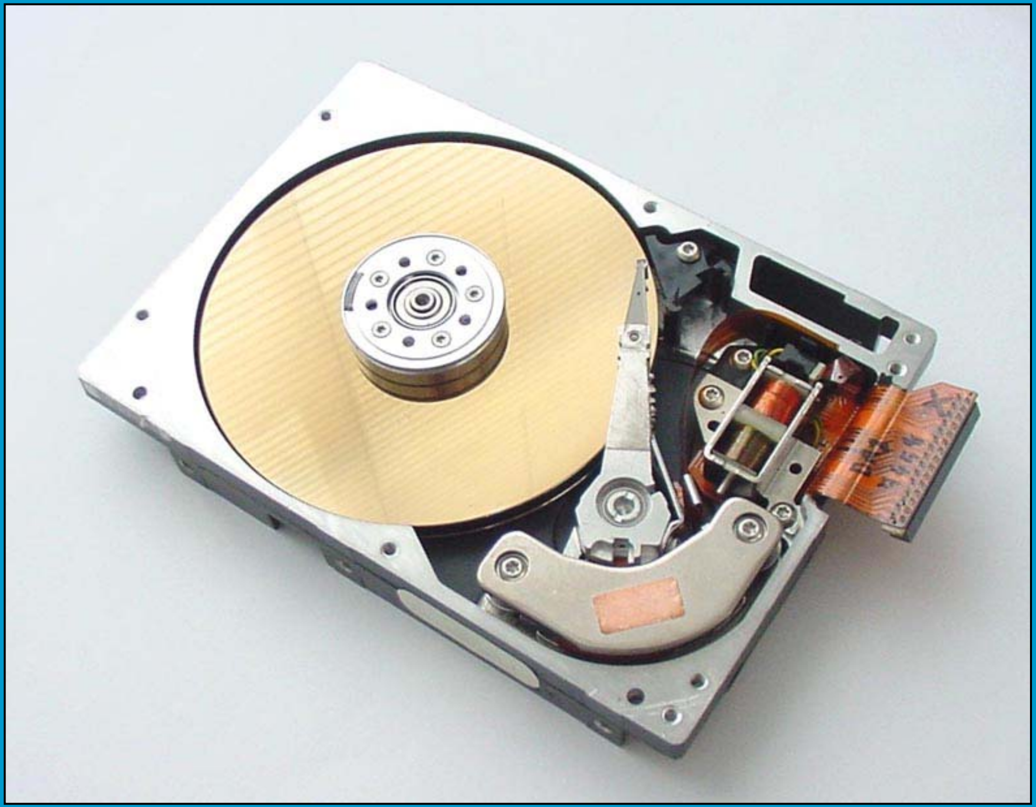


CD(DVD)-RW technology

The rewritable recorder uses 3 different laser powers:

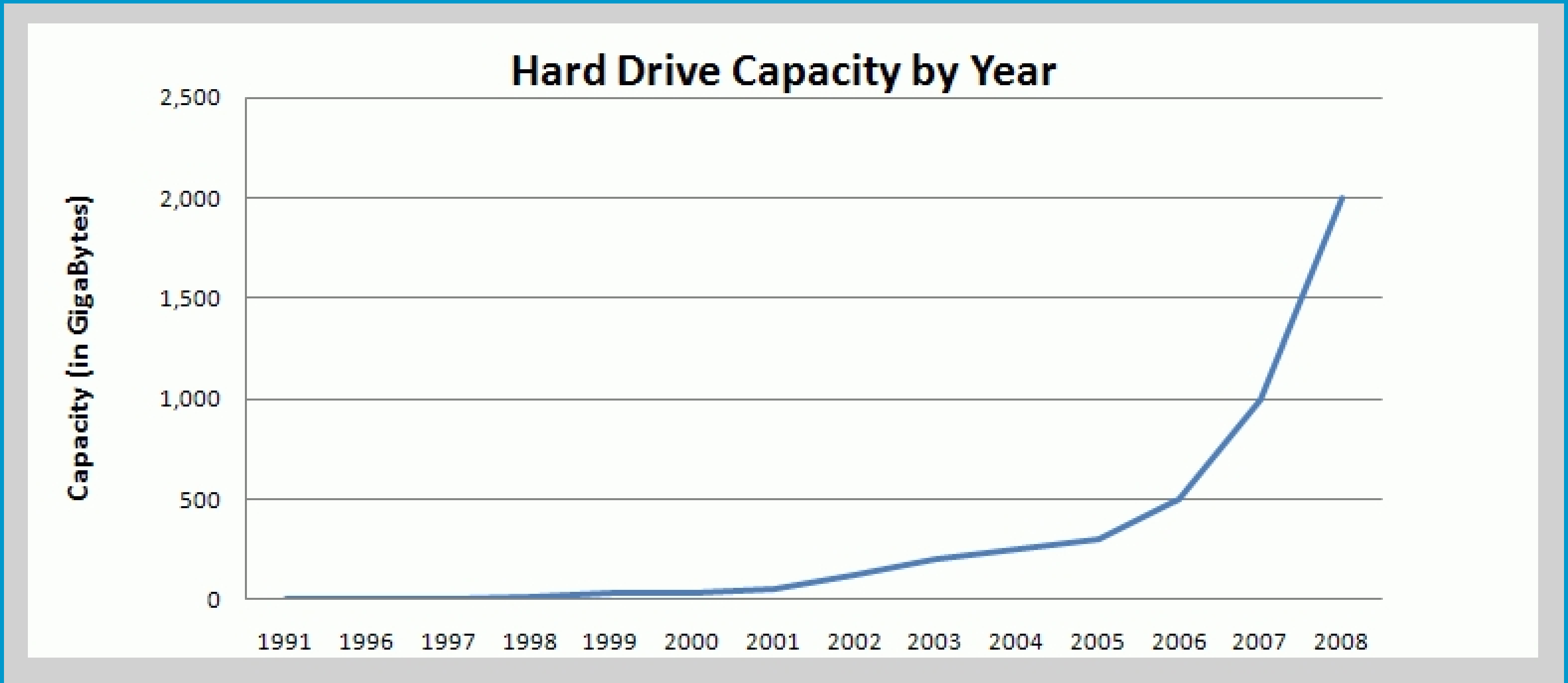
- highest (“write power”) – creates non-crystalline state in the recording layer
  - material is heated above melting temperature (500-700 ^{o}C)
  - after quick cooling (with help of dielectric layers) the random liquid state is “frozen-in”
- middle power (“erase power”) – revert the layer to a reflective state
  - heating to below the melting temperature but above the crystallization temperature (200 ^{o}C)
- lowest power (“read power”) does not alter the state of the layer
  - detects only the transitions between reflective and less reflective

Magnetic recording - hard disks



- relative young technology
- data density growing with no limits in sight
- very reliable compare to conventional devices
- cheap

