6.003: Signals and Systems

From LPs to CDs –
and how 6.003 helps get you there

December 8, 2011

Subject Evaluations

Your feedback is important to us!

Please give feedback to the staff and future 6.003 students:
http://web.mit.edu/subjectevaluation

Evaluations are open until Friday, December 16, at noon.

You will be able to view quantitative results at
http://web.mit.edu/subjectevaluation/results.html

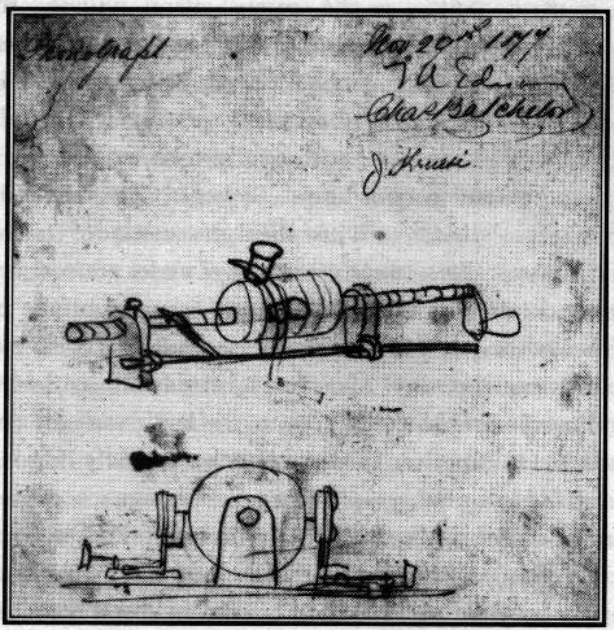
and student-written summaries at
http://hkn.mit.edu/ug_sel.php

6.003: Signals and Systems

From LPs to CDs –
and how 6.003 helps get you there

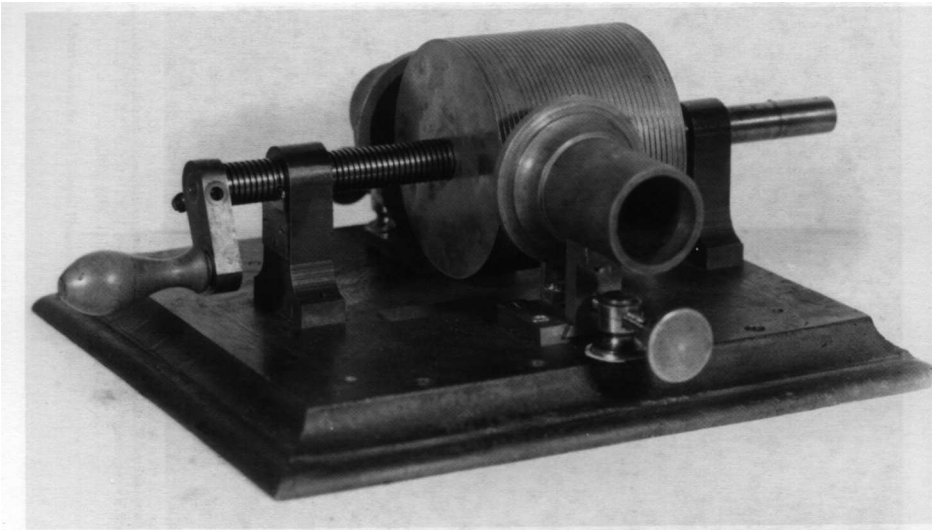
December 8, 2011

Edison's Phonograph

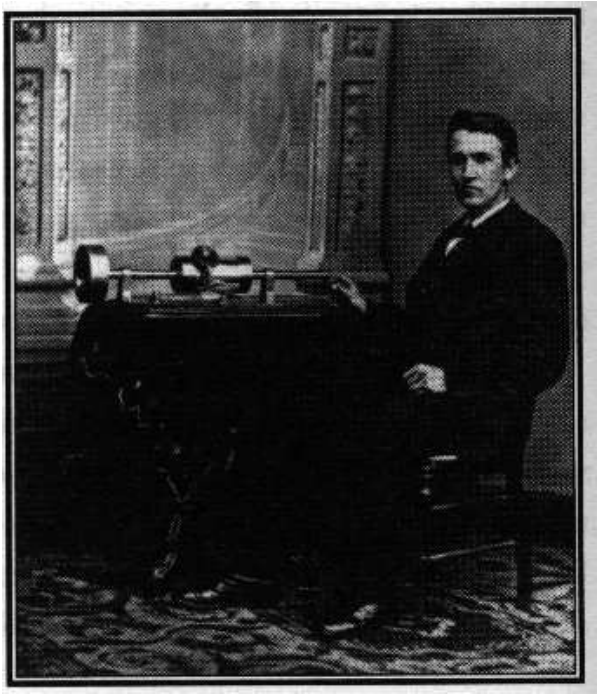


FIRST REPRESENTATIONAL SKETCH OF THE PHONOGRAPH

Edison's Phonograph



Edison's Phonograph



Edison's Phonograph

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LPs: 100 years of optimization $\rightarrow$ good fidelity, but

- fragile: easily scratched
- lots of distortions: e.g., wow and flutter
- expensive

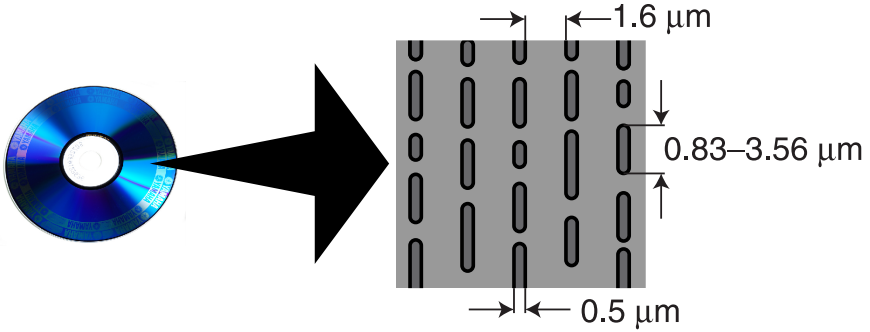
CDs: much higher fidelity

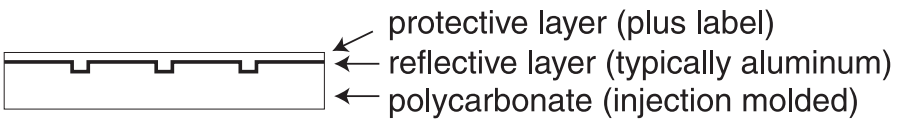
- nearly indestructible
- very low distortion
- inexpensive

$\rightarrow$ many of these advantages made possible by concepts from Signals and Systems!

Edison's Phonograph

What's on a CD?


1.6 μm
0.83–3.56 μm
0.5 μm


protective layer (plus label)
reflective layer (typically aluminum)
polycarbonate (injection molded)

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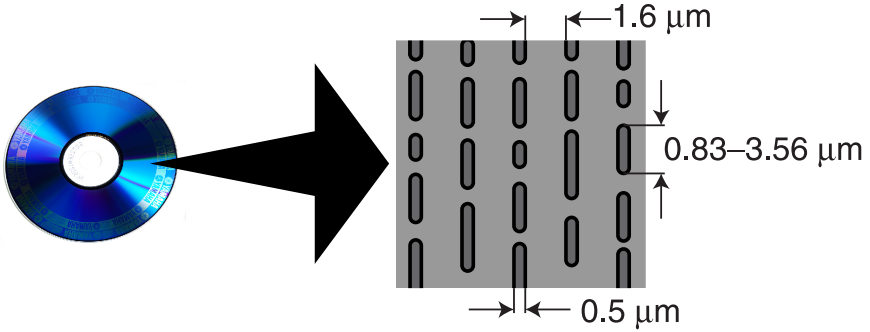
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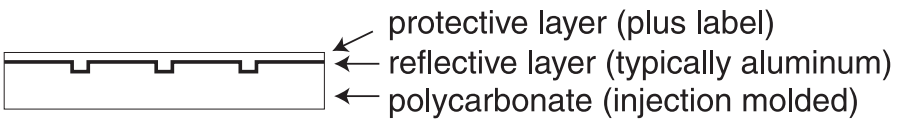

protective layer (plus label)
reflective layer (typically aluminum)
polycarbonate (injection molded)

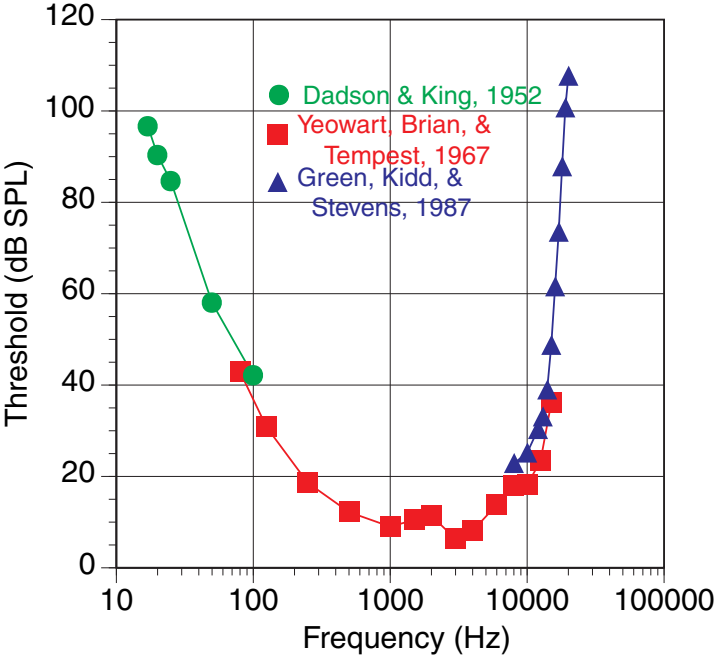
What's on a CD?

