# Amit Error Correction Scheme for Constrained Inter-Cell Interference in Flash Memory



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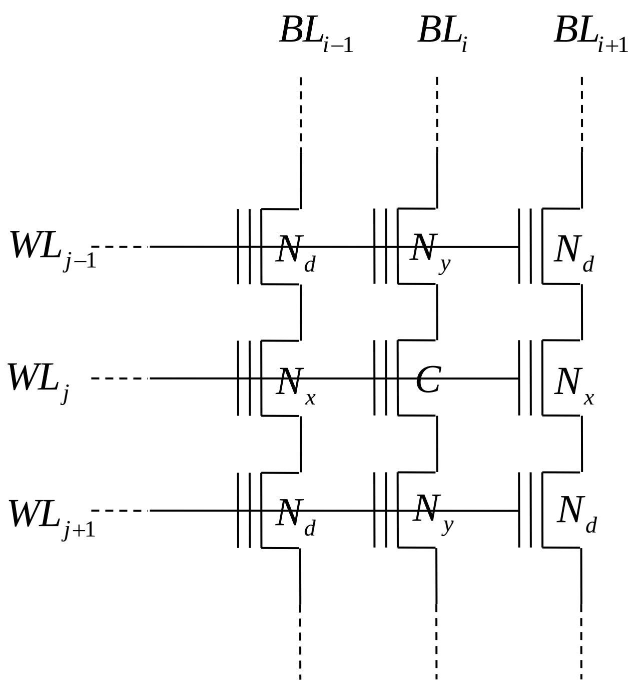
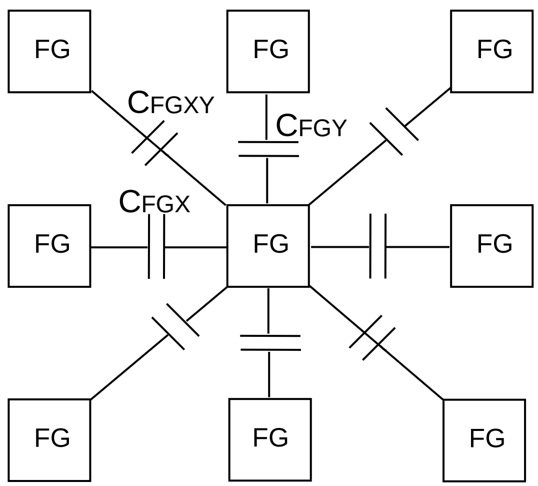
# Agenda

- Background: Inter-Cell Coupling $\rightarrow$ Inter-Cell Interference
- Mitigating Inter-Cell Interference via Constrained Coding
- Error Correction Scheme for Inter-Cell Interference
- An Example
- Conclusions

# Inter-Cell Coupling

- FG-FG inter-cell coupling causes the charge in one cell to affect a neighboring cell's threshold voltage, i.e., "interference".

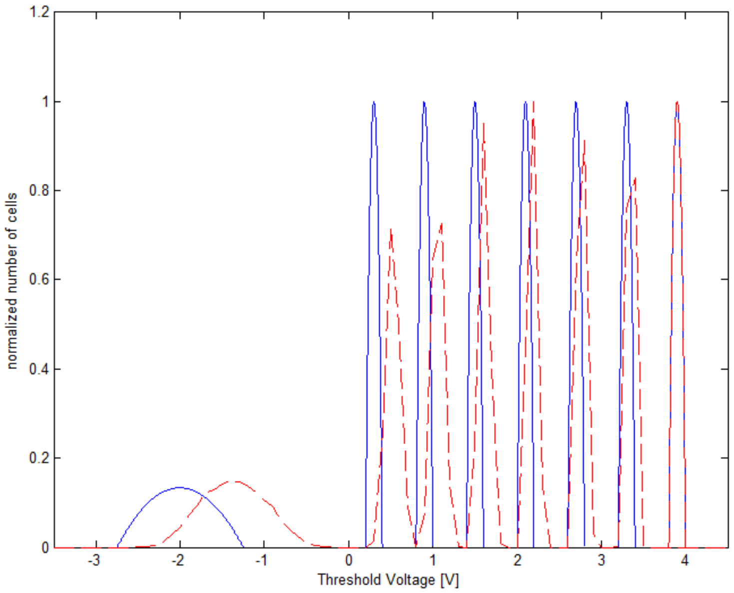



Coupling $\rightarrow$ Inter-Cell Interference (ICI)

