Fundamental of HDD Technology (8)

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Outline

- Magnetic Recording Channel Model
- Write Process

Magnetic Recording Channel Model

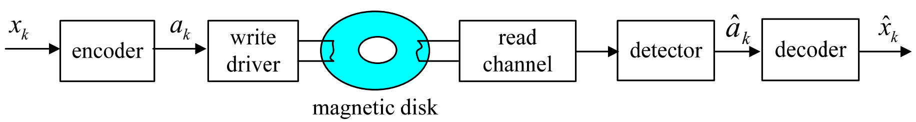
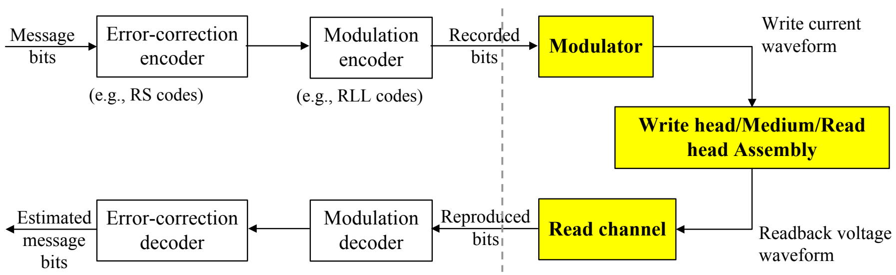
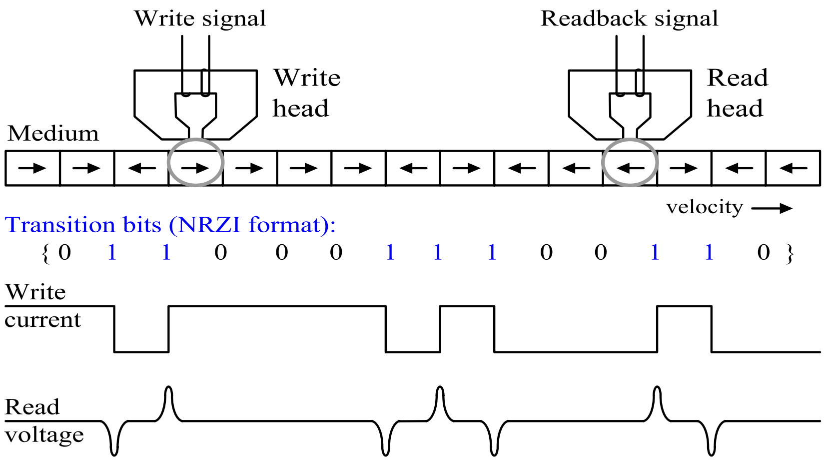
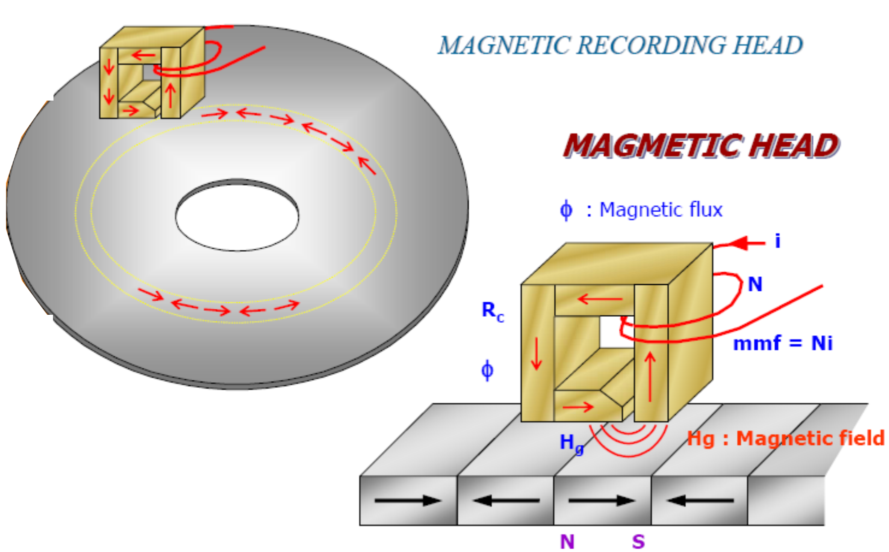


