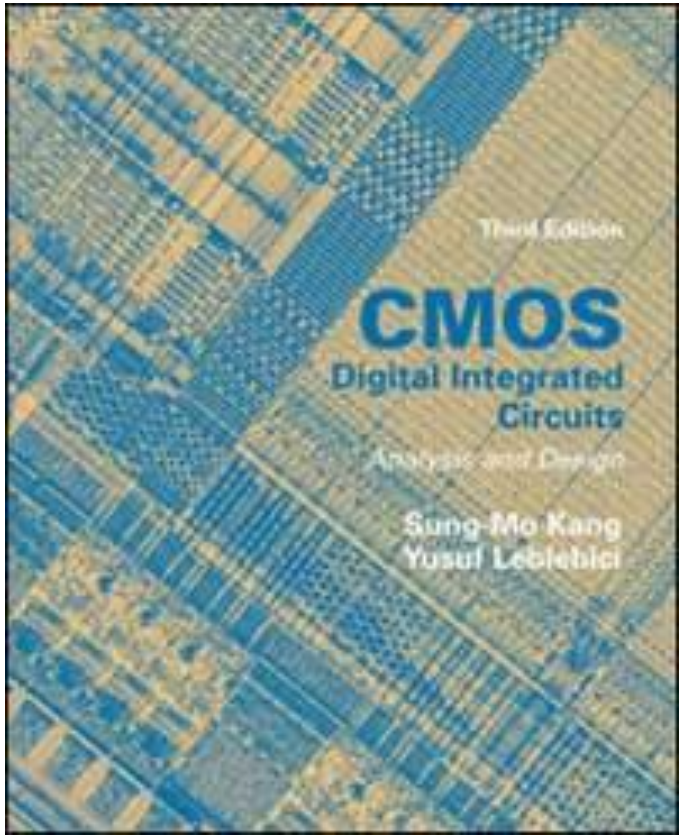
Digital IC Design and Architecture



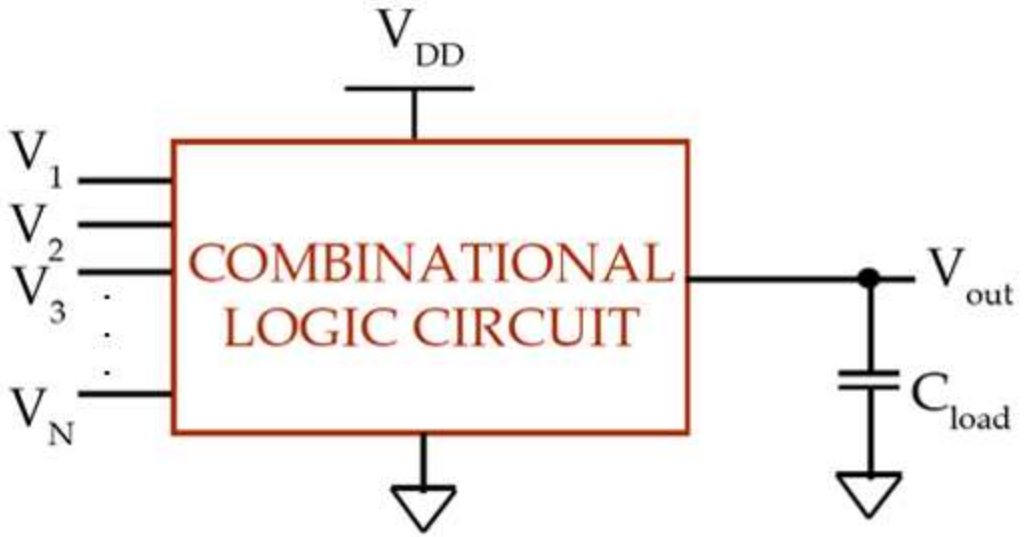
Combinational Logic and Circuits

Static CMOS Circuit

At every point in time (except during the switching transients) each gate output is connected to either V_{DD} or V_{ss} via a low-resistive path.

The outputs of the gates assume at all times the value of the Boolean function, implemented by the circuit (ignoring, once again, the transient effects during switching periods).

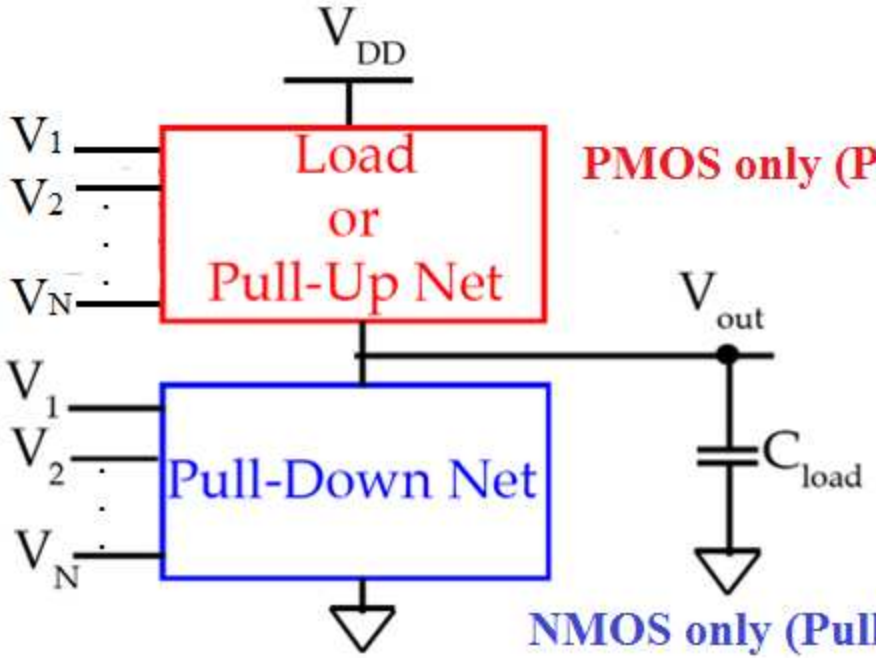
This is in contrast to the dynamic circuit class, which relies on temporary storage of signal values on the capacitance of high impedance circuit nodes.



V_{out} is Boolean function of inputs, V_1, V_2, V_3, ..., V_N.

"1" => V_{DD}

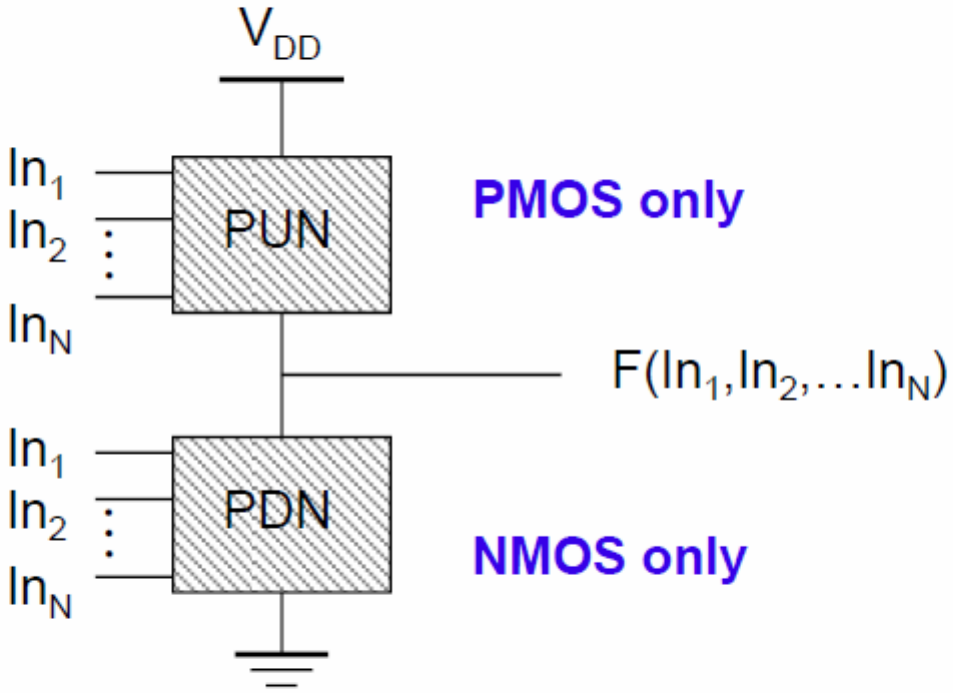
"0" => 0



PMOS only (Pull-Up Net or PUN)

NMOS only (Pull-Down Net or PDN)

Static Complementary CMOS

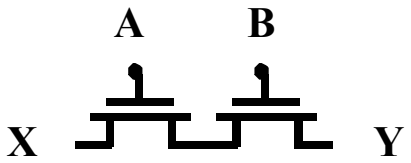


- PUN and PDN are **dual** logic networks
- PUN and PDN functions are **complementary**

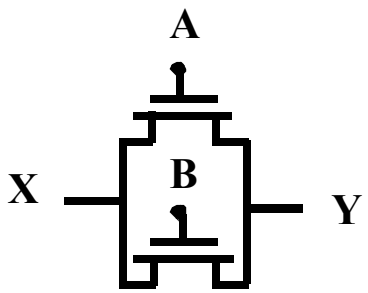
NMOS Transistors in Series/Parallel Connection

Transistors can be thought as a switch controlled by its gate signal

NMOS switch closes when switch control input is high



Y = X if A and B

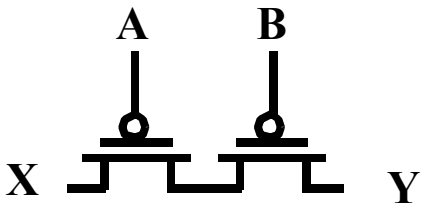


Y = X if A OR B

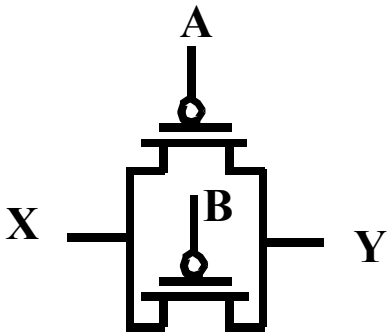
NMOS Transistors pass a "strong" 0 but a "weak" 1

PMOS Transistors in Series/Parallel Connection

PMOS switch closes when switch control input is low



Y = X if $\overline{A}$ AND $\overline{B}$ = $\overline{A + B}$

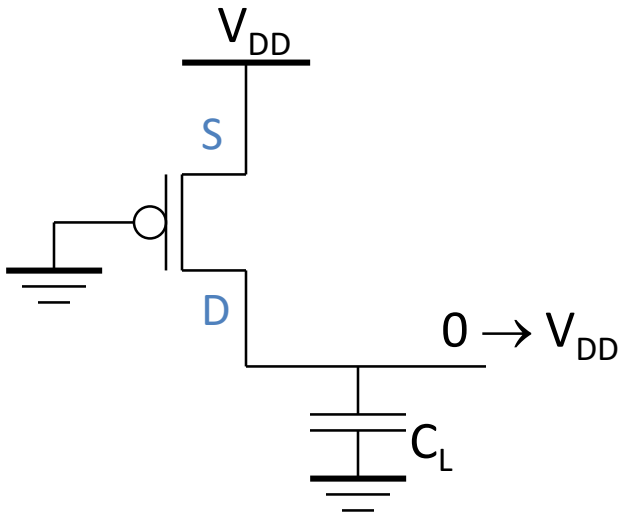


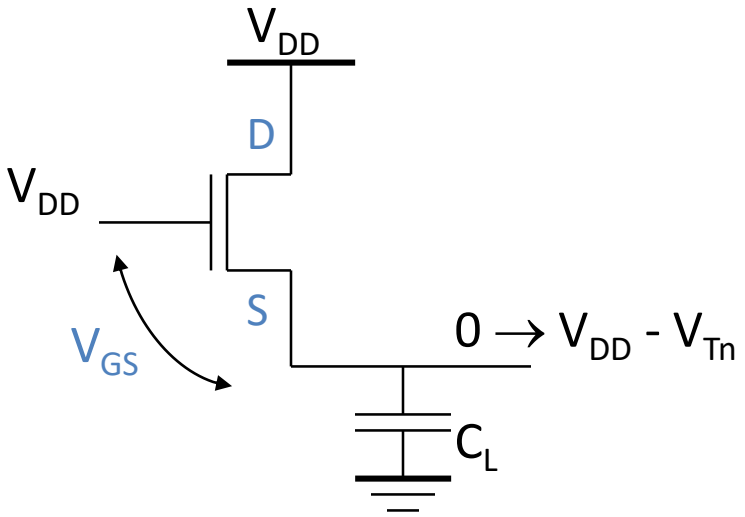
Y = X if $\overline{A}$ OR $\overline{B}$ = $\overline{AB}$

PMOS Transistors pass a "strong" 1 but a "weak" 0

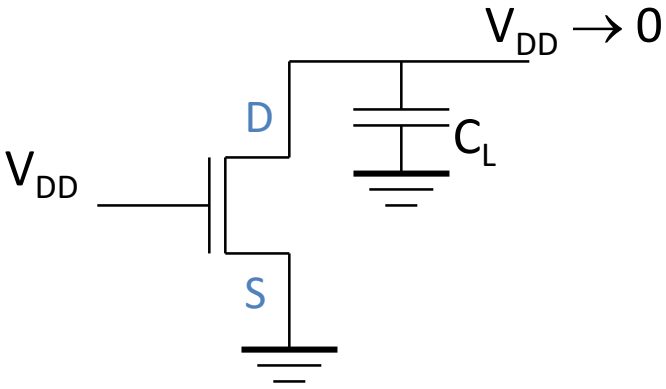
Threshold Drops

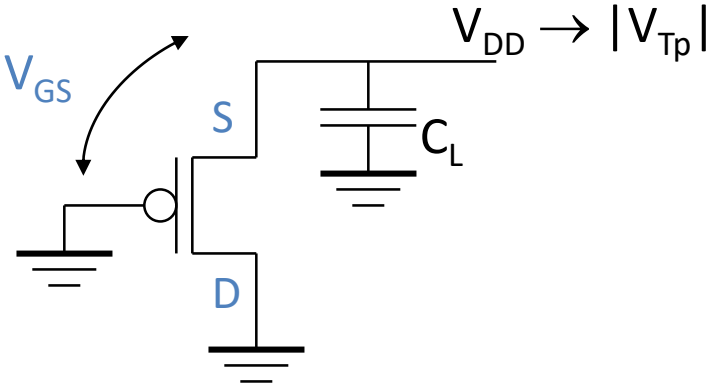
PUN – Pull Up Network





PDN – Pull Down Network





Complementary CMOS Logic Style

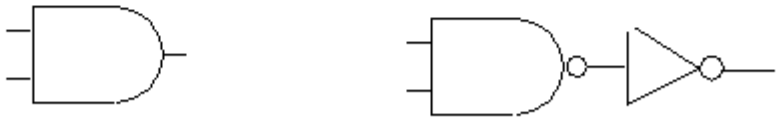
- **PUP is the DUAL of PDN**

  (can be shown using DeMorgan's Theorem's)

$$\overline{A + B} = \bar{A}\bar{B}$$

$$\overline{AB} = \bar{A} + \bar{B}$$

- **The complementary gate is inverting**

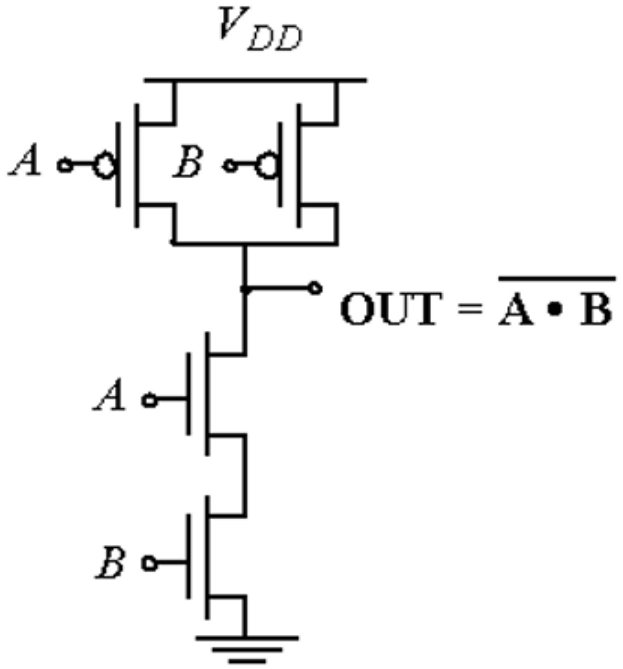


AND = NAND + INV

Example Gate: NAND

A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

Truth Table of a 2 input NAND gate



PDN: G = A B $\Rightarrow$ Conduction to GND

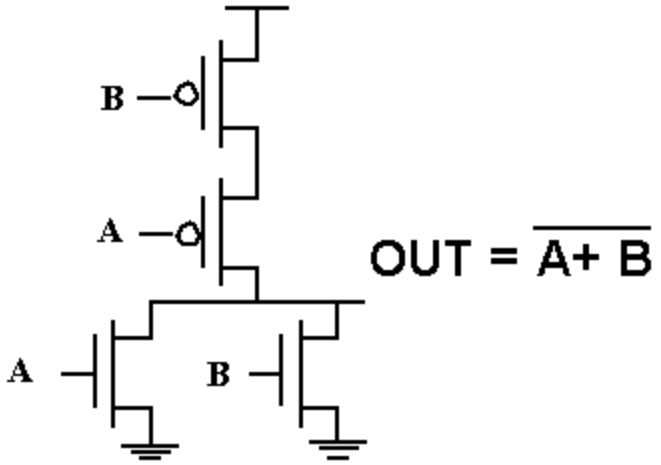
PUN: F= $\overline{A} + \overline{B} = \overline{AB} \Rightarrow$ Conduction to V_{DD}

$$\overline{G(In_1, In_2, In_3, \ldots)} \equiv F(\overline{In_1}, \overline{In_2}, \overline{In_3}, \ldots)$$