Continuous signal (audio)

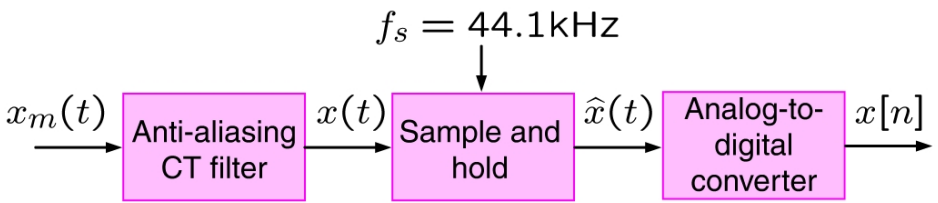
Discrete storage (pits and lands)

$\rightarrow$ sampling!

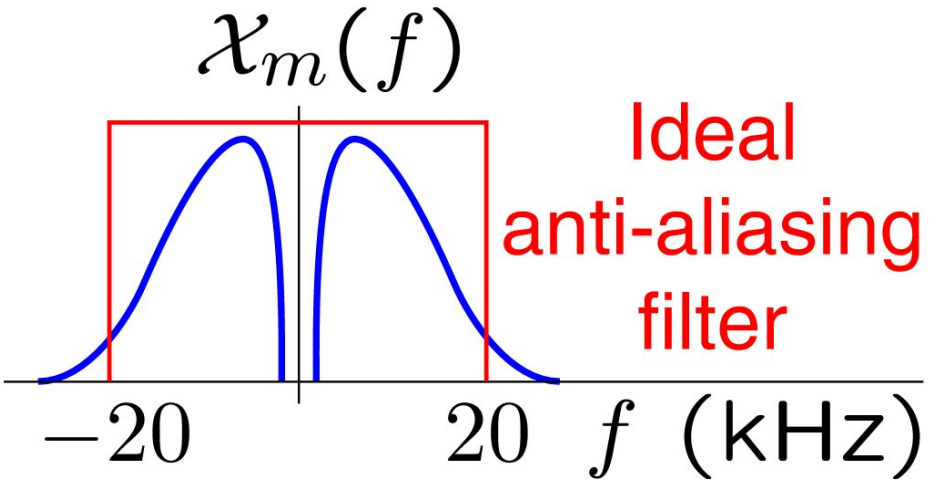
What's on a CD?


120
100
80
60
40
20
0
Threshold (dB SPL)
10
100
1000
10000
100000
Frequency (Hz)
Dadson & King, 1952
Yeowart, Brian, & Tempest, 1967
Green, Kidd, & Stevens, 1987

What's on a CD?


$f_s = 44.1\text{kHz}$
$x_m(t)$
Anti-aliasing CT filter
$x(t)$
Sample and hold
$\widehat{x}(t)$
Analog-to-digital converter
$x[n]$

What's on a CD?



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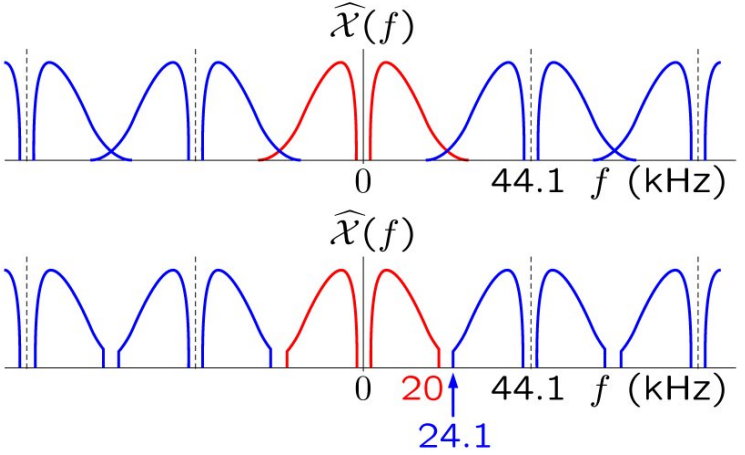
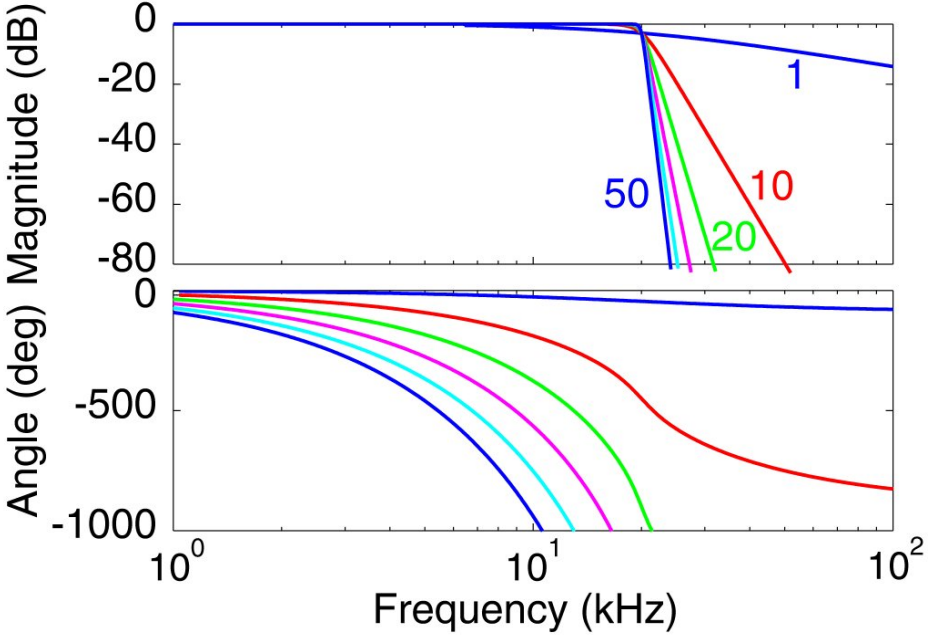


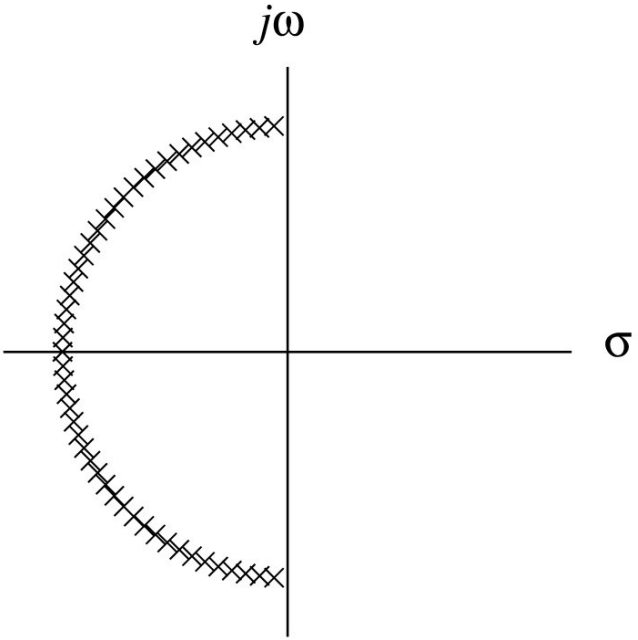
Without anti-aliasing filter

With ideal anti-aliasing filter

What's on a CD?


0
-20
-40
-60
-80
1
50
10
20
0
-500
-1000
Angle (deg) Magnitude (dB)
10^0
10^1
10^2
Frequency (kHz)

What's on a CD?