Diagram of Data Storage Systems

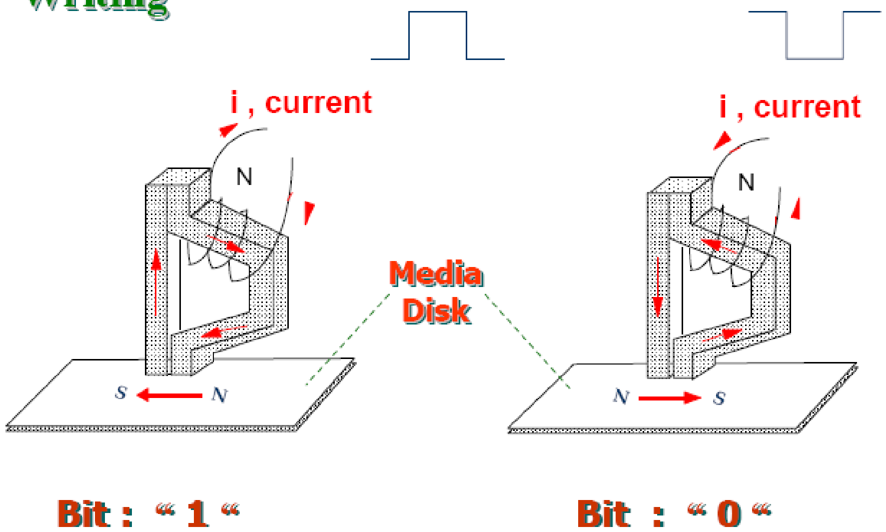


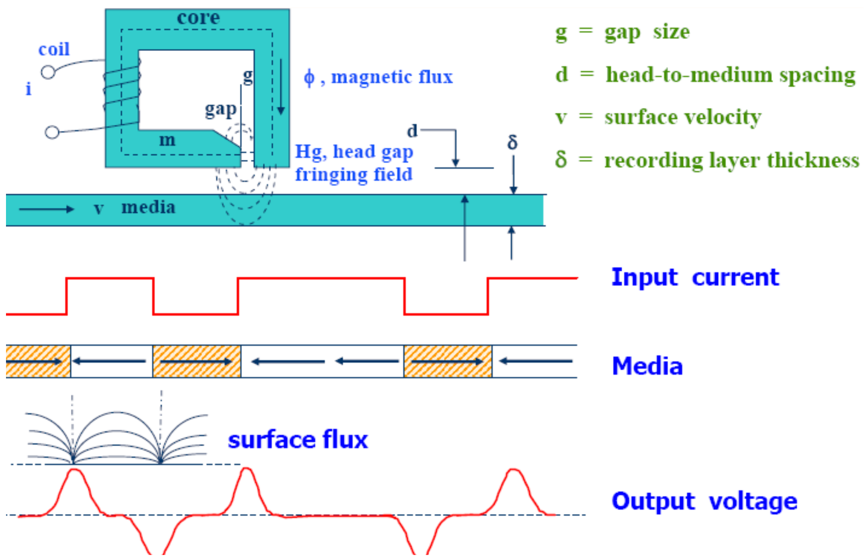
Basic Write/Read Process



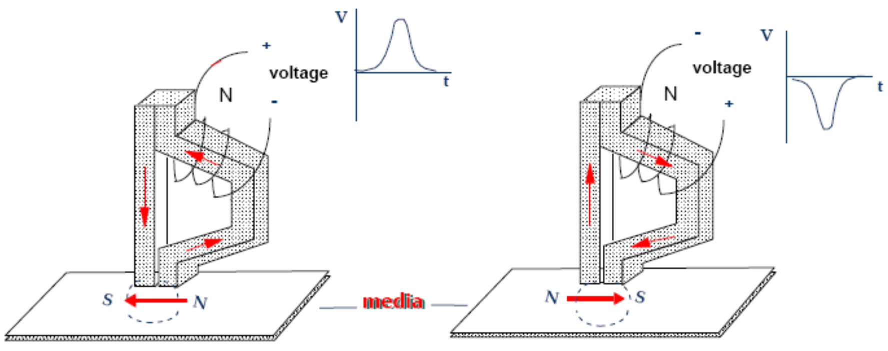


Writing





Reading or Reproducing

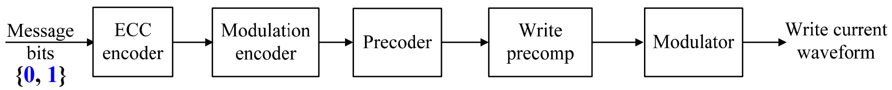


Bit : " 1 " **Bit : " 0 "**

Write Process

- ECC Encoder
- Modulation Encoder
- Precoder
- Nonlinear Transition Shift
- Write Precompensation

Write Process

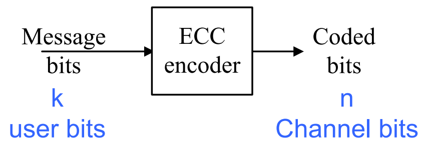


Notation:

ECC = Error-correction code

Write precomp = Write precompensation

Error-Correction Code (ECC)

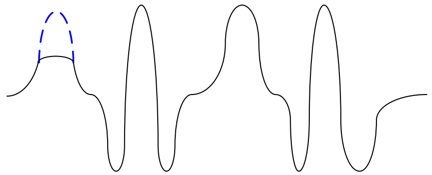


Code rate $\Rightarrow$ $R = \frac{k}{n} \leq 1$

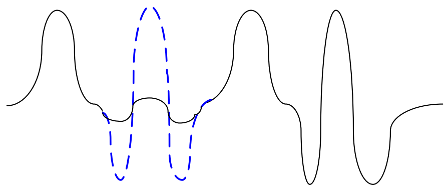
$R \to 1$ is desirable.

