Nanoengineering on a Vast Scale

The Wonders of Modern Information Storage Technology

Paul H. Siegel

Center for Magnetic Recording Research

University of California, San Diego

QTech Forum

Acknowledgments

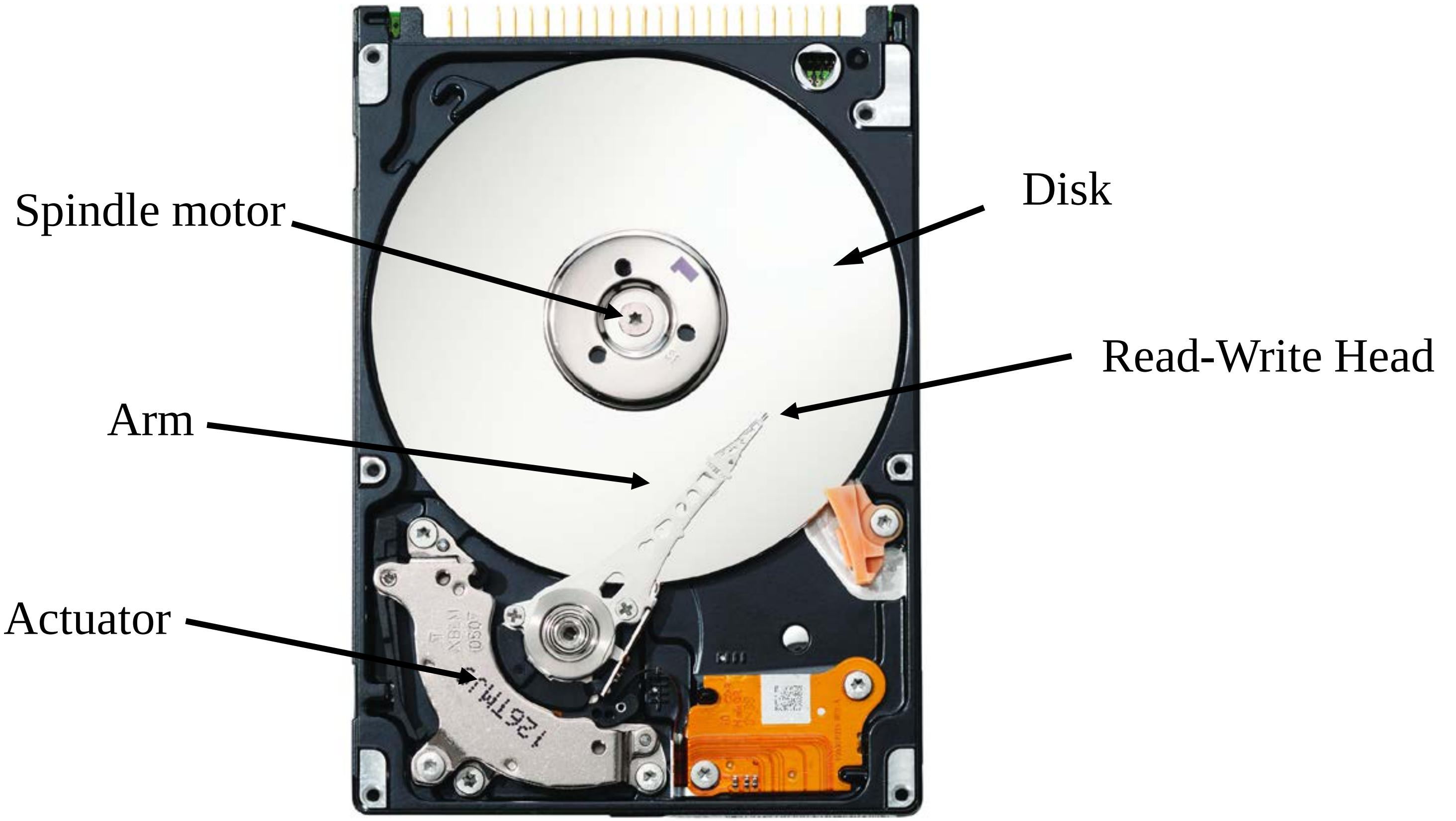
- CMRR faculty, for ideas on how to present certain topics, as well as for some nice graphics.
  - Eric Fullerton
  - Jack Wolf

- Members, past and present, of the Signal Transmission and Recording Group, for all they've taught me.

Outline

- **Preamble**
- Magnetic Recording Technology
- Storage as Communication
- What the Future Holds in Store

The Magnetic Hard Disk Drive



1 Terabyte Disk Drive

- In June 2007, several major disk drive manufacturers announced the first 1 Terabyte desktop (3.5”) drives.

Areal density:	148 Gb/sq.in.
Data rate:	1.07 / 3.0 Gb/sec
Rotation speed:	7,200 RPM
Seek time:	8.5 / 9.2 ms average
Latency:	4.17 ms average
MSRP:	$399

Hitachi Deskstar 7K1000

So How Much is 1 Terabyte?

1 Terabyte = 1,099,511,627,776 or 2^{40} bytes

- 50,000 trees made into paper and printed

- 1/10 print collection of the U. S. Library of Congress

- 754.28 days of “high quality” compressed audio

The Rodney Dangerfield of High Tech

I get no respect

Rodney Dangerfield

(1921-2004)

Hard Disk Drive

(1956 -)

An Unappreciated Technological Wonder

- The sophistication of the science and engineering embodied in state-of-the-art disk drives is largely unappreciated.

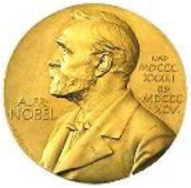
- "Isn't that kind of old stuff?"

  An often overheard remark from people passing by the Center for Magnetic Recording Research at UCSD.

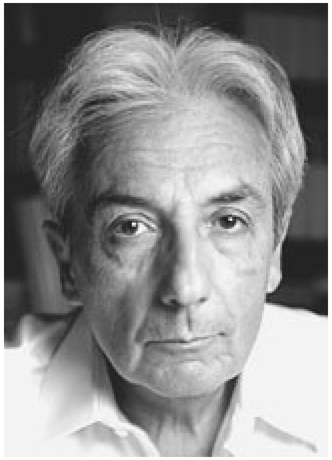
- The fact is that modern storage devices incorporate, and often motivate, cutting-edge research in physics, materials science, mechanical engineering, high-speed circuits, signal processing, and coding.

Vindication

The 2007 Nobel Prize in Physics

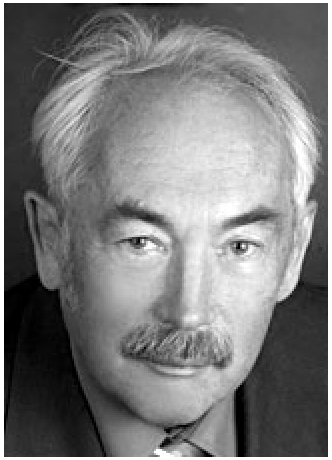


"for the discovery of Giant Magnetoresistance"



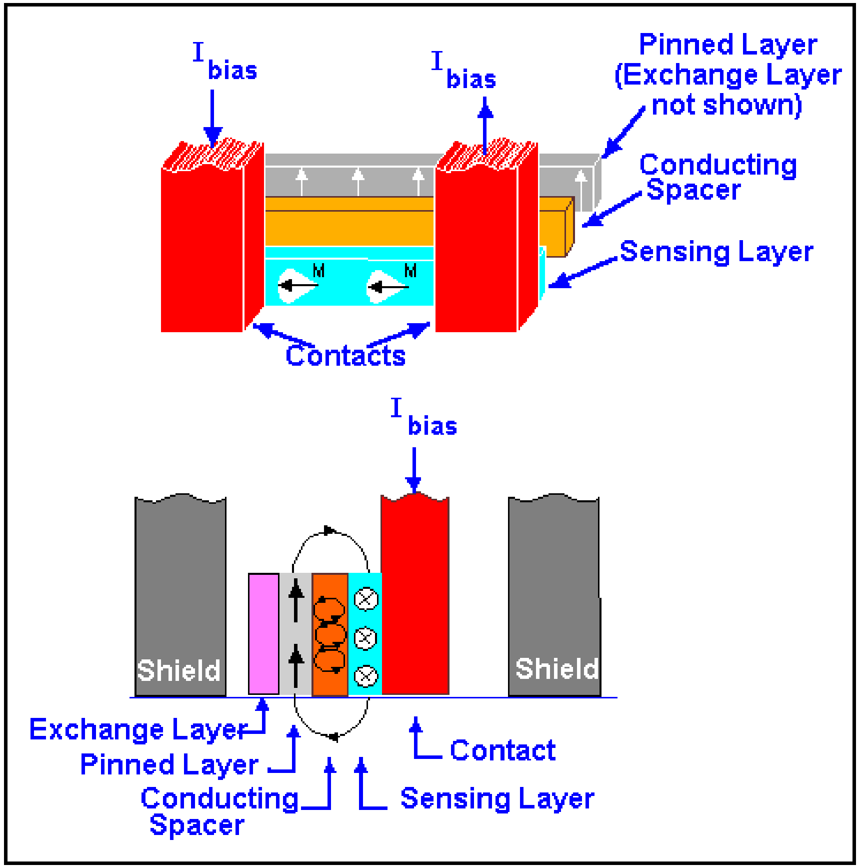
Albert Fert

GMR heads are "one of the first real applications of the promising field of nanotechnology"
-Royal Swedish Academy of Sciences



Peter Grünberg

GMR Head



I bias
I bias
Pinned Layer
(Exchange Layer
not shown)
Conducting
Spacer
Sensing Layer
M
M
Contacts
I bias
Shield
Shield
Exchange Layer
Pinned Layer
Conducting
Spacer
Contact
Sensing Layer

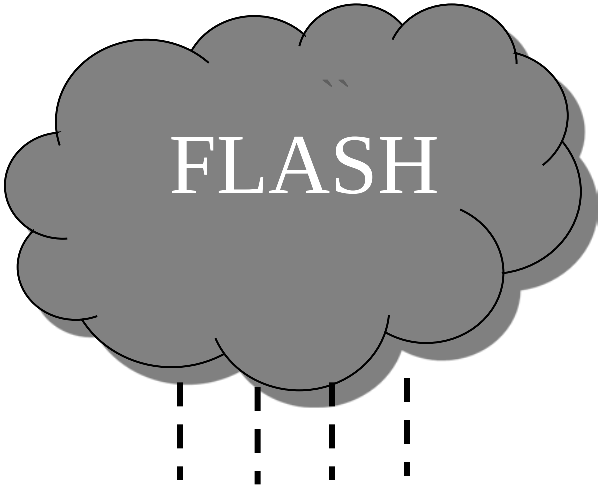
GMR Head Technology

- The GMR properties of certain magnetic multilayer materials were discovered in 1988.
- The first GMR read heads appeared in commercial disk drives in 1997.
- Some of the layers in GMR head structures are only a few atoms thick.
- The GMR head and its technological successors accelerated the development of very high capacity disk drives in small form factors.

The Ubiquitous Disk Drive

Handheld	Gaming	DVR	Notebook	Desktop	Enterprise
4GB – 160GB	20GB – 120GB	160GB – 1TB	80GB – 160GB	160GB – 1TB	150GB – 500GB – 1TB
0.85"– 1.8"	3.5"	3.5"	2.5"	3.5"	3.5"

Microdrive vs. Flash



Micro-drive

The New iPod Classic

40,000 songs

200 hours of video

Toshiba 1.8" drives

160 / 80 Gigabytes

(September 6, 2007)

Nanoengineering on a Vast Scale

- The result – ever increasing hard disk drive shipments

  - 2005 – 375.8 million
  - 2006 – 434.2 million

  ] 15.5% increase

  - 2010 – 748 million (projection)

(despite ever increasing consolidation within the storage industry, much to the chagrin of those of us at CMRR!)

Outline

- Preamble
- **Magnetic Recording Technology**
- Storage as Communication
- What the Future Holds in Store

More Bits – Denser, Cheaper, Faster

- The pervasive deployment of hard disk drives has been made possible by:
  - exponential increase in areal density (bits/in^2)
  - exponential decrease in cost per bit ($/bit)
  - increased data transfer rates (bits/sec)

all packed into smaller and smaller packages.