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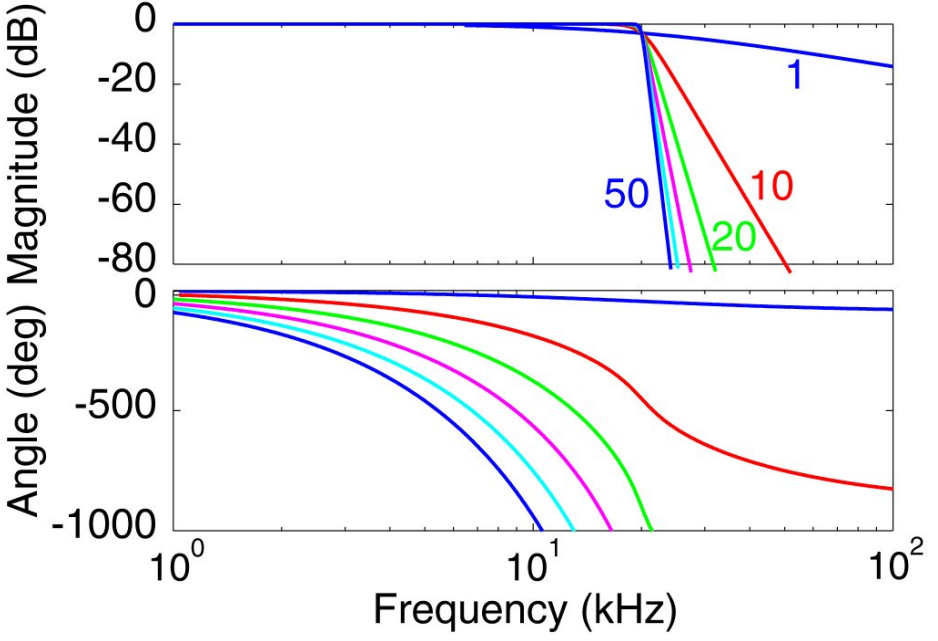
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-20
-40
-60
-80
1
50
10
20
0
-500
-1000
Angle (deg) Magnitude (dB)
10^0
10^1
10^2
Frequency (kHz)

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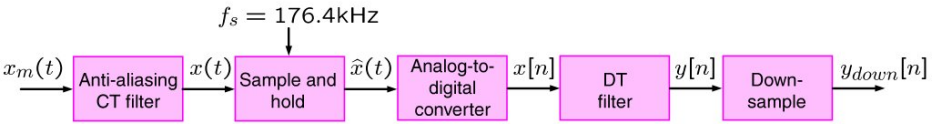
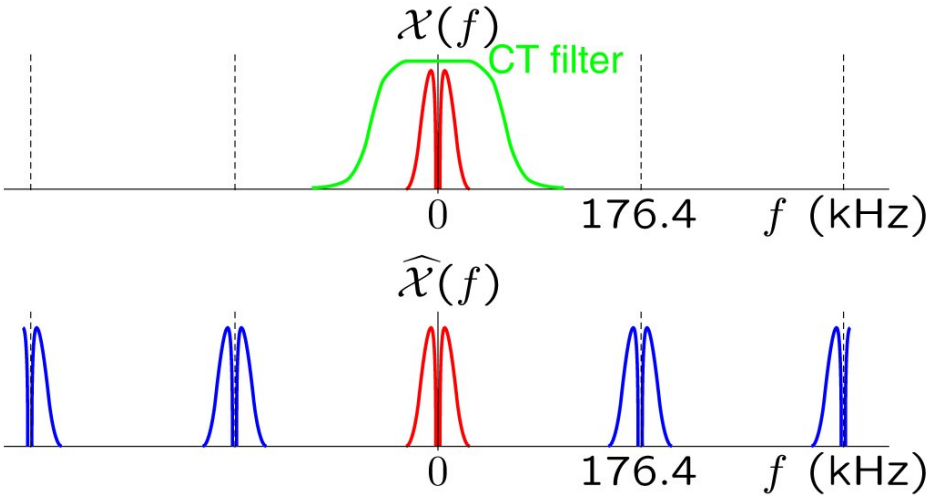
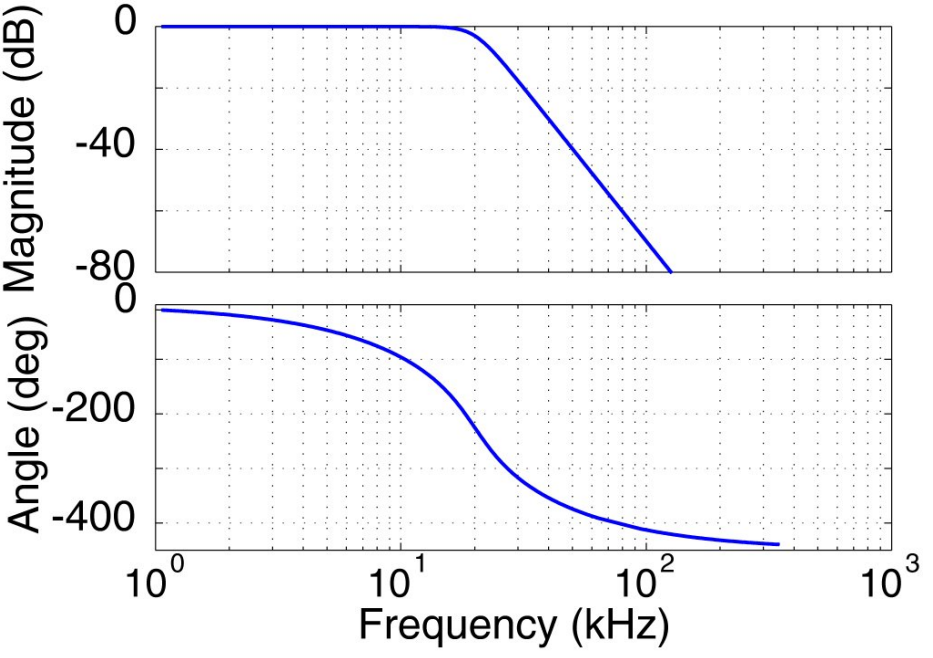

$f_s = 176.4$kHz
$x_m(t)$
Anti-aliasing CT filter
$x(t)$
Sample and hold
$\hat{x}(t)$
Analog-to-digital converter
$x[n]$
DT filter
$y[n]$
Down-sample
$y_{down}[n]$

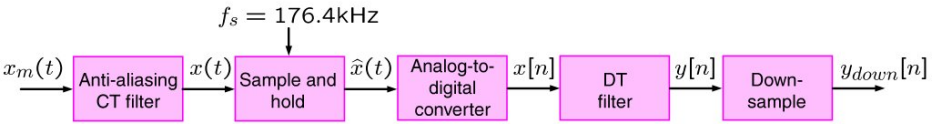
What's on a CD?


$\mathcal{X}(f)$
CT filter
0
176.4
f (kHz)
$\widehat{\mathcal{X}}(f)$
0
176.4
f (kHz)

What's on a CD?


0
-40
-80
Magnitude (dB)
0
-200
-400
Angle (deg)
10^0
10^1
10^2
10^3
Frequency (kHz)