- Improve error-rate performance
- Enhance reliability of the storage devices, thus increasing the recording densities.

- Single bit error
  - Occur due to a single short-duration noise event, which results in an extra pulse or a missing pulse



- Bursts of errors
  - Occur when a group of bits is detected erroneously
  - Due to defects of magnetic medium such as a scratch or a defective spot spanning over many bit periods



- Typically, magnetic recording systems must provide a bit-error rate (BER) **< 10^{-9}**.
- The reliability of data recovery may be greatly boosted by using ECC's.
- Once a certain number of errors are corrected by ECC, we can afford to increase the recording densities until reaching a required BER.
- Thus, the storage capacity with ECC trends to be larger than that without ECC.

Example – ECC

- Consider:
  - A simple ECC capable of correcting a single error in a group of 16 bits, which requires the overhead of 8 bits for every 16-bit block.
  - An error will occur only if 2 or more bits out of 16 bits are in error.
- If the probability of a single-bit error is p_0, then the probability of 2 bits being in error equals p_0^2, and we have a total of 120 possible 2-bit errors in a 16-bit sequence.
- Then, the probability of error using ECC is

$$P_b \approx \binom{16}{2} p_0^2 (1-p_0)^{14} = 120 p_0^2 (1-p_0)^{14}$$

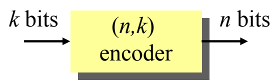
Let $P_b = 10^{-9} \Rightarrow p_0 \approx 3*10^{-6}$

- If the error rate is determined by random noise,
  - Possible to calculate the signal-to-noise ratio (SNR), required to achieve a specific BER.
- Example:
  - To achieve BER = 10^{-9} without ECC $\Rightarrow$ Require SNR = 22 dB
  - To achieve BER $\approx 3*10^{-6}$ (with ECC) $\Rightarrow$ Require SNR = 19 dB
    - Yield a gain of 3 dB to spare
- The reduction in the SNR required to achieve a specified error performance due to ECC is called the coding gain.
- The coding gain in SNR allows increased recording densities.

- For example, if the main source of noise is the medium noise,
  - A reduction of track width by a factor of 2 ⇒ Lose SNR = 3 dB [S. X. Wang and A. M.Taratorin, 1999]
- Therefore, using ECC need 50% more disk space for extra bits, but the coding gain of 3 dB allows us to recording 100% more information by doubling track density.
  - The net gain from ECC is 50% more storage capacity
- In general, using ECC will increase the storage capacity.

ECC – Reed Solomon (RS) Codes

- Reed-Solomon (RS) codes are a common family of ECCs used in commercial hard disk drive because:
  - Powerful in correcting burst errors
  - Good at handling erasures ⇒ useful in the recording industry where channel imperfection due to scratches can be effectively modeled as erasures.
- A RS code is the most efficient code among the (n, k) cyclic codes because it achieves the largest possible minimum distance:



$$d_{min} = n - k + 1$$

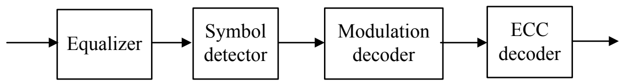
coded bits (n)

message bits (k)

- A (n, k) RS code:
  - Can detect any burst of errors having a burst length of (n – k)
  - Can correct any burst of errors having a burst length of (n – k)/2
- Example: a (31, 15) RS code
  - Can detect a burst of 16-bit error
  - Can correct a burst of 8-bit error

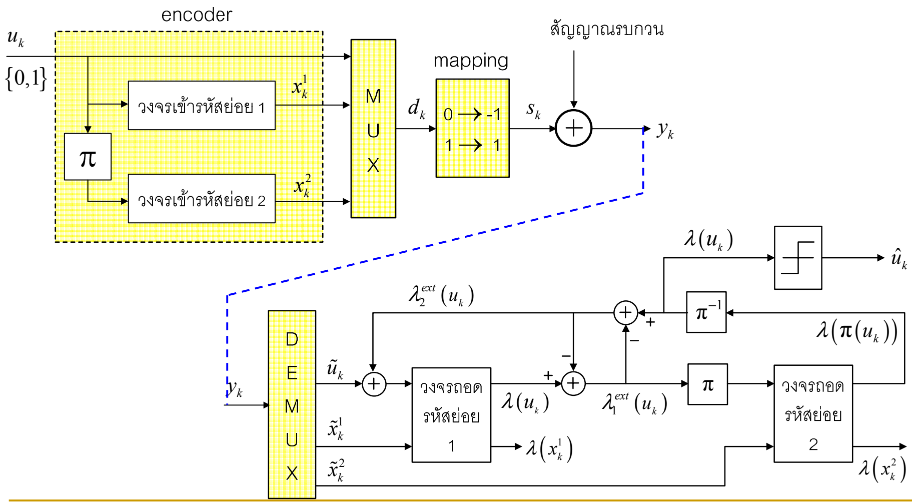
ECC Trend

- ECCs are basically independent of a bit detector.