# $V_t$ Distribution Widening

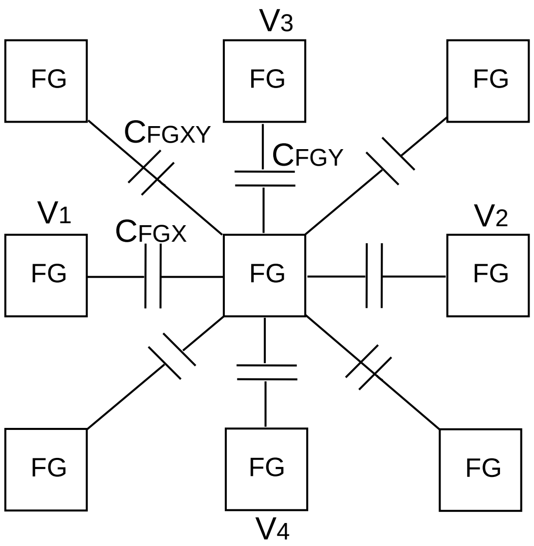
- This coupling shifts the threshold voltages by a degree that depends on the level of coupling between adjacent cells and on the amount of charge in the surrounding cells



# Coupling – a Model

- Neglecting $C_{FGXY}$, and assuming $Q_{FG}$=0 the floating gate voltage due to ICC is:

$$V_{FG}=\frac{C_{ONO}V_{CG}+C_{FGX}\left(V_1+V_2\right)+C_{FGY}\left(V_3+V_4\right)+V_{FGCG}\left(V_5+V_6\right)}{C_{TUN}+C_{ONO}+2C_{FGX}+2C_{FGY}+2C_{FGCG}}$$



# Coupling with Program & Verify

- Program & Verify:
  - Charge is added to a cell in small increments
  - $V_t$ is checked after each addition
  - Programming ceases upon reaching the desired $V_t$
- Therefore, $V_t$ of any given cell is affected only by charge changes (additions) made to its neighbors **after** its own charging has been completed.

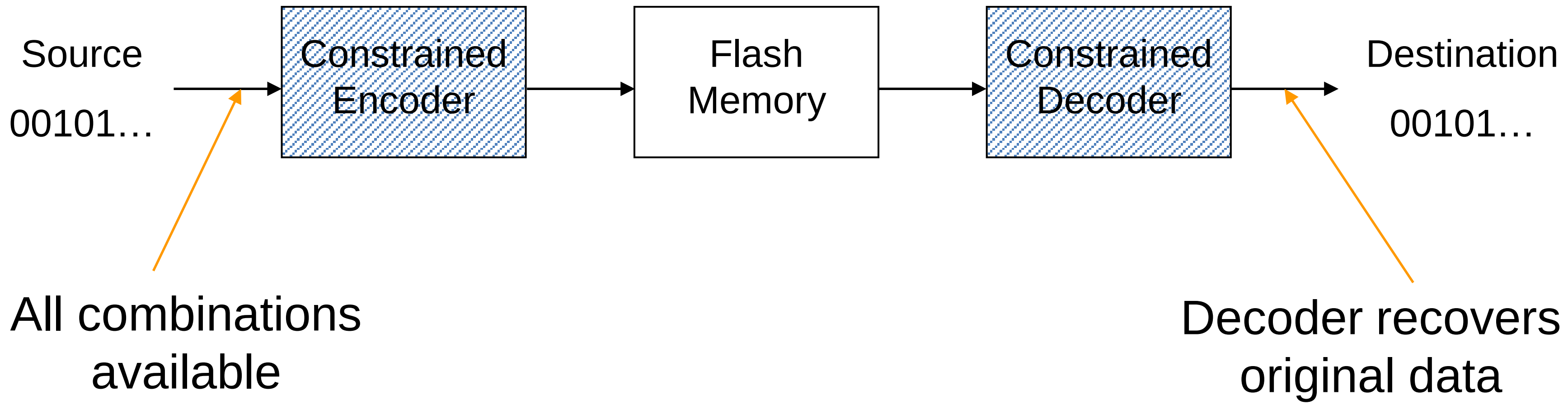
The degree of inter-cell interference depends on the programming scheme!

