

Digital Integrated Circuits (83-313)

Lecture 8: SRAM

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Lecture Content

First Look at Memory



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The 6T SRAM Bitcell



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6T SRAM Operation



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6T SRAM Layout



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SRAM Stability

"Static Noise Margin"



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SNM Calculation



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First Look at Memory



Emerging Nanoscaled
Integrated Circuits and Systems Labs

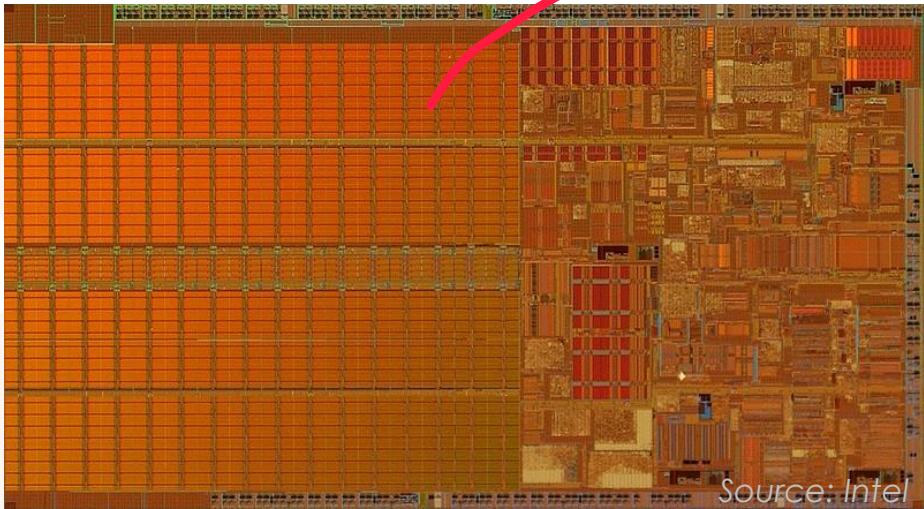
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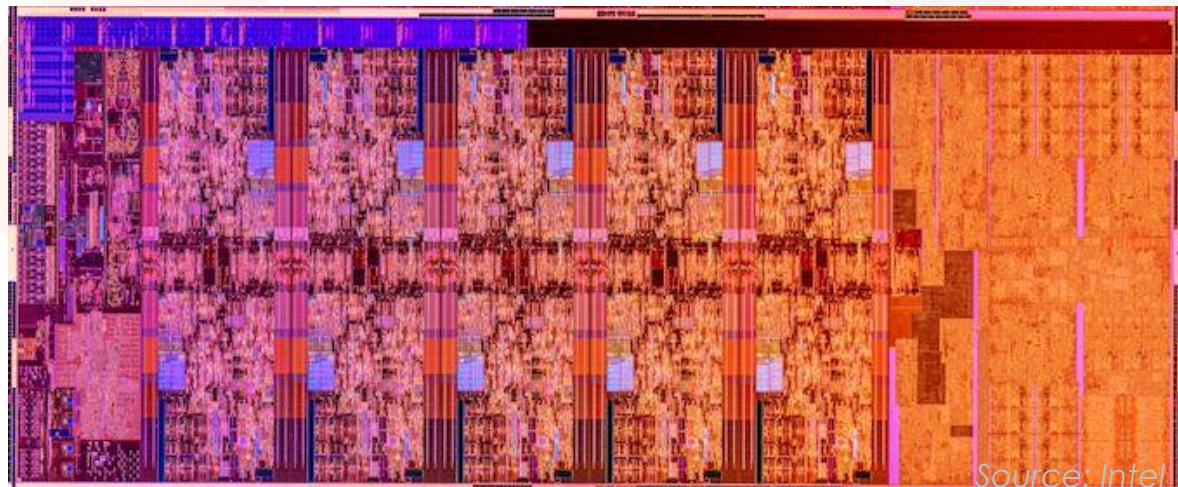


Why Memory?

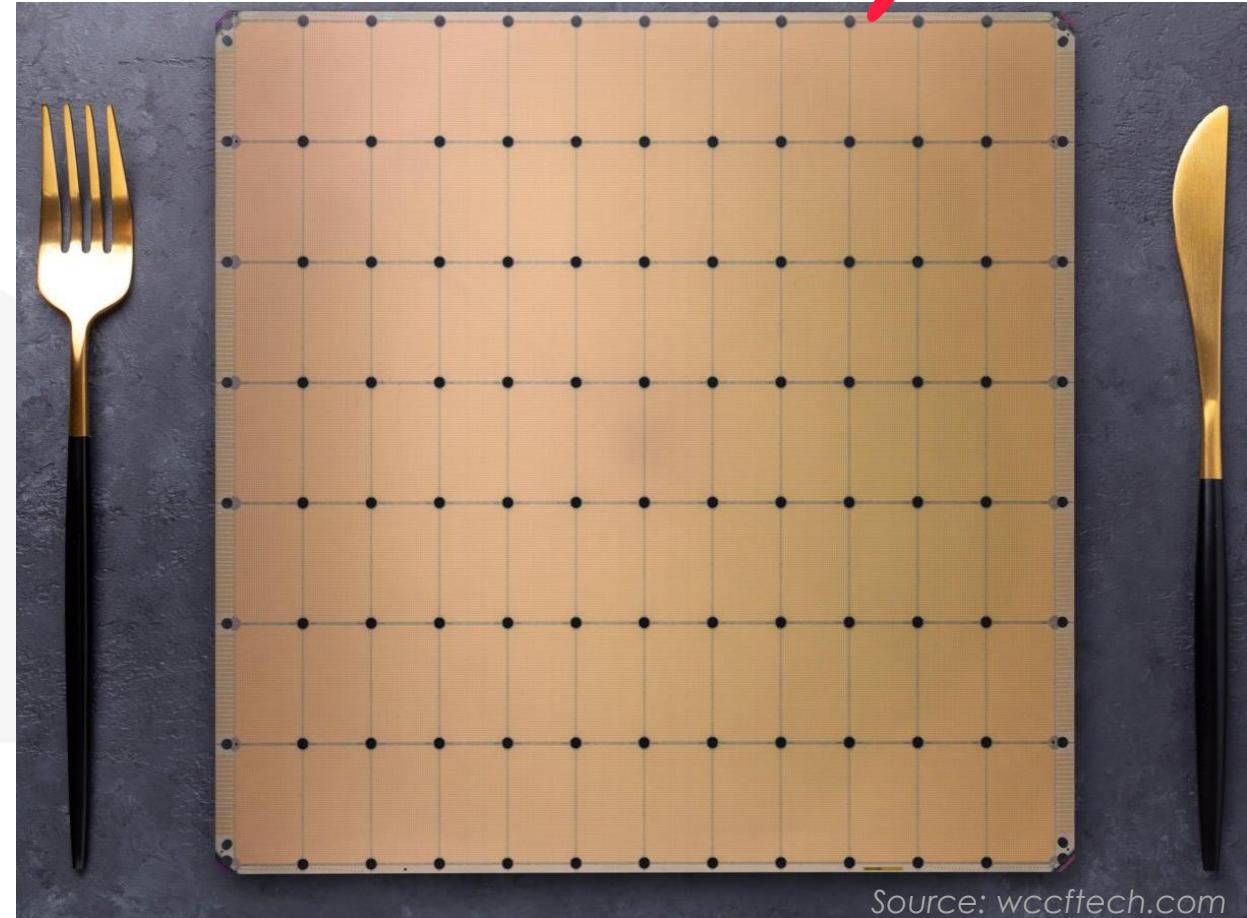
Memory is huge part of chip, takes lots of power, extra area are used for memory.



Intel Pentium-M (2001) – 2MB L3 Cache

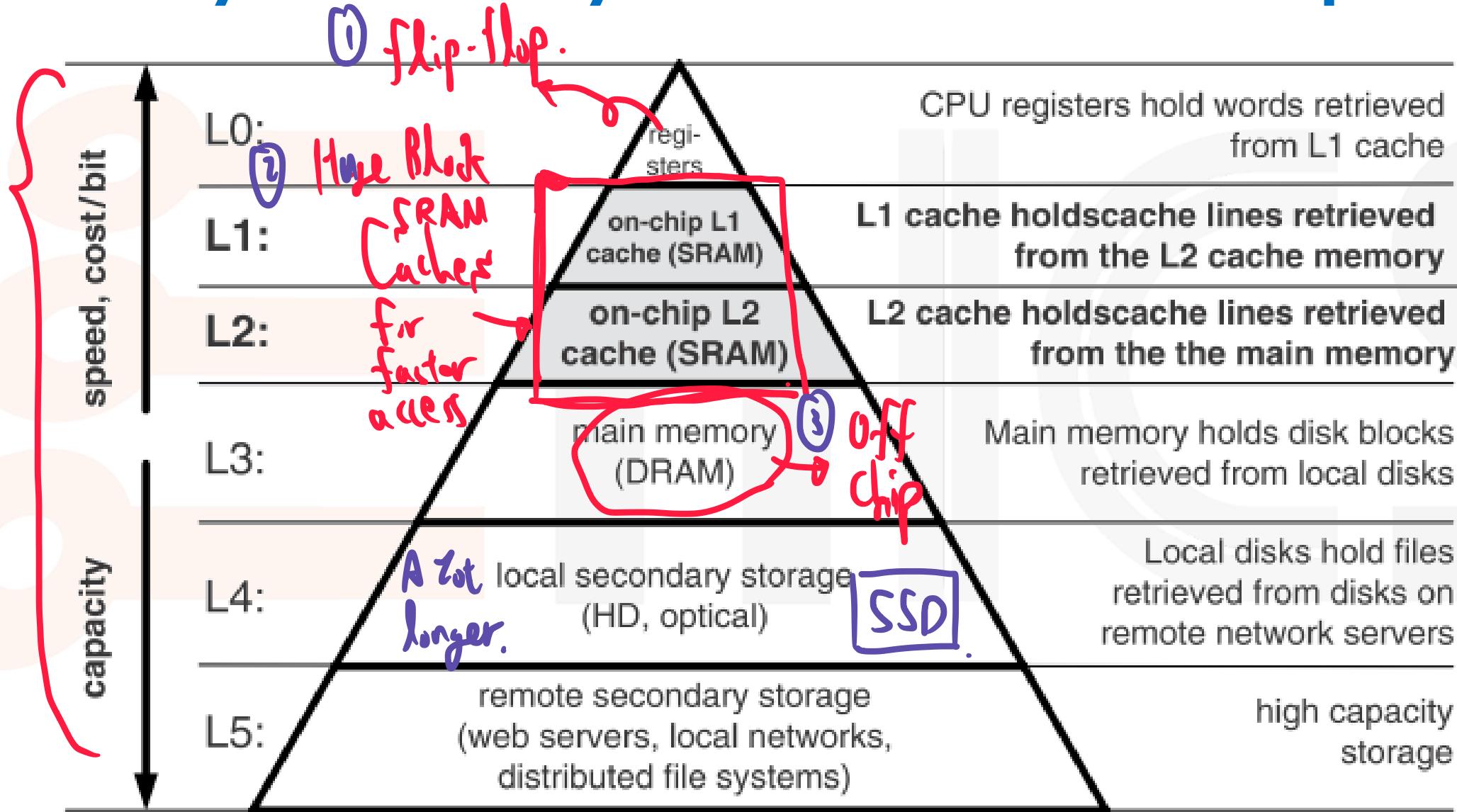


Intel 10th Gen "Comet Lake" (2020) – 20MB L3 Cache



Cerebras Wafer Scale Engine 2 (2021) – 16GB On-Chip Memory

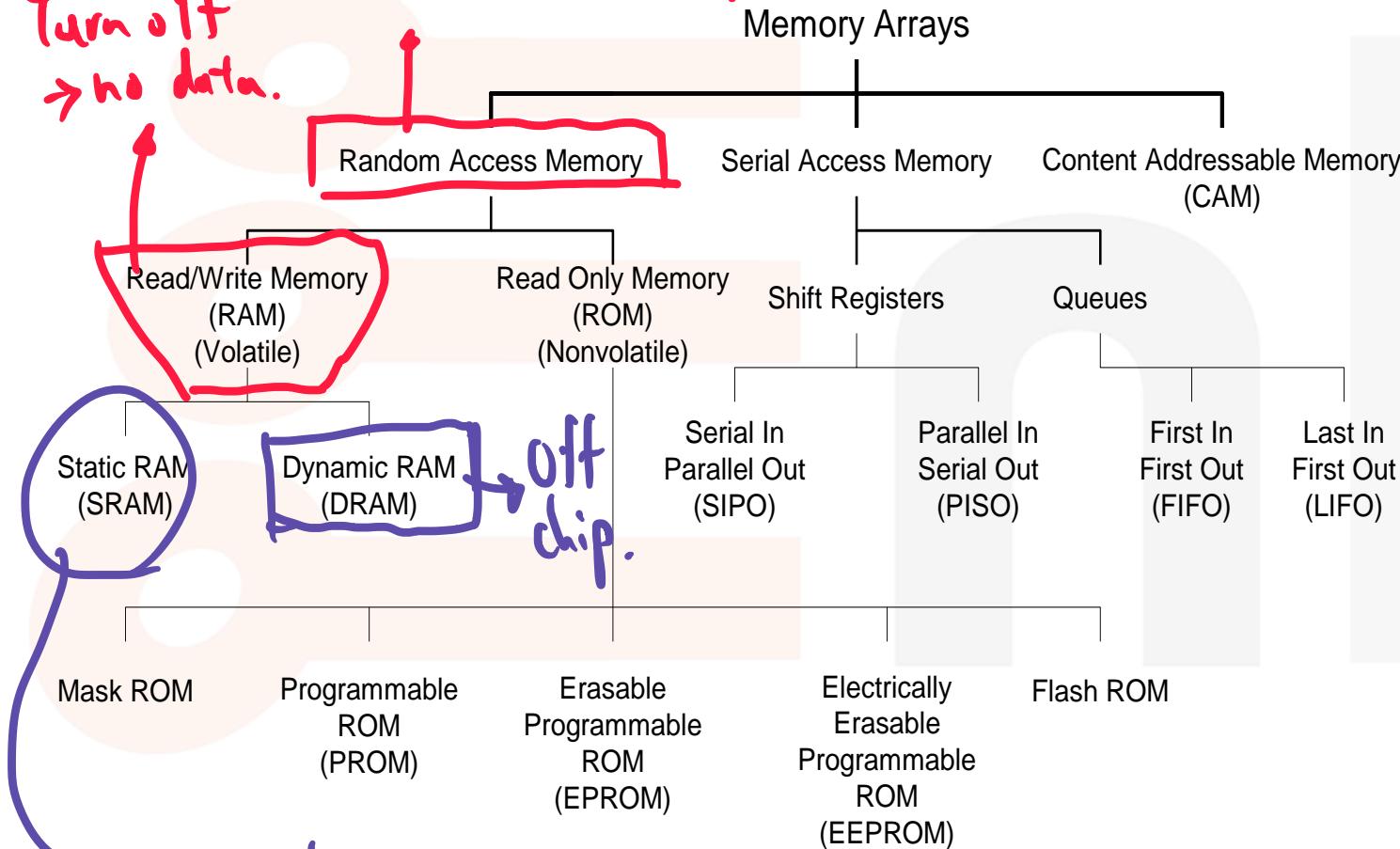
Memory Hierarchy of a Personal Computer



Semiconductor Memory Classification

What we're trying to focus
on here.

Turn off
→ no data.



On chip memory.

- **Size:**

- Bits, Bytes, Words

- **Timing Parameters:**

- Read access, write access, cycle time

- **Function:**

- Read Only (ROM) – non-volatile
- Read-Write (RWM) – volatile
- NVRWM – Non-volatile Read Write

- **Access Pattern:**

- Random Access, FIFO, LIFO, Shift Register, CAM

- **I/O Architecture:**

- Single Port, Multi-port

- **Application:**

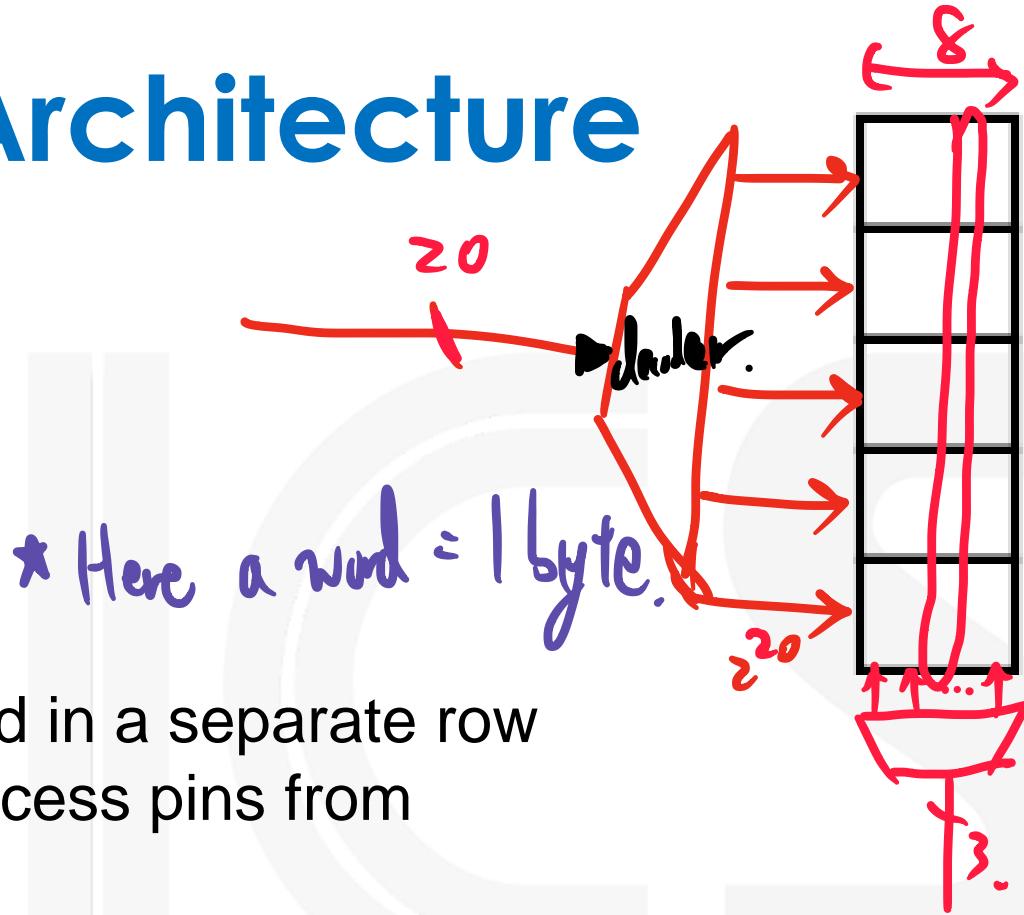
- Embedded, External, Secondary

Random Access Chip Architecture

- Conceptual: linear array
 - Each box holds some data
 - But this leads to a long and skinny shape

- Let's say we want to make a **1MB** memory:

- $1\text{MB} = 2^{20} \text{ words} \times 8 \text{ bits} = 2^{23} \text{ bits}$, each word in a separate row
- A decoder would reduce the number of access pins from 2^{20} access pins to **20 address** lines.
- We'd fit the pitch of the decoder to the word cells, so we'd have **Word Lines** with no area overhead.
- The output lines (=bit lines) would be extremely long, as would the delay of the huge decoder.
- The array's height is about 128,000 times larger than its width ($2^{20}/2^3$).

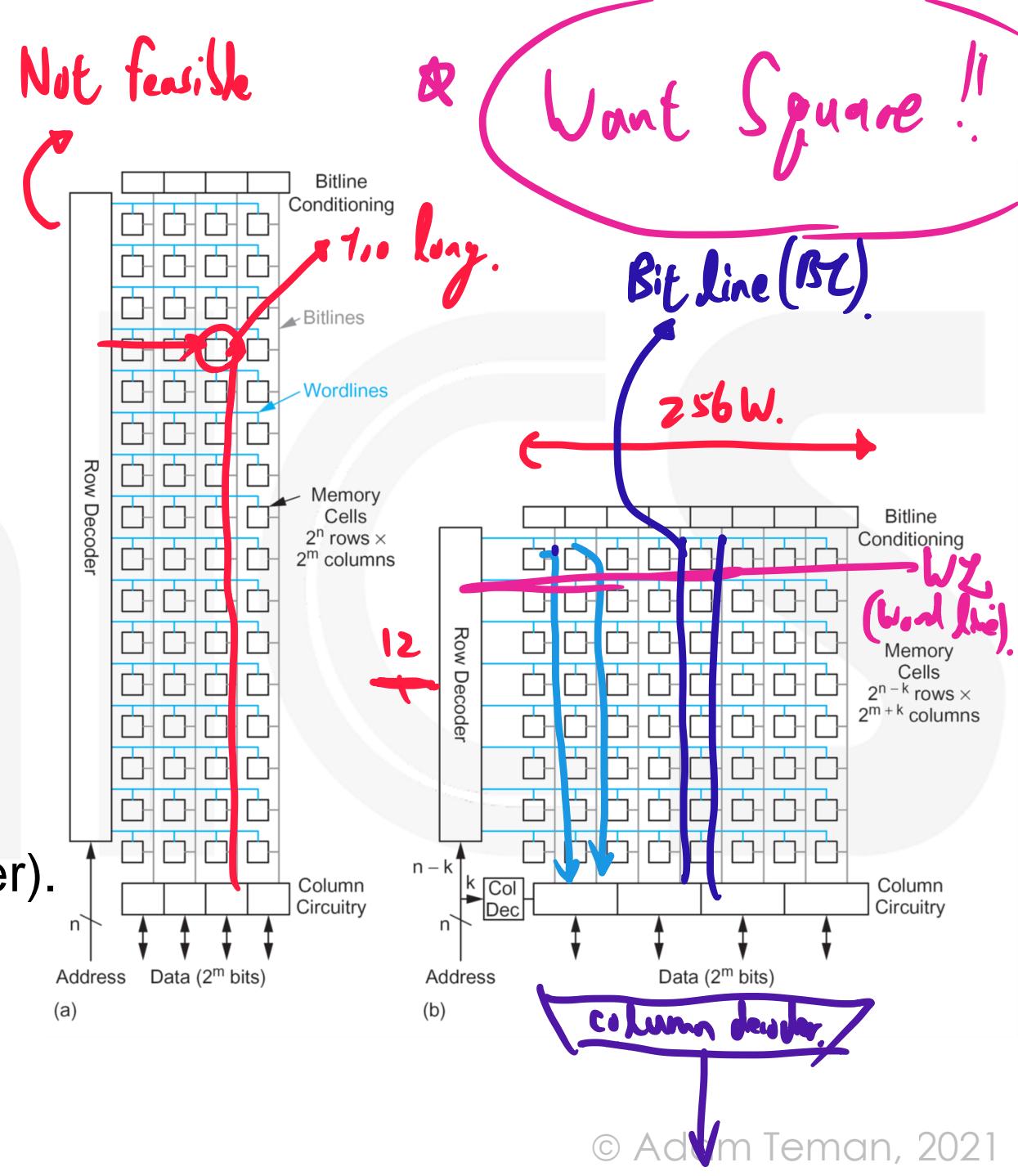


Horizontally, it is a huge & long decoder.
Very Unfeasible structure

Square Ratio

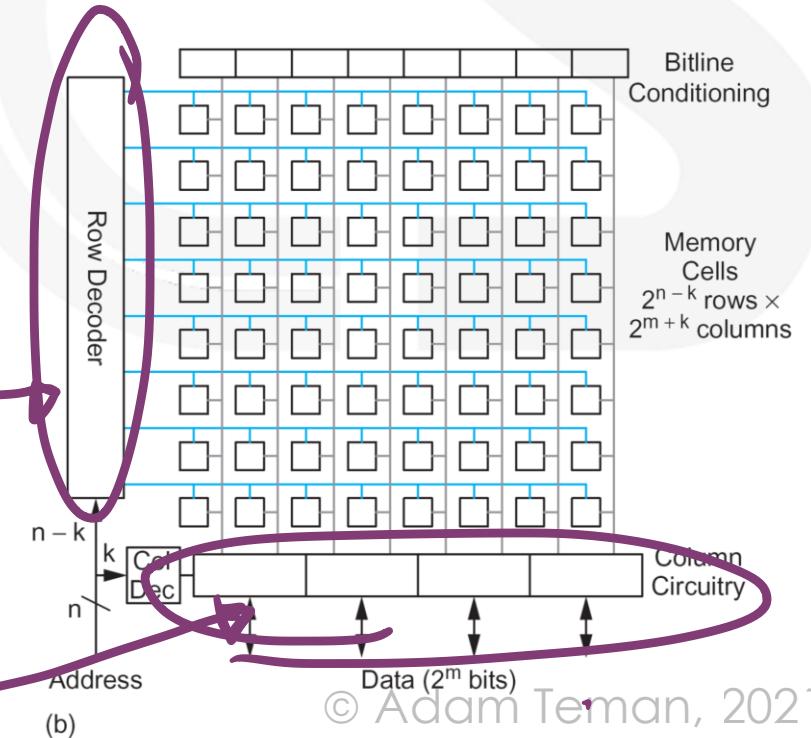
- Instead, let's make the array square:

- $1\text{MB} = 2^{23} \text{ bits} = 2^{12} \text{ rows} \times 2^{11} \text{ columns}$.
- There are 4000 rows, so we need a 12-bit row address decoder (to select a single row)
- There are 2000 columns, representing 256 8-bit words.
- We need to select only one of the 256 words through a column address decoder (or multiplexer).
- We call the row lines "Word Lines" and the column lines "Bit Lines".

