Amit Mitigating Inter-Cell Coupling Effects in MLC NAND Flash via Constrained Coding

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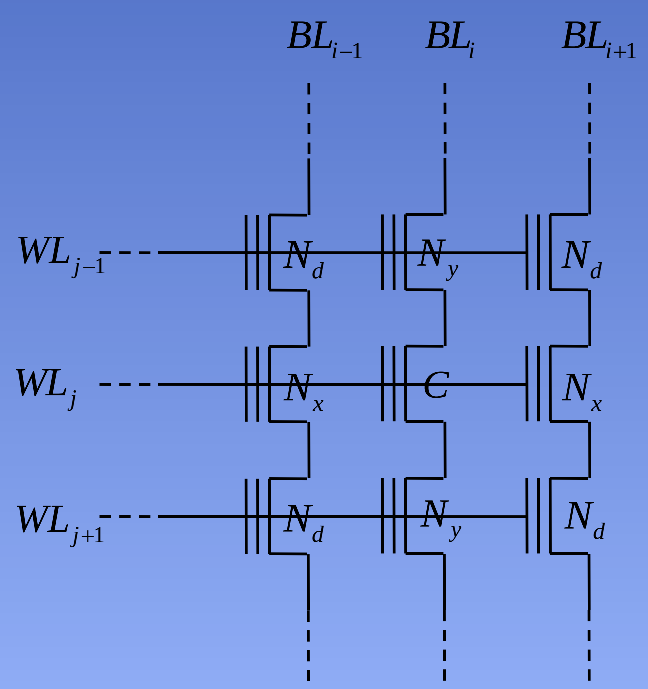
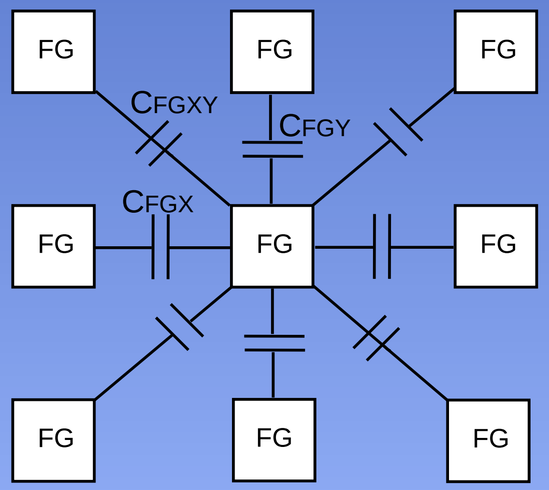
Agenda

- Problem Definition: Inter-Cell Coupling
- Related Work
- Novel Solution: Constrained Coding System
- 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.