- Trend:
  - Combine the ECC decoder and the bit detector.
  - Employ other ECCs that have large coding gains because they allow for higher recording densities.
    - Turbo codes
    - Low-density parity check (LDPC) codes

Example: Turbo Decoding



Modulation Code

- Normally, it is used to combat channel distortion and noise in transmission.
- In magnetic recording, it is used to eliminate or minimize the d.c. content in the read-back signal and to achieve spectrum shaping*.
- Specifically, it is designed to increase the distance between transitions in the recorded waveform, and thus reducing the intersymbol interference (ISI) effect.
- Run-length limited (RLL) codes are widely used for this purpose.

* Codes for spectrum shaping are used so that the spectrum of the transmitted signal matches the spectrum characteristics of the channel.

Run-Length Limited (RLL) Code

- It has a restriction on the number of consecutive 1's and 0's in a data sequence.
- It is determined by two parameters (d, k), where
  - *d* denotes the minimum number of 0's between two 1's in a sequence.
  - *k* denotes the maximum number of 0's between two 1's in a sequence.
- Specifically, (when used with NRZI format)
  - *d* ⇒ Spread the transitions farther apart, thus reducing the ISI effect.
  - *k* ⇒ Ensure that the transitions occur frequently enough so that symbol timing information can be recovered from the signal.

Example: Rate-1/2 (1, 3) Miller Code

Coding rule:

User bits	Coded bits
0	X 0
1	0 1

$$X = \begin{cases} 0 & \text{if the preceding symbol is } 1 \\ 1 & \text{else} \end{cases}$$

User bits = { 1 0 1 1 1 0 0 1 }

RLL bits = { 01 00 01 01 01 00 10 01}

clearly, we have d = 1 and k = 3

- The price for RLL coding appears in a data rate change.
  - # output bits **>** # input bits
  - In other words, RLL coding introduces lots of redundant bits
- From the previous example, we found that:
  - Rate-1/2 (1, 3) RLL code ⇒ (d = 1, k = 3)
  - 1 user bit is mapped into 2 coded bits ⇒ lose 50% of disk space

Example: 2/3 (1, 7) RLL Code

Coding Table

User bits	Encoded bits
00	101
01	100
10	001
11	010
0000	101000
0001	100000
1000	001000
1001	010000

Example: 1/2 (1, 7) RLL Code

Coding Table

User bits	Encoded bits
10	0100
11	1000
000	000100
010	100100
011	001000
0010	00100100
011	00001000

Which RLL Code is Good?

- Factors needed to be considered when choosing RLL codes:
  - Parameters: d and k
  - Code rate, R
  - Capacity, C
  - Code efficiency, η
  - Density ratio, DR
- In practice, we need to compromise all factors to best suit for a given system.
- Some RLL codes:
  - Rate 1/2 – (2, 7) code
  - Rate 4/5 – (0, 2) code ⇒ Group-Coded Recording (GCR) code
  - Rate 8/9 – (0, 3) code

A (0, G/I) RLL Code

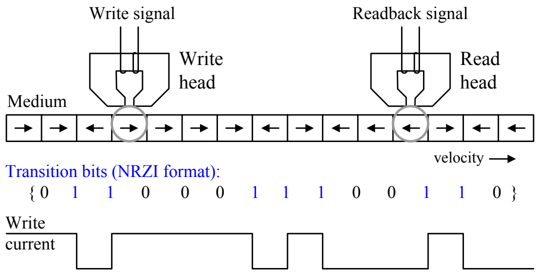
- Widely used in PRML systems
- No constraint on transition separation, i.e., two transitions may be written without additional zeros between them (i.e., d = 0)
- The notation (G/I) appears because of the specific realization of PRML channel when a stream of user bits is split into odd and even bits.
  - G = maximum # of 0's between 1's in odd data sequence
  - I = maximum # of 0's between 1's in even data sequence

Summary: RLL Codes

- Error propagation might occur when decoding RLL codes.
- Recently, a (0, G/I) sequence is employed in the PRML system.

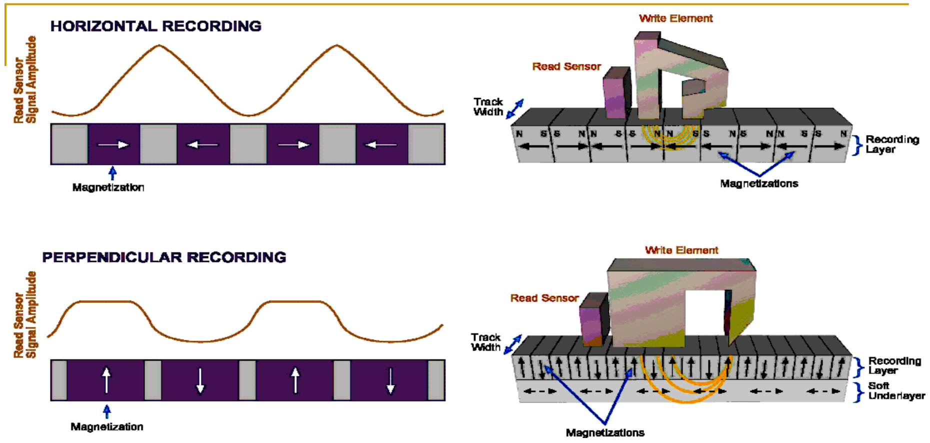
  Example:
  - Rate 8/9 - (0, 4/4) code
  - Rate 16/17 - (0, 6/6) code
- High rate RLL codes are desirable in order to reduce redundancy.