Magnetic recording - hard disks



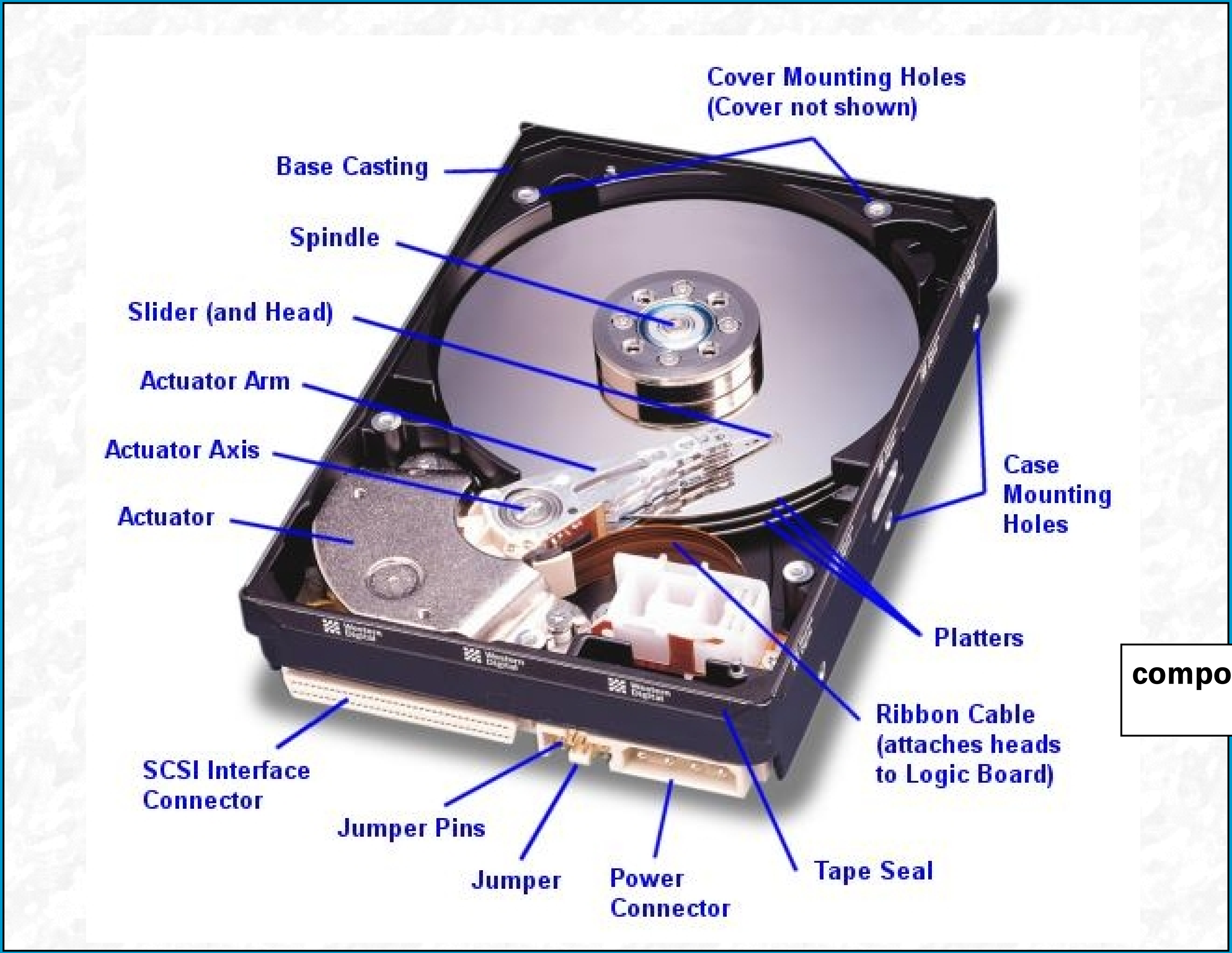
Magnetic recording - hard disks

RAMAC "Random Access Method of Accounting and Control"

First hard disk drive

- IBM
- stack of 50 disks 24" diameter
- data density 2000 bits/sq.in
- $ 10,000/ 1Mb