Evolution of Hard Disk Drives

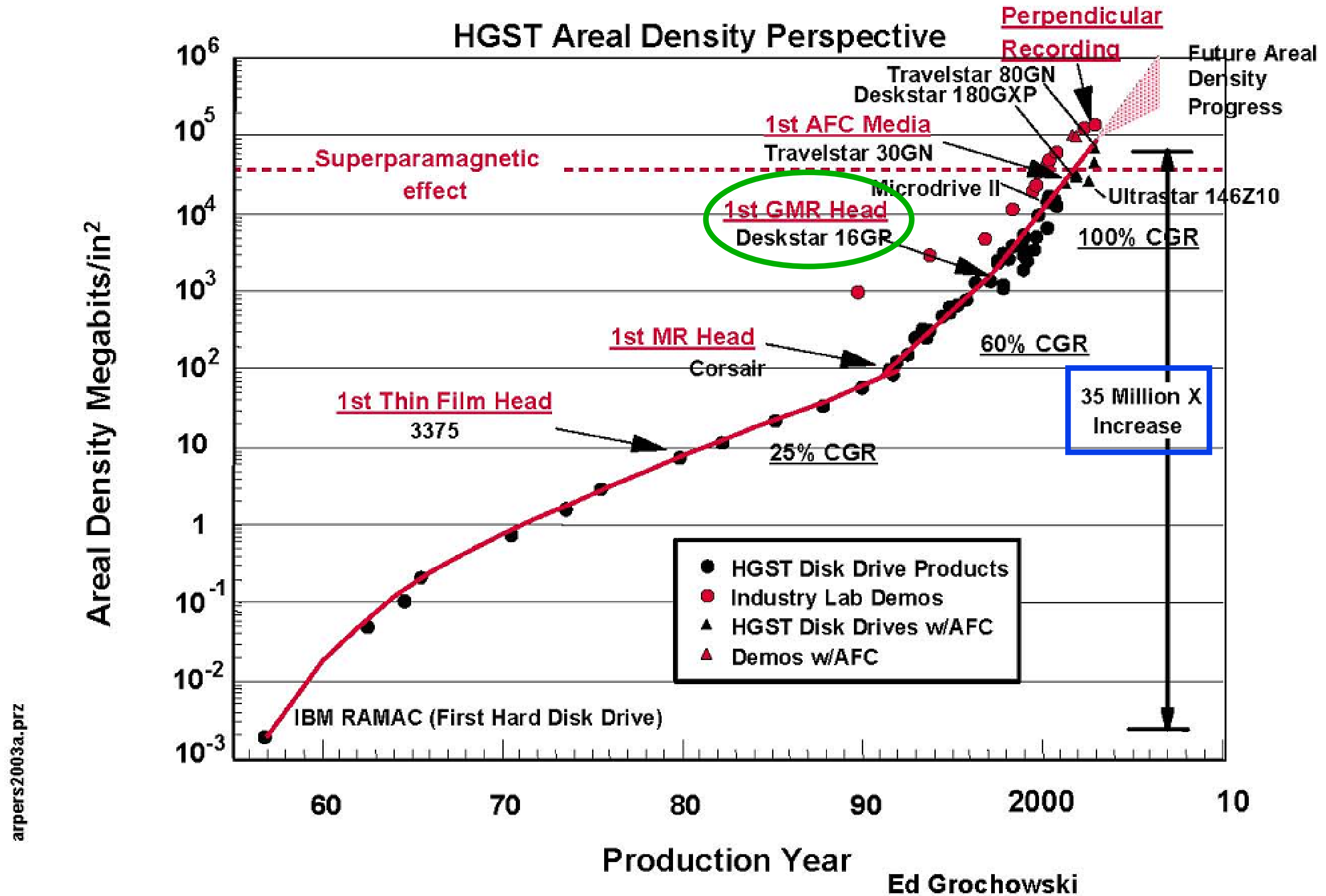
1956
IBM RAMAC
5 Mbyte

2007
Deskstar
1 TByte

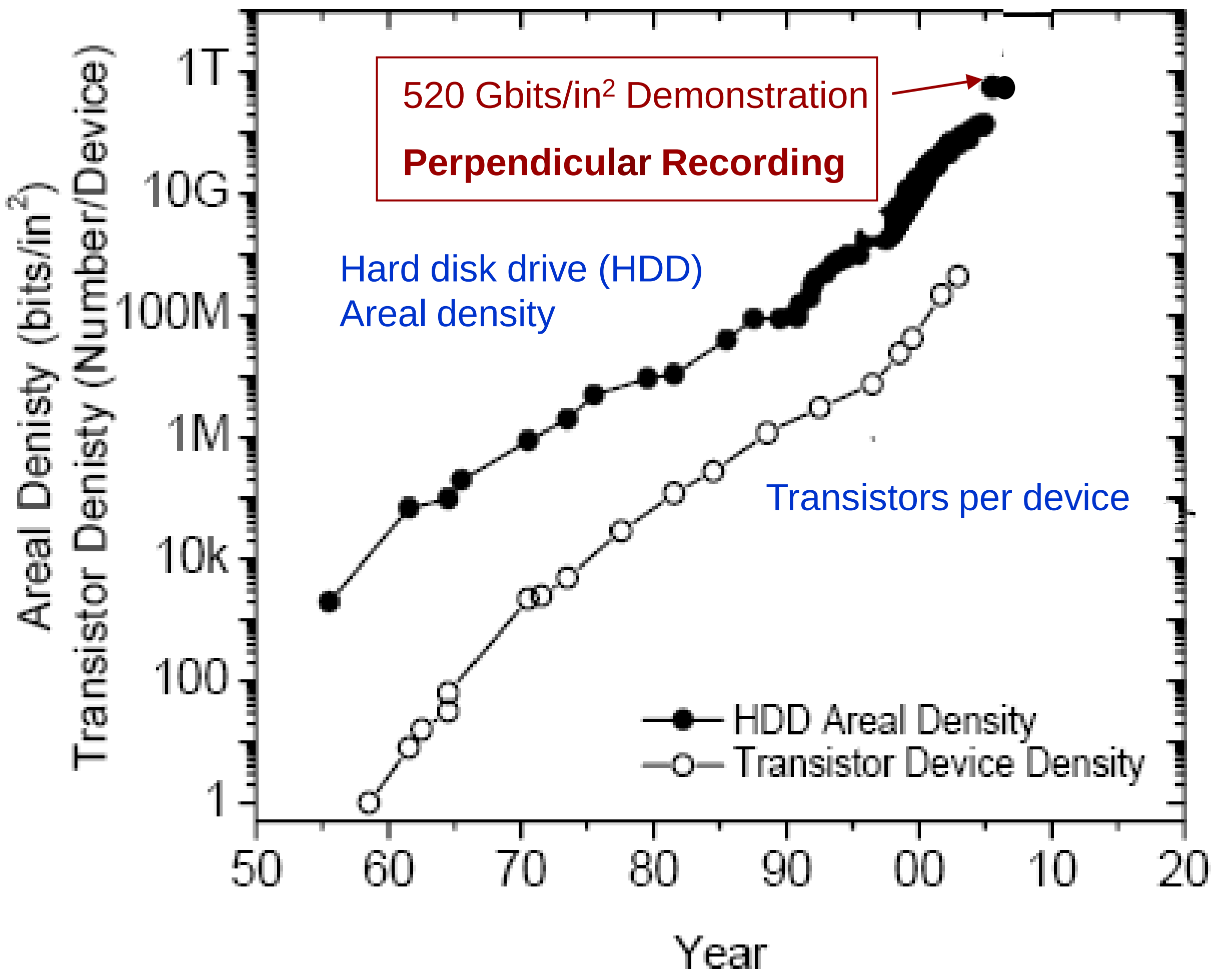
50 24” disks	**size**	**5 3.5” disks**
2 kbits/in^2	**areal density**	**148 Gbits/in^2**
70 kbits/s	**transfer rate**	**1.07/3 Gbits/s**
$10,000	**cost per Mbyte**	**< $0.0004**

Areal Density Progress

HITACHI
Inspire the Next



Kryder's Law vs. Moore's Law (Disks versus Chips)



WD
10/17/07

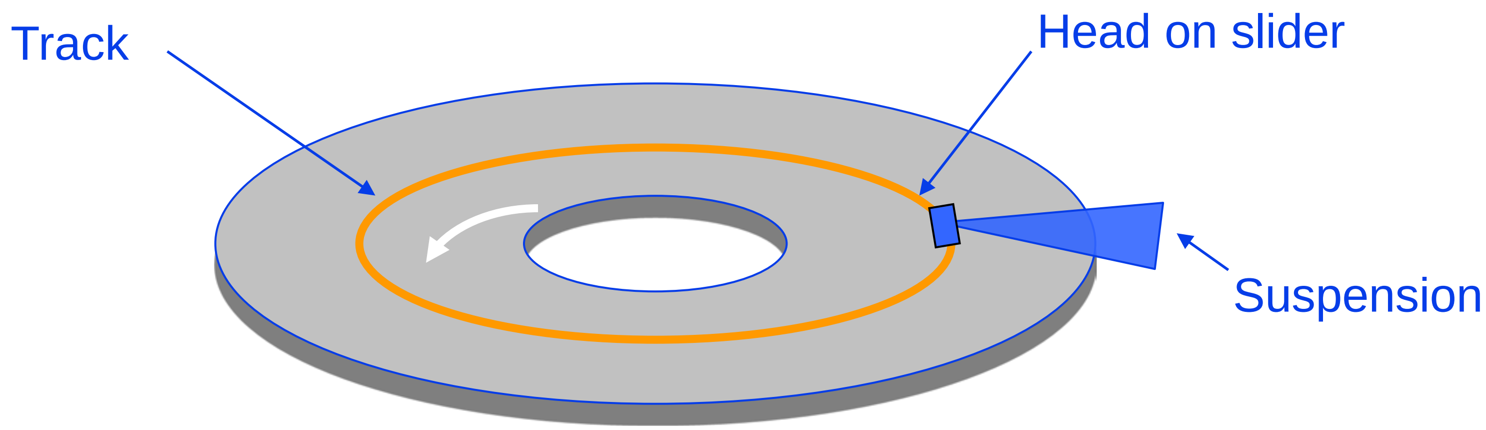
How Was This Done?

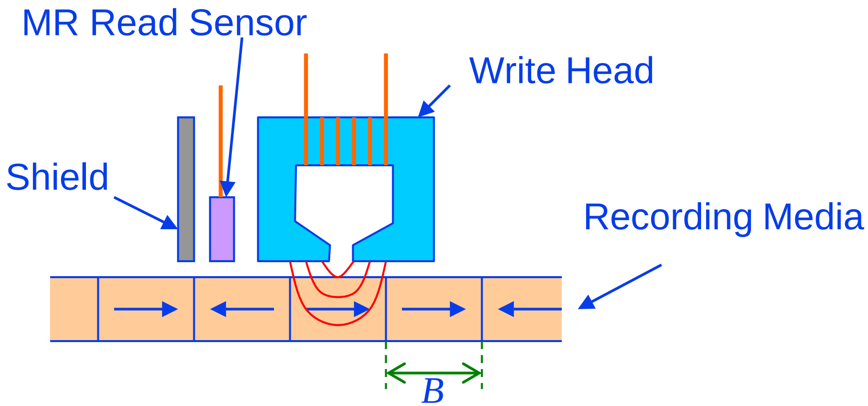
- To understand the source of this remarkable progress in disk drive technology, we need to look at the basic magnetic recording process.

- The primary source of areal density increase is dimensional scaling of all components of the system.

- Occasional technological breakthroughs allow the scaling to continue beyond expectations.

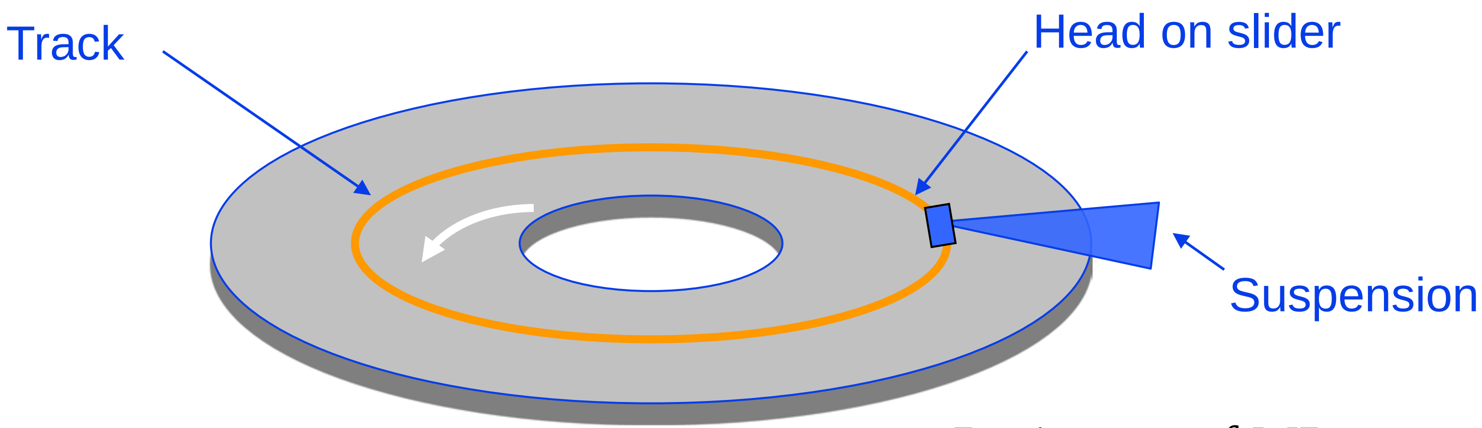
Disk Drive Basics - Writing

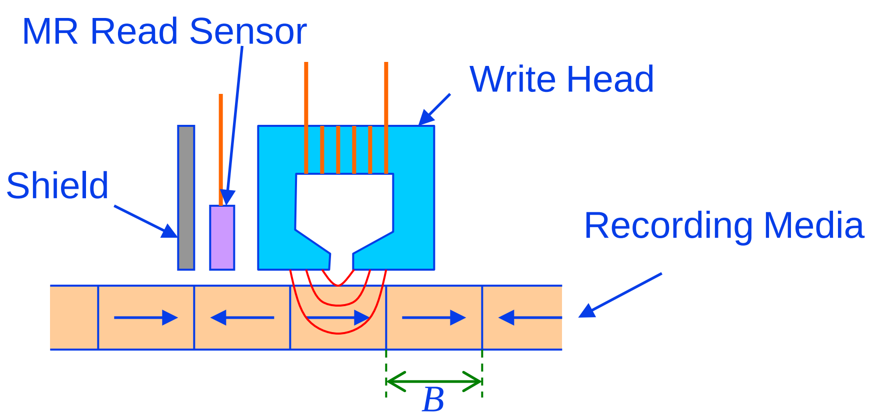




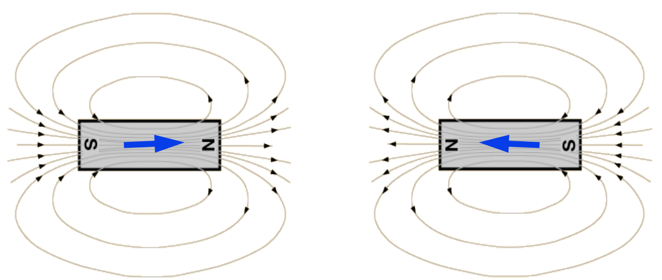
Magnetic flux leaking from the write-head gap records bits in the magnetic medium

Disk Drive Basics - Reading



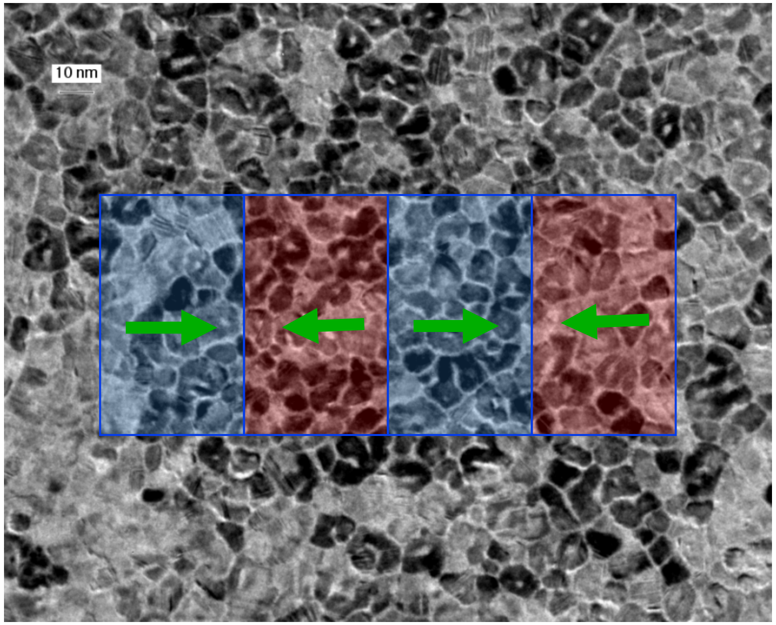


Resistance of MR read sensor changes in response to fields produced by the recorded bits