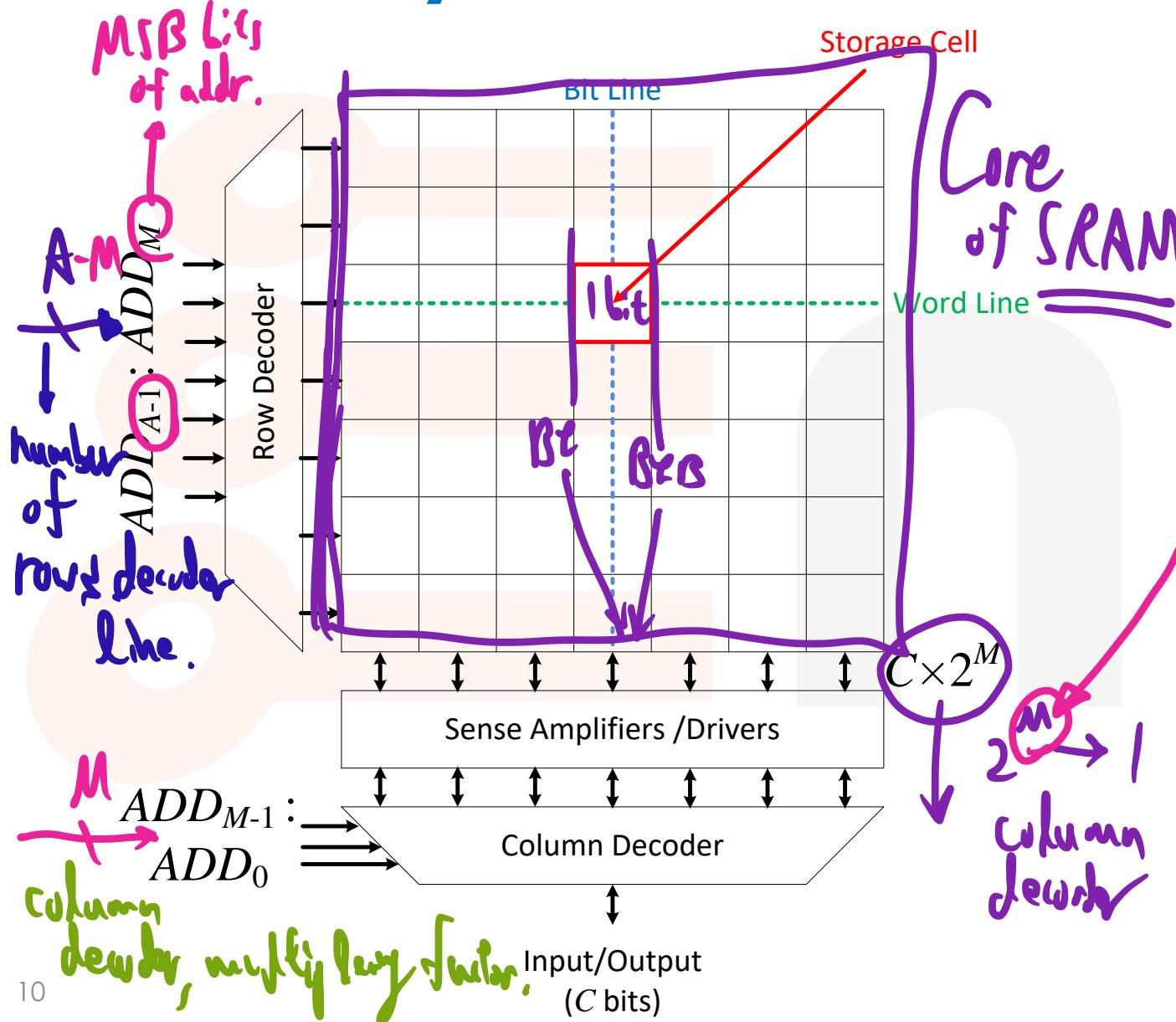


Special Considerations

- The “**core**” of the memory array is **huge**.
It can sometimes take up most of the chip area.
 - For this reason, we will try to make the “**bitcell**” as small as possible.
 - A standard Flip Flop uses at least **10** transistors per bit
(usually more than **20**). This is very area consuming.
- We will trade-off area for other circuit properties:
 - Noise Margins
 - Logic Swing
 - Speed
 - Design Rules
- This requires special peripheral circuitry.



Memory Architecture



- * Each address access 1 word of data.
- * Memory are made out of words.
1 word is usually 32 bits.
- ① Memory Size: W Words of C bits
 $= W \times C$ bits
- ② Address bus: A bits
 $\rightarrow W = 2^A \Rightarrow A = \log_2 W$
- ③ Number of Words in a Row: 2^M
- ④ Multiplexing Factor: M
- ⑤ Number of Rows: 2^{A-M}
Number of Columns: $C \times 2^M$
- ⑥ Row Decoder: $A-M \rightarrow 2^{A-M}$
Column Decoder: $M \rightarrow 2^M$
- Total address A

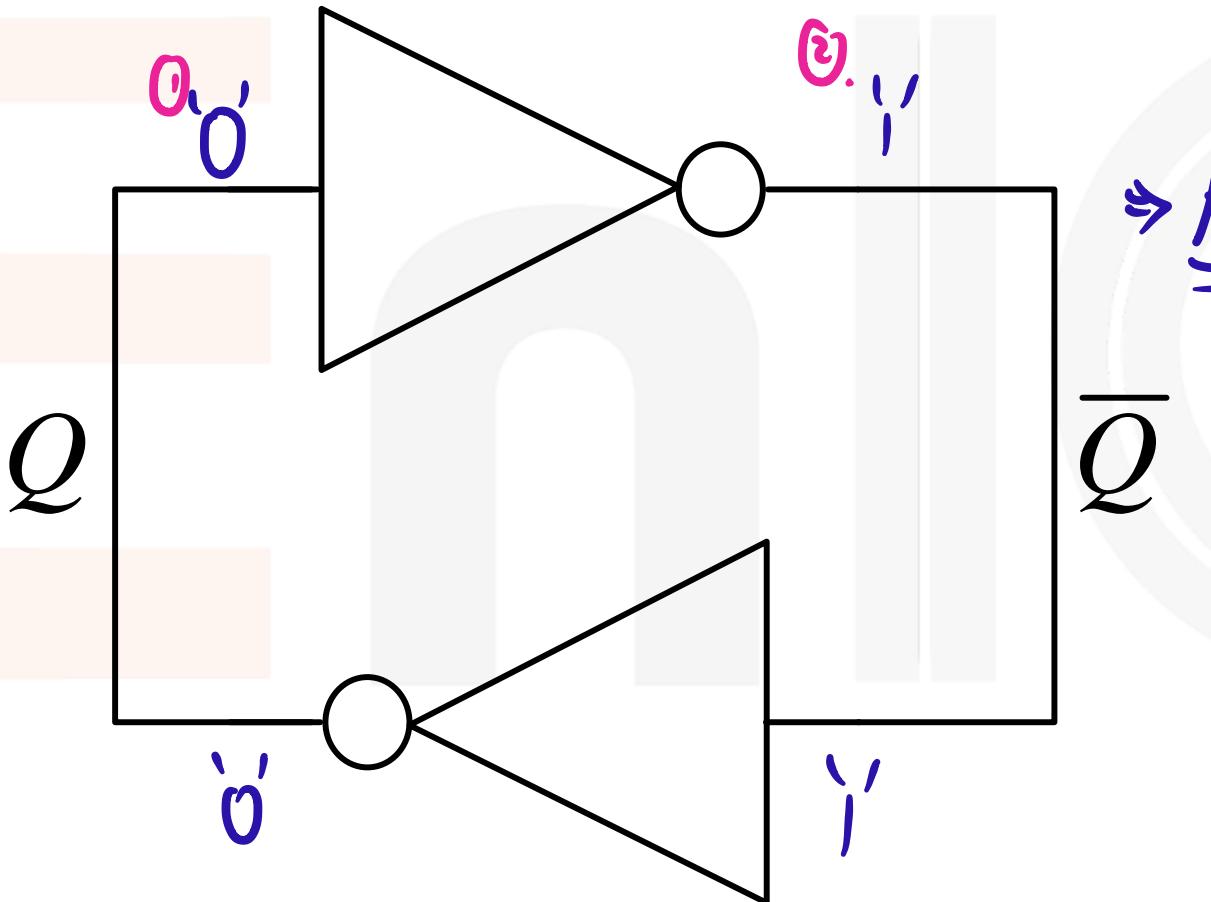
The 6T SRAM Bitcell



Basic Static Memory Element

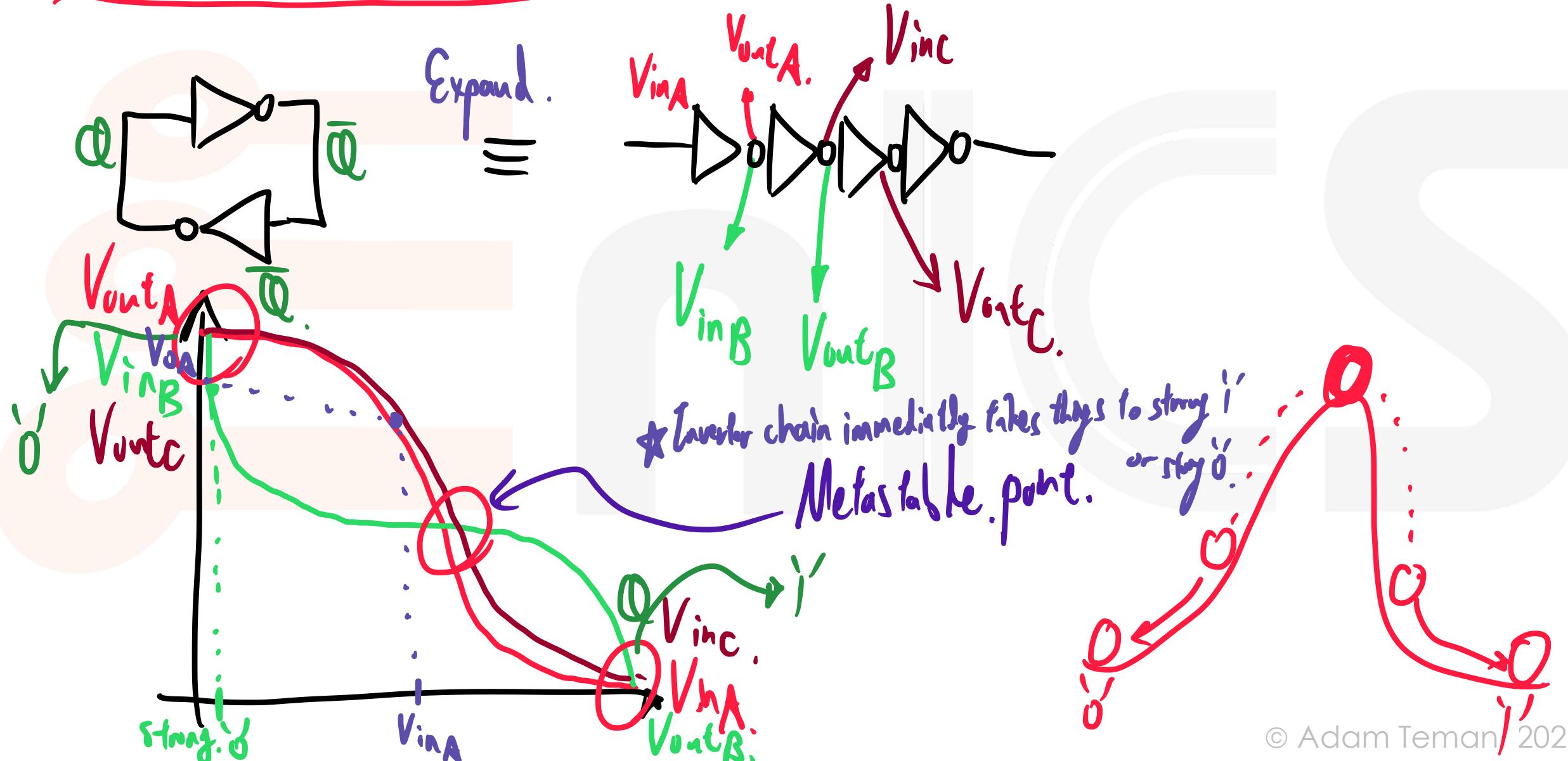
Cross-Coupled

inverter.



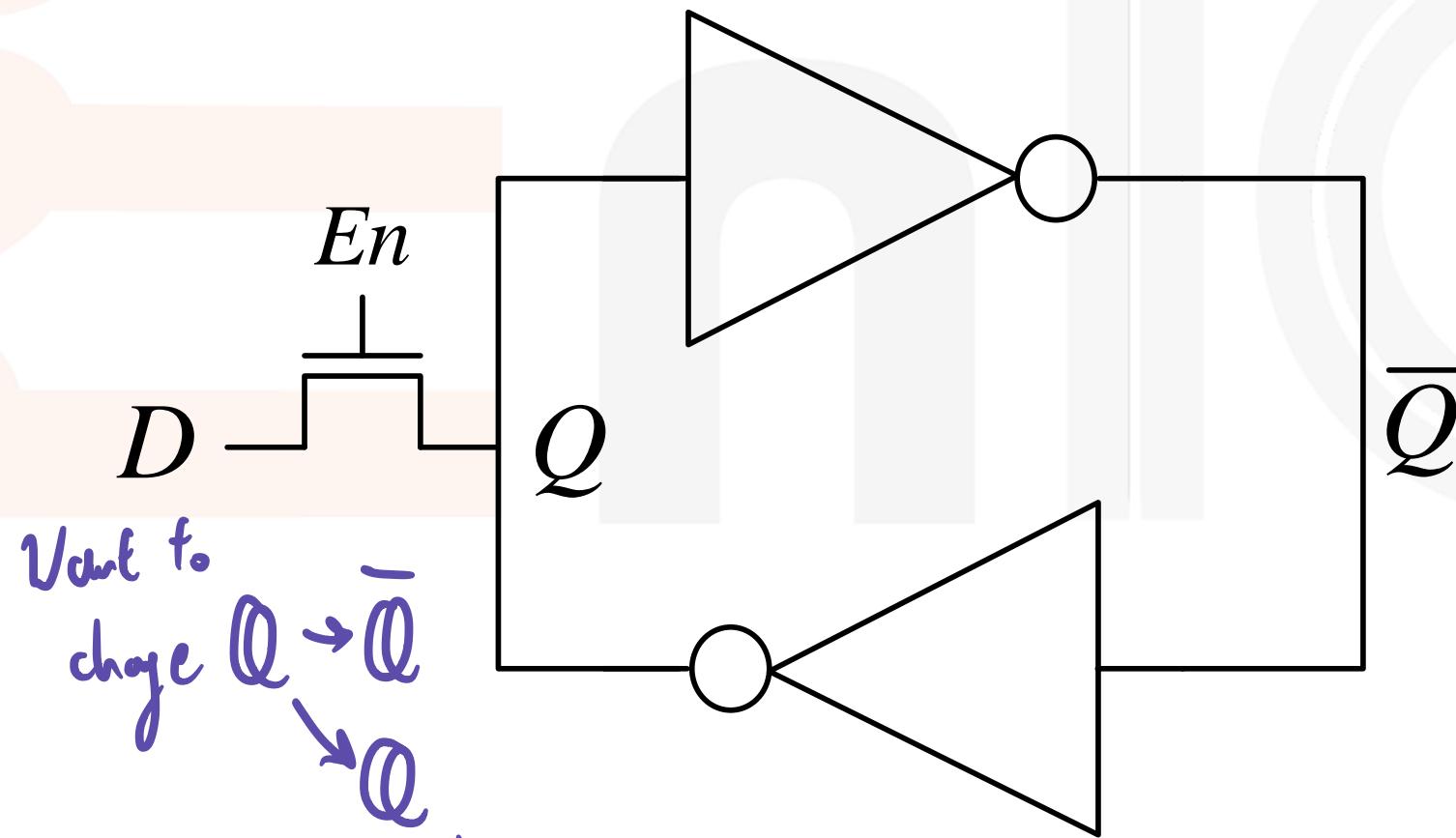
⇒ A bistable element.

Positive Feedback: Bi-Stability



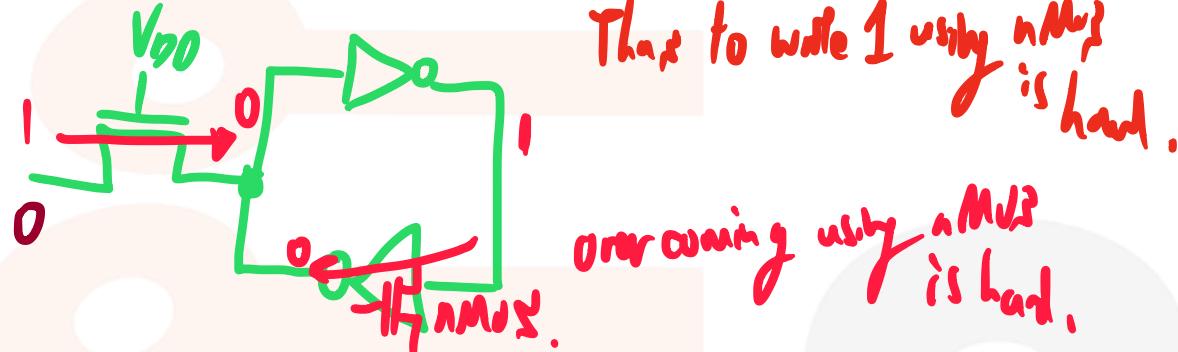
Writing into a Cross-Coupled Pair

- The write operation is ratioed
 - The access transistor must overcome the feedback.



How should we write a '1'

Option 1: nMOS Access Transistor



Passes a "weak '1'", bad at pulling up against the feedback

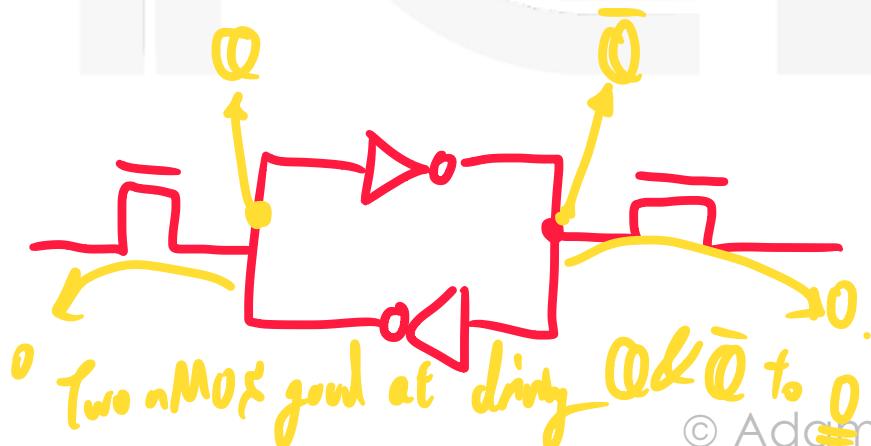
Option 2: pMOS Access Transistor

Option 2: pMOS Access Transistor

Same as nMOS, needs to overcome pMOS pullup.

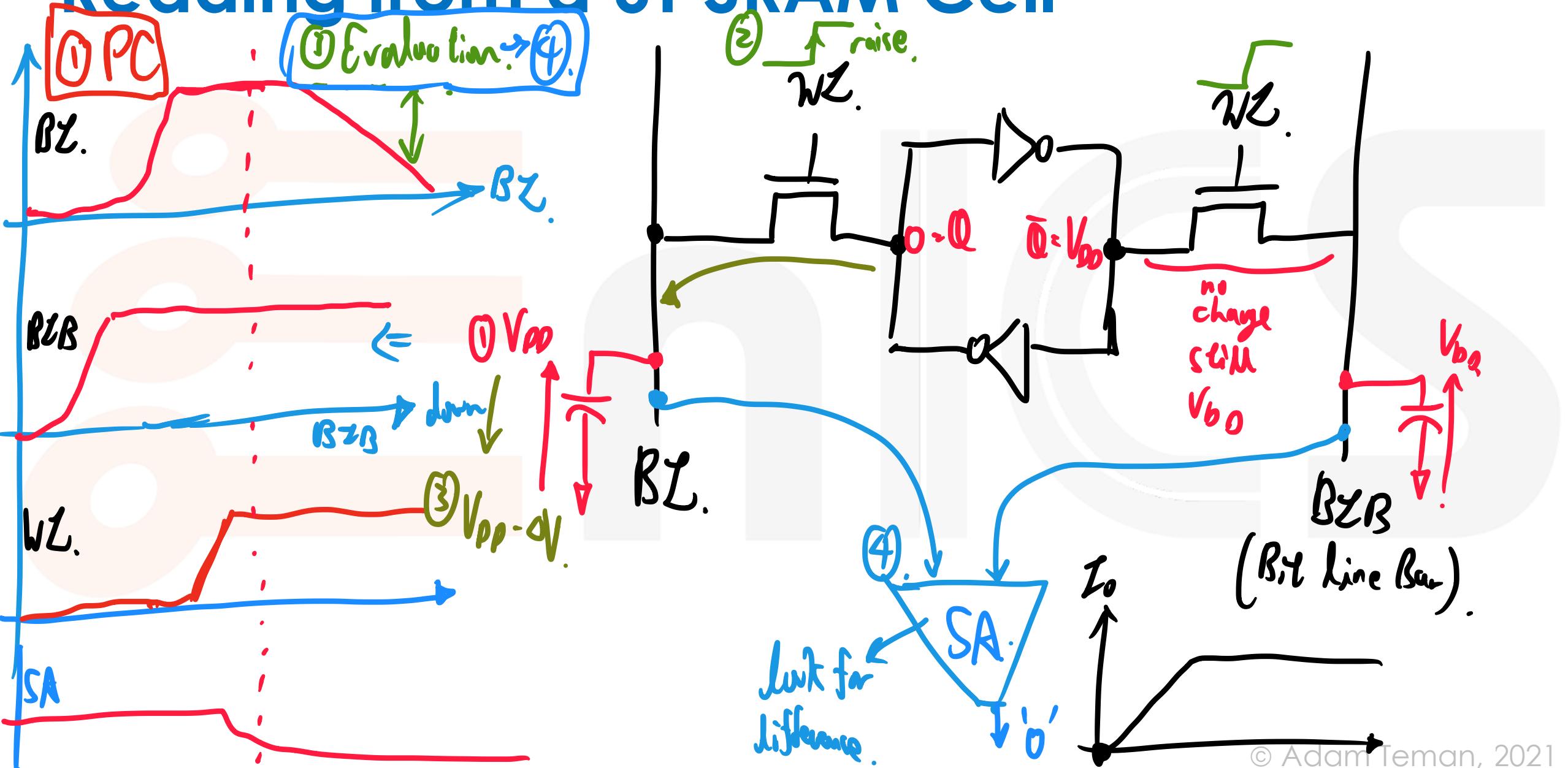
Passes a "weak '0'", bad at pulling down against the feedback

Solution: Differential nMOS Write

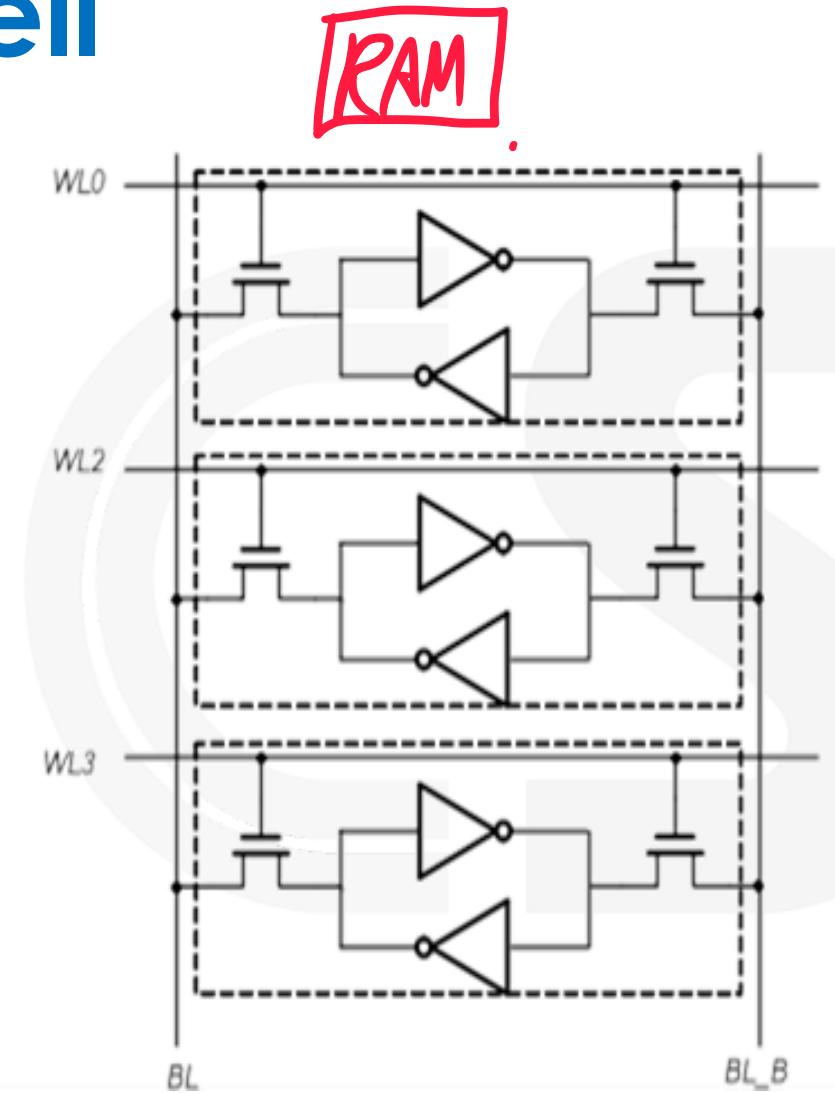
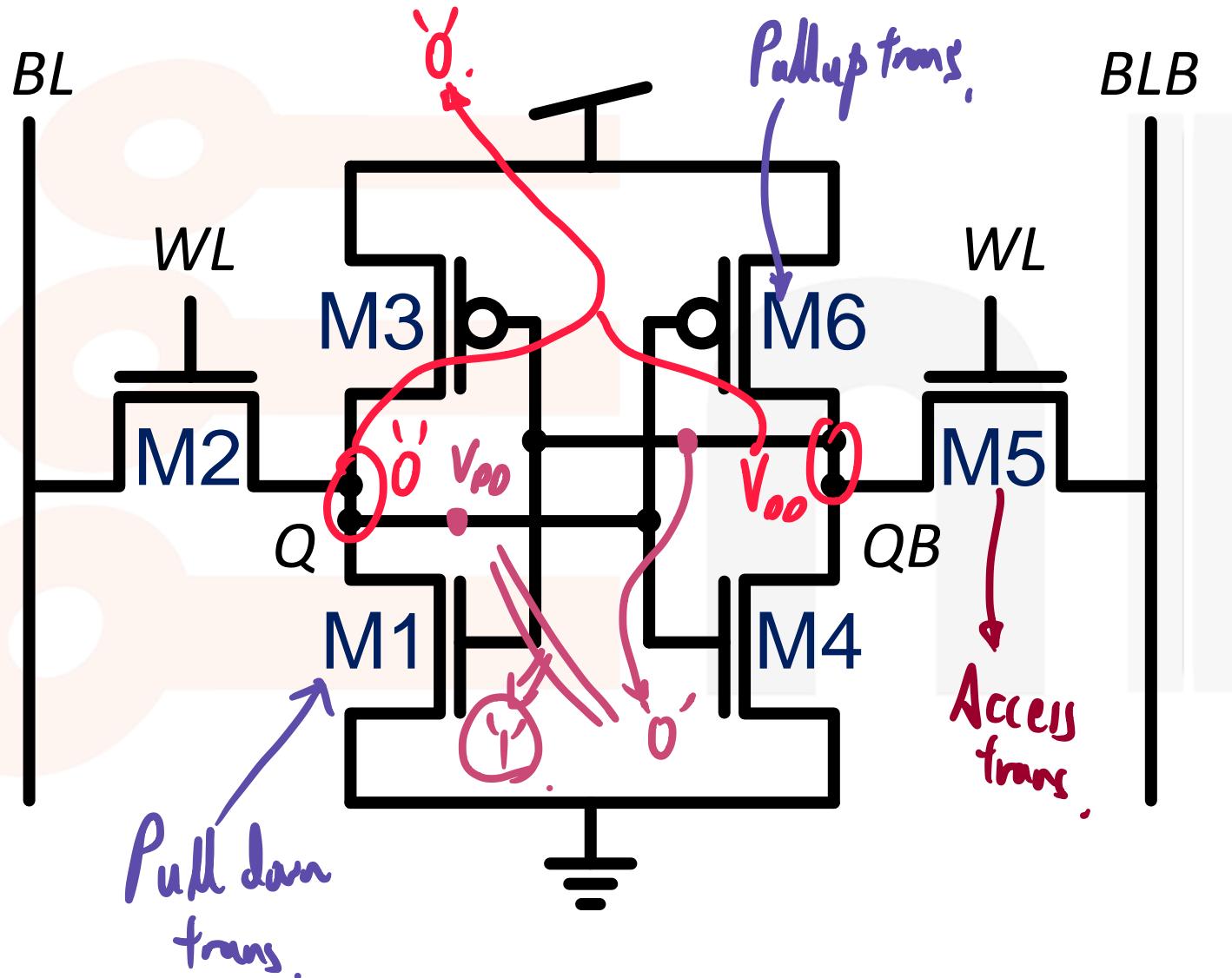


Writes well, but how do we read?