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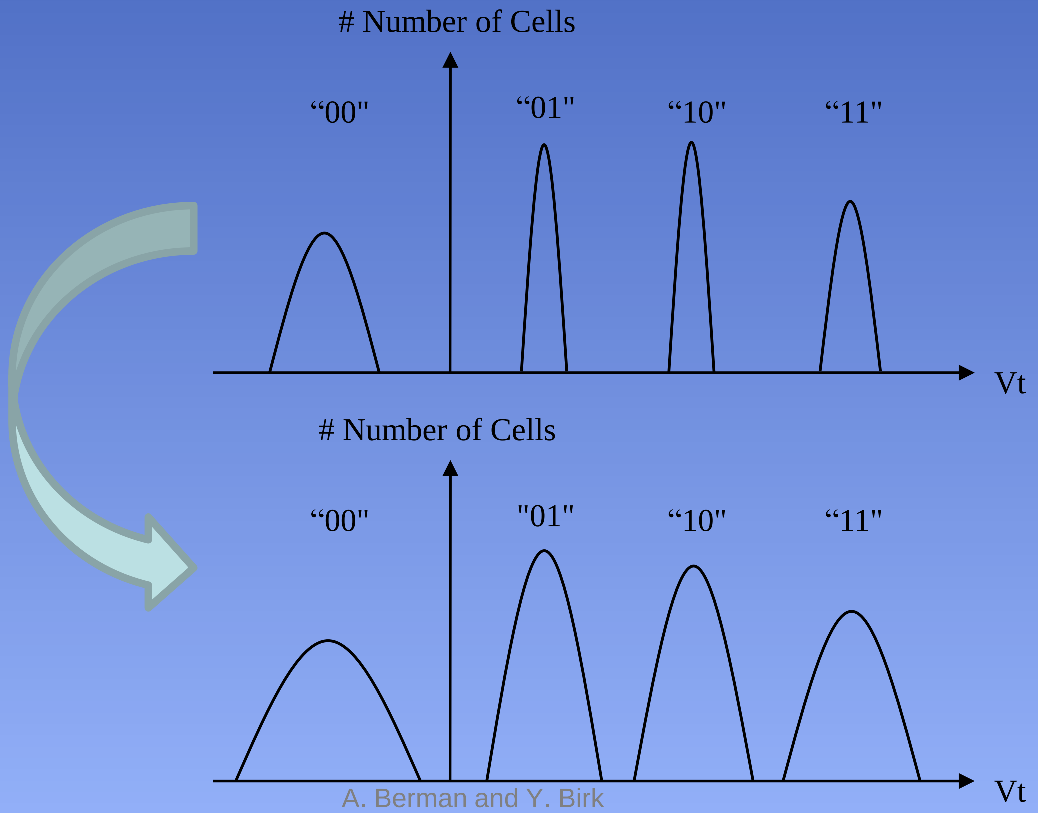
V_t Distribution Widening

- When considering each cell in isolation, the observed phenomenon is a “widening” of the threshold voltage distributions.

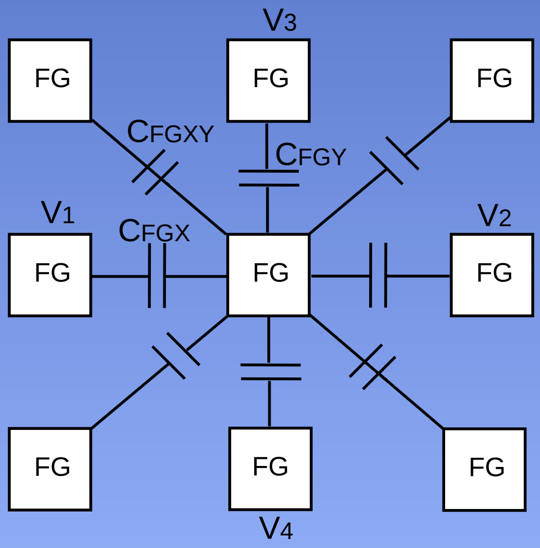
Distribution Widening due to Inter-Cell Coupling



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 charge changes made to its neighbors **after** its own charging has been completed.

The effect of inter-cell coupling depends on the programming scheme

Existing Coupling-Mitigation Schemes

- Proportional programming
  [Fastow et al, USP 6,996,004]
- Intelligent read decoding
  [Li et al, USP 7,301,839]

Proportional Programming [Fastow et al]

- Concurrent, incremental programming of all cells, tailored for near-simultaneous completion.
- Pros:
  - Desired V_t for all cells (altered only by the last pulse of each neighbor);
  - Narrow distributions.
  - Insensitive to coupling parameters.
  - Simple read
- Shortcomings:
  - Complicated, possibly slow programming
  - Can't account for next line if programmed later
  - Can't fully compensate when "pull" is greater than desired level (would require negative "bias")

Intelligent Read Decoding [Li et al]

- Simple, conventional programming
- Based on coupling equations, parameters and on programming scheme, decode smartly to offset coupling effects.
- Pros:
  - Simple programming
  - Overlapping distributions are separated by decoding
- Cons:
  - Must know coupling parameters; no variation allowed.
  - Requires accurate reading of V_t
  - Complex, slow read