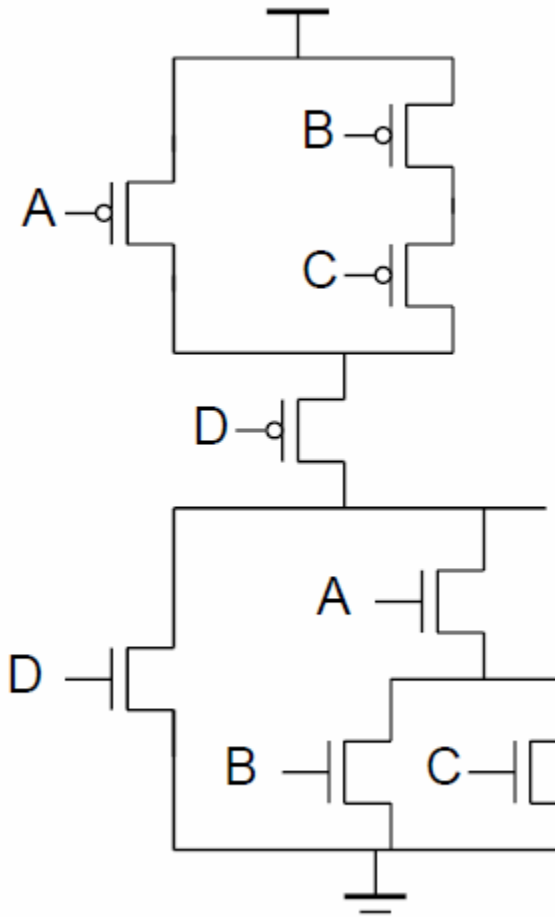
Example Gate: NOR

A	B	Out
0	0	1
0	1	0
1	0	0
1	1	0

Truth Table of a 2 input NOR gate

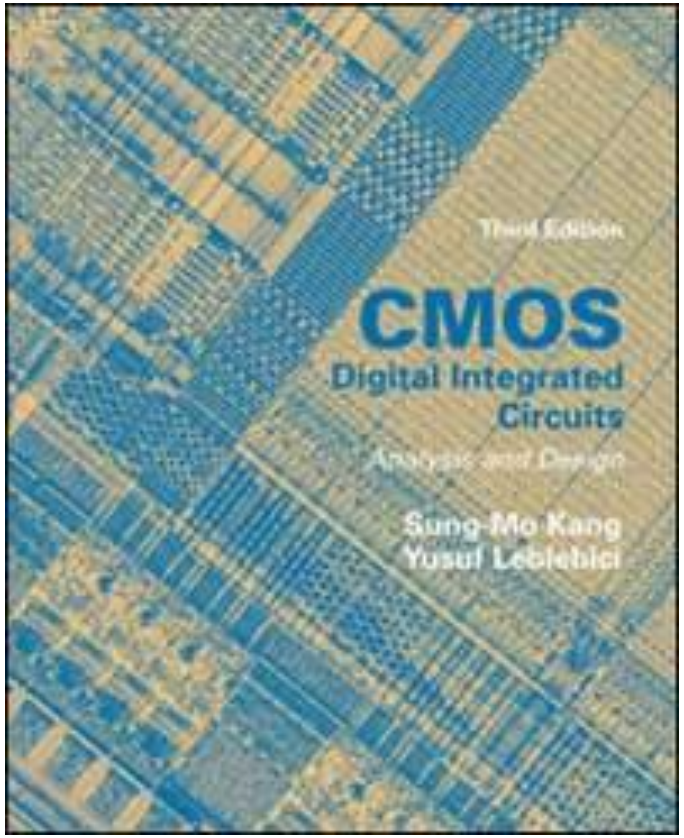


Complex CMOS Gate



$$OUT = \overline{D + A \bullet (B + C)}$$

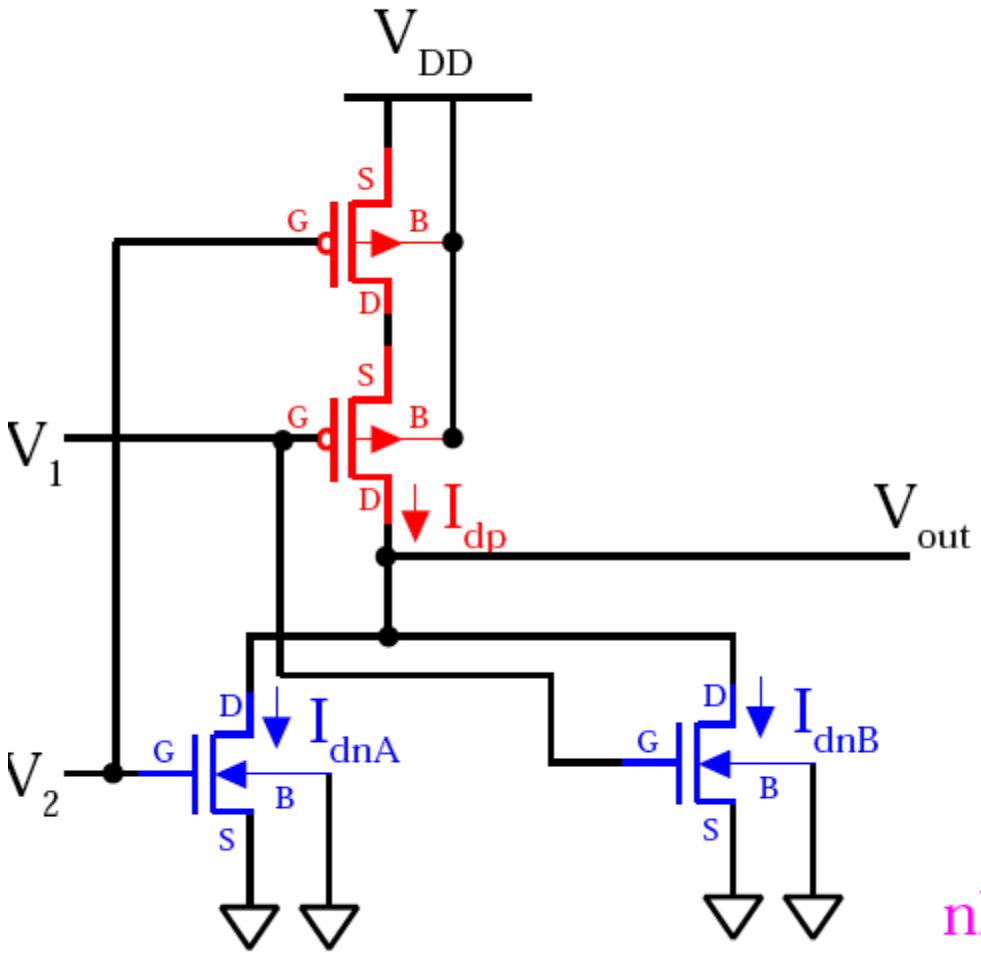
Digital IC Design and Architecture

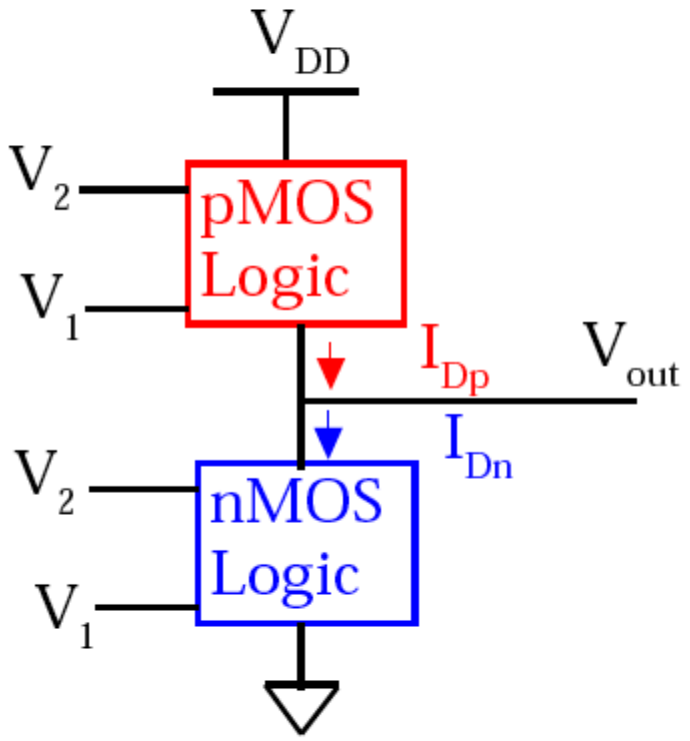


Combinational Logic: CMOS Implementation

CMOS LOGIC GATES

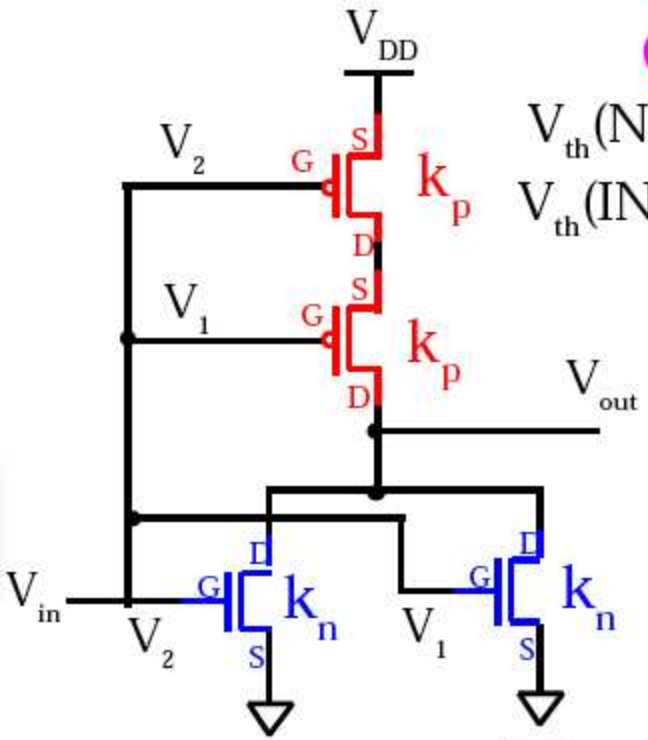
2-INPUT NOR (NR2)





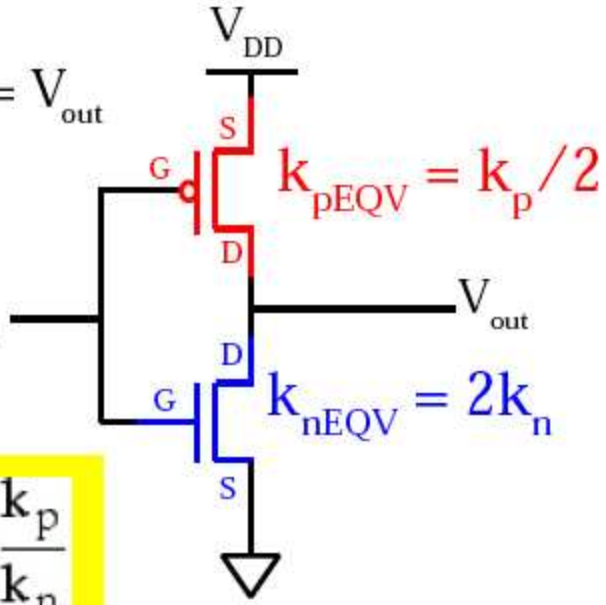
nMOS Net ON, pMOS Net OFF
or
nMOS Net OFF, pMOS Net ON

CMOS NR2



$V_{th}(NR2) => V_1 = V_2 = V_{out}$

$V_{th}(INV) = V_{in} = V_{out}$



$$\frac{k_{pEQV}}{k_{nEQV}} = \frac{1}{4}\frac{k_p}{k_n}$$

$$V_{th}(NOR2) = \frac{V_{Tn} + \frac{1}{2}\sqrt{\frac{k_p}{k_n}}\left(V_{DD} + V_{Tp}\right)}{1 + \frac{1}{2}\sqrt{\frac{k_p}{k_n}}}$$