Reading from a 6T SRAM Cell



6-transistor CMOS SRAM Cell



The Computer Hall of Fame

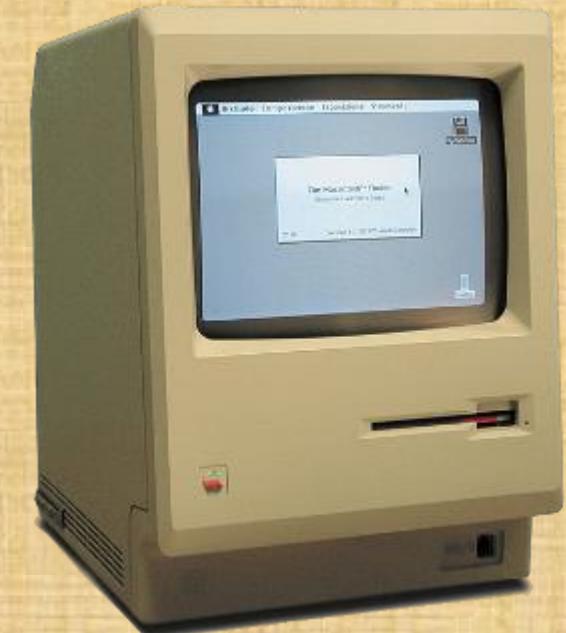
- The machine that introduced the GUI, the mouse, and Steve Jobs to the mainstream.

The Macintosh

- The personal computer that “was designed so easy to use that people could actually use it”.
- Developed based on a 3-day tour of Apple at Xerox PARC, where they saw the Xerox Alto.
- Introduced in 1984, sold for \$2500 with an 8MHz Motorola 6800 processor, 128kB RAM.
- Included MacPaint and MacWrite
- Despite initial success, sales declined and Steve Jobs was fired from Apple in 1985.



Source: macworld.co.uk



Source: macworld.co.uk



6T SRAM Operation



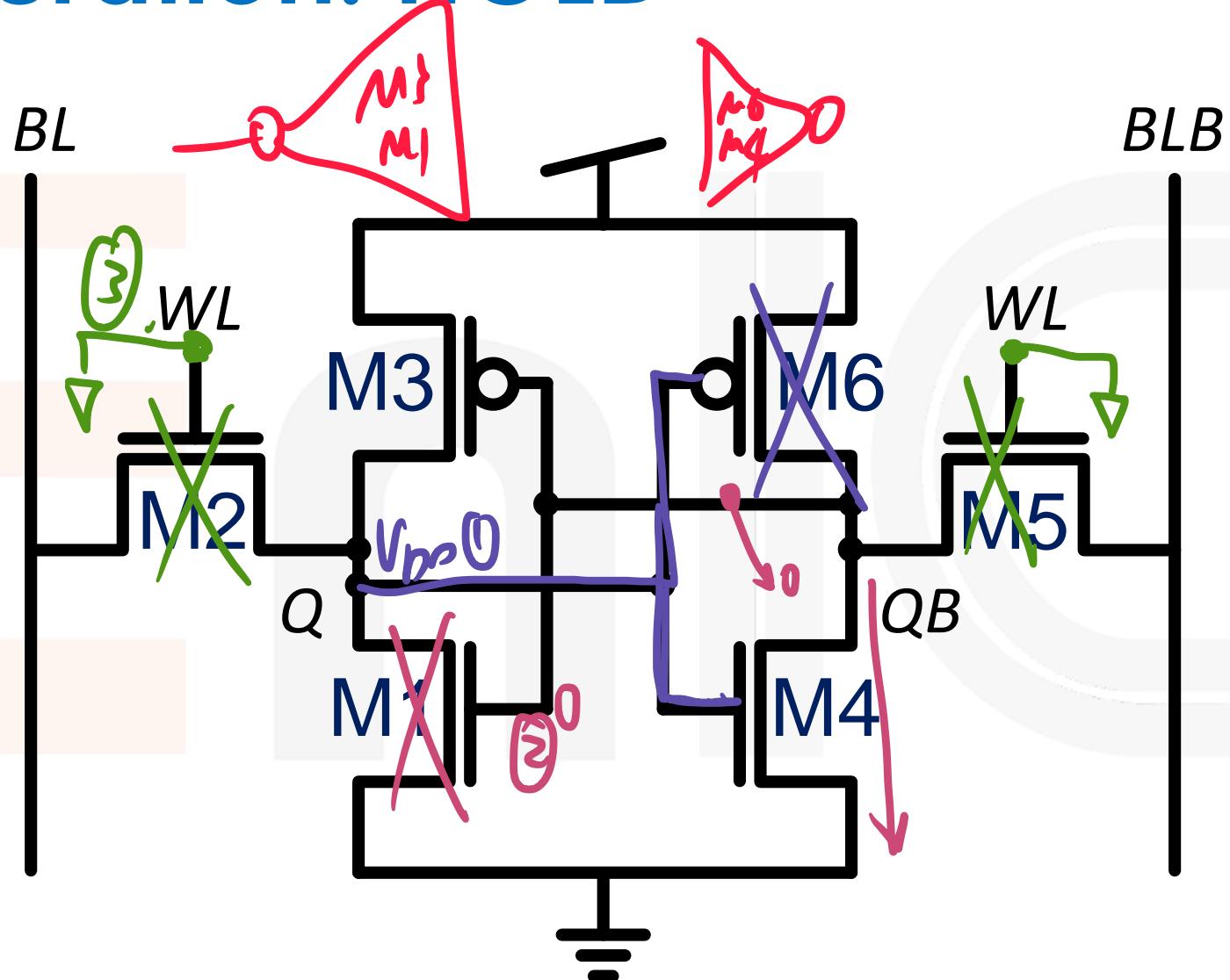
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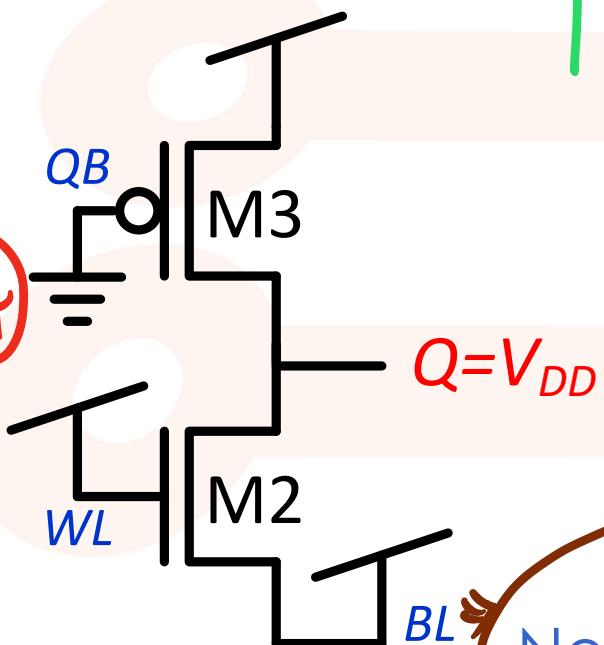


SRAM Operation: HOLD

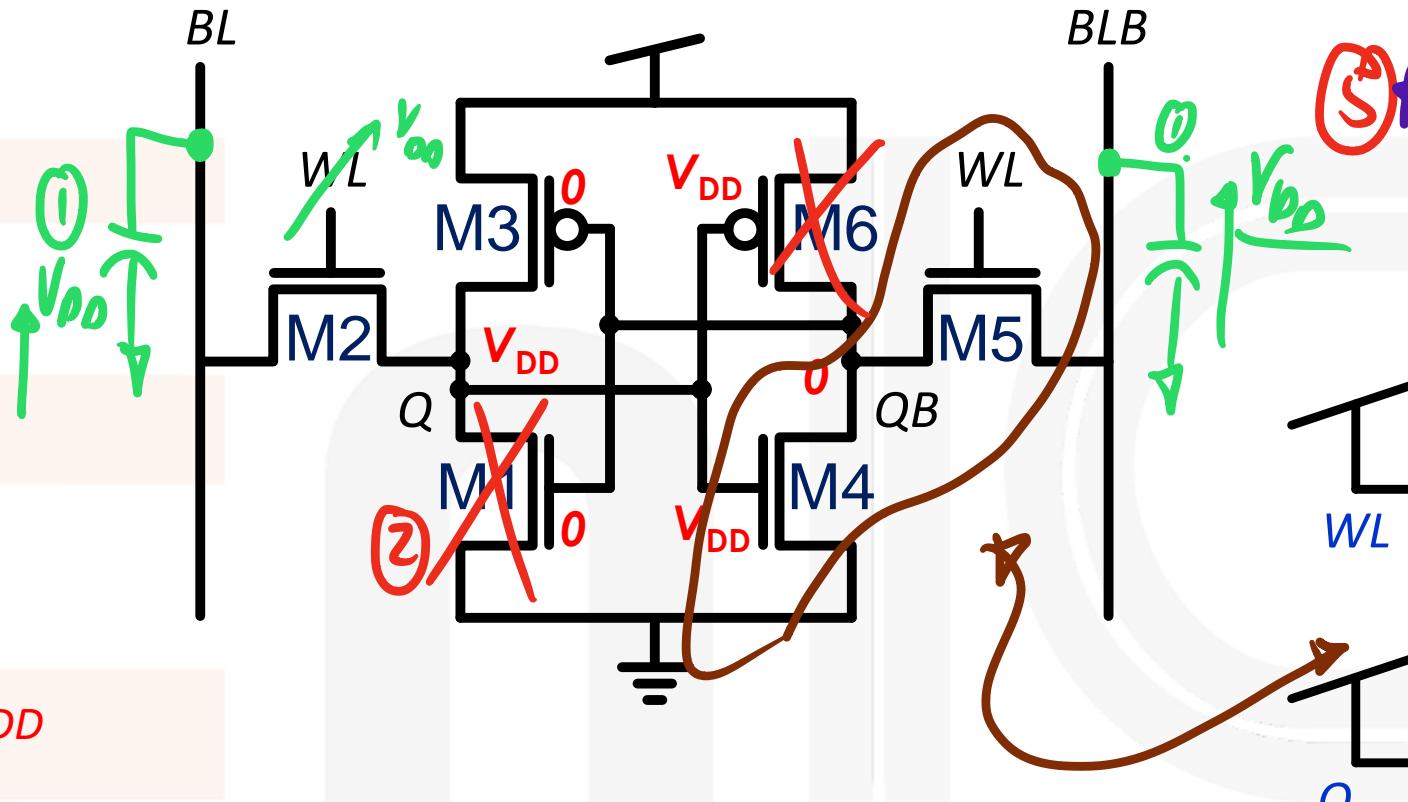


SRAM Operation: READ

③ Redraw the equivalent ckt.

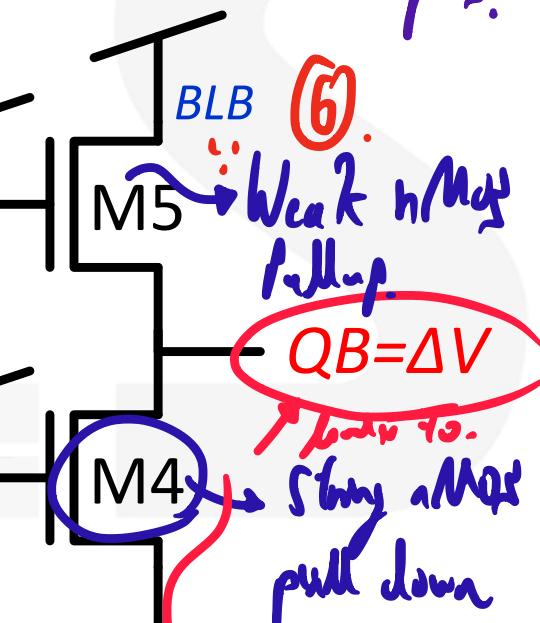


Left Side:
Nothing Changes...



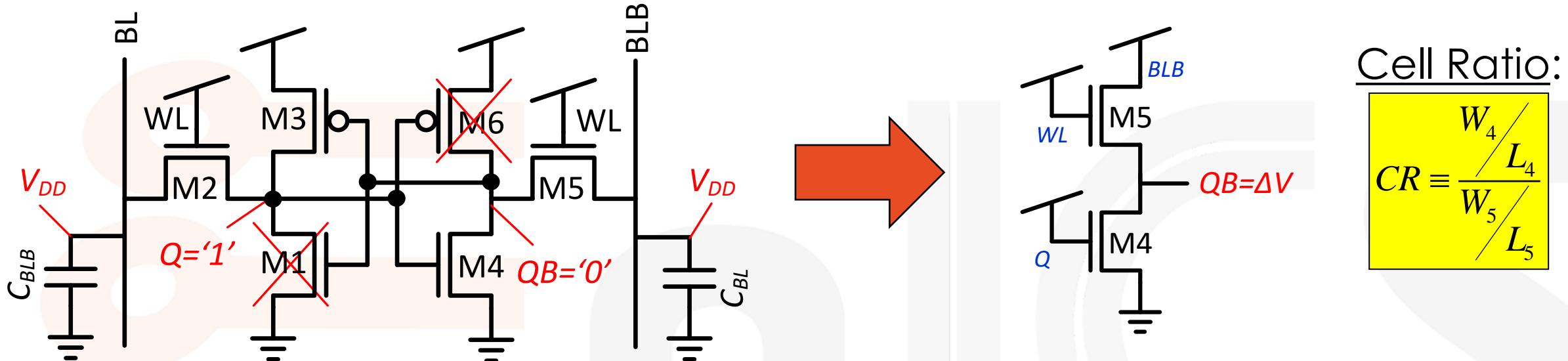
Right Side:
“nMOS” inverter –
 QB voltage rises

$Q = Q_B \&$
 $V_{DD} \approx BLB$, $M5$ op \downarrow .



Q_B is ok as long as $Q_B < V_{tq}$.

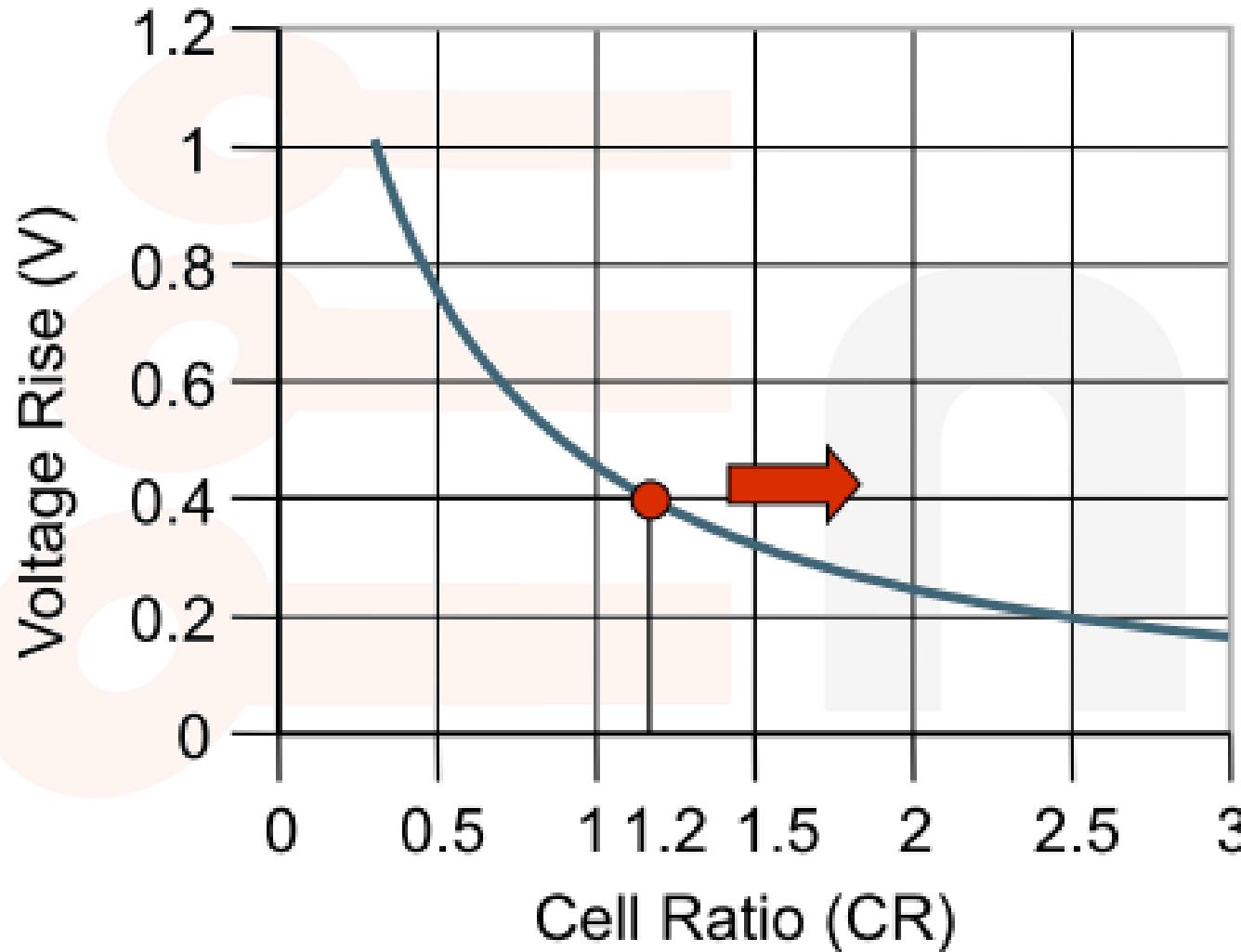
SRAM Operation - Read



$$k_{M5} \left[(V_{DD} - \Delta V - V_{T,n}) V_{DSat,n} - \frac{V_{DSat,n}^2}{2} \right] = k_{M4} \left[(V_{DD} - V_{T,n}) \Delta V - \frac{\Delta V^2}{2} \right]$$

$$\Delta V = \frac{V_{DSat,n} + CR(V_{DD} - V_{T,n}) - \sqrt{V_{DSat,n}^2 (1+CR) + CR^2 (V_{DD} - V_{T,n})^2}}{CR}$$

Cell Ratio (Read Constraint)

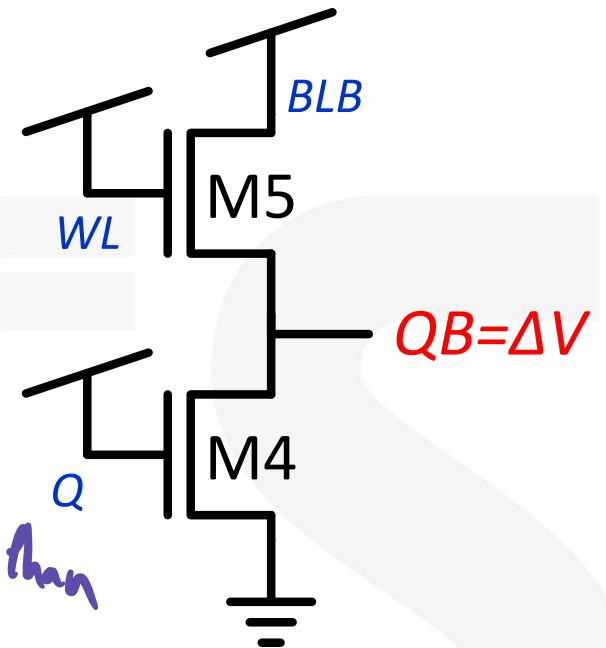


Want cell ratio high,

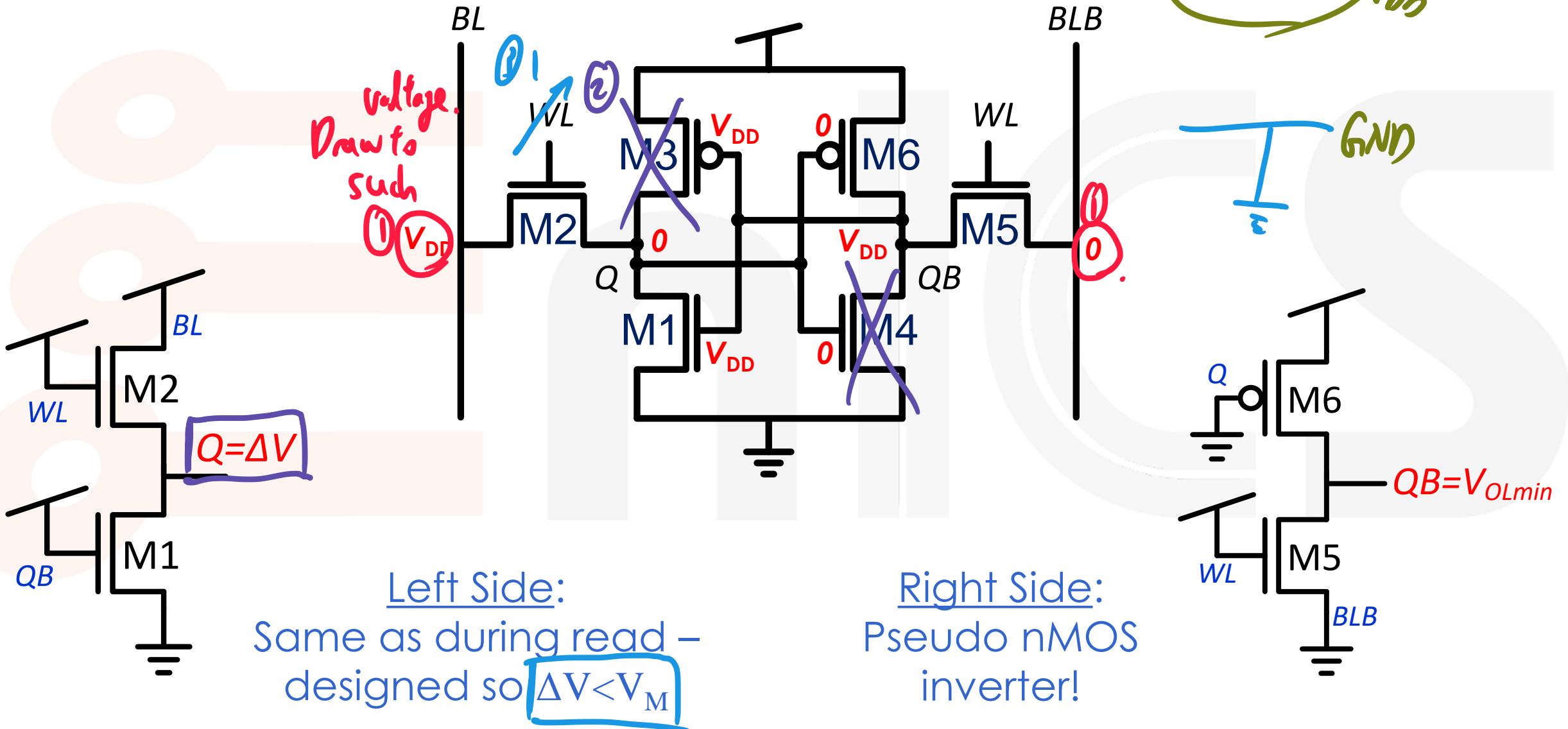
$$CR \equiv \frac{W_4/L_4}{W_5/L_5}$$

Pull down stronger than
pull up.

So we need the pull
down transistor to be
much stronger than the
access transistor...