Our Approach: Constrained Coding

- Forbid certain adjacent-cell level combinations:
  - Criterion depends on programming order
  - Threshold is a design trade-off
- Programming: use only permissible combinations (legal code words)
- Decoding: use inverse mapping

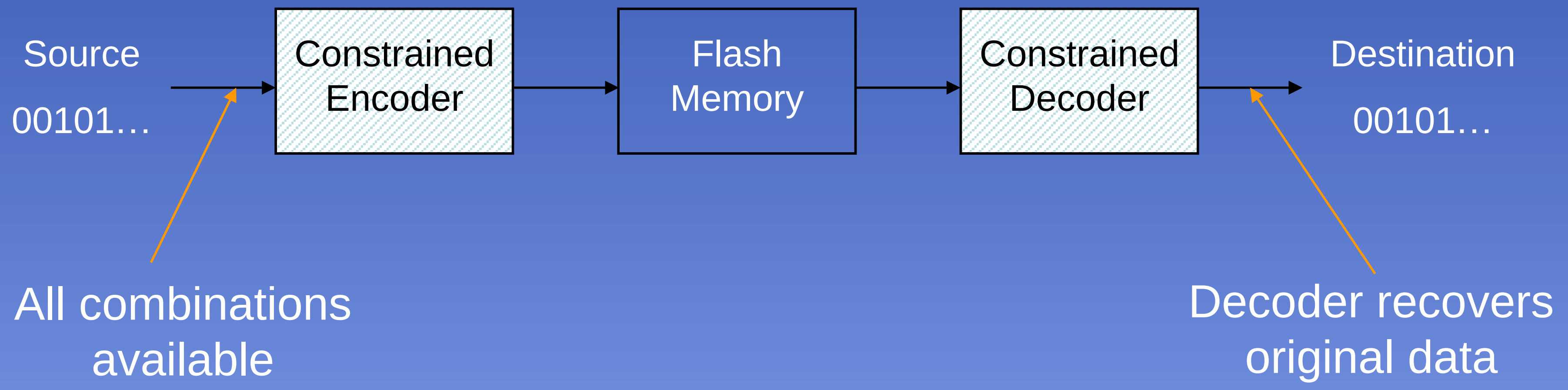
Constrained Coding – Main Features

- Pros:
  - Limits the effect of inter-cell coupling → narrow distributions → many levels
  - Fairly simply encoding and decoding
  - Only need to know an upper bound on coupling coefficients
- Cons:
  - Code rate <1 → some loss of capacity relative to ideal with narrow distributions.

Constrained Coding - Remarks

- Can easily be combined with ECC
- Complementary to the previous schemes and can be combined with them:
  - Semi-accurate programming + minimal restrictions
  - Some restrictions with simpler intelligent read decoding

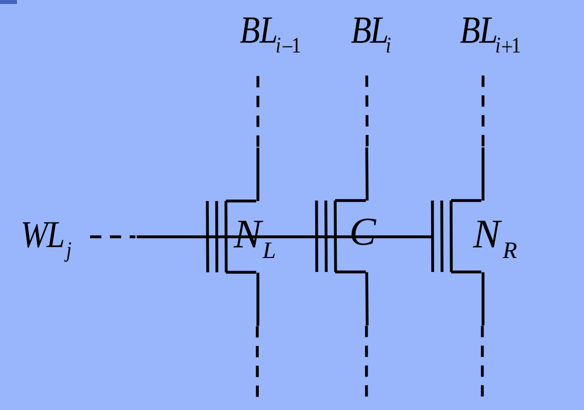
Constrained Coding System



Example: 1-D, "Breadth 1st" Coding

- 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
  - …
- Sequence eligibility criterion:

N_L, C, N_R: respective target levels



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

- T represents a trade-off:
  - Large T: efficient coding, but wider distributions and fewer levels
  - Small T: opposite pros and cons

Required Redundancy (T=5,2 bpc)

$$Redu(S) = 1 - \frac{\lim_{l \to \infty} \frac{\log_2 N(l;S)}{l}}{\log_2 n} = 0.0483$$