Write Process



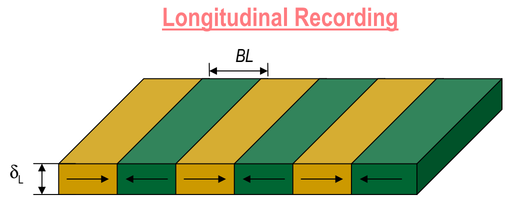
- Data bits are converted into a rectangular current waveform by the modulator.
  - This write current is applied to the write head to produce the magnetic write field in the medium near the head gap.
  - By switching the direction of the write current, magnetization transitions can be written in the medium.

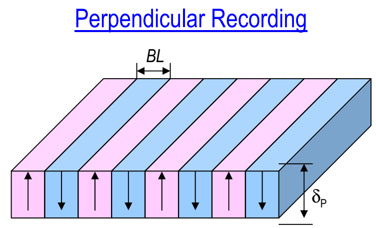
- Commercial digital recording systems normally employ **binary saturation recording** (i.e., only two data levels).
- If more than two data levels were recorded:
  - Nonlinearity would cause a major problem
  - Signal-to-disturbance ratios would diminish considerably



- **Longitudinal recording** $\Rightarrow$ medium magnetization is parallel to the disk plane.
- **Perpendicular recording** $\Rightarrow$ medium magnetization is perpendicular to the disk plane

Comparison of Recording Modes



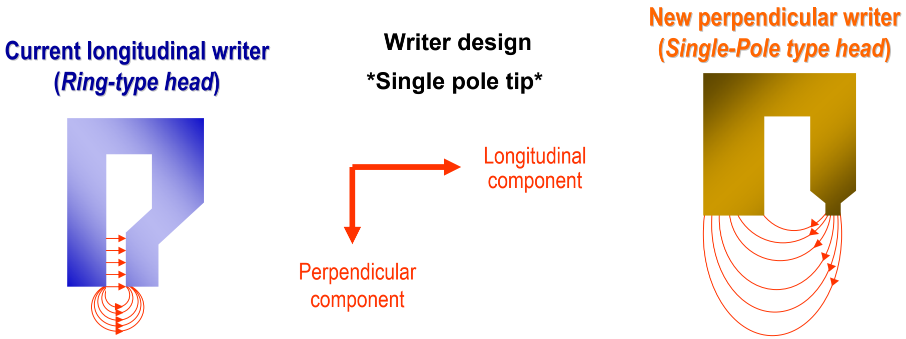


As Bit Length $\rightarrow 0$, $H_d \rightarrow 4\pi M_S$
Demag field H_d resists bit length reduction
Medium: In-plane anisotropy
Low M_S
High H_C
Thin δ_L

As Bit Length $\rightarrow 0$, $H_d \rightarrow 0$
Demag field H_d diminishes with bit length reduction
Medium: Perpendicular anisotropy
High M_S
High H_C
Thick δ_P

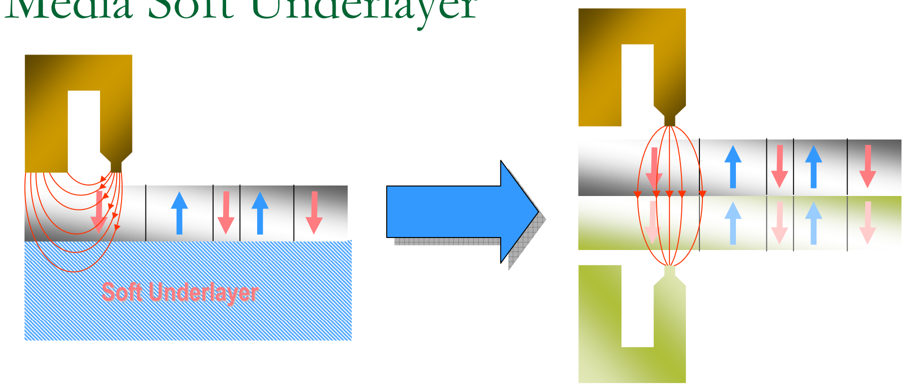
S.Iwasaki, IEEE Trans. on Magnetics (1985)