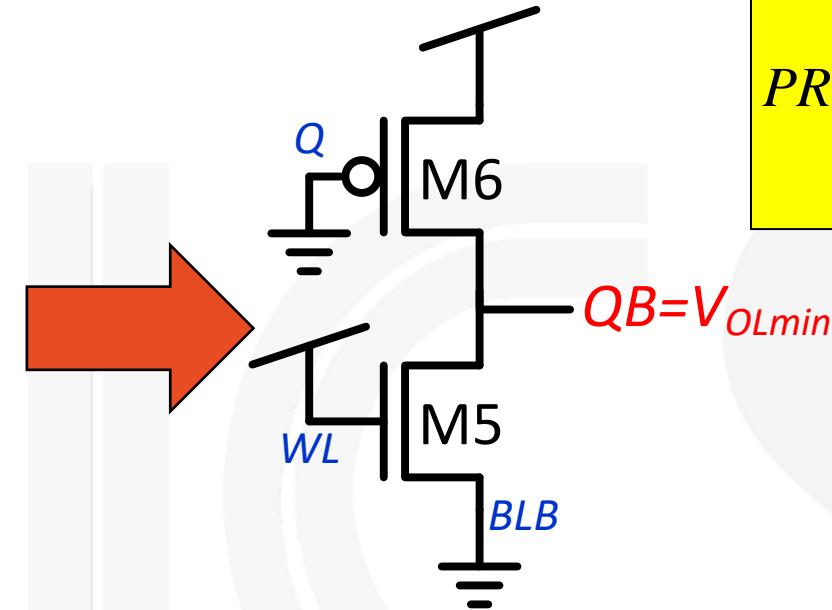
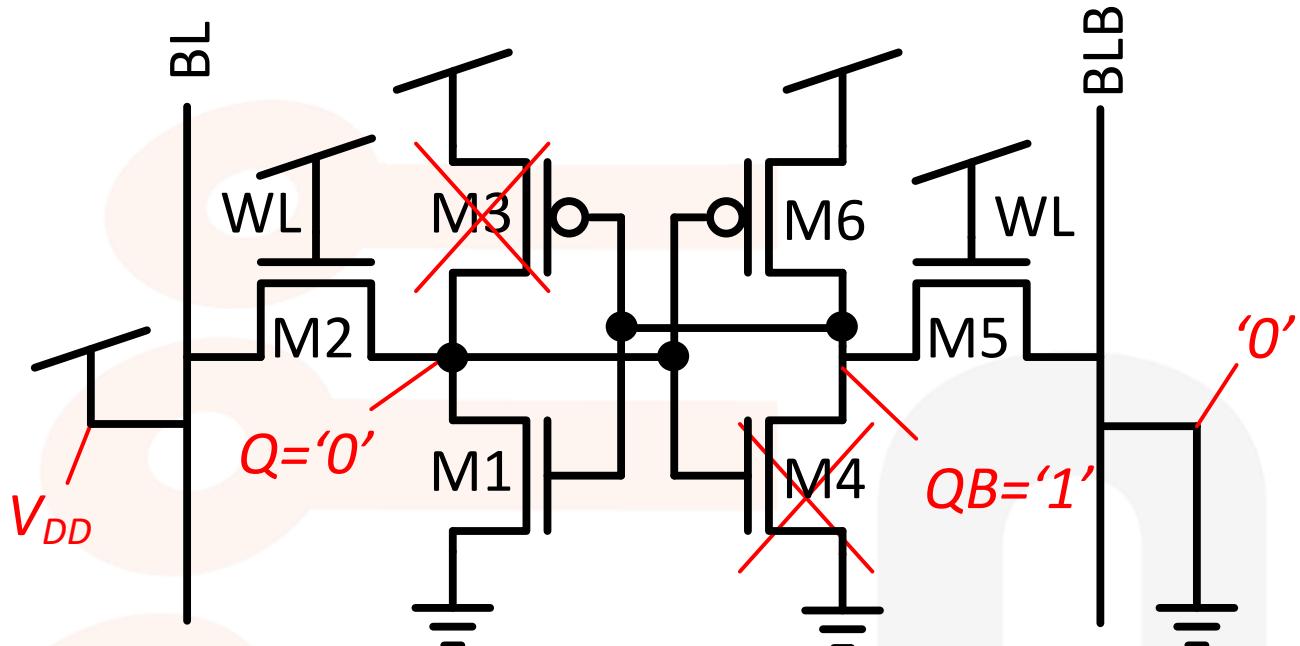
SRAM Operation: WRITE



SRAM Operation - Write

Pull-Up Ratio

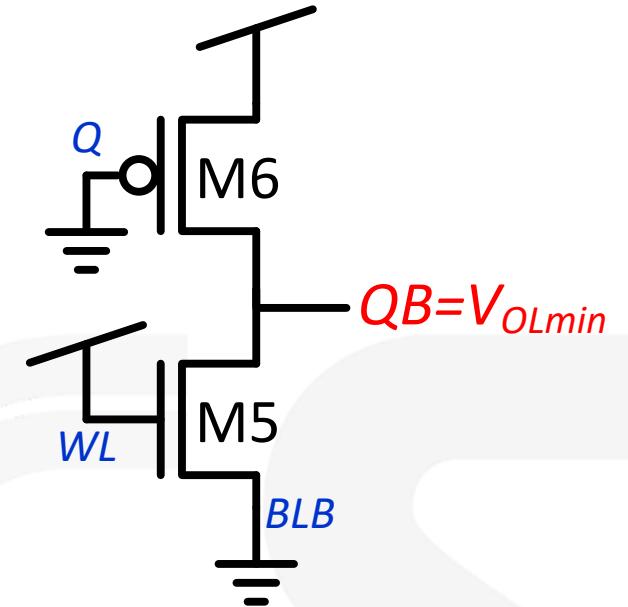
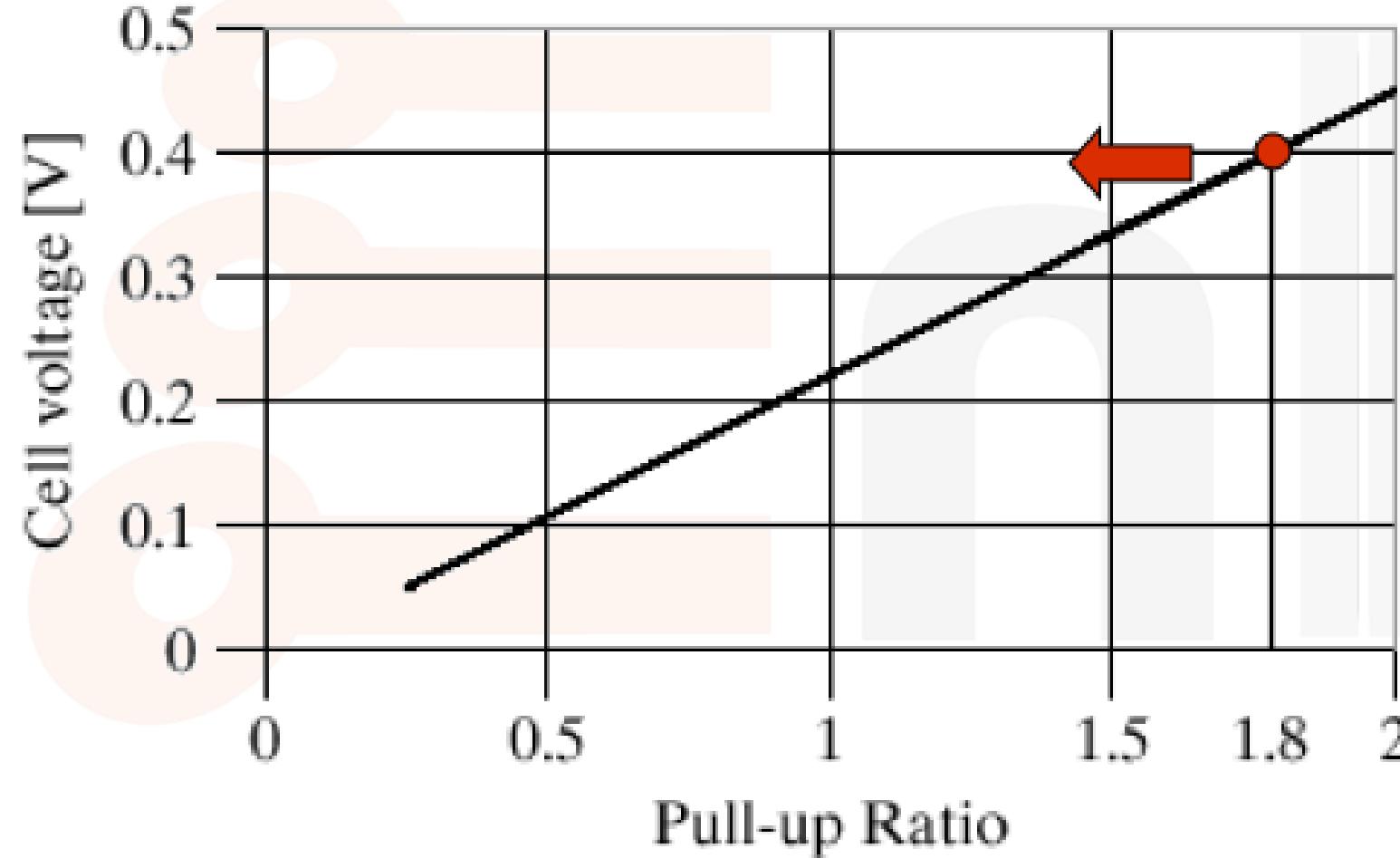
$$PR \equiv \frac{W_6/L_6}{W_5/L_5}$$



$$k_{M6} \left[(V_{DD} - |V_{T,p}|) V_{DSat,p} - \frac{V_{DSat,p}^2}{2} \right] = k_{M5} \left[(V_{DD} - V_{T,n}) V_{QB} - \frac{\Delta V_{QB}^2}{2} \right]$$

$$V_{QB} = V_{DD} - V_{T,n} - \sqrt{(V_{DD} - V_{T,n})^2 - 2 \frac{\mu_p}{\mu_n} PR \left[(V_{DD} - |V_{T,p}|) V_{DSat,p} - \frac{V_{DSat,p}^2}{2} \right]}$$

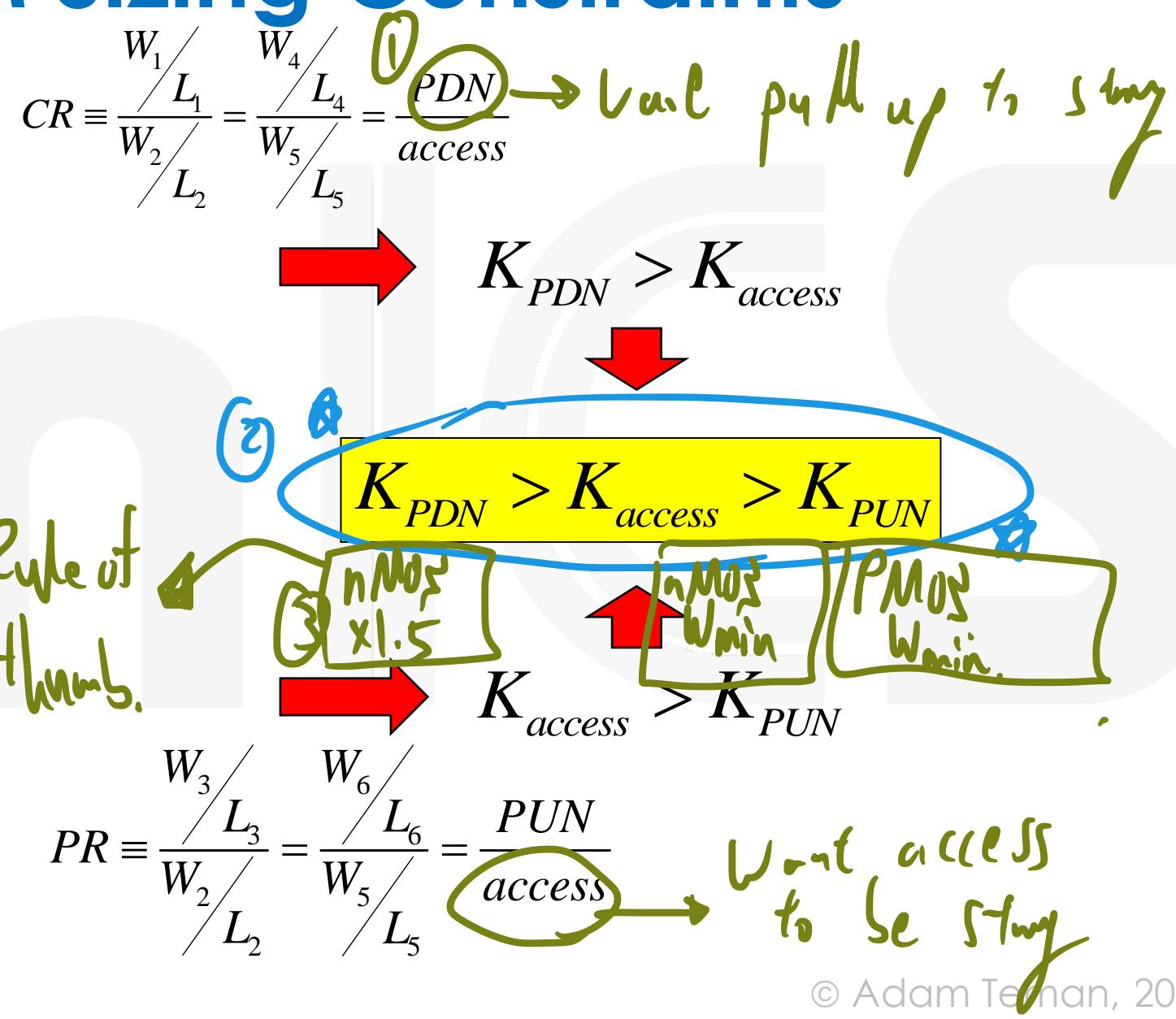
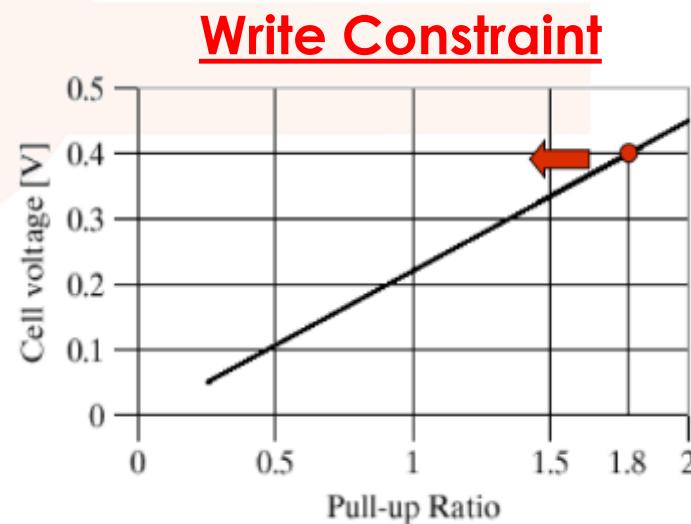
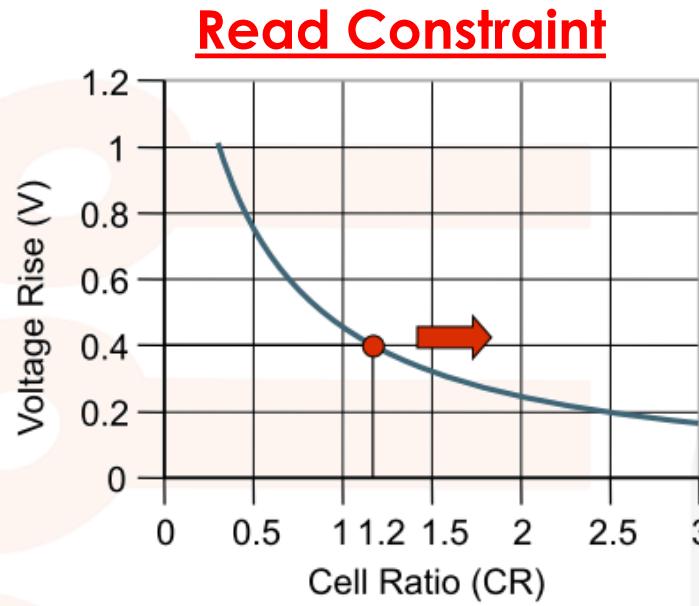
Pull Up Ratio – Write Constraint



So we need the access transistor to be much stronger than the pull up transistor...

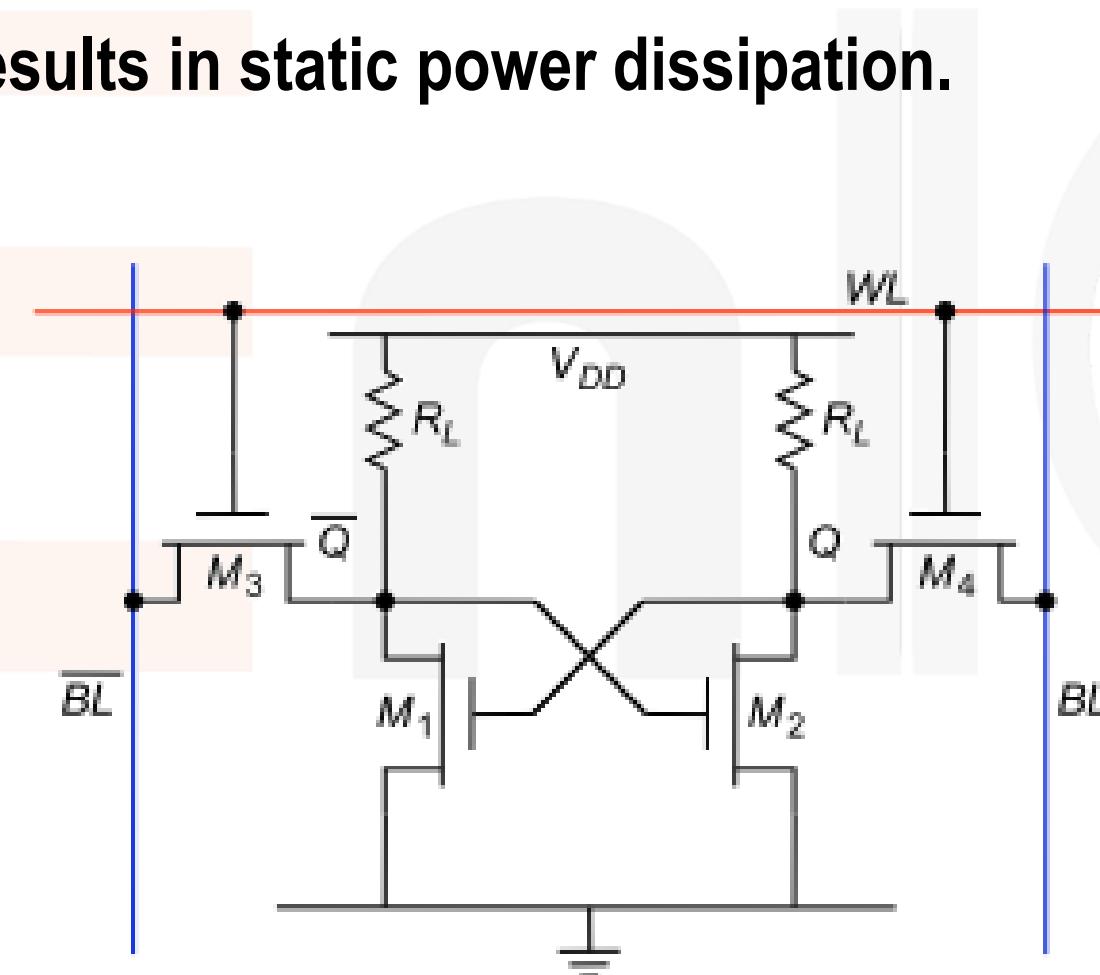
$$PR \equiv \frac{W_6/L_6}{W_5/L_5}$$

Summary – SRAM Sizing Constraints



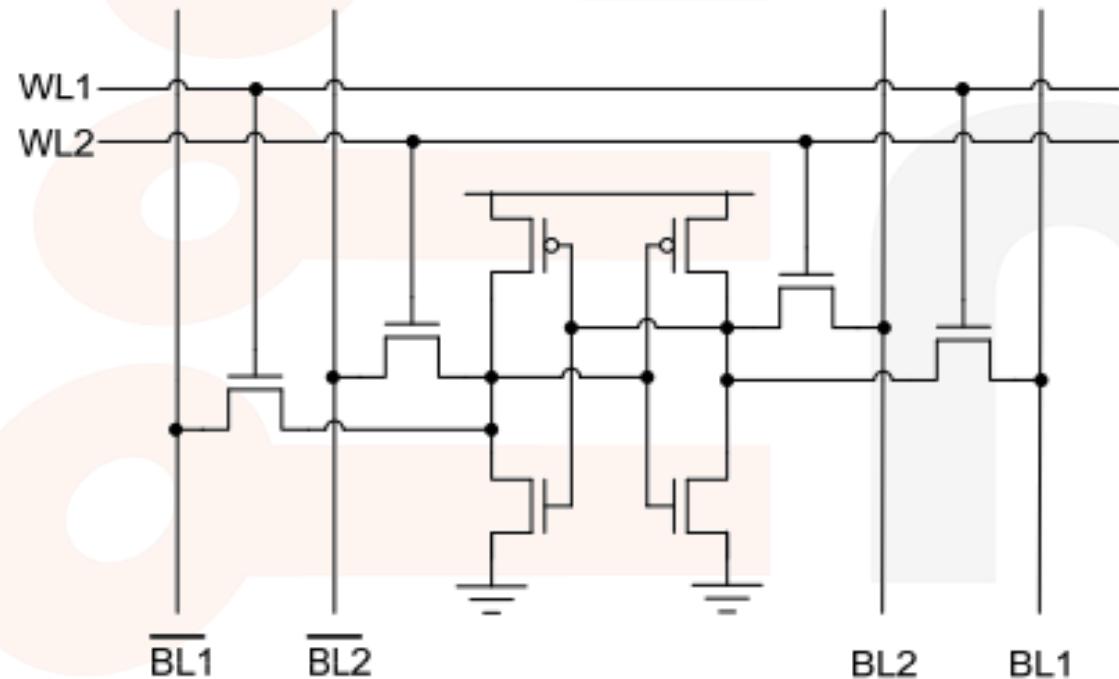
4T Memory Cell

- Achieve density by removing the PMOS pull-up.
- However, this results in static power dissipation.