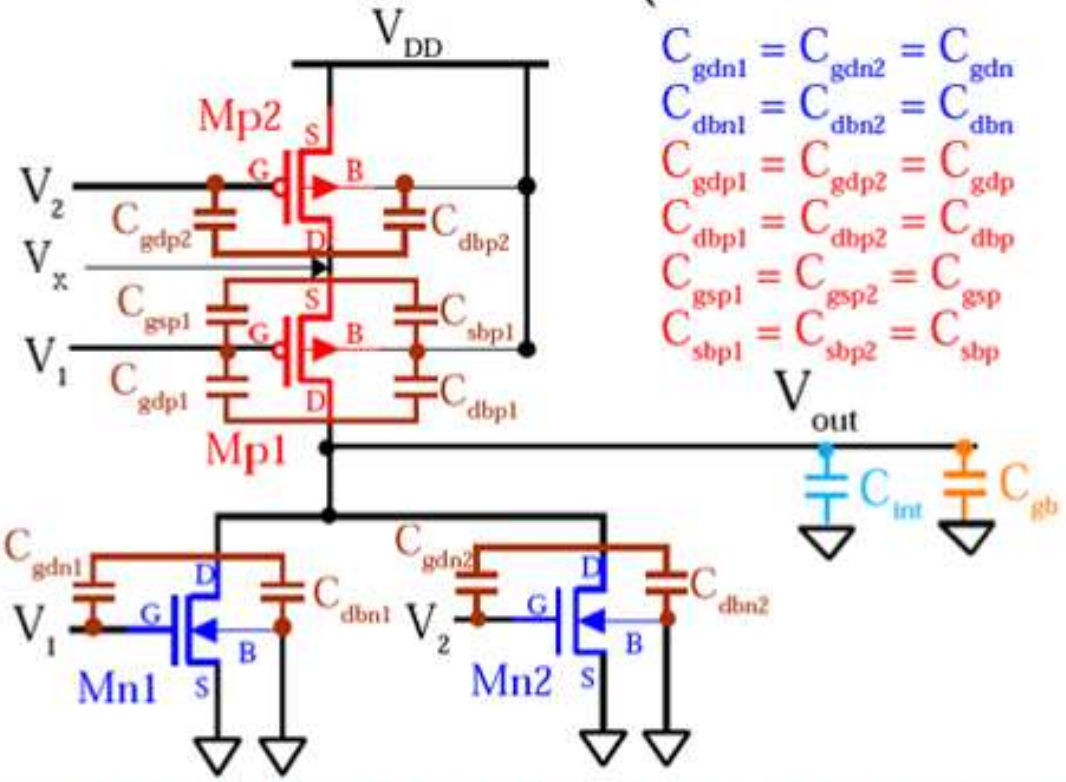
$$V_{th}(INV) = \frac{V_{Tn} + \sqrt{\frac{k_{pEQV}}{k_{nEQV}}}\left(V_{DD} + V_{Tp}\right)}{1 + \sqrt{\frac{k_{pEQV}}{k_{nEQV}}}}$$

Symmetrical EQUIV INV

$k_{pEQV} = k_{nEQV}$ or $k_{pEQV}/k_{nEQV} = 1$ and $V_{Tn} = |V_{Tp}| => V_{th}(INV) = V_{DD}/2$

$V_{th}(NR2) = V_{DD}/2 => k_p = 4k_n$

PARASITIC CAPS FOR CMOS NR2 (CONSERVATIVE)



$C_{gdn1} = C_{gdn2} = C_{gdn}$
$C_{dbn1} = C_{dbn2} = C_{dbn}$
$C_{gdp1} = C_{gdp2} = C_{gdp}$
$C_{dbp1} = C_{dbp2} = C_{dbp}$
$C_{gsp1} = C_{gsp2} = C_{gsp}$
$C_{sbp1} = C_{sbp2} = C_{sbp}$

WORST CASE for PULL-UP => $V_1 = 0$, $V_2 = V_{DD} \rightarrow 0$ & V_x = low -> high

$C_{load\text{-}NR2} \approx 2C_{dbn} + 2C_{dbp} + C_{sbp} + C_{int} + C_{gb} = 2C_{dbn} + 3C_{dbp} + C_{int} + C_{gb}$

WORST CASE for PULL-DOWN => $V_1 = 0$, $V_2 = 0 \rightarrow V_{DD}$ & V_x = high -> low

$C_{load\text{-}NR2} \approx 2C_{dbn} + 2C_{dbp} + C_{sbp} + C_{int} + C_{gb} = 2C_{dbn} + 3C_{dbp} + C_{int} + C_{gb}$

NRn: $C_{load\text{-}NRn} \approx nC_{dbn} + (2n-1)C_{dbp} + C_{int} + C_{gb}$

CMOS NR DESIGN STRATEGIES

NR2:

1. Symmetric Inverter $V_{th} = V_{DD}/2$:

$$V_{th}(NR2) = V_{DD}/2 \Rightarrow k_p = 4k_n$$

2. Propogation delay τ_{PHL} or τ_{PLH}:

$$\tau_{PHL-NR2} \approx \frac{C_{load-NR2}}{2kn(VDD-VT0n)}\left[\frac{2V_{T0n}}{V_{DD}-V_{T0n}} + \ln\left(\frac{4(V_{DD}-V_{T0n})}{V_{DD}} - 1\right)\right]$$

$$\tau_{PLH-NR2} \approx \frac{C_{load-NR2}}{\frac{kp}{2}(VDD-|VT0p|)}\left[\frac{2|V_{T0p}|}{V_{DD}-|V_{T0p}|} + \ln\left(\frac{4(V_{DD}-|V_{T0p}|)}{V_{DD}} - 1\right)\right]$$

NRn:

1. Symmetric Inverter $V_{th} = V_{DD}/2$:

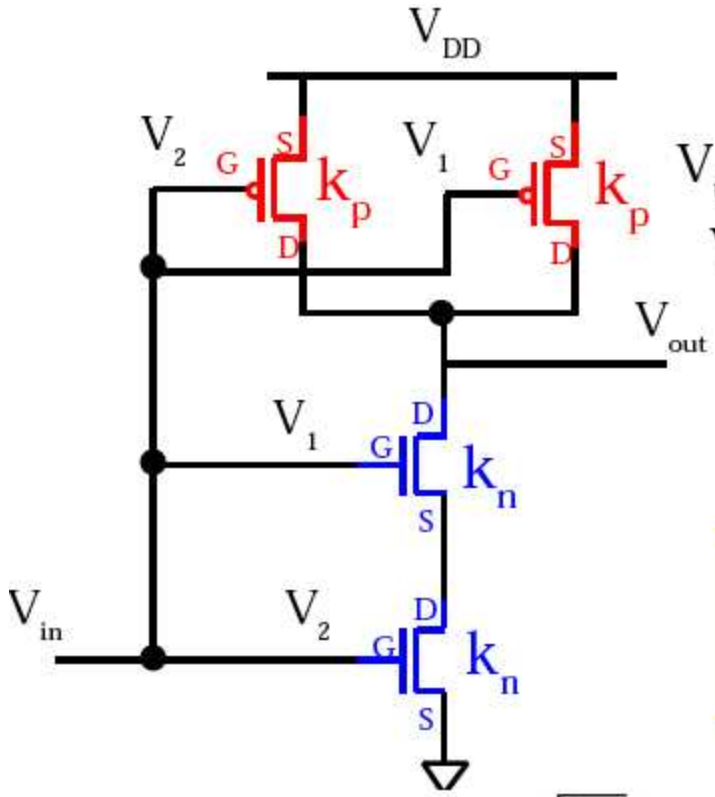
$$V_{th}(NRn) = V_{DD}/2 \Rightarrow k_p = n^2k_n$$

2. Propogation delay τ_{PHL} or τ_{PLH}:

$$\tau_{PHL-NRn} \approx \frac{C_{load-NRn}}{nkn(VDD-VT0n)}\left[\frac{2V_{T0n}}{V_{DD}-V_{T0n}} + \ln\left(\frac{4(V_{DD}-V_{T0n})}{V_{DD}} - 1\right)\right]$$

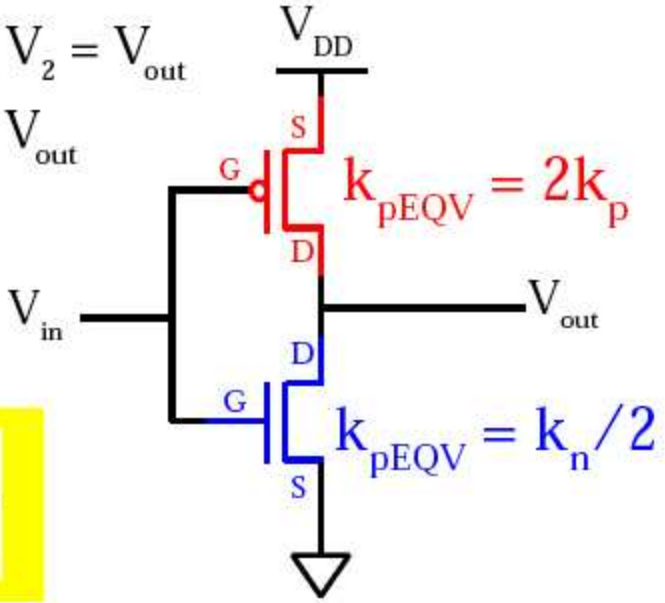
$$\tau_{PLH-NRn} \approx \frac{C_{load-NRn}}{\frac{kp}{n}(VDD-|VT0p|)}\left[\frac{2|V_{T0p}|}{V_{DD}-|V_{T0p}|} + \ln\left(\frac{4(V_{DD}-|V_{T0p}|)}{V_{DD}} - 1\right)\right]$$

CMOS ND2



$$V_{th}(ND2) => V_1 = V_2 = V_{out}$$

$$V_{th}(INV) = V_{in} = V_{out}$$



$$\frac{k_{pEQV}}{k_{nEQV}} = 4\frac{k_p}{k_n}$$

$$V_{th}(NAND2) = \frac{V_{Tn} + 2\sqrt{\frac{k_p}{k_n}}(V_{DD} + V_{Tp})}{1 + 2\sqrt{\frac{k_p}{k_n}}}$$

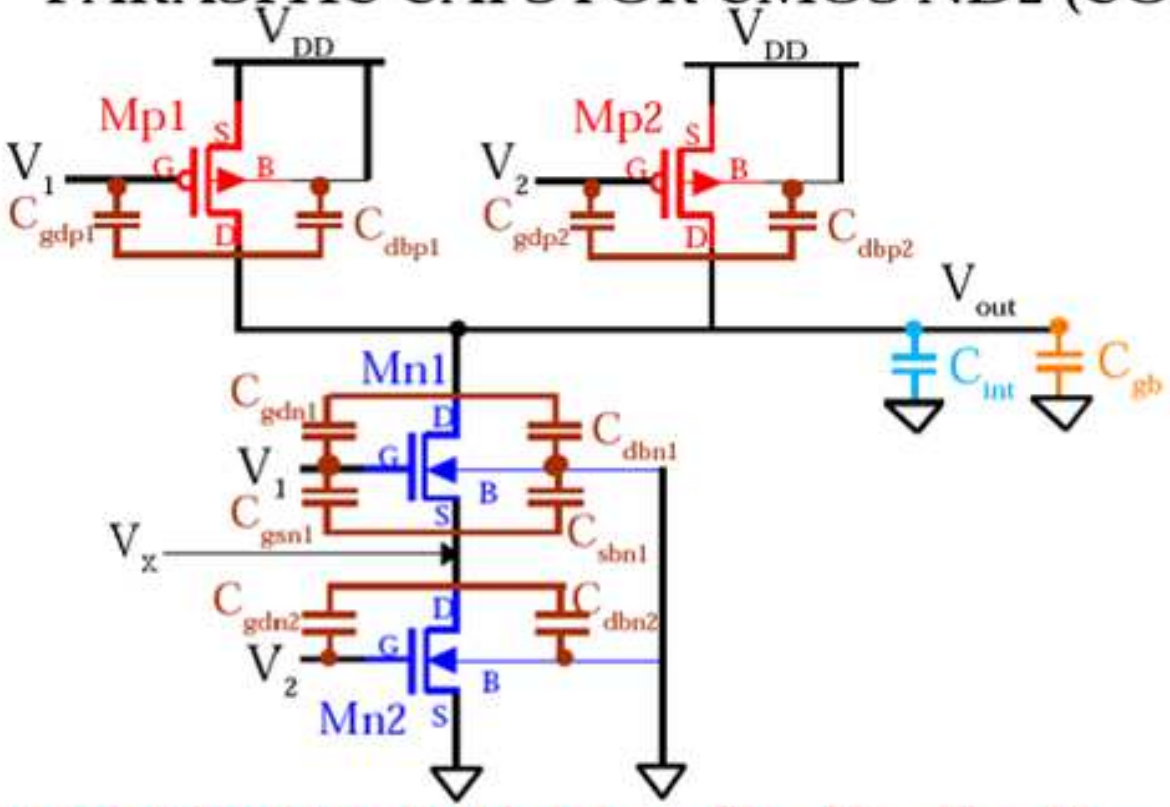
$$V_{th}(INV) = \frac{V_{Tn} + \sqrt{\frac{k_{pEQV}}{k_{nEQV}}}(V_{DD} + V_{Tp})}{1 + \sqrt{\frac{k_{pEQV}}{k_{nEQV}}}}$$

Symmetrical EQUIV INV

$k_{pEQV} = k_{nEQV}$ and $V_{Tn} = |V_{Tp}| => V_{th}(INV) = V_{DD}/2$

$V_{th}(ND2) = V_{DD}/2 => k_n = 4k_p$

PARASITIC CAPS FOR CMOS ND2 (CONSERVATIVE)



$C_{gdn1} = C_{gdn2} = C_{gdn}$
$C_{dbn1} = C_{dbn2} = C_{dbn}$
$C_{gdp1} = C_{gdp2} = C_{gdp}$
$C_{dbp1} = C_{dbp2} = C_{dbp}$
$C_{gsp1} = C_{gsp2} = C_{gsp}$
$C_{sbp1} = C_{sbp2} = C_{sbp}$

WORST CASE for PULL-UP => $V_1 = V_{DD}$, $V_2 = V_{DD}$ -> 0 & V_x = low -> high

$C_{load\text{-}ND2} \approx 2C_{dbn} + C_{sbn} + 2C_{dbp} + C_{int} + C_{gb} = 3C_{dbn} + 2C_{dbp} + C_{int} + C_{gb}$

WORST CASE for PULL-DOWN => $V_1 = V_{DD}$, $V_2 = 0$ -> V_{DD} & V_x = high -> low

$C_{load\text{-}ND2} \approx 2C_{dbn} + C_{sbn} + 2C_{dbp} + C_{int} + C_{gb} = 3C_{dbn} + 2C_{dbp} + C_{int} + C_{gb}$

NDn: $C_{load\text{-}NDn} \approx (2n-1)C_{dbn} + nC_{dbp} + C_{int} + C_{gb}$

CMOS ND DESIGN STRATEGIES

ND2:

1. Symmetric Inverter $V_{th} = V_{DD}/2$:

$$V_{th}(ND2) = V_{DD}/2 \Rightarrow k_n = 4k_p$$

2. Propogation delay τ_{PHL} or τ_{PLH}:

$$\tau_{PHL-ND2} \approx \frac{C_{load-ND2}}{\frac{kn(VDD-VT0n)}{2}}\left[\frac{2V_{T0n}}{V_{DD}-V_{T0n}} + \ln\left(\frac{4(V_{DD}-V_{T0n})}{V_{DD}} - 1\right)\right]$$

$$\tau_{PLH-ND2} \approx \frac{C_{load-ND2}}{2kp(VDD-|VT0p|)}\left[\frac{2|V_{T0p}|}{V_{DD}-|V_{T0p}|} + \ln\left(\frac{4(V_{DD}-|V_{T0p}|)}{V_{DD}} - 1\right)\right]$$

NDn:

1. Symmetric Inverter $V_{th} = V_{DD}/2$:

$$V_{th}(NDn) = V_{DD}/2 \Rightarrow k_n = n^2k_p$$

2. Propogation delay τ_{PHL} or τ_{PLH}:

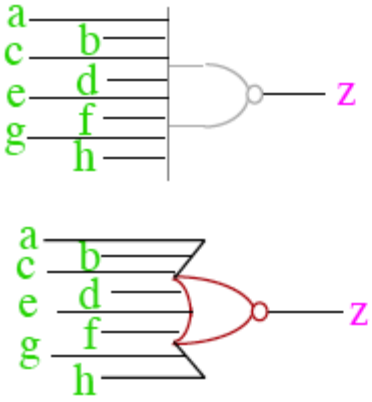
$$\tau_{PHL-NDn} \approx \frac{C_{load-NDn}}{\frac{kn(VDD-VT0n)}{n}}\left[\frac{2V_{T0n}}{V_{DD}-V_{T0n}} + \ln\left(\frac{4(V_{DD}-V_{T0n})}{V_{DD}} - 1\right)\right]$$