# Existing Interference-Mitigation Schemes

- Proportional programming [Trinh *et-al.*]
  - Concurrent, incremental programming of all cells, tailored for near-simultaneous completion.
  - Pros: insensitive to coupling parameters, simple read.
  - Cons: complicated, possibly slow programming, can't account for next line.
- Intelligent read decoding [Li *et-al.*]
  - Based on programming order, decode w. successive interference cancellation.
  - Pros: simple programming.
  - Cons: Must know coupling params, no variation allowed, complex, slow read.
- Constrained Coding [A. Berman and Y. Birk]
  - Forbid certain adjacent-cell level combinations.
  - Pros: fairly simply encoding and decoding.
  - Cons: code rate <1 → some loss of capacity relative to ideal with narrow distributions.

# Mitigating Inter-Cell Interference via Coding

- Approach: forbid those adjacent-cell charge combinations that result in the greatest threshold voltage shifts
  $\rightarrow$ narrower distributions $\rightarrow$ additional charge levels
  $\rightarrow$ higher capacity,
  But code rate < 1 $\rightarrow$ lower "per level" capacity
- Capacity is maximized via optimal trade-off.



# Constrained Coding Framework

- Given the programming order, we express the change to the cell's $V_t$ as a function of the charge levels of its neighboring cells. We refer this function as ICI severity function, D(c).
- Program data is constrained according to a pre-defined constraint T, such that for every cell c, D(c)≤T.

$$\Delta V_t(c) \propto D(c)$$

$$D:\{\text{cell and its 8 neighbors levels}\} \rightarrow \{0,1,\ldots,8\cdot L\}$$

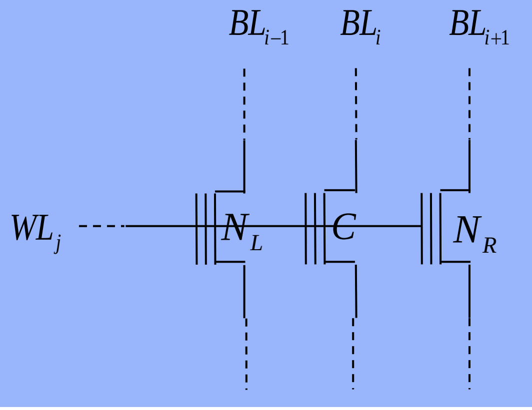
L – highest charge level of a single cell

$$D(c) \leq T$$

# Coding for Breadth-First Programming Order

- 1-D: a single row of cells is considered
- Programming (charge & verify)
  - All >0 cells programmed to level 1
  - All >1 cells programmed to level 2
  - …

$N_L$, C, $N_R$: respective target levels



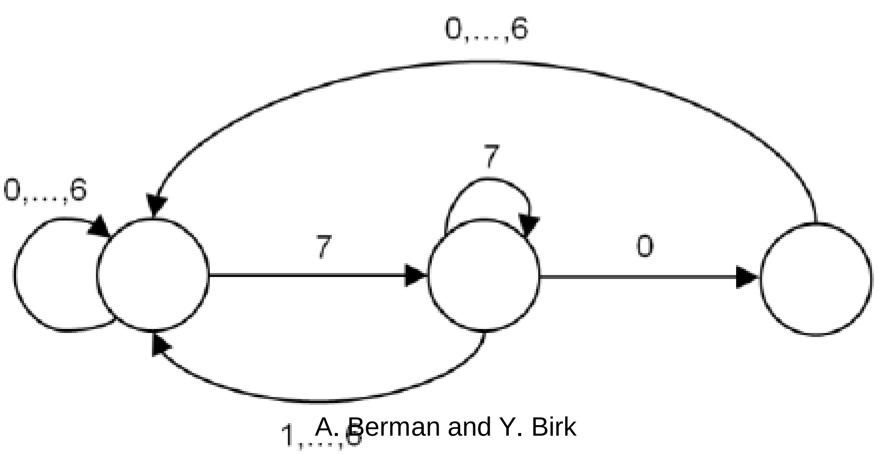

- Sequence eligibility criterion:

$$D(c) = \max\{N_L - c, 0\} + \max\{N_R - c, 0\} \le T$$

- T represents a trade-off:
  - Large T: efficient coding, but wider distributions and fewer levels
  - Small T: vice versa