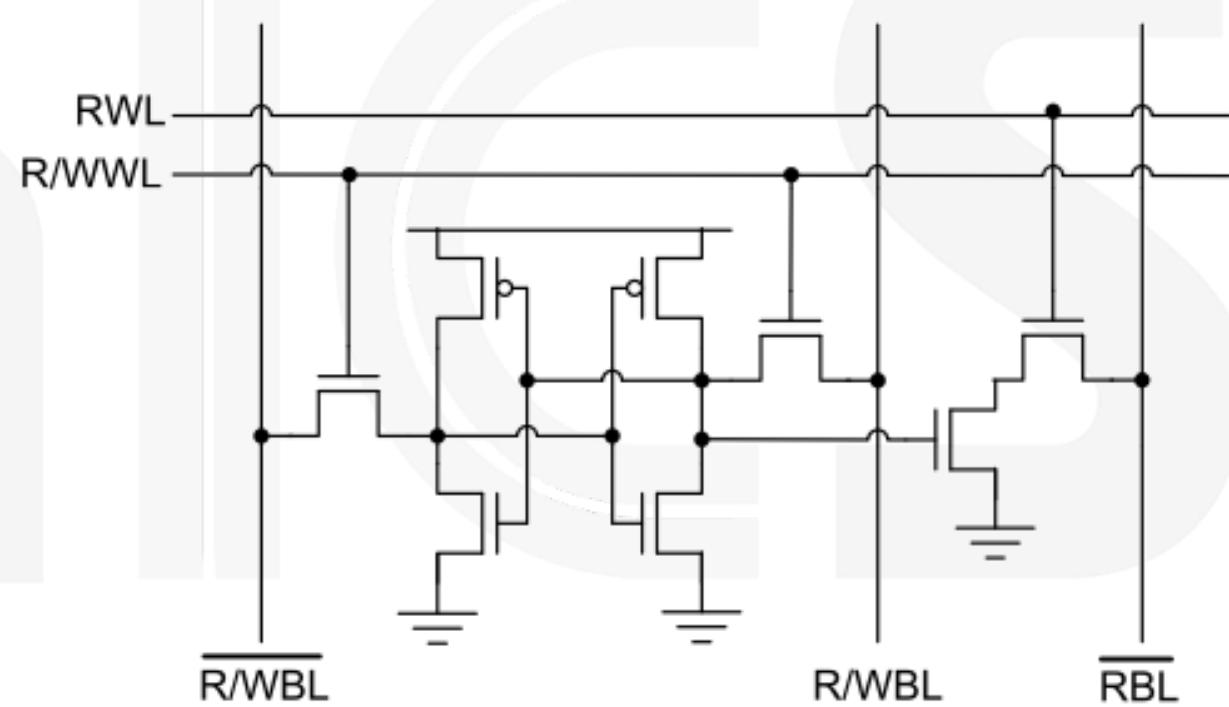


Multi-Port SRAM

Dual Port SRAM



Two Port SRAM



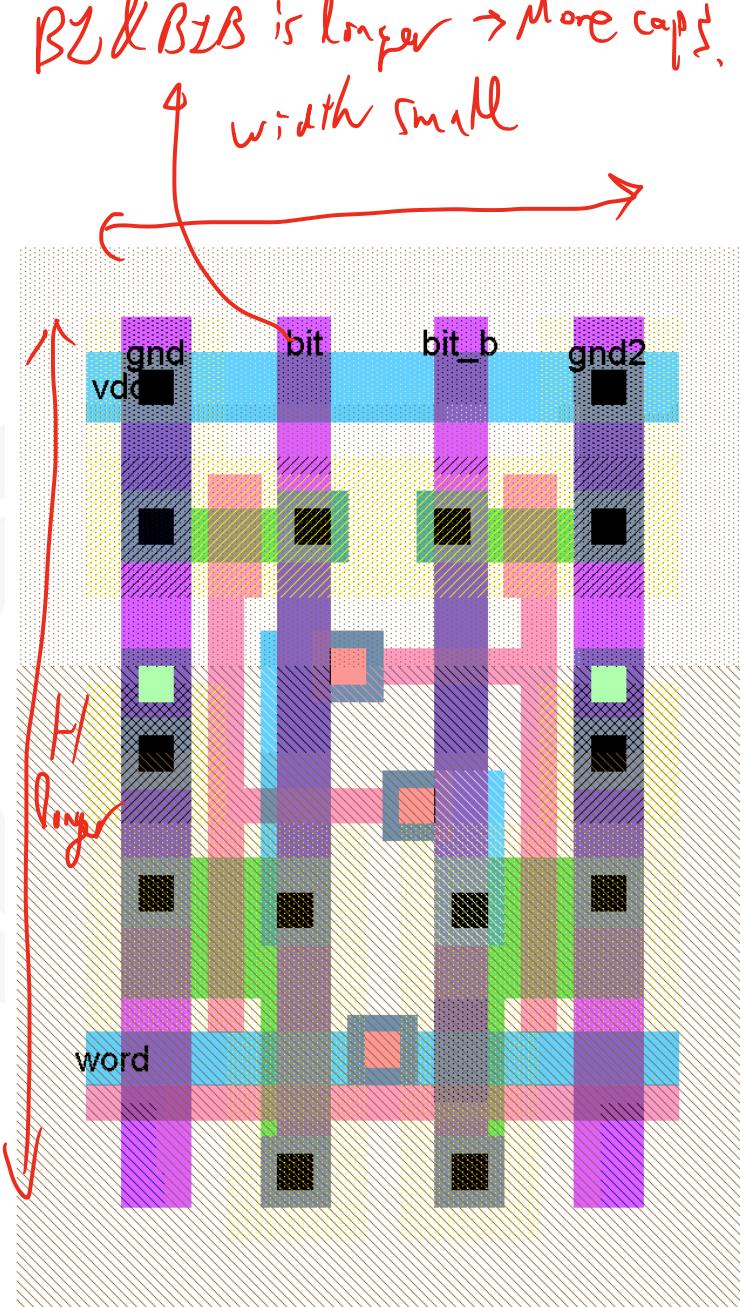
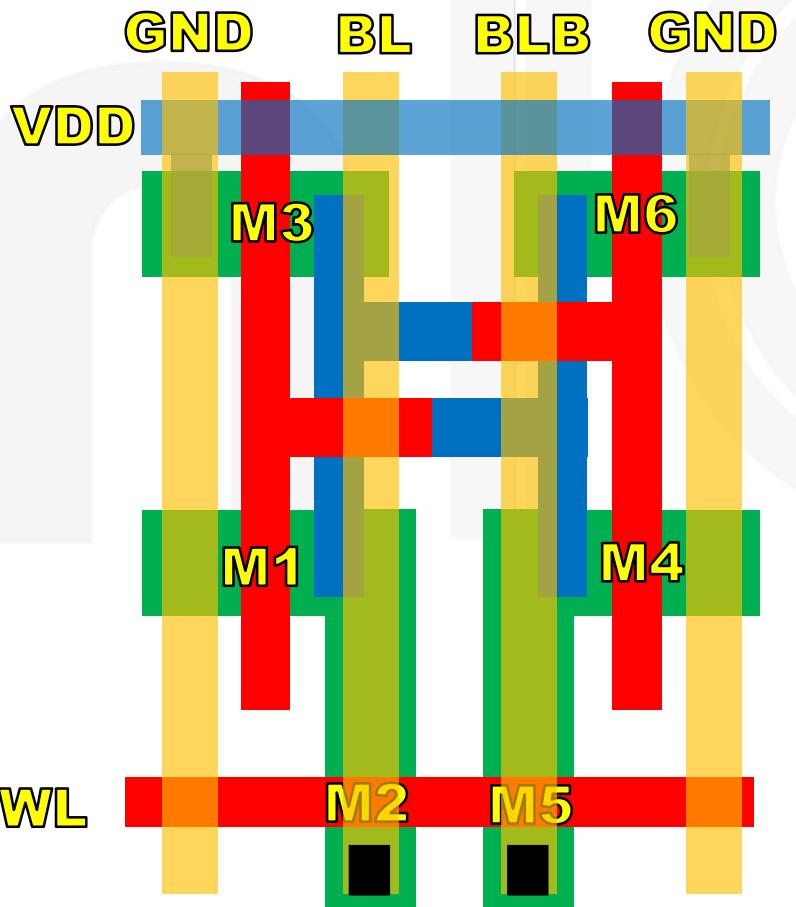
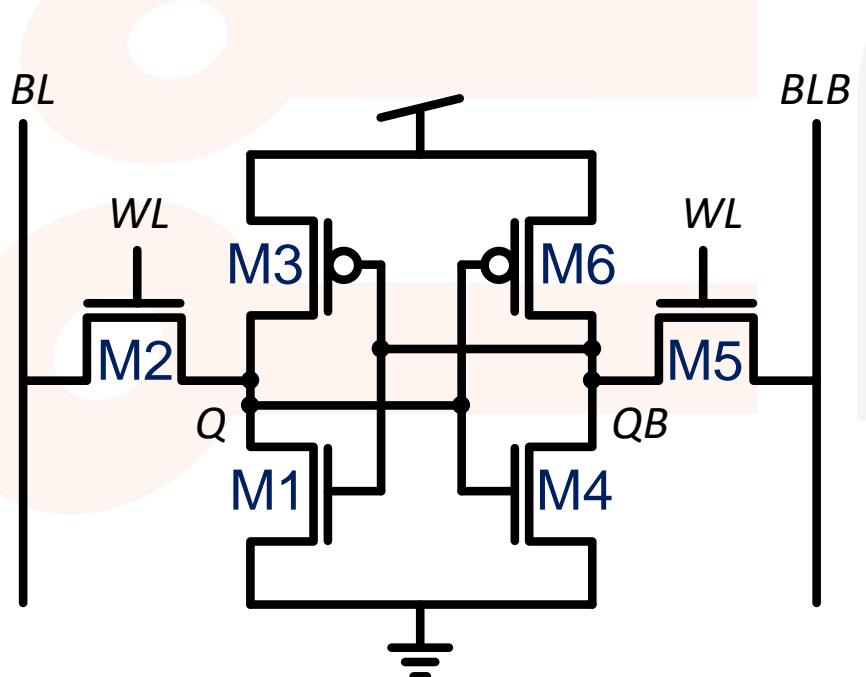
6T SRAM Layout



SRAM Layout - Traditional

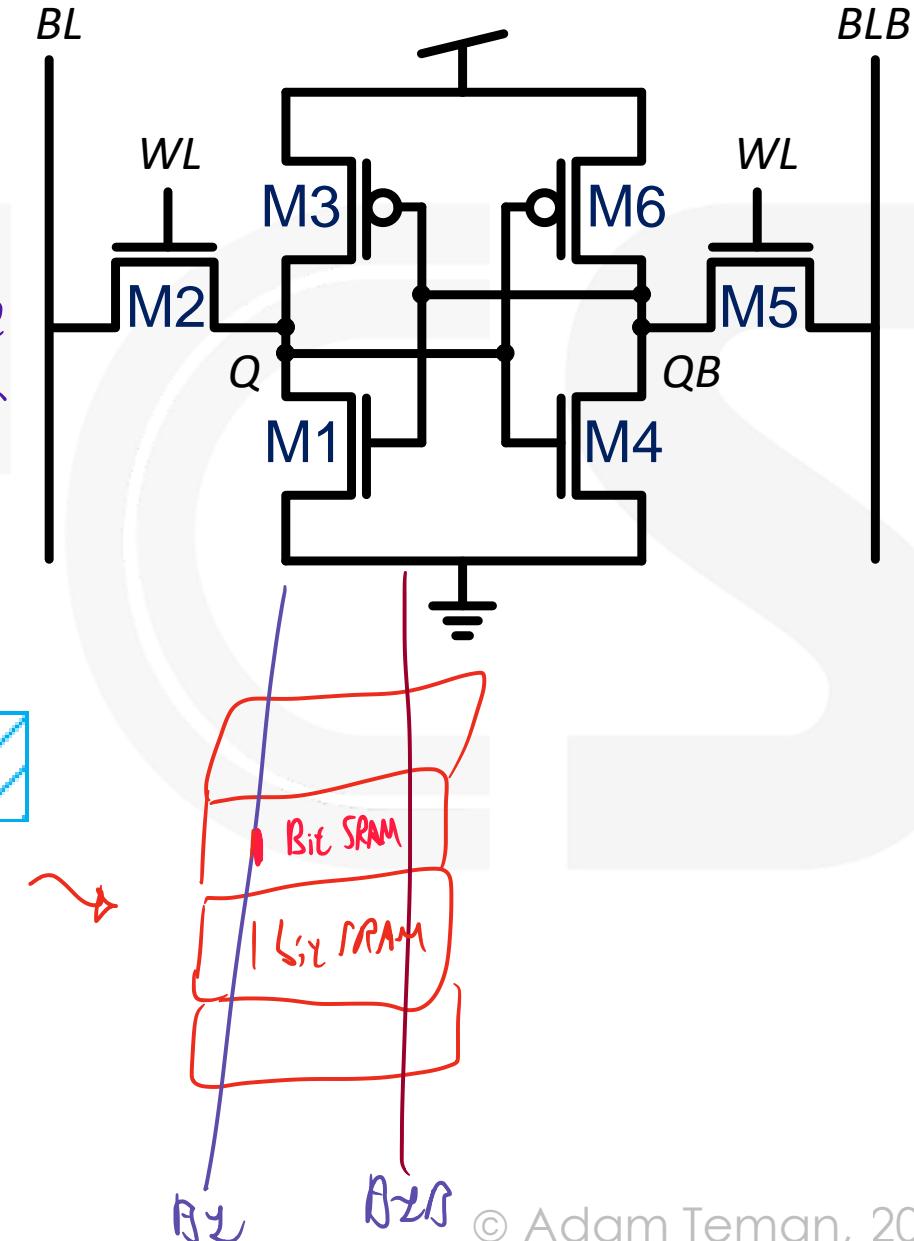
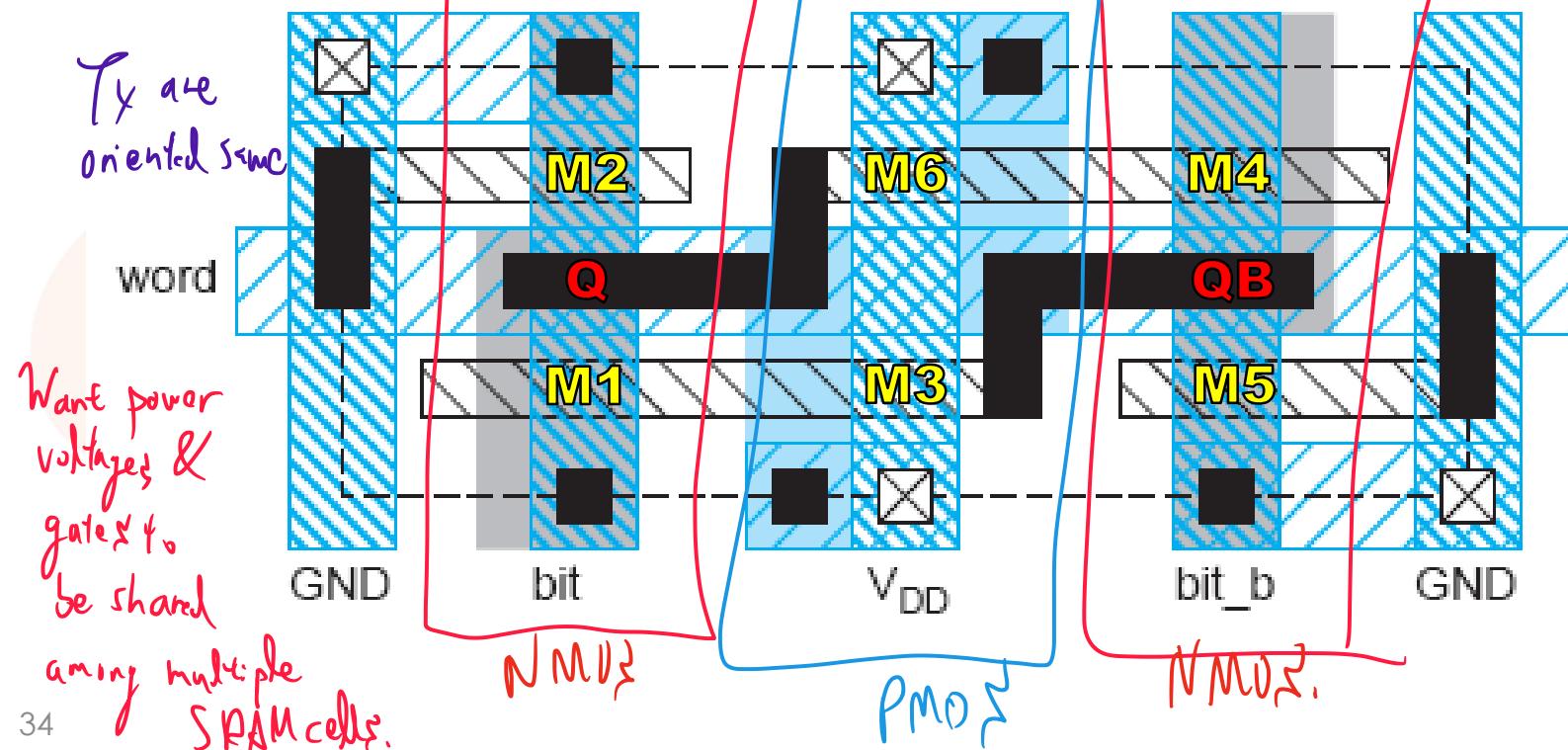
- Share Horizontal Routing (**WL**).
- Share Vertical Routing (**BL**, **BLB**).
- Share Power and Ground.

★ We want to share as many contact as possible.



SRAM Layout – Thin Cell

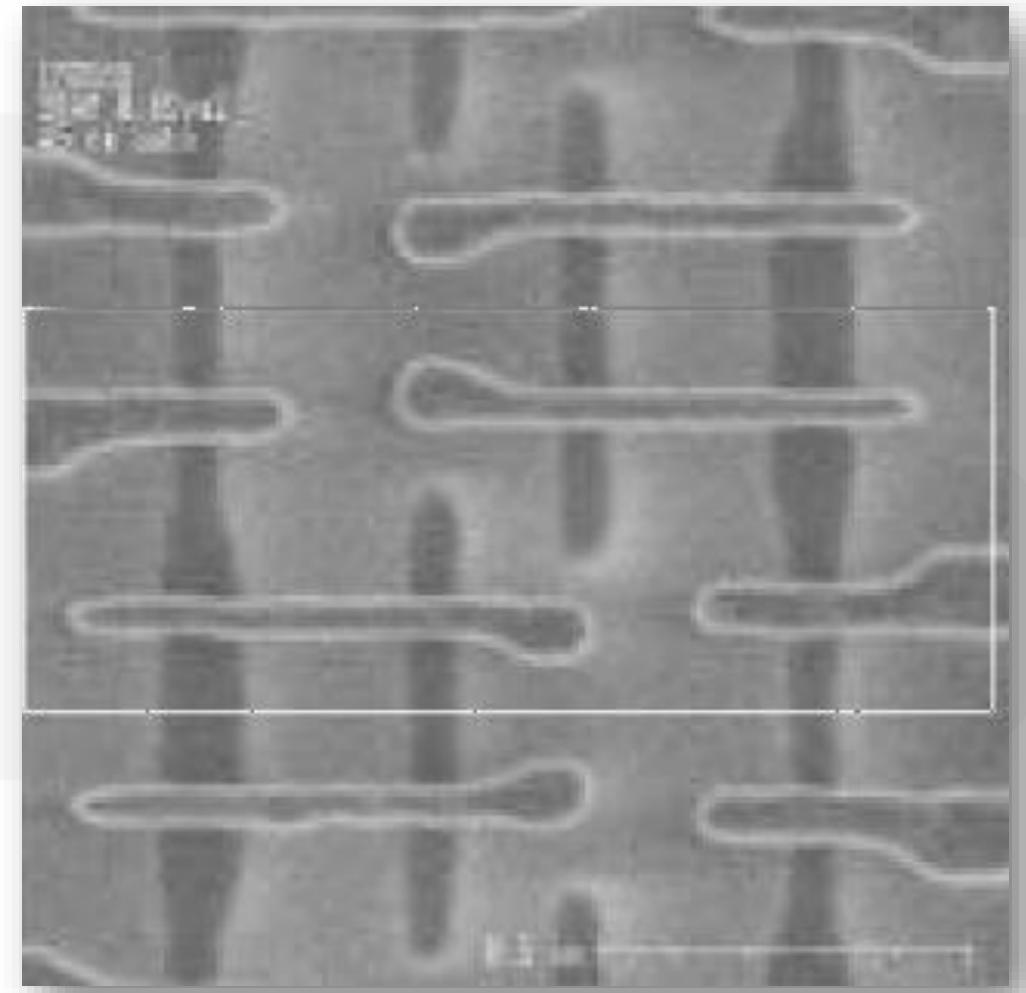
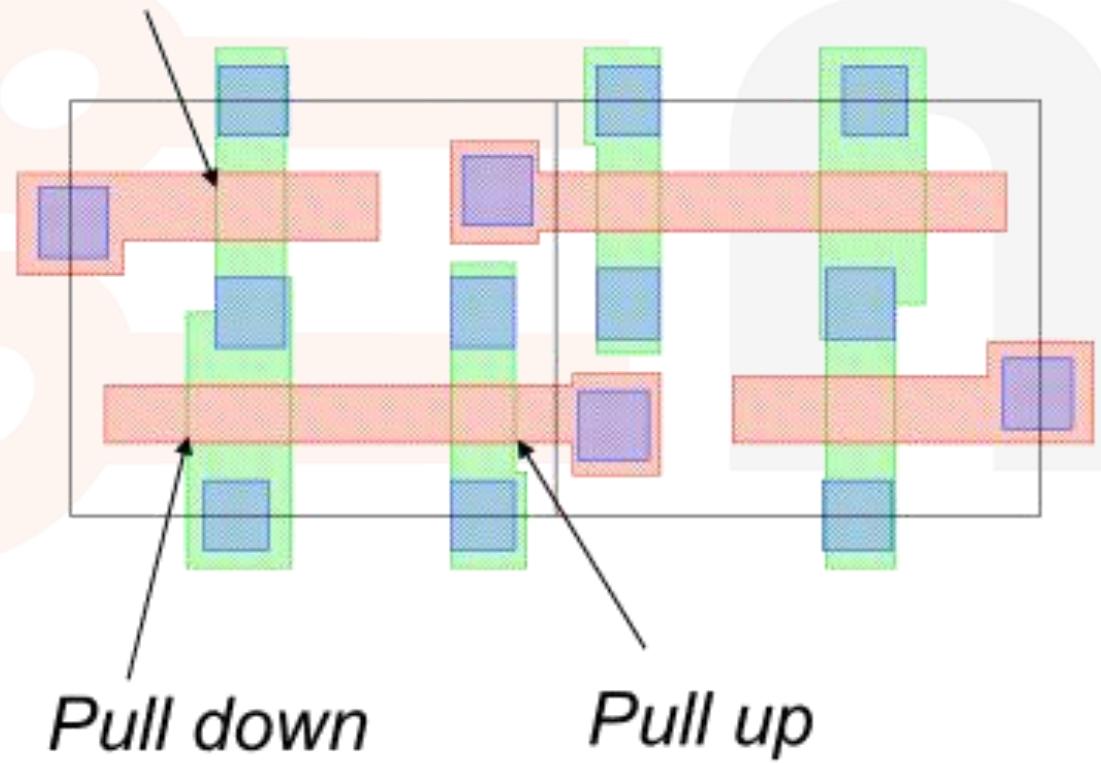
- Avoid Bends in Polysilicon and Diffusion
- Orient all transistors in one direction.
- Minimize Bitline Capacitance.



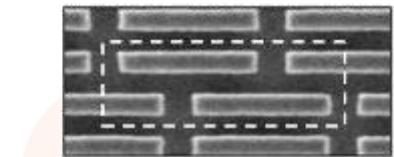
65nm SRAM

- Industrial example from ST/Phillips

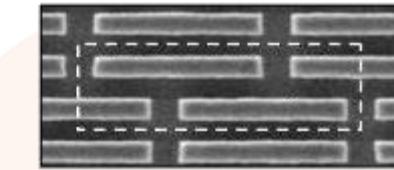
Access Transistor



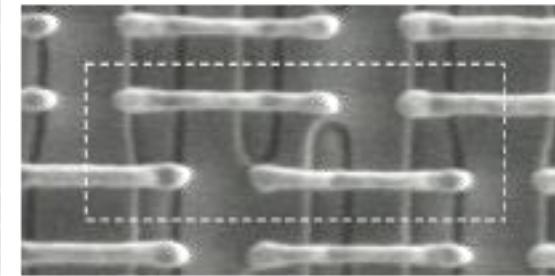
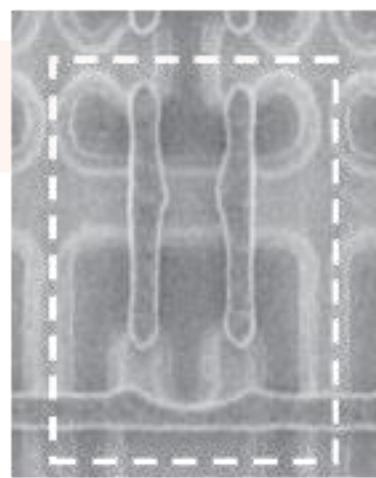
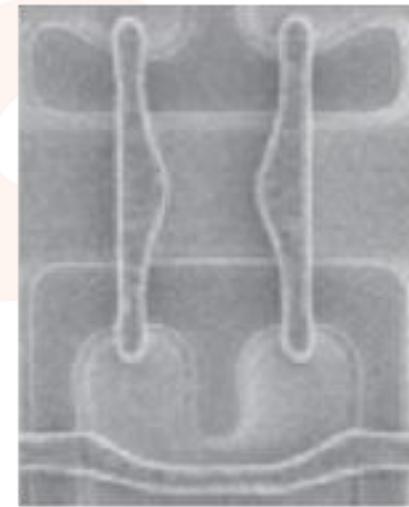
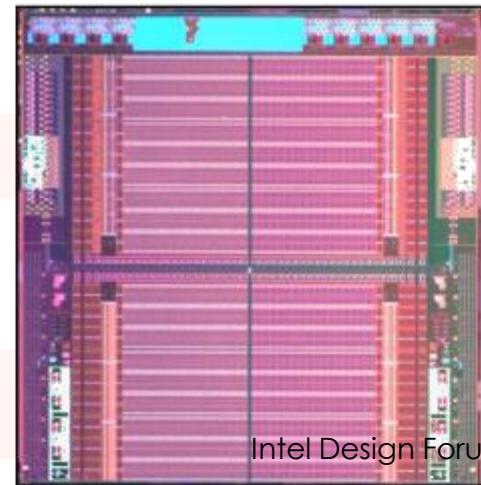
Commercial SRAMs



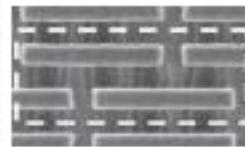
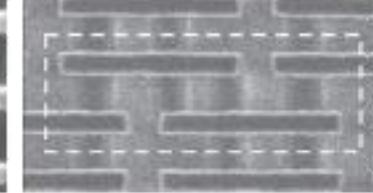
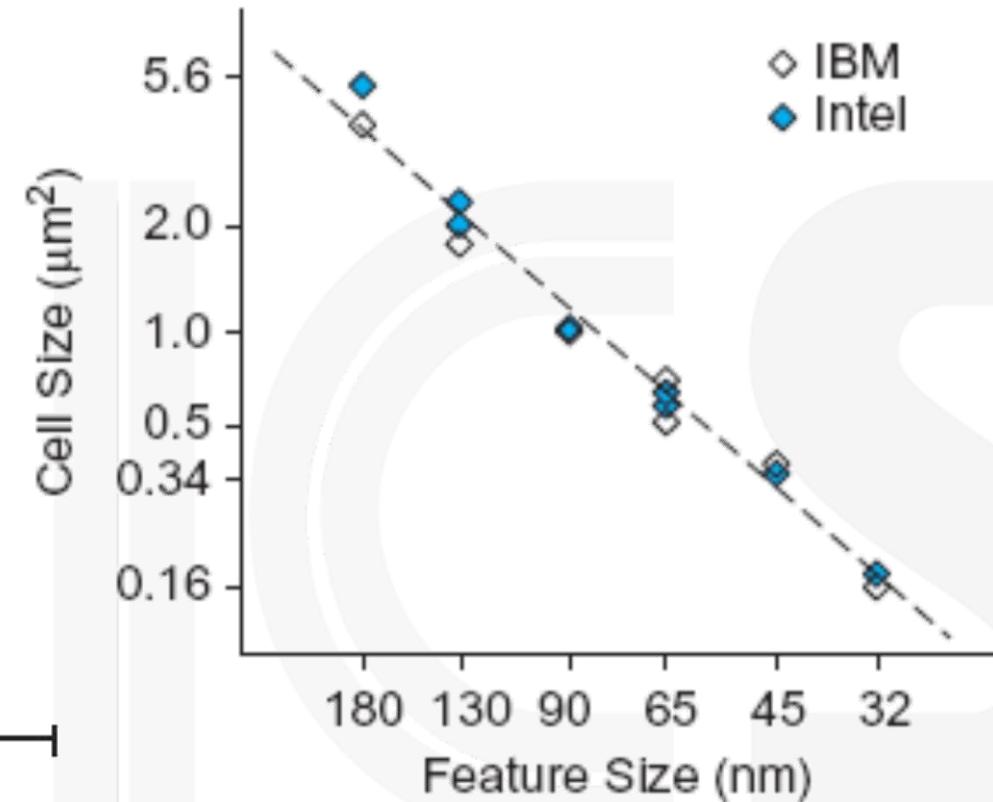
0.092 μm^2 SRAM cell
for high density applications