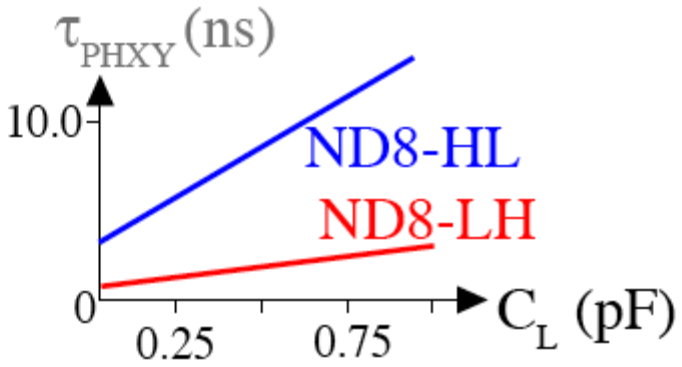
$$\tau_{PLH-NDn} \approx \frac{C_{load-NDn}}{nkp(VDD-|VT0p|)}\left[\frac{2|V_{T0p}|}{V_{DD}-|V_{T0p}|} + \ln\left(\frac{4(V_{DD}-|V_{T0p}|)}{V_{DD}} - 1\right)\right]$$

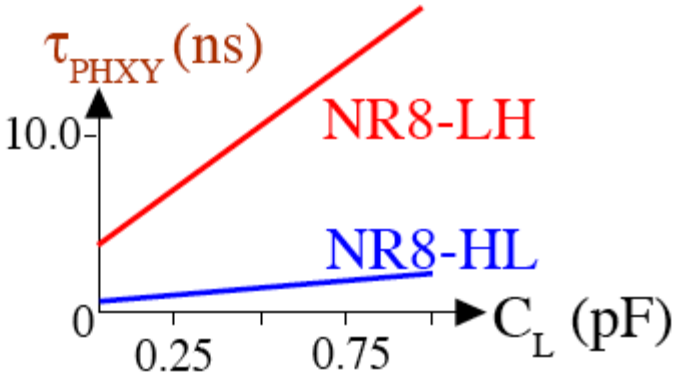
TYPICAL CMOS NAND AND NOR DELAYS

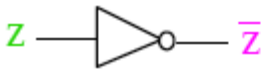
Delays for a Family of NAND & NOR gates

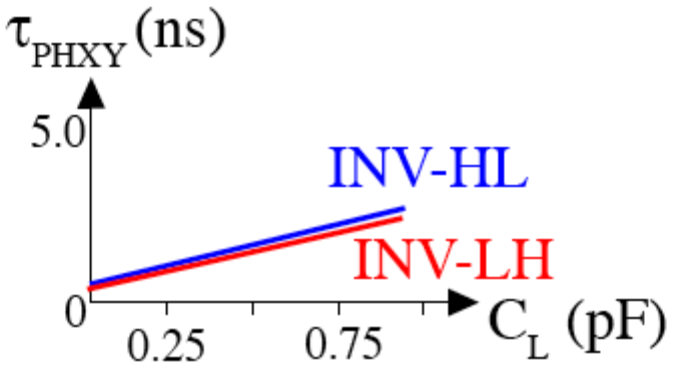
1. $W_n = 6.4\ \mu m$, $L_n = 1\ \mu m$, and $W_p = 12.8\ \mu m$, $L_p = 1\ \mu m$.
2. $t_{input\text{-}rise/fall} = 0.1\ ns$ and $C_{load} = 0 \rightarrow 1\ pF$.



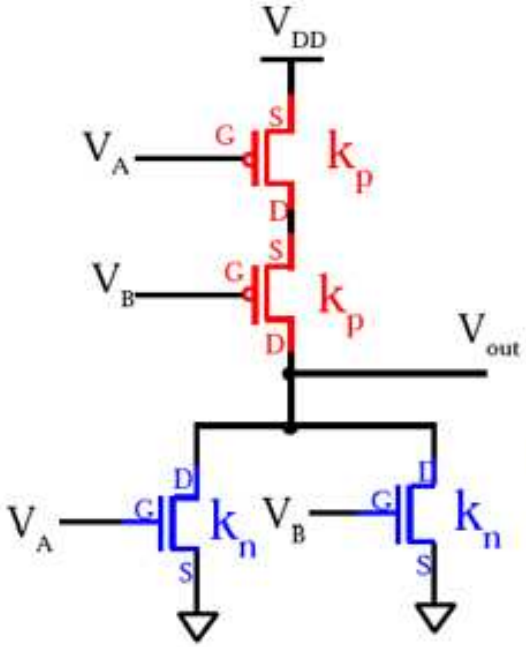


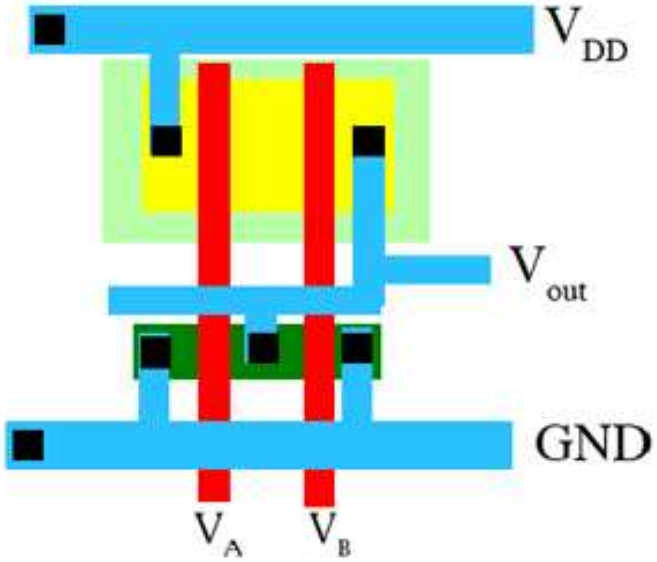




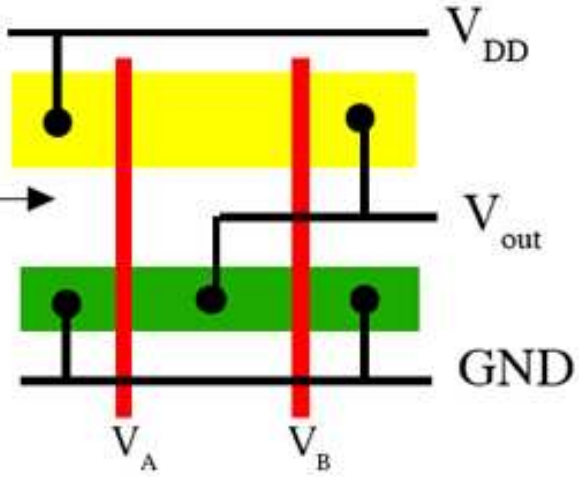


NR2 Layout Example





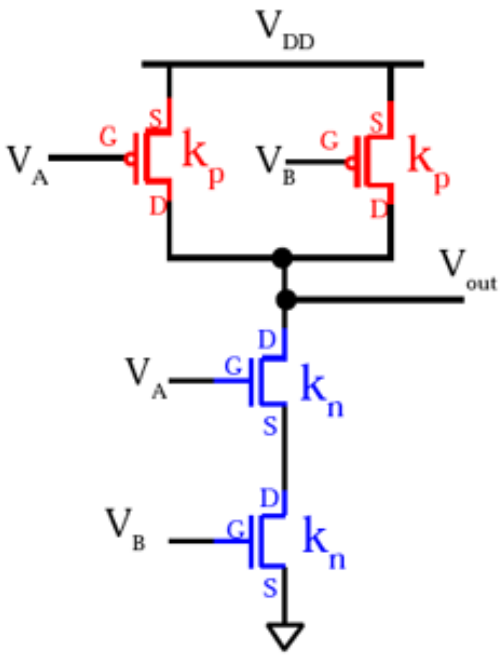
STICK DIAGRAM →

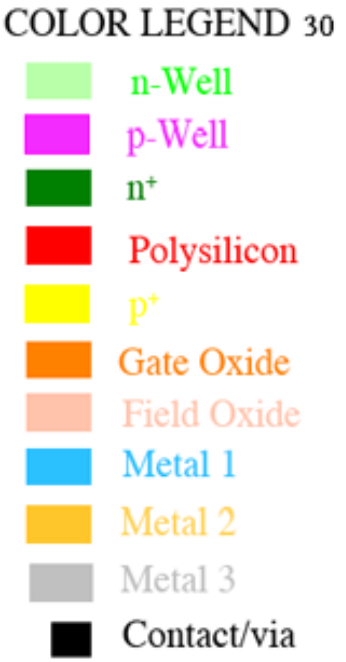


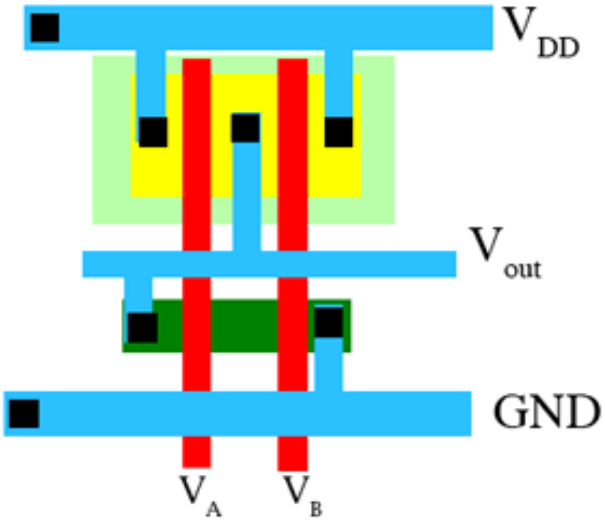
COLOR LEGEND

- n-Well
- p-Well
- n^+
- Polysilicon
- p^+
- Gate Oxide
- Field Oxide
- Metal 1
- Metal 2
- Metal 3
- Contact/via

ND2 Layout Example



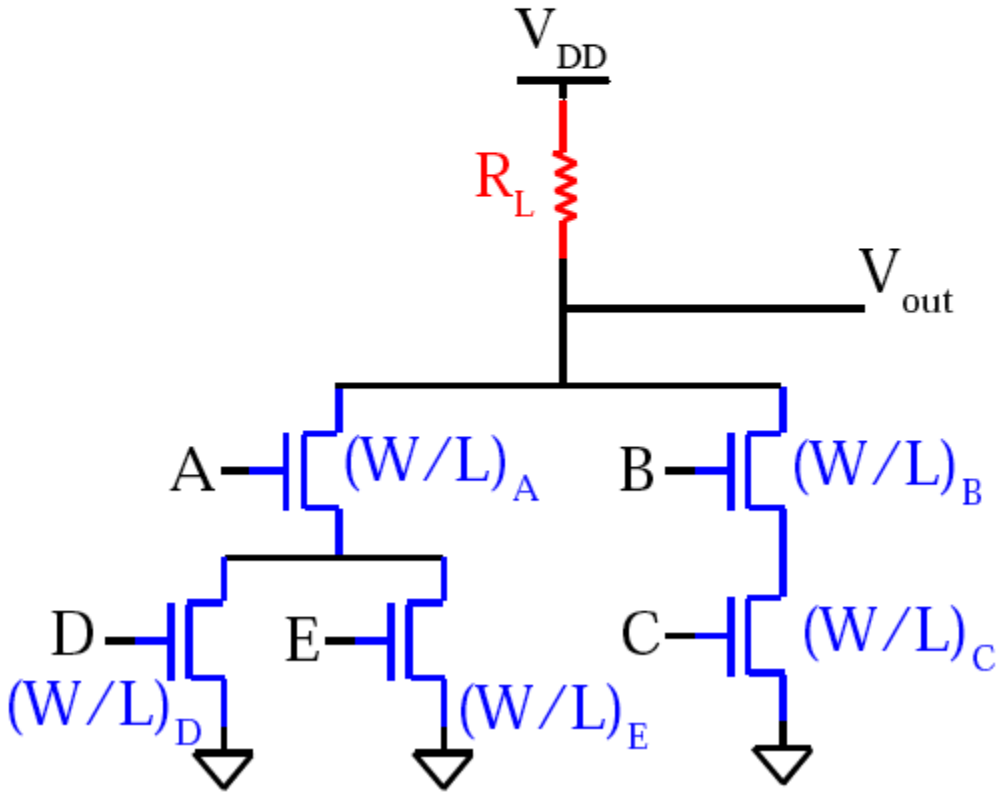


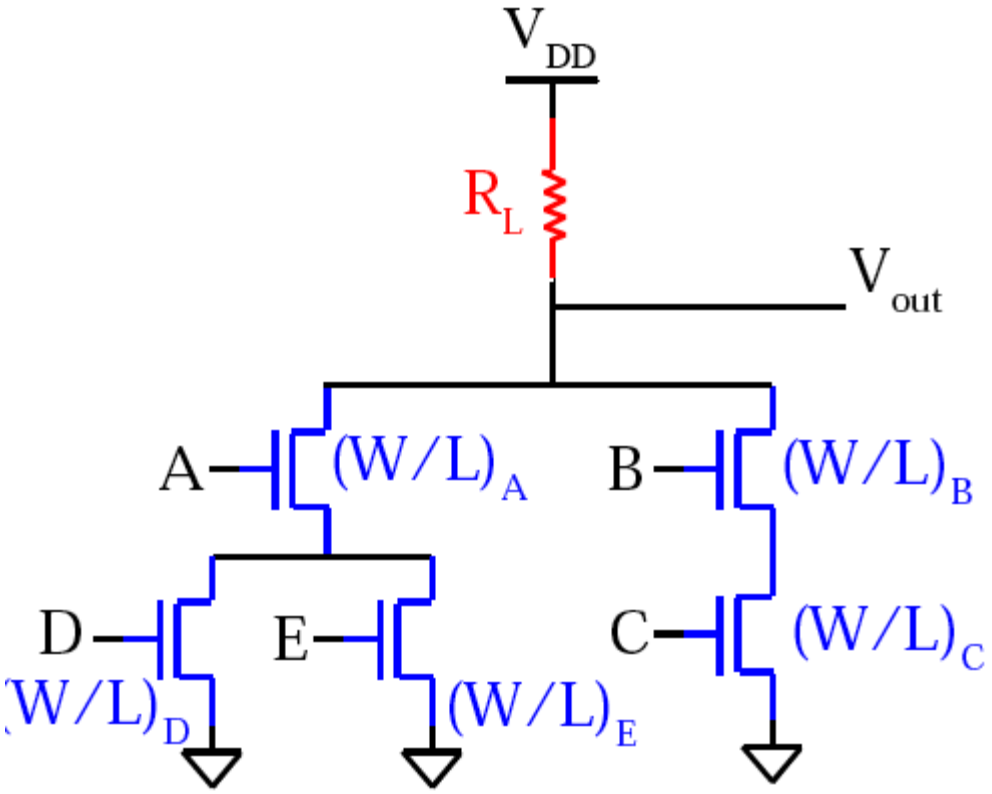


COMPLEX LOGIC GATES

$$Z = \overline{A(D + E) + BC}$$

"OR" OPS PERFORMED BY PARALLEL CONECTED DRIVERS.
"AND" OPS PERFORMED BY SERIES CONNECTED DRIVERS.
"INVERSION" IS PROVIDED BY NATURE OF MOS CIRCUIT OP.