Magnetic recording - hard disks



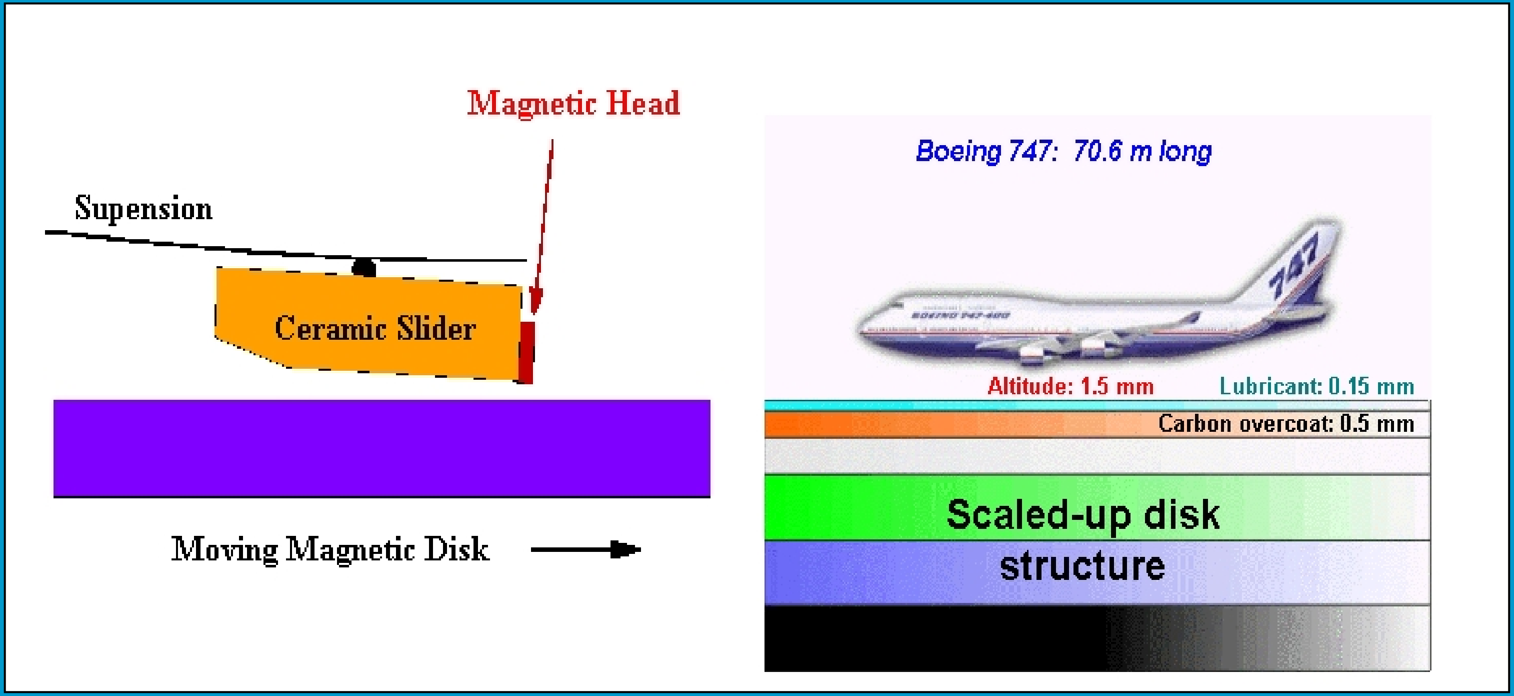
data density up to

100 Gb/sq in

components of the hard disk drive

Magnetic recording - hard disks

- Comparison of dimensions, speed and accuracy of modern hard disks



Intermezzo – comparing technologies

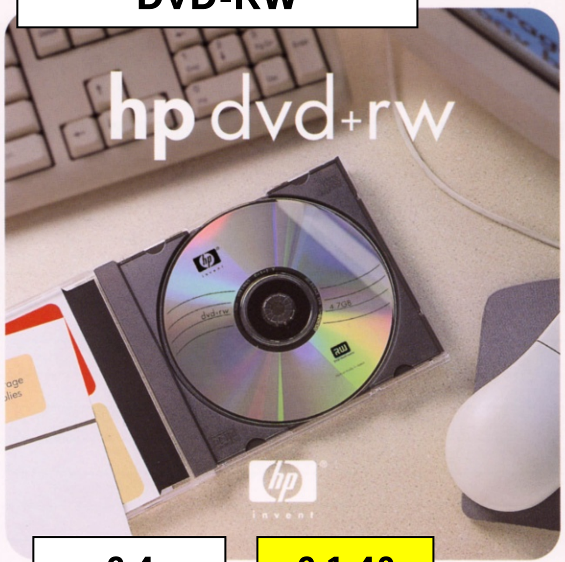
Costs of 2 hours movie in DVD format – 4Gb (erasable media)

continuing large gap between devices with movable parts and solid state memories

2004	2008

April 2011

DVD-RW



€ 4 | € 1,40

€ 0,60

hard disk

€ 4 | € 0,80

€ 0,18

Compact Flash

€ 1600 | € 58

€ 30

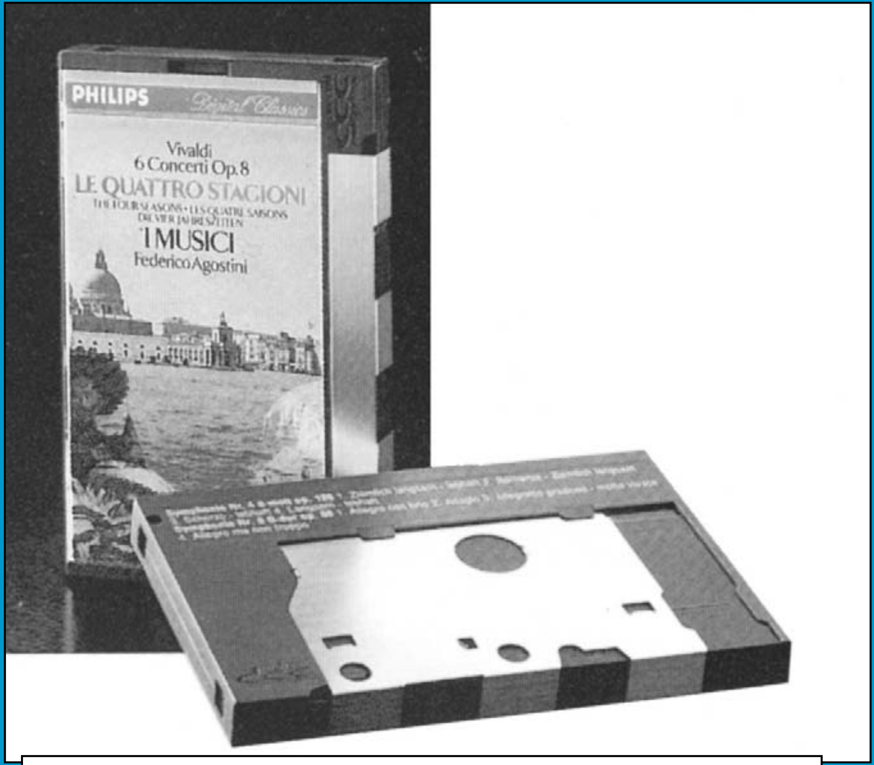
required data transfer > 1 Mb/s

Intermezzo – comparing technologies

€ 5.35 / 4 Gb !!!

Recording technologies which did not survived (in the consumer market)

DAT (Digital Audio Tape)



DCC – Digital Compact Cassette

Recording technologies which did not survived

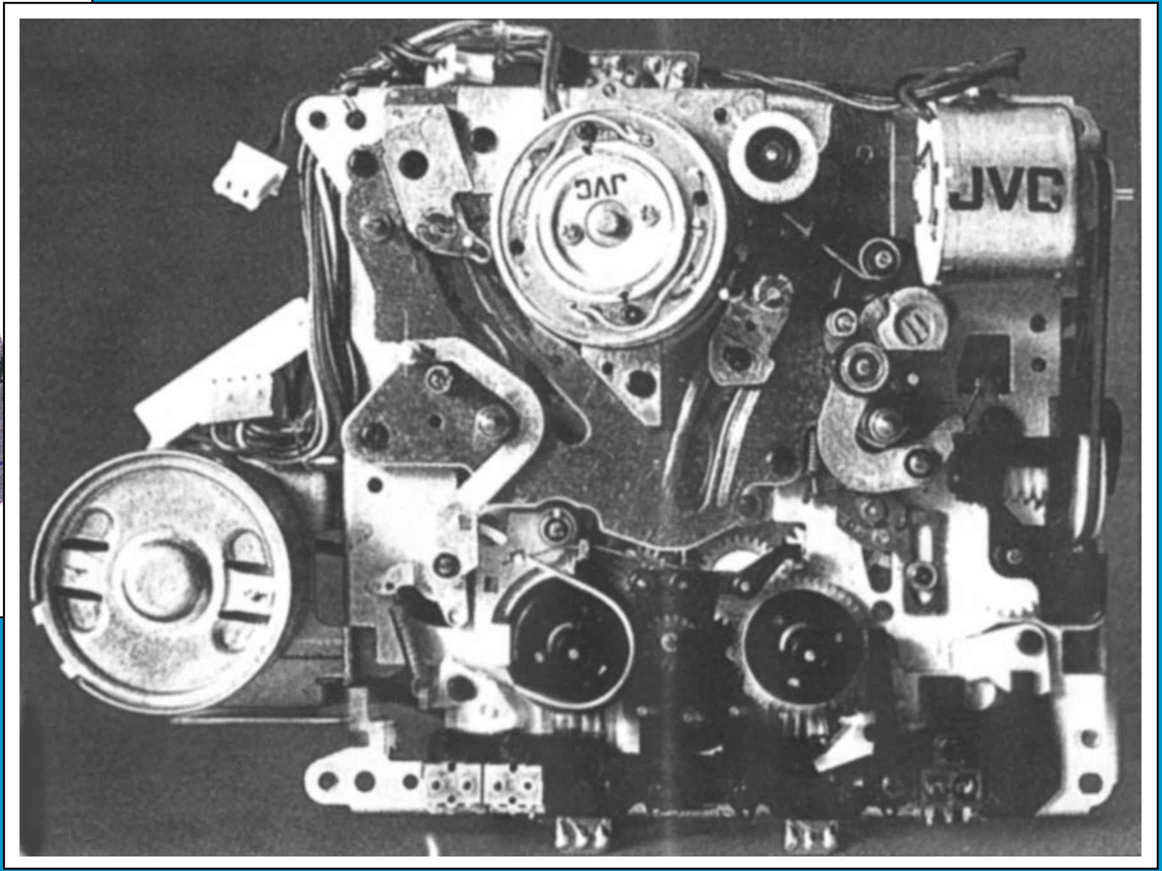
Technologies meant for the consumer market:

- DAT (Digital Audio Tape) – recording
- DCC (Digital Compact Cassette)

Main common reasons for not being successful (in spite of excellent audio quality)

- expensive mechanical parts
- using of tape (slow random access)
- to few recordings on the market
- insufficient market share (lack of large support by many manufacturers)

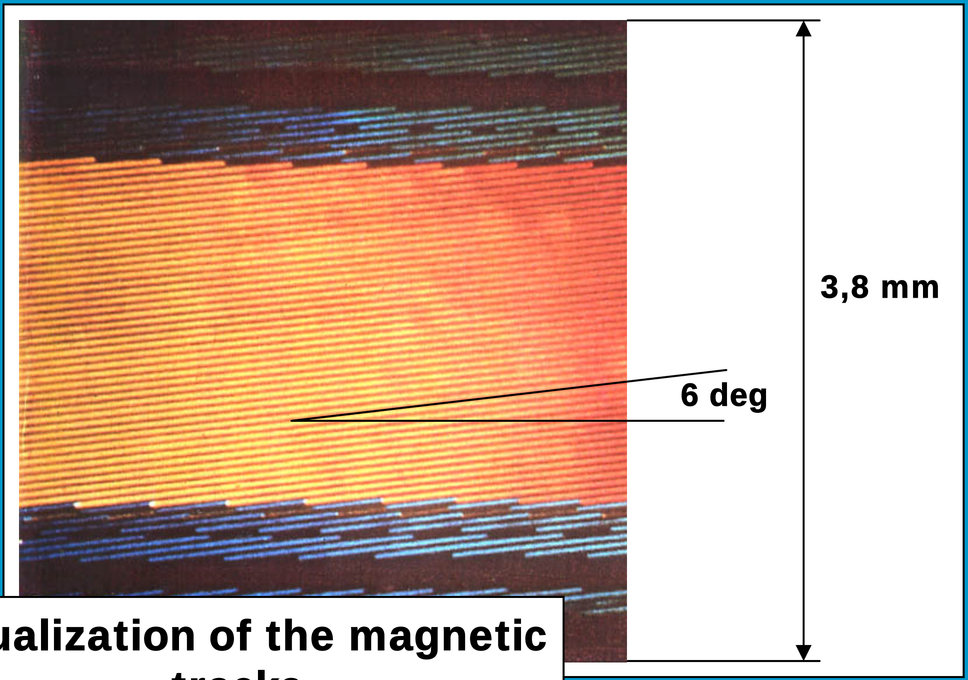
DAT (Digital Audio Tape)



DAT (Digital Audio Tape)

Basic properties

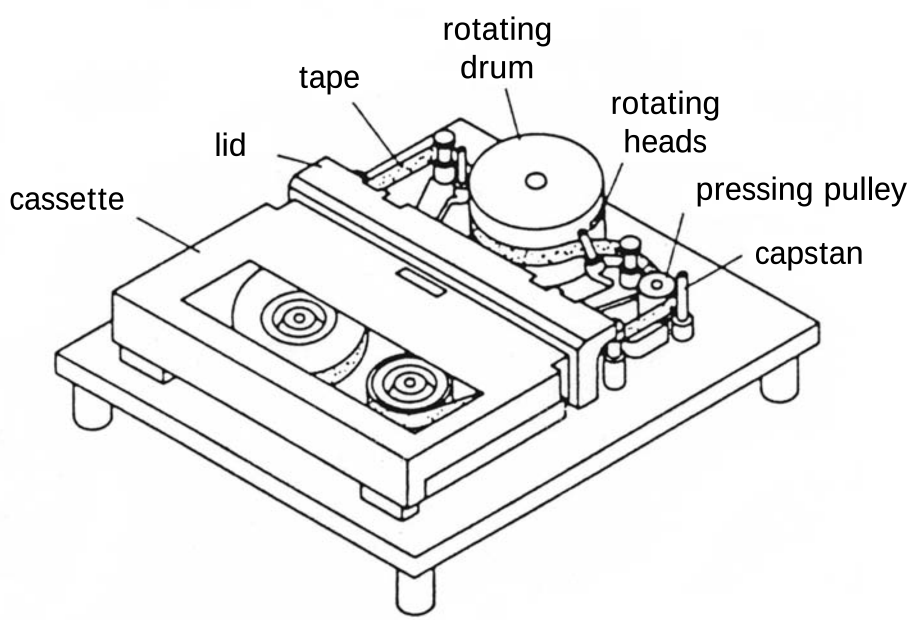
- diam. rotating drum – 30 mm
- tape speed – 8,15 mm/s
- relative speed tape – heads – 3 m/s !!
- length tracks – 23 mm
- information density – 185000 bits/mm^2
- playing time – 2 hours
- max seek time – 40 s !!
- no compression of audio information using psychoacoustic properties



