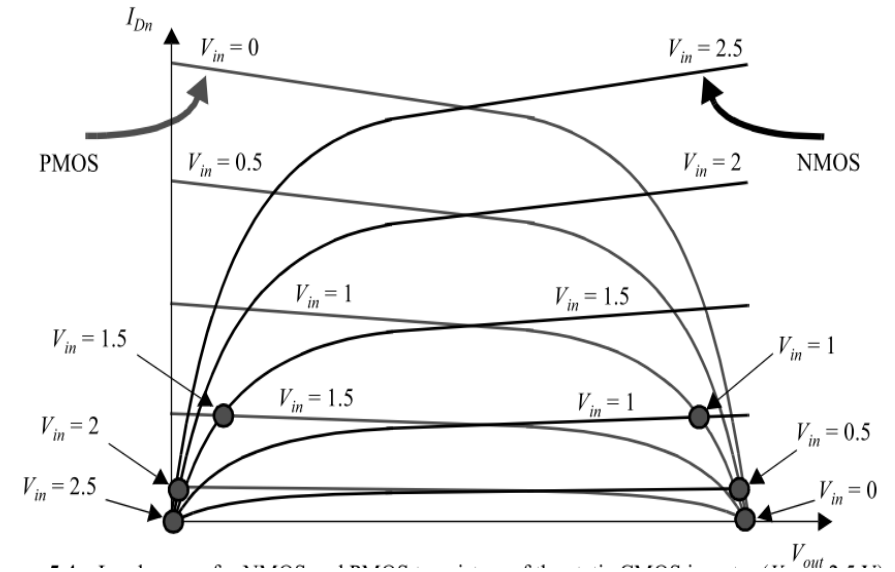
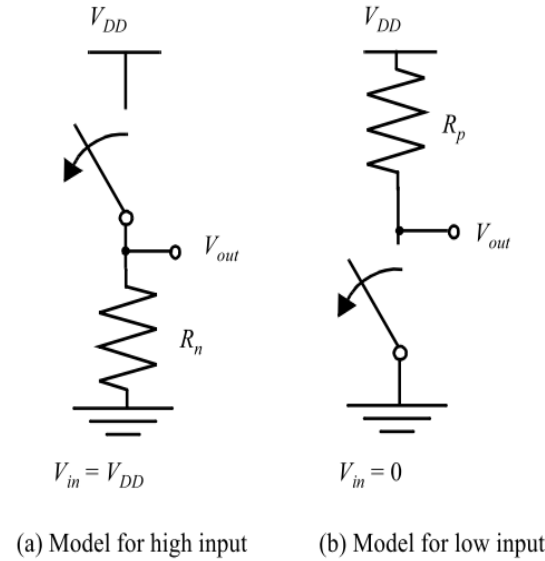
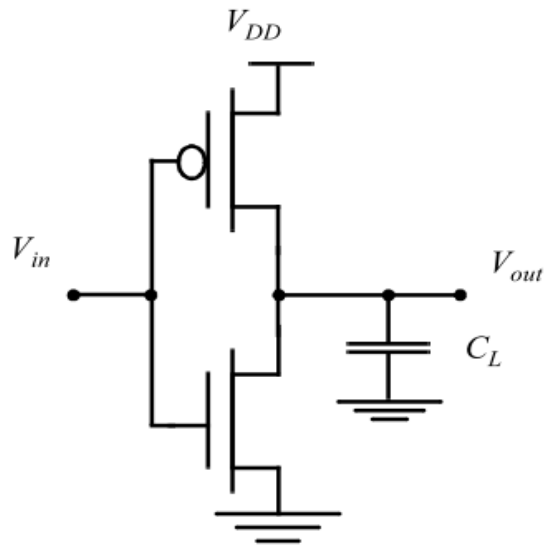


CMOS INVERTOR

Note Title

10.6.2019

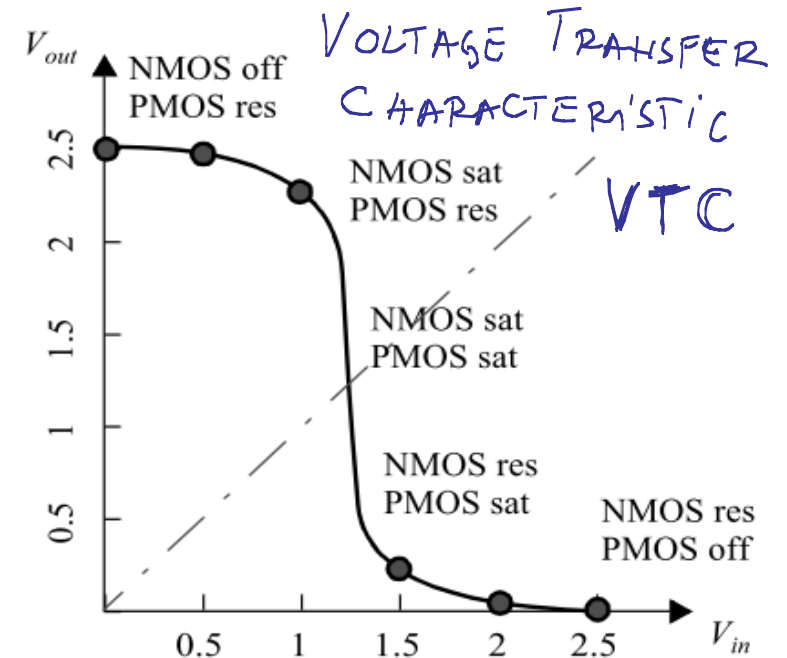
□ STATIČKE KARAKTERISTIKE.



- VISOK / NIZAK LOGIČKI NIVO ODGOVARA NAPOLU NAPAJANJA (V_{DD}) / MASI (GND) ⇒ VELIKI DITAMIČKI OPSEG (HIGH-SWITZ) ⇒ VELIKE MAFŠINE ŠUMA.

- LOGIČKI NIVOI NE ZAVISE OD VELIČINE TRANZISTORA (RATIOLESS LOGIC).

- U STACIONARNOM STATIJU UVEK POSTOJI KOHATNA OTPORNOST OD IZLAZA KA NAPAJANJU ($R_{out} \propto k_{SL}$).

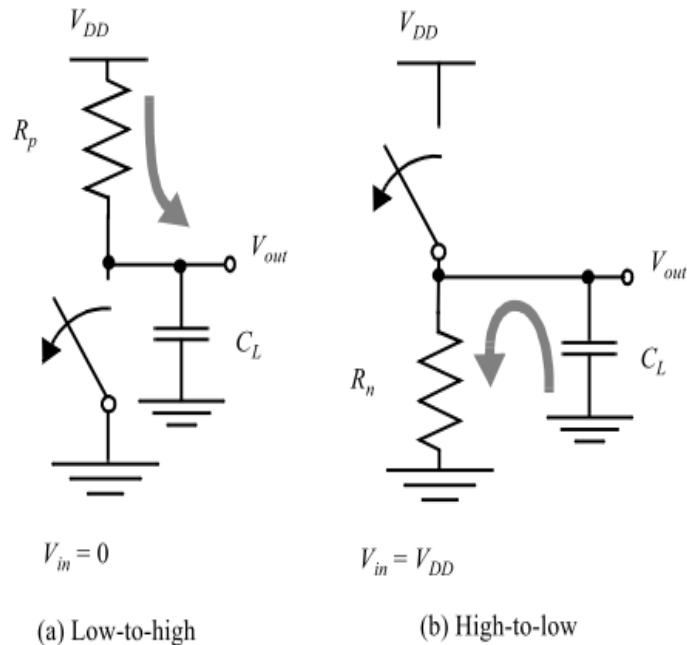


⇒ KOLO IZUŽETIHO OTPORNO HIA ŠUMOVE I SMETNJE.

- ULAZNA OTPORNOST IZUŽETIHO VELIKA @ DC. TEORETSKI, CMOS INVERTOR MOŽE DA POBUDI BESKONAČNI BR. GEJTOVA (BESKONAČNI FAH-OUT) A DA SE PRI TOME FUNKCIJA KOLA ODRŽI. MEĐUTIM, PERFORMANSE KOLA (DINAMIČKE K-KĚ, KAŠIČENJE, POTROŠIJA) SE ZNAČAHO DEGRADIRAJU UKOLIKO SE PRETPOSTAVI FAH-OUT $\rightarrow \infty$.

- U IDEALNOM SLUČAJU, KADA NEMA PROMJENE ULAZNOG / IZLAZNOG SIGNALA, NEMA POTROŠIJE KOLA ($I_{DD} \rightarrow 0A$). NARAVNO, UVEK POSTOJE STRUJE CURENIJA PREMA SUPSTRATU, ACI SE U PRVOJ APROKSIMACIJI MOGU ZAHEMARITI.

- ODZIV UGL. OPREĐENI KAPACITIVNIM OPTEREĆENJEM KOJE UKLJUČUJE:



$$C_{L_i} = \underbrace{(C_{DBH} + C_{DBP})}_i + \underbrace{C_{WIRE}}_{\text{KAPACITIVNOST VEŽE}} + \underbrace{(C_{GSP} + C_{GSP})}_{\text{KAPACITIVNOST ULAZNA (GEJTOVA) (POBUDENOG) GEJTA.}}_{i+1}$$

DIFUZIJNE KAPACITIVNOSTI KONTAKTNOG GEJTA (i-TOG) SELF-LOADING

• POD PRETPOSTAVKOM DA JE OTPORNOST KANALA KONSTANTNA ($R_p, R_n \propto C^{+1}$)

PROPAGACIONO KAŠIJEŃJE ODREĐENO VREMENISKOM KONSTANTOM R_p I C_L .

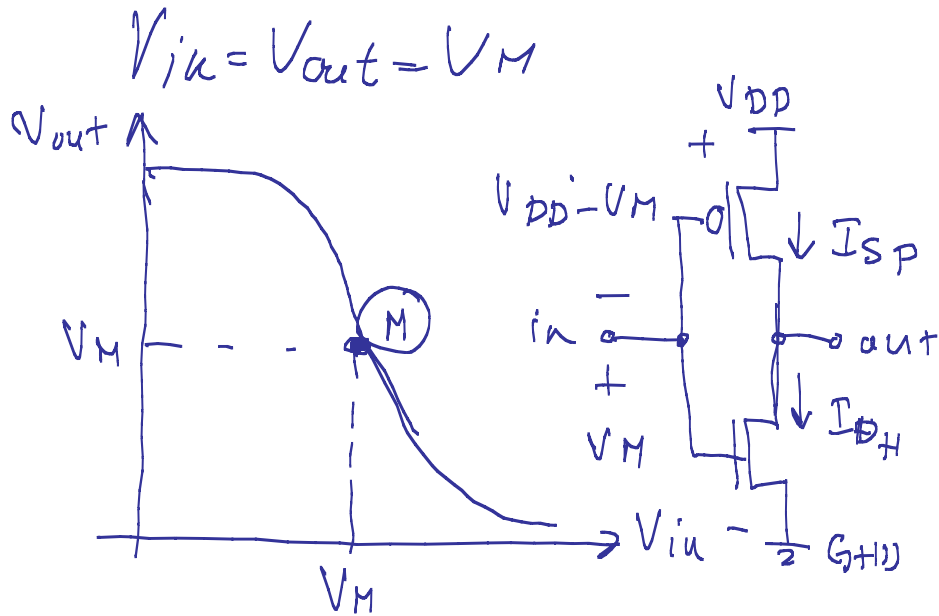
DAKLE "BRZ" GEDT (SA MALIM PROPAGACIONIM KAŠIJEŃJEM) SE DOBIJA ILI SMANJEŃJEM

C ILI SMANJEŃJEM R . GENERALNO, NIJE MOGUĆE MINIMIZOVATI OBA PARAMETRA

ISTOVREMENO POSTO. TIP. ZA $R \downarrow$ TREBA $(W/L) \uparrow \Rightarrow C \uparrow$ I OBRNUTO.

▷ NAPOMENA PRAGA CMOS INVERTORA. (SWITCHING THRESHOLD)

$$I_{D_H} = I_{S_P}$$



$$k_n \left(\frac{W}{L}\right)_n V_{DSAT_H} \left(V_{GS_n} - V_{TH_n} - \frac{V_{DSAT_H}}{2} \right) =$$

$$k_p \left(\frac{W}{L}\right)_p V_{DSAT_P} \left(V_{GS_p} - V_{TH_p} - \frac{V_{DSAT_P}}{2} \right) =$$

$$k_n \left(\frac{W}{L}\right)_n V_{DSAT_H} \left(V_M - V_{TH_n} - \frac{V_{DSAT_H}}{2} \right) =$$

$$k_p \left(\frac{W}{L}\right)_p V_{DSAT_P} \left(V_{DD} - V_M - V_{TH_p} - \frac{V_{DSAT_P}}{2} \right) =$$

$$V_{DSAT_P}, V_{DSAT_H} > 0V$$

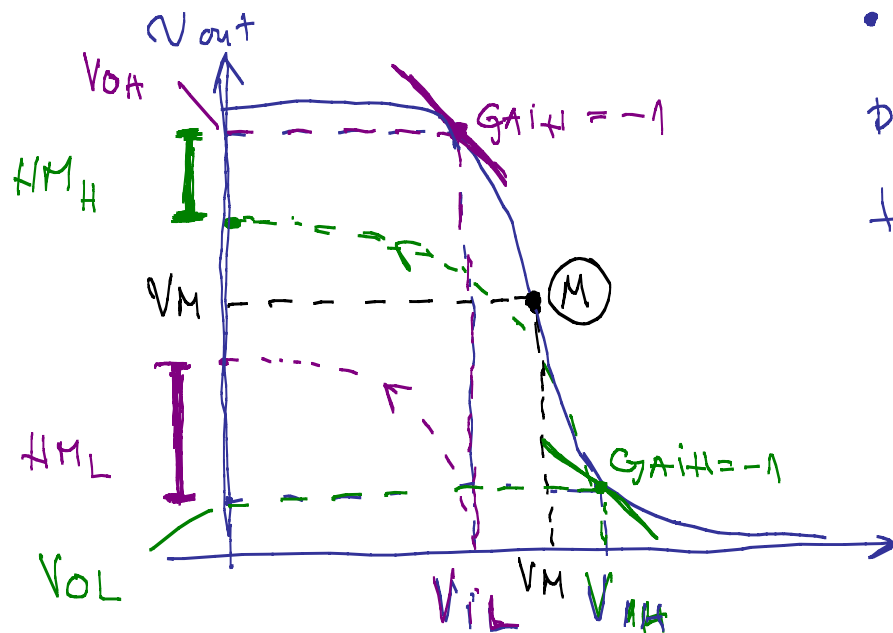
$$V_{TH_P}, V_{TH_H} > 0V$$

$$\left(V_M - V_{TH_n} - \frac{V_{DSAT_H}}{2} \right) = r \left(V_{DD} - V_M - V_{TH_p} - \frac{V_{DSAT_P}}{2} \right)$$

$$r = \frac{k_p (W/L)_p V_{DSATp}}{k_n (W/L)_n V_{DSATn}} = \frac{\mu_n C_{ox} (W)_p V_{DSATp} / L_p}{\mu_p C_{ox} (W)_n V_{DSATn} / L_n} \left| \begin{array}{l} \approx \frac{v_{sat,p} W_p}{v_{sat,n} W_n} \\ E_c \approx \frac{V_{DSAT}}{L}; v_{sat} = \mu \cdot E_c \end{array} \right.$$

$$V_M = \frac{(V_{THn} + \frac{V_{DSATn}}{2}) + r(V_{DD} - V_{THp} - \frac{V_{DSATp}}{2})}{1+r} \approx \frac{r \cdot V_{DD}}{1+r} \left| V_{DD} \gg \{V_{DSAT}, V_{TH}\} \right.$$

- V_M UGL. ODREĐEJI RELATIVNI ODHOSI ŠIRINA TRANZISTORA. TIPR. ZA V_M BLIŽE KAPOHU NAPAJANJA (V_{DD}) TREBA IZABRATI ($W_p > W_n$) $\Rightarrow r \uparrow$. DA BI SE OBEZBEDILE MAKSIMALNE MARGINE ŠUMA (H_{MH}, H_{ML}), OBIČNO SE BIRA $r=1$ T.J. $V_M = V_{DD}/2$.



- V_M HIJE ZNAČAJNO OSETLJIV NA VARIJACIJE ODHOSA DIMENZIJA PMOS I NMOS TRANZISTORA (W_p/W_n). TIPR. ZA $V_{THn} = 0.43V$, $V_{THp} = 0.4V$, $V_{DSATn} = 0.63V$, $V_{DSATp} = 1V$, $k_n = 115 \mu A/V^2$, $k_p = 30 \mu A/V^2$, $(W_p/W_n) = \{3, 2.5, 2\}$ I $V_{DD} = 2.5V$ DOBIJA SE:

$$r = \frac{k_p V_{DSATP}}{k_n V_{DSATH}} = \frac{k_p' (W/L)_p V_{DSATP}}{k_n' (W/L)_n V_{DSATH}} \Big|_{L_p=L_n=L_{min}} = \frac{k_p'}{k_n'} \cdot \frac{V_{DSATP}}{V_{DSATH}} \cdot \frac{W_p}{W_n} = \{1.24, 1.03, 0.83\}$$

$$V_M = \frac{(V_{THn} + V_{DSATH}/2) + r (V_{DD} - V_{THp} - V_{DSATP}/2)}{1+r} = \{1.22, 1.18, 1.13\} V.$$

• NESIMETRIČNA VTC JE POŽELJNA U NEKIM PRIMENAMA. NPR. UKOLIKO HVOZ LOGIČKE KULE SADRŽI PIKOVE

VELIKE VREDNOSTI, ODA SE POKERAJEM

V_M KA V_{DD} SIGNAL MOŽE OPORAVITI.

MEĐUTIM, TREBA IMATI HA UTM DA

POKERAJE V_M U ODHOSU NA $\frac{V_{DD}}{2}$

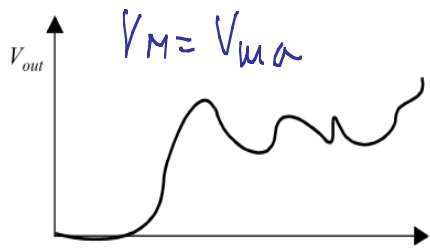
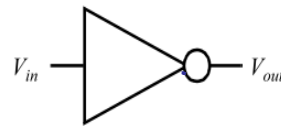
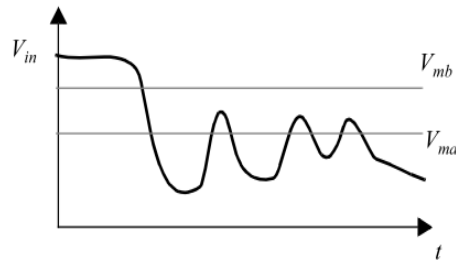
ZA VEĆI IZHOS REZULTUDE ZHAGADHIM

POVEČAJEM POKRŠITIE. NPR. DA BI

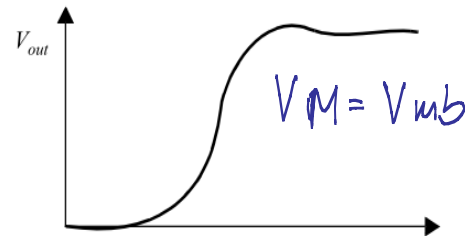
POVEČAJEM POKRŠITIE. NPR. DA BI

JE V_M SA $V_{DD}/2 = 1.25V$ POVEČAO NA $V_M = 1.5V$ POTREBAH JE

ODHOS TRANZISTORA:



(a) Response of standard inverter



(b) Response of inverter with modified threshold

$$V_M = \frac{(V_{THN} + V_{DSATN}/2) + r(V_{DD} - V_{THP} - V_{DSATP}/2)}{1+r}$$

$$[V_M - V_{THN} - V_{DSATN}/2] = r[V_{DD} - V_{THP} - V_{DSATP}/2 - V_M]$$

$$[V_M - V_{THN} - V_{DSATN}/2] = \frac{k'_p}{k'_n} \frac{V_{DSATP}}{V_{DSATN}} \cdot \left(\frac{W_p}{W_n}\right) [V_{DD} - V_M - V_{THP} - V_{DSATP}/2]$$

$$\frac{W_p}{W_n} = \frac{k'_n V_{DSATN}}{k'_p V_{DSATP}} \frac{V_M - V_{THN} - V_{DSATN}/2}{V_{DD} - V_M - V_{THP} - V_{DSATP}/2} = 18.33 \Rightarrow 19 \times \text{širi PMOS OD NMOS!}$$

D MARGINE ŠUMA CMOS INVERTORA.