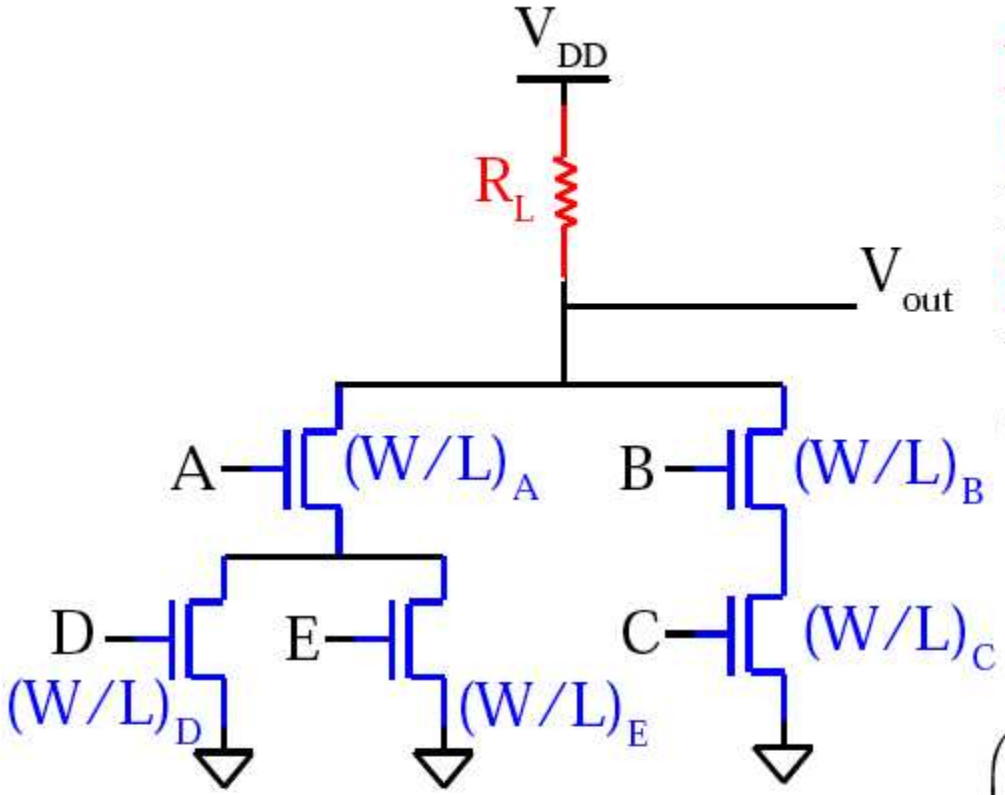
ON Drivers	Out-GND Path
A-D	Class 1
A-E	Class 1
B-C	Class 1
A-D-E	Class 2
A-D-B-C	Class 3
A-E-B-C	Class 3
A-D-E-B-C	Class 4

$G1 < G2 < G3 < G4$

$V_{OL1} > V_{OL2} > V_{OL3} > V_{OL4}$

EQV INVERTER (for case G4 where A = B = C = D = E = 1)

$$\left(\frac{W}{L}\right)_{EQV} = \frac{1}{\frac{1}{\left(\frac{W}{L}\right)_B} + \frac{1}{\left(\frac{W}{L}\right)_C}} + \frac{1}{\frac{1}{\left(\frac{W}{L}\right)_A} + \frac{1}{\left(\frac{W}{L}\right)_D + \left(\frac{W}{L}\right)_E}}$$



$$\left(\frac{W}{L}\right)_{EQV-ND2} = \frac{1}{2}\left(\frac{W}{L}\right)$$

DESIGN STRATEGY:

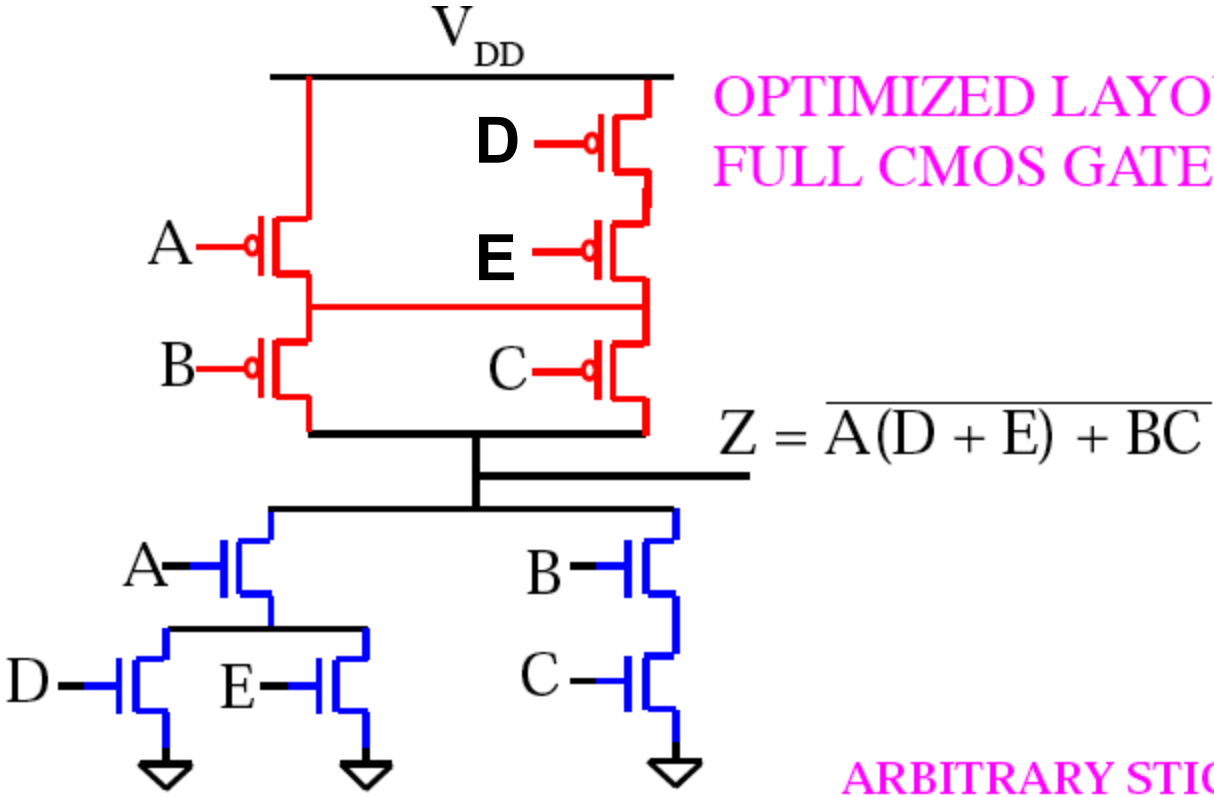
1. Identify all WORST CASE Paths (e.g. Class 1).
2. Determine nMOS transistor sizes such that each Class 1 path has $(W/L)_{EQV}$.

$$\left(\frac{W}{L}\right)_A = \left(\frac{W}{L}\right)_D = 2\left(\frac{W}{L}\right)_{EQV}$$

$$\left(\frac{W}{L}\right)_A = \left(\frac{W}{L}\right)_E = 2\left(\frac{W}{L}\right)_{EQV}$$

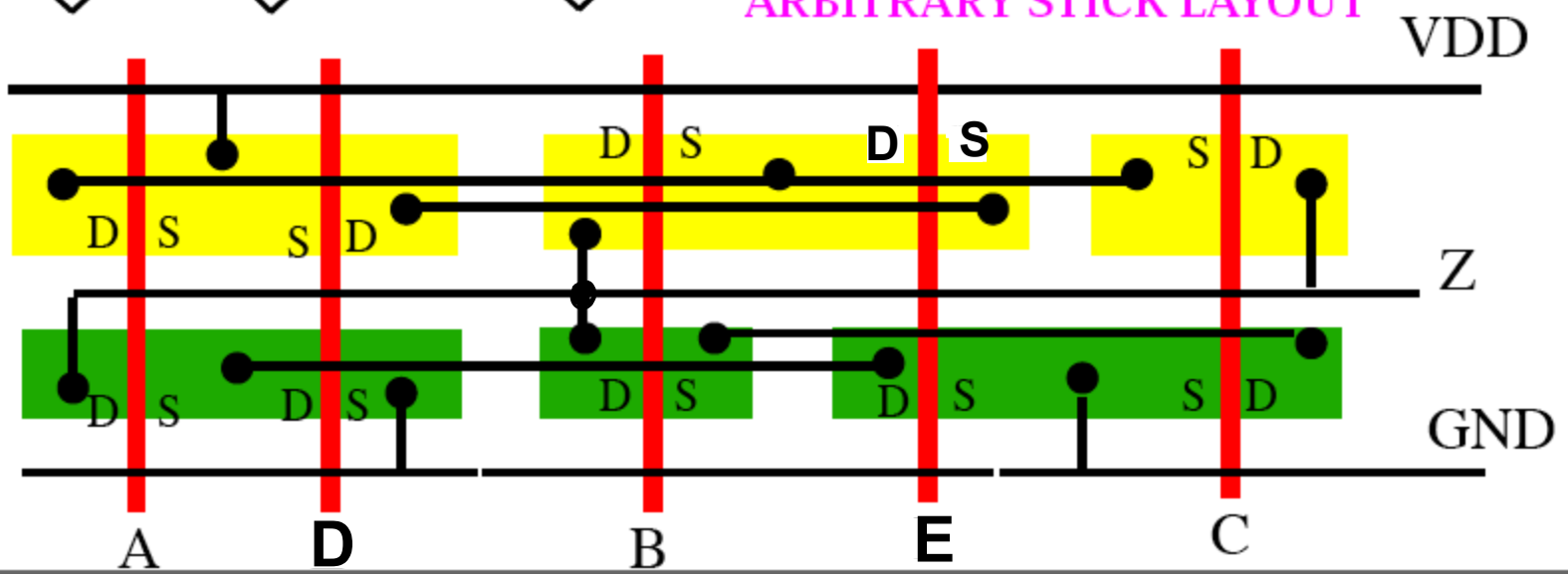
$$\left(\frac{W}{L}\right)_B = \left(\frac{W}{L}\right)_C = 2\left(\frac{W}{L}\right)_{EQV}$$