Single Pole Type head



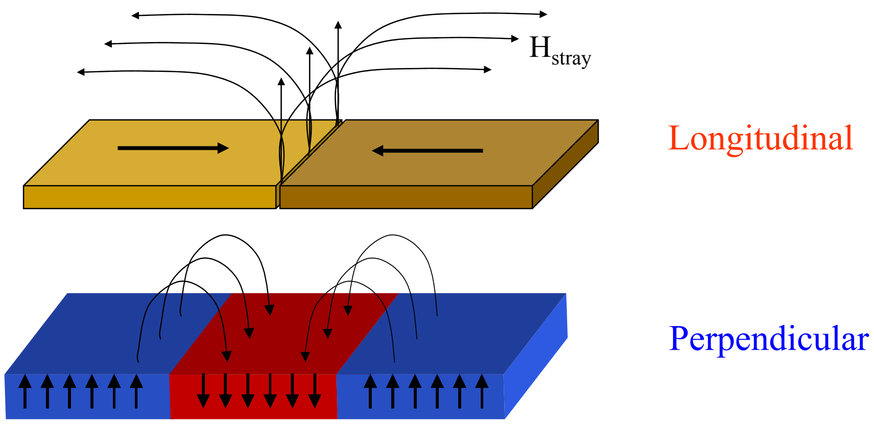
- Perpendicular recording needs writer that can supply the field that perpendicular to media plane
- Longitudinal writer can supply field with longitudinal component more than perpendicular component $\Rightarrow$ Not effective for perpendicular recording
- Single pole tip writer is design specifically to produce very high perpendicular field component approximately 3-4 times more field strength than longitudinal writer.

Media Soft Underlayer

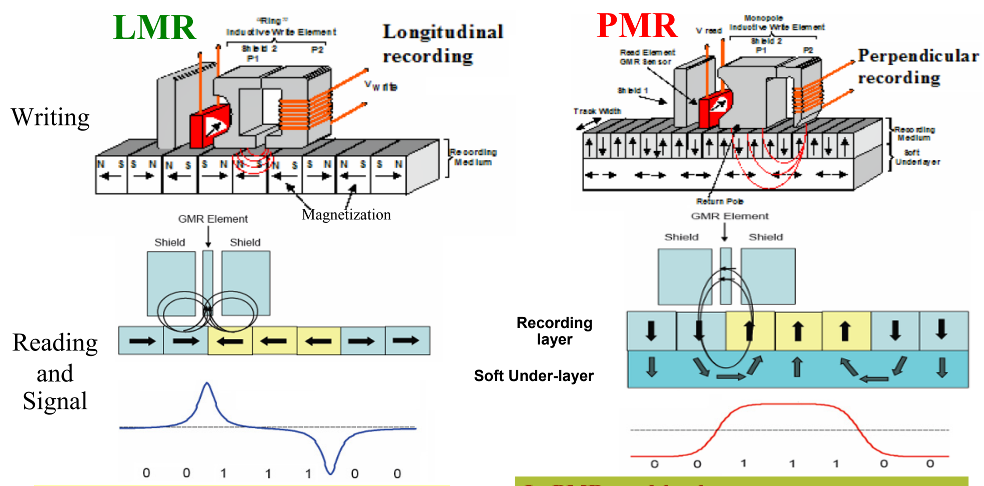


- Adding soft magnetic underlayer is like adding a virtual "mirror"
- A perfect mirror image can improve field strength from writer by 200%
  - Enable media to has higher switching field
- Media grain volume also effectively increases by 200%
  - Higher robustness against data loss

Magnetizations and Fields



Writing & Reading of LMR vs. PMR

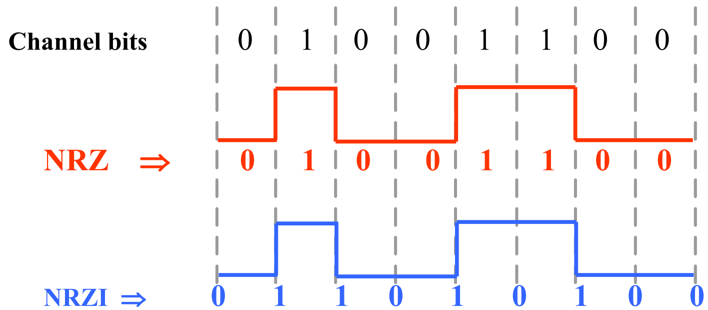


In LMR read-back:
- Peak signal at transitions
- But Zero signal between transition

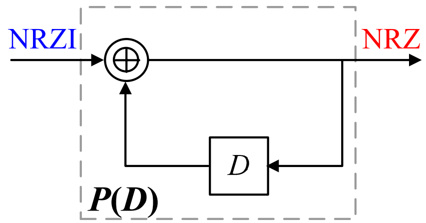
In PMR read-back:
- Zero signal at transitions
- But Non-Zero between transition

Data Format

- Two data formats for generating the write current waveform:
  - ❑ Non-return-to-zero-interleaved (**NRZI**): "1" ⇒ transition
    "0" ⇒ no transition
  - ❑ Non-return-to-zero (**NRZ**): The amplitude level of the waveform directly reflects the given binary bit.