What's on a CD?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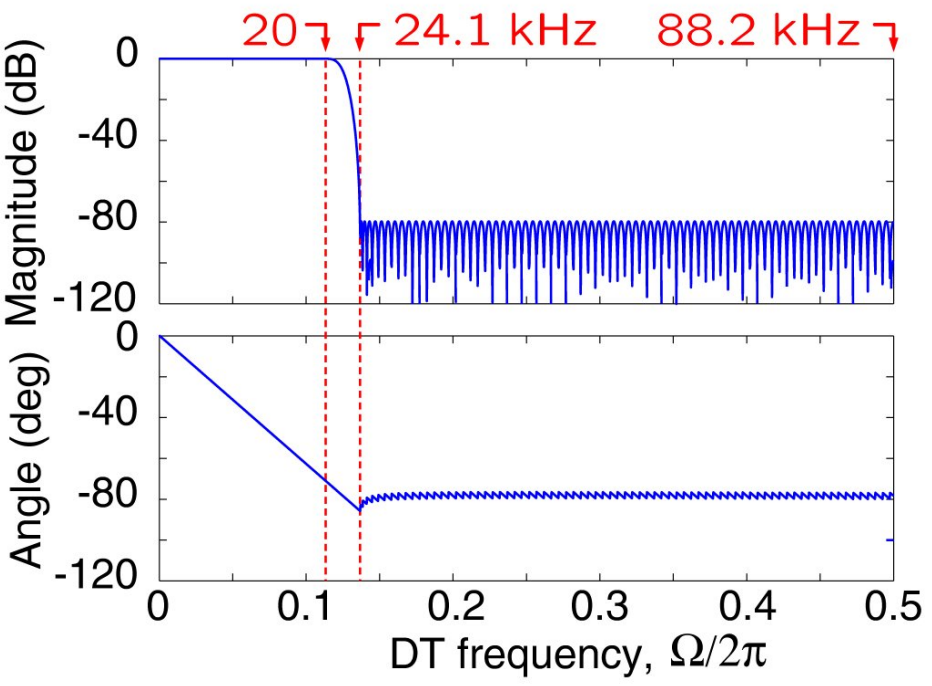
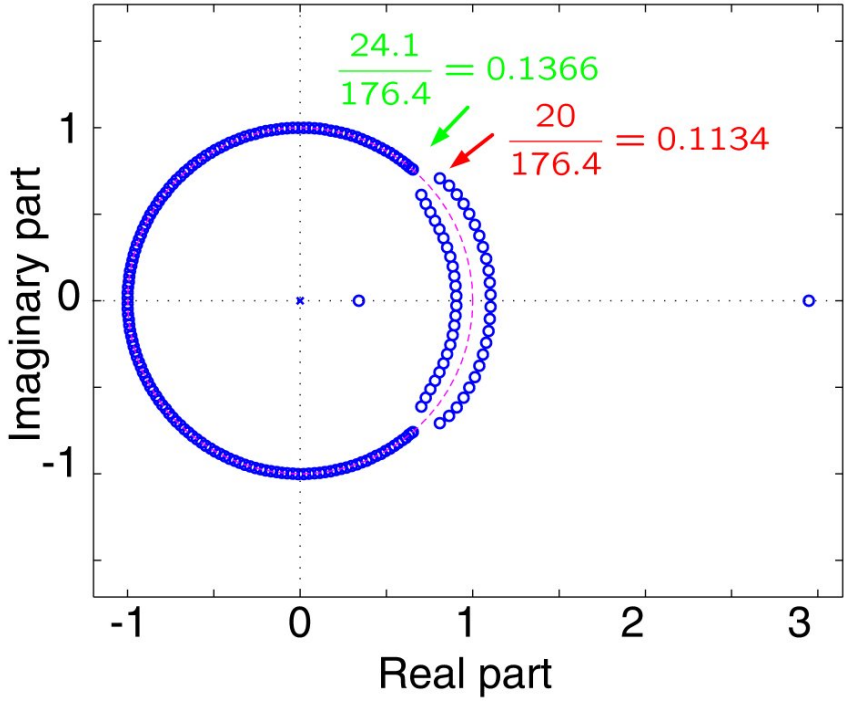
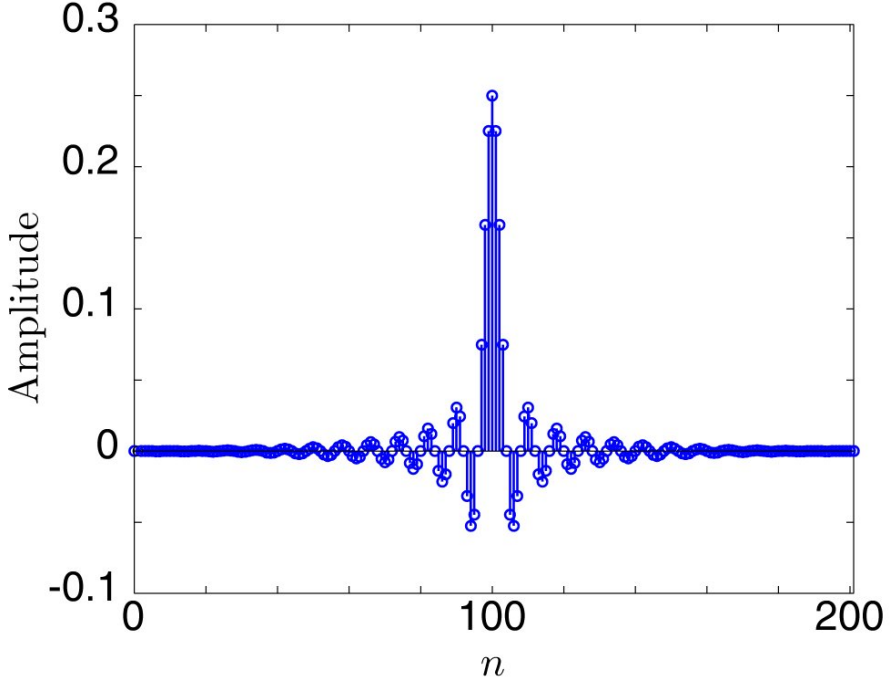

20
24.1 kHz
88.2 kHz
Magnitude (dB)
0
-40
-80
-120
Angle (deg)
0
-40
-80
-120
0
0.1
0.2
0.3
0.4
0.5
DT frequency, Ω/2π

What's on a CD?


$\frac{24.1}{176.4} = 0.1366$
$\frac{20}{176.4} = 0.1134$
Imaginary part
Real part
1
0
-1
-1
0
1
2
3

What's on a CD?



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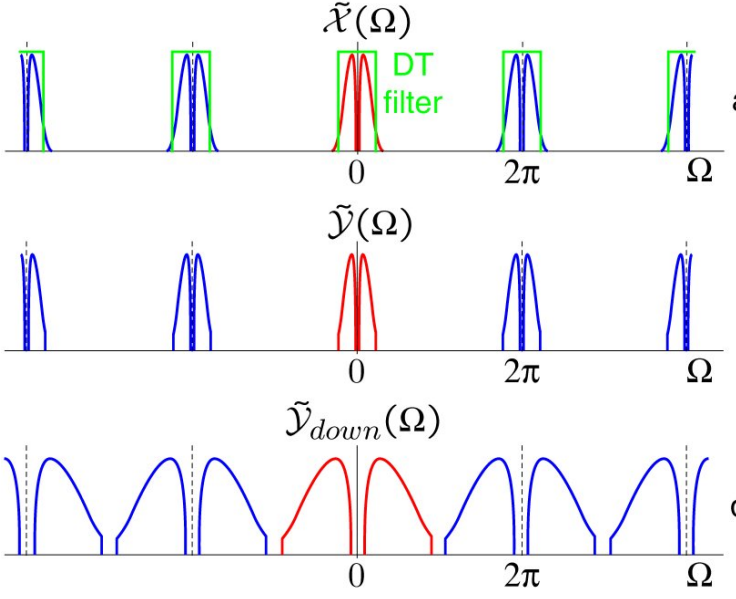


DT signal after sampling at 176 kHz

After filtering with DT filter

After downsampling

What's on a CD?

LPs: 100 years of optimization, good fidelity, but

- fragile: easily scratched
- lots of distortions: e.g., wow and flutter
- expensive

CDs: much higher fidelity

- nearly indestructible ✓
- very low distortion ✓
- very cheap

$\rightarrow$ many of these advantages made possible by concepts from Signals and Systems!

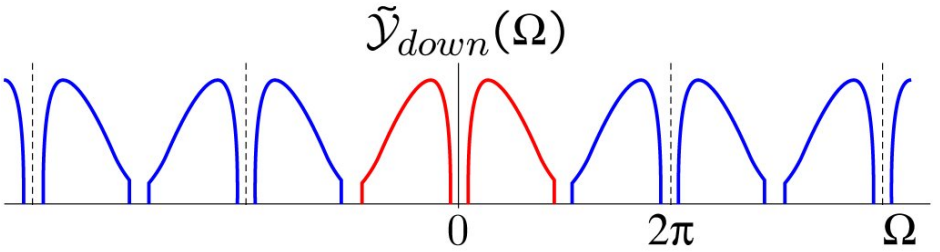
What's on a CD?

Audio $\rightarrow$ bits:

- sampling
- filtering
- DT processing of CT signals
- downsampling

Next issue: how to you build a player?

What's on a CD?



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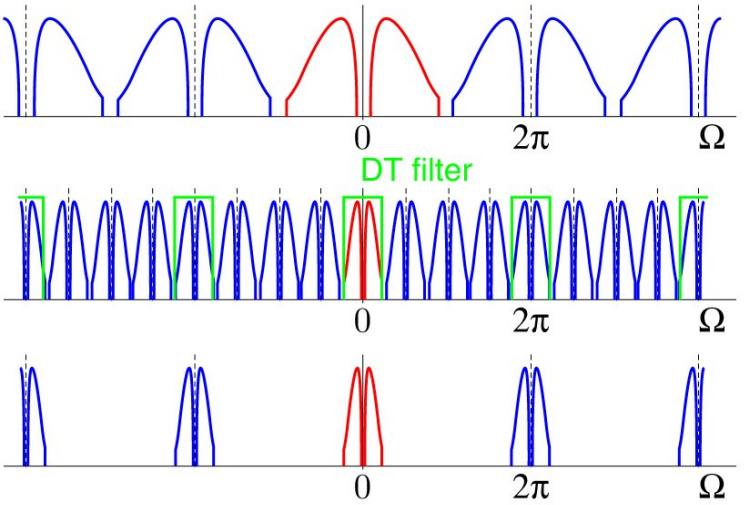
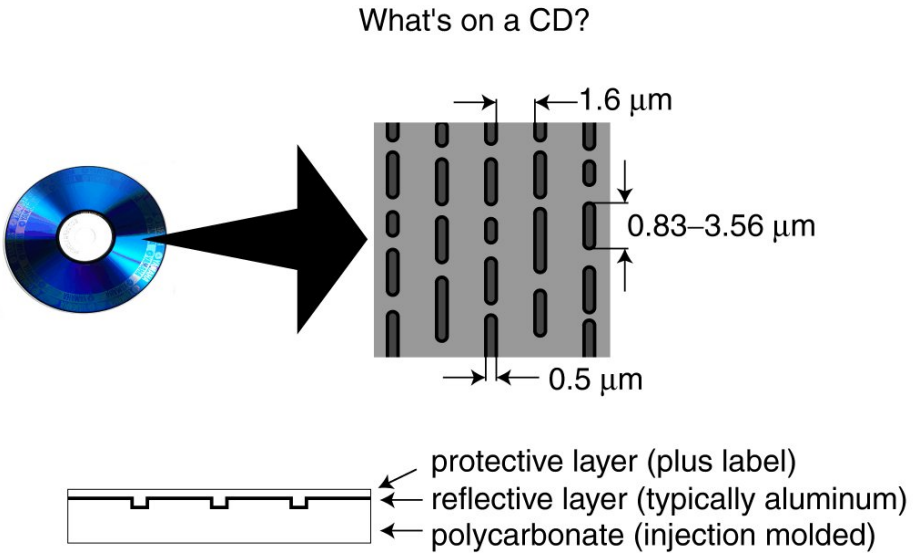