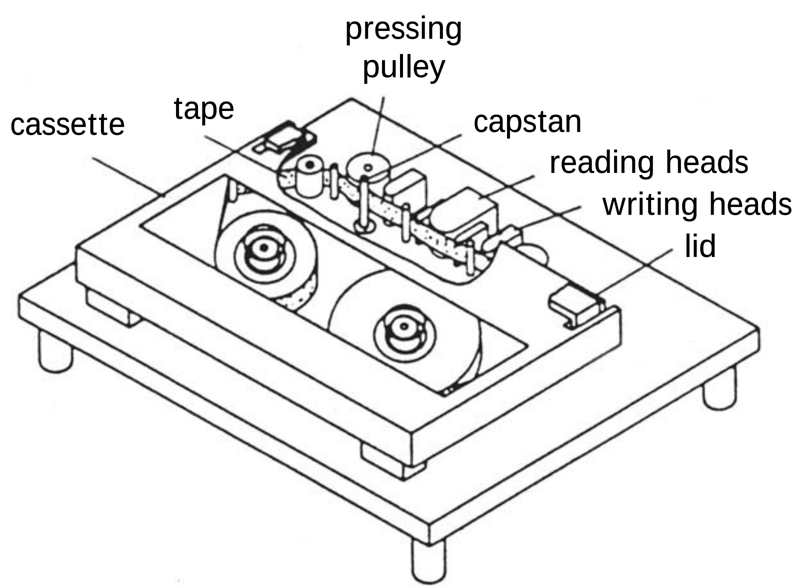
visualization of the magnetic tracks

DAT – DCC (comparison)

Dimensions of the cassettes approximately the same



DAT – Digital Audio Tape



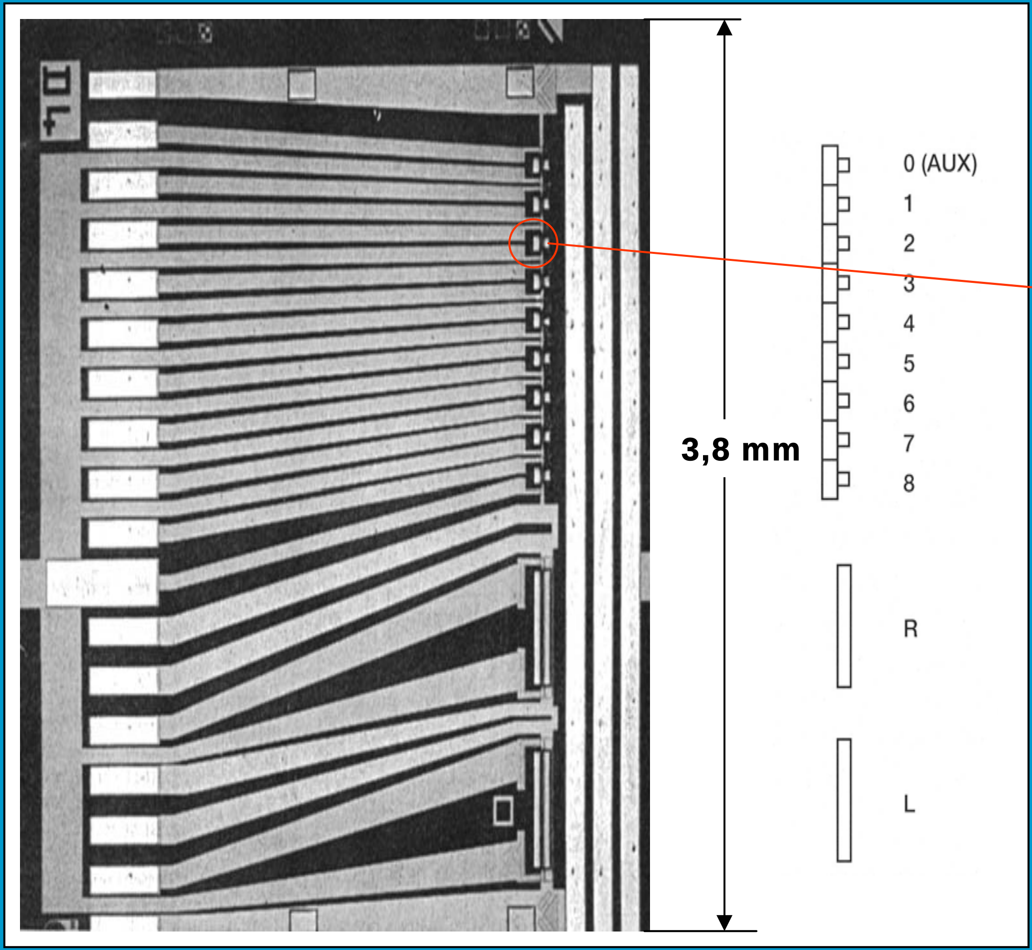
DCC – Digital Compact Cassette

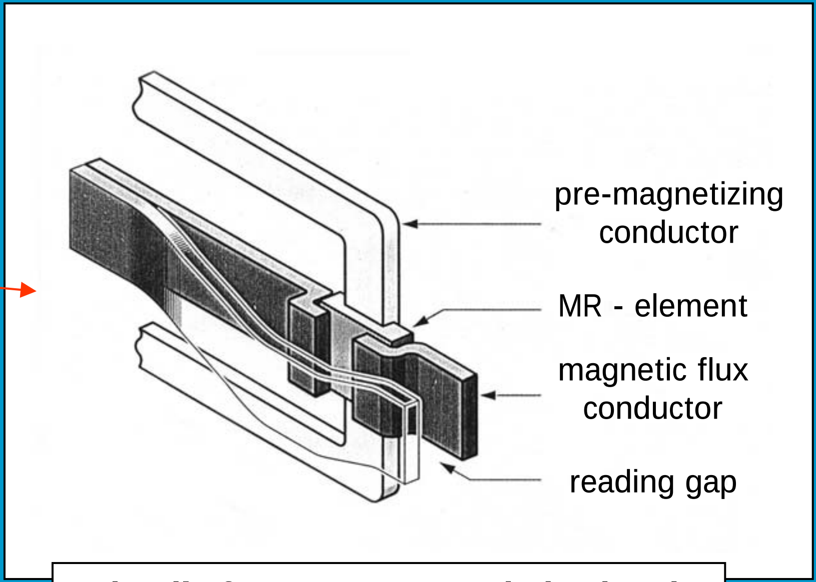
DCC – Digital Compact Cassette

Basic properties

- linear motion of tape – speed 8 mm/s
- max. playing time 2 hours possible due to:
  - digital off-line processing of the audio signal
  - simultaneous (parallel) writing to 8 heads
  - miniaturization of heads possible by using magneto-restrictive principle
  - use of data compression PASC (Precision Adaptive Subband Coding) – use of psychoacoustic properties of human ear

DCC – Digital Compact Cassette





detail of 1 magneto-restrictive head

parallel recording on 8 tracks possible due to the off-line digital processing of information