NRZI & NRZ Relationship



Precoder: $P(D) = \dfrac{1}{1 \oplus D}$

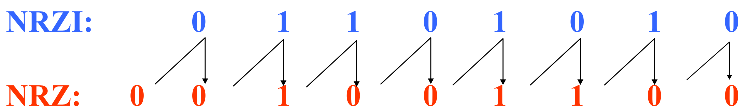
NRZI = $(1 \oplus D) \cdot$ NRZ

$\oplus$ = a modulo-2 addition

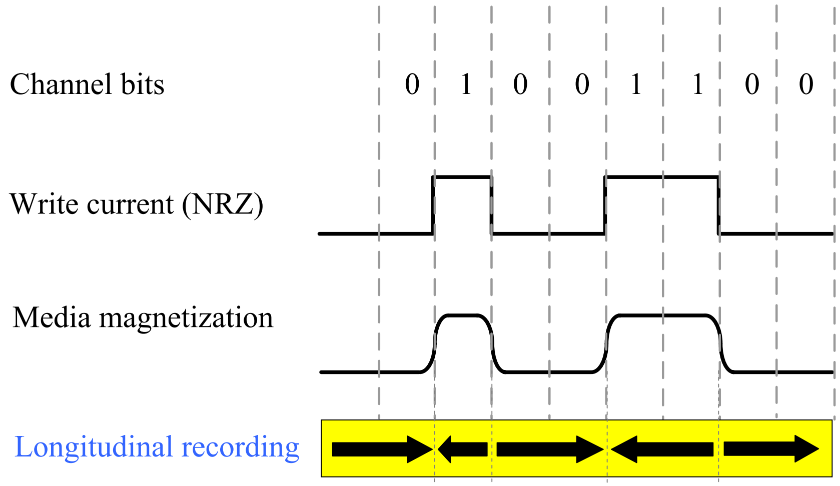
$0 \oplus 0 = 0$ $\quad$ $1 \oplus 1 = 0$

$1 \oplus 0 = 1$ $\quad$ $0 \oplus 1 = 1$

Example:



Magnetization Pattern



Summary: NRZI & NRZ

- In the NRZ scheme:
  - "1" means one direction of medium magnetization,
  - "0" means opposite direction of medium magnetization.
- In the NRZI scheme:
  - "1" means transition
  - "0" means no transition

Precoder

- A portion of the equalization task can be shifted to the transmitter by precoding the data symbols at the transmitter.
- The data symbols are precoded and then are written onto the medium.
- This has the effect of increasing a minimum Euclidean distance, d_{min}, of a data sequence, resulting in lower bit-error rate performance.

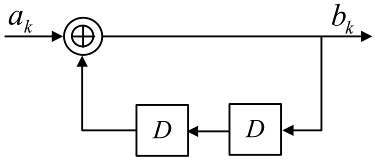
- **Advantage:**
  - With knowledge of the channel characteristics, the precoder can be chosen to partly
    - **Undo** the channel distortion
    - **Reducing** the equalization burden at the receiver
  - Precoder help **prevent** catastrophic error propagation.
  - A **widely used** precoder in commercial HDD is

$$P(D) = \frac{1}{1 \oplus D^2}$$

Example

$$P(D)=\frac{1}{1\oplus D^2} \Rightarrow$$

Transfer function of a precoder



Block diagram

$$B(D)=\frac{1}{(1\oplus D^2)}A(D)$$

$$b_k = a_k \oplus b_{k-2}$$

Output equation

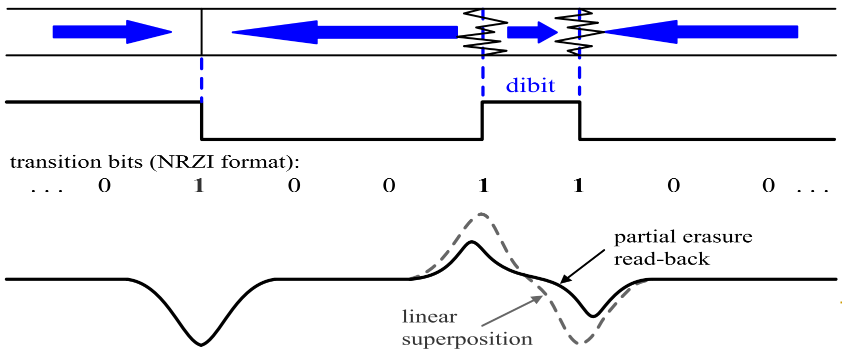
a_k			0	1	1	0	1	0	1	0	0	1	1
b_k	0	0	0	1	1	1	0	1	1	1	1	0	0