- Notation:
  - N(l;S) - number of legal (permissible) l-symbol code words
  - n - number of program levels in a cell
  - S - language of all legal code words
- The required redundancy is (at least) 4.83%

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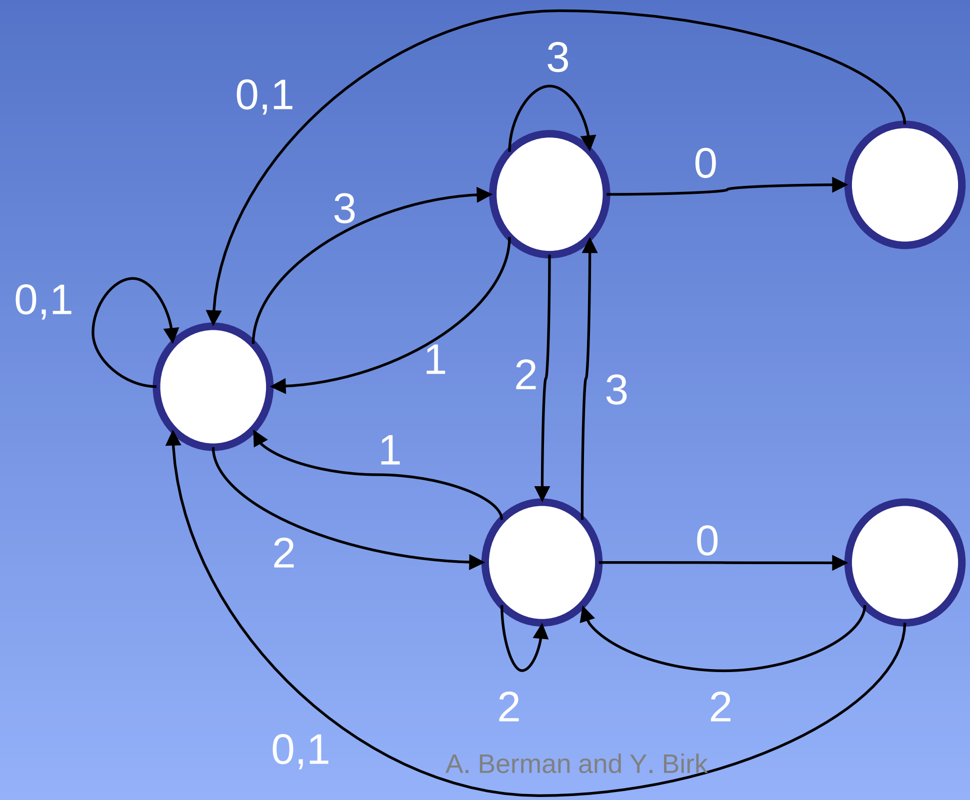
Capacity Implication (T=5)

- Assumption: constrained coding permitted an increase in the number of levels from 4 to 5.
- Baseline: $1.0 \cdot \log_2(4) = 2$
- Constrained coding: $0.95 \cdot \log_2(5) = 2.2 > 2$
- A 10% increase in capacity

Design of encoder/decoder block

- We build graph of the constraint language
  - With 4 levels per cell, this example excludes the combinations (sequences) 3-0-3, 3-0-2 and 2-0-3.