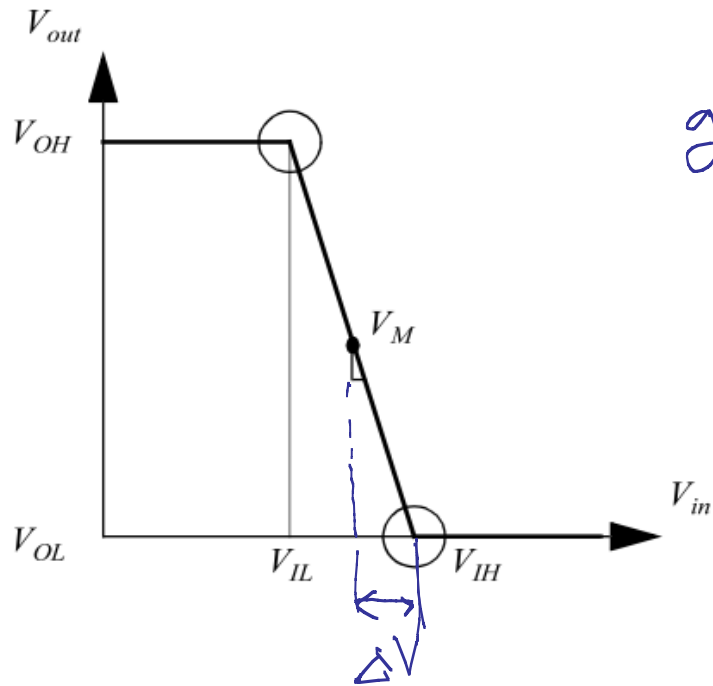
$$\{V_{IL}, V_{IH}\} = V_{in} @ \left. \frac{\partial V_{out}}{\partial V_{in}} = -1 \right|_{@V_{in}=V_M} = g \rightarrow \text{POJAČAČIJE INVERTORA}$$

TRAŽEHIJE ANALITIČKOG IZRAZA ZA $\{V_{IL}, V_{IH}\}$ POMOĆU $\frac{\partial V_{out}}{\partial V_{in}} = -1$ JE,

IAKO MOGUĆE, ŽARETATI POSAO PA SE ČESTO ZA PROCETU $\{V_{IL}, V_{IH}\}$

KORISTI APROKSIMACIJA VTC LINEARNIM SEGMENTIMA (PIECE-WISE-LINEAR)

NEGATIF HASIB



$$g \triangleq \frac{\Delta V_{out}}{\Delta V_{in}} = - \frac{V_{OH} - V_{OL}}{V_{IH} - V_{IL}} \quad \left| \begin{array}{l} = \frac{-V_{DD}}{V_{IH} - V_{IL}} < 0 \quad (1) \\ V_{OH} = V_{DD}, V_{OL} = 0V \end{array} \right.$$

$$\frac{V_{OH} - V_{OL}}{V_{IH} - V_{IL}} = \frac{V_M}{\Delta V} \Rightarrow \left| \begin{array}{l} \Delta V = \frac{V_M}{V_{DD}} (V_{IH} - V_{IL}) \quad (2) \\ V_{OH} = V_{DD}, V_{OL} = 0V \end{array} \right.$$

$$(1) \quad V_{IH} = -\frac{V_{DD}}{g} + V_{IL}$$

$$(2) \quad V_{IH} = V_M + \Delta V = V_M + \frac{V_M}{V_{DD}} (V_{IH} - V_{IL}) \Rightarrow V_{IH} \left[1 - \frac{V_M}{V_{DD}} \right] + \frac{V_M}{V_{DD}} V_{IL} = V_M$$

$$\left[\frac{-V_{DD}}{g} + V_{IL} \right] \left[1 - \frac{V_M}{V_{DD}} \right] + \frac{V_M}{V_{DD}} V_{IL} = V_M$$

$$-\frac{V_{DD}}{g} + \frac{V_M}{g} + V_{IL} - \cancel{V_{IL} \frac{V_M}{V_{DD}}} + \cancel{\frac{V_M}{V_{DD}} V_{IL}} = V_M \Rightarrow \boxed{V_{IL} = V_M + \frac{V_{DD} - V_M}{g}}$$

$$V_{iH} = -\frac{V_{DD}}{g} + V_{iL} = -\frac{V_{DD}}{g} + V_M + \frac{V_{DD}}{g} - \frac{V_M}{g} \Rightarrow V_{iH} = V_M - \frac{V_M}{g}$$

NOISE MARGIN HIGH

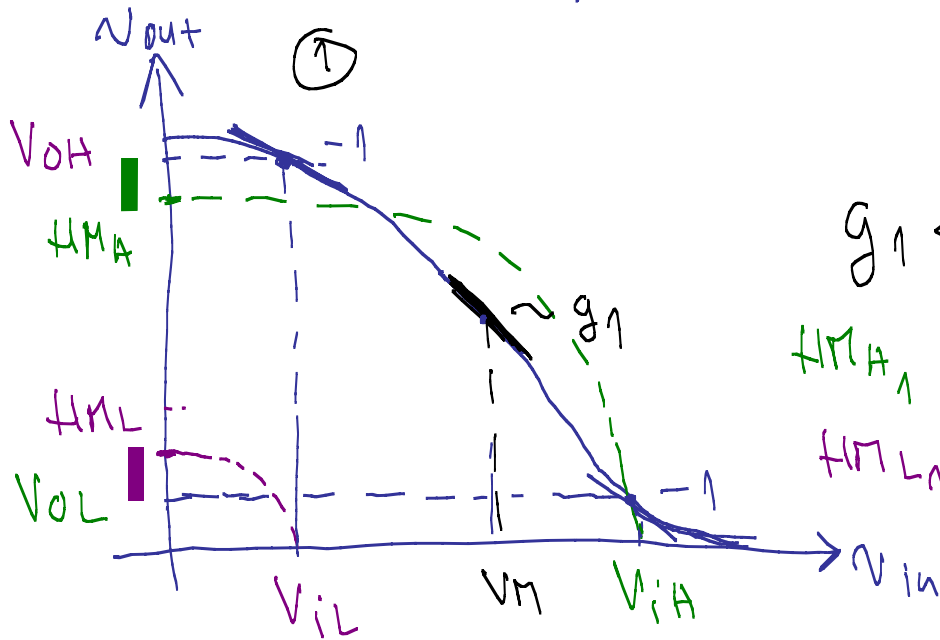
$$NM_H = V_{OH} - V_{iH} = V_{DD} - V_{iH}$$

$$NM_L = V_{iL} - V_{OL} = V_{iL}$$

NOISE MARGIN LOW

• Iz prethodne analize se može videti da je veliko pojačanje invertora (g) poželjno (maksimizuju se margine sume). U idealnom slučaju

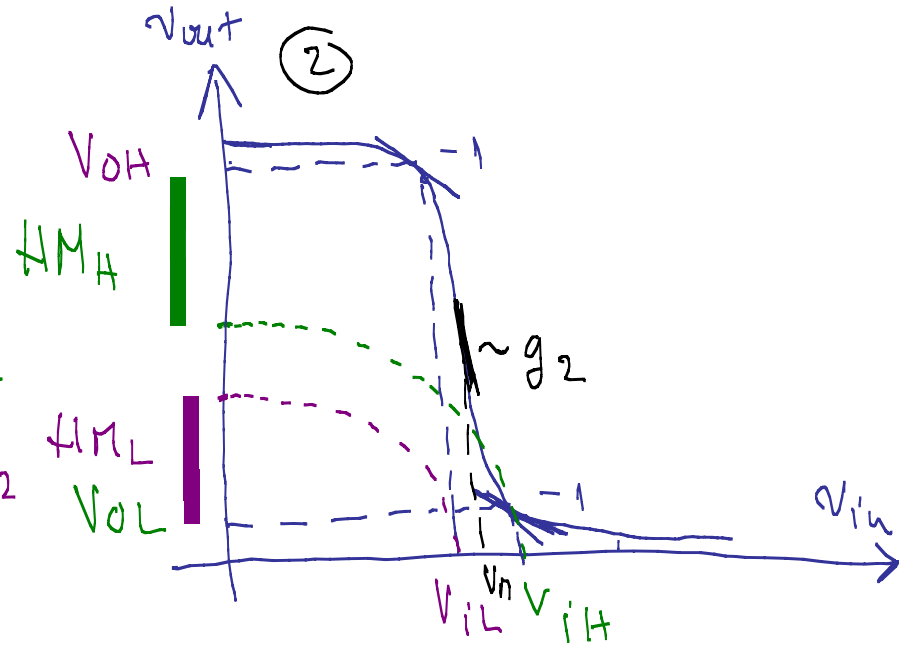
$$g \rightarrow \infty \Rightarrow V_{iH} = V_M, V_{iL} \rightarrow V_M \Rightarrow NM_H = V_{DD} - V_M, NM_L = V_M$$



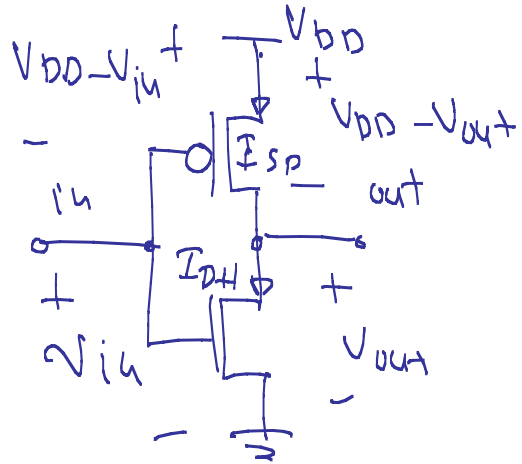
$$g_1 \ll g_2$$

$$NM_{H1} \ll NM_{H2}$$

$$NM_{L1} \ll NM_{L2}$$



• DO POJACANJA (g) SE DOLAZI DIFERENCIJALNIM STRUJNE JEDNAČINE PO V_{in}
 ZA SLUČAJ $V_{in} \rightarrow V_M$.



$$I_{D_H} = I_{S_P}$$

$$k_n V_{DSAT_H} \left(v_{in} - V_{TH_H} - \frac{V_{DSAT_H}}{2} \right) \left[1 + \lambda_H v_{out} \right] =$$

$$k_p V_{DSAT_P} \left(V_{DD} - v_{in} - V_{TH_P} - \frac{V_{DSAT_P}}{2} \right) \left[1 + \lambda_p (V_{DD} - v_{out}) \right] \Big/ \frac{\partial}{\partial v_{in}}$$

$$k_n V_{DSAT_H} \left[1 + \lambda_H v_{out} + \left(v_{in} - V_{TH_H} - \frac{V_{DSAT_H}}{2} \right) \lambda_H \frac{\partial v_{out}}{\partial v_{in}} \right] =$$

$$k_p V_{DSAT_P} \left[-1 - \lambda_p (V_{DD} - v_{out}) + \left(V_{DD} - v_{in} - V_{TH_P} - \frac{V_{DSAT_P}}{2} \right) \left(-\lambda_p \frac{\partial v_{out}}{\partial v_{in}} \right) \right] = 0$$

$$\frac{\partial v_{out}}{\partial v_{in}} = \frac{\left[k_n V_{DSAT_H} (1 + \lambda_H v_{out}) + k_p V_{DSAT_P} (1 + \lambda_p (V_{DD} - v_{out})) \right]}{\left[k_n V_{DSAT_H} \lambda_H \left(v_{in} - V_{TH_H} - \frac{V_{DSAT_H}}{2} \right) + k_p V_{DSAT_P} \lambda_p \left(V_{DD} - v_{in} - V_{TH_P} - \frac{V_{DSAT_P}}{2} \right) \right]}$$

$$\underbrace{k_n V_{DSAT_H}}_{I_{D_H}} \lambda_H \left(v_{in} - V_{TH_H} - \frac{V_{DSAT_H}}{2} \right) + \underbrace{k_p V_{DSAT_P}}_{I_{S_P}} \lambda_p \left(V_{DD} - v_{in} - V_{TH_P} - \frac{V_{DSAT_P}}{2} \right)$$

I_{D_H}

I_{S_P}

$$I_{D_H} = I_{S_P} = I_D(V_M) @ V_{in} = V_M \quad \wedge \quad \left. \begin{array}{l} 1 + \lambda_n V_{out} \\ 1 + \lambda_p (V_{DD} - V_{out}) \end{array} \right\} \rightarrow 1 @ V_{in} = V_M$$

$$\left. \frac{\partial V_{out}}{\partial V_{in}} \right|_{V_{in}=V_M} \triangleq g \approx - \frac{1}{I_D(V_M)} \cdot \frac{k_n V_{DSAT_H} + k_p V_{DSAT_P}}{\lambda_n + \lambda_p} = \frac{k_n V_{DSAT_H} (1+r)}{I_D(V_M) [\lambda_n + \lambda_p]}$$

$$= \frac{\cancel{k_n V_{DSAT_H}} [1+r]}{\cancel{k_n V_{DSAT_H}} \left[V_M - V_{TH_H} - \frac{V_{DSAT_H}}{2} \right] [\lambda_n + \lambda_p]}$$

$$g \approx \frac{-(1+r)}{\left(V_M - V_{TH_H} - \frac{V_{DSAT_H}}{2} \right) (\lambda_n + \lambda_p)}$$

"POJAČAČIJE CMOS INVERTORA UGL. ODREĐENO"

"TEHNOLOŠKIM PARAMETRIMA (NAJVIŠE SA λ)"

- PRAKTIČNO, PROJEKTAHT MOŽE DO NEKE DA UTIČE NA (g) IZBOROM NAPONA NAPAJANJA (V_{DD}) I NAPONA PRAGA INVERTORA (V_M).

PRIMER 1 ZA CMOS INVERTOR DIMENZIJA $(W_P/W_N) = 3.5$ IZRAĐENOG

U 250nm TEHNOLOŠKOM PROCESU GDE JE MINIMALNI CMOS TRANZISTOR

$(W/L)_N = \left(\frac{375\mu\text{m}}{250\text{nm}} \right)$, ODREDITI MARGINE ŠUMA. POZHATU JE: $K'_n = 115 \frac{\text{mA}}{\text{V}^2}$,

$k'_p = 30 \frac{\text{mA}}{\text{V}^2}$, $V_{THN} = 0.43\text{V}$, $V_{THP} = 0.4\text{V}$, $V_{DSATN} = 0.63\text{V}$, $V_{DSATP} = 1\text{V}$,

$\lambda_n = 0.06\text{V}^{-1}$, $\lambda_p = 0.1\text{V}^{-1}$, $V_{DD} = 2.5\text{V}$. INVERTOR IMA SIMETRIČNU VTC.

$$r = \frac{k'_p V_{DSATP}}{k'_n V_{DSATN}} \cdot \frac{W_P}{W_N} = 1.45 ; I_D(V_M) = k'_n \left(\frac{W}{L} \right)_N V_{DSATN} \left(V_M - V_{THN} - \frac{V_{DSATN}}{2} \right)$$

$$= 54.88\mu\text{A}$$

SIMETRIČNA VTC $\Rightarrow V_M = \frac{V_{DD}}{2} = 1.25\text{V}$

$$g = - \frac{k'_n V_{DSATN} + k'_p V_{DSATP}}{I_D(V_M) (\lambda_n + \lambda_p)} = - \frac{k'_n \left(\frac{W}{L} \right)_N V_{DSATN} + k'_p \left(\frac{W}{L} \right)_P V_{DSATP}}{I_D(V_M) (\lambda_n + \lambda_p)} = -30.31$$

$$g \approx - \frac{1+r}{(V_M - V_{THN} - V_{DSATN}/2)} \cdot \frac{1}{\lambda_n + \lambda_p} = -30.31 \text{ V/V}$$

$$V_{iL} = V_M + \frac{V_{DD} - V_M}{g} = V_M - \frac{(V_{DD} - V_M)}{|g|} = 1.2 \text{ V}; \quad V_{iH} = V_M - \frac{V_M}{g} = V_M + \frac{V_M}{|g|} = 1.29 \text{ V}$$

$$\Delta V_L \approx V_{iL} = 1.2 \text{ V}, \quad \Delta V_H = V_{DD} - V_{iH} = 2.5 - 1.29 \approx 1.21 \text{ V}$$

- GENERALIJO, IZVEDETA FORMULA ZA POJACANJE CMOS INVERTORA UVEK DAJE OPTIMISTIČNI (BEST-CASE) REZULTAT. ZA TAČNIJU PROCENU TREBA KORISTITI SPICE SIMULACIJU.

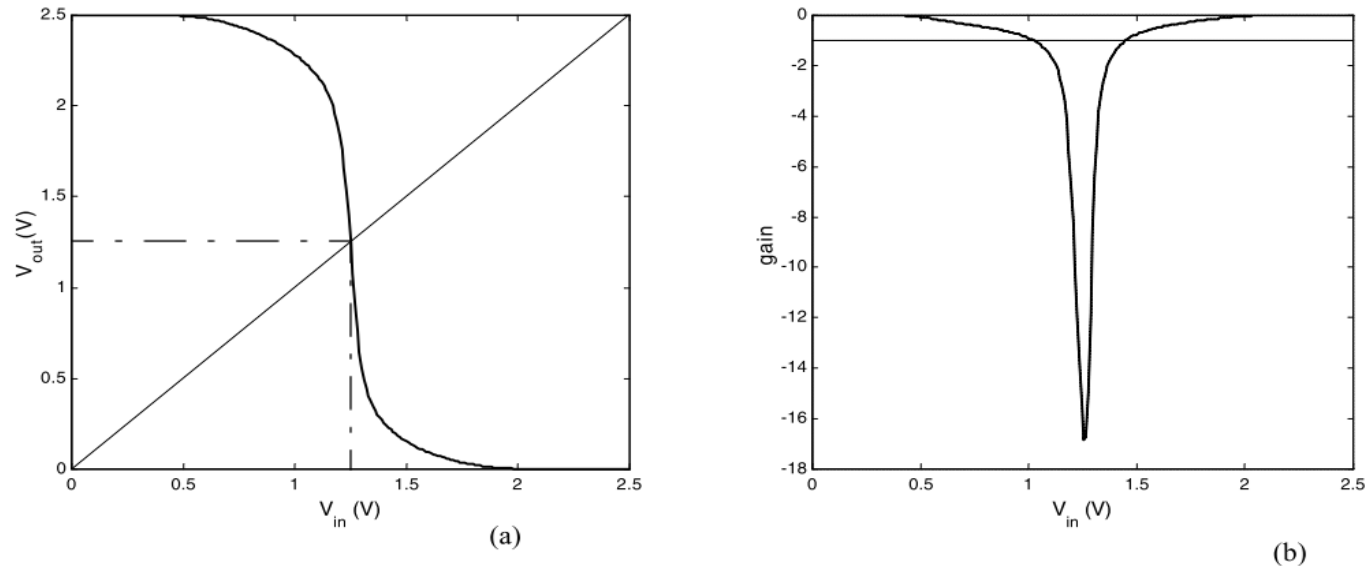


Figure 5.10 Simulated Voltage Transfer Characteristic (a) and voltage gain (b) of CMOS inverter ($0.25 \mu\text{m}$ CMOS, $V_{DD} = 2.5 \text{ V}$).

D UTICAJ VARIJACIJA DIMENZIJA TRANZISTORA NA VTC.

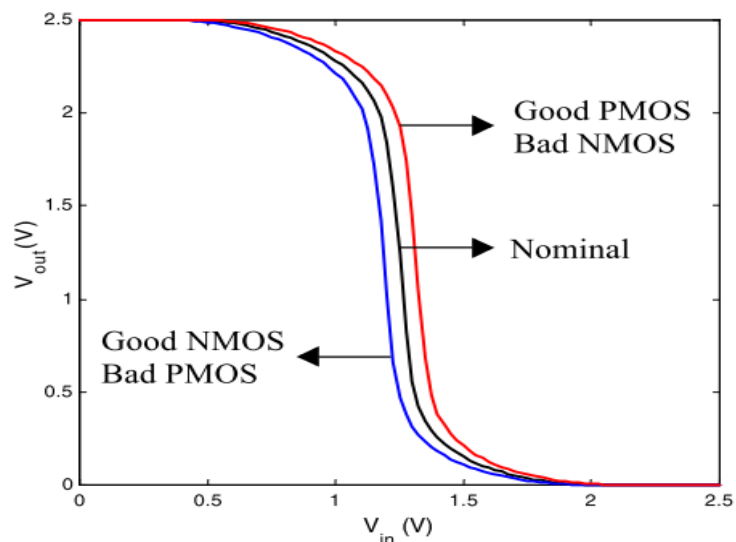
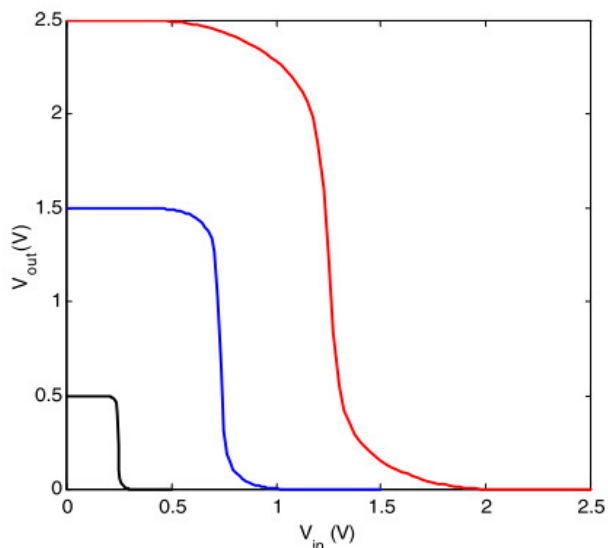
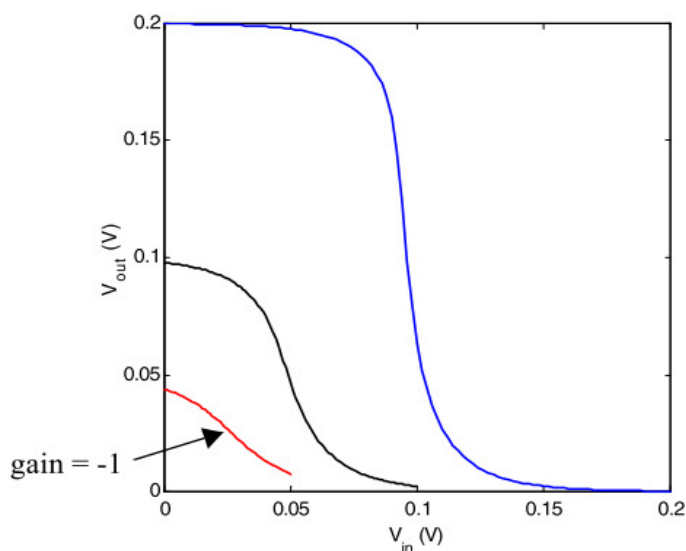


Figure 5.11 Impact of device variations on static CMOS inverter VTC. The “good” device has a smaller oxide thickness (-3nm), a smaller length (-25 nm), a higher width (+30 nm), and a smaller threshold (-60 mV). The opposite is true for the “bad” transistor.

D UTICAJ SKALIRANJA V_{DD} NA VTC.



(a) Reducing V_{DD} improves the gain...