0.108 μm^2 SRAM cell
for low voltage applications

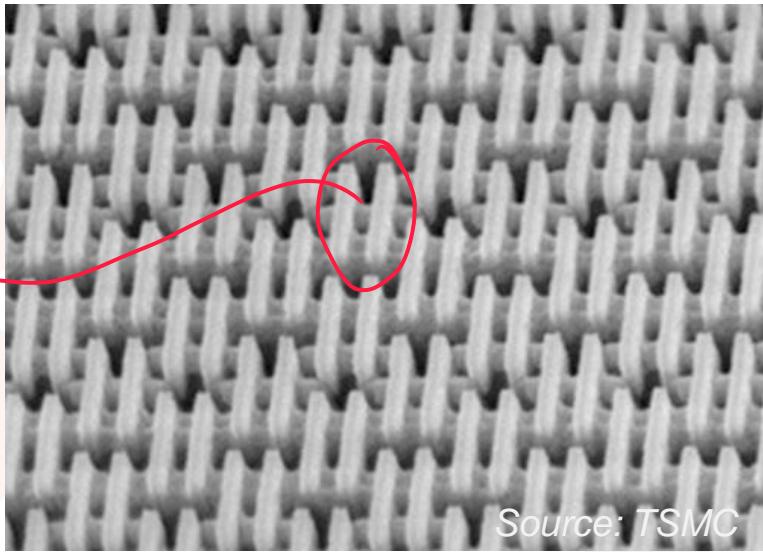


1 μm

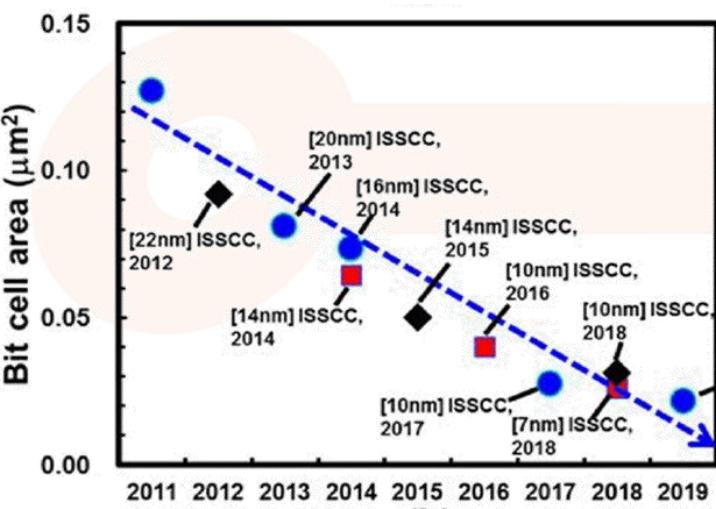


And very recent SRAMs

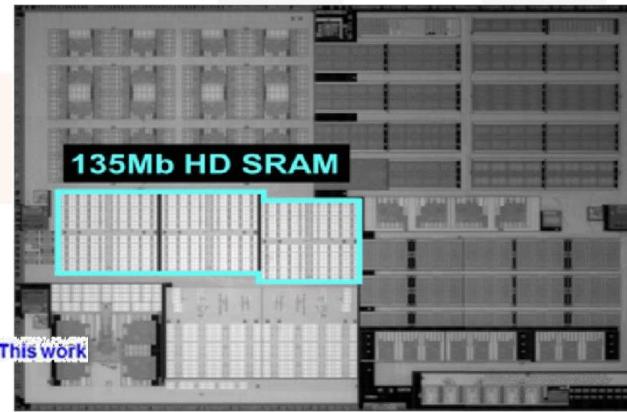
TSMC 7nm
SRAM



Source: TSMC

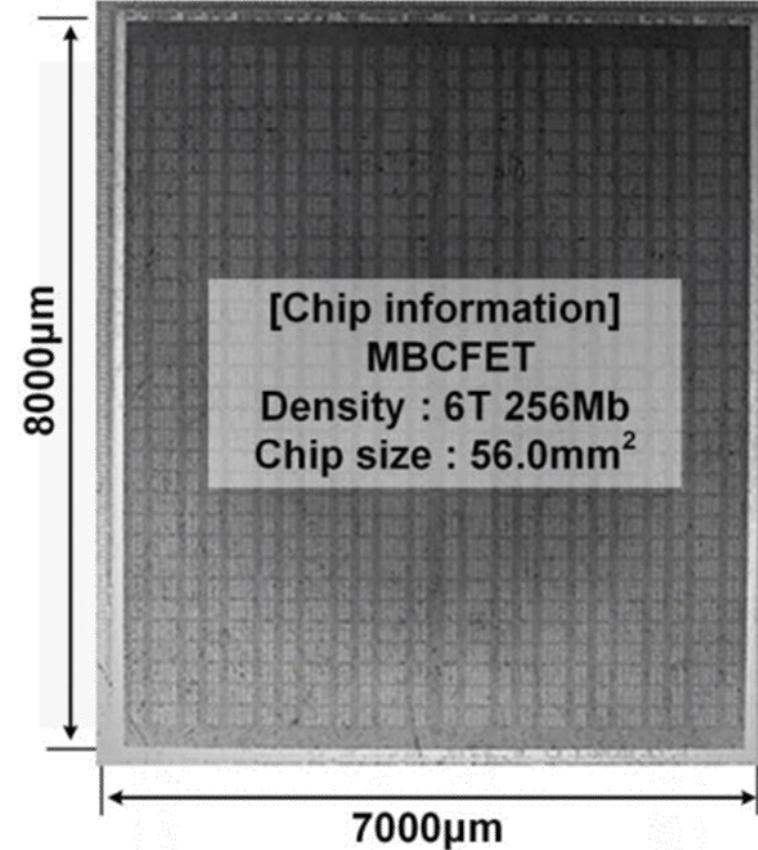


TSMC 5nm SRAM Test Chip



Source: ISSCC 2020

Samsung 3nm
GAA SRAM Test Chip



MBCFET SRAM
Vertical TEM Image

Source: ISSCC 2021

SRAM Stability

“Static Noise Margin”



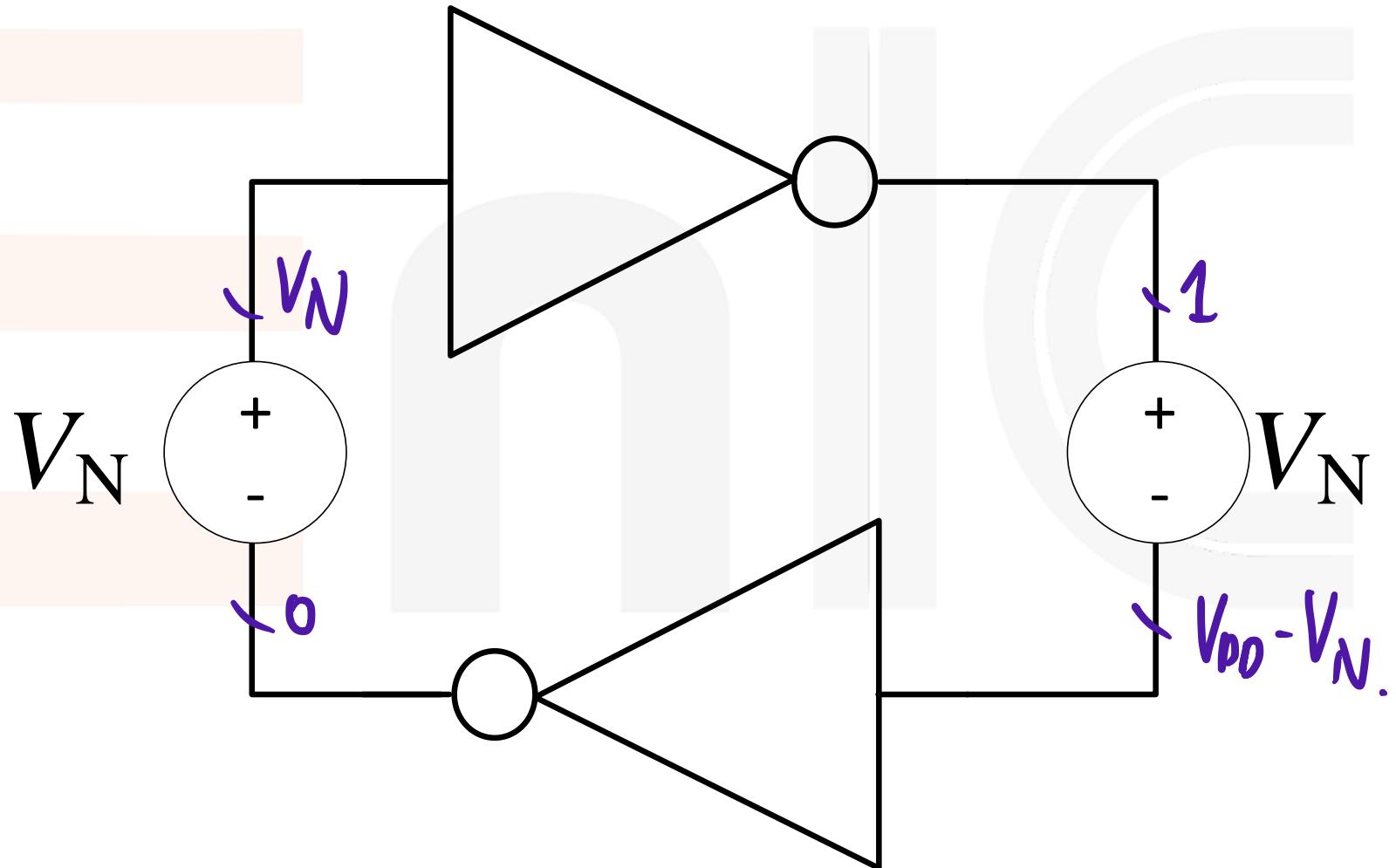
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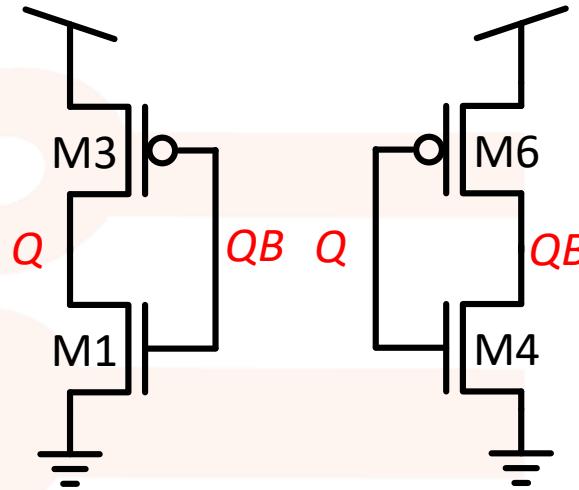
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Static Noise Margin - Hold

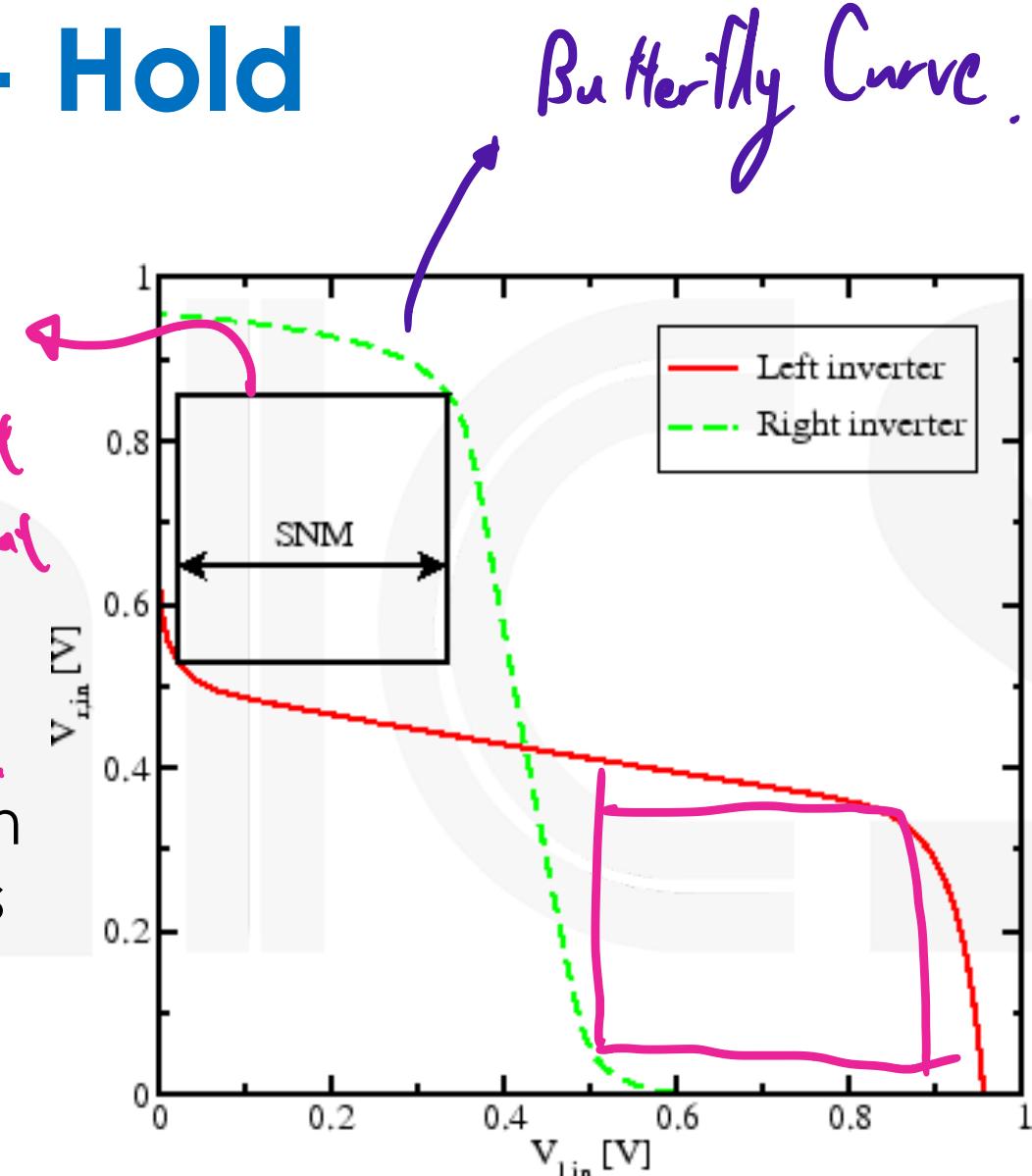


Static Noise Margin - Hold



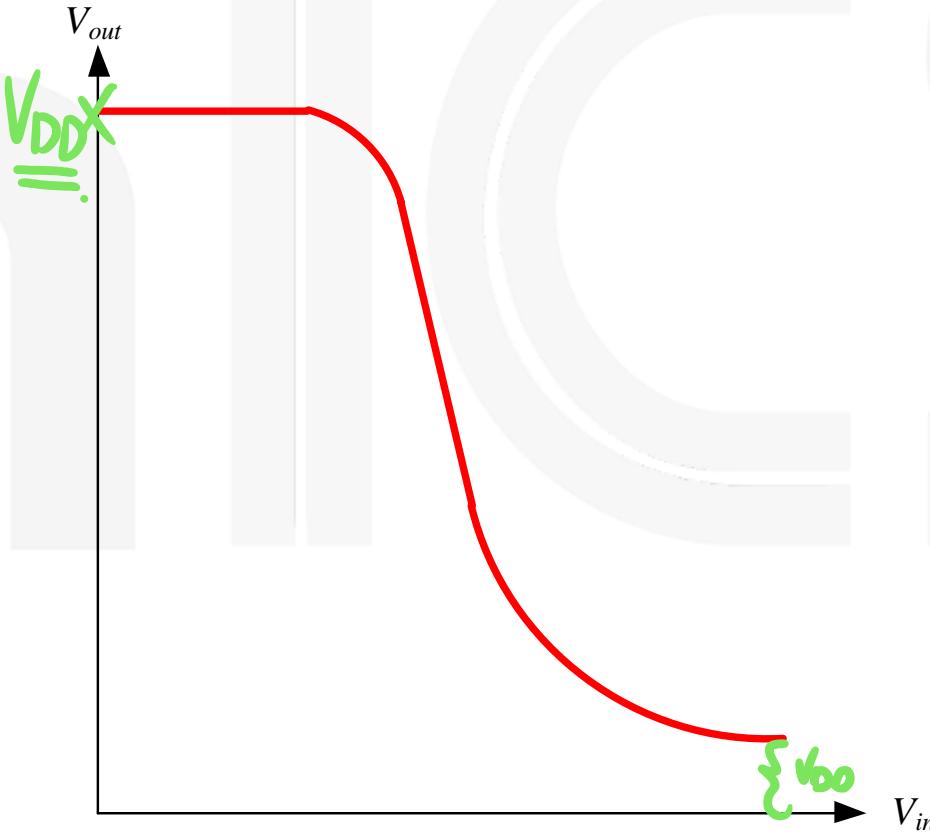
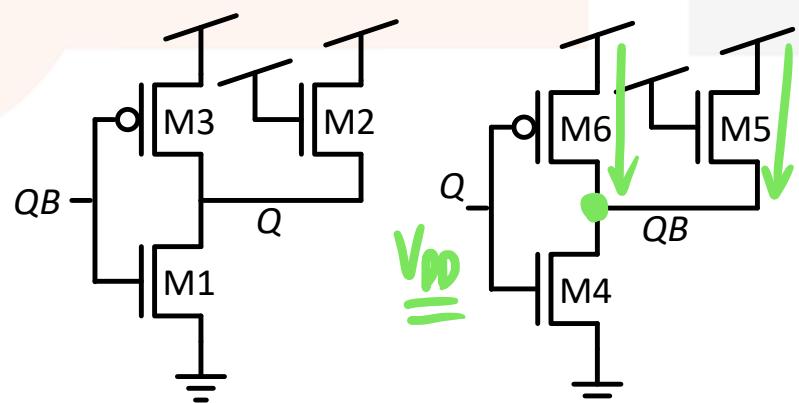
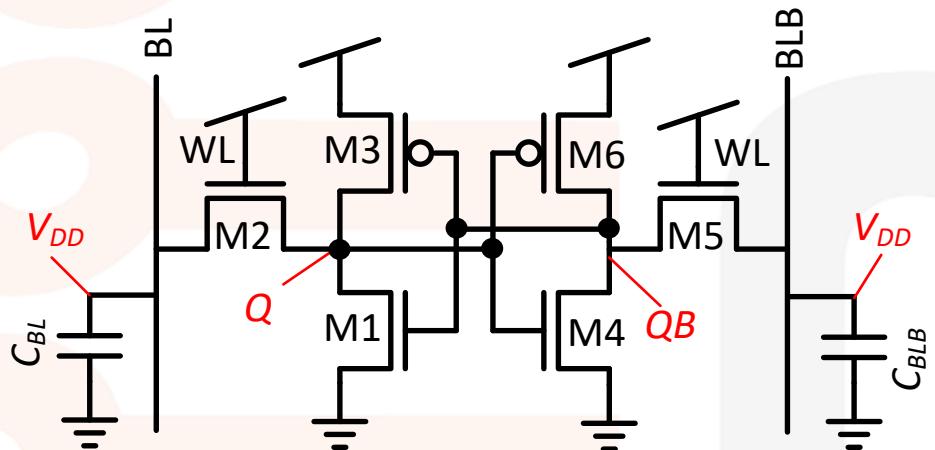
The edge size of the largest square that fits into the VTC.

1. Plot both VTCs on the same graph
2. Find the maximum square that fits in the VTC.
3. The SNM is defined as the side of the maximum square.



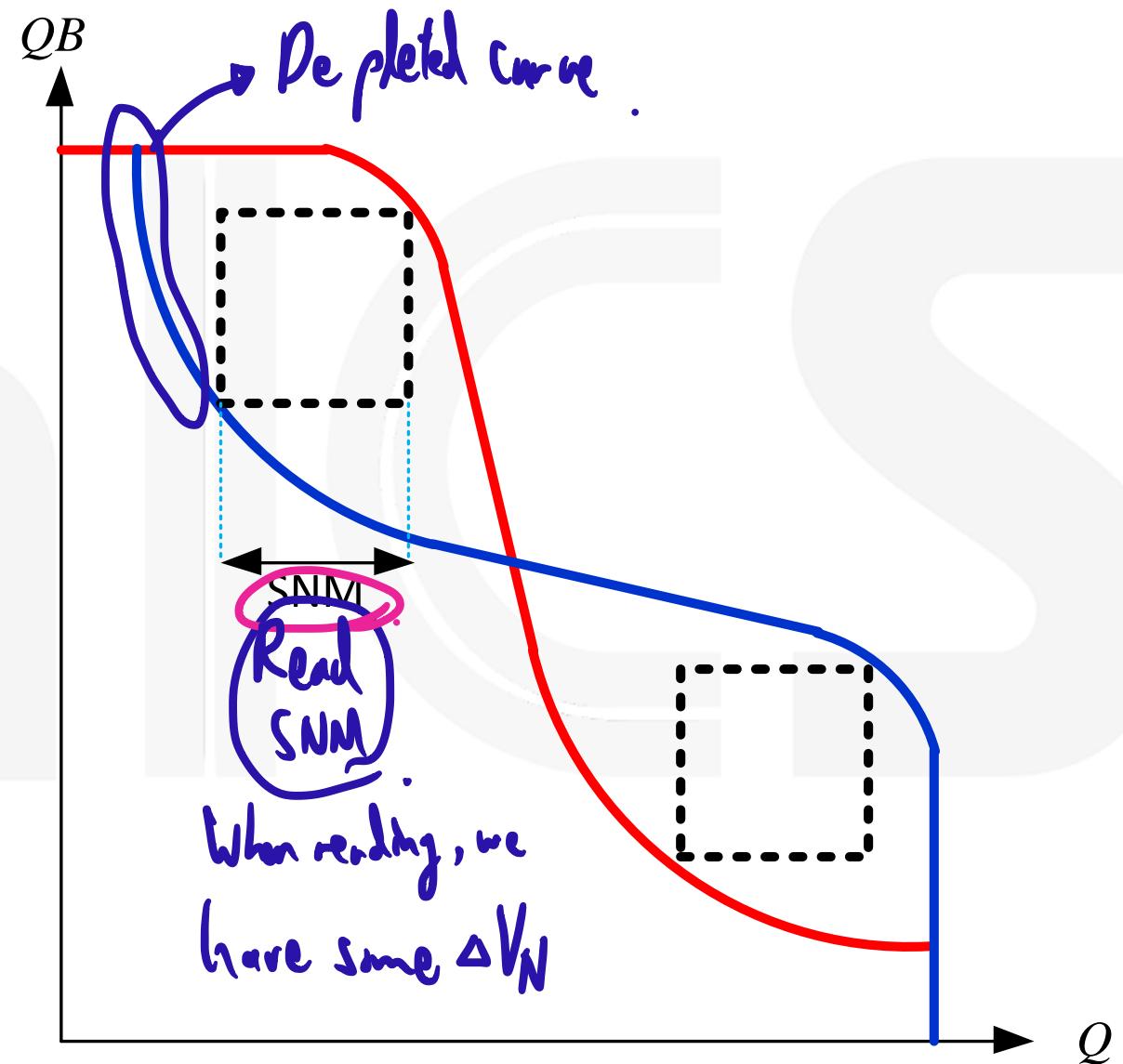
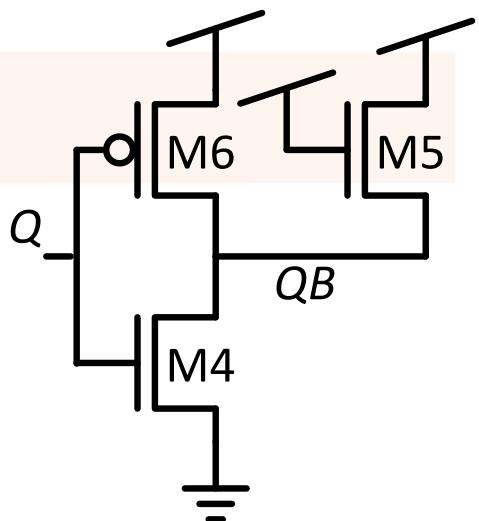
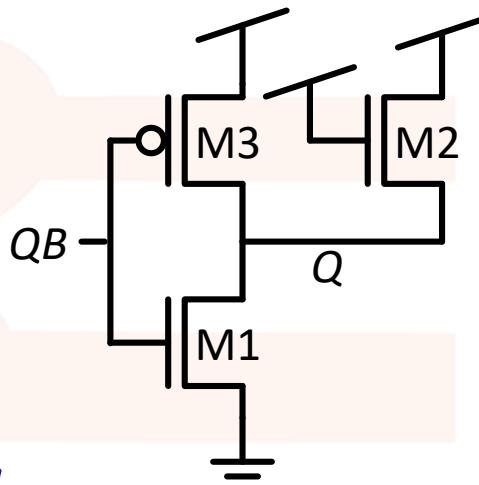
Static Noise Margin - Read

- What happens during Read?
 - We can't ignore the access transistors anymore...



Static Noise Margin - Read

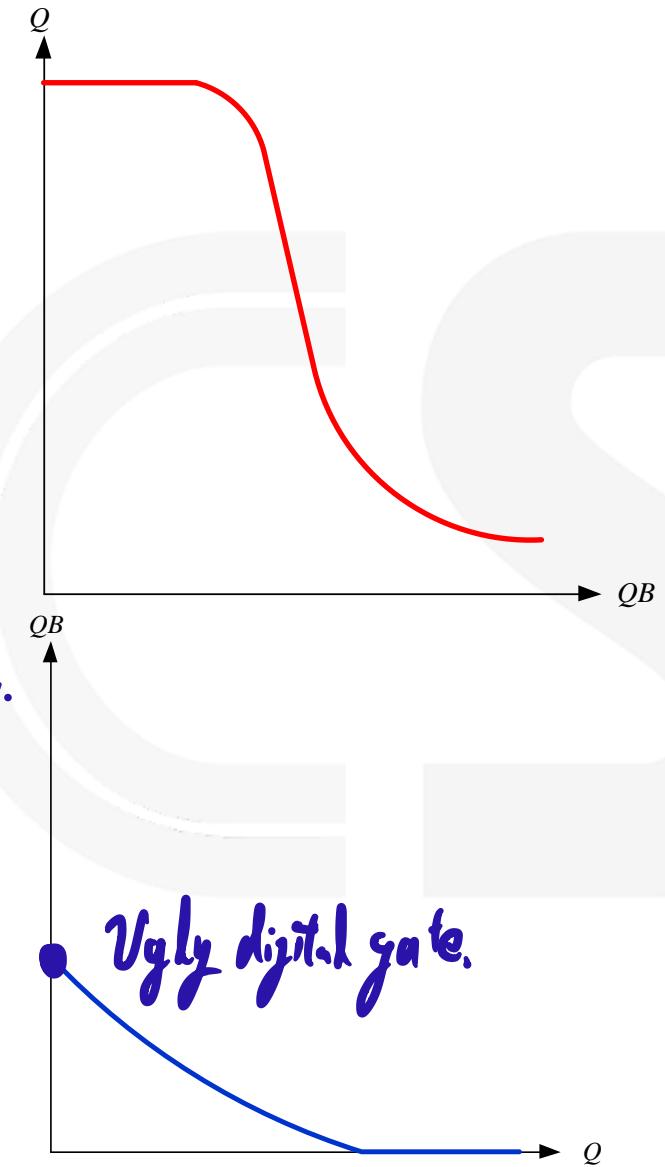
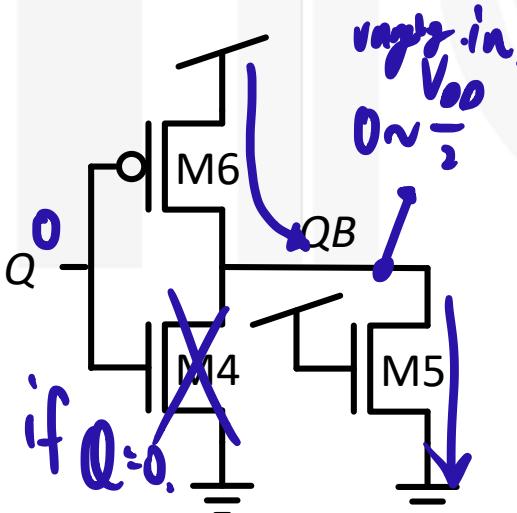
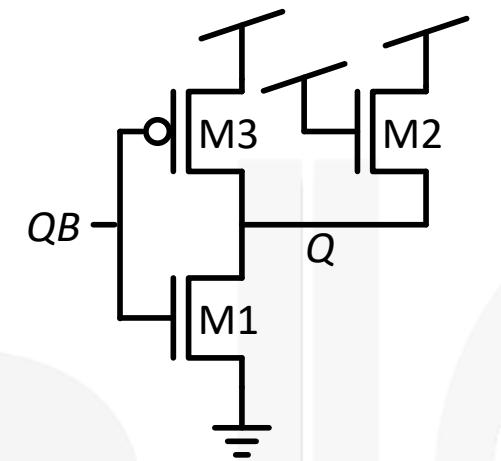
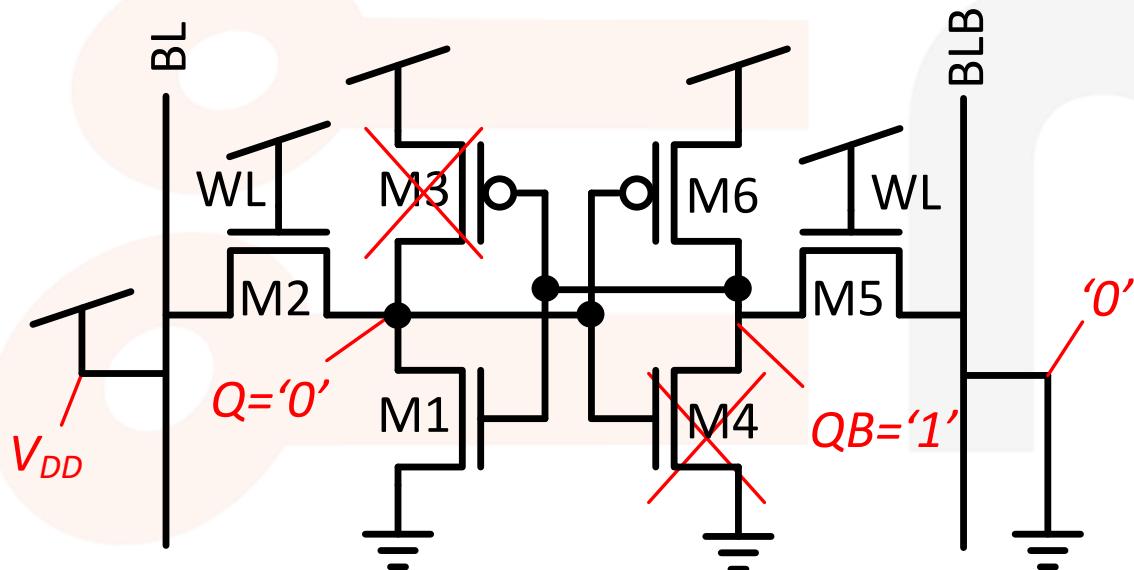
Symmetric
for
both sides
in Read.