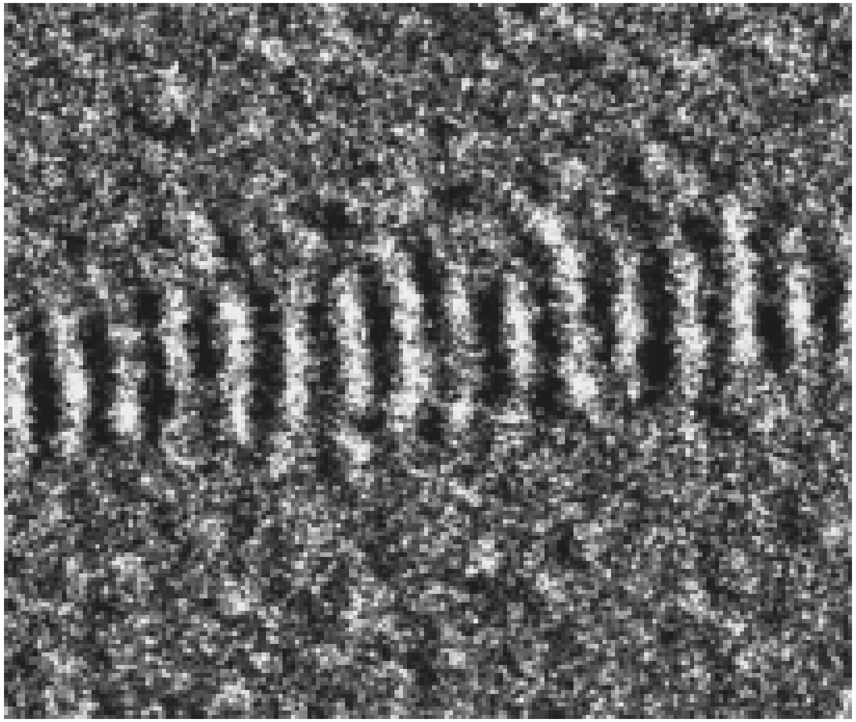
Recorded Data

Transmission Electron Microscope



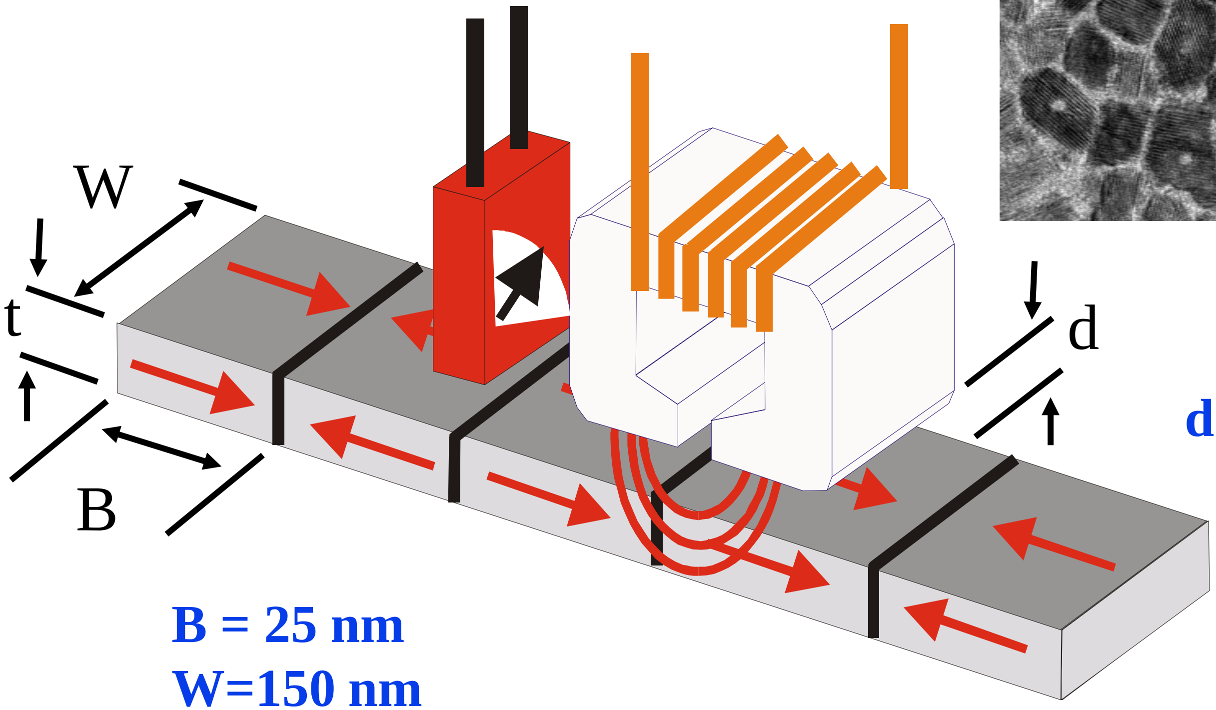
100 nm

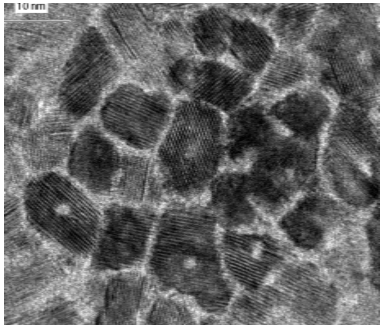
Magnetic Force Microscope

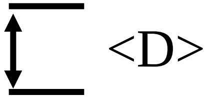


1000 nm

Scaling in all Dimensions







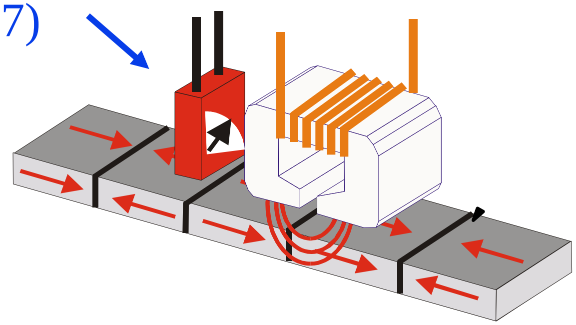
< D > = 8nm

d = 10nm

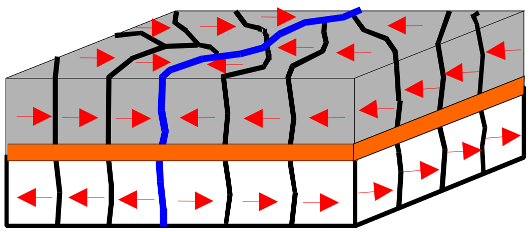
B = 25 nm
W=150 nm
t = 14 nm

Fundamental Innovations

MR/GMR sensors
(1991/1997)

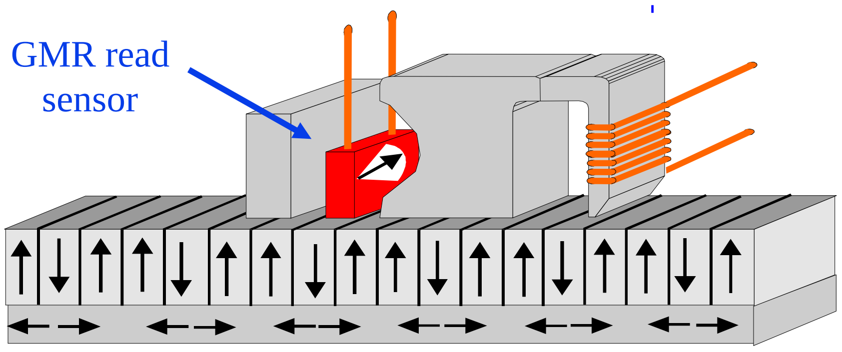


AFC media
(2001)



to 100 Gb/in^2

GMR read
sensor



Perpendicular
media

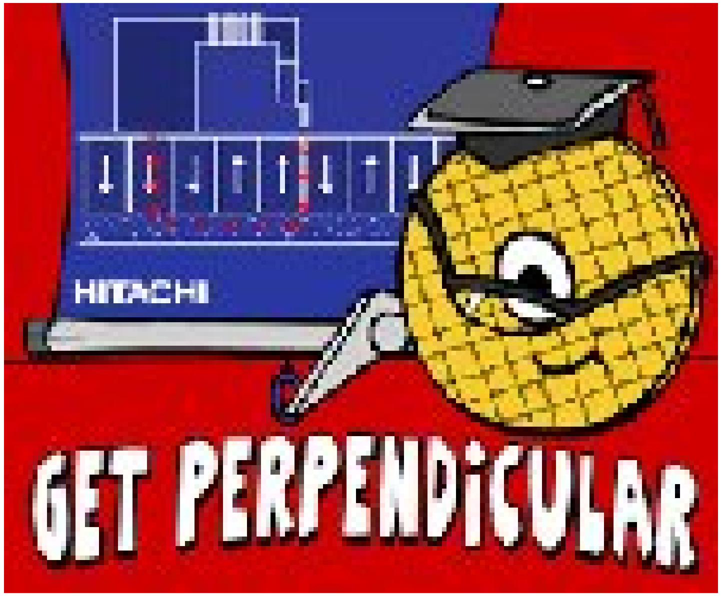
Perpendicular recording

(2006)

to 500$^+$ Gb/in^2

Perpendicular Recording

http://www.hitachigst.com/



Outline

- Preamble
- Magnetic Recording Technology
- **Storage as Communication**
- What the Future Holds in Store

Storage as Communication

- A data communication system transmits information through space, i.e.,

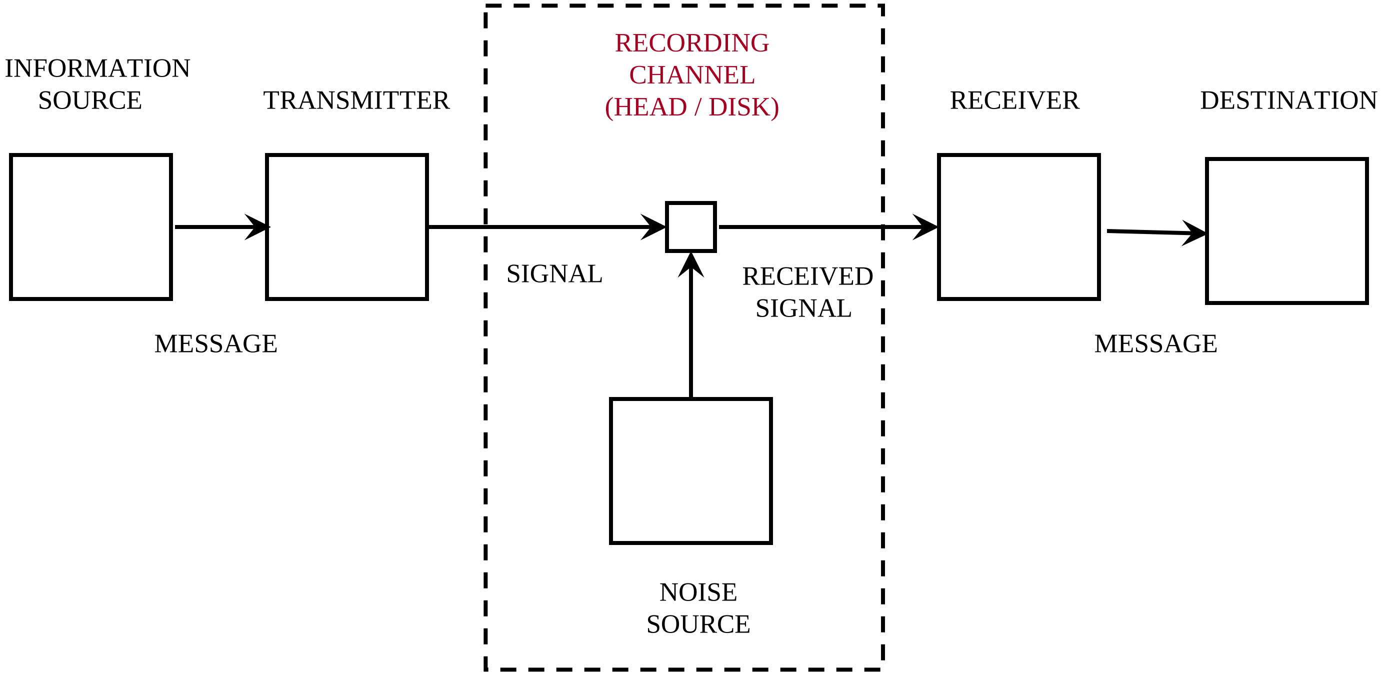
  "from here to there."

- A data storage system transmits information through time, i.e.,

  "from now to then."

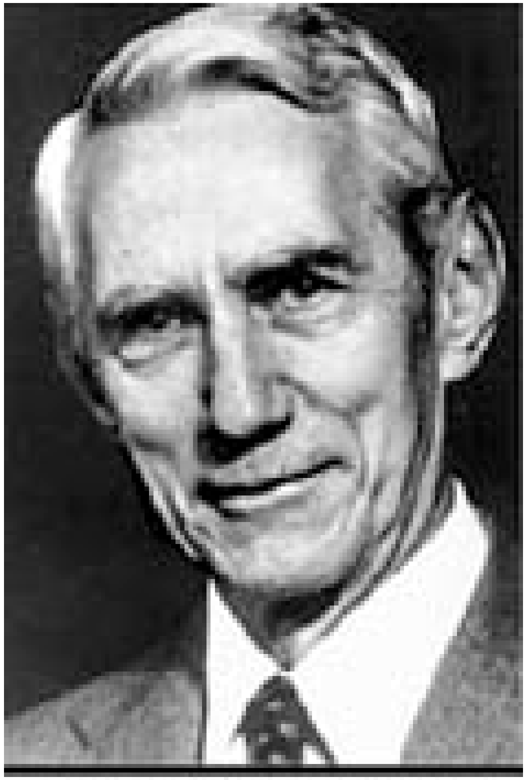
[Berlekamp, 1980]

A Communication Theorist's View of Magnetic Recording



Adapted from C.E. Shannon, "A Mathematical Theory of Communication," 1948

Claude E. Shannon



Claude Elwood Shannon
1916 - 2001

Shannon Statue – CMRR

The Inscription on the Statue

CLAUDE ELWOOD SHANNON

1916 – 2001

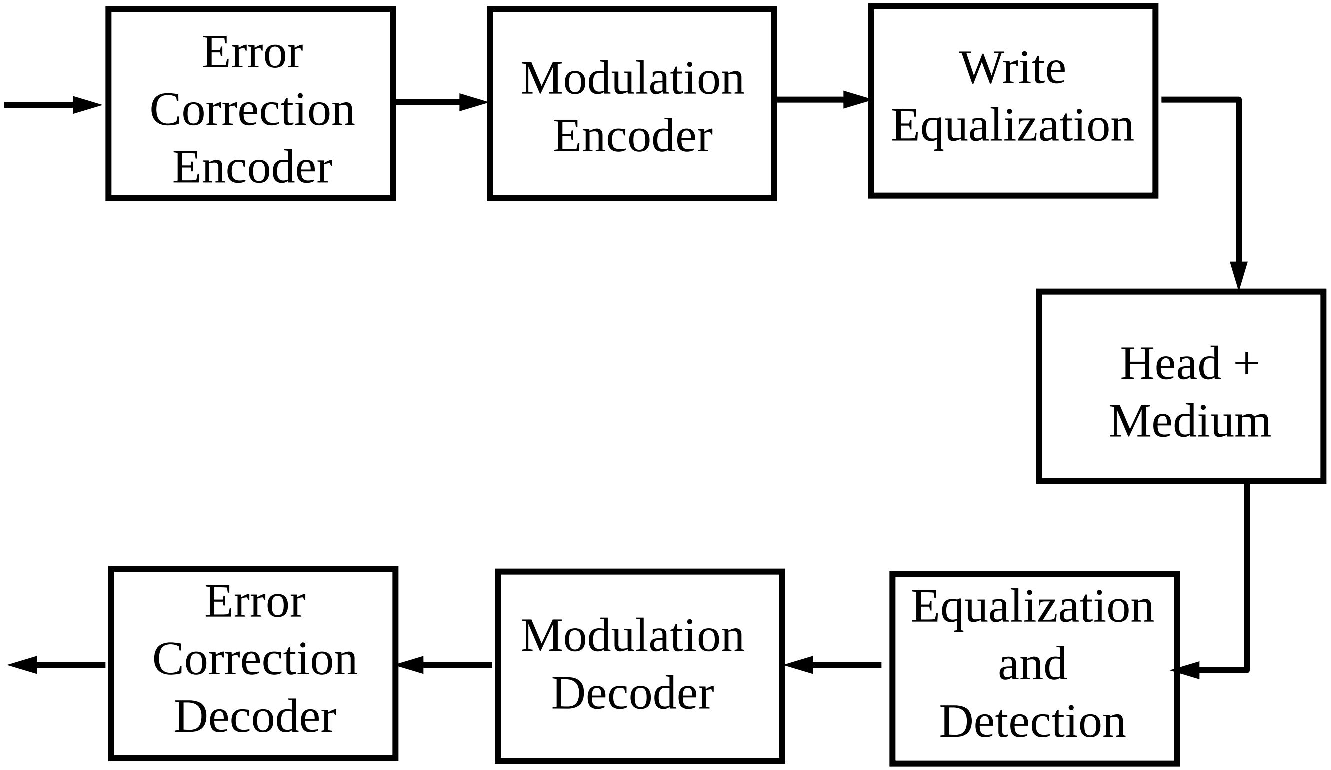
FATHER OF INFORMATION THEORY

HIS FORMULATION OF THE MATHEMATICAL
THEORY OF COMMUNICATION PROVIDED
THE FOUNDATION FOR THE DEVELOPMENT OF
DATA STORAGE AND TRANSMISSION SYSTEMS
THAT LAUNCHED THE INFORMATION AGE.