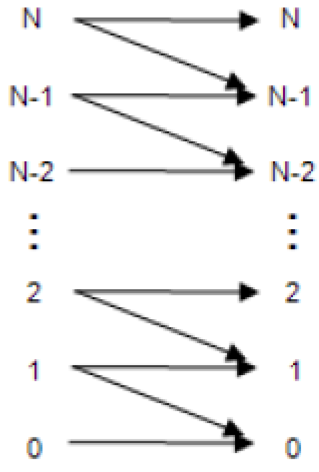
# Example of Coding for Breadth-First

- 1-D (2 neighbors), 8-levels (i.e., ideally 3 bits) per cell and T=13. Traversing the graph edges will generate legal codewords, i.e., $D(c) \leq 13$.
- In this language, the legal words do not contain the sequence 7-0-7. The capacity is 2.99 (R=2.99/3=0.99).
- Encoder and decoder at rate p/q can be obtained by raising the graph to the power q, removing redundant edges, and using the state-splitting algorithm as necessary.



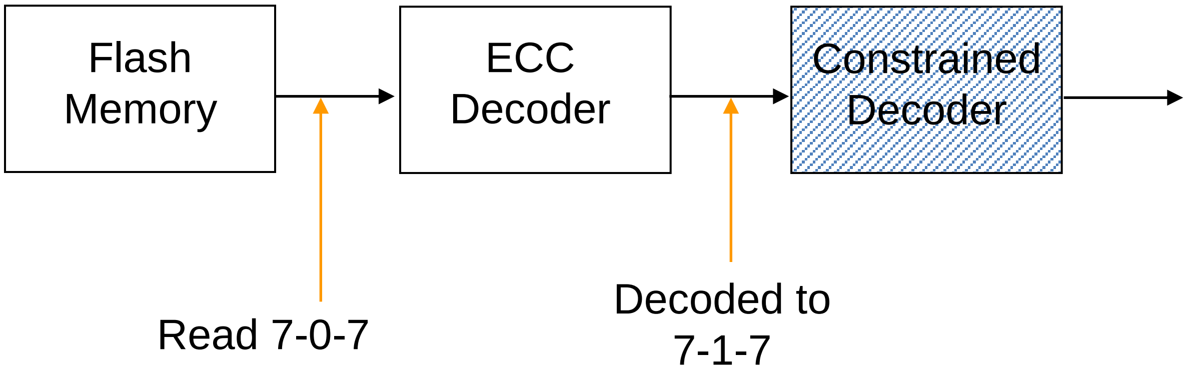
# Error Handling in Constrained Inter-Cell Interference

- Our focus here is on decoding algorithms for the case that an illegal codeword was read due to errors induced by retention problems.
- Retention errors are due to charge leakage from the floating gate (leakage determines the memory retention). They are uni-directional towards the erased level (level 0).



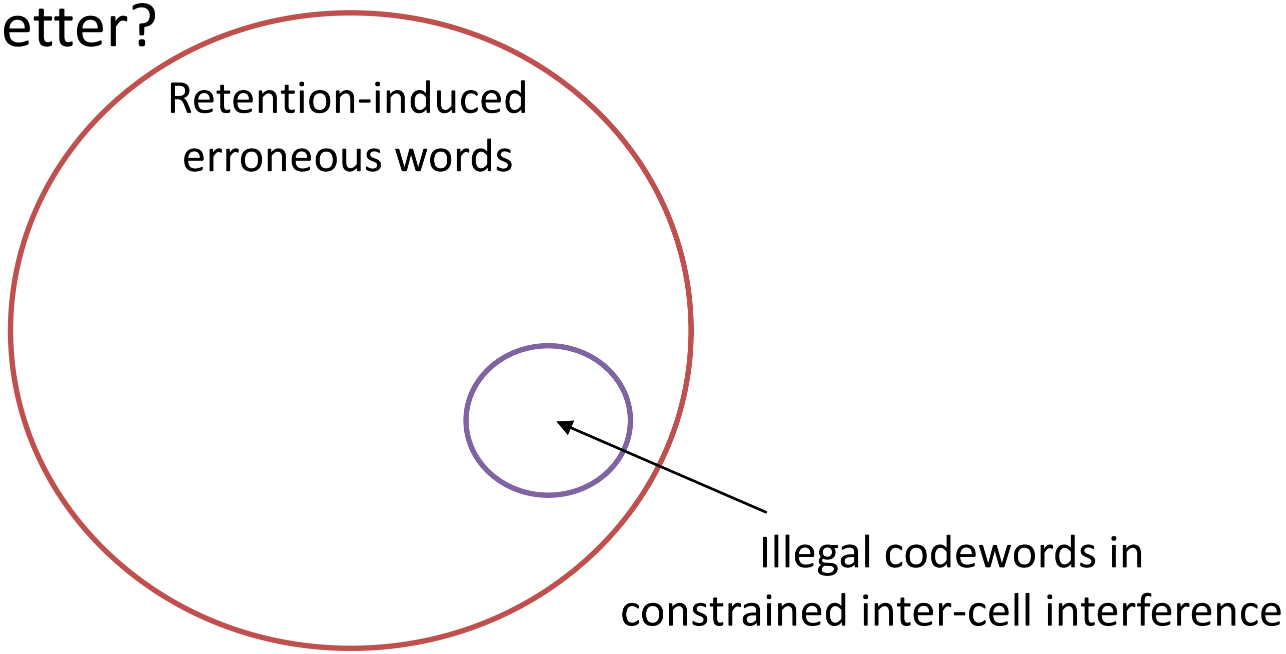
# Error Handling in Constrained Inter-Cell Interference