OPTIMIZED LAYOUT OF COMPLEX FULL CMOS GATES

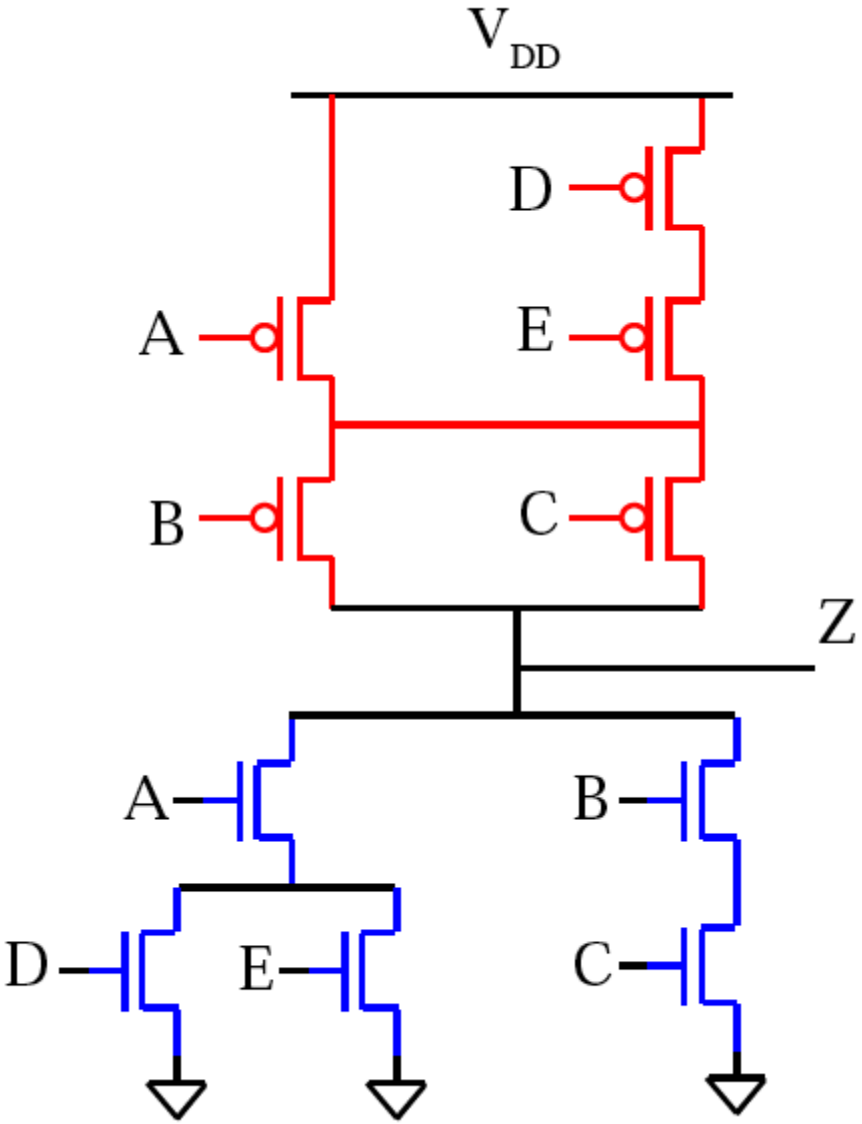


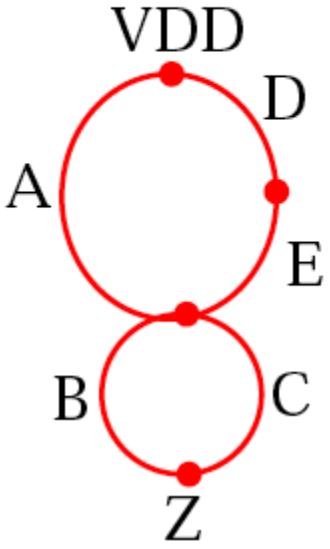
$$Z = \overline{A(D + E) + BC}$$

ARBITRARY STICK LAYOUT

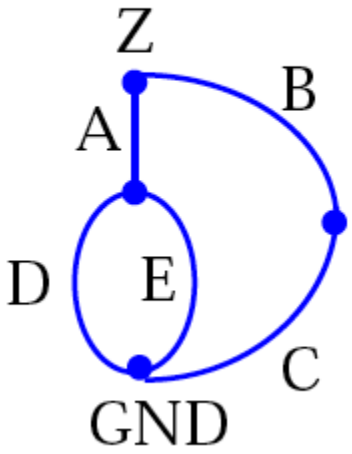


OTIMIZED LAYOUT OF COMPLEX FULL CMOS GATES



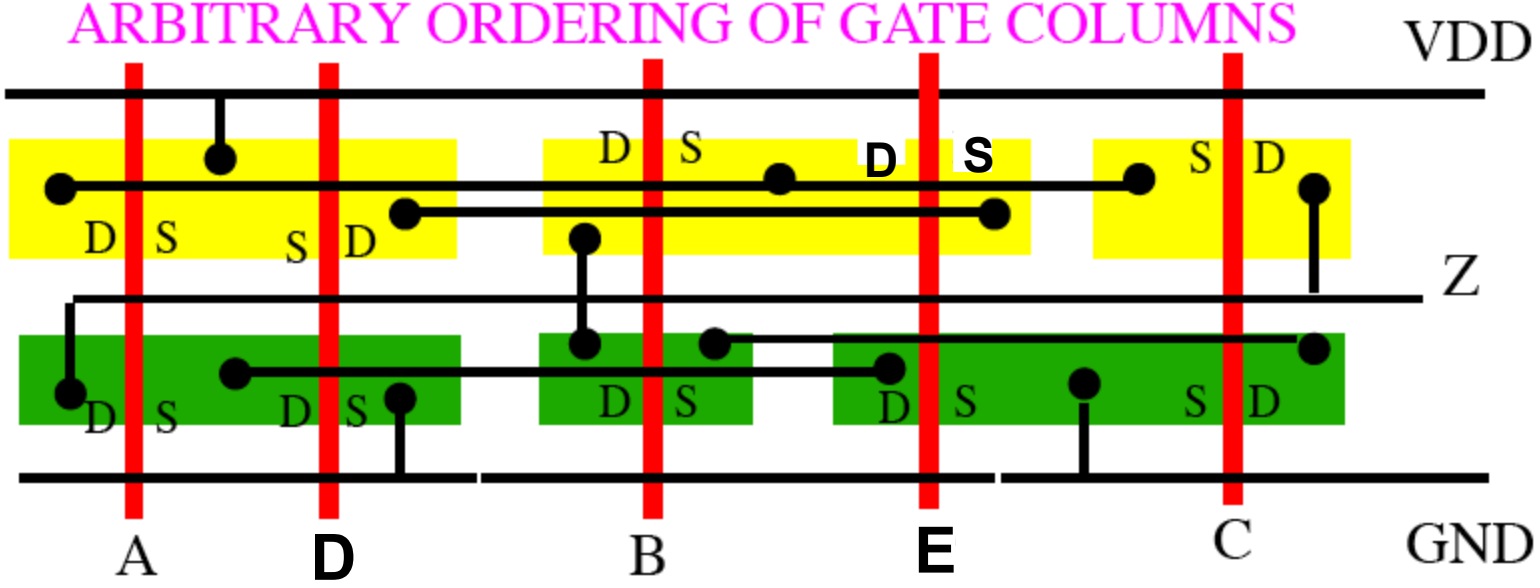


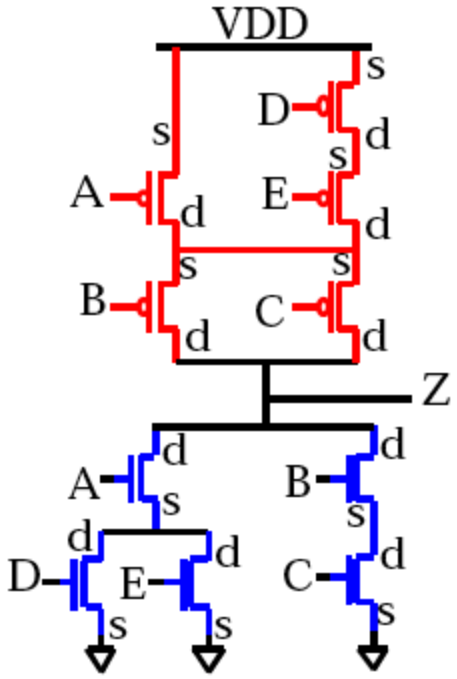
pMOS NET GRAPH

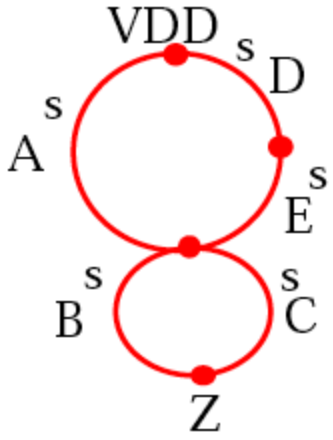


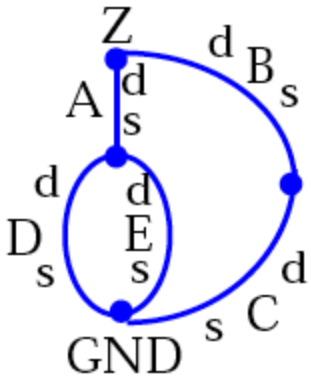
nMOS NET GRAPH

ARBITRARY ORDERING OF GATE COLUMNS





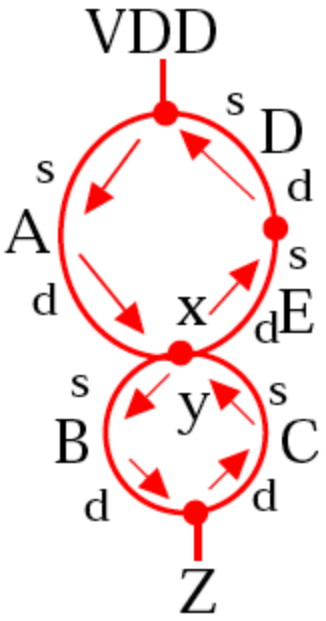




Euler path - connected sequence of edges

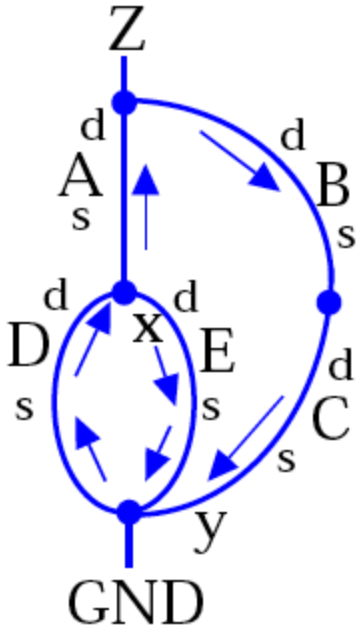
n, p diffusions for common Euler paths have layouts with no diffusion breaks.

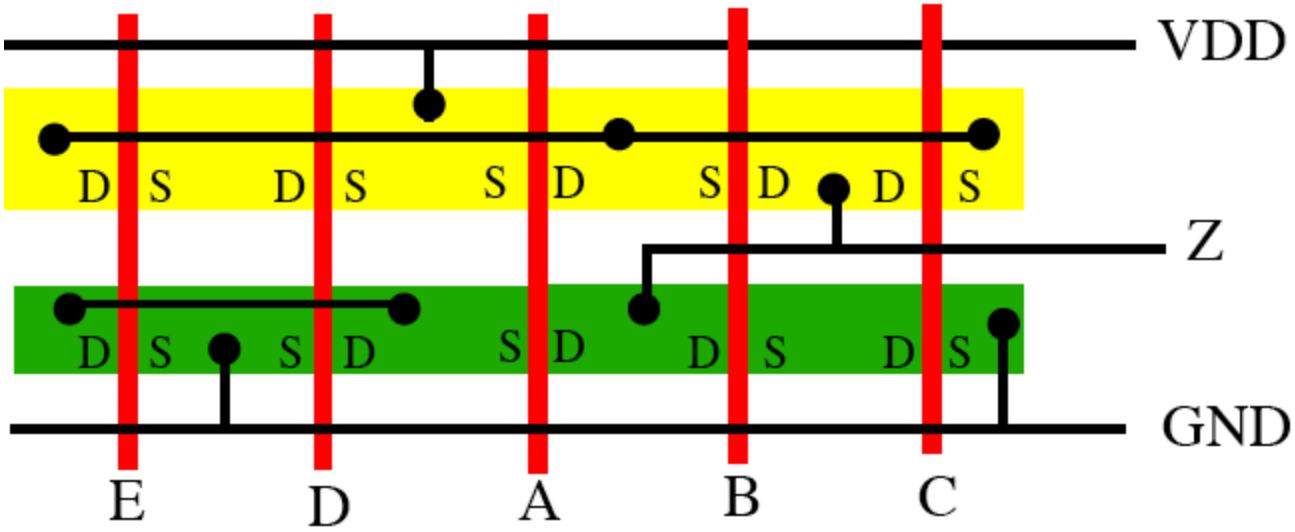
MINIMIZE NUMBER OF DIFFUSION BREAKS

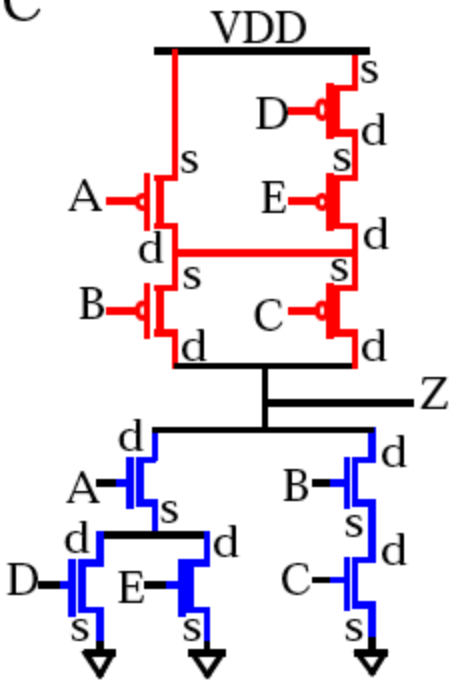


COMMON EULER PATH:
E-D-A-B-C

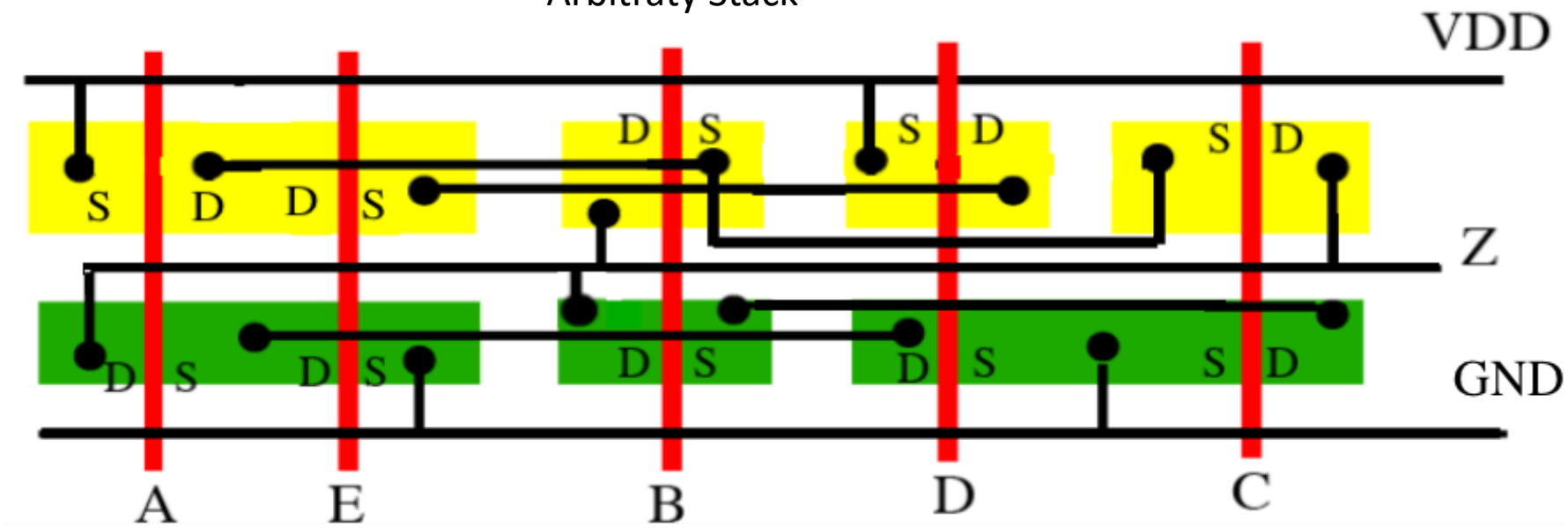
Is A-D-E-C-B a common Euler path?



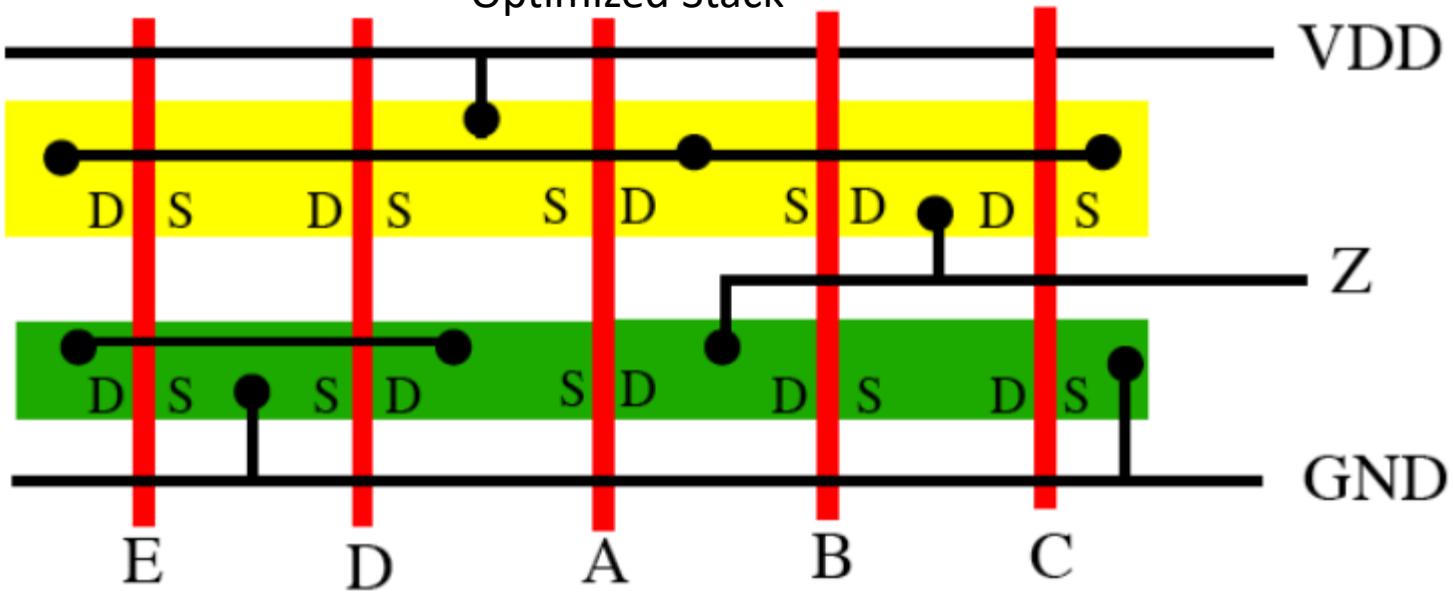




Arbitraty Stack



Optimized Stack



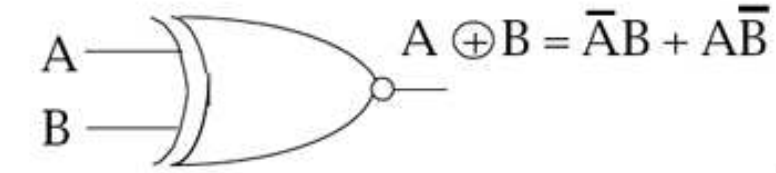
ALGORYTHYM FOR LINE OF GATES LAYOUT STYLE

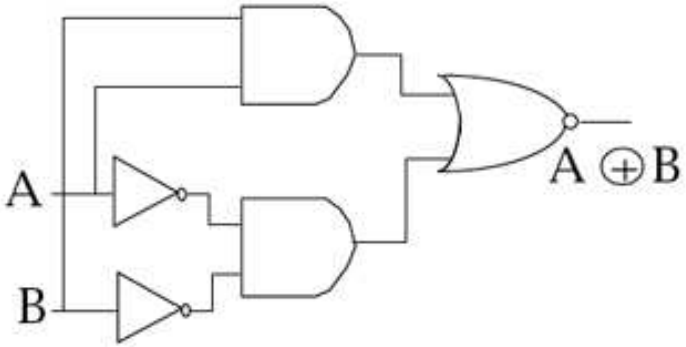
1. Find all Euler paths that cover the graph.