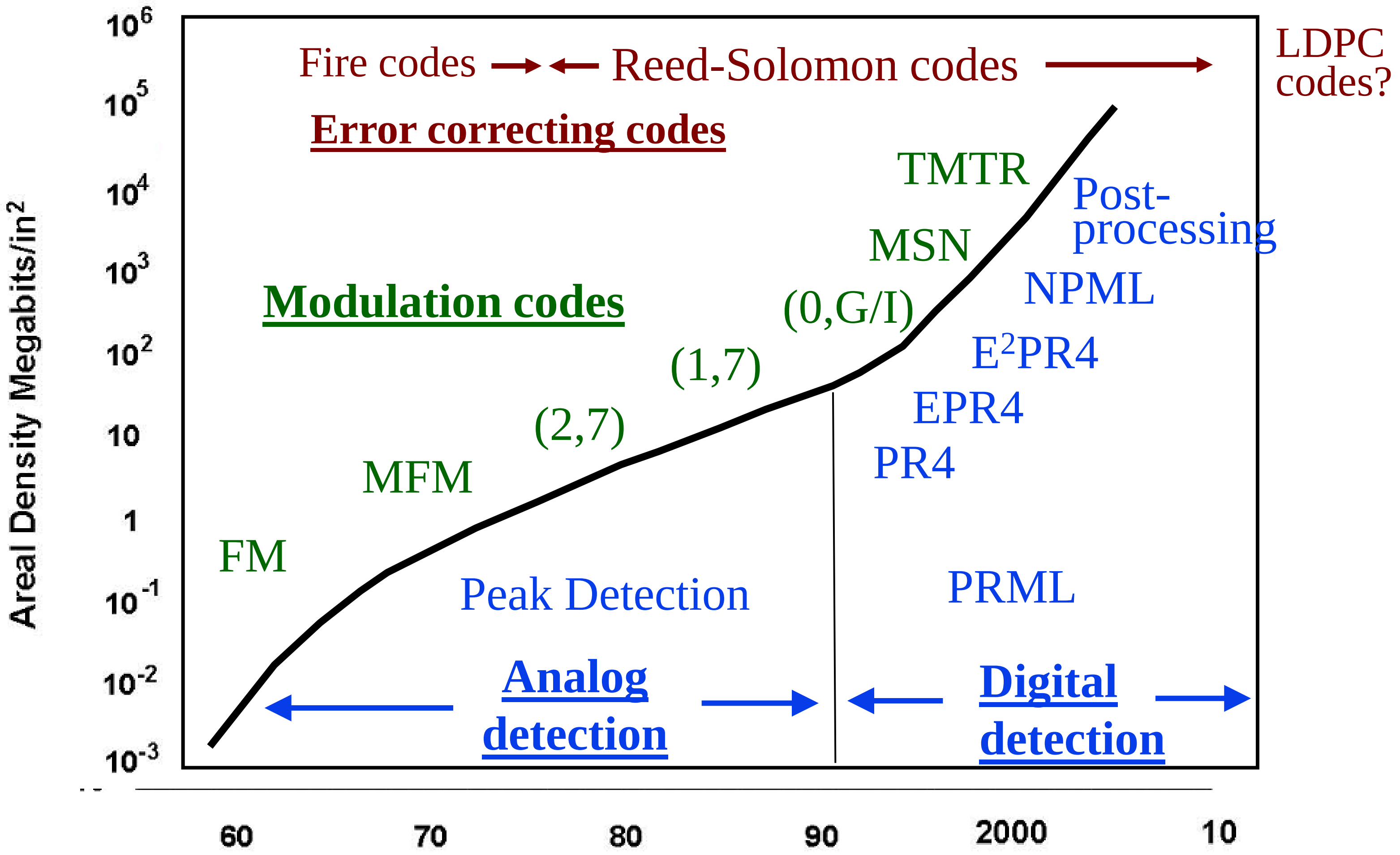
DEDICATED OCTOBER 16, 2001

EUGENE DAUB, SCULPTOR

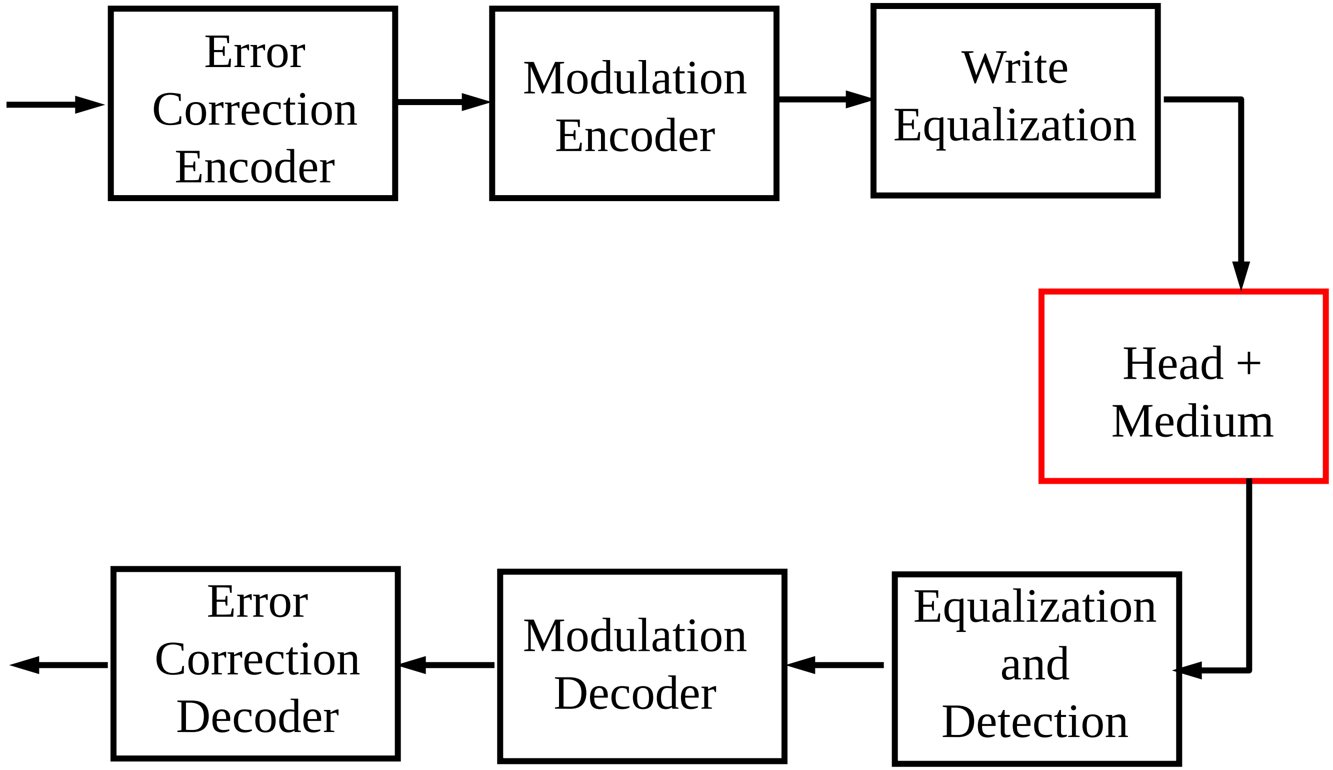
Magnetic Recording Channel



Communication Theorist's View of Areal Density Growth



Channel Characterization



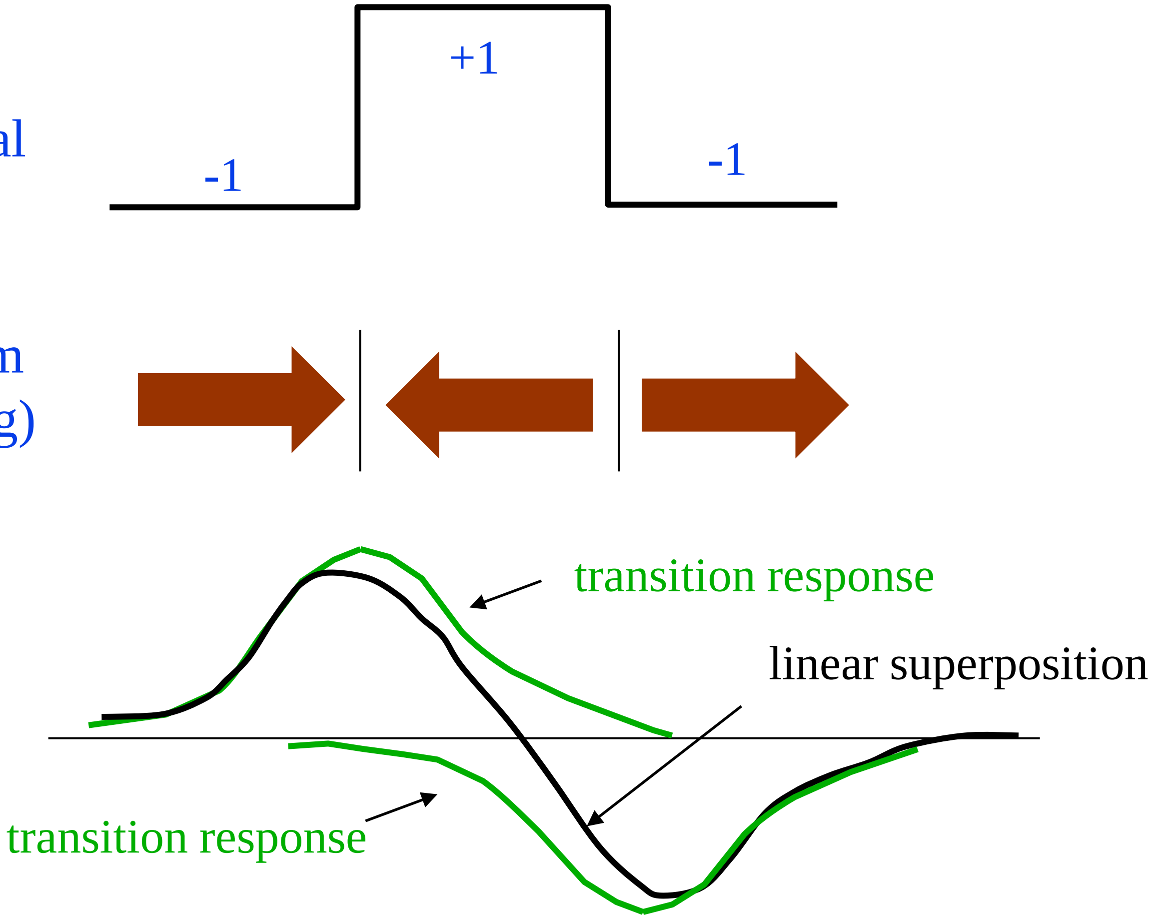
Magnetic Recording Process

Two-level input signal

Magnetized medium
(saturation recording)

Readback signal

(intersymbol interference)

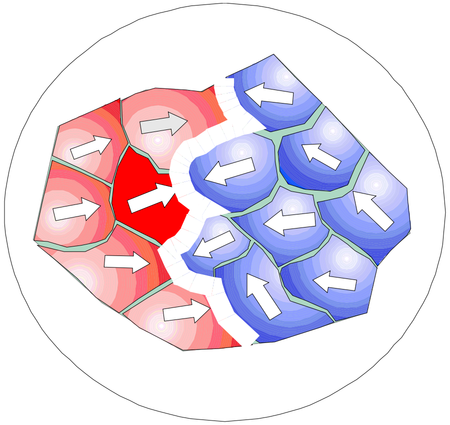


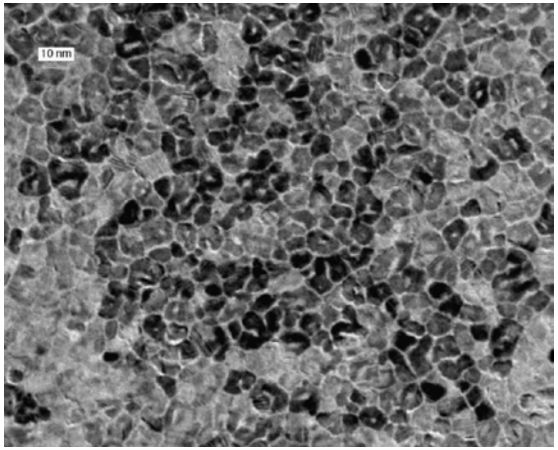
Noise Sources

- Electronics noise: additive white Gaussian noise
- Granular media noise: additive Gaussian noise
- Transition noise:
  - "transition jitter"
  - "pulse broadening"
- Thermal asperities /defects: burst noise
- Non-linear transition shift (NLTS): "deterministic" noise
- Adjacent track interference

Transition Noise

- The transitions have a “zig-zag” appearance due to the granular nature of the medium.

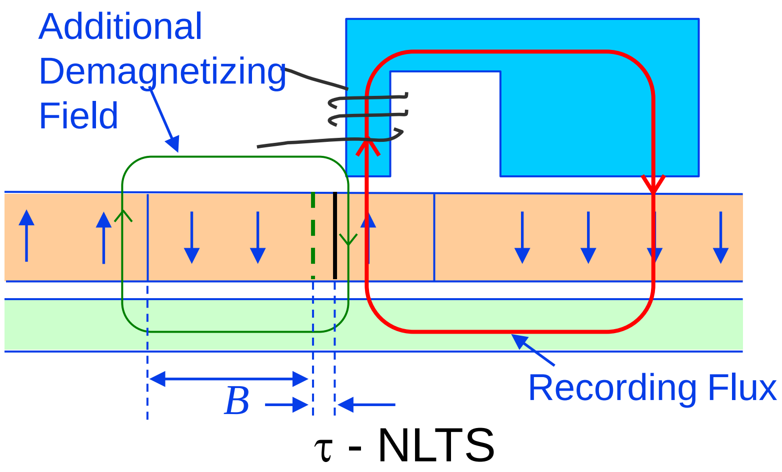


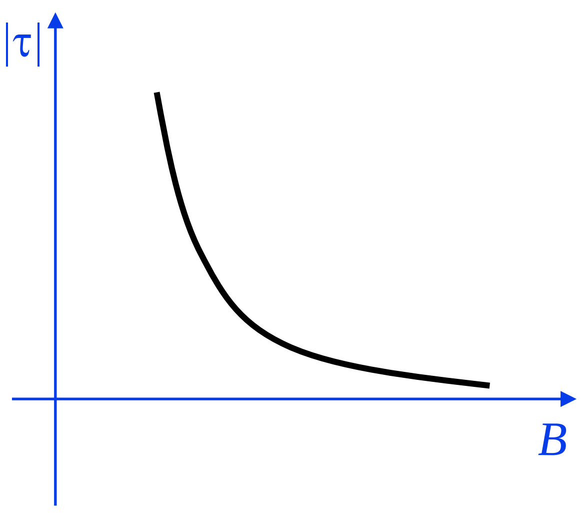


- This creates variations in their average width and position.
- This translates into a data-dependent noise, often modeled as independent, Gaussian-distributed transition “jitter”.

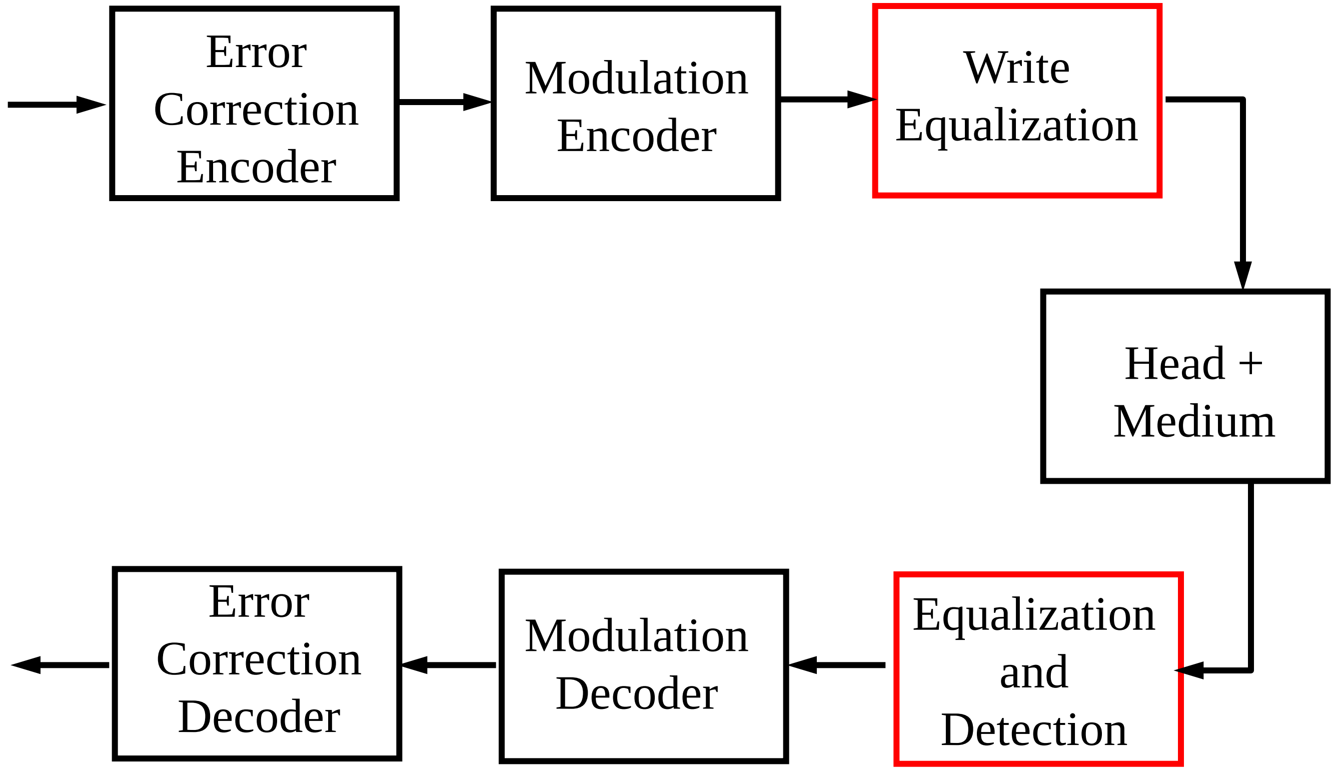
Non-linear Transition Shift

- At high bit density, non-linear transition shift (NLTS) arises from the effect of the magnetic field generated by previously written bits.