Spectrum of samples on CD

Upsampled 4×◯

After filtering with DT filter

What's on a CD?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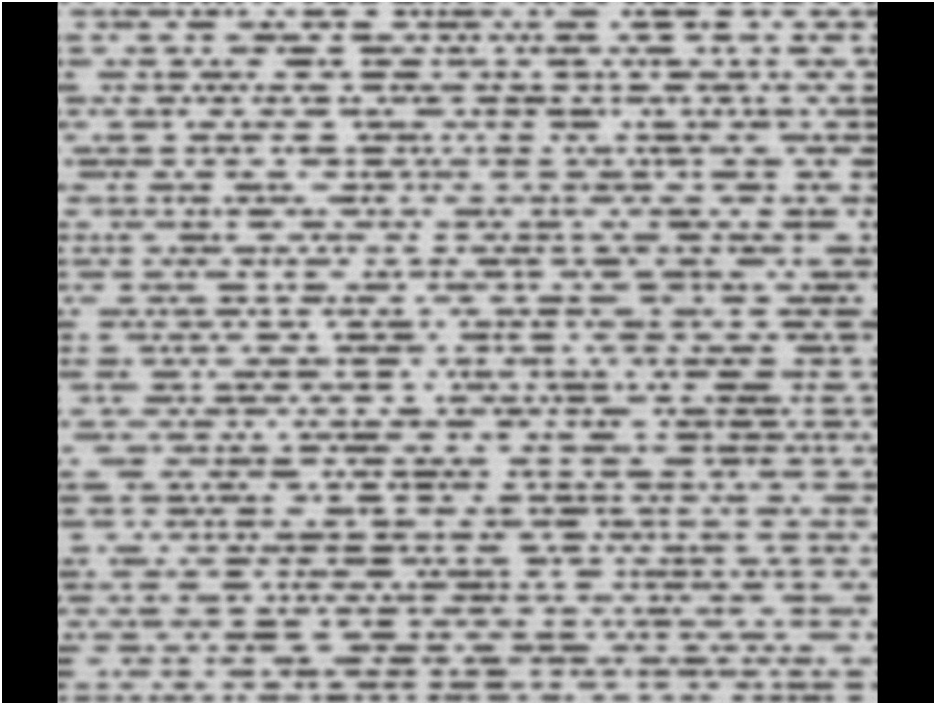

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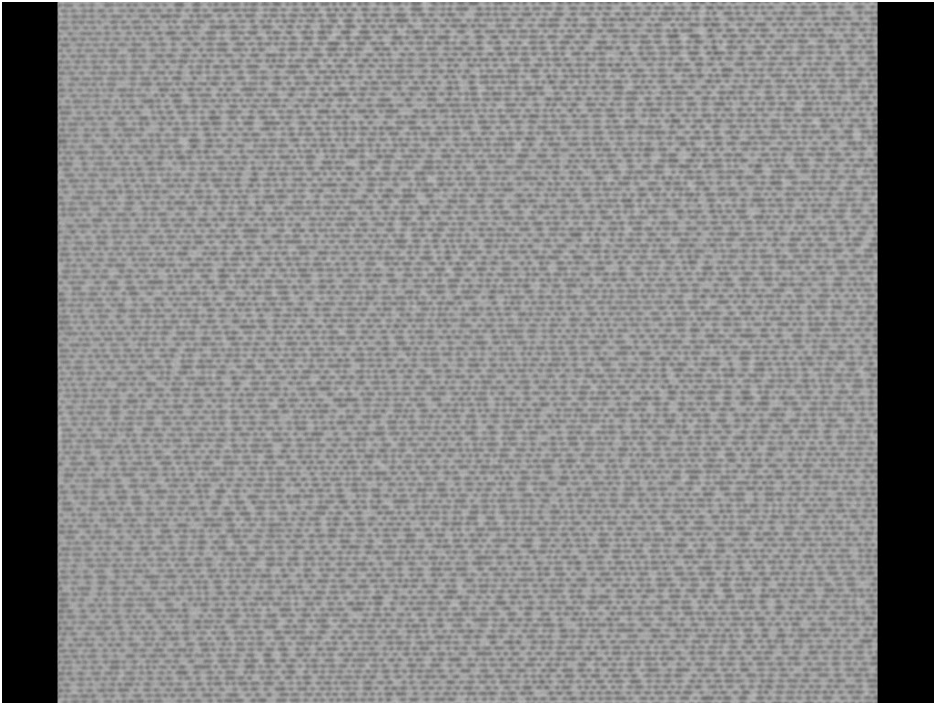
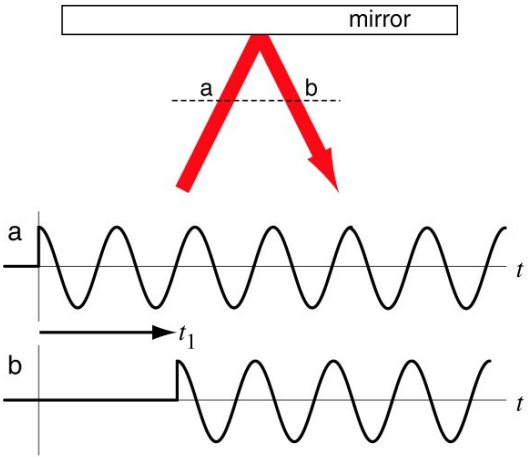


What's on a CD?

Interferometric sensing: 6.003 explanation



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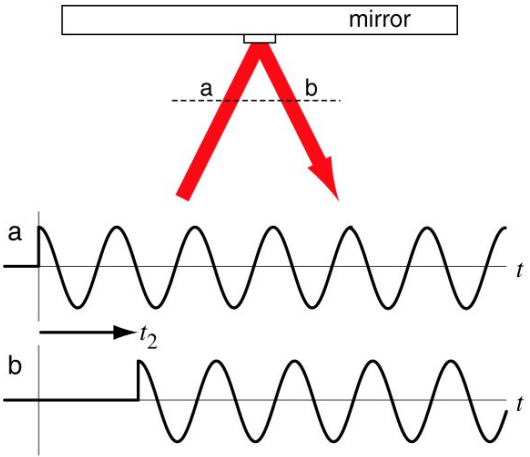

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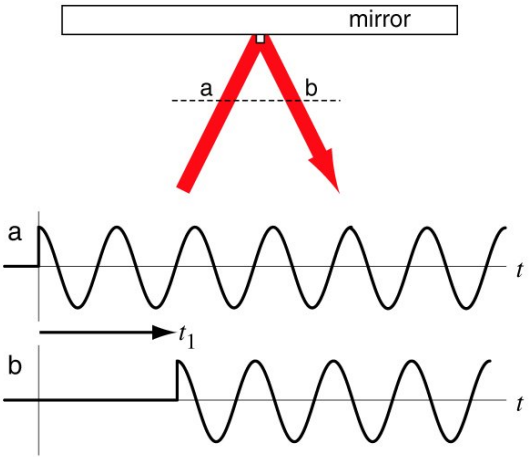

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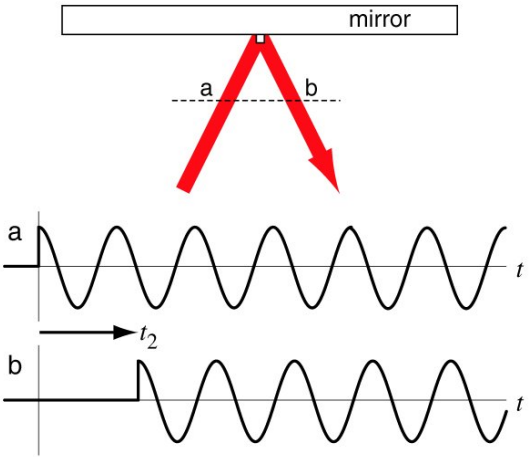