Nonlinearity in Write Process

- Refer to a phenomenon that causes linear superposition to be invalid.
  - The readback signal can be represented by the linear combination of the transition pulses according to the pulse amplitude modulation (PAM) technique.
- Included:
  - Partial erasure
  - Hard transition shift
  - Overwrite
  - Nonlinear transition shift

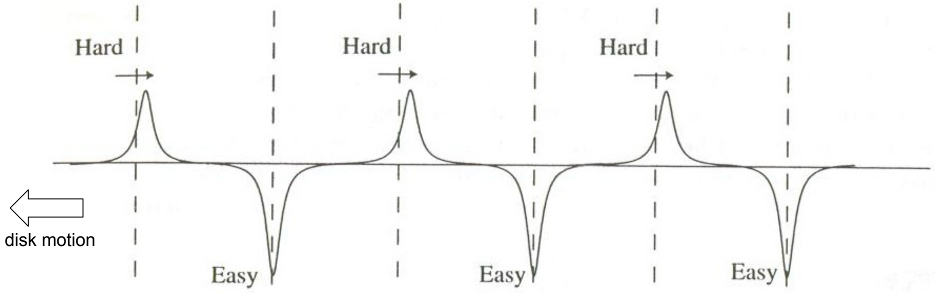
Nonlinearity – Partial Erasure

- Also known as nonlinear amplitude loss
- Percolation occurs at high densities
  - Regions across the track become partially erased and the amplitude loss results from an effective trackwidth narrowing.



Nonlinearity – Hard Transition Shift

- In magnetic recording, the erasure of old information is accomplished by directly writing new data pattern over old data pattern.
- An easy transition is written if the head field is in the direction of the incoming magnetization
- A hard transition $\Rightarrow$ when the head field is opposing the incoming magnetization
  - More **difficult** to write because it requires more head field to saturate the magnetization under the head gap
  - A hard transition always gets **shifted later** than desired in the absence of other nonlinear effects



Hard and easy transitions written over DC-erased medium

- Since the incoming magnetization direction is unknown during the write process, hard transition shift cannot be removed by write precompensation.

Nonlinearity – Overwrite

- The erasure of old information is accomplished by directly writing new data pattern over old data pattern.
- The write field must be sufficient to reduce any residual original information to levels low enough not to cause errors while reading the new data.

- How to compute an overwrite ratio:
  - First, write a square-wave pattern at frequency f_1
  - Then, overwrite with a square-wave pattern at frequency f_2 (mostly often $f_2 = 2f_1$)
  - The overwrite ratio (f_2/f_1) is the level of the residual f_1 signal $V_{f2}(f_1)$ divided by the original f_1 signal level $V_{f1}(f_1)$
  - Define

$$OW = 20*\log(V_{f2}/V_{f1}) \text{ in dB}$$

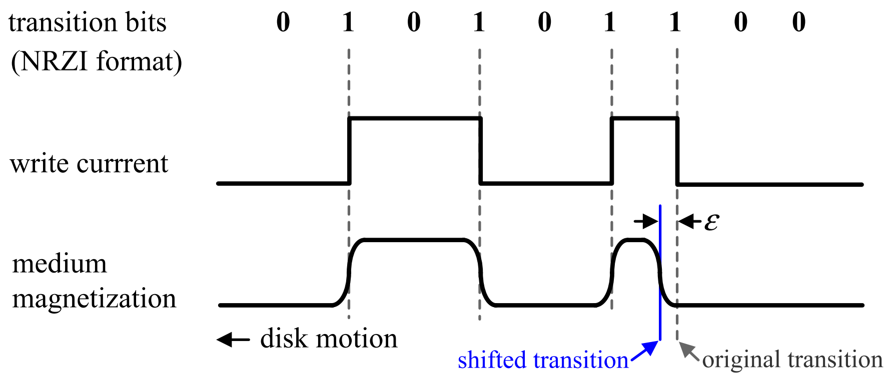
- For typical magnetic recording system, OW < -30 dB

Nonlinearity – Nonlinear Transition Shift (NLTS)

- Occur due to the demagnetizing field from previous written transitions.
- Since opposite charges attract each other, the two magnetic transitions (dibit) must be shifted closer.
- NLTS always causes the transition to be written earlier than desired.
  - Data dependent
  - Degrade the SNR of the channel
  - Serious problem at high recording densities

- Use write precompensation to combat with NLTS
  - Intentionally delay switching the write current so that the resulting transition center is in the desired location
- PRML detection is capable of handling large amounts of linear ISI, but it is based on the assumption that the recording channel is linear.
  - Even moderate amounts of NLTS can cause high error rates in PRML system
- NLTS cannot be eliminated but can be reduced to achieve better linearity of the recording channel by using write precompensation.

NLTS in Longitudinal Recording



Write Precompensation

- Used to combat with NLTS.
- Adjust the transition delay of the write current by taking into account of neighboring write bits.
- Techniques to determine amount of precompensation and bit patterns:
  - Extracted pulse shape
  - Frequency-domain technique
- High recording densities require a high-order write precompensation because the impact of older transitions becomes significant.