Equalization and Detection

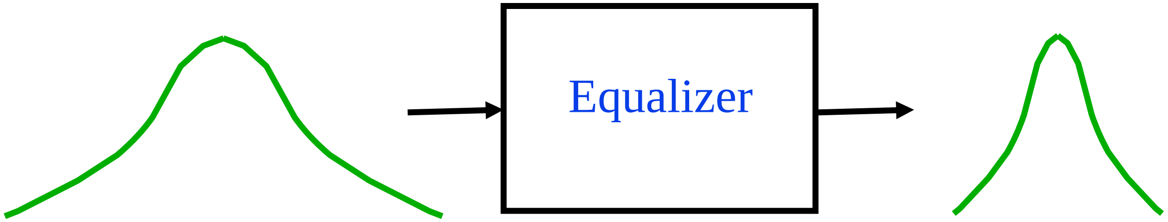


Peak Detection

- Prior to 1990, disk drives used “analog” signal processing in the form of peak detection.
- Transition locations were detected by finding the location of peaks in the readback signal.
- At high densities, linear intersymbol interference (ISI) could be severe enough to cause “peak shift” errors.
- To combat these errors, several techniques were used:
  - “Pulse-slimming” equalization
  - (d,k) Runlength-limited (RLL) codes
  - Write-precompensation of worst-case ISI patterns

(1,7)-RLL Equalized Peak Detection

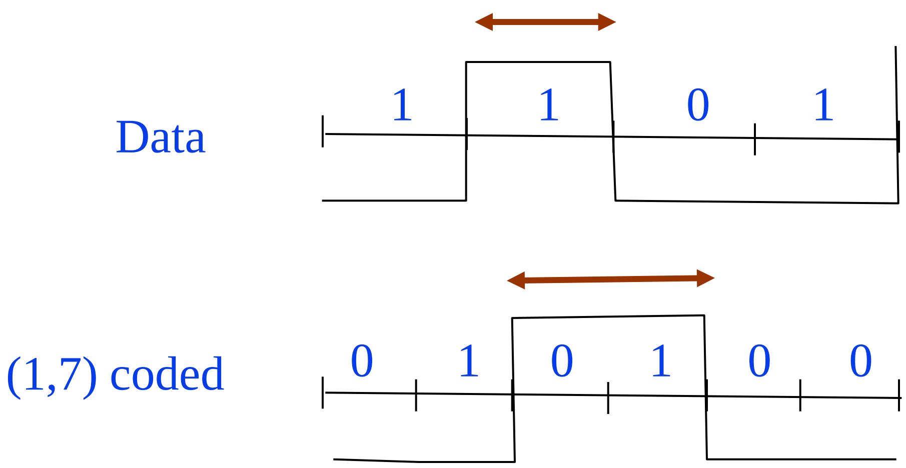
- Equalizer “slims” readback pulses, but boosts high frequency noise.



- RLL (1,7) code separates transitions by at least 2 bit times, but uses 3 channel bits per 2 information bits.

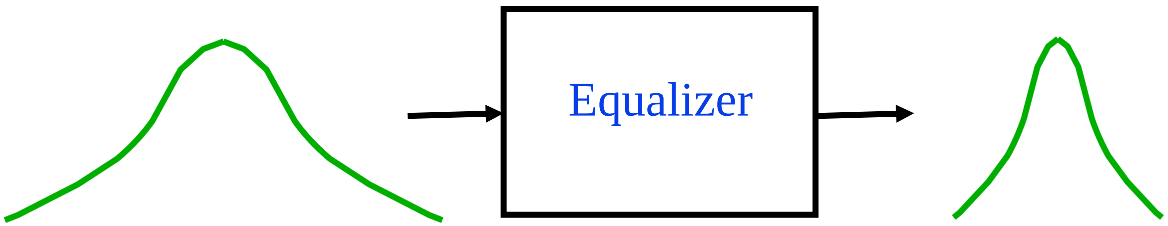
1 = “transition”

0 = “no transition”



(1,7)-RLL Equalized Peak Detection

- Equalizer “slims” readback pulses, but boosts high frequency noise.



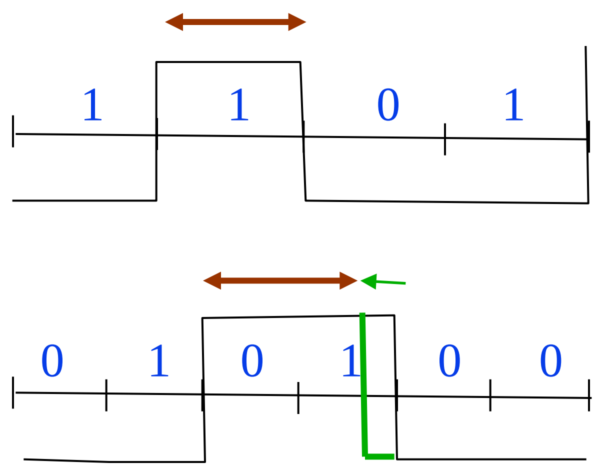
- Write precompensation shifts transition to offset ISI

1 = “transition”

0 = “no transition”

Data

(1,7) coded

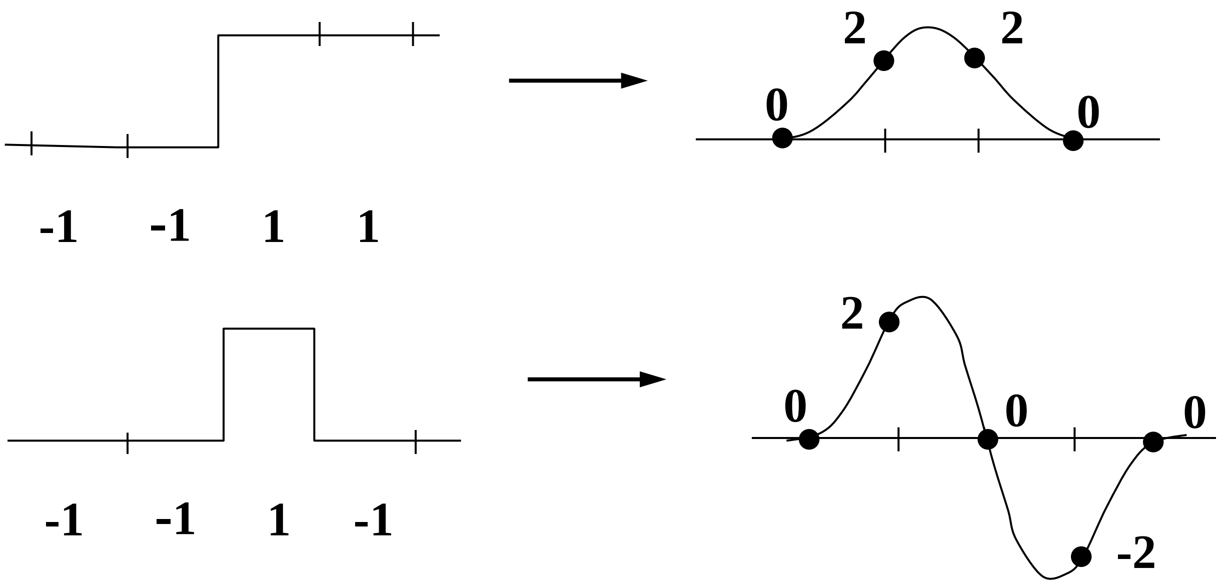


The Digital Revolution in Disk Storage

- Beginning in 1990, the entire industry switched to "digital" signal processing, in the form of sampled detection.
- The digital approach is broadly known as **PRML**
  - **P**artial **R**esponse equalization
  - **M**aximum **L**ikelihood detection
- The approach had been proposed by Tang and Kobayashi in the late 1960's and early 1970's.
- The acronym "PRML" was coined in the early 1980's by Andre Milewski, of IBM LaGaude.

What is PRML?

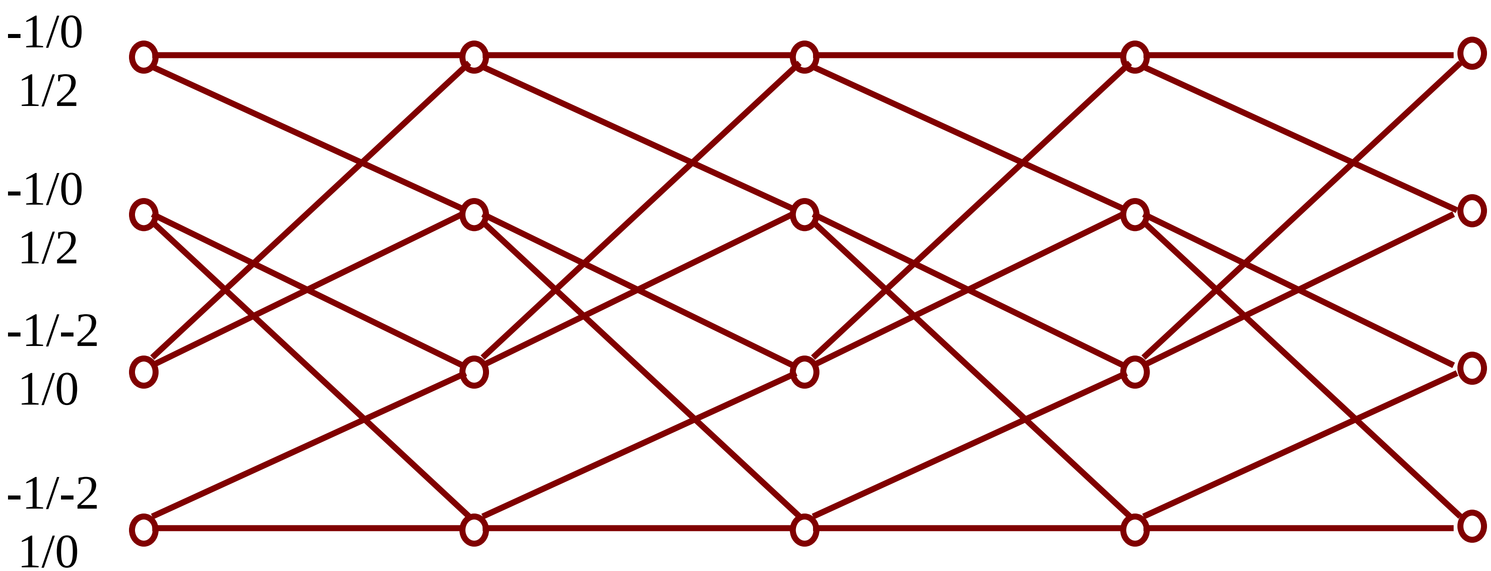
- “PR” = Partial Response [Class-4] Equalization



- PR equalization creates controlled intersymbol interference
- Discrete-time input-output relation: $y_n = x_n - x_{n-2}$
- Transfer polynomial: $h(D) = 1 - D^2 = (1 - D)(1 + D)$

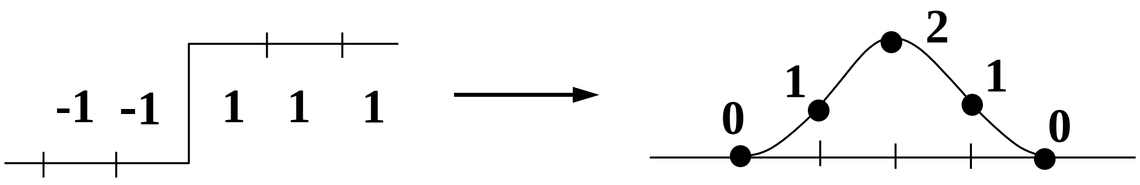
What is PRML?

- “ML” = Maximum Likelihood sequence detection
- Uses the Viterbi algorithm to determine the PR4 sample sequence “closest” to the noisy channel output sequence.
- The algorithm does an exhaustive comparison to all possible PR4 sequences, but it does it very efficiently.



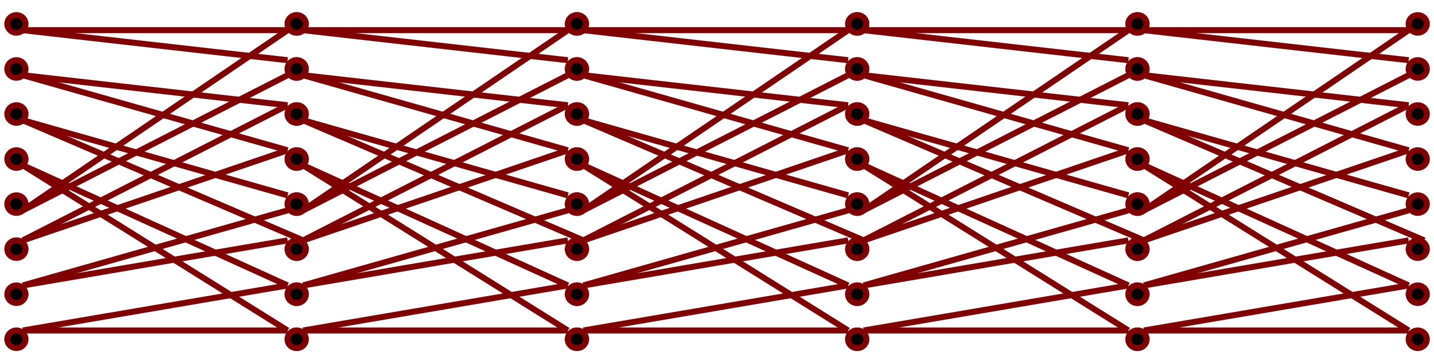
Beyond PRML

- Extended PR4 - “EPRML”
- Allows more intersymbol interference ⇒ higher bit density



$$y_n = x_n + x_{n-1} - x_{n-2} - x_{n-3}$$

- Viterbi detector requires 8 states ⇒ higher complexity



Beyond EPRML

- More generally – "E^NPRML" for N>1
  - Intersymbol interference affects N+2 subsequent samples.

$$h(D) = (1-D)(1+D)^{N+1}, N \geq 1$$

  - Viterbi detector operates on trellis with 2^{N+2} states.
  - EPR4 and E^2PR4 were widely used in commercial drives during the late 1990's.

- Write precompensation of NLTS is required.

Beyond E^NPRML

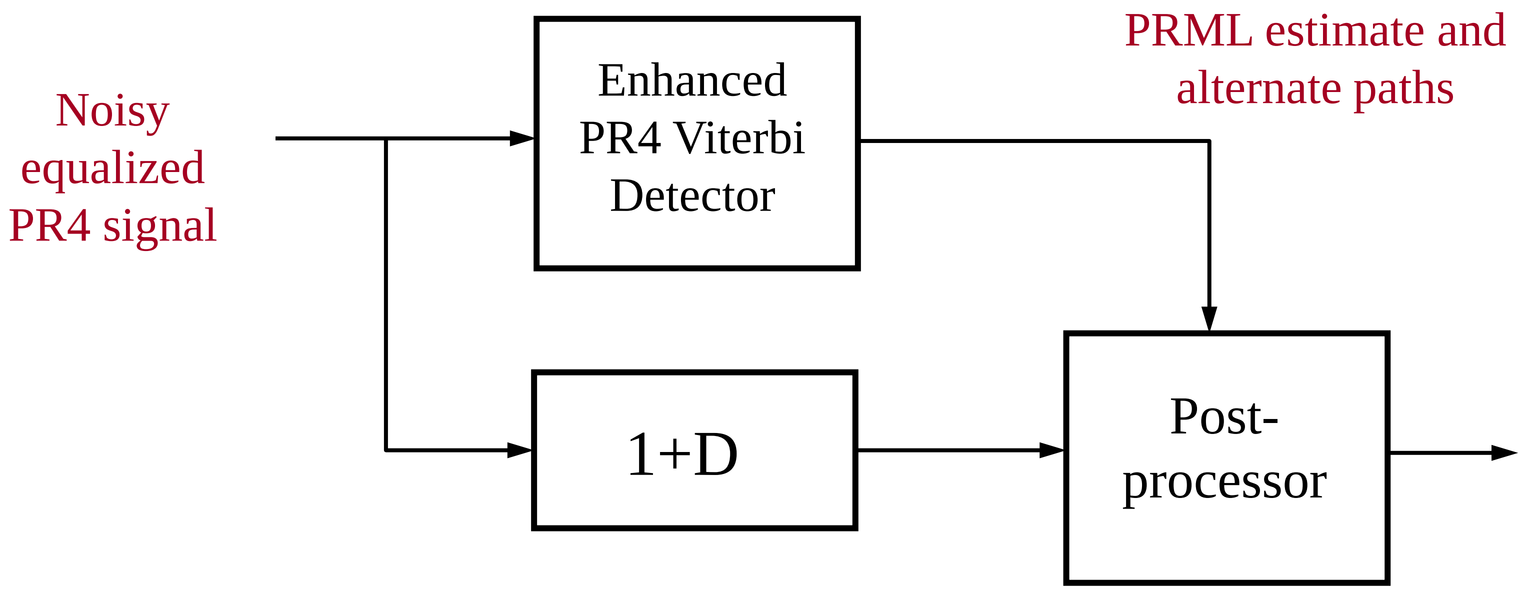
- Noise-predictive PRML (NPML)
  - Modifies Viterbi algorithm to take into account spectral coloration of equalized noise.
- Generalized PRML (GPRML)
  - Equivalent to NPML, GPRML modifies PR4 equalizer target to include noise whitening.

$$h(D) = (1 - D^2)(1 + p_1 D + p_2 D^2)$$

- Pattern-dependent noise-predictive PRML (PDNP)
  - Incorporates transition noise effects into detector metric calculations.