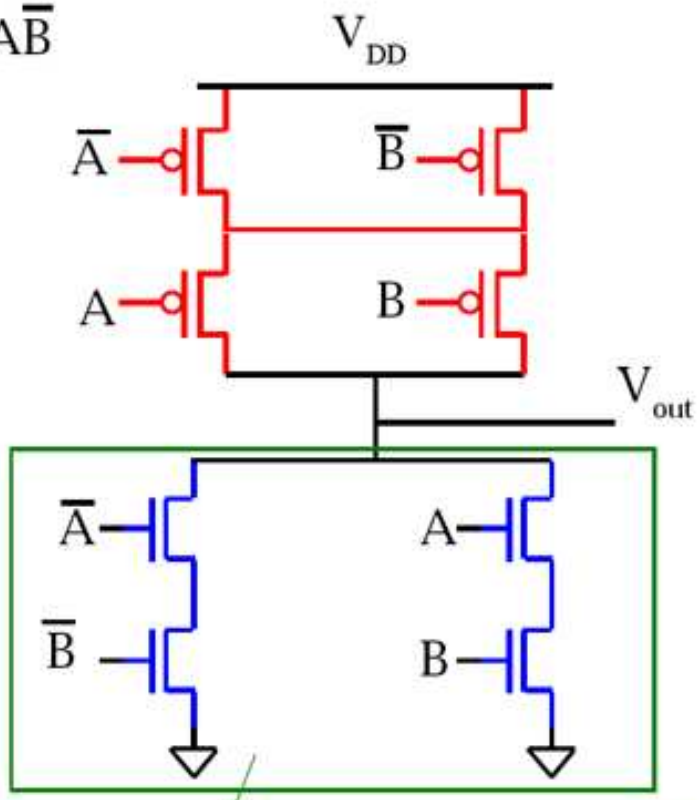
2. Find common n- and p- Euler paths.

3. If no Euler paths are found in step 2, break the gate in the minimum number of places that to achieve step 2 with separate common Euler paths.

FULL CMOS XOR GATE







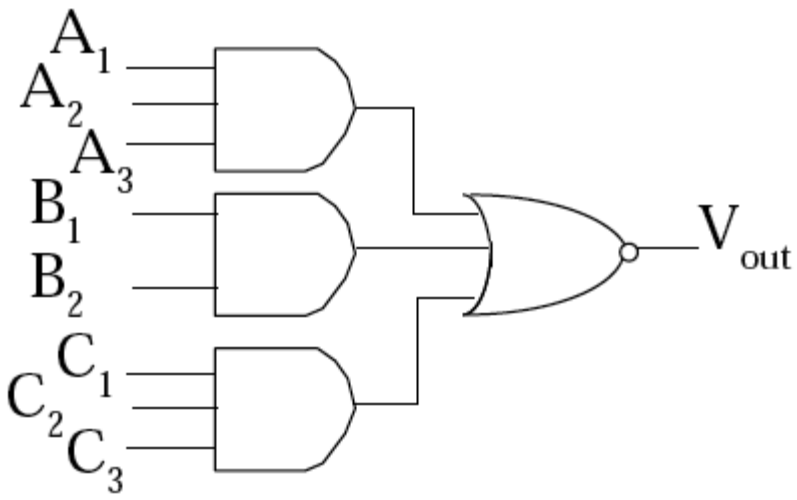
$$\overline{(\overline{A}\cdot\overline{B})+(A\cdot B)}=\overline{(\overline{A}\cdot\overline{B})}\cdot\overline{(A\cdot B)}=(A+B)\cdot(\overline{A}+\overline{B})$$

$$(A+B)\cdot(\overline{A}+\overline{B})=A\cdot\overline{A}+\overline{A}\cdot B+A\cdot\overline{B}+B\overline{B}=\overline{A}\cdot B+A\cdot\overline{B}$$

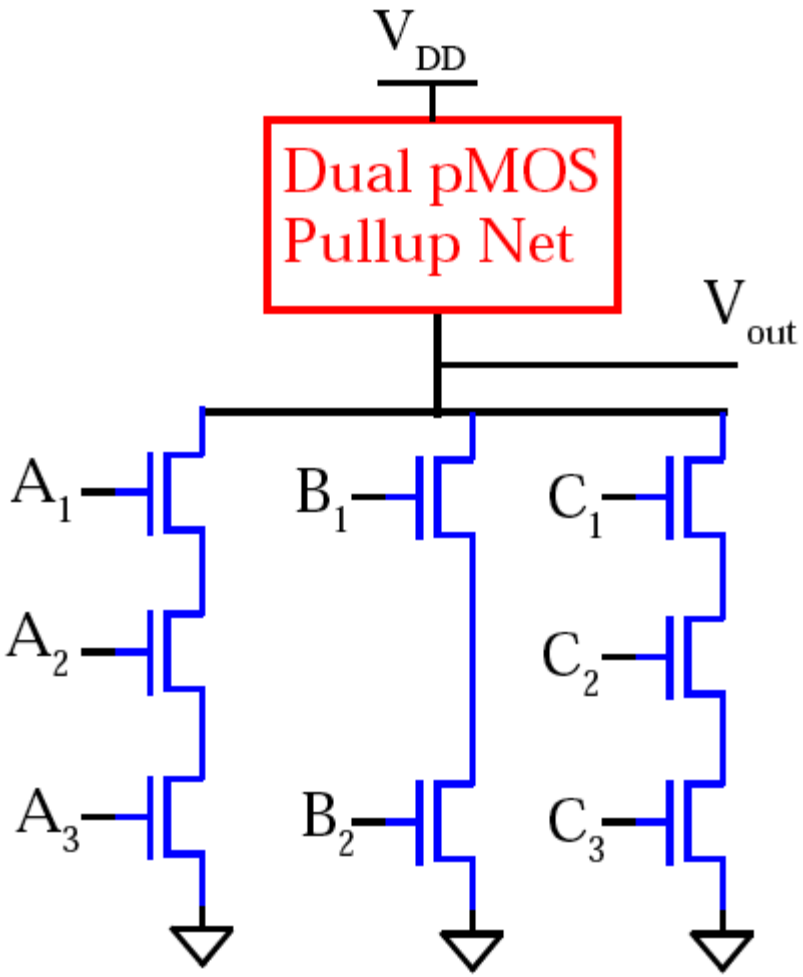
AOI & OAI GATES

AOI -> AND-OR-INVERT (for SUM - of - PRODUCTS Realization)

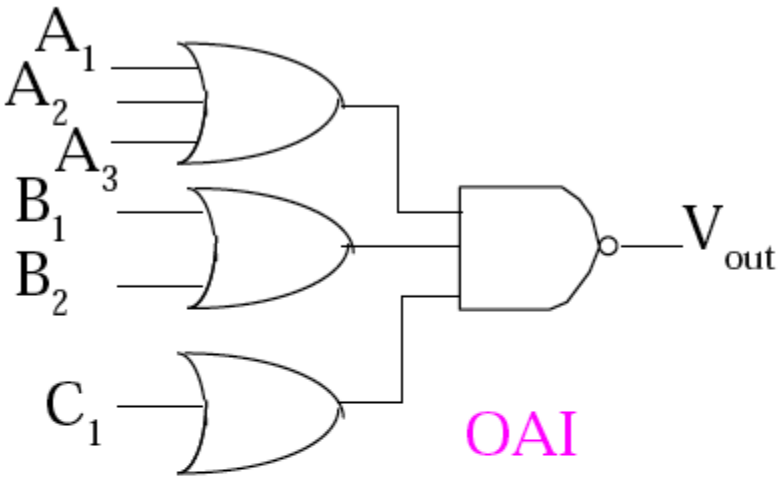
OAI -> OR-AND-INVERT (for PRODUCT - of - SUMS Realization)



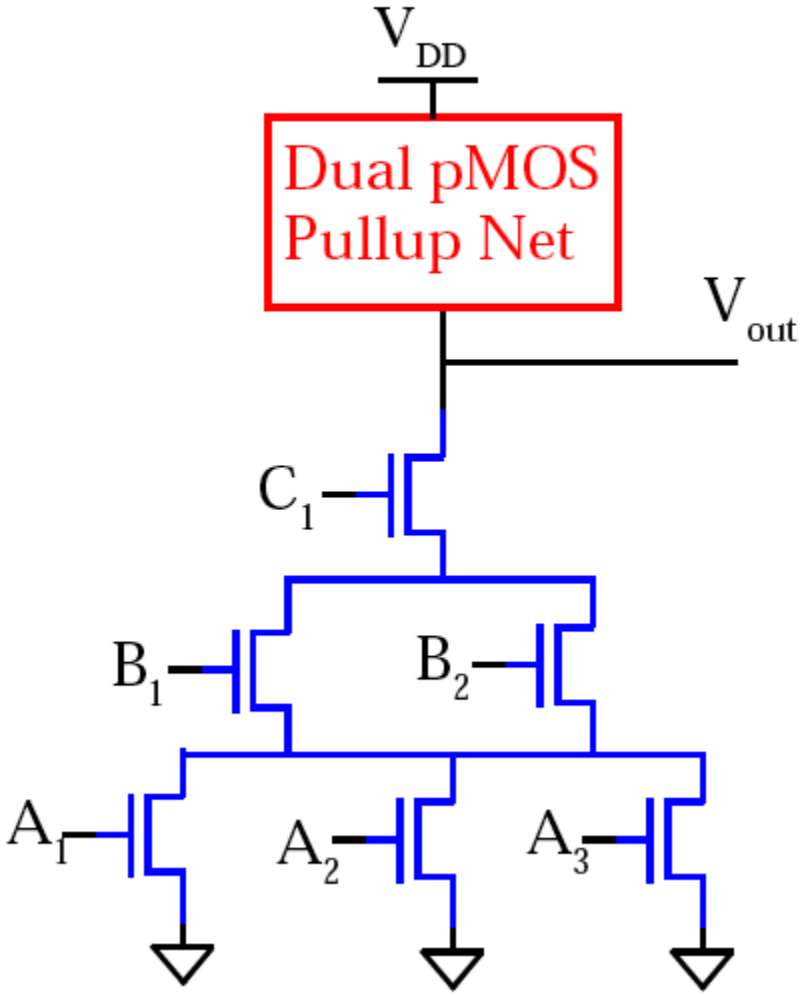
AOI



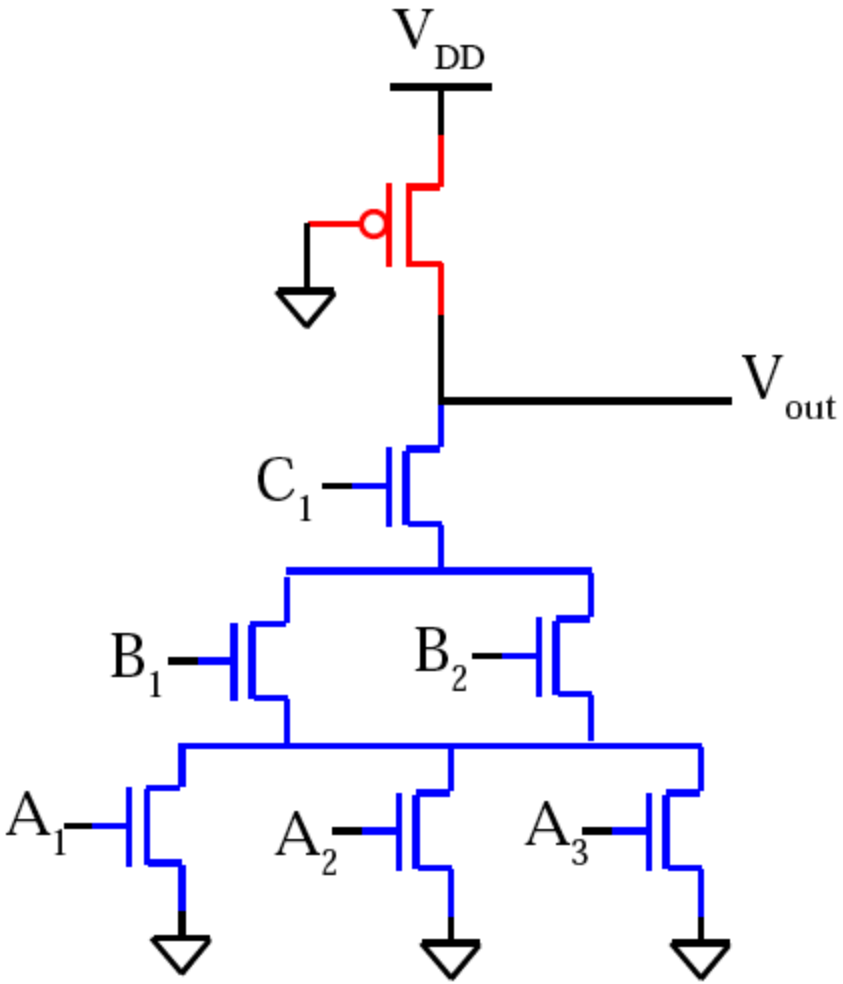
OAI -> OR-AND-INVERT (for PRODUCT - of - SUMS Realization)



OAI

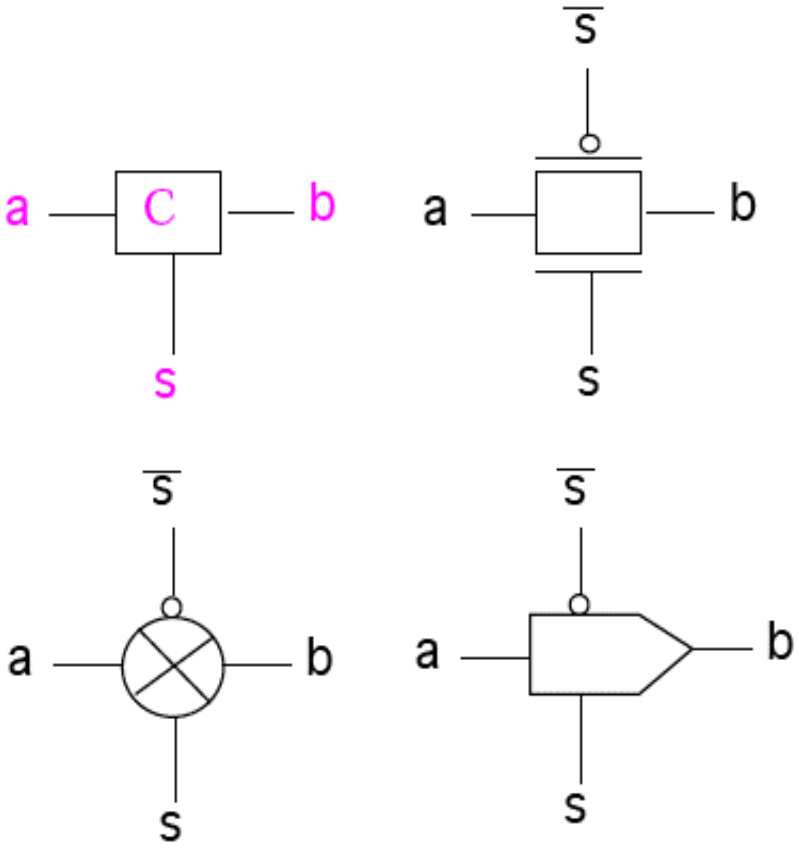


Pseudo-nMOS OAI Realization



CMOS Transmission Gates (TGs) & TG Logic

SYMBOLS

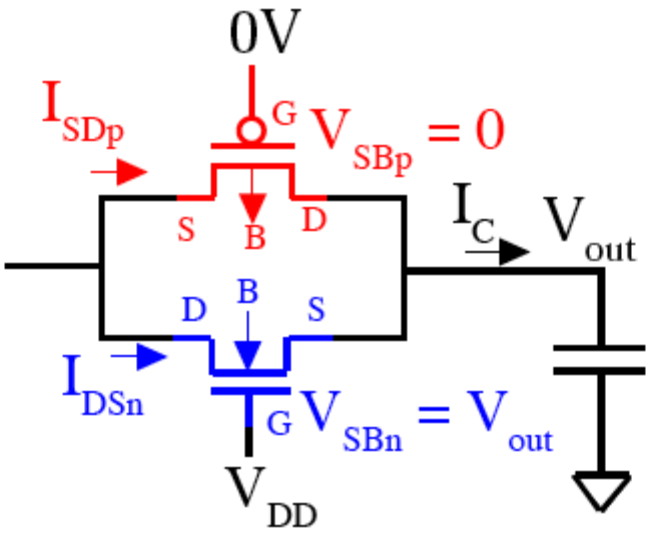


SWITCH CHARACTERISTICS

Input		Output
0	a — b	Strong 0
1	a — b	Strong 1

$I_C = I_{DSn} + I_{SDp}$

$V_{in} = V_{DD}$



$V_{DSn} = V_{DD} - V_{out}$

$V_{GSn} = V_{DD} - V_{out}$

$V_{DSp} = V_{out} - V_{DD}$

$V_{GSp} = - V_{DD}$

REGION 1
nMOS: SAT
pMOS: SAT
$V_{DSn} > V_{GSn} - V_{Tn}$
$V_{DSp} < V_{GSp} - V_{Tp}$

REGION 2
nMOS: SAT
pMOS: LIN
$V_{DSn} > V_{GSn} - V_{Tn}$
$V_{DSp} > V_{GSp} - V_{Tp}$

REGION 3
nMOS: OFF
pMOS: LIN
$V_{GSn} < V_{Tn}$
$V_{DSp} > V_{GSp} - V_{Tp}$

V_{out}

0V $\quad |V_{Tp}| \quad (V_{DD} - V_{Tn}) \quad V_{DD}$

$$R_{eqn} = \frac{V_{DD} - V_{out}}{I_{DSn}} \qquad R_{eqp} = \frac{V_{DD} - V_{out}}{I_{SDp}} \qquad R_{eqTOT} = R_{eqn} \| R_{eqp}$$