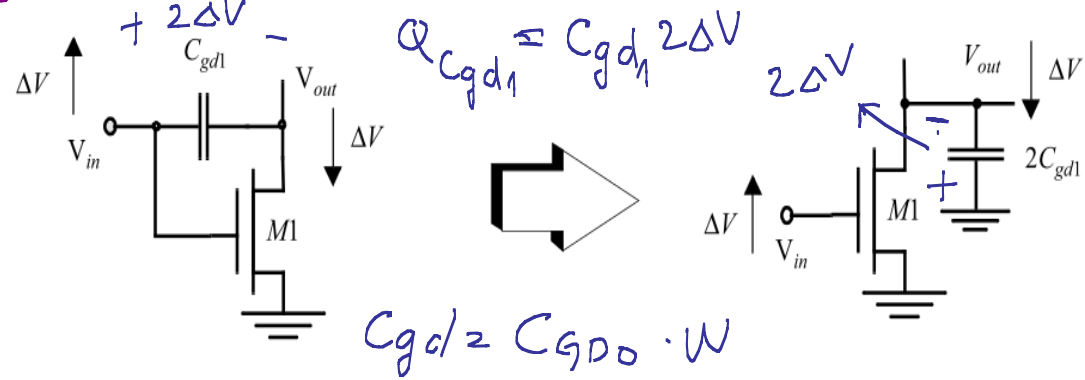
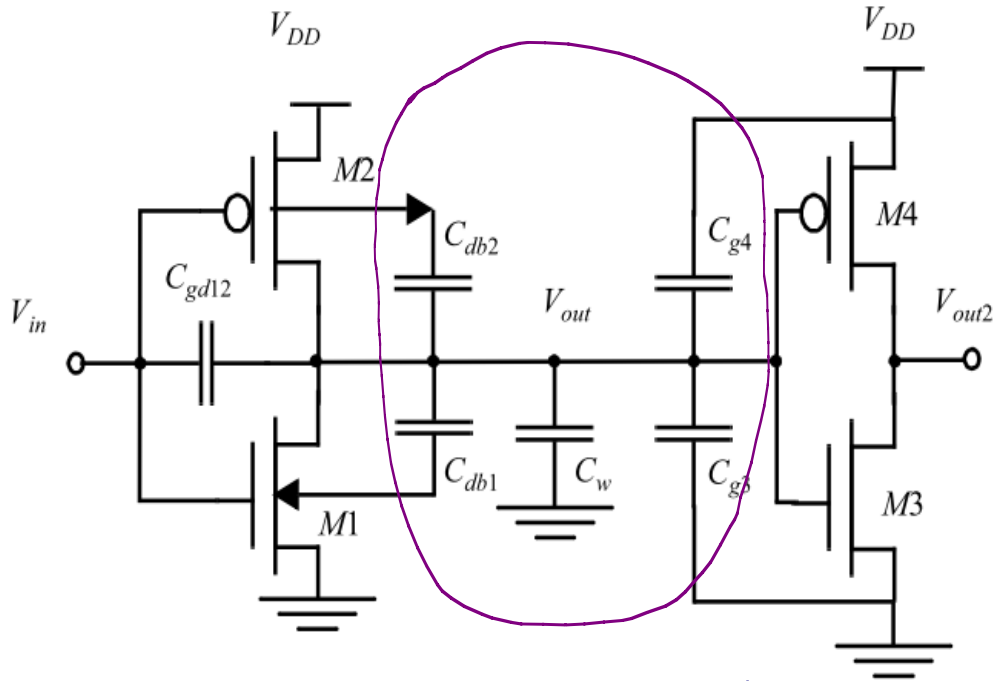
(b) but it deteriorates for very-low supply voltages.

- ZA $V_{DD} < 100mV$ KVALITET VTC OPADA I DOLAZI DO IZRAŽAJA UTICAJ TEMPERATURE ($V_T = kT/q$).
- $V_{DD\min} > (2 \div 4) \frac{kT}{q}$

□ DYNAMIČKE KARAKTERISTIKE CMOS INVERTORA.

Za minimizaciju kašnjenja (povećanje brzine rada) treba minimizovati kapacitivno opterećenje (C_L). ➤ **GEJT - DREŽNI** KAPACITIVNOST

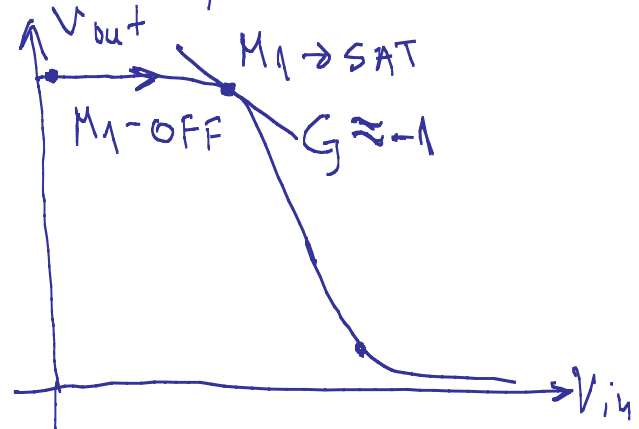
$$C_L = 2C_{gd1,2} + C_{db2} + C_{db1} + C_w + C_{g3} + C_{g4} \quad (\text{MILEROVA KAPACITIVNOST})$$



$$C_{gd} = 2 C_{gd0} \cdot W$$

• KADA M_1 ULAZI U ZASIĆENJE

POJAČANJE JE ≈ -1



$$t_M = t \frac{g}{g-1} \Rightarrow \frac{1}{sC_M} = \frac{1}{sC_{gd1,2}} \cdot \frac{-1}{-1-1} \Rightarrow C_M = 2C_{gd1,2}$$

GENERALNO, POJAČANJE VELIKIH SIGNALA CMOS INVERTORA UVEK -1 .

D DREŽU - BALK KAPACITIVNOSTI (DIFUZIONIE KAPACITIVNOSTI)

C_{db} - KAPACITIVNOSTI INVERZNO POLARISANOG PJI SPOJA. ZA $t_p 50\%$ MOGU SE LINEARIZOVATI UVOĐENIJE KOREKCIJSKOG FAKTORA:

$$k_2 = \frac{-V_0^{m_j}}{(V_H - V_L)^{(1-m_j)}} \cdot \left[(V_0 - V_H)^{(1-m_j)} - (V_0 - V_L)^{(1-m_j)} \right]; C_j = k_2 C_{j0}$$
$$m_j = [1/3, \dots, 1/2].$$

D KAPACITIVNOST VEŽE (C_w) JAKO ZAVISI OD GEOMETRIJE I LEJERA U KOME JE VEŽA REALIZOVANA.

D KAPACITIVNOSTI GEOTA ($C_{g3,4} \equiv$ FAN-OUT OPTEREĆENJE, C_{F0})

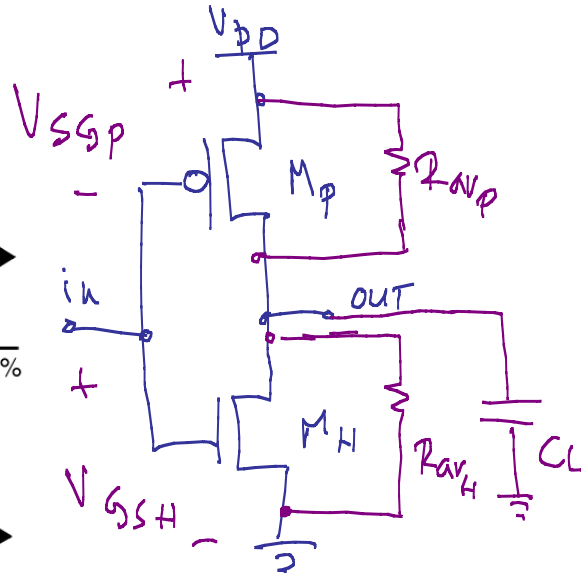
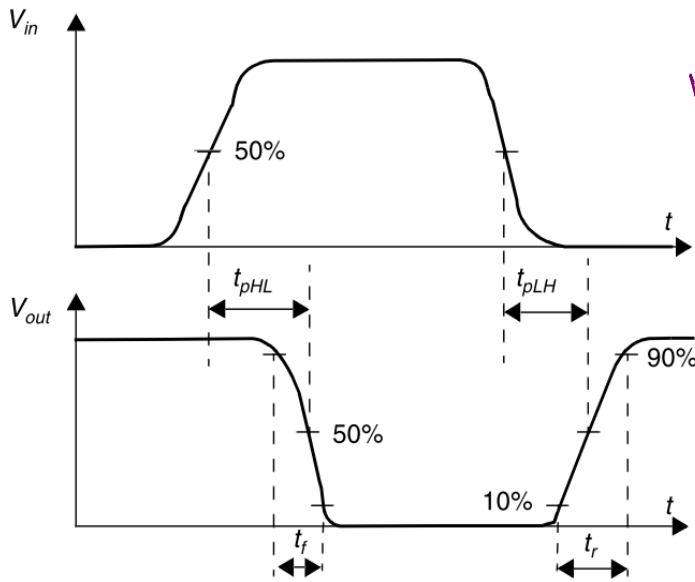
PRETPOSTAVKE: INTERVAL OD INTERESA $V_M + \frac{\Delta V}{2} < V_{out} < V_M - \frac{\Delta V}{2}$, $\Delta V \rightarrow 0V$

① V_{out} RELATIVNO KONSTANTAN U INTERVALU OD INTERESA \Rightarrow NIEMA MILEROVOG EFEKTA ZA $C_{gd3,4} \Rightarrow C_{g3,4}$ SE VIDE OD V_{out} PREMA MASI.

② KAPACITIVNOST KANALA $M_{3,4}$ RELATIVNO KONSTANTNA I IZNOSI $C_{ox} W L$.

$$C_{F0} = C_{g3} + C_{g4} = (C_{gs0} W + C_{gd} W + C_{ox} W L)_3 + (C_{gs0} W + C_{gd0} W + C_{ox} W L)_4$$

▷ PROPAGACIÓI KA $\bar{S}+i, E+I, E$, $t_p = \frac{t_{pHL} + t_{pLH}}{2}$



$$R_{AVp} \approx \frac{3}{4} \frac{V_{DD}}{I_{DSATp}} \left(1 - \frac{7}{9} \lambda_p V_{DD} \right)$$

$$I_{DSATp} = k_p V_{DSATp} \left(V_{GSP} - V_{THp} - \frac{V_{DSATp}}{2} \right)$$

$$R_{AVn} \approx \frac{3}{4} \frac{V_{DD}}{I_{DSATn}} \left(1 - \frac{7}{9} \lambda_n V_{DD} \right)$$

$$I_{DSATn} = k_n V_{DSATn} \left(V_{GSH} - V_{THn} - \frac{V_{DSATn}}{2} \right)$$

$$t_{pHL} = C_L R_{AVn} \ln(2), \quad t_{pLH} = C_L R_{AVp} \ln(2) \Rightarrow t_p = \left(\frac{R_{AVn} + R_{AVp}}{2} \right) C_L \ln(2)$$

• ZA $t_{pHL} = t_{pLH} \Rightarrow R_{AVn} = R_{AVp}$. OVAO USLOV SE POPUĐARA SA USLOVOM ZA SIMETRIČNU VTC.

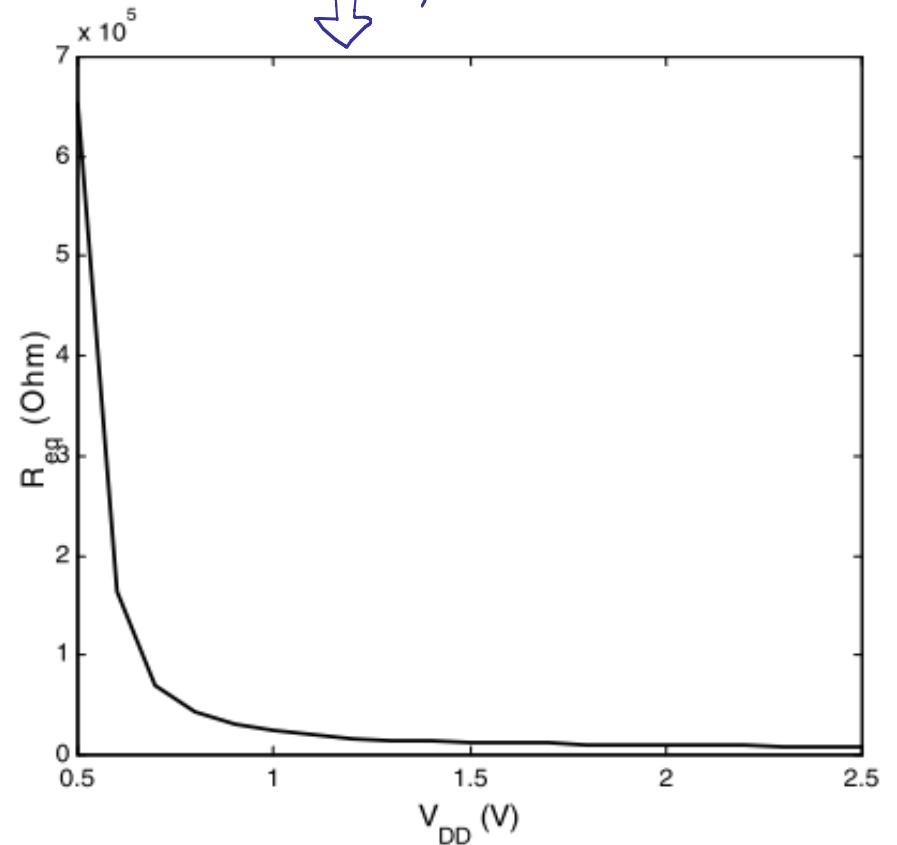
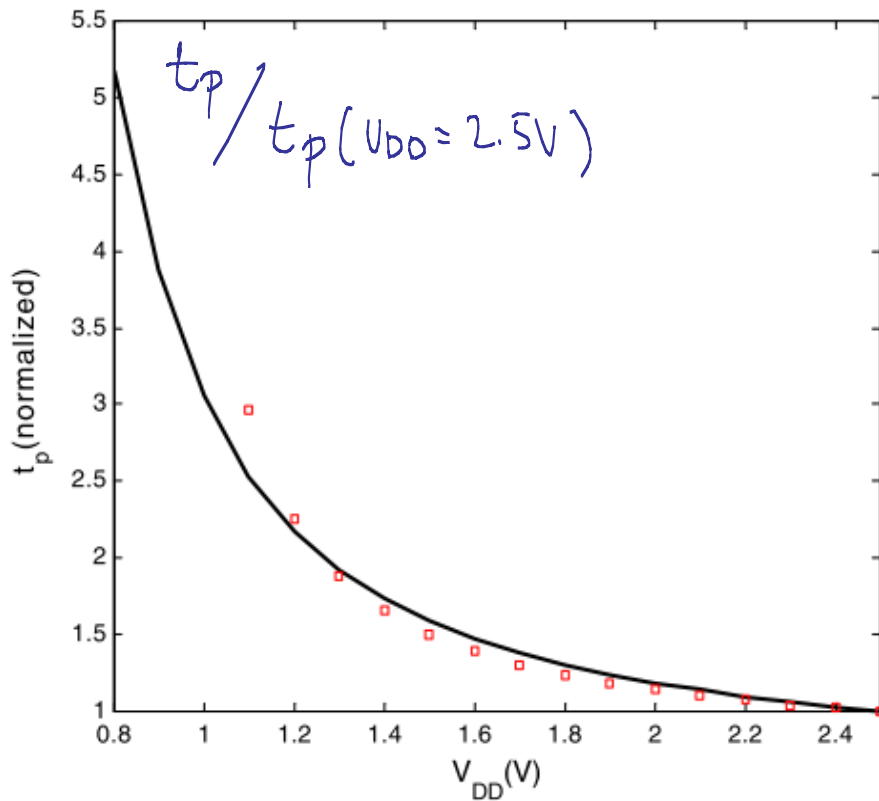
$$t_{pHL} \approx 0.69 C_L \frac{3}{4} \frac{V_{DD}}{I_{DSATn}} \Big|_{\lambda_n \rightarrow 0, V^{-1}} \approx 0.52 \frac{C_L V_{DD}}{k_n V_{DSATn} \left(V_{GSH} - V_{THn} - \frac{V_{DSATn}}{2} \right)}$$

@ $V_{GSH} = V_{in} = V_{DD} \Rightarrow t_{pHL} \approx 0.52 \frac{C_L V_{DD}}{k_n V_{DSATn} \left(V_{DD} - V_{THn} - \frac{V_{DSATn}}{2} \right)} \approx 0.52 \frac{C_L}{k_n V_{DSATn}}$
 $V_{DD} \gg V_{THn} + \frac{V_{DSATn}}{2}$

$$t_{pHL} \approx 0.52 \frac{C_L}{k'_n \left(\frac{W}{L}\right)_n V_{DSATn}} ; t_{pLH} \approx 0.52 \frac{C_L}{k'_p \left(\frac{W}{L}\right)_p V_{DSATp}}$$

$$t_p = \frac{t_{pHL} + t_{pLH}}{2} \approx 0.26 C_L \left(\frac{1}{k'_n \left(\frac{W}{L}\right)_n V_{DSATn}} + \frac{1}{k'_p \left(\frac{W}{L}\right)_p V_{DSATp}} \right)$$

- t_p ugl. nezavisno od V_{DD} (slično kao i R_{eq})



• STRATEGIJA ZA MINIMIZACIJU t_p

① MINIMIZOVATI C_L (KOMPAKTAN LETAUT SA ŠTO MAJIOM PORŠIOM DIFUZIJA SORSA/PREJHA, MINIMIZE $\{C_{clb}\}$).

② MAKSIMIZOVATI (W/L) (ALI OPREZNO DA NE BI DOŠAO DO IZRAŽAJA "SELF-LOADING" EFEKAT, $(W/L) \uparrow \Rightarrow C \uparrow$).

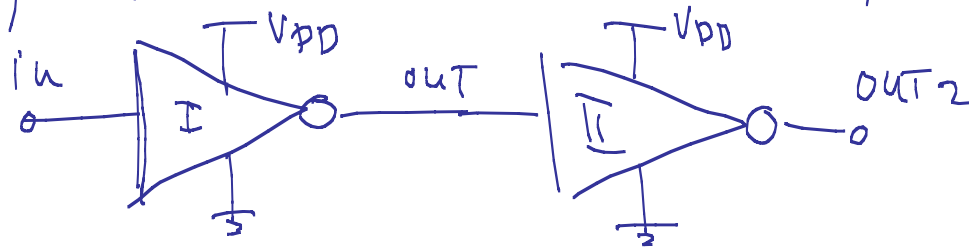
③ MAKSIMIZOVATI V_{DD} ($t_p \propto \frac{V_{DD}}{I_{PSAT}} \propto \frac{V_{DD}}{(V_{DD} - V_{THH} - V_{PSAT}/2)}$). OVA TEHNIKA TAKOĐE TREBA KORISTITI SA OPREZOM ($V_p \uparrow \propto E \uparrow \Rightarrow$ OKIDE BREAK-DOWN I HOT-CARRIERS EFEKTI DOLAZE DO IZRAŽAJA).