Post-Processing EPRML Detector
(Wood 1993, Knudson 1998)

- Enhanced PR4 detector outputs binary estimate along with some “soft” information.
- Post-processor determines most likely EPR4 error event, if any, and corrects the PRML estimate.

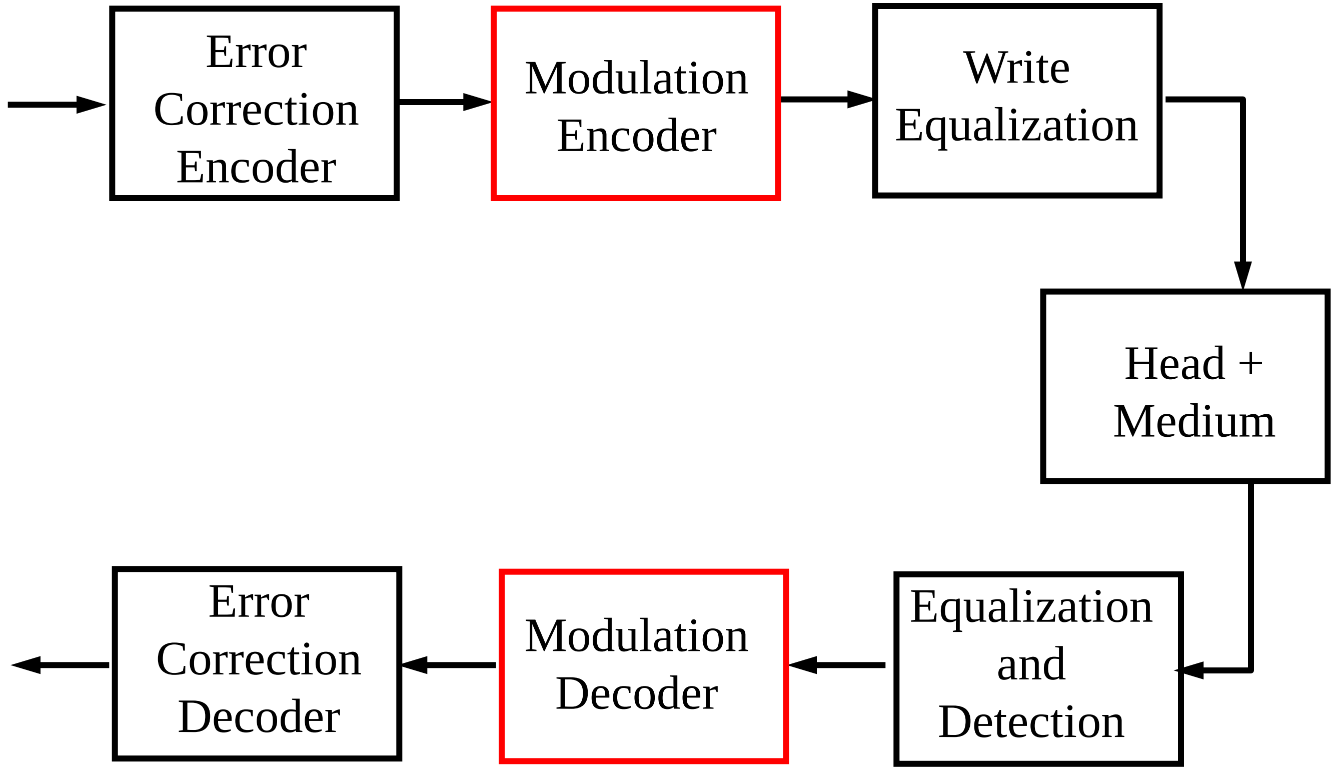


“Turbo-PRML” [Wood]

Post-Processor for Coded GPRML

- Most drives today use a simple high-rate parity-check code.
  - Parity-check error in GPRML detector output is flagged.
  - Post-processor identifies most-likely error event and location using “soft information” from detector.
  - Correction is applied to GPRML output sequence.
- Post-processing has been applied to other coded PRML-type systems.
  - Runlength limited codes
  - Matched-spectral null codes (esp. dc-free codes)

Modulation Codes



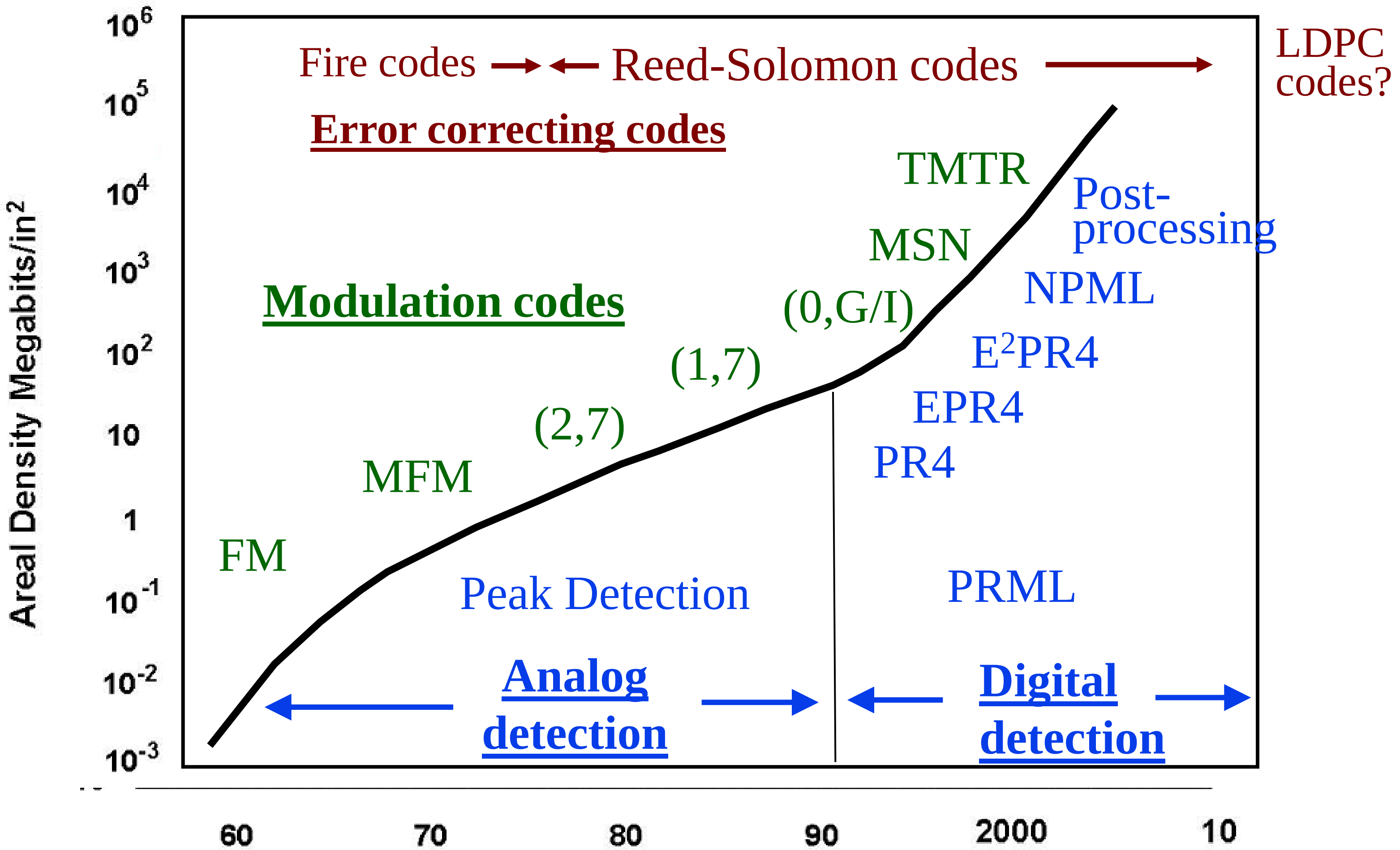
Modulation Codes

- Modulation codes are sometimes called "line codes" in communications.
- They codes prohibit the occurrence of certain channel input sequences that cause errors in data recovery.

Modulation Codes for Storage

- In peak detection systems, (d,k) codes reduced ISI and helped timing recovery.
- In PRML systems, (0,G/I) codes reduced the required "trellis history" and helped timing recovery.
- In E^NPRML systems, for N>1, matched-spectral null (MSN) and time-varying maximum-transition-run (TMTR) codes eliminated the most-likely error events in the Viterbi detector (increasing effective SNR).

Communication Theorist's View of Areal Density Growth



(d,k) Runlength-Limited Constraints

d = minimum number of 0's between 1's

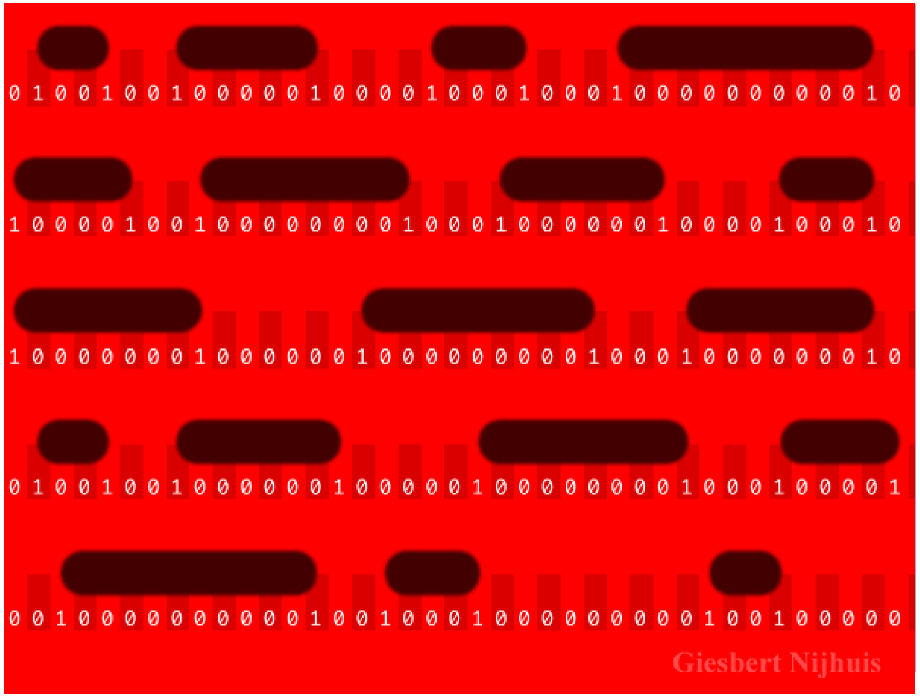
k = maximum number of 0's between 1's

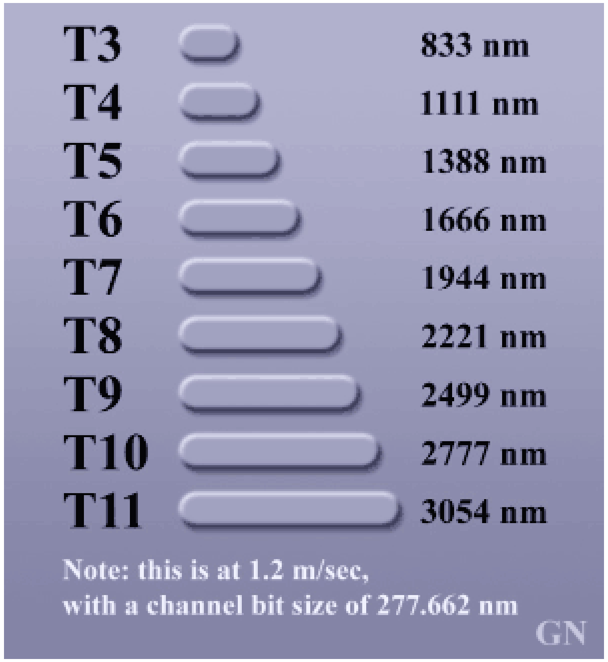
- Peak detection systems used (d,k) RLL codes
  - $d > 0$ constraint separates pulses to reduce ISI.
  - $k < \infty$ ensures regular peaks to help timing recovery

- In disk drives, (1,3); (1,7); and (2,7) codes were used.
- In the Compact Disc, a code satisfying (2,10) constraints is used.

CD - Pits and Lands

Linear Density: 39.4 kb/in or 1.55 bits/µm





Courtesy of Giesbert Nijhuis

(0,G/I) PRML Constraints

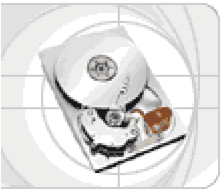
G = maximum number of 0's between 1's

I = maximum number of 0's between 1's
in interleaved even/odd subsequences

- Early PRML systems used (0,G/I) codes
  - G ensures non-zero samples to help timing recovery
  - I limits the required trellis history

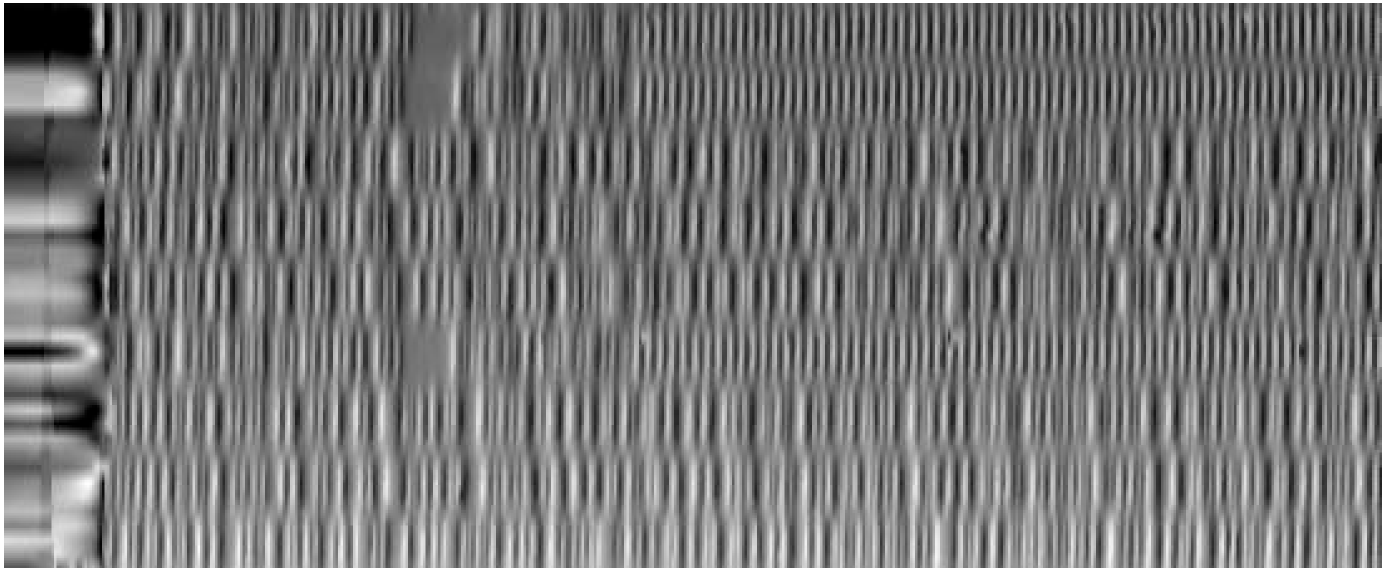
- IBM disk drives with PRML used (0,4/4) constraints

Hard Disk Drive – Magnetic Transitions



Linear Density: 135.4 kb/in or 5.33bits/µm

32µm



78µm

Courtesy of Fred Spada

Design of Distance-Enhancing Codes for E^NPRML

- Characterize Viterbi detector error-events using error-state diagram analysis.
- Determine modulation constraints that reduce and/or forbid dominant error events, and design code.
- Incorporate channel and code constraints into detector trellis, or use reduced-state trellis and a post-processor.