- Illegal words resulting from a retention-related error correspond to situations in which D(c)>T for at least one cell.
- Assuming one such error, detected by noticing that D(c)>T, it is most likely that the error is a result of the charge leakage from the cell c itself, as charge leakage from a neighbor cell would usually reduce D(c), resulting in a legal codeword.
  **Remark:** this also works for multiple such errors in distant cells.
- Error Correction: decode c+1 instead of c where D(c)>T.



# Error Handling in Constrained Inter-Cell Interference

- Constrained inter-cell interference coding can be used to detect and correct retention errors.
- However, many retention errors do not cause illegal codeword read.
- Can we do better?



"If the facts don't fit the theory – change the facts…"

*Albert Einstein*

# Channel Tuning

- For simplicity, we examine the case of codewords of length three. We observe that illegal words contain the sequences $L_1$-0-$L_2$, $L_1$-1-$L_2$, $L_1$-3-$L_2$, …, $L_1$-N-$L_2$, according to constraint T.
- The first sequence has the largest number of illegal codewords, second largest number is the second sequence, and so on. Therefore, changing the Flash memory channel such that:

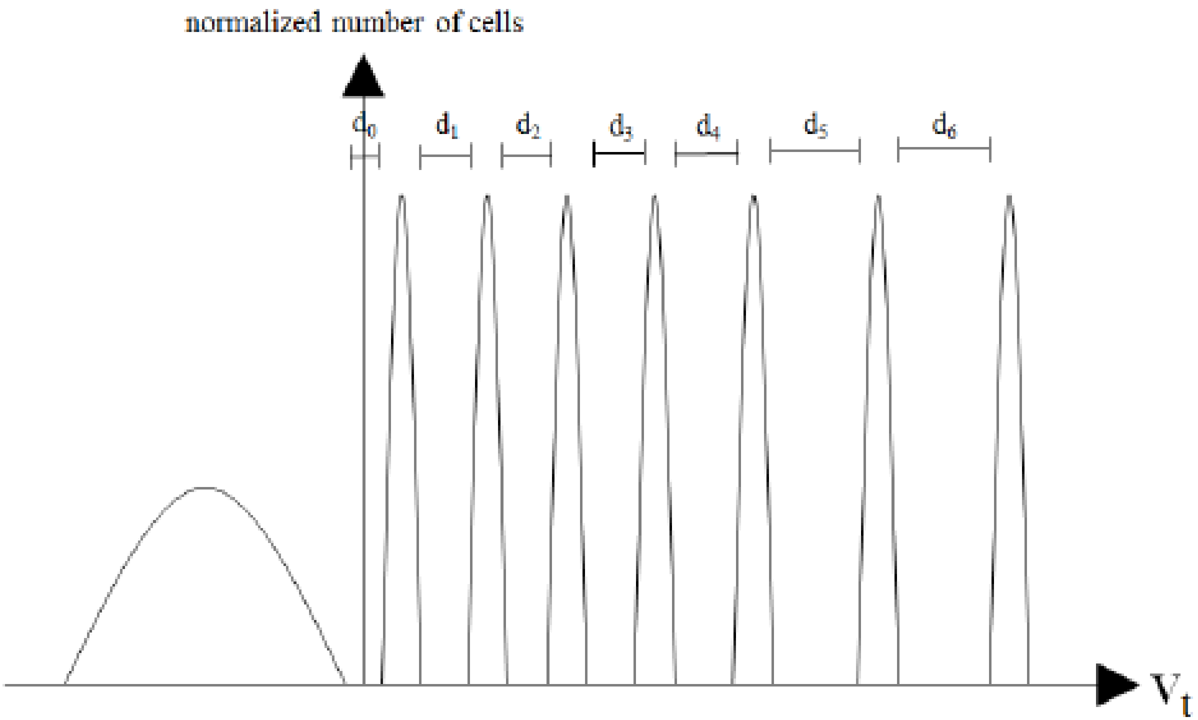
$$P_{N\to N-1} < P_{N-1\to N-2} < P_{N-2\to N-3} < \ldots < P_{2\to 1} < P_{1\to 0}$$