• USLOV $R_{avH} = R_{avP}$ OBEZBEĐUJE SIMETRIČNU VTC I $t_{pHL} = t_{pLH}$, ALI TO NE ZNAČI DA JE PRI OVOM USLOVU POSTIGNUTO MINIMALNO (OPTIMALNO)

t_p . POSTOJE ZA $\left(\frac{W_p}{W_H}\right) \uparrow \Rightarrow R_{avP} \downarrow \Rightarrow C_{clbP} \uparrow$ T.J. POSTOJE DVA OPREČNA

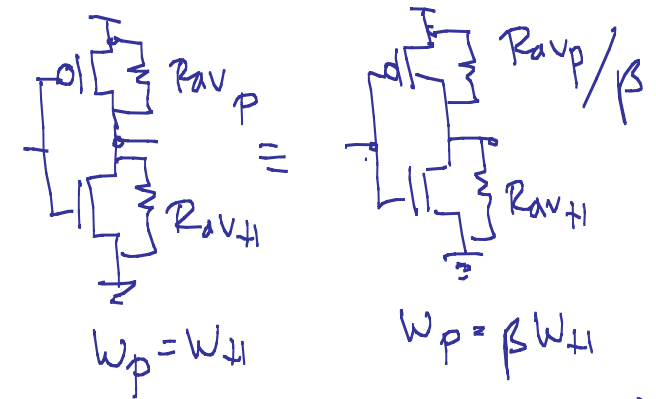
USLOVA ZA ODPORNOST; KAPACITIVNOST \Rightarrow POSTOJI OPTIMALNI

ODNOS $(W_P/W_H) = \beta_0$ KOJI MINIMIZUJE t_p .



$$C_L \approx C_{db_{H,I}} + C_{db_{P,I}} + C_w + C_{g_{H,I}} + C_{g_{P,II}}; \quad \frac{W_P}{W_H} = \beta \Rightarrow C_P = \beta C_H$$

$$C_L = (1 + \beta) C_{db_{H,I}} + C_w + (1 + \beta) C_{g_{H,II}}$$



$$C_L = (1 + \beta) (C_{db_{H,I}} + C_{g_{H,II}}) + C_w$$

$$t_p = \frac{t_{pLA} + t_{pHL}}{2} = \frac{1}{2} \ln(2) C_L \left(R_{avH} + \frac{R_{avP}}{\beta} \right) = \frac{1}{2} \ln(2) C_L R_{avH} \left(1 + \frac{\alpha}{\beta} \right)$$

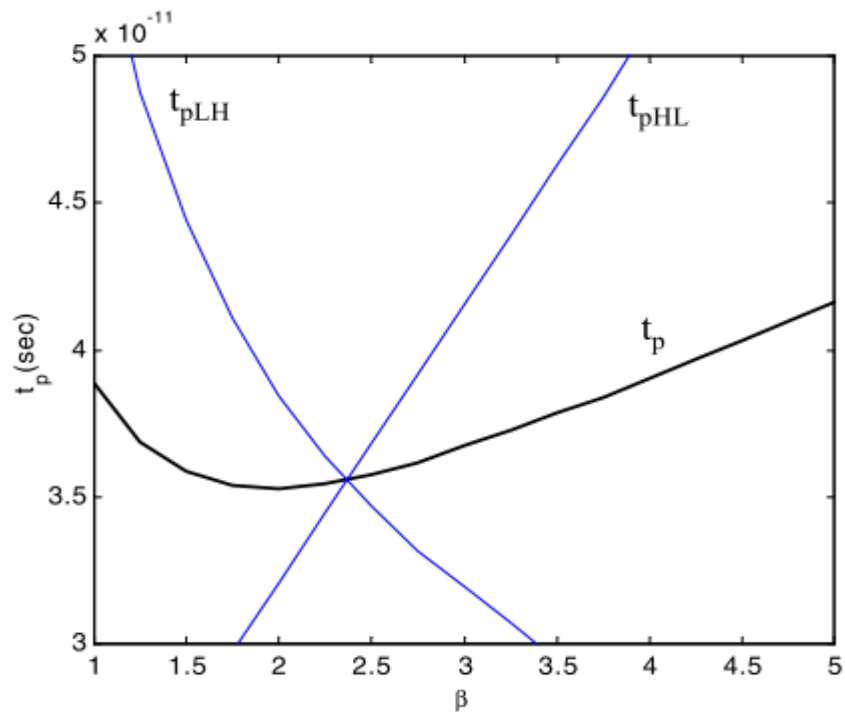
$\alpha = \frac{R_{avP}}{R_{avH}}$ - ODNOS ODPORNOST KANALA PMOS I NMOS TRANZISTORA ISTIH DIMENZIJAMA ($W_P = W_H$)

$$t_p = 0.345 \left[(1+\beta) (C_{db_{H,I}} + C_{g_{H,II}}) + C_w \right] R_{avH} \left(1 + \frac{\alpha}{\beta} \right)$$

$$t_p = R_A \left[(1+\beta) C_A + C_w \right] \left[1 + \frac{\alpha}{\beta} \right]; \quad R_A = 0.345 R_{avH}$$

$$C_A = C_{db_{H,I}} + C_{g_{H,II}}$$

$$\frac{\partial t_p}{\partial \beta} = R_A \left\{ C_A \cdot \left(1 + \frac{\alpha}{\beta} \right) + \left[(1+\beta) C_A + C_w \right] \cdot \left(-\frac{\alpha}{\beta^2} \right) \right\} = 0 \quad / \beta = \beta_0$$



$$\beta_0 C_A (\beta_0 + \alpha) + \left[(1+\beta_0) C_A + C_w \right] (-\alpha) = 0$$

$$\beta_0^2 C_A + \cancel{\beta_0 \alpha C_A} - \alpha (C_A + C_w) - \cancel{\beta_0 \alpha C_A} = 0$$

$$\beta_0 = \sqrt{\alpha \left(1 + \frac{C_w}{C_A} \right)} \approx \sqrt{\alpha} \quad / C_w \ll C_A$$

D t_p НЕОПТРЕЖЕНОГО ИНВЕРТОРА ("INTRINSIC" t_p)

ПРЕДПОСТАВКА: СИМЕТРИЧНА ВТЛ ($t_{pLH} = t_{pHL}$)

$$C_L = \underbrace{2C_{gd_{1,2}} + C_{db_2} + C_{db_1}}_{C_{int}} + \underbrace{C_w + C_{g_3} + C_{g_4}}_{C_{ext}}$$

C_{int} (ИНТЕРНО ОПТРЕЖЕНИЕ)
 C_{ext} (ЭКСТЕРНО ОПТРЕЖЕНИЕ)

$$t_p = \ln(2) \cdot C_L \cdot R_{av}, \quad R_{av} = \frac{R_{avH} + R_{avP}}{2} = \text{ЭКИВАЛЕНТНА ОТПОРНОСТ ГЕТА}$$

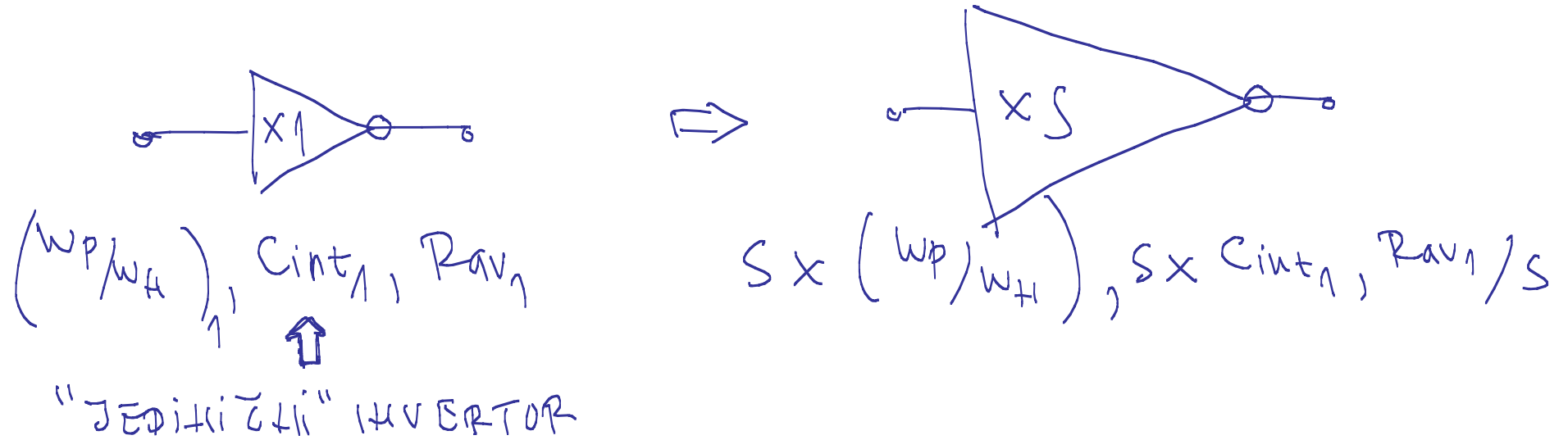
$$t_p = 0.69 R_{av} (C_{int} + C_{ext}) = 0.69 R_{av} C_{int} \left(1 + \frac{C_{ext}}{C_{int}} \right)$$

$$t_p = t_{p0} \left(1 + \frac{C_{ext}}{C_{int}} \right)$$

"INTRINSIC" t_p : $t_{p0} = 0.69 R_{av} C_{int} = t_p (C_{ext} = 0F)$!

▷ UTICAJ PROMENE DIMENZIJA GEJTA NA t_p .

PRETPOSTAVKA: DIMENZIJA INVERTORA SE POVEĆA S PUTA!



(NAJMAJI MOGUĆI INVERTOR ZA DATU TEHNOLOGIJU)

$$t_{ps} = 0.69 \frac{R_{av1}}{S} \cdot (C_{int1} \times S + C_{ext}) = 0.69 R_{av1} C_{int1} \left(1 + \frac{C_{ext}}{S \times C_{int1}} \right)$$

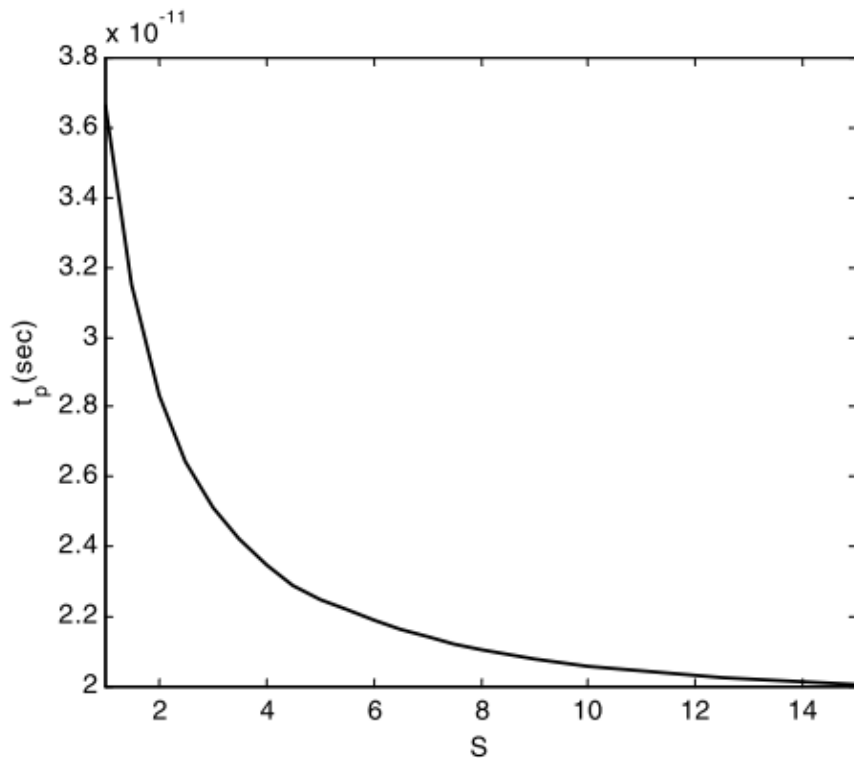
$$t_{ps} = t_{p0} \left(1 + \frac{C_{ext}}{S \cdot C_{int1}} \right)$$

NA OSNOVU IZRAZA ZA t_{ps} MOŽE SE ZAKLJUČITI:

① POVEĆANJE DIMENZIJA GEOTA NE UTIČE NA t_{p0} KOJE ZAVISI ISKLJUČIVO OD TEHNOLOGIJE I LEJUTA JEDINIČNOG INVERTORA.

PRAKTIČNO NE MOŽE SE OSTVARITI KAŠHJEVIJE MAHIJE OD t_{p0} !

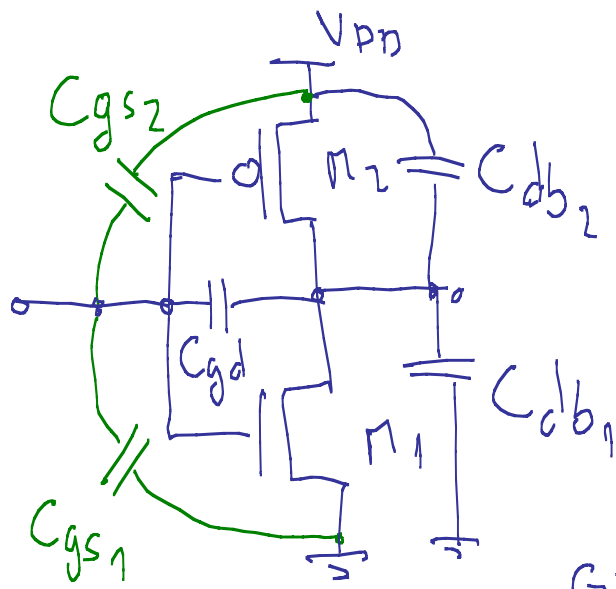
② MAKSIMIZOVANJE I MINIMIZACIJE SE UTICAJ EKSTERNOG OPTEREĆENJA ($S \rightarrow \infty \Rightarrow t_{ps} \rightarrow t_{p0}$). OVA POJAVOST POLAZI PO CENI POVEĆANJA POKRŠIJE / POTPOŠIJE.



• ZA OSNOVU RELACIJE IZMEĐU SOPSTVENIH ULAZNIH I IZLAZNIH KAPACITIVNOSTI INVERTORA DEFINIŠE SE FAKTOR μ .

$$\mu = \frac{C_{int}}{C_g}$$

SVE SOPSTVENE KAPACITIVNOSTI SU PROPORCIONALNE VELIČINI GEOTA S .



$$C_{int} = 2C_{gd_{1,2}} + C_{db_1} + C_{db_2}$$

MILLER

$$C_g = 2C_{gd_{1,2}} + C_{gs_1} + C_{gs_2}$$

$$\mu = \frac{2C_{gd} + 2C_{db}}{2C_{gd} + 2C_{gs}}$$

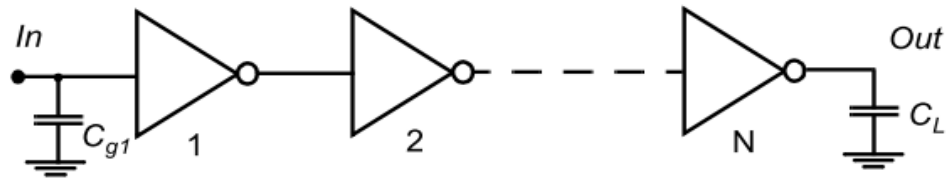
• ZA VEĆINI SUB-MIKROMSKIH PROCESA $\mu \approx 1$.
 GENERALNO, μ JE TEHNOLOŠKI PARAMETAR.

$$t_p = t_{p0} \left(1 + \frac{C_{ext}}{\underbrace{\mu \cdot C_g}_{C_{int}}} \right) = t_{p0} \left(1 + \frac{f}{\mu} \right) \approx t_{p0} (1 + f)$$

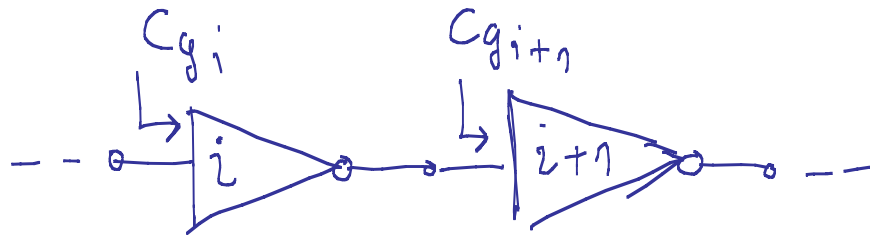
$$f = \frac{C_{ext}}{C_g} \rightarrow \text{EFEKTIVNI (ELEKTRIČNI) FAH-OUT}$$

- t_p DIREKTNO ZAVISI OD ODHOSA EKSTERNOG OPTEREĆENJA (C_{ext}) I ULAŽNE KAPACITIVNOSTI GEDA (C_g).

D OPTIMIZACIJA KASNIJE, A VIŠA INVERTORA



t_p i -TOG INVERTORA JE:



$$t_{pi} = t_{p0} \left(1 + \frac{C_{gi+1}}{\mu \cdot C_{gi}} \right) = t_{p0} \left(1 + \frac{f_i}{\mu} \right) ; f_i = \frac{C_{gi+1}}{C_{gi}}$$

$$t_p = \sum_{i=1}^N t_{pi} = \sum_{i=1}^N t_{p0} \left(1 + \frac{C_{gi+1}}{\mu C_{gi}} \right)$$

$$\frac{\partial t_p}{\partial C_{gi}} = 0 ; i = 1, \dots, N$$

PROBLEM: NAĆI OPTIMALAN BROJ INVERTORSKIH STEPENA (N) I DIMENZIJU SVAKOG STEPENA TAKO DA SE KAPACITIVNOST (C_L) HAPUJI ZA MINIMALNO VREME.

$$\frac{\partial}{\partial C_{g_i}} \left[t_{po} \left(1 + \frac{C_{g_2}}{\mu C_{g_1}} + 1 + \frac{C_{g_3}}{\mu C_{g_2}} + \dots + 1 + \frac{C_{g_i}}{\mu C_{g_{i-1}}} + 1 + \frac{C_{g_{i+1}}}{\mu C_{g_i}} + \dots \right) \right] = 0$$

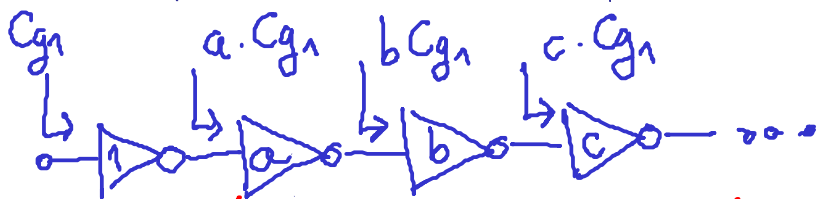
$$\frac{1}{\mu C_{g_{i-1}}} - \frac{C_{g_{i+1}}}{\mu C_{g_i}^2} = 0 \Rightarrow C_{g_i} = \sqrt{C_{g_{i+1}} \cdot C_{g_{i-1}}} \quad (1)$$

$$\frac{1}{C_{g_{i-1}}} - \frac{C_{g_{i+1}}}{C_{g_i}^2} = 0 \quad / \cdot C_{g_i} \Rightarrow \frac{C_{g_i}}{C_{g_{i-1}}} = \frac{C_{g_{i+1}}}{C_{g_i}} \Rightarrow f_i = f_{i+1} \quad (2)$$

(1) i (2) SU DVA EKVIVALENTNA USLOVA KOJI UKAZUJU DA SVAKI HAPEDHI

INVERTOR U LANCU TREBA DA BUDE SKALIRANI ISTIM FAKTOROM KAO I

PRETHODNI. PRAKTIČNO LANAC TREBA DIZAJNIRATI KAO :

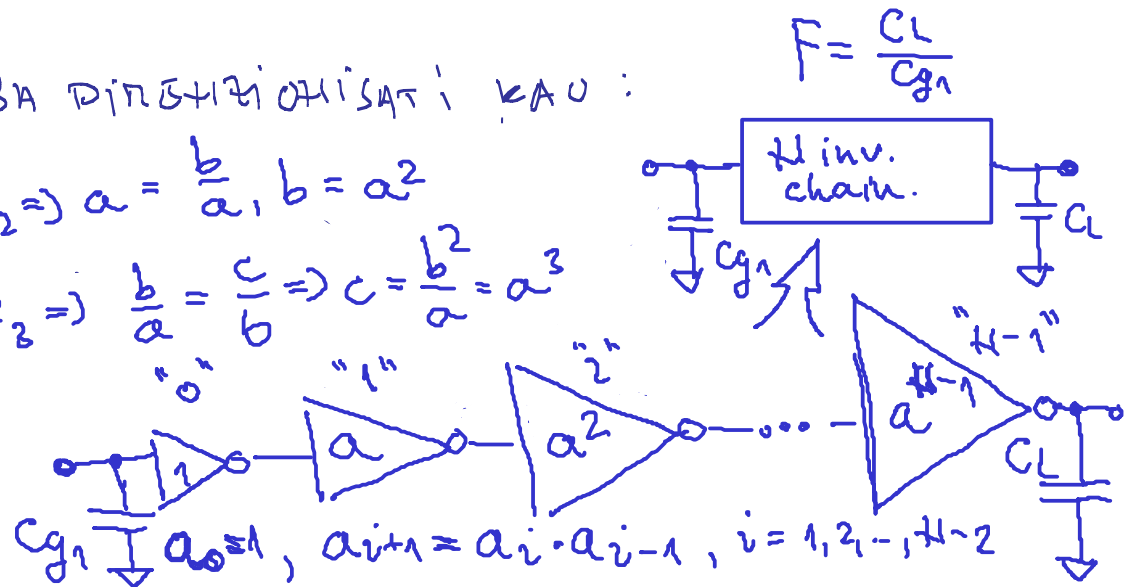


$$f_1 = \frac{a C_{g_1}}{C_{g_1}}, \quad f_2 = \frac{b C_{g_1}}{a C_{g_1}}, \quad f_3 = \frac{c C_{g_1}}{b C_{g_1}}$$

$$f_1 = a; \quad f_2 = b/a; \quad f_3 = c/b$$

$$f_1 = f_2 \Rightarrow a = \frac{b}{a}, \quad b = a^2$$

$$f_2 = f_3 \Rightarrow \frac{b}{a} = \frac{c}{b} \Rightarrow c = \frac{b^2}{a} = a^3$$



$$C_{g_1}, \quad a_0 = 1, \quad a_{i+1} = a_i \cdot a_{i-1}, \quad i = 1, 2, \dots, n-2$$

- AKO JE EFEKTIVNI FAH-OUT ZA CELO HIČ INVERTORA $F = \frac{C_L}{C_{g_n}}$, ODAJE EFEKTIVNI FAH-OUT SVAKOG STEPENA $f = \sqrt[n]{F}$, A MINIMALNO KAŠTIJEJIJE

$$t_p = H \cdot t_{p0} \left(1 + \frac{f}{\mu} \right) = H \cdot t_{p0} \left(1 + \frac{\sqrt[n]{F}}{\mu} \right).$$

- DALJE JE POTREBNO ODREDITI OPTIMALNI BROJ STEPENA H KOJI MINIMIZUJE t_p :

① KADA JE H VELIKO DOMINANTNA KOMPONENTA I KAŠTIJEJIJE POSTAJE t_{p0}

② KADA JE H MALO EFEKTIVNI FAH-OUT (f) SVAKOG STEPENA RASTE I ČLAN $\left(\frac{f}{\mu} \right)$ POSTAJE DOMINANTNI