MSN and TMTR Constraints

- For E^2PR4 channel, distance-enhancing codes include:

- Matched-Spectral-Null (MSN) codes
  - DC-null and order-K Nyquist null

- TMTR(2,3) codes
  - Limit consecutive 1's to 2 (resp. 3) on even (resp. odd) phases

Constrained Coding

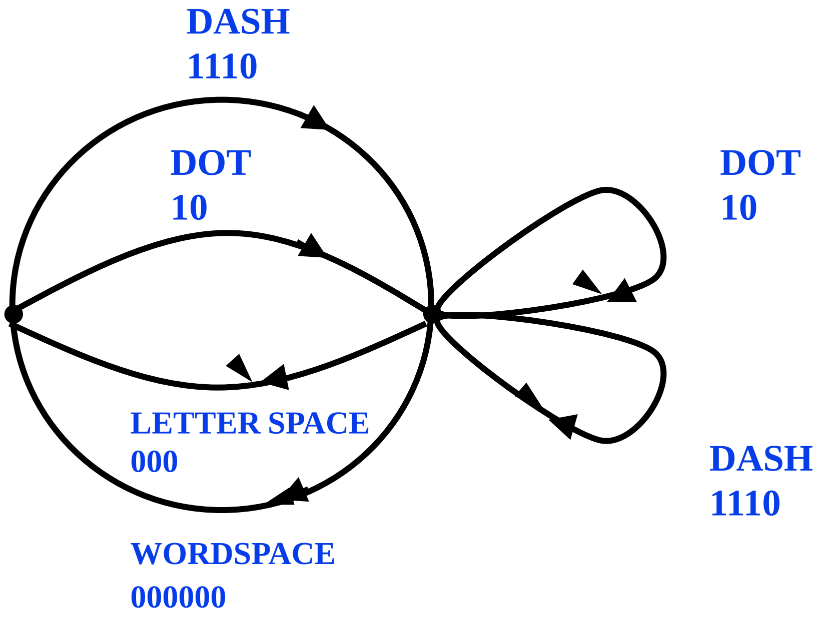
- Problem:
  - How can we efficiently transform unconstrained binary data streams into constrained binary code streams?

- Issues:
  - Invertibility of transformation (unique decodability)
  - Rate R, i.e., average ratio of # data bits to # code bits
  - Complexity of encoding and decoding operations

- Shannon was the first to address these theoretically.

Shannon's Disk Drive

- Shannon had no disk drive, but he did have the telegraph channel!



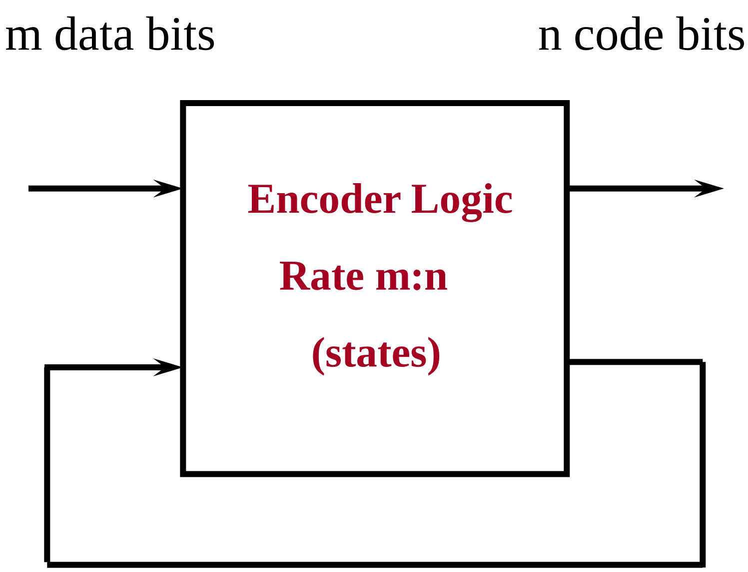
Modulation Codes and Capacity

- Shannon showed that the number of length-n constrained sequences is approximately 2^{Cn}.
- C is the capacity, the maximum possible rate, and Shannon showed how to compute it.
- He showed that block codes with rates approaching C exist, but they may be **very** long.
- Powerful coding theorems and practical code design methods were developed in the 1980's, motivated largely by the problem of modulation code design for magnetic recording.

Practical Constrained Codes

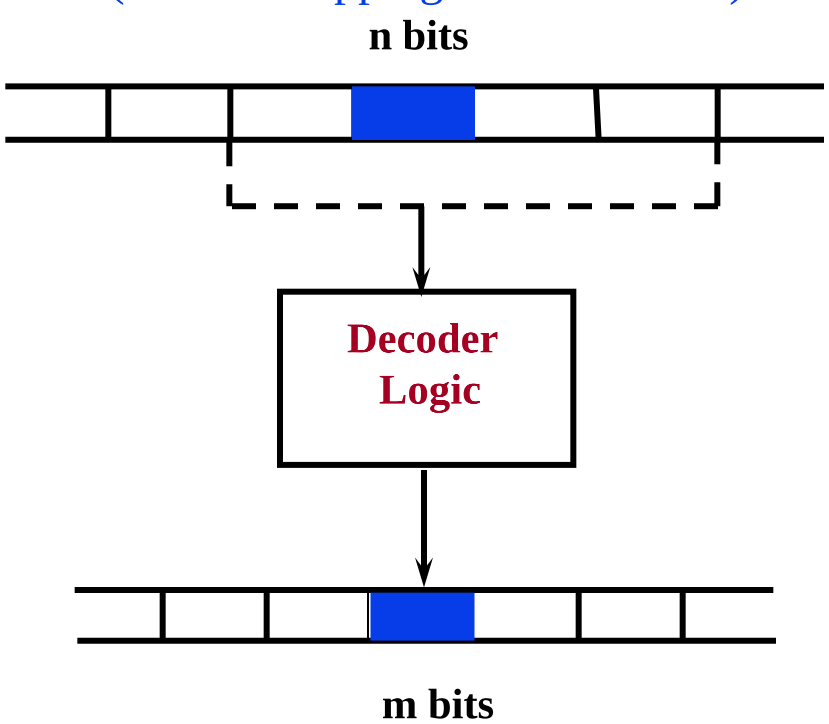
Finite-state encoder

(from binary data into S)



Sliding-block decoder

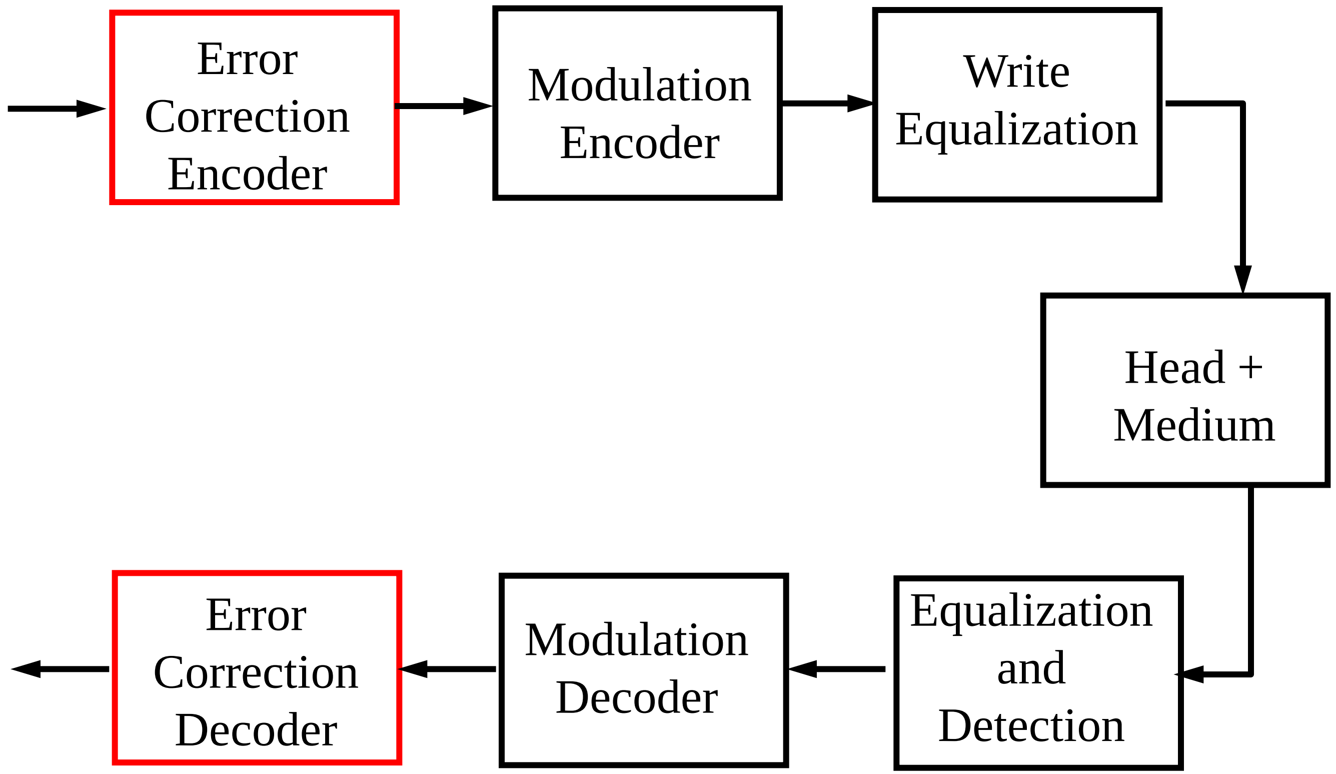
(inverse mapping from S to data)



We want: high rate R=m/n

low complexity

Modulation Codes



Error-Correcting Codes

- Disk drives have always used burst-error correcting codes.
- Early drives used simple Fire codes.
- By the 1980's, the codes of choice were Reed-Solomon codes and their variants.

Reed-Solomon Codes in Disk Drives

- The 1983 vintage IBM 3380, which used the (2,7) RLL code, had a 2-way interleaved Reed-Solomon code with 16-bit symbols and a variable block length up to 64K symbols (an entire track)
- It corrected any burst-error contained within 2 consecutive symbols (all 17-bit bursts and some up to 32 bits).
- Correction was done by the CPU!
- Detected but uncorrectable errors triggered an error recovery procedure that included many re-read attempts with head offsets.
- A study found that the CPU was interrupted about once every 20 minutes.

IBM 3380

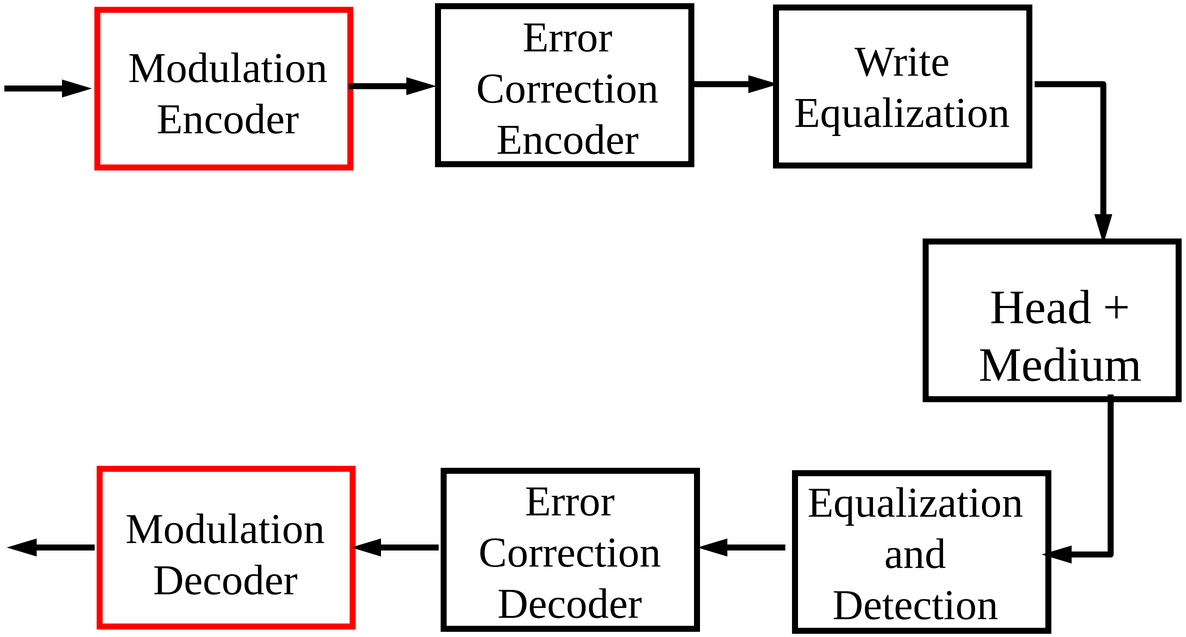
Jack Wolf with IBM 3380 HDA in CMRR

Error-Correcting Codes

- After the early 1980's, disk drives used sectors with 512 bytes of data.
- Various configurations of interleaved, shortened RS codes have been used, with symbol lengths of 8, 9, and 10 bits.
- Today, the code redundancy is approximately 10%, and multiple byte errors are corrected "on-the-fly".
- Because of the seriousness of a miscorrection, considerable use is made of error detection.
- The disk drive industry will soon move to longer sectors containing 4K symbols to improve efficiency.

Reverse Concatenation

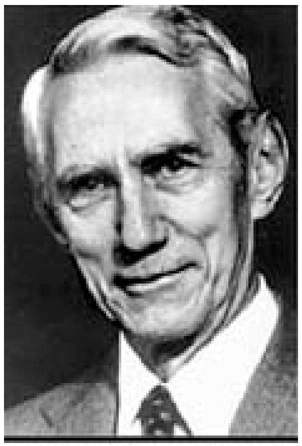
- Some systems today use a reverse-concatenation architecture to limit error propagation in high-rate, large blocklength modulation codes.



New Opportunities

- There are several exciting research directions being pursued in advanced coding for disk drives.
- At CMRR, we have been exploring various aspects of the following:
  - Algebraic list (soft-decision) decoding
  - Iterative decoding and detection (turbo equalization)
  - LDPC-coded GPRML
- These techniques should allow us to come close to achieving the noisy channel capacity, speaking of which...

Shannon Capacity


Claude Elwood Shannon
1916 - 2001

Every communication channel is characterized by a single number C, called the **channel capacity**.

It is possible to transmit information over this channel reliably (with probability of error $\rightarrow 0$) if and only if:

$$R \stackrel{def}{=} \frac{\#\,\text{information bits}}{\text{channel use}} < C$$

Shannon Capacity of Noisy Recording Channels

- Until recently, there was no known way to compute or accurately estimate information rates of noisy input-constrained ISI channels.
- An ingenious simulation-based approach, grounded in information theory, was independently discovered by 3 teams of researchers in 2001.
- One of those teams included 2 of my students who both joined Qualcomm upon graduation
  - Joseph Soriaga
  - Henry Pfister (now an Asst. Prof. at Texas A&M)

Outline

- Preamble
- Magnetic Recording Technology
- Storage as Communication
- **What the Future Holds in Store**

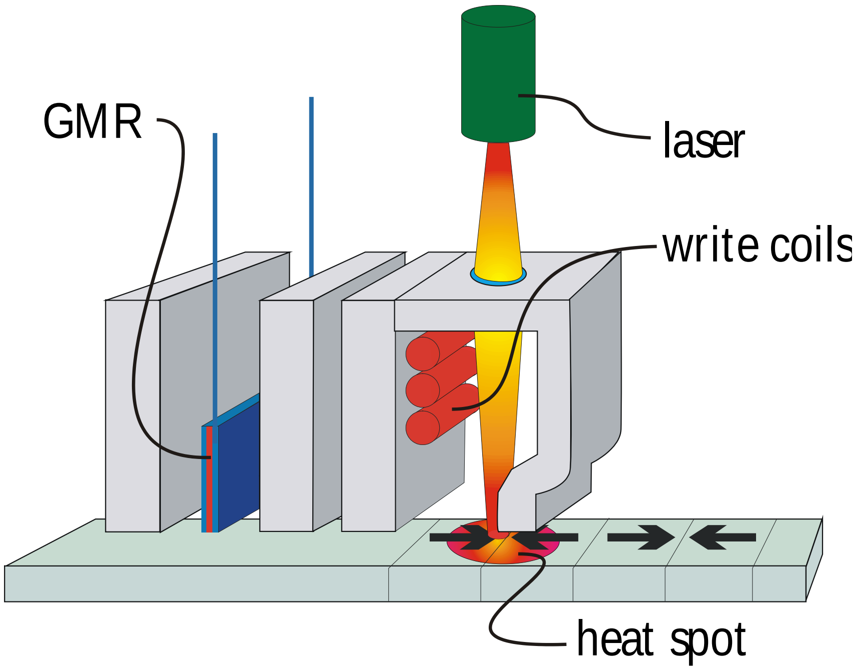
The Superparamagnetic Effect

- As scaling of perpendicular recording leads to densities approaching 1 Tb/in^2, it is expected that the magnetic grains will become thermally unstable at room temperature.