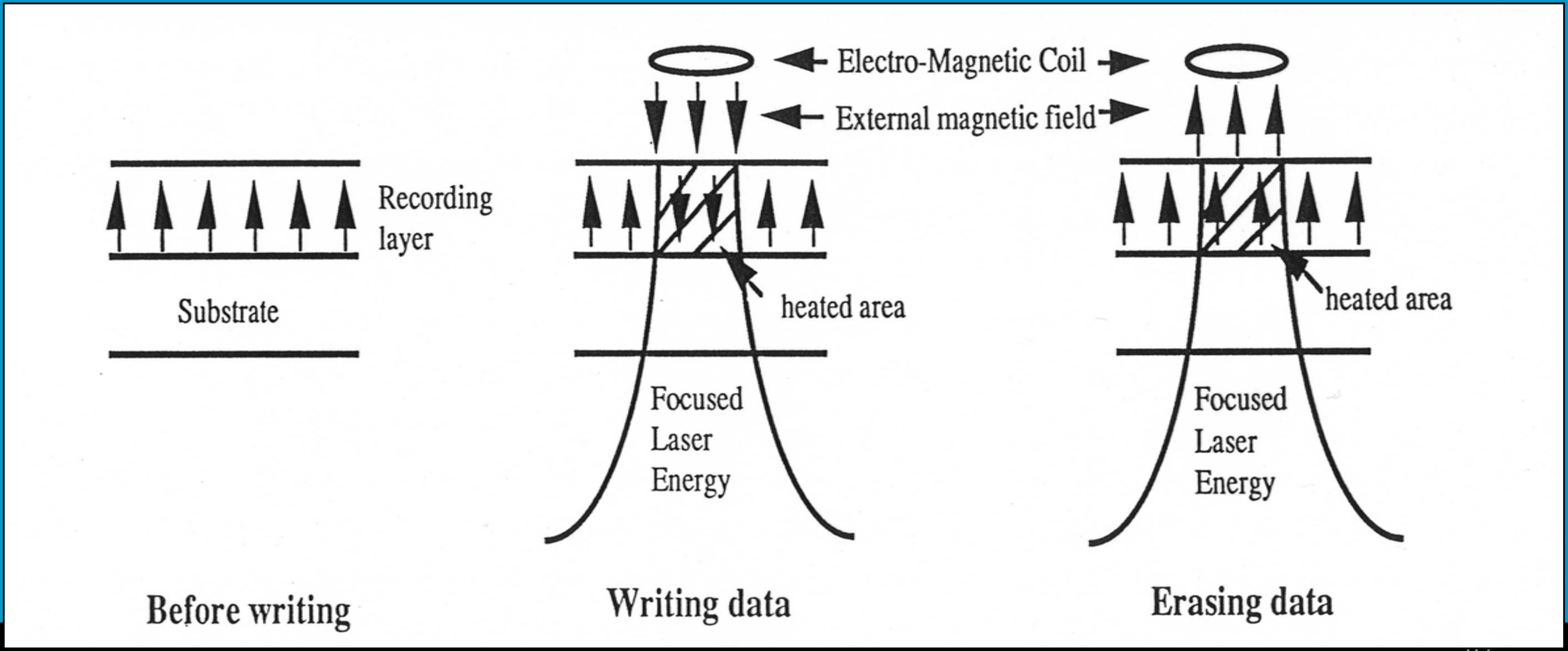
Magneto-optical recording

- developed by a large number of companies (Sony, Philips, DuPont Optical)
- first in use for professional data storage
- now mostly known from the consumer market:
  - Mini Disc by Sony
- MO – recording allows for writing and erasing many times (like other types of magnetic recording)
- use of audio data compression techniques made the miniaturization of Mini Disc possible
- the handling of digital data very similar to “classical” CD technology

Magneto-optical recording

Principle of writing (and erasing) data

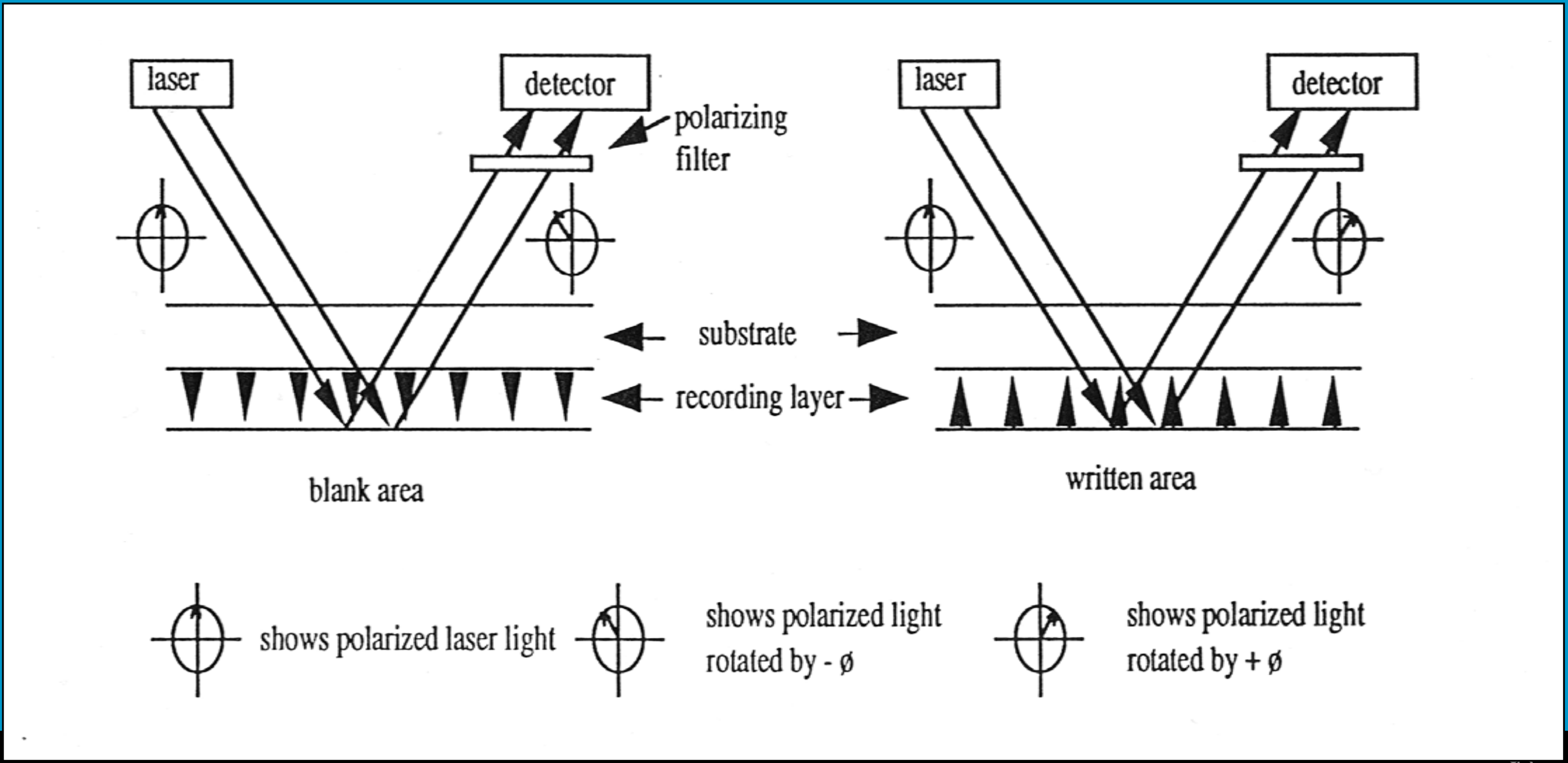
- heating of MO-layer by laser energy above Curie-temperature disrupt well-ordered magnetism
- electromagnetic field prescribes the magnetic direction during cooling (“freezing”)