REGION 1:
nMOS: SAT
pMOS: SAT

$$R_{eqn} = \frac{2(V_{DD} - V_{out})}{k_n (V_{DD} - V_{out} - V_{Tn})^2}$$

$$R_{eqp} = \frac{2(V_{DD} - V_{out})}{k_p (V_{DD} - |V_{Tp}|)^2}$$

REGION 2
nMOS: SAT
pMOS: LIN

$$R_{eqn} = \frac{2(V_{DD} - V_{out})}{k_n (V_{DD} - V_{out} - V_{Tn})^2}$$

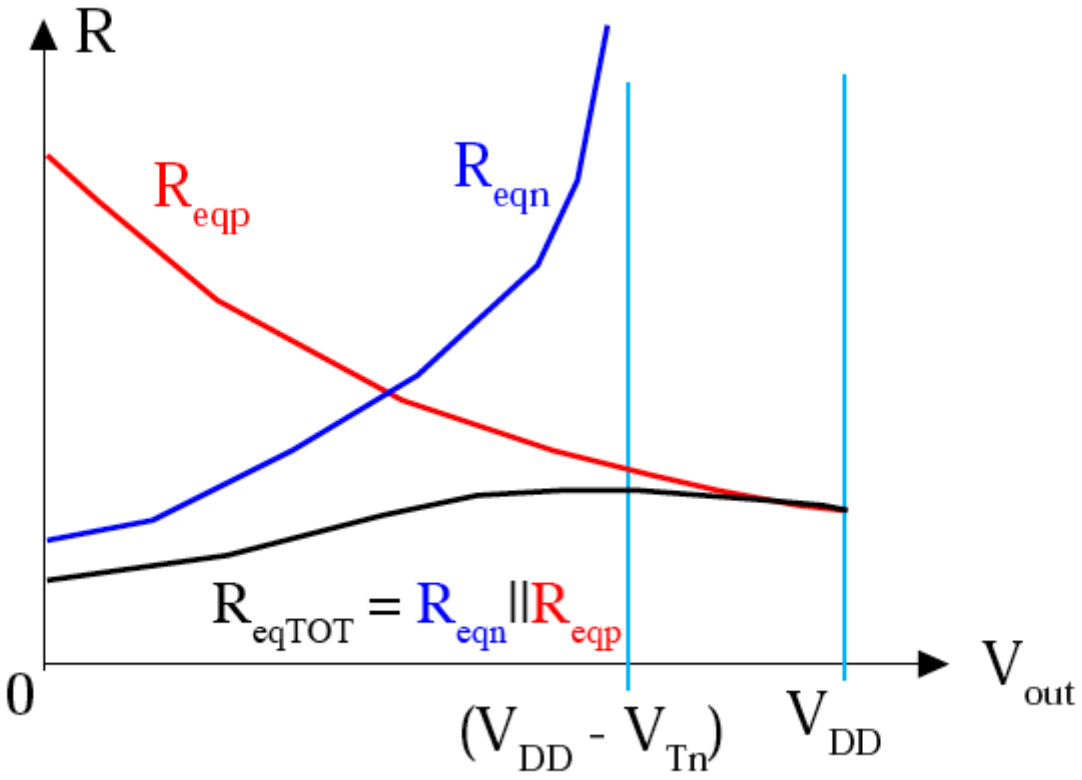
$$R_{eqp} = \frac{2(V_{DD} - V_{out})}{k_p \left[2(V_{DD} - |V_{Tp}|)(V_{DD} - V_{out}) - (V_{DD} - V_{out})^2 \right]}$$

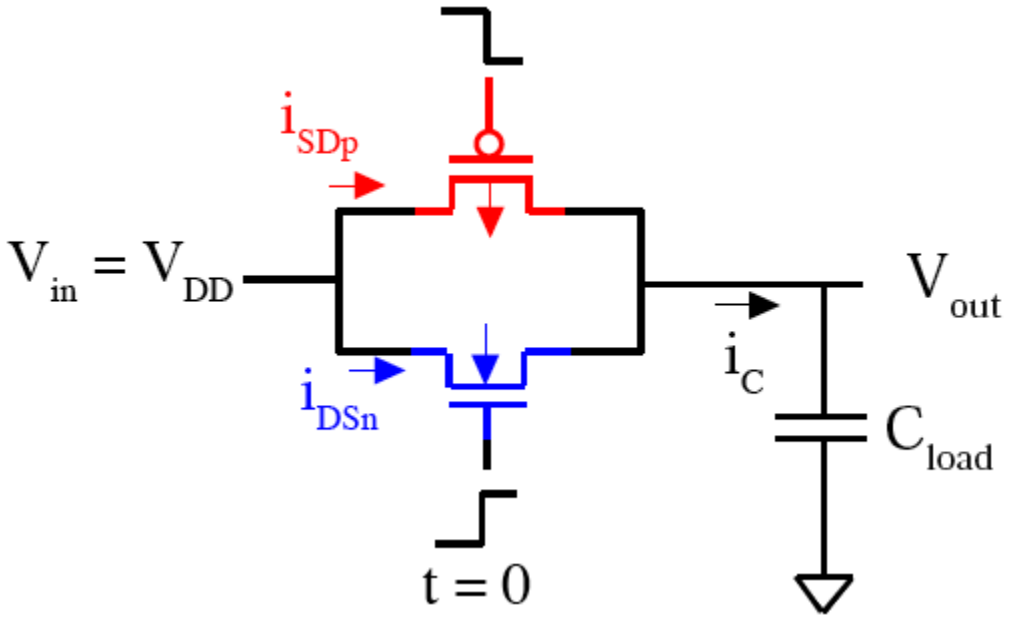
$$= \frac{2}{k_p \left[2(V_{DD} - |V_{Tp}|) - (V_{DD} - V_{out}) \right]}$$

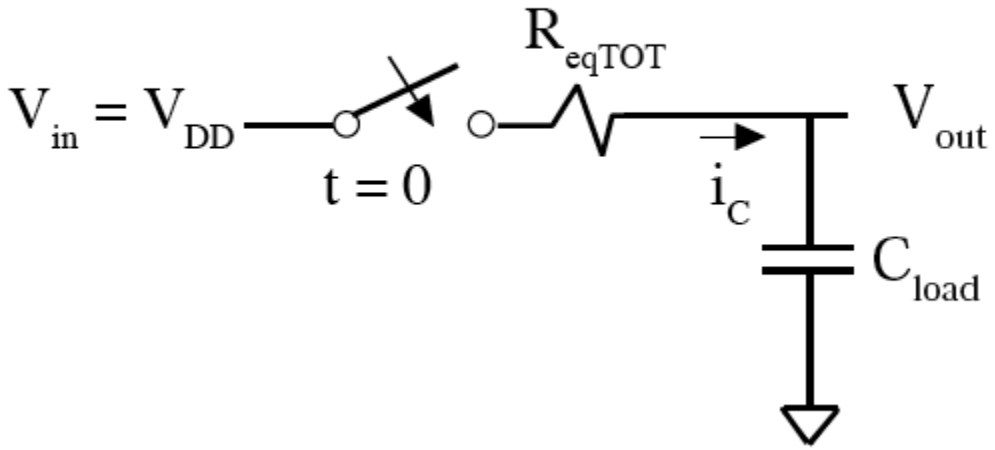
REGION 3
nMOS: OFF
pMOS: LIN

$$R_{eqn} = \infty$$

$$R_{eqp} = \frac{2}{k_p \left[2(V_{DD} - |V_{Tp}|) - (V_{DD} - V_{out}) \right]}$$


R
R_{eqp}
R_{eqn}
$R_{eqTOT} = R_{eqn} || R_{eqp}$
0
V_{out}
$(V_{DD} - V_{Tn})$
V_{DD}


i_{SDp}
$V_{in} = V_{DD}$
V_{out}
i_C
i_{DSn}
C_{load}
t = 0


R_{eqTOT}
$V_{in} = V_{DD}$
V_{out}
t = 0
i_C
C_{load}

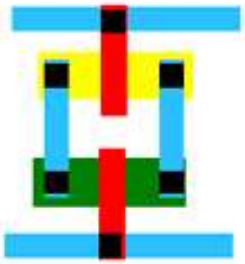
TRANSMISSION GATE LAYOUTS

Simple and small, but no metal lines can pass horizontally

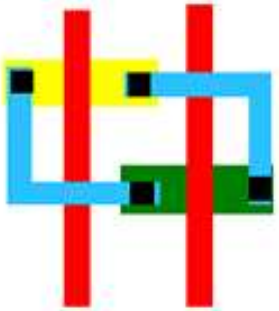
poly used to achieve horizontal metal1 transparency

metal2 used to achieve horizontal metal1 transparency

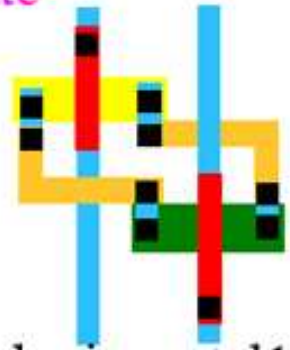
Routing Gate Signals to Transmission Gate



horizontal, via metal1



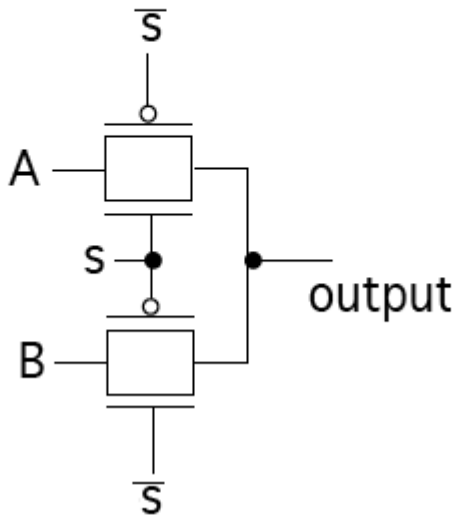
vertical, via poly



vertical, via metal1 straps

metal2 used to achieve vertical metal1 transparency

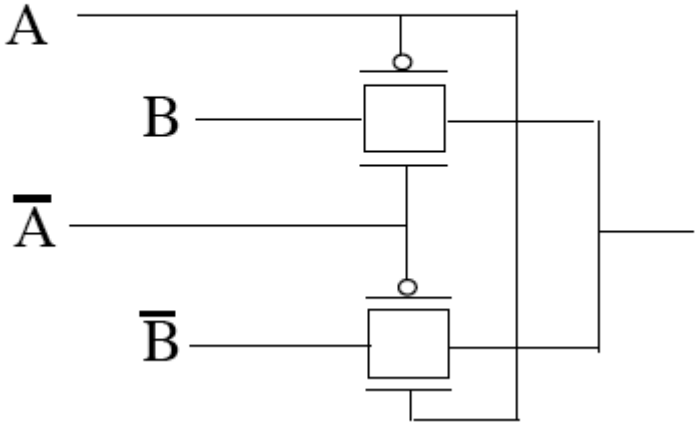
2-INPUT MULTIPLEXER



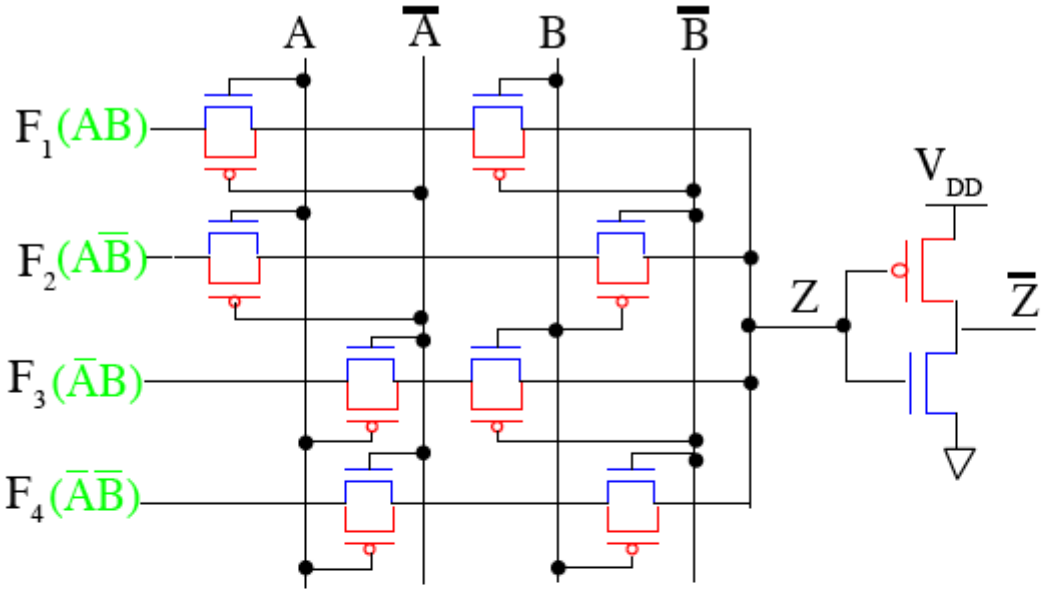
$$output = A.s + B \quad .\overline{s}$$

A	B	s	$\overline{s}$	output
x	0	0	1	0 (B)
x	1	0	1	1 (B)
0	x	1	0	0 (A)
1	x	1	0	1 (A)

XOR (COMPLEMENTARY PASS-TRANSISTOR LOGIC OR CPL)



$$F = A\overline{B} + \overline{A}B$$



SOME OF THE FUNCTIONS REALIZED BY THE BOOLEAN FUNCTION UNIT (CPL)

OPERATION (Z)	F_1	F_2	F_3	F_4
NOR(A,B)	0	0	0	1
XOR(A,B)	0	1	1	0
NAND(A,B)	0	1	1	1
AND(A,B)	1	0	0	0
OR(A,B)	1	1	1	0