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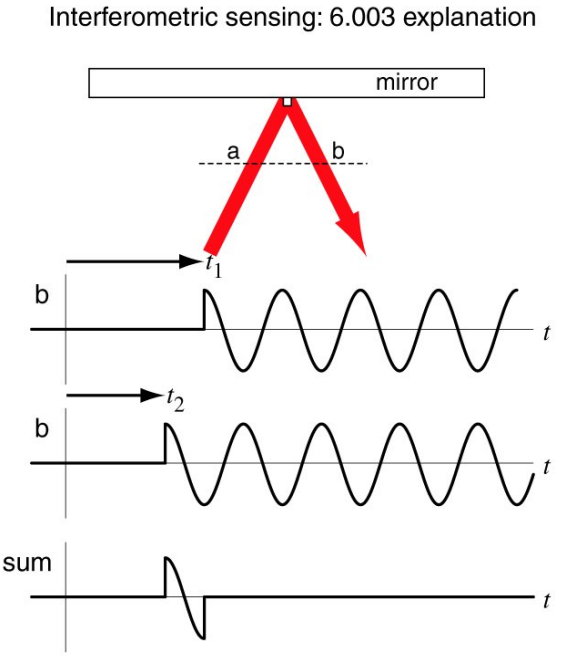
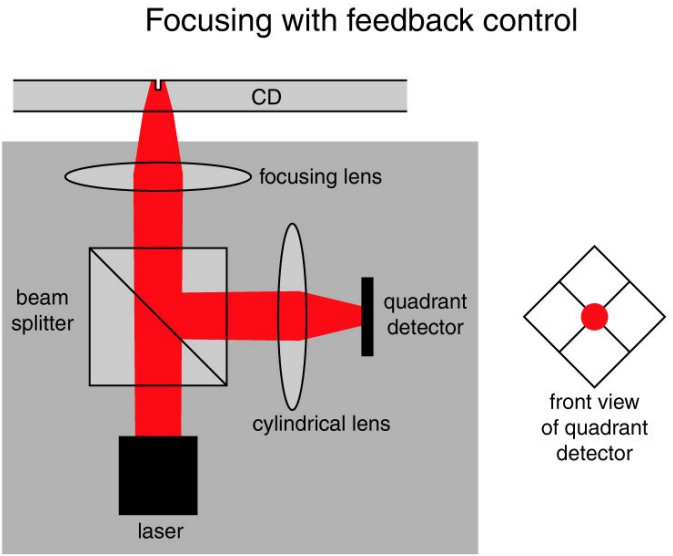
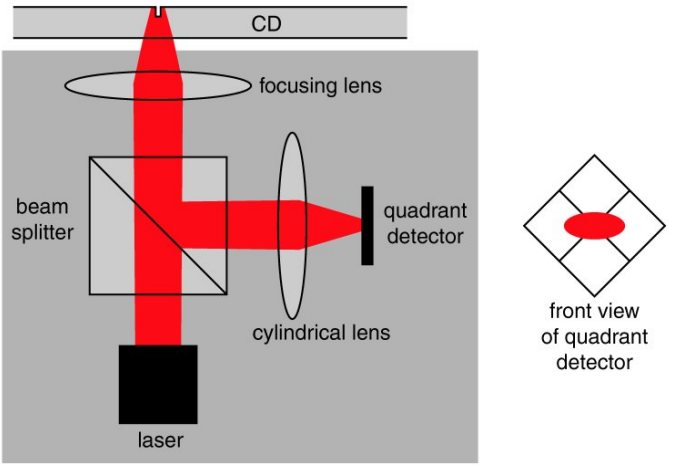

Interferometric sensing: 6.003 explanation
mirror
a
b
t_1
b
t
t_2
b
t
sum
t

What's on a CD?


Focusing with feedback control
CD
focusing lens
beam
splitter
quadrant
detector
cylindrical lens
laser
front view
of quadrant
detector

What's on a CD?

Focusing with feedback control



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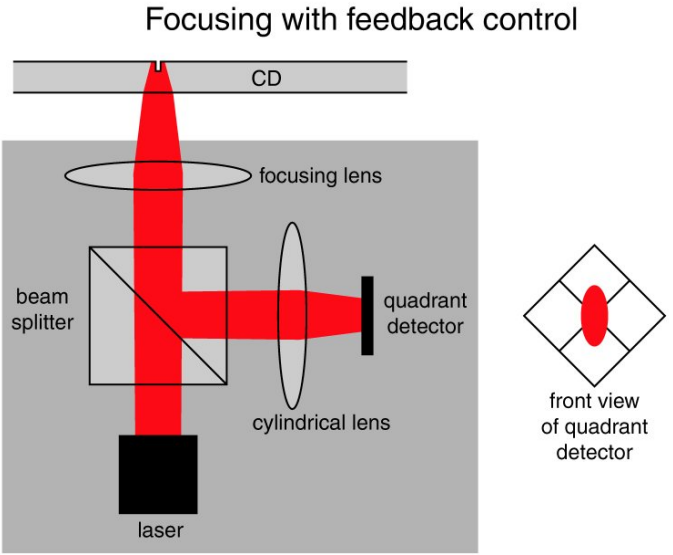
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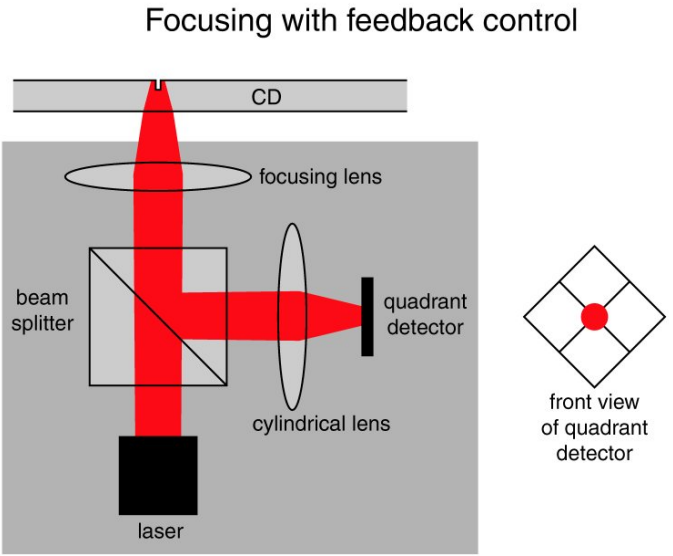
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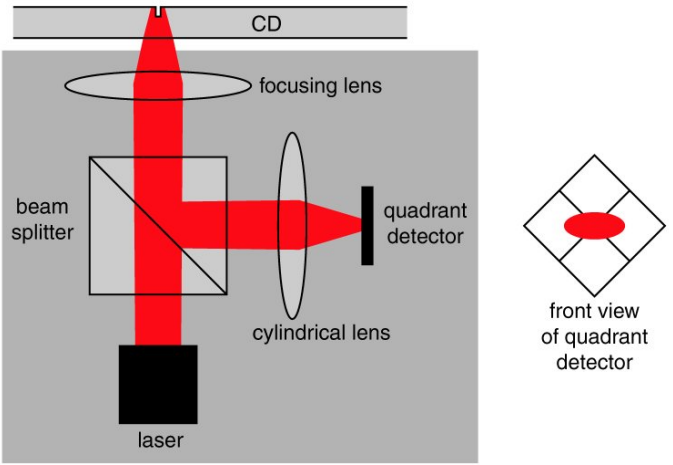