Magneto-optical recording

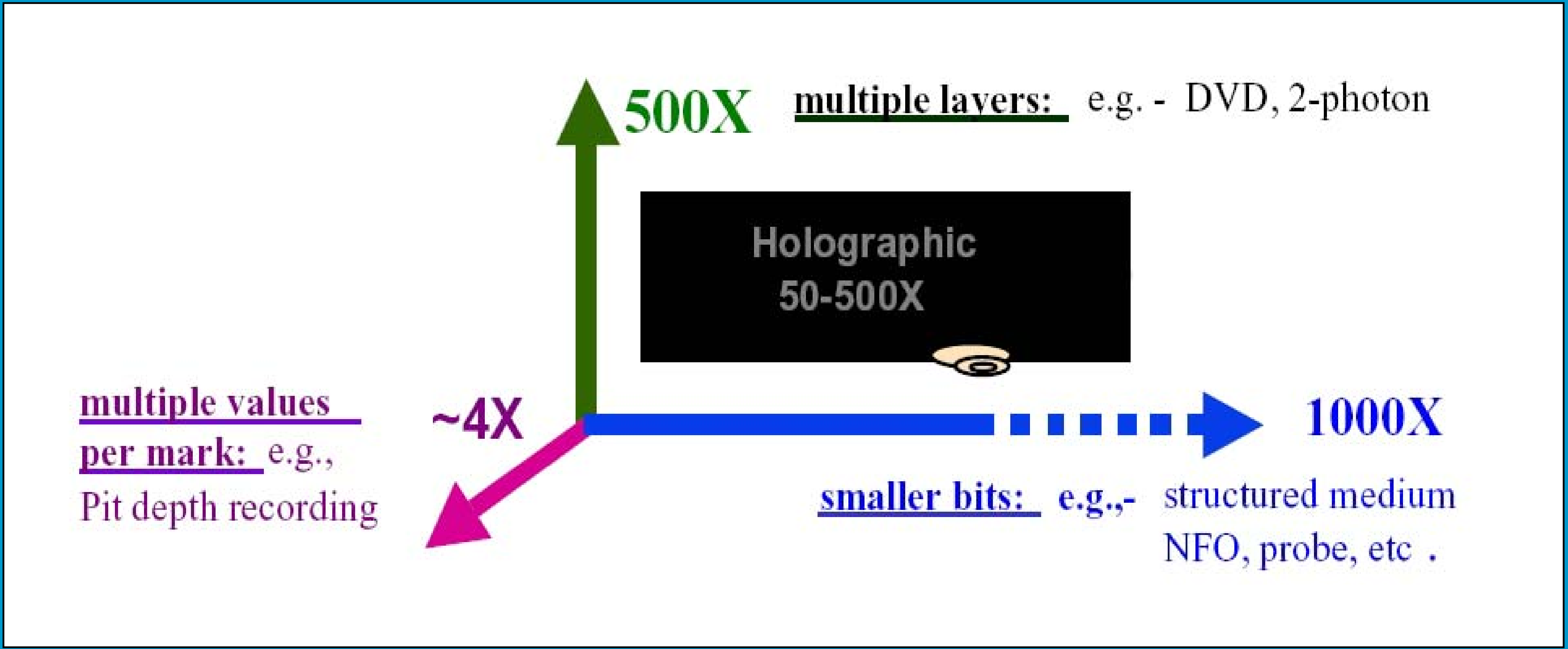
Principle of reading stored data

- detector recognizes the magnetic direction by slight change in the light polarization angle – the Kerr effect (max +/- 0,5 º !!)