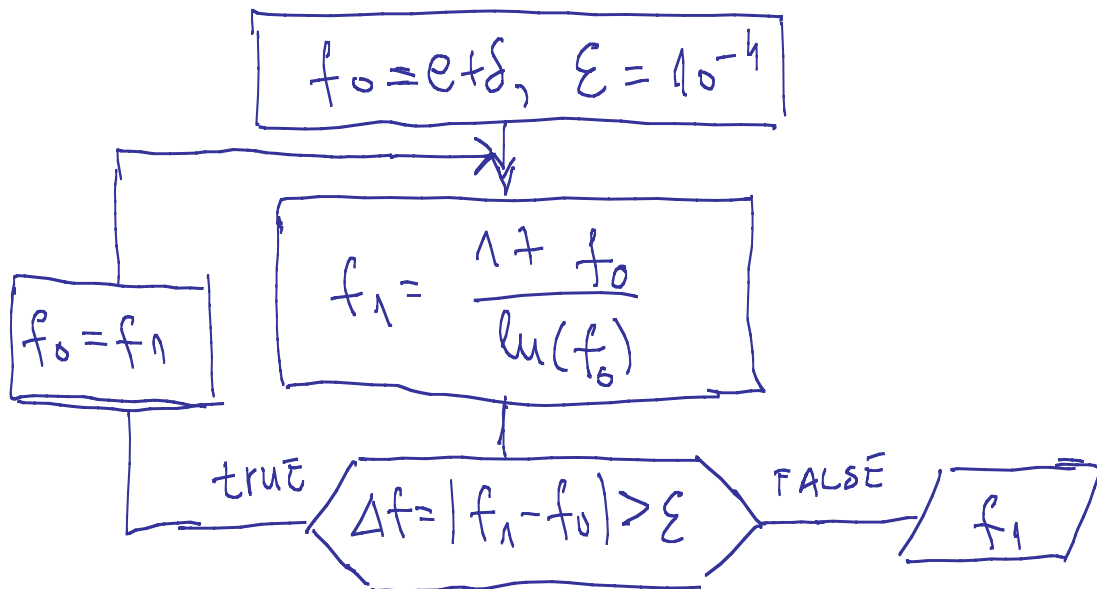
OPTIMUM JE NEGDE IZMEĐU ① I ②.

$$\frac{\partial t_p}{\partial H} = \frac{\partial}{\partial H} \left[H t_{p0} \left(1 + \frac{F^{1/n}}{\mu} \right) \right] = 0 \Rightarrow 1 + \frac{F^{1/n}}{\mu} + \frac{H}{\mu} \left(\frac{1}{H} \ln(F) \cdot \left(-\frac{1}{H} \right) \right) = 0$$

$$\mu + \sqrt[\mu]{F} - \frac{1}{\mu} \ln(F) \sqrt[\mu]{F} = 0 \Rightarrow \mu + f - \frac{1}{f} \ln(f^\mu) \cdot f = 0$$

$$\mu + f - f \ln(f) = 0 \Rightarrow \ln(f) = \frac{\mu + f}{f} \Rightarrow \boxed{f = e^{1 + \mu/f}} \quad (3)$$