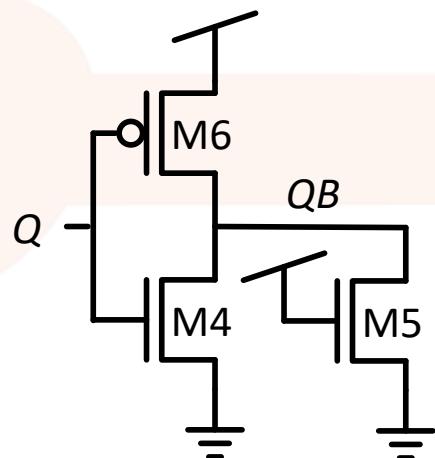
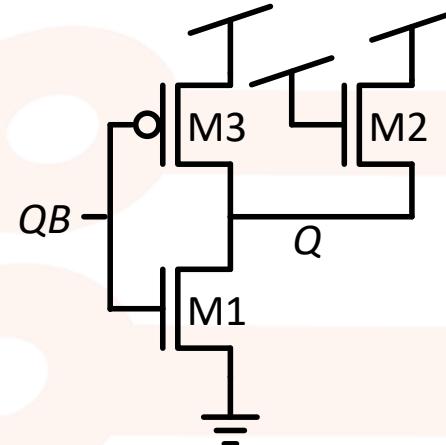
Static Noise Margin - Write

- What happens during Write?
 - The two sides are now different.

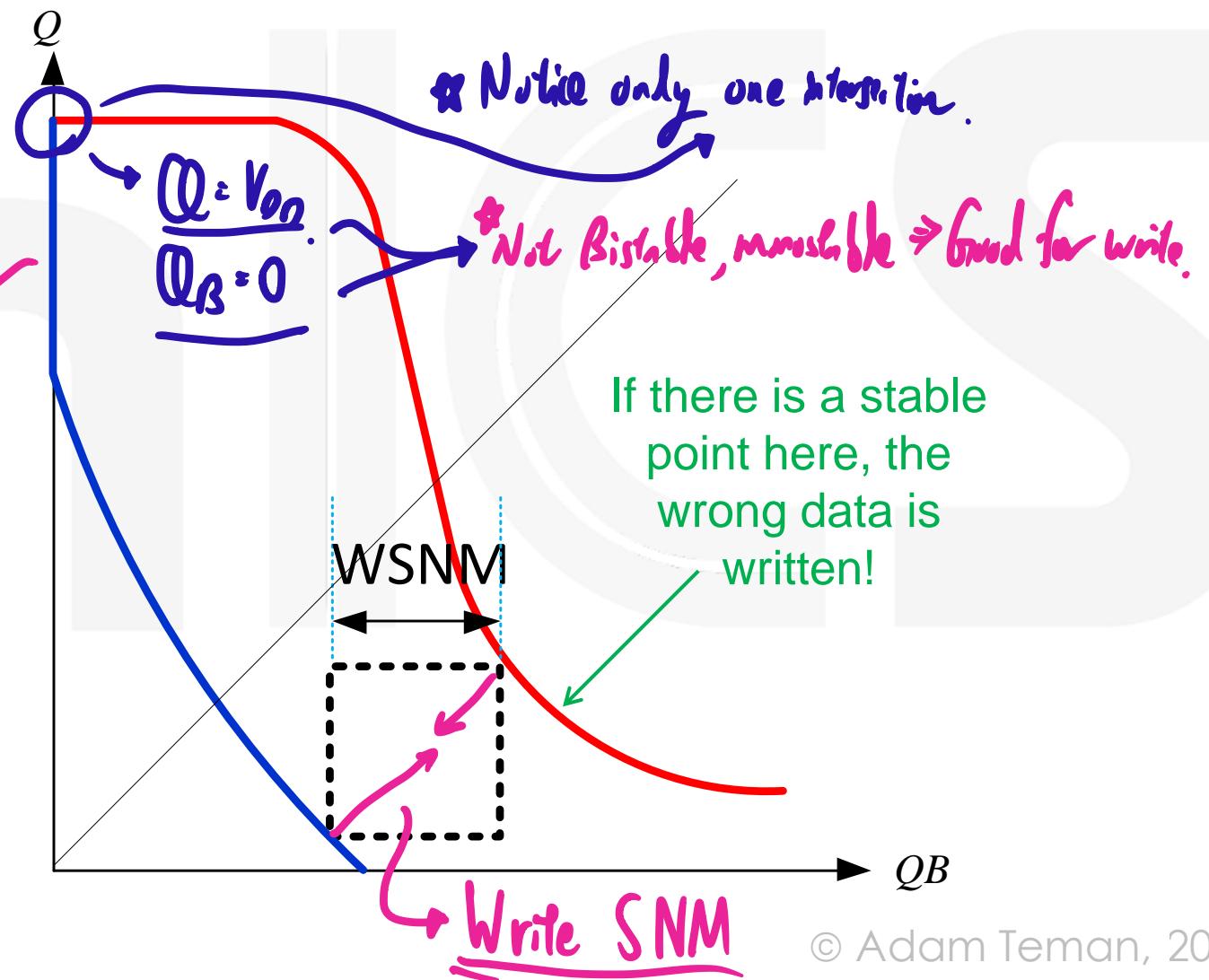
However, Write is not symmetric.



Static Noise Margin - Write

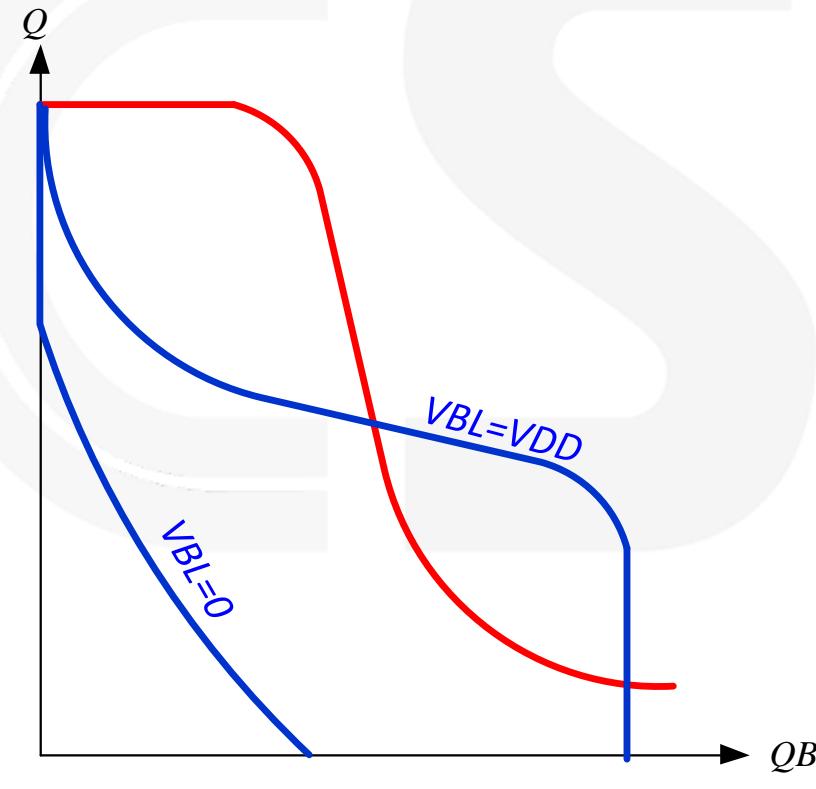
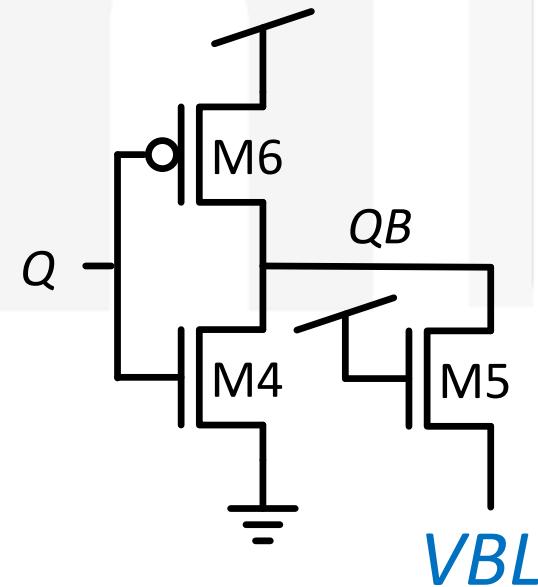
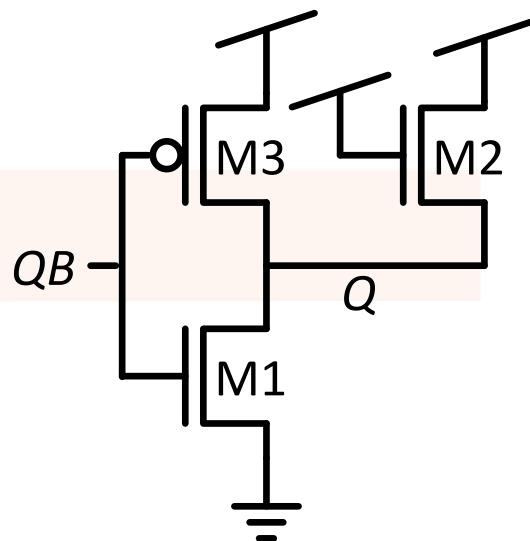


We can write
because we break
the bistability.



Alternative Write SNM Definition

- Write SNM depends on the cell's separatrix, therefore alternative definitions have been proposed.
- For example, add a DC Voltage (V_{BL}) to the 0 bitline and see how high it can be and still flip the cell.



Dynamic Stability



SNM Calculation



Emerging Nanoscaled
Integrated Circuits and Systems Labs

47

The Alexander Kofkin
Faculty of Engineering
Bar-Ilan University



Simulating SNM

- Problem:
 - How can we calculate *SNM* with *SPICE*?

- Some options:

- ① • Insert *DC sources* at *Q* and *QB*
 - But where exactly do we connect them?
- ② • Draw *Butterfly Curves*
 - But how do we find the largest squares?

- To run Monte Carlo Simulations we should have an easy way of calculation.



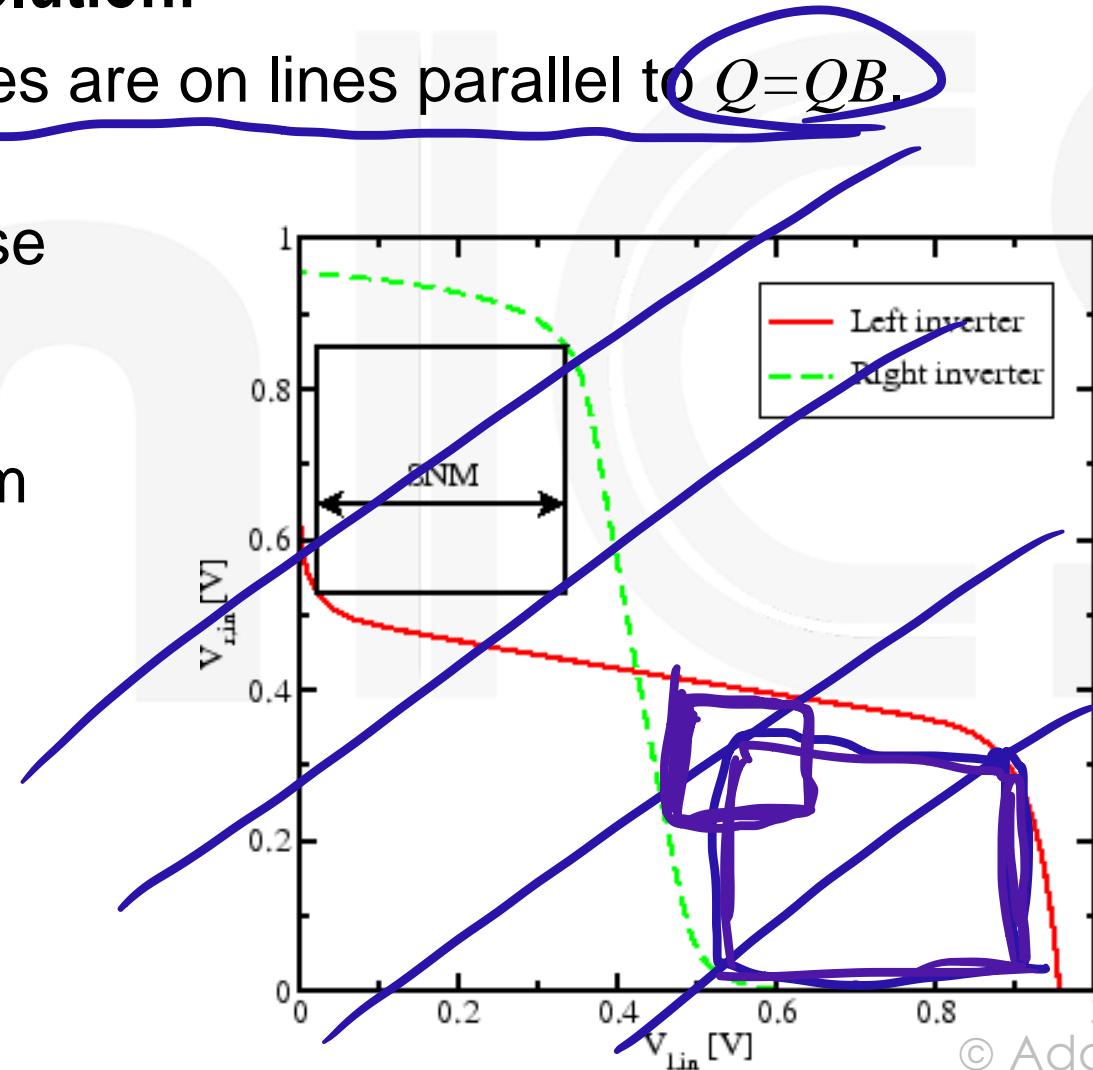
Simulating SNM

- First let's define the graphical solution:



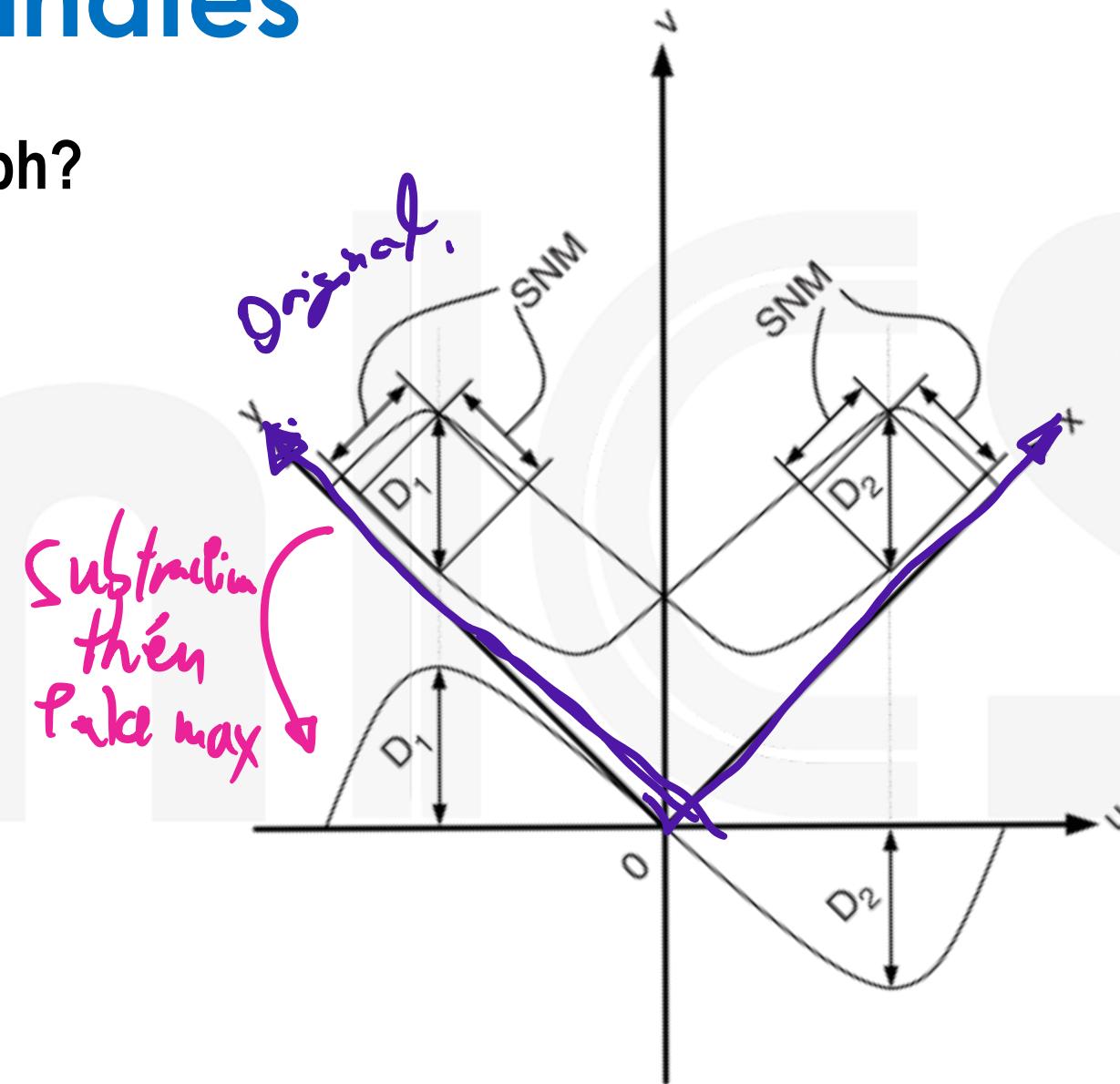
The diagonals of all the squares are on lines parallel to $Q=QB$.

- We need to find the distance between the points where these intersect the butterfly plot.
- The largest of these distances is the diagonal of the maximum square in each lobe.
- Multiply this by $\cos 45^\circ$ and we get the SNM.
- Easy, right?



Changing Coordinates

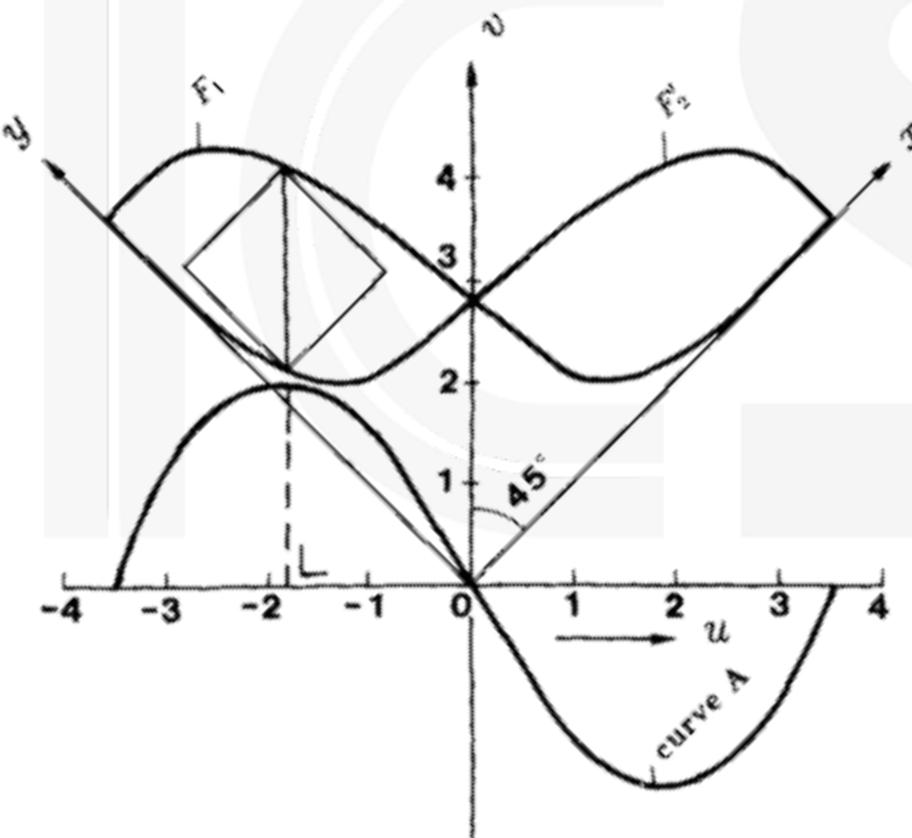
- What if we were to turn the graph?



Changing Coordinates

- If we were to use new axes, we could just subtract the graphs.
 - This gives us the distances between the intersections with the $Q=QB$ parallels.
 - Now all we have to do is find the maximum of the subtraction.
 - (Don't forget to multiply by $\cos 45^\circ$)

* Thus simply change coordinates



Changing Coordinates

- The required transformation is:

$$x = \frac{1}{\sqrt{2}}u + \frac{1}{\sqrt{2}}v$$

$$y = -\frac{1}{\sqrt{2}}u + \frac{1}{\sqrt{2}}v$$

- Now let's define some function as F_1

- Substituting $y=F_1(x)$ gives:

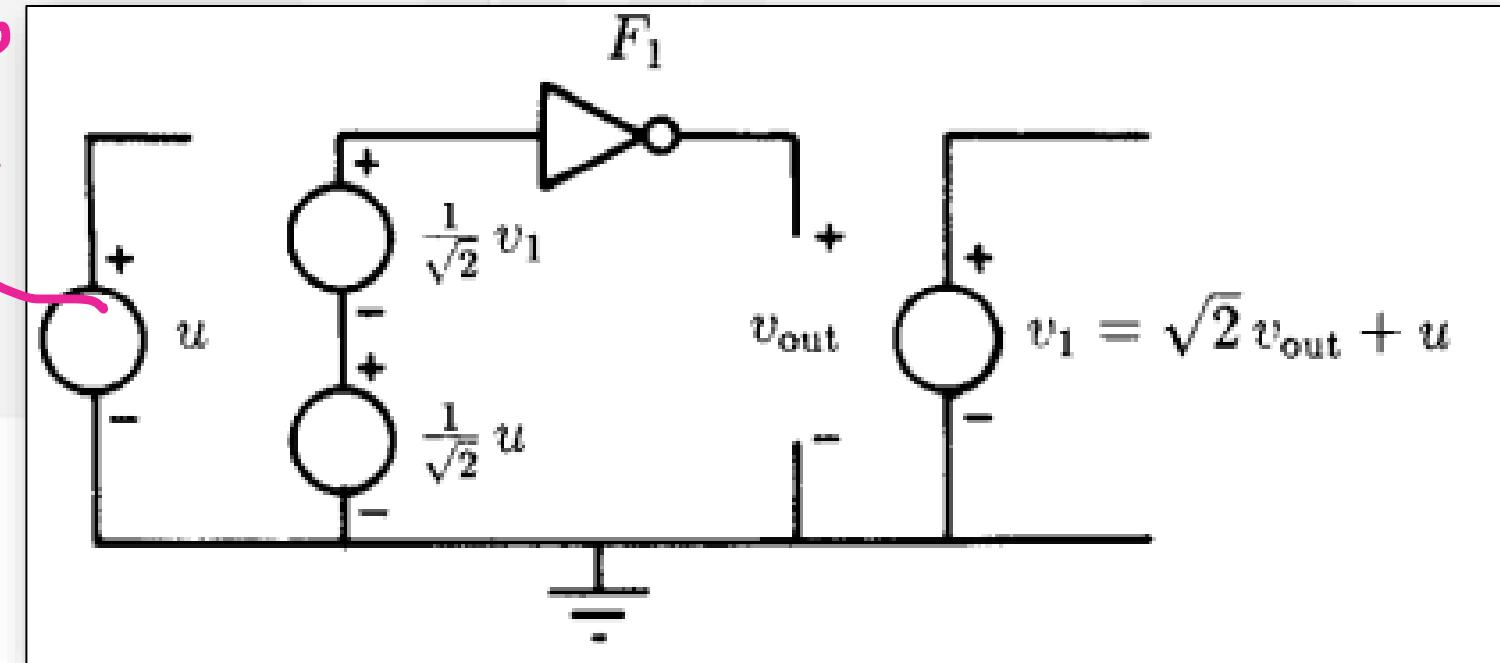
$$\begin{aligned} v &= u + \sqrt{2}y = \\ &= u + \sqrt{2}F_1\left(\frac{1}{\sqrt{2}}u + \frac{1}{\sqrt{2}}v\right) \end{aligned}$$

Changing Coordinates

- What we did is turn some function (F_1) *45 degrees counter clockwise*.
- This can easily be implemented with the following circuit:

This is for feedforward VTC

- What is F_1 ? \approx
- It could be the VTC of $V_{in}=Q$, $V_{out}=QB\dots$



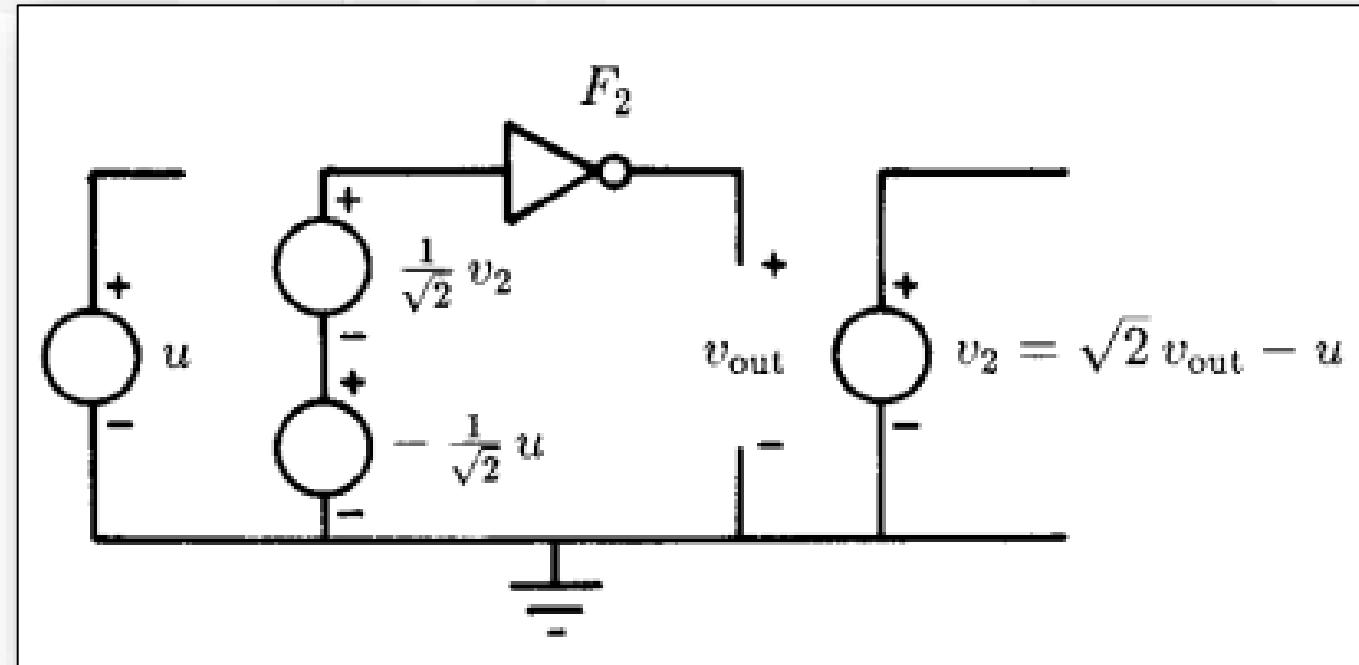
Changing Coordinates

- But what about the “mirrored” VTC?