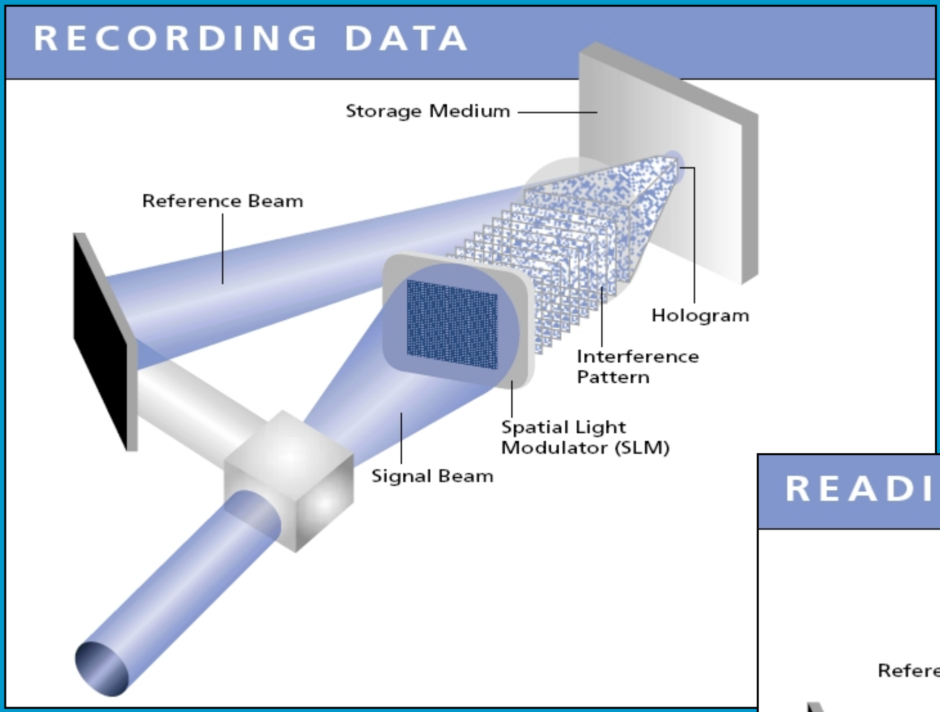


What the future brings

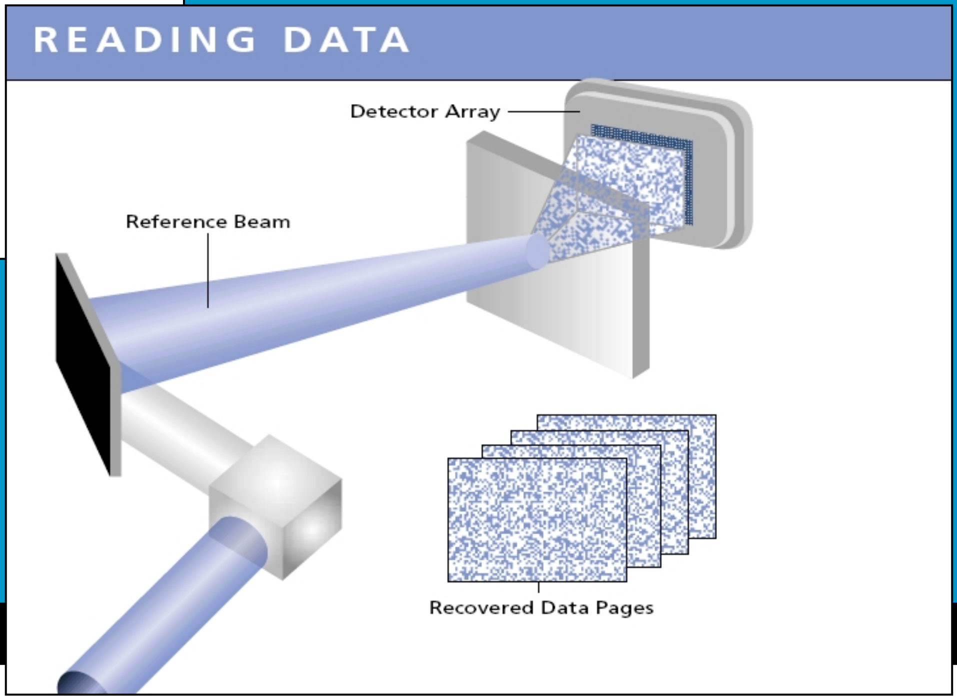
New degrees of freedom in data storage



Holographic data storage



- FEATURES
- • Parallel access to data
- • Multiplex data pages in one location
- BENEFITS
- • Fast data transfer rates
- • Ultrahigh storage densities

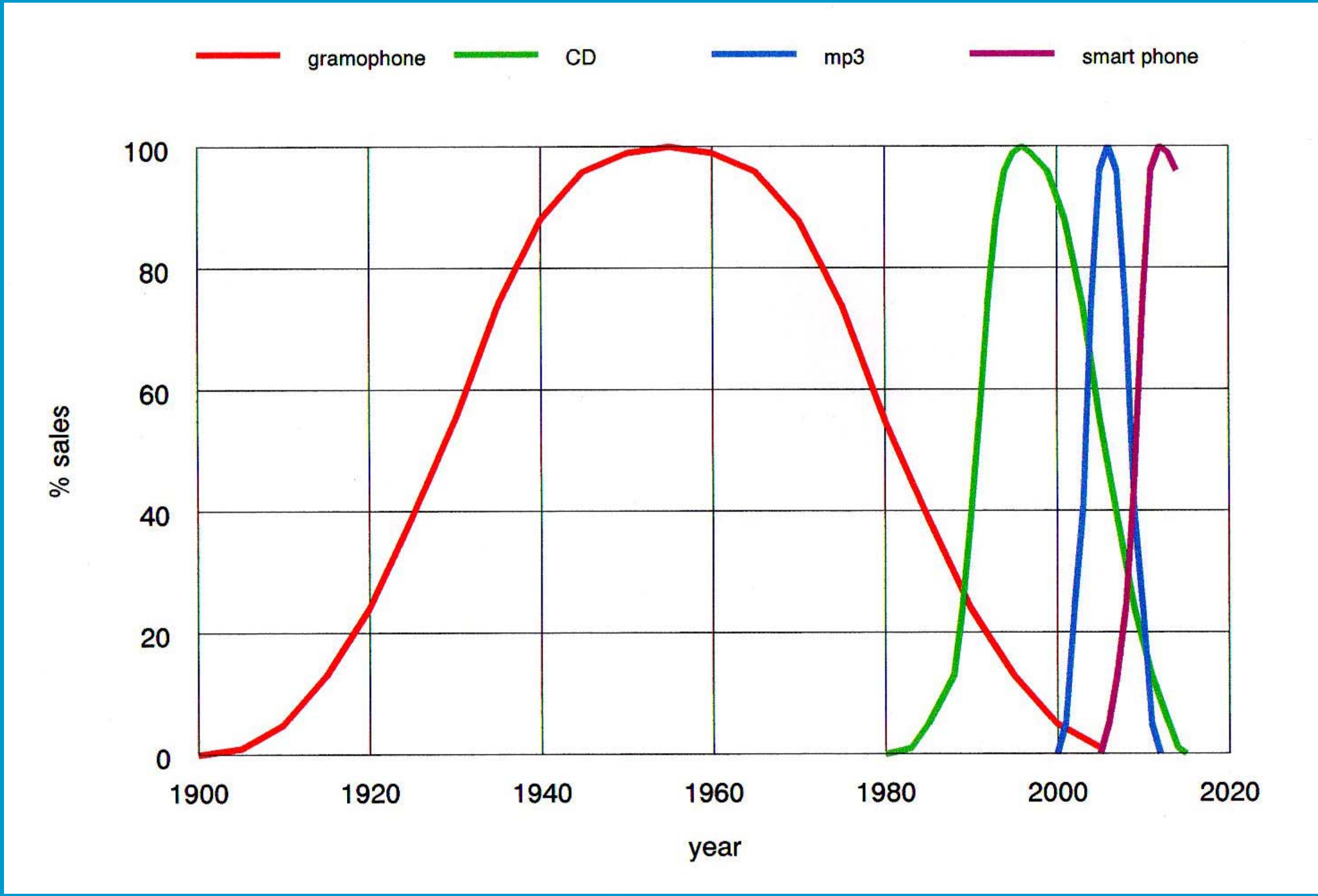


Holograms can be stored in the same location throughout the entire depth of the medium.

Holographic data storage

- FEATURES
- • parallel access to data
- • multiplex data pages in one location
- BENEFITS
- • fast data transfer rates
- • ultrahigh storage densities

Life cycle of audio media



What the future brings

Use your imagination

- in a couple of years even the latest model of portable music player will be obsolete

obsolete in 2006

obsolete in 2011 ?

What the future brings

Use your imagination

- in a couple of years even the latest model of a mobile phone will be obsolete

obsolete in 2006

obsolete in 2012

What the future brings

ipad 2

May 2011

?

2016

Use your imagination

- in a couple of years even the latest gadget will be obsolete

What the future brings

Users getting younger and younger