- This is the superparamagnetic effect.

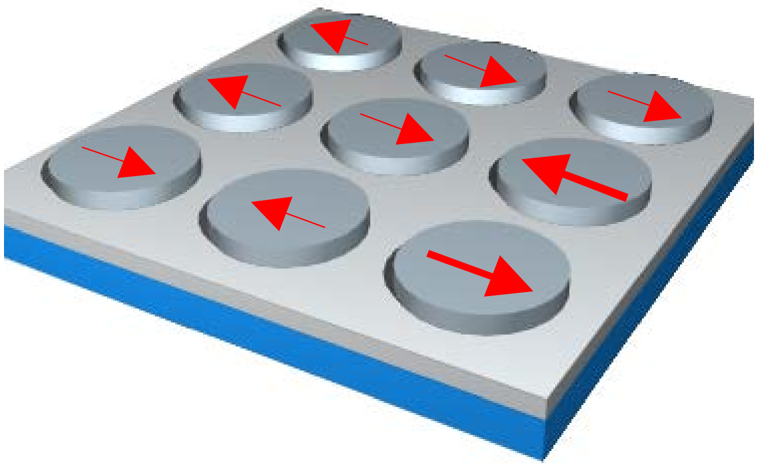
- Two magnetic approaches are being actively explored
  - Heat-assisted magnetic recording (HAMR)
  - Bit-patterned media (BPM)

HAMR



- Use very high coercivity magnetic material
- Need laser to heat the material to enable writing

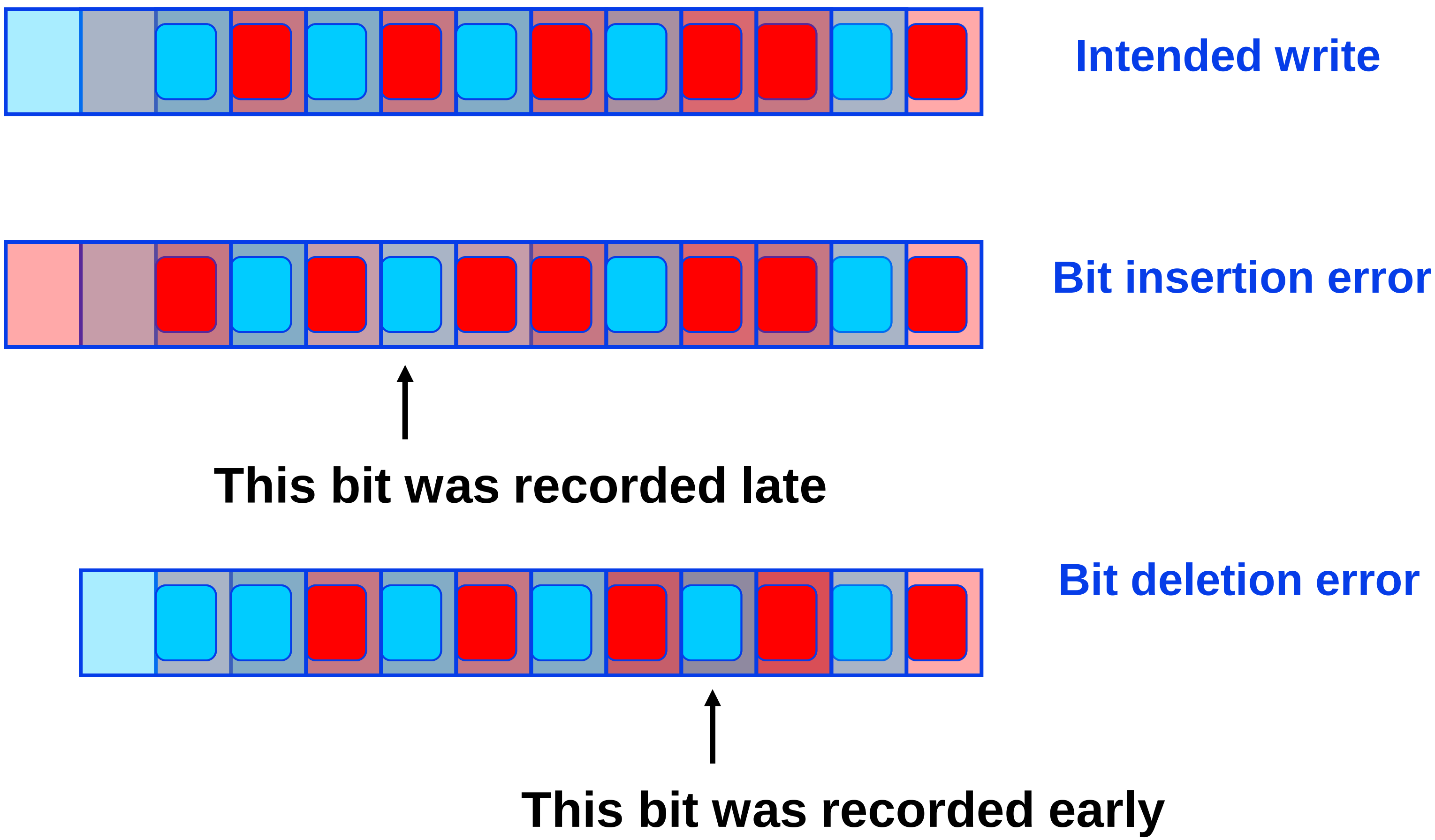
Bit Patterned Media



- Each "island" stores one bit
- 1 Tb/in^2 needs 25nm cells
- Densities up to 10Tb/in^2

- Many challenging research issues:
  - Media fabrication
  - Write synchronization:
    insertion and deletion errors
  - Tracking servo
  - Coding and data detection

Write Synchronization Errors in BPM



Our Current Research on Patterned Media

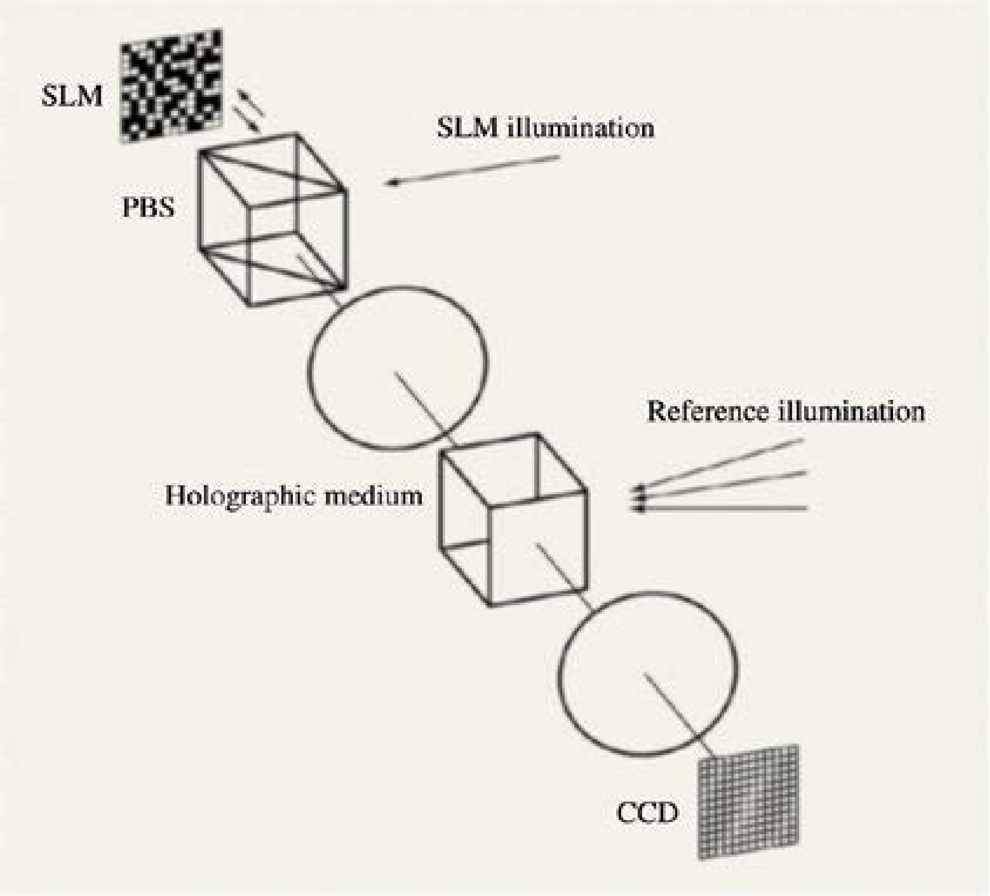
- Runlength-limited insertion and deletion correcting codes.

- Information-theoretic analysis of input-constrained insertion and deletion channels.

- Analytical models of island jitter noise.

- Detection methods for channels with intersymbol-interference and intertrack-interference.

Holographic Recording

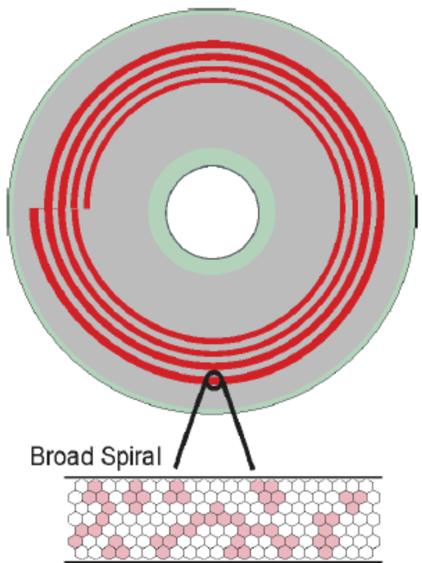


2-D Intersymbol Interference

$$h = \begin{bmatrix} 0.05 & 0.21 & 0.05 \\ 0.20 & 0.91 & 0.19 \\ 0.01 & 0.10 & 0.02 \end{bmatrix}$$

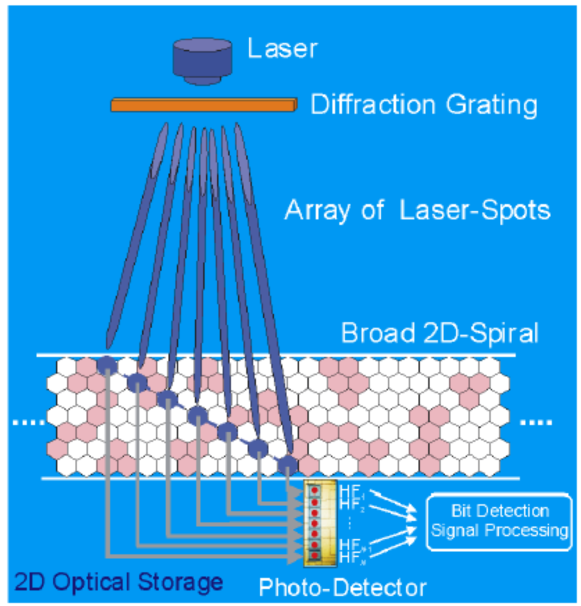
Two-Dimensional Optical Storage (TwoDOS)

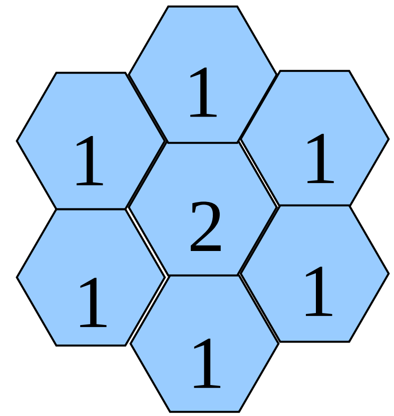
Disc



(spiral contains 11 bit-rows)

Readout





2-D Impulse response

Courtesy of Wim Coene, Philips Research

Our Current Research on Page-Oriented Storage

- Coding, detection, and information-theoretic analysis for page-oriented recording channels require new methods.
- We have been working on the following problems:
  - Capacity analysis of 2-D modulation constraints
  - Design of 2-D modulation codes
  - Detection algorithms for 2-D ISI channels
  - Bounds on channel capacity of 2-D ISI channels.

IBM Millipede Probe Storage

- Uses a dense 2-D array of atomic force microscope cantilevers with probe tips.
- By heating the cantilevers, data is written thermo-mechanically on a nano-meter thick polymer medium.
- Areal density of 1 Tb/in^2 has been demonstrated.
- Parallel read-out is used for high data transfer rate.

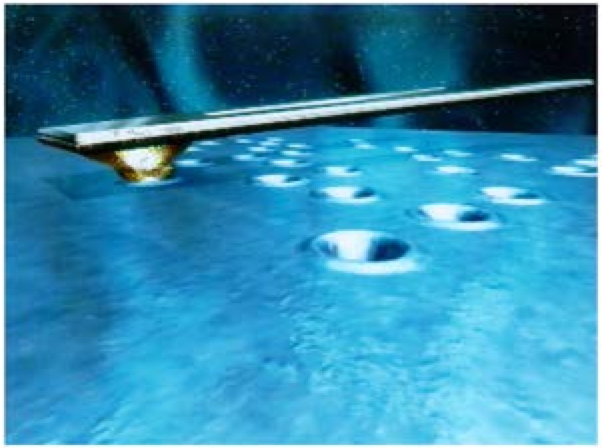
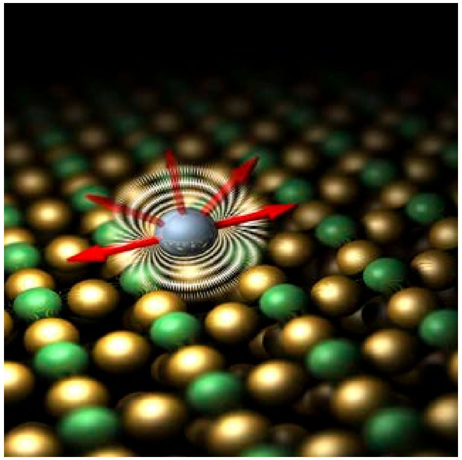
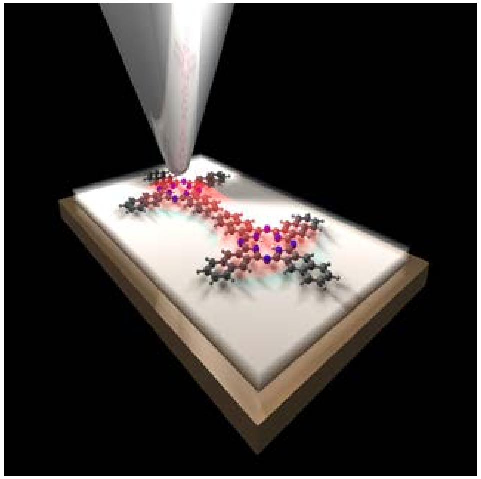


Image courtesy of IBM

Atomic Storage
(IBM Research)





- Use magnetic anisotropy to store data in individual atoms
- Densities up to 150 Tb/in^2 !!
- An “atomic storage” iPod could hold 30,000 movies...

Image: Courtesy of IBM

Concluding Remarks

- Modern information storage devices are marvels of scientific and engineering achievement.
- The need for storage appears to be insatiable, and many new applications will surely arise that make use of advances in storage technology.
- Communication theory will continue to play a vital role in the design of future storage systems.

The End

Thank you