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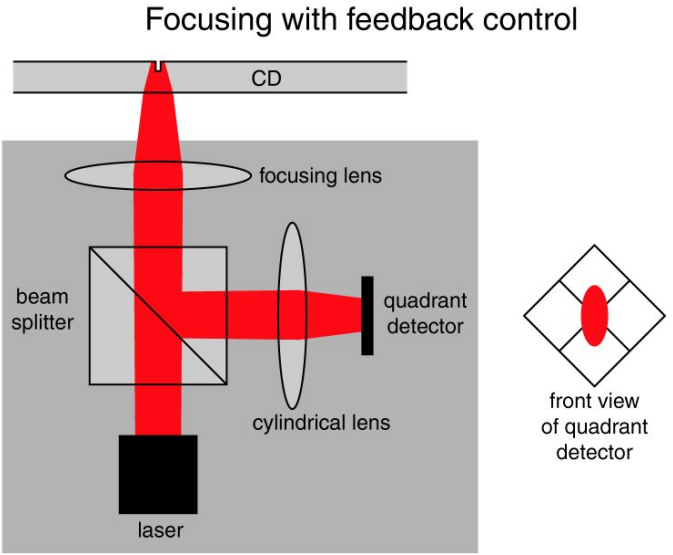
Focusing with feedback control
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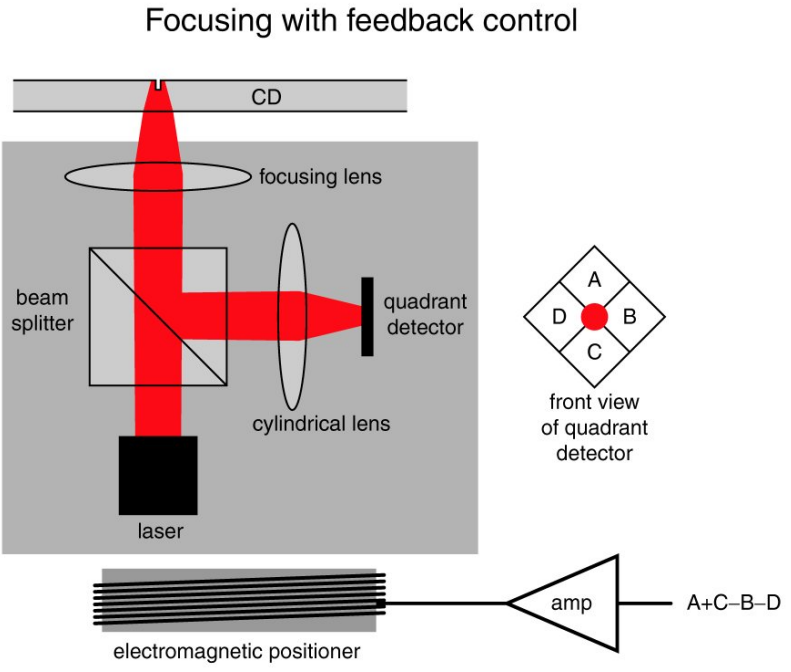
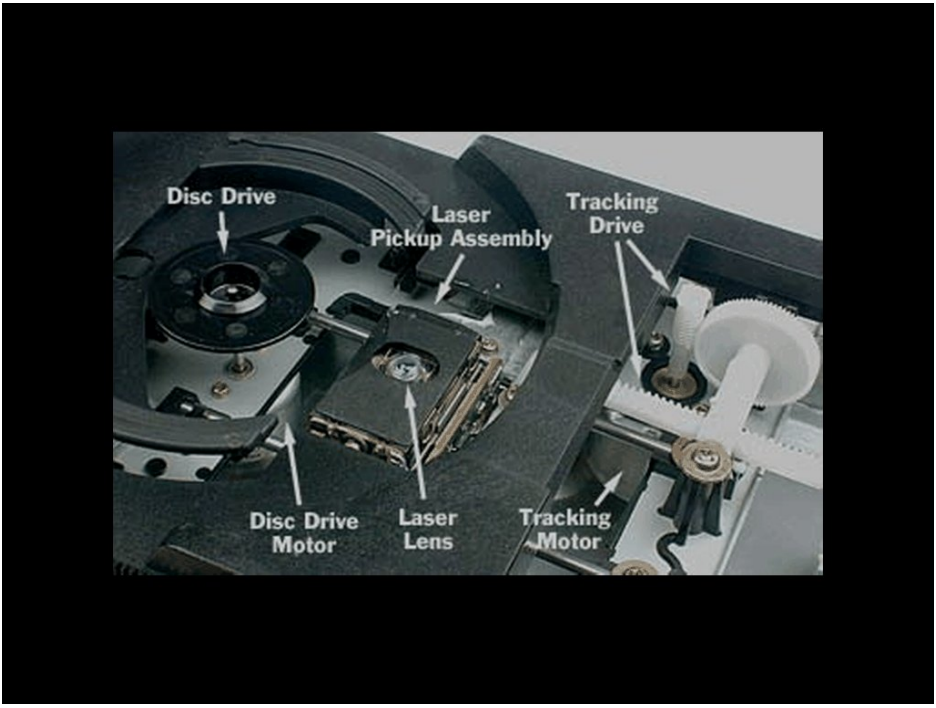
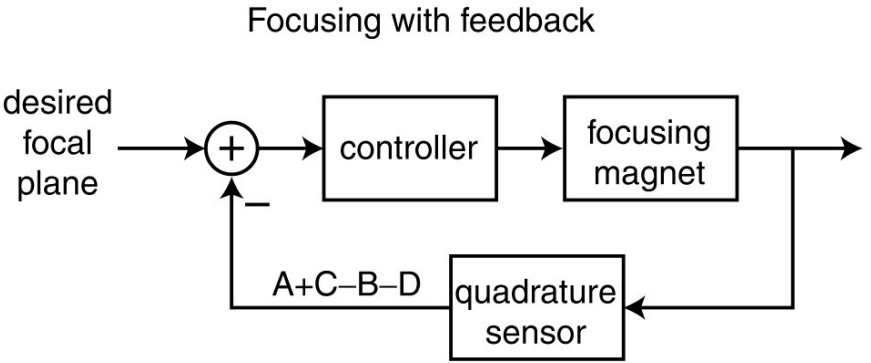

Focusing with feedback control
CD
focusing lens
beam
splitter
quadrant
detector
cylindrical lens
laser
A
D
B
C
front view
of quadrant
detector
amp
A+C–B–D
electromagnetic positioner

What's on a CD?

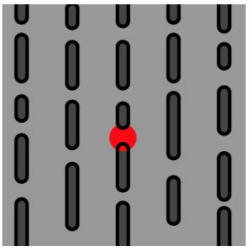

Disc Drive
Laser
Pickup Assembly
Tracking
Drive
Disc Drive
Motor
Laser
Lens
Tracking
Motor

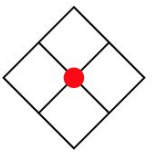
What's on a CD?


Focusing with feedback
desired
focal
plane
+
−
controller
focusing
magnet
A+C−B−D
quadrature
sensor

What's on a CD?

Translating pits to bits





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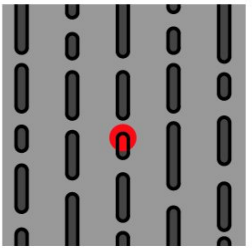
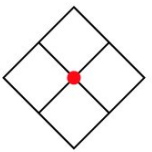
Translating pits to bits





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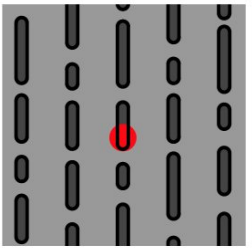

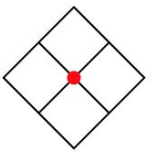

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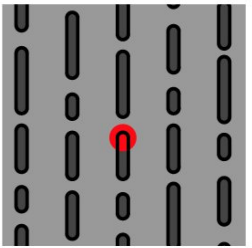

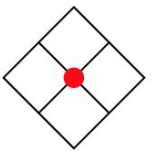

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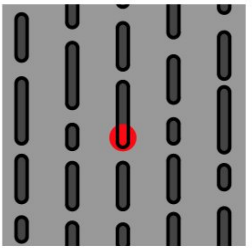

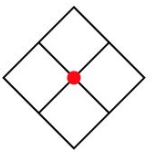

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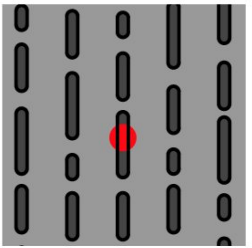

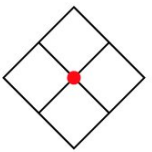

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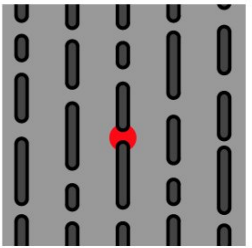

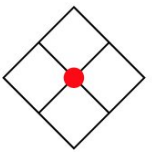

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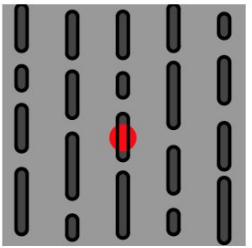

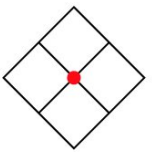

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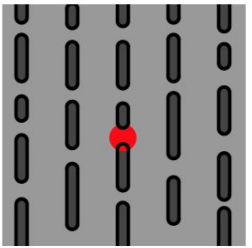

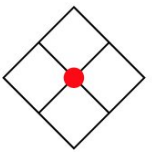

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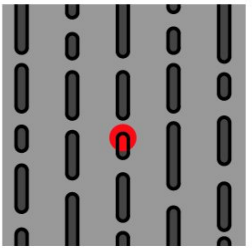

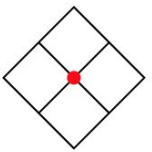

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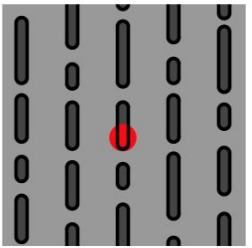
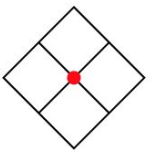
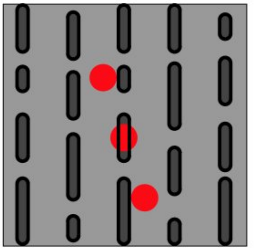
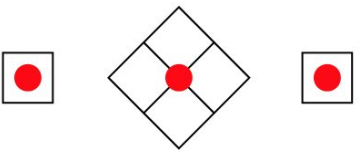




What's on a CD?