- ZA $\mu = 0$ (BEZ SAMO-OPTEPEĆENJA \equiv HO SELF-LOADING) $f = e \approx 2.73$
- ZA $\mu \neq 0$ (3) SE NUMERIČKI REŠAVA (KEMA REŠETIJA U ZATUPEJION OBLIKU).
- ZA SLUČAJ, $\mu = 1$, $f_{OPT} \approx 3.6$.



```

1 % MATLAB/GNU Octave code
2 gamma = 1;
3 fo = 2.8;
4 f1 = fo;
5 it = 1;
6 ferr = 1e-4;
7 df = 100;
8 while( df > ferr)
9     fo = f1;
10    f1 = (gamma + fo)/log(fo);
11    df = abs(f1 - fo);
12    fprintf("Iter.: %u, f1: %f, fo: %f\n", [it, f1, fo]);
13    it = it + 1;
14 end

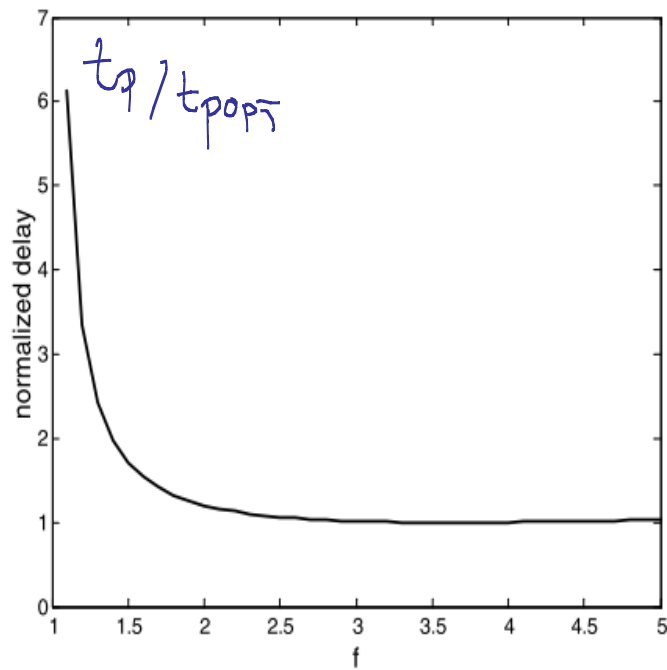
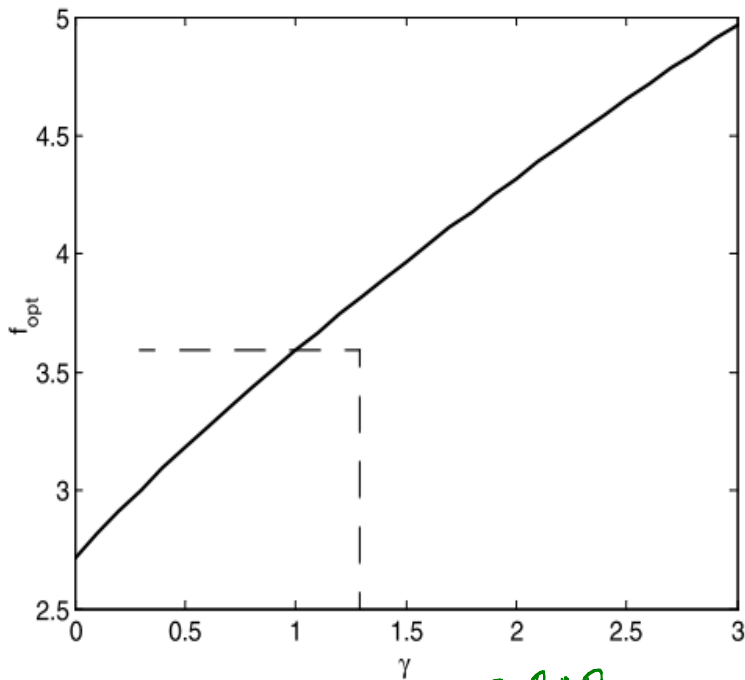
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• ZA DATO F OPTIMALNI BROJ INVERTOSKIH STEPENA JE:

$$N_{opt} \sqrt{F} = f_{opt} \Rightarrow \frac{1}{N_{opt}} \ln(F) = \ln(f_{opt}) \Rightarrow N_{opt} = \frac{\ln(F)}{\ln(f_{opt})}$$

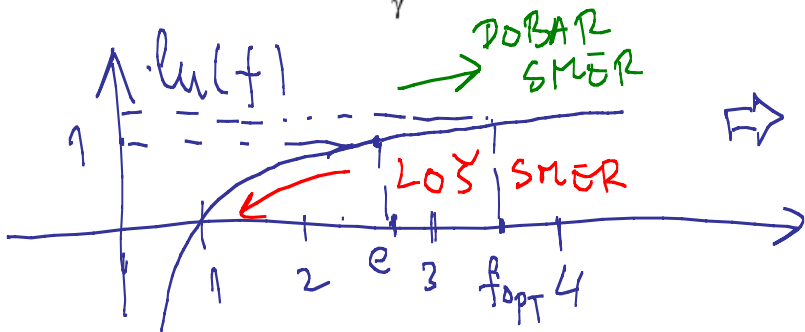
$$t_{popt} = N_{opt} t_{po} \left(1 + \frac{f_{opt}}{\mu} \right)$$

• IZBOR $f > f_{opt}$ NE DOPRINOSI
KASNIJE U ZNAČAJNOJ MERI, ALI SE



DOBIVA MAHI BROJ
STEPENA ($f \uparrow \Rightarrow \downarrow$).

• OPCIJU $f < f_{opt}$
TREBA IZBEGAVATI
POŠTO SE NE DOBIVA
ZNAČAJNO MAHJE t_p , ALI
SE ZATO UVEĆAVA N
(VEĆA POKRŠIHA).

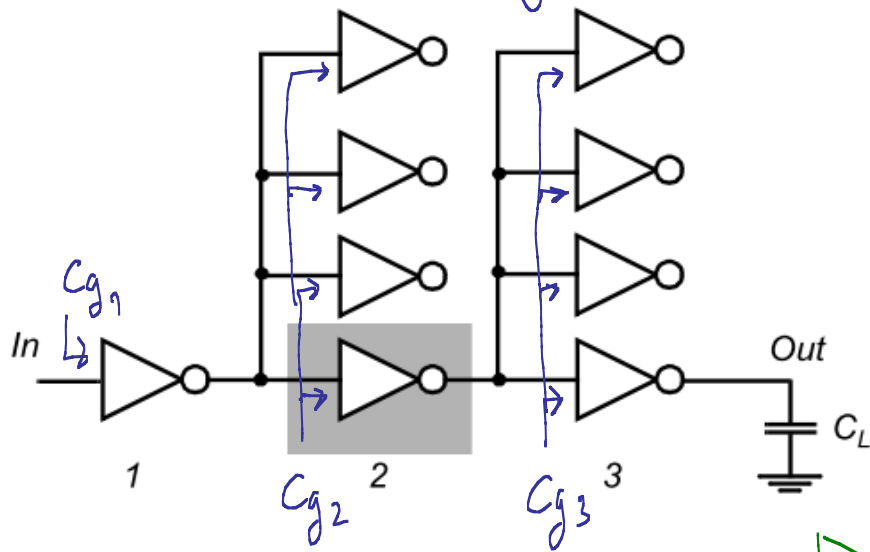


⇒ ZA $f < f_{opt}$ $\ln(f)$ HLAGLO PADA ⇒ LI BRZO RASTE!

$$N = \frac{\ln(F)}{\ln(f)}$$

PRIMER 2

ODREDITI DIMENZIJU INVERTORA TAKO DA t_p BUDE MINIMALNO AKO JE $C_L = 64 C_{g1}$.



$$f_3 = f_2 = f_1 \Rightarrow \frac{C_L}{C_{g3}} = \frac{4 C_{g3}}{C_{g2}} = \frac{4 C_{g2}}{C_{g1}}$$

$$\frac{C_L}{C_{g3}} = \frac{4 C_{g2}}{C_{g1}} \Rightarrow C_L C_{g1} = 4 C_{g2} C_{g3}$$

$$64 C_{g1}^2 = 4 C_{g2} C_{g3}$$

$$16 C_{g1}^2 = C_{g2} C_{g3}$$

$$C_{g2} = C_{g3} C_{g1}^2 (*)$$

$$16 C_{g1}^2 = C_{g2} \cdot \frac{C_{g2}}{C_{g1}}$$

$$16 C_{g1}^3 = C_{g2}^2$$

$$C_{g2} = \sqrt[3]{16 C_{g1}}$$

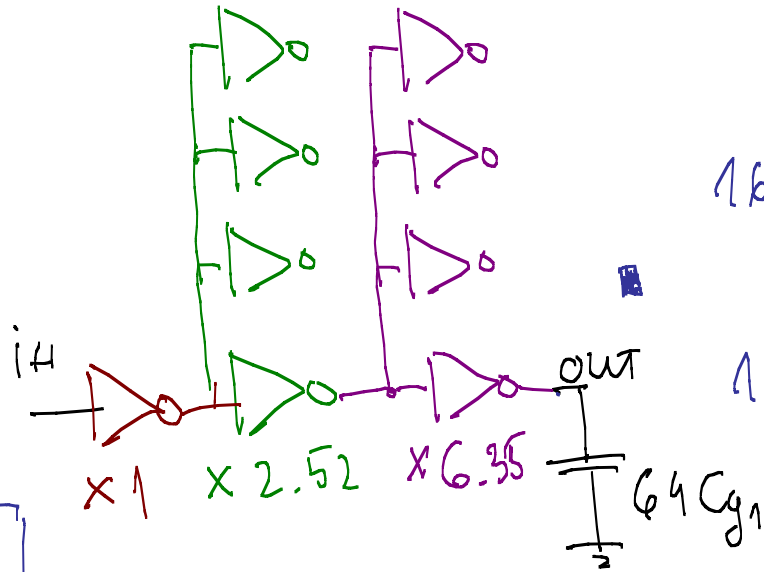
$$C_{g2} \approx 2.52 C_{g1}$$

$$(*) C_{g2} = C_{g3} C_{g1}^2$$

$$16^{2/3} C_{g1}^2 = C_{g3} C_{g1}^2$$

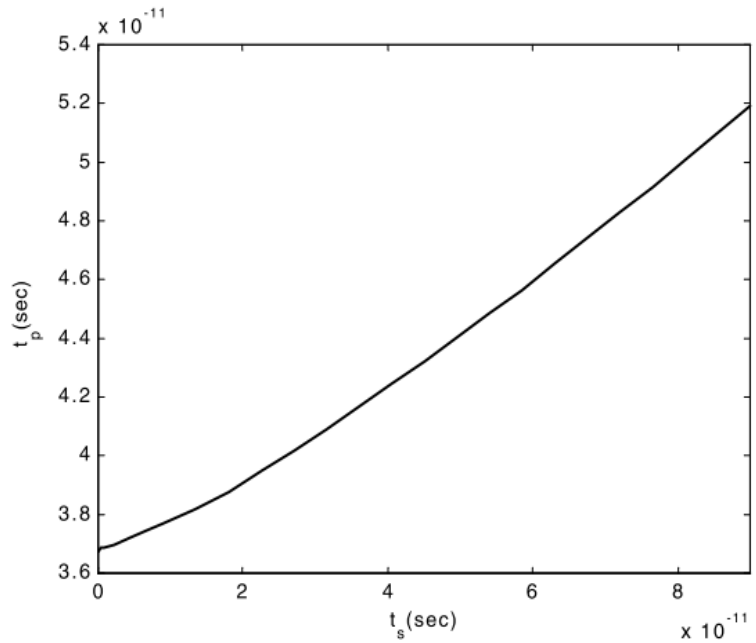
$$C_{g3} = 16^{2/3} C_{g1}$$

$$C_{g3} = 6.35 C_{g1}$$

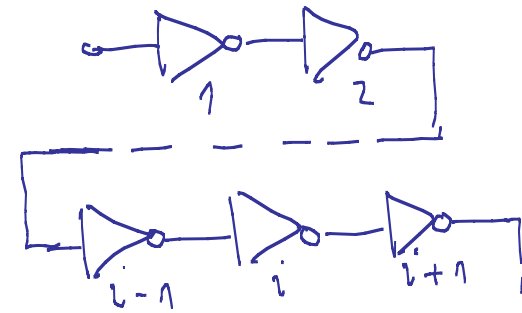
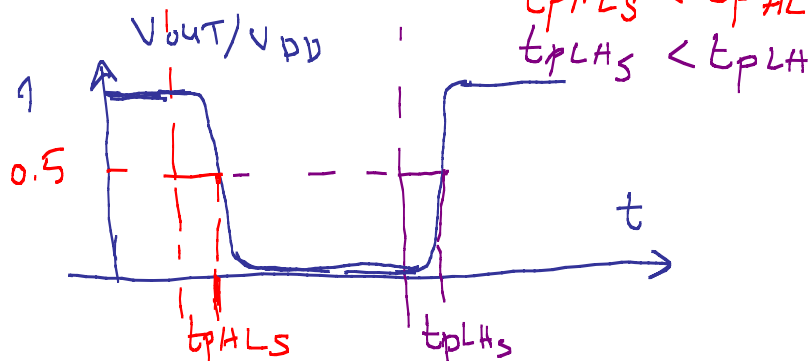
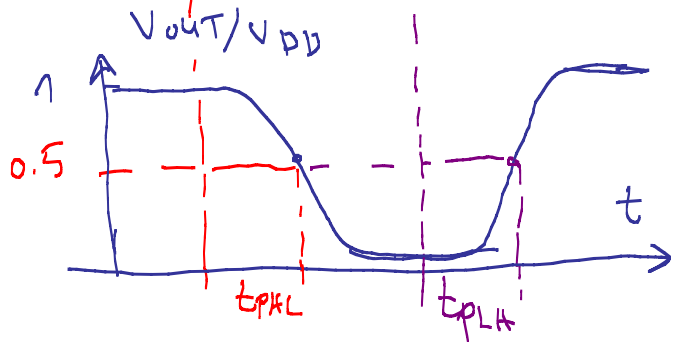
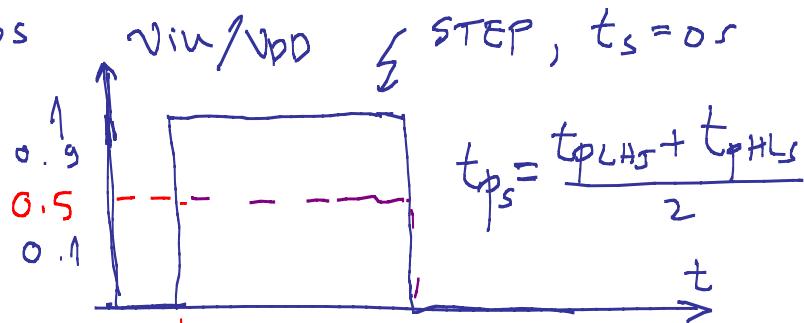
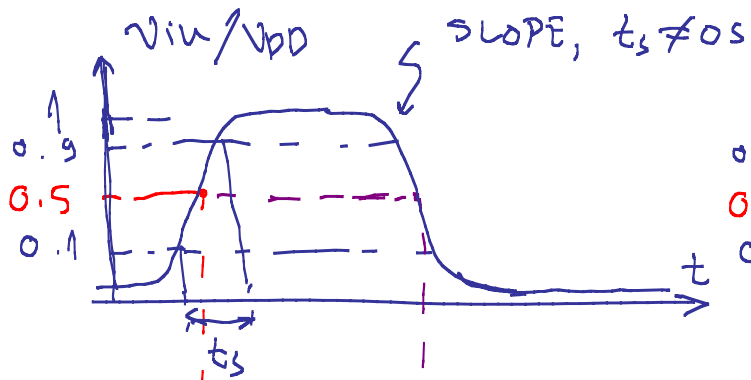
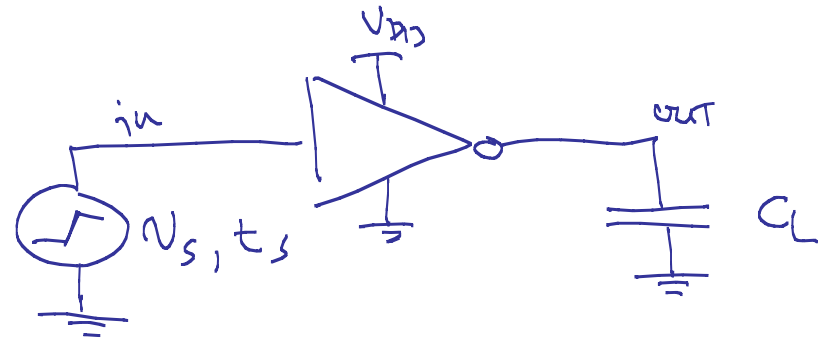


$$f_3 = \frac{C_L}{C_{g3}} = \frac{64 C_{g1}}{6.35 C_{g1}} = f_2 = \frac{4 C_{g3}}{C_{g2}} = \frac{4 \times 6.35 C_{g1}}{2.52 C_{g1}} = f_1 = \frac{4 C_{g2}}{C_{g1}} = 4 \times 2.52 = 10.08$$

D UTKAN RASTUĆE/OPADAJUĆE IVICE SIGNALA NA t_p



• t_s = "MASIB" ULAZNIOS SIGNALA, t_p PRIBLIŽNO LINEARNO RASTE SA t_s .



[Hedenstierna87]

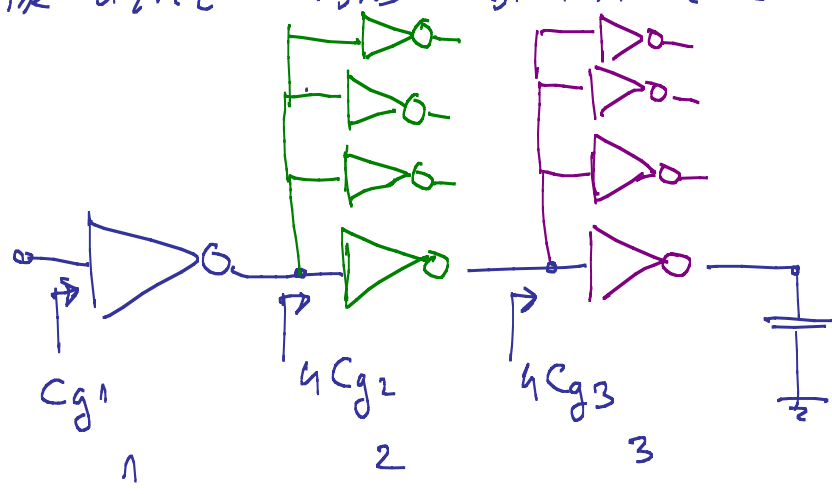
$$t_{p_i} = t_{p_{i,s}} + \eta t_{p_{i-1,s}}$$

EMPIRISKI FAKTOR
KOJI OBIČNO IZNOSI

$$\eta \approx 0.25 = 1/4$$

PRIMER 3

ODREDITI t_p ZA INVERTOR U DRUGOM STEPENU IZ PRIMERA 2 AKO SE U OZIRU UZME NAJIB SIGNALA ($\eta = 0.25$).



$$t_{p2} = t_{p2,s} + \eta t_{p1,s}$$

$$t_{p2} = t_{p0} \left(1 + \frac{4C_{g3}}{\mu C_{g2}} \right) + \eta t_{p0} \left(1 + \frac{4C_{g2}}{\mu C_{g1}} \right)$$

$$t_{p3} = t_{p3,s} + \eta t_{2,s}$$

$$t_{p3} = t_{p0} \left(1 + \frac{C_L}{\mu C_{g3}} \right) + \eta t_{p0} \left(1 + \frac{4C_{g3}}{\mu C_{g2}} \right)$$

$$t_p = t_{p1} + t_{p2} + t_{p3}$$

$$t_{p1} = t_{p0} \left(1 + \frac{\eta C_{g2}}{\mu C_{g1}} \right)$$

$$t_p = t_{p0} \left[1 + \frac{4C_{g2}}{\mu C_{g1}} + 1 + \frac{4C_{g3}}{\mu C_{g2}} + \eta + \frac{4\eta C_{g2}}{\mu C_{g1}} + 1 + \frac{C_L}{\mu C_{g3}} + \eta + \frac{4\eta C_{g3}}{\mu C_{g2}} \right]$$

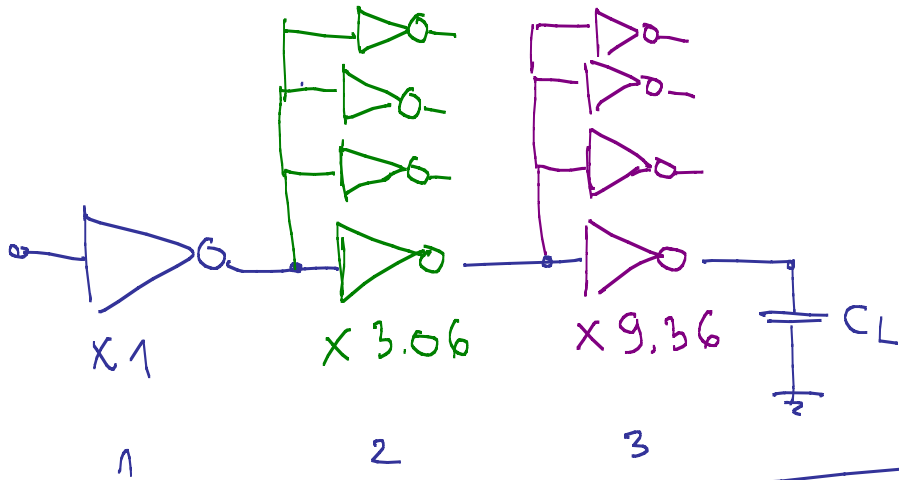
$$= t_p \left[1 + \frac{4(1+\eta)C_{g2}}{\mu C_{g1}} + 1 + \frac{4(1+\eta)C_{g3}}{\mu C_{g2}} + \eta + 1 + \frac{C_L}{\mu C_{g3}} + \eta \right]$$

$$\frac{\partial t_p}{\partial C_{gi}} = 0, \quad i=1,2,3 \Rightarrow \frac{4(1+\eta)C_{g2}}{C_{g1}} = \frac{4(1+\eta)C_{g3}}{C_{g2}} = \frac{C_L}{C_{g3}} \quad ;$$

$$C_L = 4C_{g1} \Rightarrow C_{g3}^2 = \frac{C_L C_{g2}}{4(1+\eta)} = \frac{C_L}{4(1+\eta)} \sqrt{C_{g3} C_{g1}} \Rightarrow C_{g3}^{\frac{3}{2}} = \frac{C_L^{\frac{1}{2}}}{4(1+\eta)} C_{g2} \cdot C_{g1}$$

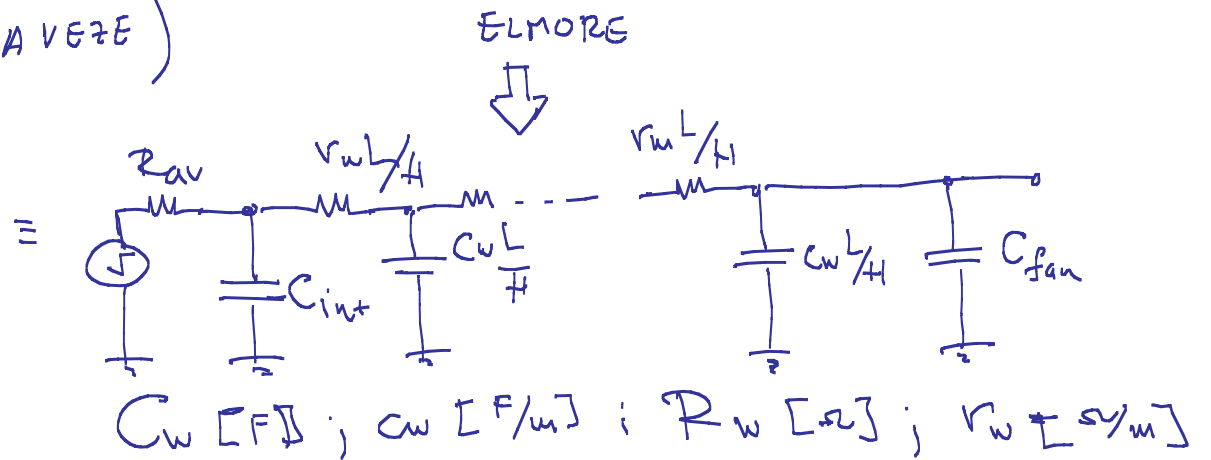
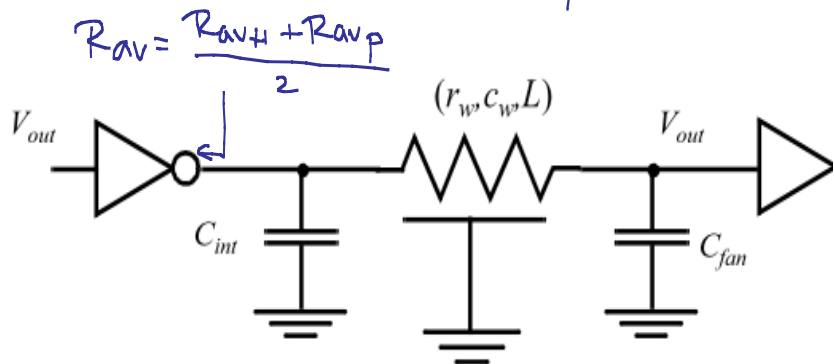
$$C_{g3} = \frac{G^2 \cdot C_{g1}^2}{4(1+\mu)} \cdot C_{g1} \Rightarrow C_{g3} = \left(\frac{2^{22} \cdot 10}{2^2(1+\mu)} \right)^{1/3} C_{g1} = \left(\frac{4}{5} \cdot 2^{10} \right)^{1/3} C_{g1} = \frac{2^4}{5^{1/3}} C_{g1} = 9.357 C_{g1}$$

$$C_{g2} = \sqrt{C_{g3} C_{g1}} = \sqrt{9.357 C_{g1} C_{g1}} = \sqrt{9.357} \cdot C_{g1} = 3.059 \cdot C_{g1}$$



- GENERALNO, U SUB-MIKRONSKIM PROCESIMA INŽENJERSKI IZAZOV JE POSTIĆI $t_s \approx t_p$ [SLOPE-ENGINEERING].

D UTICAJ VEŽA NA t_p . (2-DUŽINA VEŽE)



$$\begin{aligned}
 t_p &\approx 0.69 \left[R_{av} C_{int} + \left(R_{av} + r_w \frac{L}{H} \right) C_w \frac{L}{H} + \left(R_{av} + 2r_w \frac{L}{H} \right) \cdot C_w \frac{L}{H} + \dots + \left(R_{av} + H r_w \frac{L}{H} \right) \left(C_w \frac{L}{H} + C_{fan} \right) \right] \\
 &= 0.69 \left[R_{av} C_{int} + H R_{av} \cdot C_w \frac{L}{H} + r_w C_w \frac{L^2}{H^2} (1 + 2 + \dots + H) + R_{av} C_{fan} + r_w L C_{fan} \right] \\
 &= 0.69 \left[R_{av} C_{int} + R_{av} \cdot \underbrace{C_w L}_{C_w} + r_w C_w \frac{L^2}{H^2} \cdot \frac{H(H+1)}{2} + R_{av} C_{fan} + \underbrace{r_w \cdot L}_{R_w} C_{fan} \right] \quad H \gg 1 \\
 &\approx 0.69 R_{av} (C_{int} + C_{fan}) + 0.69 (R_{av} C_w + R_w \cdot C_{fan}) + 0.38 r_w C_w \cdot L^2 \\
 t_p &\approx \underbrace{0.69 R_{av} (C_{int} + C_{fan})}_{t_{psop}} + \underbrace{0.69 (R_{av} C_w + r_w \cdot C_{fan}) \cdot L + 0.38 r_w C_w \cdot L^2}_{t_{pw}}
 \end{aligned}$$

PRIMER 4 | ODREDITI PRI KOJOJ DUŽINI VEŽE KOMPONENTA t_p KOJA POTIČE OD VEŽE (t_{pw})

POSTAJE UPOREDIVA SA SOPSTVENIM PROPAGACIONIM KAŠHJEHIJEM (BEZ UTICAJA PARAMETARA

VEŽE). POZHATU JE: $C_w = 95 \text{ aF}/\mu\text{m}$; $r_w = 0.2 \text{ } \Omega/\mu\text{m}$; $C_{int} = 3 \text{ fF}$, $C_{fan} = C_{int}$,

$$R_{avP} = 9 \text{ k}\Omega; R_{avH} = 7 \text{ k}\Omega.$$

SOPSTVENO KAŠHJEHIJE

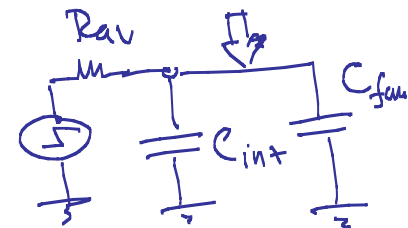


$$t_{psop} = 0.69 (C_{int} + C_{fan}) R_{av}$$

$$R_{av} = \frac{R_{avP} + R_{avH}}{2} = \frac{16 \text{ k}\Omega}{2} = 8 \text{ k}\Omega;$$

$$t_{psop} = 0.69 (6 \text{ fF}) \cdot 8 \text{ k}\Omega = 33.12 \text{ ps}$$

UTICAJ PARAMETARA VEŽE ZAHEMAREN



$$t_{psop} = t_{pw} \Rightarrow t_{psop} \approx 0.69 (R_{av} C_w + r_w \cdot C_{fan}) L + 0.38 r_w \cdot C_w \cdot L^2$$

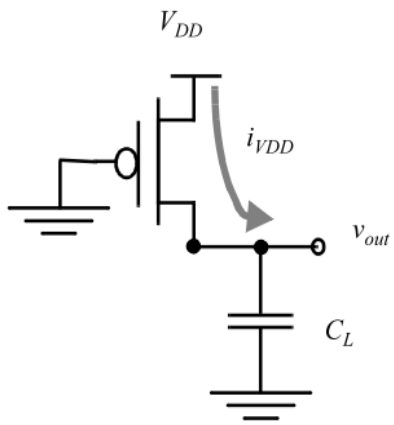
$$L^2 \left(0.38 \times 0.2 \frac{\Omega}{\mu\text{m}} \times 95 \frac{\text{aF}}{\mu\text{m}} \right) + L \left[0.69 \times \left(8 \text{ka} \cdot 95 \frac{\text{aF}}{\mu\text{m}} + 0.2 \frac{\Omega}{\mu\text{m}} \cdot 3 \text{fF} \right) \right] - 33.12 \text{ps} = 0$$

$$L^2 \left(7.22 \frac{\text{aS}}{\mu\text{m}^2} \right) + L \left(524.81 \frac{\text{fs}}{\mu\text{m}} \right) - 33.12 \text{ps} = 0$$

~~$$L_1 \approx -72.75 \mu\text{m}, L_2 = 63 \mu\text{m} \checkmark$$~~