would increase the probability that a retention error will cause an (correctable) illegal codeword read.


A. Berman and Y. Birk

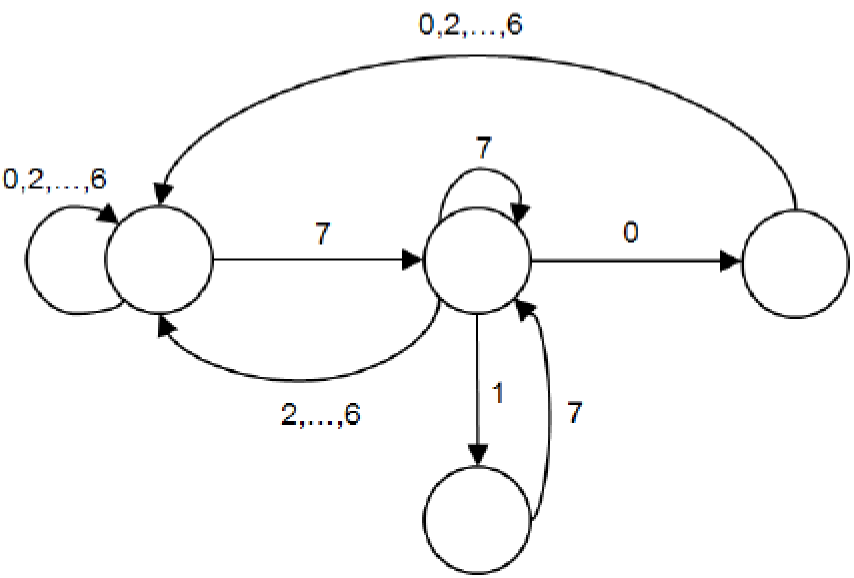
# Gap Allocation

- This modification can be made by unequal allocation of read margins between adjacent levels, so that lower levels have smaller margins than higher ones.



# Adding Constraints

- Legal codewords are constrained to be offsets of illegal words.
- For example, for L=7, T=13, the language is constrained such that the sequence 7-1-7 is the only sequence in the form of $L_1$-1-$L_2$. Charge leakage from level 1 to level 0 would necessary lead to 7-0-7 (illegal).
- This reduces the language capacity from 0.99 to 0.93.



# Iterative Decoding for Multiple Errors

- In the event of multiple errors during read, i.e., multiple cells in which D(c)>T, the decoding scheme first focuses on the cell with the most higher-level neighbors and corrects it.
- The process is then repeated until a legal codeword is reached.
- If the errors are sufficiently far apart (distance of 2 cells at least) in this example, they are simply independent can are treated as single errors.

  (In the example, in "codeword" we refer to a "sliding window" of three cells.)

# Conclusions

- Constrained inter-cell interference coding can be used to detect and correct retention errors.
  - The errors of low program levels can be detected at read due to violation of constrained coding restrictions.
- As the constraint *T* tightened, the probability to capture and correct retention error increases.
  - However, lower T also reduces the language capacity.
- We can increase the probability to capture and correct retention error by using two methods:
  - Change the flash read channel by reducing the error rates of higher levels at the cost of increasing the error rates of the lower ones.
  - Add constraints as necessary.