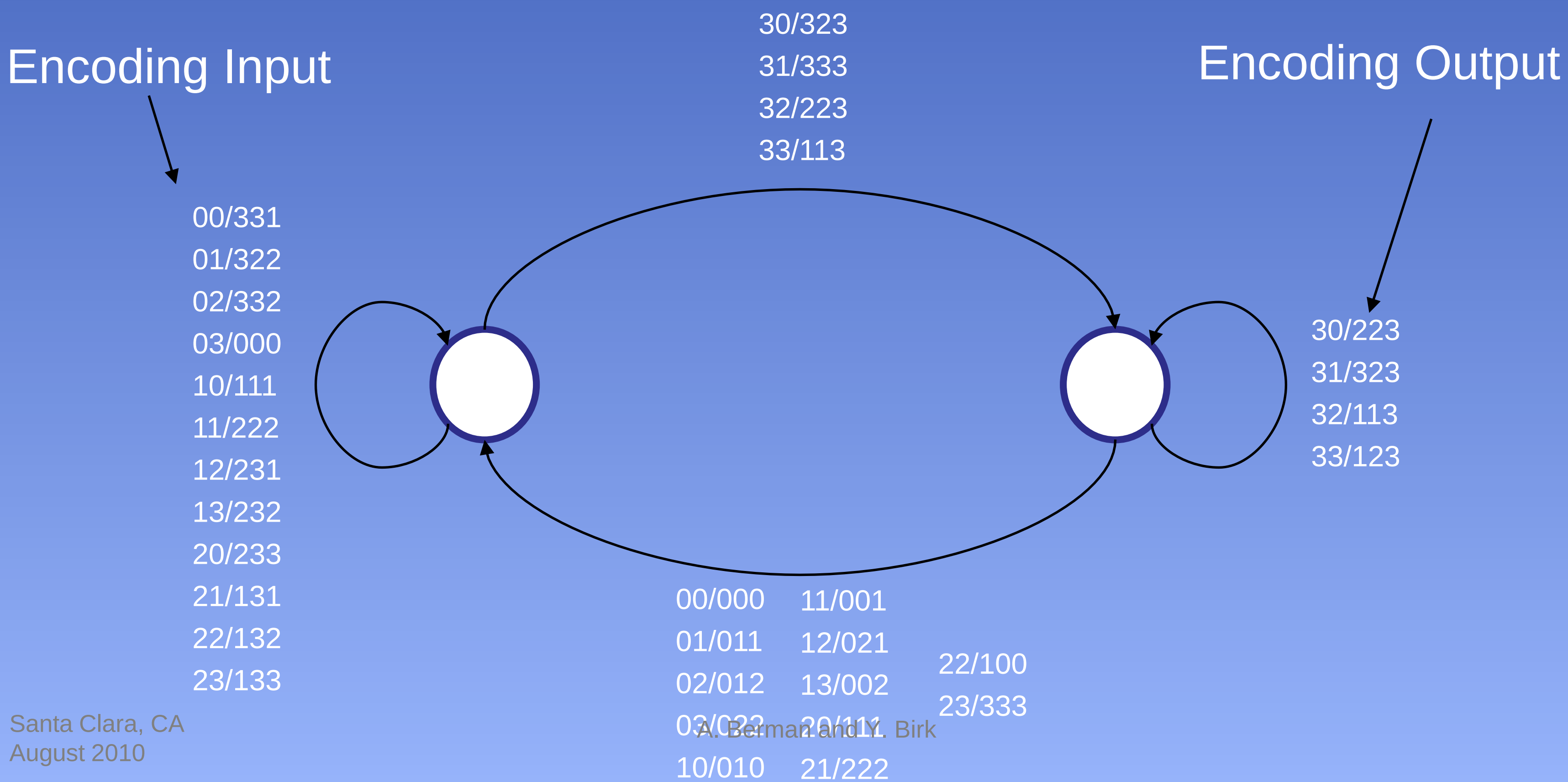
Design of encoder/decoder block (cont.)

- For demonstration, consider code rate = 2/3
- For this, we can build a lookup table and use it.

Input	Output
00	031
01	131
02	331
03	321
10	301
11	300
12	310
13	311
20	021
21	121
22	210
23	211
30	221
31	231
32	200
33	201

Design of encoder-decoder block (cont.)

- The design can also be implemented with state machine. E.g., to exclude 3-0-3:



Conclusions

- Constrained coding can be used to chop off the tail of V_t distributions with only a minor reduction in coding rate
- Can be used beneficially to increase capacity or to increase reliability
- Can replace proportional programming and intelligent decoding or complement them

- Detailed papers in preparation
- A patent application has been filed by Technion

End

Questions?

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