□ STAGA / ENERGIJA INVERTORA.

Dinamička staga disipacije (pretpostavka N i P MOS NIKADA NIJU ISTOVREMENO UKLJUČENI):



$$E_{VDD} = \int_0^{+\infty} i_{VDD} \cdot V_{DD} dt = C_L \int_0^{+\infty} \left(\frac{dv_{out}}{dt} \right) V_{DD} dt = C_L V_{DD} \int_0^{V_{DD}} dv_{out}$$

SREDNJA ENERGIJA KOJA SE "UZME" IZ NAPAJANJA

$$E_{VDD} = C_L V_{DD}^2$$

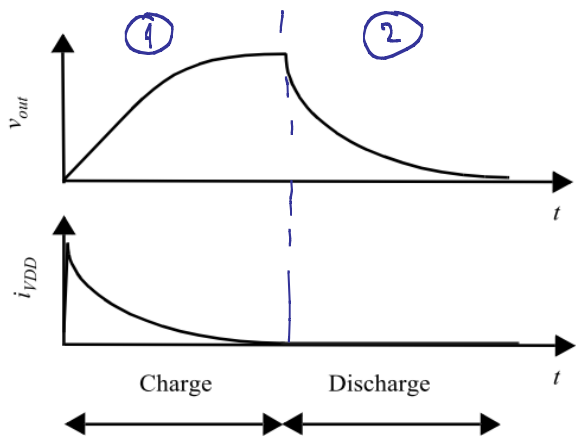
① P MOS VODI, N MOS NE VODI \Rightarrow iz NAPAJANJA se "uzme" $Q_{LH} = C_L V_{DD}$.

② P MOS NE VODI, N MOS VODI \Rightarrow iz KONDENZATORA se "uzme" $Q_{HL} = C_L V_{DD}$

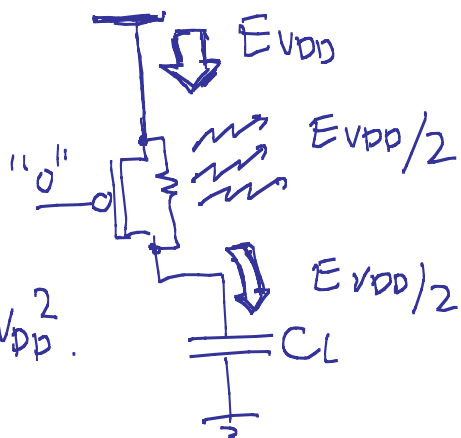
POŠTO VAŽI $Q = Q_{LH} = Q_{HL} = C_L V_{DD} \Rightarrow E_{VDD} = Q \cdot V_{DD} = C_L V_{DD}^2$

$$E_c = \int_0^{+\infty} i_{V_{DD}} \cdot v_{out} dt = C_L \int_0^{+\infty} \left(\frac{d v_{out}}{dt} \right) \cdot v_{out} dt = C_L \int_0^{V_{DD}} v_{out} dv_{out} = C_L \frac{v_{out}^2}{2} \Big|_0^{V_{DD}} = \frac{C_L V_{DD}^2}{2}$$

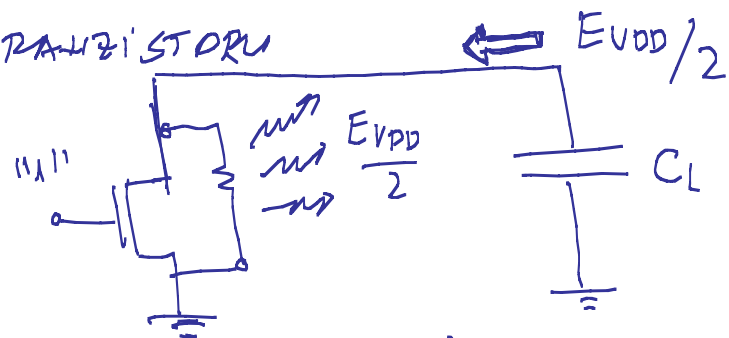
ENERGIJA KOJA SE FORMIRA U KONDENZATORU



① $E_c = \frac{E_{V_{DD}}}{2} \Rightarrow$ SARU POLOVINA PREUZETE ENERGIJE IZ NAPAJANJA SE PREDAJE KONDENZATORU, A DRUGA POLOVINA SE DISIPIRA NA PMOS TRANZISTORU.



② ENERGIJA SNEŠTENJA U KONDENZATORU SE DISIPIRA NA NMOS TRANZISTORU



NAKON ① i ② iz

NAPAJANJA SE "UZME" $E_{V_{DD}} = C_L V_{DD}^2$.

• $E_{V_{DD}}$ NE ZAVISI OD DIMENZIJA TRANZISTORA $\Rightarrow E_{V_{DD}} \neq (P_{avH}, P_{avP})$.

• DYNAMIČKA KONSUMIETNA SNAGE DISIPACIJE SE MOŽE LAKO PROCENITI POMOĆU:

$$P_d = C_L \cdot V_{DD}^2 \cdot f_0 \rightarrow$$

\downarrow UČESTANOST (FREKVENCIJA) PRELAZA "0 \rightarrow 1".

• Upr. za $f_{ck} = 500\text{MHz}$, $V_{DD} = 2.5\text{V}$, $C_L = 15\text{fF} \Rightarrow P_d \approx C_L V_{DD}^2 f_{ck} \approx 50 \mu\text{W}/\text{geitov}$, za

10^6 geitova $\Rightarrow P_d = 10^6 \cdot P_{dg} = 50\text{W}$! Naravno, ova procena je veoma konzervativna (pesimistična) pošto je praktično nemoguće da svi geitovi rade istovremeno sa f_{ck} .

• Realističnija procena P_d se bazira na statistici promena ulaznih signala:

$$P_d = V_{DD}^2 C_L f_{0 \rightarrow 1} = V_{DD}^2 \underbrace{C_L P_{0 \rightarrow 1}}_{C_{EFF}} \cdot f_{ck} = V_{DD}^2 C_{EFF} \cdot f_{ck}$$

• C_{EFF} - efektivna kapacitivnost opterećenja, $P_{0 \rightarrow 1}$ - verovatnoća prelaza sa "0" \rightarrow "1" (prekidacka aktivnost - switching activity).



↔ OD 8 TAKTOVA, 2 PRELAZA "0" \rightarrow "1"
 $\Rightarrow P_{0 \rightarrow 1} = 2/8 = 1/4 = 0.25$ (25%).



• ГЕТЕРАЛНО, СА СУАКИМ КЛОВИМ ПРОЦЕСОМ $f \uparrow$, (КОМПЛЕКСНОСТ / ВР. СЕТОУА) ДИМЕНЗИЈЕ СІРА) $\uparrow \Rightarrow C_L \uparrow$, ШТО ДОВОДИ ДО $P_d \uparrow \uparrow$.

• ТЕХНИКЕ ЗА МИНИМИЗАЦИЈУ P_d :

① МИНИМИЗАЦИЈА V_{DD} ($P_d \propto V_{DD}^2$). СКАЛИРАЊЕ $V_{DD} \rightarrow V_{DD}/2 \Rightarrow P_d \rightarrow P_d/4$,

ПРАКТИЧНО, ГЛАВНИ МОТИВ РЕДУКОВАЊА V_{DD} ЈЕ МИНИМИЗАЦИЈА P_d . ИАКАКОСТ, ОВА ТЕХНИКА НИЈЕ ПОГУЉЕ УВЈЕК ИЗВЕСТИ ПОШТО ЈЕ V_{DD} ЧЕСТО ОДРЕЂЕТИ ПРИМЕНУ СІРА (ОКРУЉЕЊЕМ НА СИСТЕМСКОМ НИВОУ). ГЕТЕРАЛНО, ДОИЈА

ГРАНИЦА ЗА V_{DD} ЈЕ ПОД-ПРАГОВСКА ОБЛАСТ ($V_b = 2V_T \Rightarrow$

ПОВАЌАЊЕ ИНВЕРТОРА, $g \rightarrow -1 \Rightarrow$ ФУНКЦИЈА КОЛА УГРОЉЕНА).

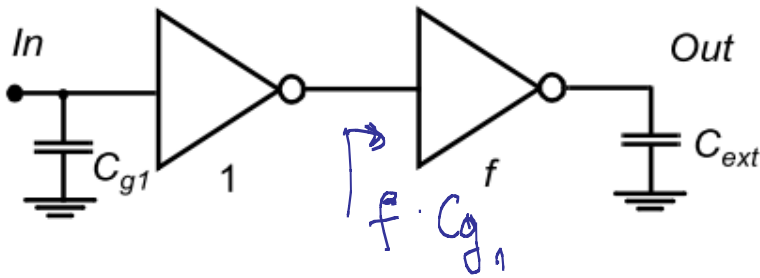
② РЕДУКЦИЈА $P_o \rightarrow \eta$. ИЗВОДИ СЕ ИЗБОРОМ / РАЗУИЈАЊЕМ АРХИТЕКТУРЕ НА СИСТЕМСКОМ НИВОУ.

③ МИНИМИЗАЦИЈА C_L . РАЉЛИВА И ТРАДИ ЛЕДАУТА (КОРИСТИТИ ТРАНЗИСТОРЕ МИНИМАЛНИХ ДИМЕНЗИЈА КАДА ГОД ЈЕ ТО ПОГУЉЕ). УКОЛИКО ЈЕ МИНИМИЗАЦИЈА P_d ПРИМАРНИ СІЛЈ ОУДА ТРЕБА УВЈЕК КОРИСТИТИ ТРАНЗИСТОРЕ МИНИМАЛНИХ ДИМЕНЗИЈА, А ПЕРФОРМАНСЕ ПОСТИЌИ ИЗБОРОМ / РАЗУИЈАЊЕМ

KUVIH TOPOLOGIJA KOLA, ILI KORISTITI NEKE OD STANDARDNIH TEHNIKA ZA POVEĆANJE BRZINE PADA IIA ARHITEKTUROM KOLA (PARALELIZAM, PROTOKOST).

▶ POSTUPAK OPTIMIZACIJE POTROŠIJE. PROBLEM: MINIMIZOVATI P_d KOLA

TAKO DA PERFORMANSE KOLA NE BUDU GORE OD PERFORMANSI REFERENTNOG KOLA ZA KOJE VAŽI $f_{ret} \approx 1$, $V_{DD} = V_{ref}$.



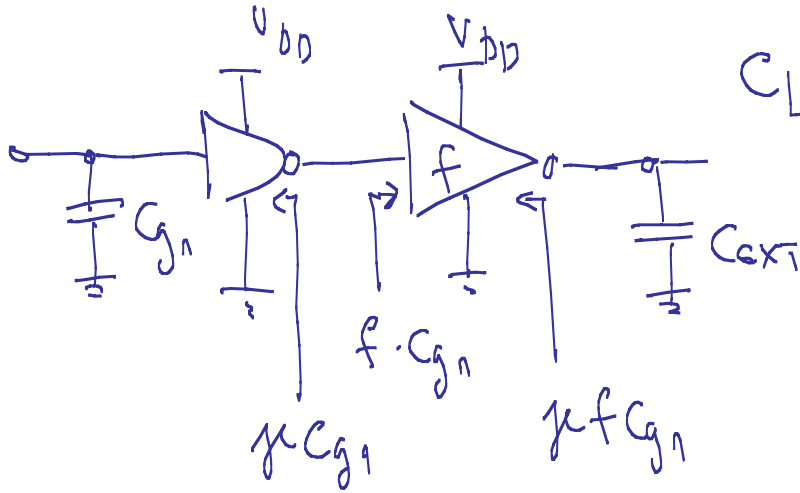
PRETPOSTAVKA: UHIT UNDER DESIGN (UUD) JE INVERTOR VEĆI OBLJE f , POBUĐEN JEDINIČNIM INVERTOROM.

$$t_p = t_{p0} \left(1 + \frac{f \cdot C_{g1}}{\mu C_{g1}} \right) + t_{p0} \left(1 + \frac{C_{ext}}{\mu \cdot (f C_{g1})} \right)$$

$$t_p = t_{p0} \left[2 + \frac{f}{\mu} + \frac{F}{\mu f} \right]; \quad F = \frac{C_{ext}}{C_{g1}} \equiv \text{EFJEKTIVNI FAN-OUT ZA CELO KOLA.}$$

$(1 + \mu)(1 + f) + F \cdot f$

$$t_{p0} = 0.69 R_{av} C_{g1} = 0.69 C_{g1} \frac{3}{4} \frac{V_{DD}}{I_{DSAT}} \propto \frac{V_{DD}}{V_{DSAT} (V_{DD} - \underbrace{V_{TH} - V_{DSAT}/2}_{-V_{TE}})} \propto \frac{1}{V_{DSAT}} \cdot \frac{V_{DD}}{V_{DD} - V_{TE}}$$



$$\begin{aligned} C_{Ltot} &= C_{g1} + \mu C_{g1} + f C_{g1} + \mu f C_{g1} + C_{ext} \\ &= C_{g1} (1 + \mu + f + \mu \cdot f + F) \\ &= C_{g1} [(1 + \mu) \cdot (1 + f) + F] \end{aligned}$$

$$E_{VDD} = V_{DD}^2 C_{Ltot} = V_{DD}^2 C_{g1} [(1 + \mu) (1 + f) + F]$$

- УСЛОВ (CONSTRAINT) : $t_p = t_{pref}$; $t_{pref} = t_p \Big|_{\substack{f = f_{ref} \\ V_{ref}}} = t_{p0_{ref}} \left(2 + \frac{1}{\mu} + \frac{F}{\mu} \right)$
- ПОШТО $\mu \approx 1$; $t_{pref} = t_{p0_{ref}} (3 + F)$, $t_p = t_{p0} \left(2 + f + \frac{F}{f} \right)$

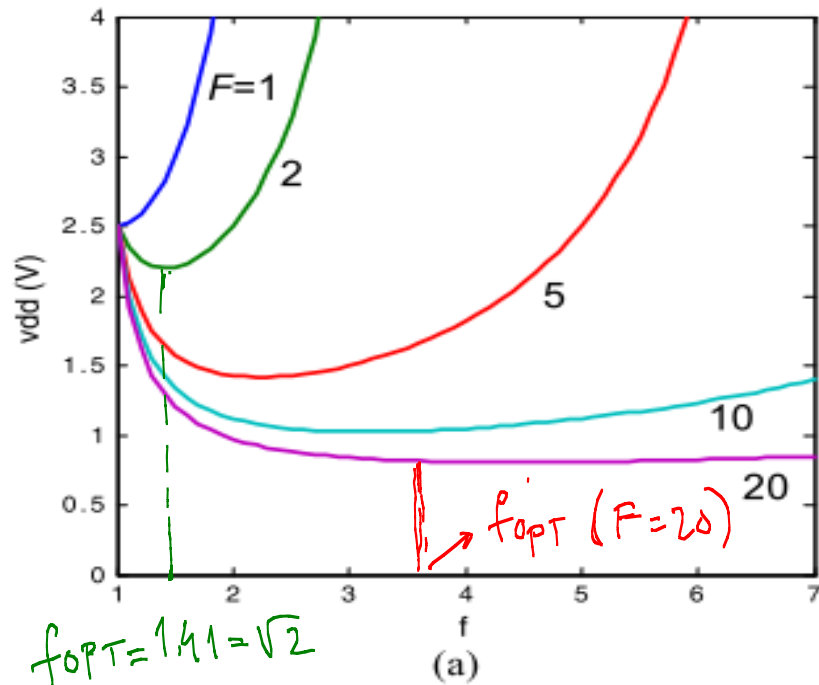
$$\frac{t_p}{t_{pref}} = \frac{t_{p0} \left(2 + f + \frac{F}{f} \right)}{t_{p0_{ref}} (3 + F)} = \frac{\frac{V_{DD}}{V_{DSAT} (V_{DD} - V_{TE})} [2 + f + F/f]}{\frac{V_{ref}}{V_{DSAT} (V_{ref} - V_{TE})} [3 + F]} = 1$$

$$\frac{t_p}{t_{pref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{(V_{ref} - V_{TE})}{(V_{DD} - V_{TE})} \cdot \frac{(2 + f + F/f)}{(3 + F)} = 1 \Rightarrow V_{DD} = \text{func}(f, F)$$

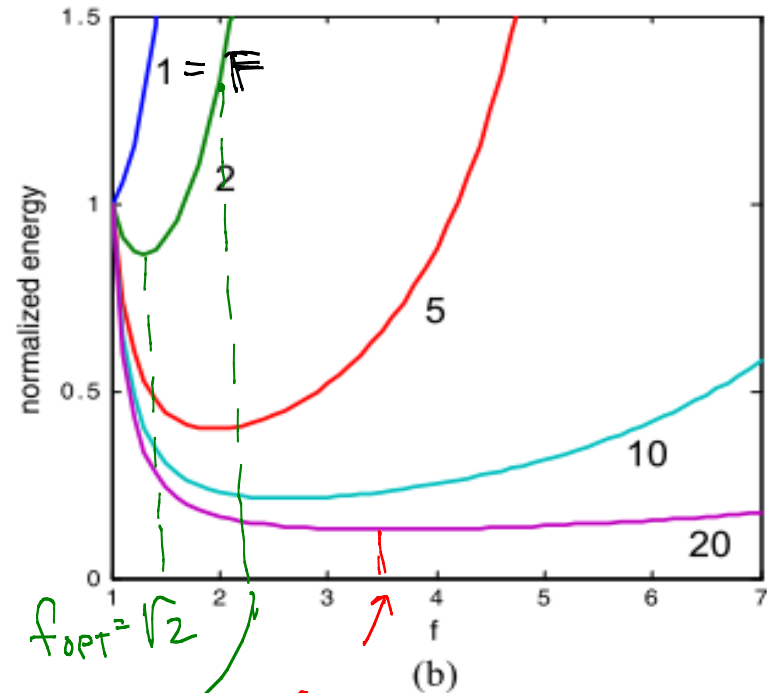
$$\frac{E_{VDD}}{E_{VDDref}} = \frac{V_{DD}^2}{V_{ref}^2} \cdot \frac{(2 + 2f + F)}{(2 + 2f_{ref} + F)} \Big|_{f_{ref}=1} = \frac{V_{DD}^2}{V_{ref}^2} \cdot \frac{(2 + 2f + F)}{(4 + F)} \Rightarrow \frac{E_{VDD}}{E_{VDDref}} = \text{func}(f, F)$$

$$V_{DD} = \text{func}(f, F)$$

$$E_{VDD}/E_{VDDref} = \text{func}(f, F)$$



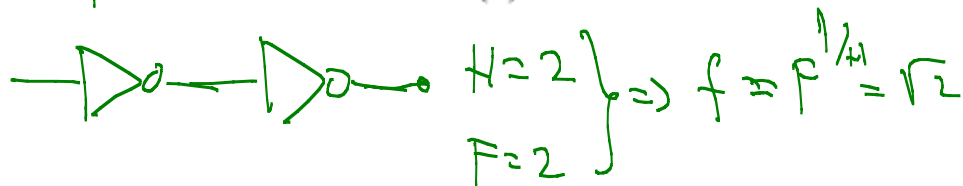
$$f_{opt} = 1/1 = \sqrt{2}$$



$$f_{opt} = \sqrt{2}$$

$$f_{opt}(F=20)$$

(*) $f > f_{opt} \Rightarrow E_{VDD} \uparrow \uparrow$



• ANALIZOM GRAFIKA (a) i (b) POLAZI SE DO STRATEGIJE ZA MINIMIZACIJU

P_d ZA KONKRETAN $F = C_{ext} / C_{gn}$

• P_d SE MINIMIZUJE KOMBINOVAŃO, REDUKCIJOM V_{DD} I SKALIRANJEM DIMENZIJA f PUTA.

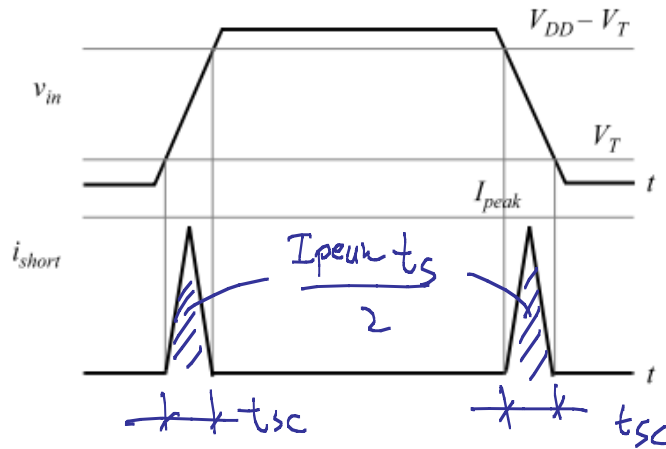
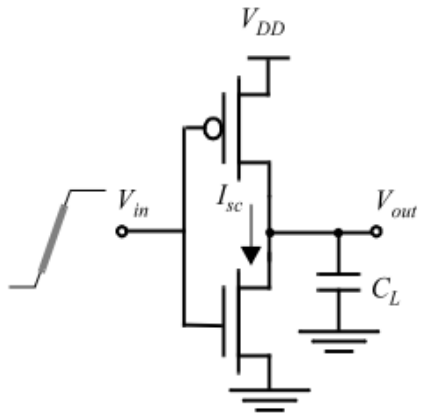
• MOŽE SE UOČITI DA JE ZA VEĆE F (TIPR. 20) f_{OPT} ZA MINIMIZACIJU POTROŠNJE ($f_{OPT}(F=20) = 3.5$) MAŃJE U ODHOSU NA f_{OPT} ZA MINIMIZACIJU KLAŠIČNIJA (POVEĆANJE PERFORMANSI, $f_{OPT}(F=20) = F^{1/2} = 4.47$).

• ZA MAŃJE F , USVAJANJEM $f > f_{OPT}$ REZULTUJE ZNAČAJNIM (NAGLIN) POVEĆANJEM POTROŠNJE (*) $f > f_{OPT}(F=2) \Rightarrow E_{VDD} \uparrow \uparrow !$

• ZA POŃJU GRANICU $V_{DD} \approx 2 \dots 4 \frac{kT}{\Sigma}$ (SUB-THRESHOLD) I PRI VELIKIM F NE POSTIŽE SE ZNAČAJNA UŠTEDA POTROŠNJE POVEĆANJEM DIMENZIJA.