Tracking with feedback control





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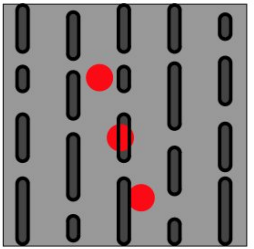

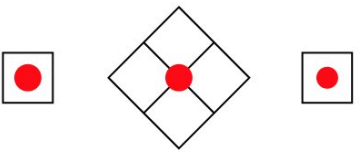

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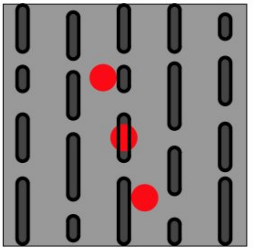

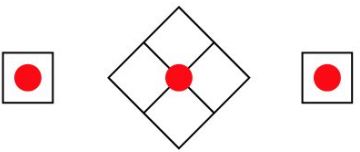

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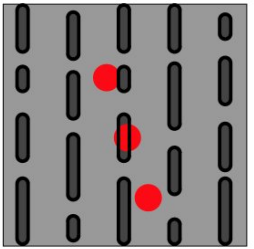

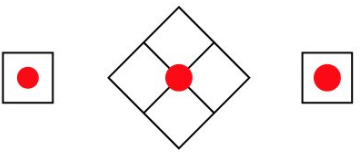

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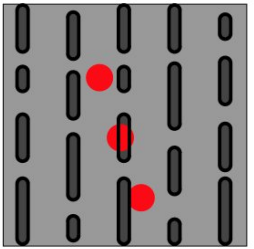

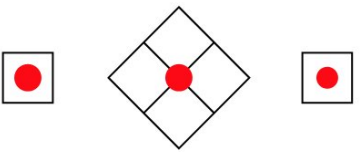

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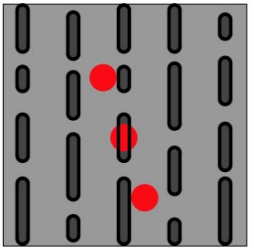

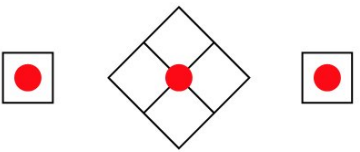

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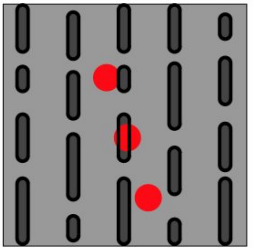

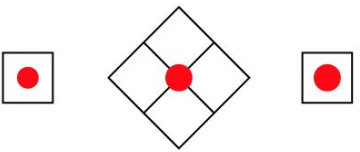

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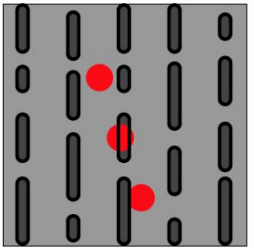

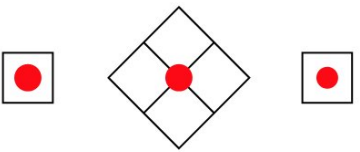

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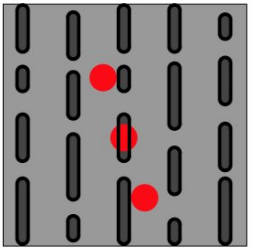

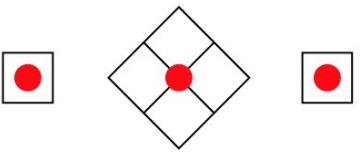

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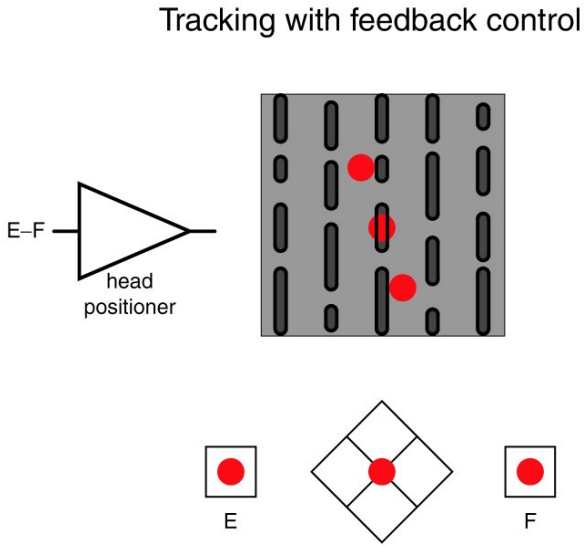

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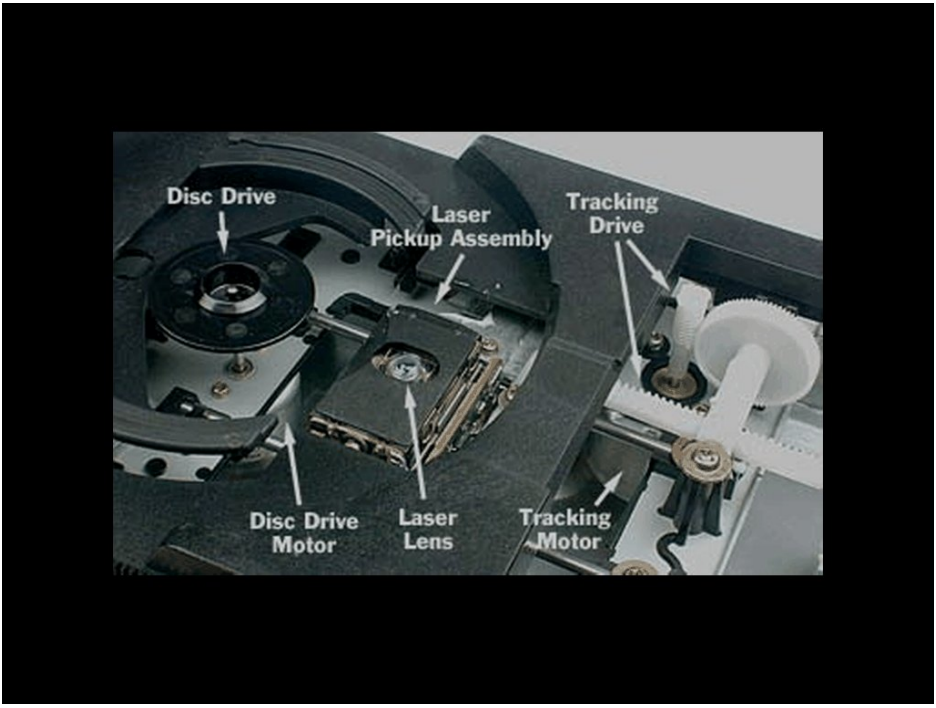
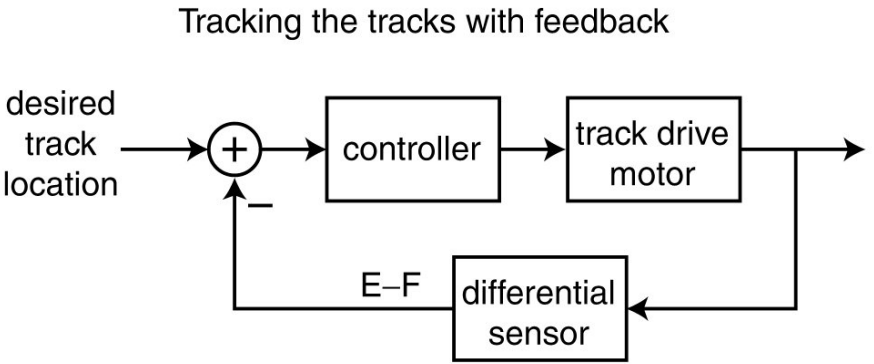

Disc Drive
Laser
Pickup Assembly
Tracking
Drive
Disc Drive
Motor
Laser
Lens
Tracking
Motor

What's on a CD?


Tracking the tracks with feedback
desired
track
location
+
−
controller
track drive
motor
E–F
differential
sensor

What's on a CD?

LPs: 100 years of optimization, good fidelity, but

- fragile: easily scratched
- lots of distortions: e.g., wow and flutter
- expensive

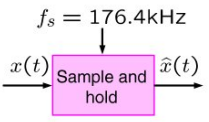
CDs: much higher fidelity

- nearly indestructible
- very low distortion
- very cheap

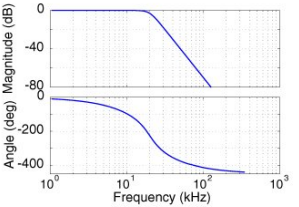
$\rightarrow$ many of these advantages made possible by concepts from Signals and Systems!

What's on a CD?

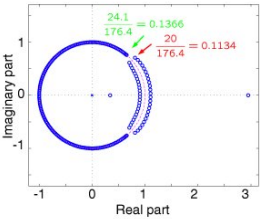
From LPs to CDs –
and how 6.003 helps get you there



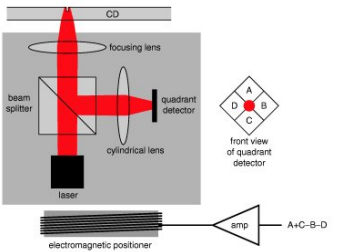
Sampling

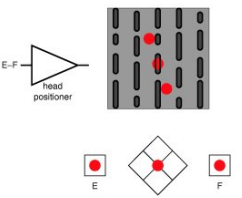


Filtering



DT processing of CT signals





Feedback

What's on a CD?

References:

"The History of the Edison Cylinder Phonograph"
http://memory.loc.gov/ammem/edhtml/edcyldr.html

"Audio Compact Disk -- An Introduction" by Kelin J. Kuhn
http://www.ee.washington.edu/conselec/CE/kuhn/cdaudio/95x6.htm

"How CDs Work" by Marshall Brain
http://electronics.howstuffworks.com/cd.htm