- This needs to first be mirrored with respect to the v axis and then transformed to the (u, v) system.
- If we call the second VTC F_2 with $x=F_2(y)$ then the operation we need is:

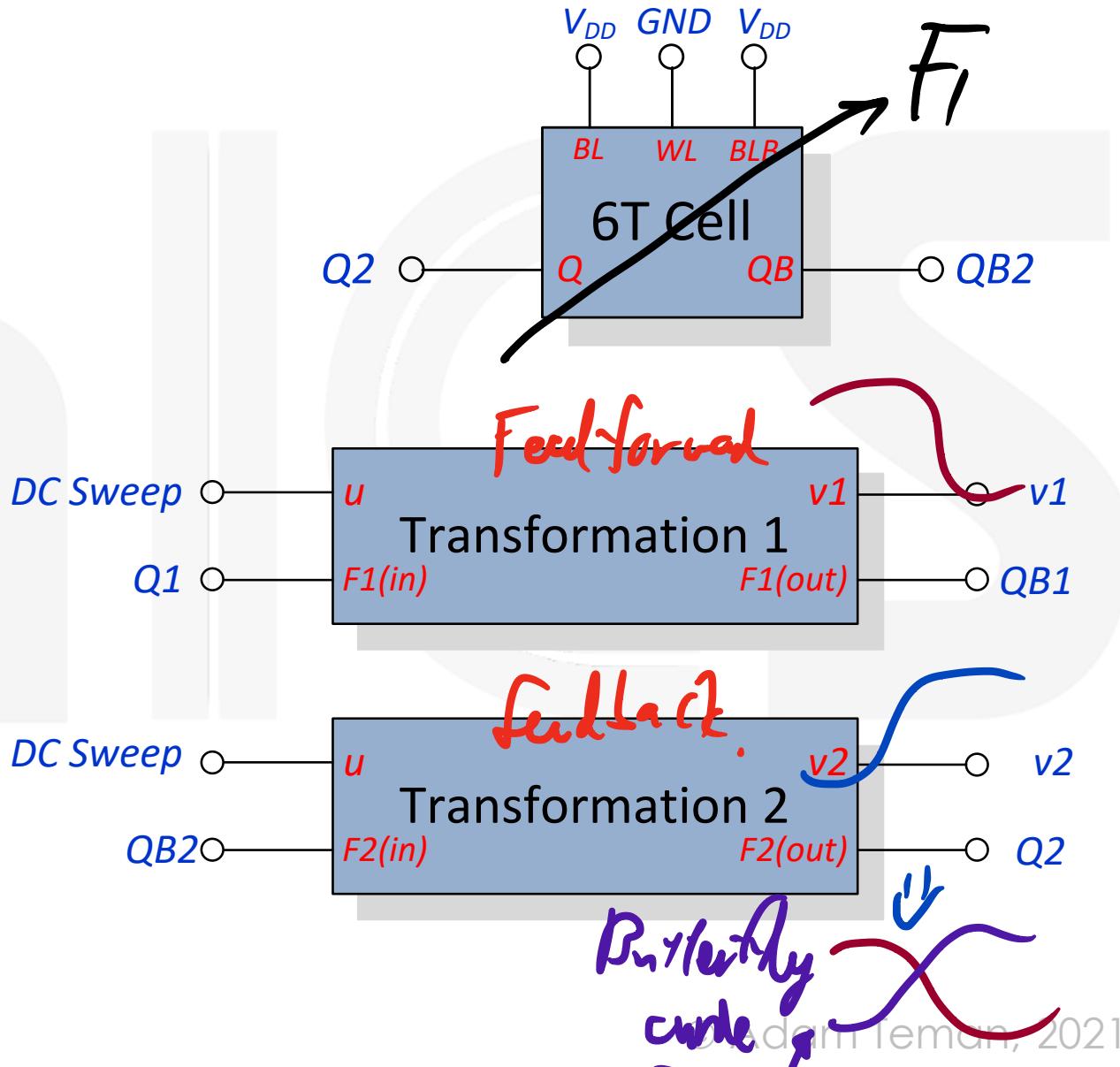
$$v = -u + \sqrt{2}x$$

$$= -u + \sqrt{2}F_2\left(\frac{v}{\sqrt{2}} - \frac{u}{\sqrt{2}}\right)$$

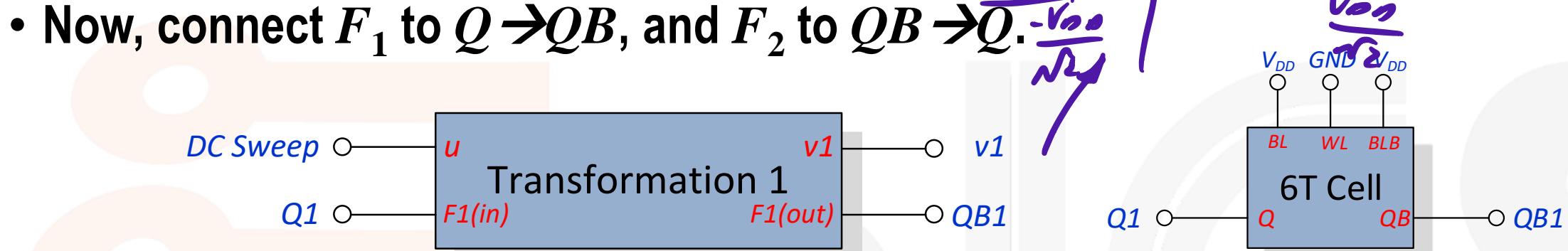


Final SNM Calculation

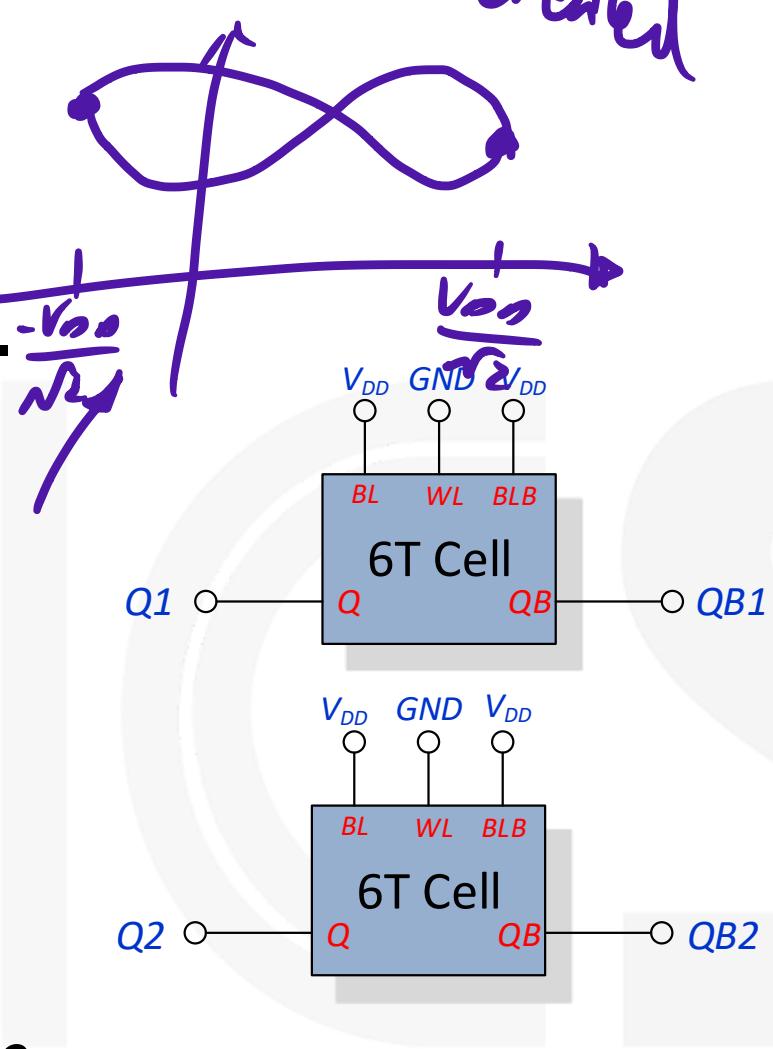
- Now we need to:
 - Make a schematic of our SRAM cell with two pins: Q and QB .
 - Create a coordinate changing circuit for each of the transformations.



Final SNM Calculation



- Run a *DC Sweep* on u from $-V_{DD}/\sqrt{2}$ to $V_{DD}/\sqrt{2}$
- This will present the butterfly curves turned 45 degrees.



Final SNM Calculation

- Now just:

- Subtract the bottom graph from the top one.
- Find the local maxima for each lobe.
- The smaller of the local maxima
is the diagonal of the largest square.
- Multiply this by $\cos 45^\circ$ for the *SNM*

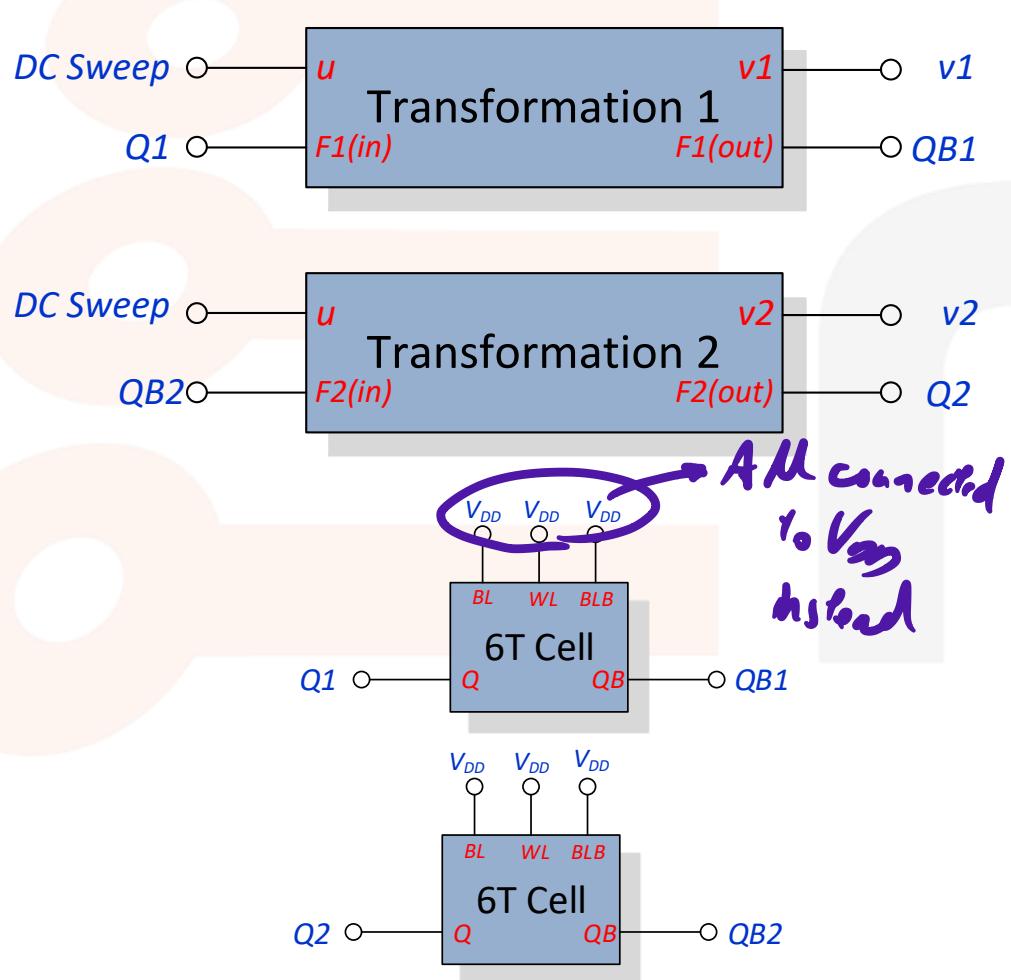
$$SNM = \frac{1}{\sqrt{2}} \cdot \min \left[\max \left(|v_1 - v_2| \right) \Big|_{-\sqrt{2} < u < 0}, \max \left(|v_1 - v_2| \right) \Big|_{0 < u < \sqrt{2}} \right]$$

Read/Write SNM

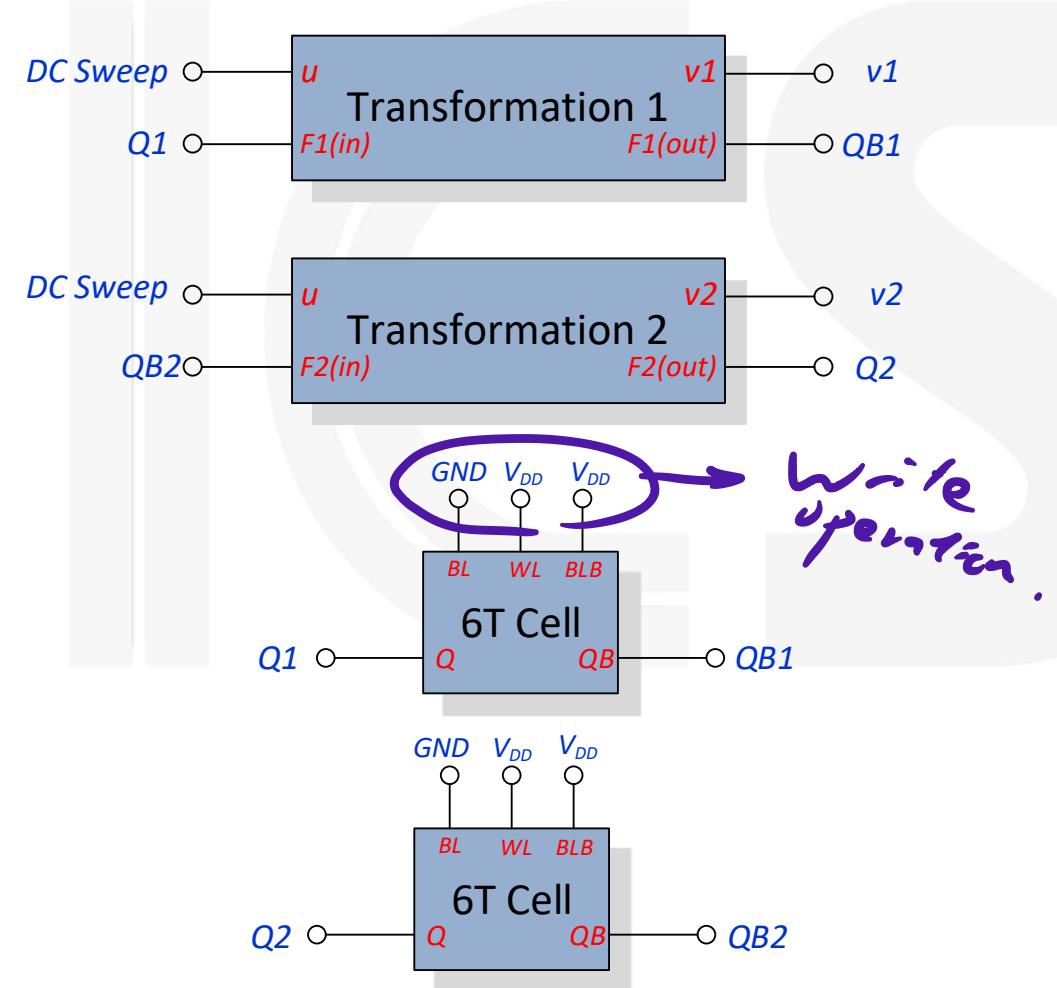
- How about Read SNM:
 - Use the exact same setup.
 - Connect BL and BLB to VDD .
 - Connect WL to VDD .
 - Run the same calculation.
- And Write SNM.
 - Now connect one BL to GND .
 - This is trickier, so you'll have to play around with the calculation.
 - There are other options for WM calculation.

Testbench Setup – Read/Write

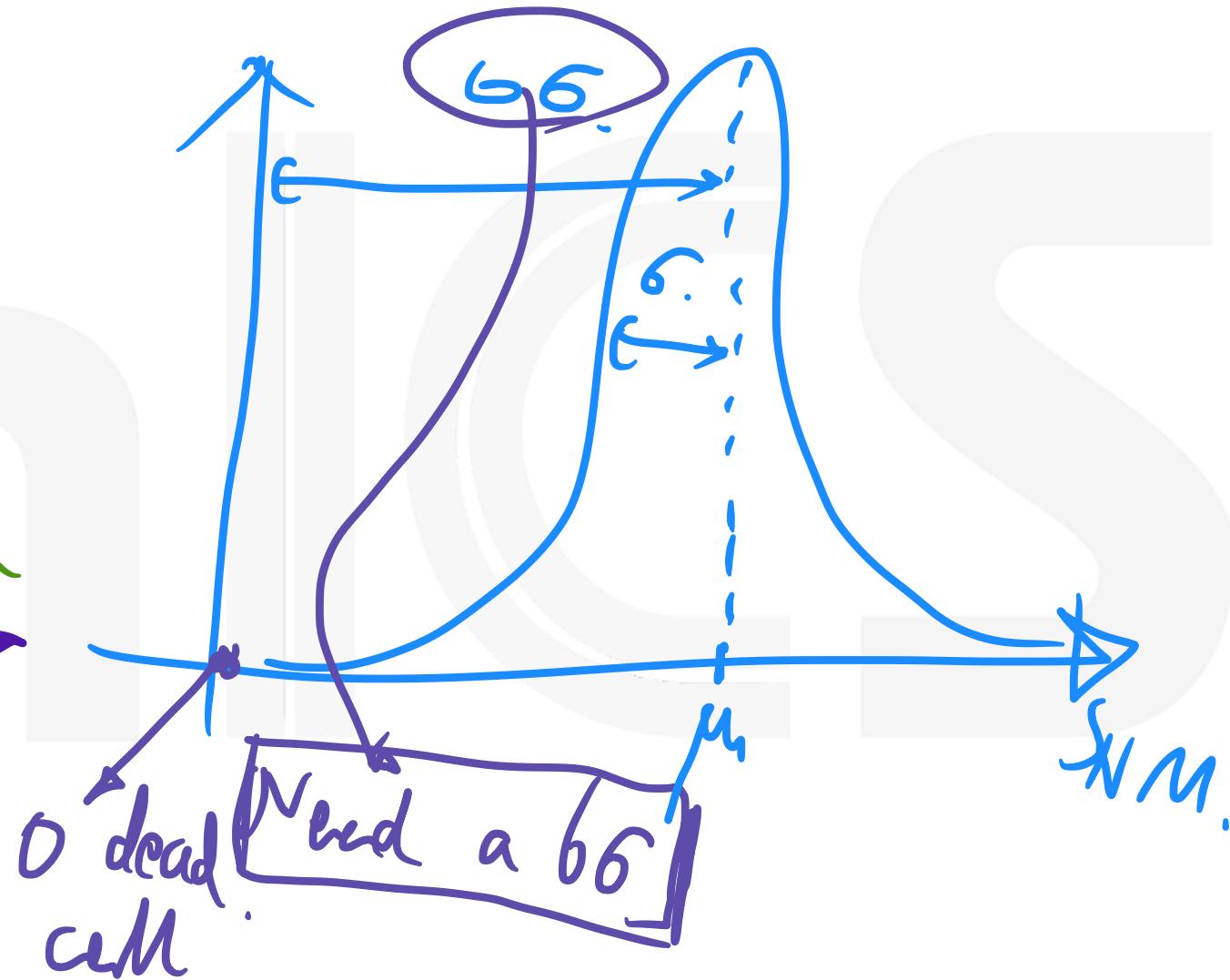
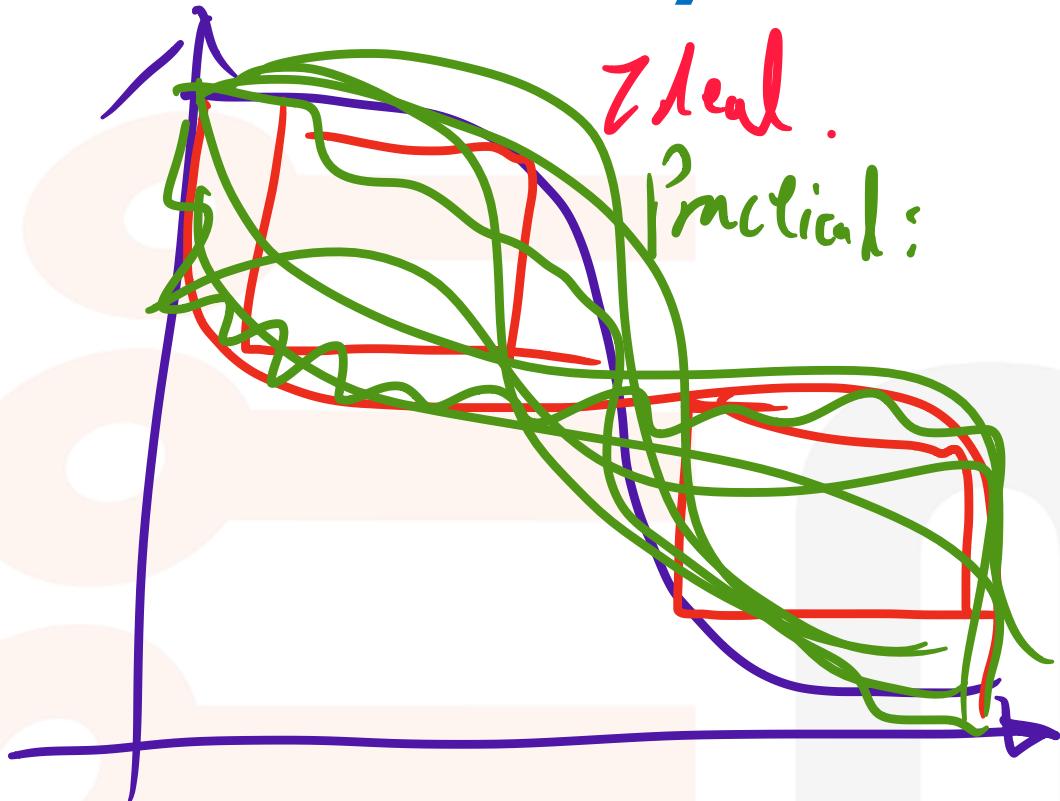
Read Testbench:



Write Testbench:



SRAM Stability under process variations



⇒ 6T SRAM is very
unstable due to process variations.

Metastability Convergence in Spectre

- Node Sets
 - What solution does Virtuoso find with a standard OP?
 - To fix this, make sure you use the “Node Set” option.

Node Sets vs. Initial Conditions

- SPICE supports two types of conversion aids :

- **Node Sets:**

- Help SPICE converge by providing it with an *initial guess*.
- Used only for DC convergence!
Disregarded for Transient Analysis.

- **Initial Conditions:**

- Enforce a node voltage at time $t=0$.
- Used only for Transient analysis!
Disregarded for DC convergence.

Additional simulation tips



Work with Design Hierarchy

- Create transformation functions and DUTs as symbols.
- Create multiple tests in single ADE-XL view.
- Use variables/parameters to define initial conditions/node sets.
- Create supply voltages in separate symbol.
- Use buffers to smooth transitions and reduce cross cap.

Further Reading

- Rabaey, et al. “Digital Integrated Circuits” (2nd Edition)
- Elad Alon, Berkeley ee141 (online)
- Weste, Harris, “CMOS VLSI Design (4th Edition)”
- Seevinck, List, Lostroh, “Static Noise Margin Analysis of SRAM Cells”
IEEE Journal of Solid State Circuits, 1987
- Teman and Visotsky. "A fast modular method for true variation-aware separatrix tracing in nanoscaled SRAMs." IEEE TVLSI, 2014.