$[E_{VDD} \not\approx f_{UNC}(f)]$

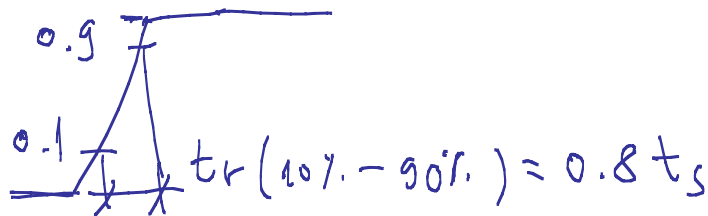
▷ ПОТРОШИЈА У ПРЕЛАЗНОМ РЕЖИМУ



" t_{sc} " - INTERVAL U KOME OBA TRANZISTORA VODE.

$$t_{sc} = t_s - 2\Delta t = t_s - 2 \frac{V_{TH}}{V_{DD}} t_s = t_s \frac{V_{DD} - 2V_{TH}}{V_{DD}}$$

$$t_{sc} \approx \frac{V_{DD} - 2V_{TH}}{V_{DD}} \cdot \frac{t_{r,f}}{0.8}$$



$$E_{Dp} = V_{DD} \cdot \frac{I_{peak} t_{sc}}{2} \times 2$$

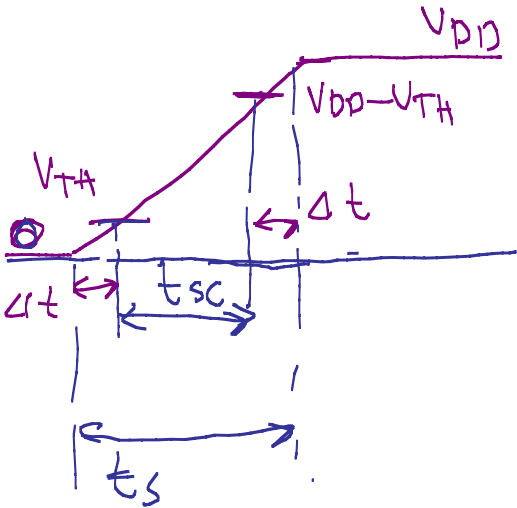
$$E_{pp} = V_{DD} \cdot I_{peak} t_{sc}$$

$$P_{dp} = f \cdot E_{pp} = V_{DD} I_{peak} t_{sc} f_{clk}$$

$$P_{dp} = V_{DD}^2 \frac{I_{peak} t_{sc}}{V_{DD}} \cdot f_{clk}$$

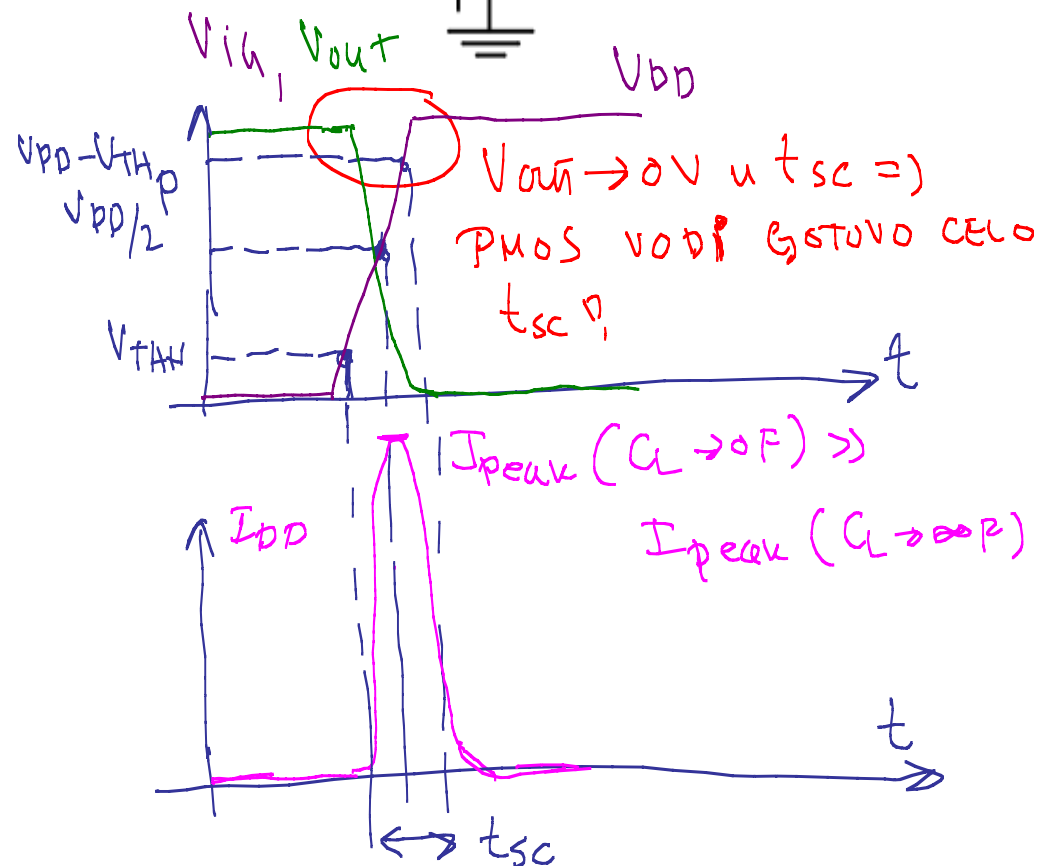
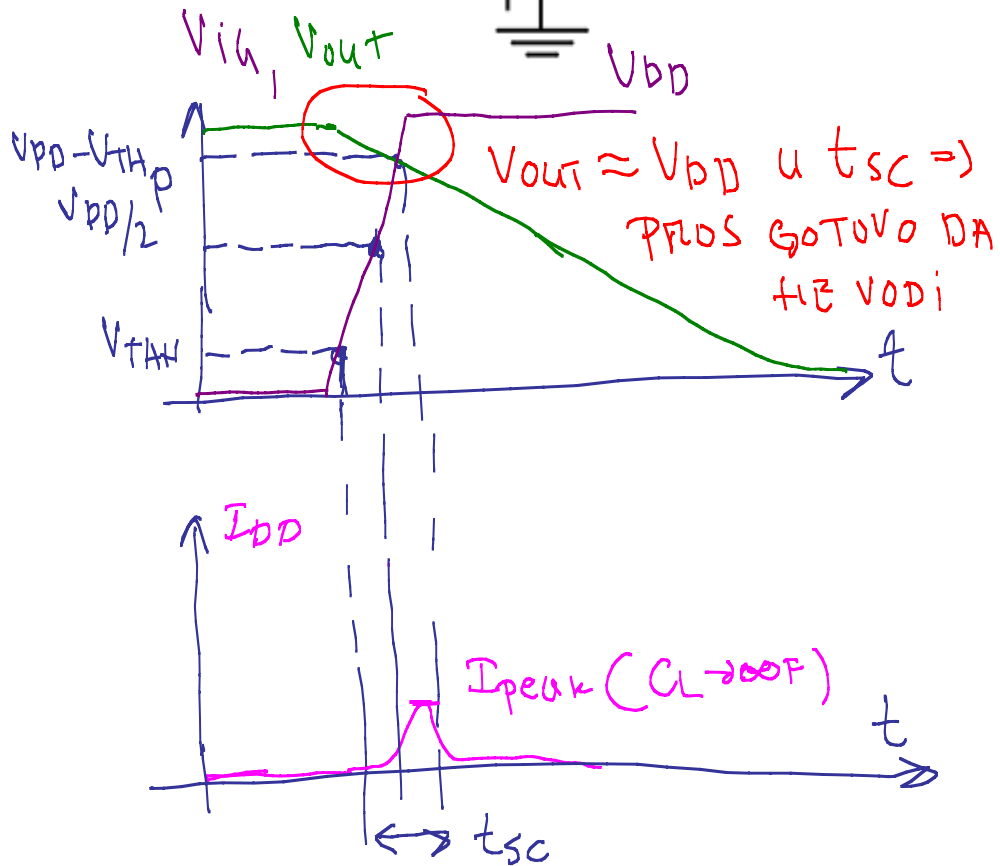
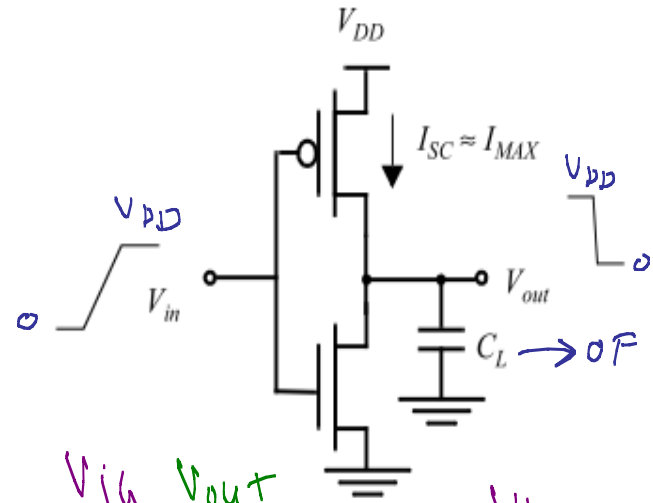
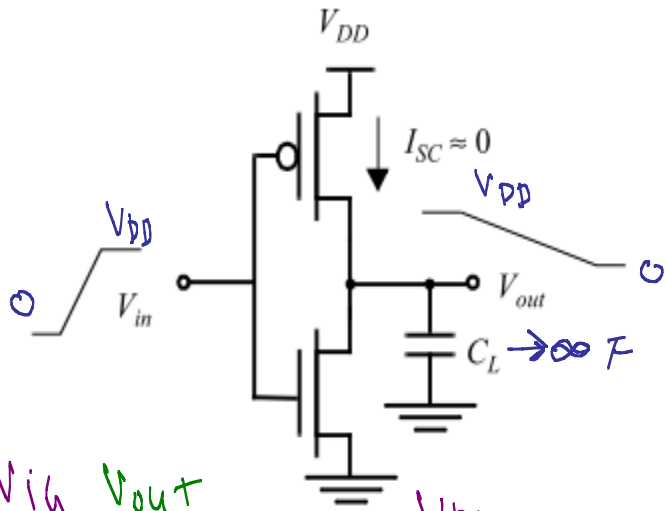
$$P_{dp} = C_{sc} V_{DD}^2 \cdot f_{clk}$$

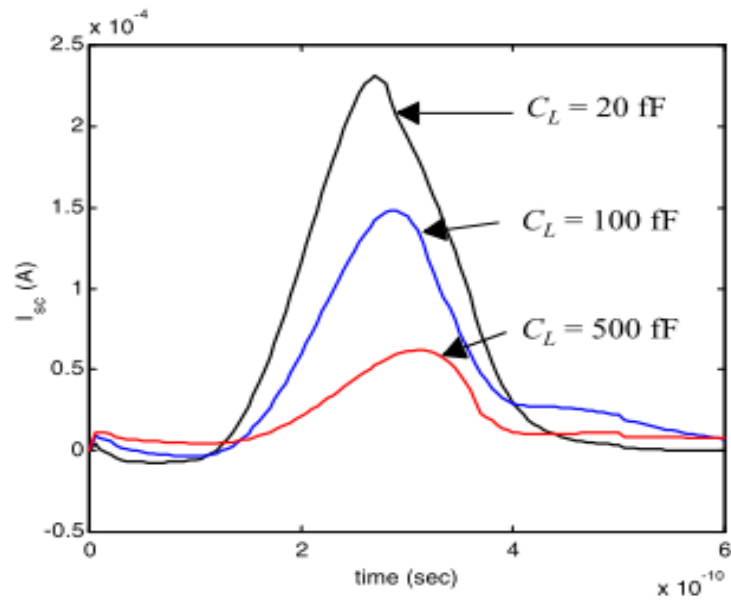
$$C_{sc} = \frac{I_{peak} \cdot t_{sc}}{V_{DD}}$$



$$\frac{V_{TH}}{\Delta t} = \frac{V_{DD}}{t_s} \Rightarrow \Delta t = \frac{V_{TH}}{V_{DD}} t_s$$

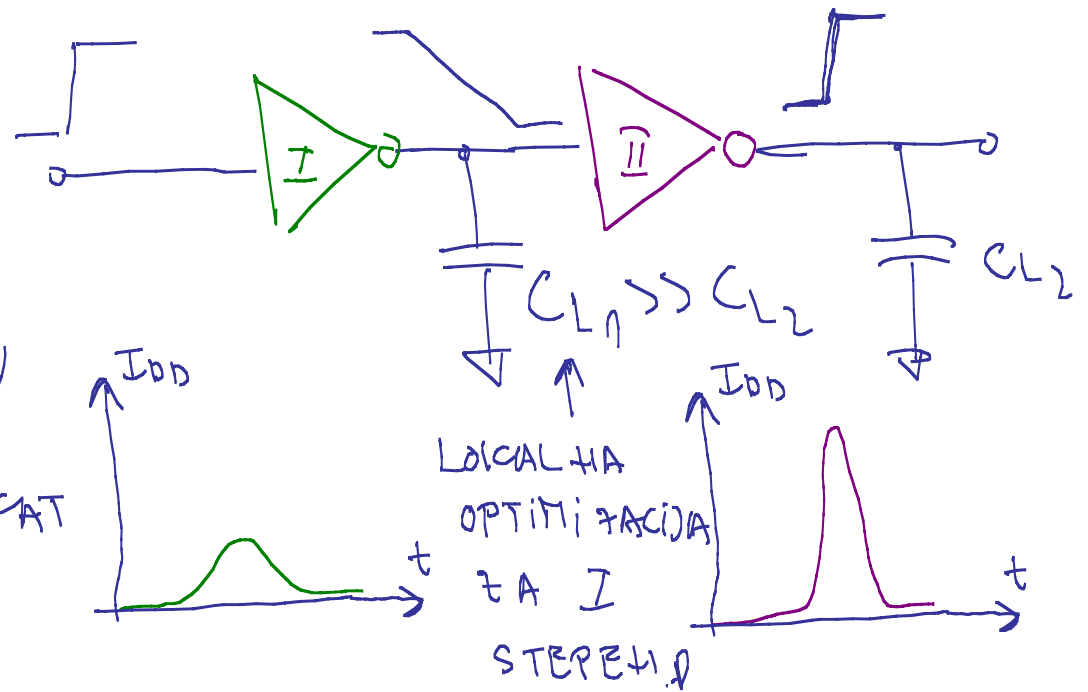
• I_{peak} & I_{DSAT} & $\left(\frac{W}{L}\right)$





• ZA MINIMIZACIJU I_{peak} TREBA OSIGURATI
 $t_{r, f input} < t_{r, f output}$, ALI NE PRETERIVATI!
 NE TREBA IZSUBITI IZ VIDA DA JE OVAJ USLOV
 ZA IZOLOVANI INVERTOR (LOKALNA OPTIMIZACIJA)

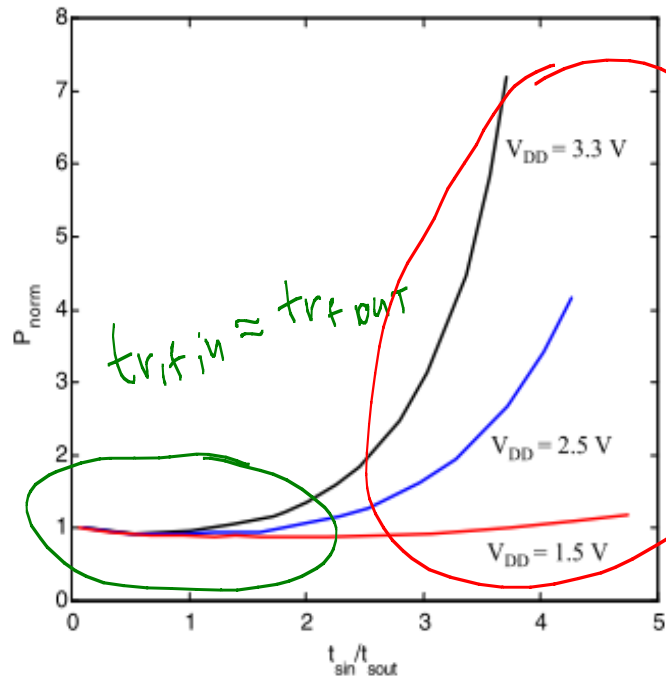
• AKO SE POSMATRA SAMO IZOLOVANI
 INVERTOR, BEZ HOLISTIČKOG PRISTUPA,
 REZULTAT LOKALNE OPTIMIZACIJE
 MOŽE DA IZAZOVE NEGATIVAN EFEKT
 U NAREĐENIM STEPENIMA.



• GENERALNO, TREBA IZBEŽAVATI LOKALNU OPTIMIZACIJU UKOLIKO SE
 RADI O VEĆEM KOLU GDE SE SPOREDNI EFEKT TEŠKO MOGU ISPRATITI.

USLOV $t_{r, f input} \approx t_{r, f output}$, IAKO NE DAJE LOKALNI OPTIMUM,

BAR OBEZBEĐUJE DA SE I_{peak} KRERE U HORIZONTALIM GRANICAMA, PA SE OBIČNO NI UZIMA KAO STRATEŠKO REŠENJE ZA OPTIMIZACIJU $P_{d/p}$.



• DRUGI PRISTUP ZA MINIMIZACIJU $P_{d/p}$ JE STE MINIMIZACIJA t_{sc}

$$V_{DD} \downarrow \Rightarrow t_{sc} = \frac{V_{DD} - 2V_{TH}}{V_{DD}} \frac{t_s}{0.8} \downarrow$$

ZA GRANICNI USLOV $V_{DD} \approx 2V_{TH} \Rightarrow t_{sc} \rightarrow 0 \Rightarrow$

$$C_{sc} = \frac{I_{peak} t_{sc}}{V_{DD}} \rightarrow 0 \Rightarrow P_{d/p} \rightarrow 0.$$

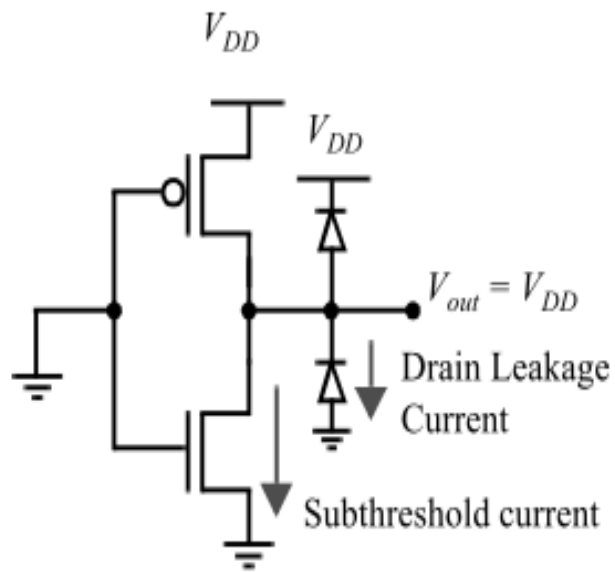
D STATIČKA POTROŠNJA

$$P_{stat} = I_{stat} V_{DD}$$



STRUJA KOJA TEČE IZMEĐU V_{DD} I MASE U

ODSUSTVU POBUĐENOG SIGNALA (ZERO SWITCHING ACTIVITY)

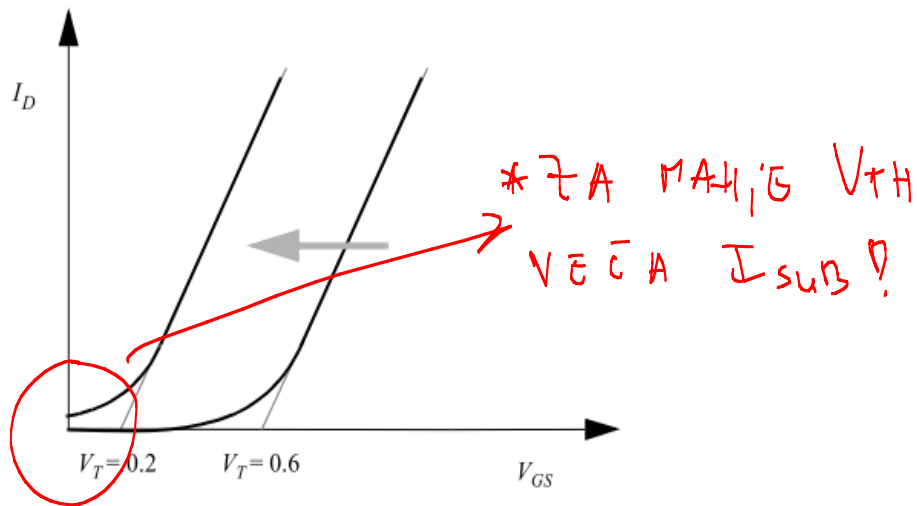


• Najdominantijske komponente I_{stat} su :

① I_{db} - struje inverzno polariziranih P i N spojeva sorsa i drezna i oshove/well-a. Tipične vrijednosti $(10-100) pA/\mu m^2$. Problem, eksponentično zavise od temperature.

② I_{Dsub} - pod-pragovska struja između

sorsa i drezna. Praktično, tranzistori se nikada zaista ne isključe u potpunosti. I_{Dsub} postaje dominantna komponenta u sub-mikroskopskim procesima. Pošto se sa smanjenjem (V_{GS}/V_{TH}) I_{Dsub} povećava, obično je strategija minimizacije P_{stat} maksimizacija V_{TH} . Ovo, iako nije moguće uvek sprovesti pošto se teži da V_{DD} bude što manje zbog minimizacije P_{ol} . Kada maksimizacija V_{TH} nije moguća onda se koriste tehnološke opcije koje nude bolje sub-threshold karakteristike (FD SOI)



▷ UKUPNA SNAGA DISIPACIJE

$$P_{tot} = P_d + P_{dp} + P_{stat} = [C_L V_{DD}^2 + V_{DD} I_{peak} t_{sc}] f_{0 \rightarrow 1} + V_{DD} I_{stat}$$

▷ EFIKASNOST \equiv POWER-DELAY-PRODUCT (PDP) \equiv ENERGY PER OPERATION

$$PDP = P_{av} \cdot t_p \approx P_d t_p = C_L V_{DD}^2 f_{max} \cdot t_p = \frac{C_L V_{DD}^2}{2} \Rightarrow \text{ENERGIJA KOJA SE KONZUMIRA IPREDA U JEDNOM LOGIČKOM PREGLEDU ("0" \rightarrow "1" ILI "1" \rightarrow "0").}$$

$f_{max} = \frac{1}{2t_p} \rightarrow$ MAKSIMALNA FREKVENCIJA TAKTA

$$E_{av} = PDP_{0 \rightarrow 1} + PDP_{1 \rightarrow 0} = 2 PDP = C_L V_{DD}^2 = E_{VDD}$$

▷ ENERGY-DELAY PRODUCT (EDP)

$$EDP = PDP \times t_p = P_{av} t_p^2 \approx C_L V_{DD}^2 f_{max} \cdot t_p^2 = C_L V_{DD}^2 \frac{t_p}{2}$$

$$P_{av} = P_d = C_L V_{DD}^2 \cdot f_{max}, \quad f_{max} = \frac{1}{2 t_p}$$

① $V_{DD} \uparrow \Rightarrow t_p \downarrow$ ALI $EDP \uparrow$; ② $V_{DD} \downarrow \Rightarrow EDP \downarrow$ ALI $t_p \uparrow \Rightarrow$

POSTOJI OPTIMALNO REŠENJE ZA V_{DD} .

$$t_p = 0.69 \times R_{ov} C_L \approx 0.52 \frac{V_{DD} C_L}{k_{np} V_{DSAT} (V_{DD} - V_{TH} - V_{DSAT}/2)} \approx \frac{\alpha V_{DD} C_L}{V_{DD} - V_{TE}}$$

α - TEHNOLOŠKI PARAMETAR; $V_{TE} = V_{TH} + V_{DSAT}/2$

PRETPOSTAVKA: $V_{THn} = V_{THp}$, $V_{DSATn} \approx V_{DSATp} = V_{DSAT}$, $V_{TEn} = V_{TEp} = V_{TE}$

$$EDP = \frac{C_L V_{DD}^2}{2} \times \frac{\alpha V_{DD} C_L}{V_{DD} - V_{TE}} = \frac{1}{2} \frac{C_L^2 V_{DD}^3}{V_{DD} - V_{TE}}$$

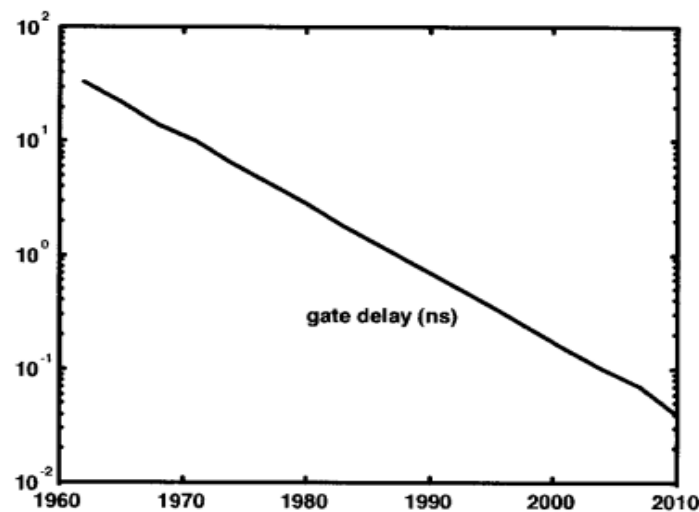
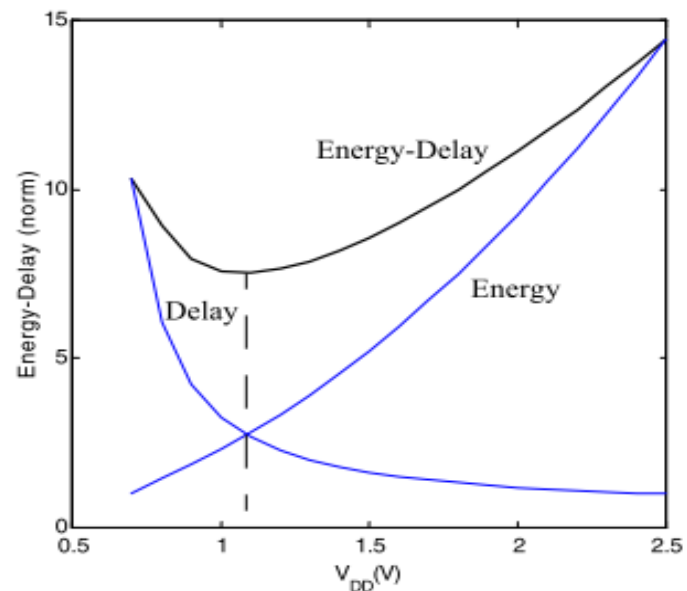
$$\frac{\partial EDP}{\partial V_{DD}} = \frac{1}{2} C_L^2 \left[\frac{3 V_{DD}^2 (V_{DD} - V_{TE}) - V_{DD}^3}{(V_{DD} - V_{TE})^2} \right] = 0 \Rightarrow \boxed{V_{DD, opt} = \frac{3 V_{TE}}{2}}$$

ПРИМЕР ЗА ПРОЦЕС У КОЈЕМ ЗА P И N MOS ТРАНЗИСТОРЕ ВАЖИ $V_{TH} \approx 0.5V$, $V_{DSAT} \approx 0.7V$, ОДРЕДИ ОПТИМАЛНИ НАПОН НАПАЗАЊА КОЈИ МИНИМИЗУЈЕ EDP.

$$V_{TE} = V_{TH} + \frac{V_{DSAT}}{2} = 0.85V \quad V_{D, opt} = \frac{3}{2} \times V_{TE} = \frac{3}{2} \times 0.85V \approx 1.28V$$

- ТРЕБА ИМАТИ НА УМУ ДА ЈЕ $V_{DD, opt}$ ИЗВЕДЕНО ЗА ИЗОЛОВАНИ ГЕЈТ (ИНВЕРТОР) И ДА САМО ПРЕДСТАВЉА ГРУБУ ПРОЦЕНУ, А НИКАКО НЕ ОПТИМАЛНО РЕШЕЊЕ У ОПШТЕМ СМИСЛУ.

EDP CLOS IZKERTORA D UTICAO SKALIRANJA



• KASHIJEH, E GEJTA
OPADA $\approx 13\%$ / GODIJI
ODKOSTIO OKO
2 PUTA I A SUAKIH
5 GODIJA .

Figure 5.39 Scaling of the gate delay (from [Dally98]).

Parameter	Relation	Full Scaling	General Scaling	Fixed-Voltage Scaling
Area/Device	WL	$1/S^2$	$1/S^2$	$1/S^2$
Intrinsic Delay	$R_{on}C_{gate}$	$1/S$	$1/S$	$1/S$

Parameter	Relation	Full Scaling	General Scaling	Fixed-Voltage Scaling
Intrinsic Energy	$C_{gate}V^2$	$1/S^3$	$1/SU^2$	$1/S$
Intrinsic Power	Energy/Delay	$1/S^2$	$1/U^2$	1
Power Density	$P/Area$	1	S^2/U^2	S^2

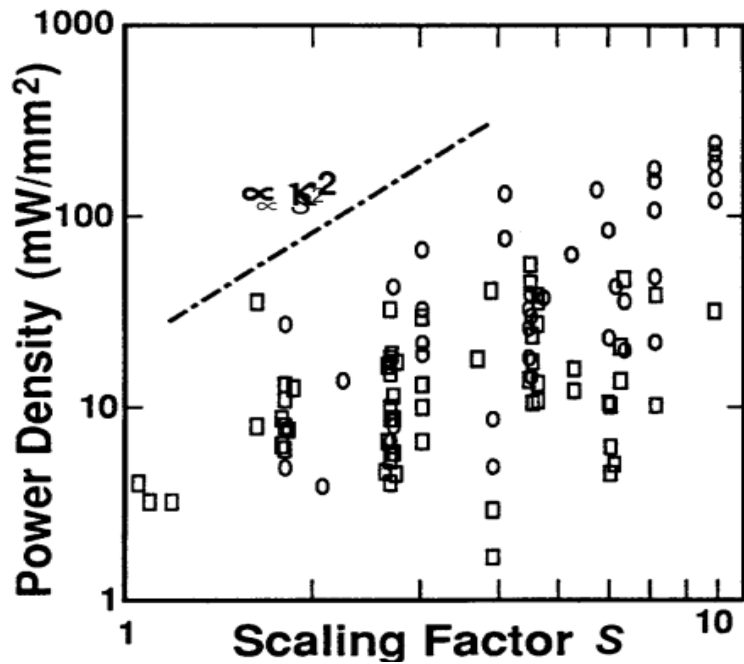


Figure 5.40 Evolution of power-density in micro- and DSP processors, as a function of the scaling factor S ([Sakurai97]). S is normalized to 1 for a $4\ \mu\text{m}$ process.

• GUSTINA STAJE (POWER-DENSITY) RASTE SA FAKTOROM S^2 . (FIXED-VOLTAGE SCALING).

• U SUB-MIKROMSKIM PROCESIMA SVE VIŠE PULAZI DO IZRAŽAJA DYNAMIČKA POTROŠNJA USLED KAPACITIVNOSTI VEŽA. PREDUHA SE TREND:

$$\frac{t_p(C_{int})}{t_p(C_w)} \rightarrow 1$$

Table 5.5 Scaling scenarios for wire capacitance. S and U represent the technology and voltage scaling parameters, respectively, while S_L stands for the wire-length scaling factor. ϵ_c represents the impact of fringing and inter-wire capacitances.

Parameter	Relation	General Scaling
Wire Capacitance	WL/t	ϵ_c/S_L
Wire Delay	$R_{on}C_{int}$	ϵ_c/S_L
Wire Energy	$C_{int}V^2$	$\epsilon_c/S_L U^2$
Wire Delay / Intrinsic Delay		$\epsilon_c S/S_L$
Wire Energy / Intrinsic Energy		$\epsilon_c S/S_L$

