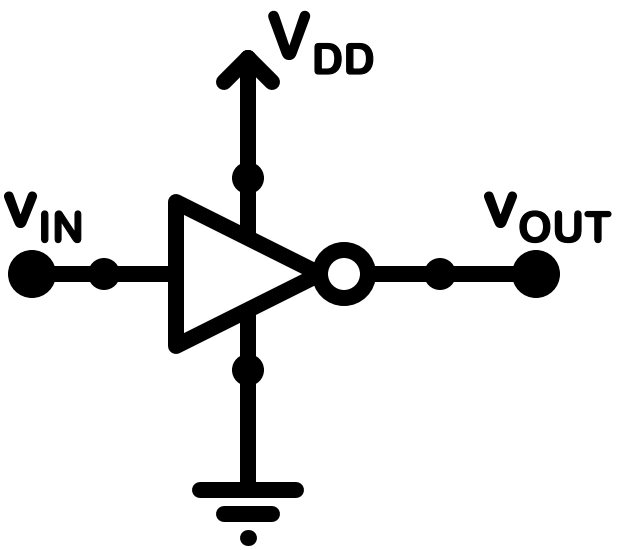
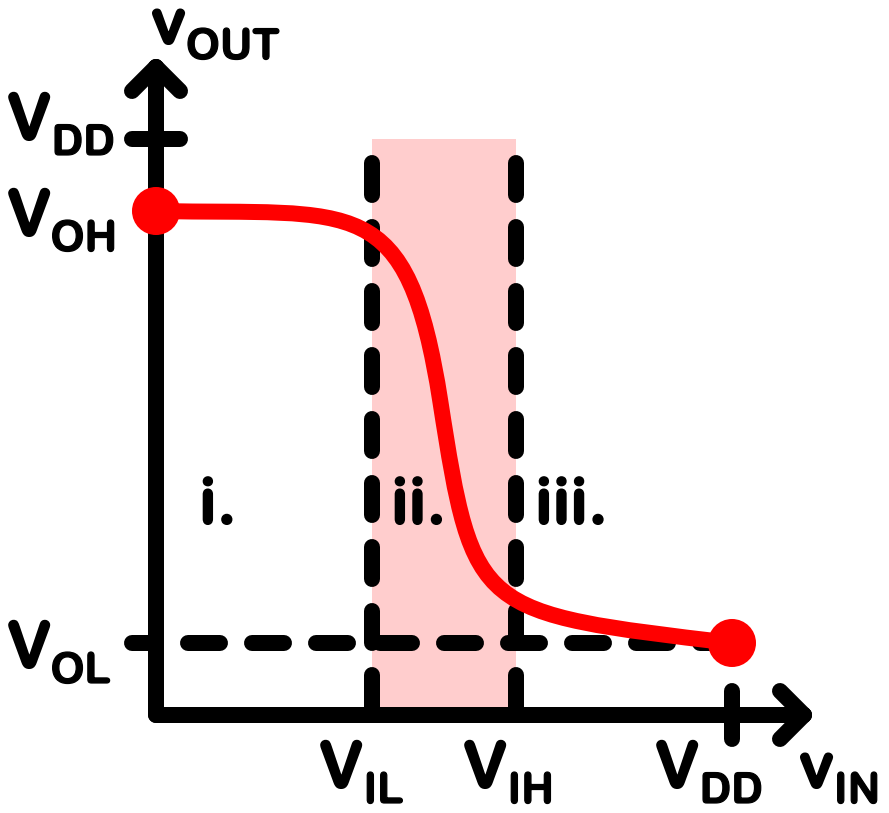
A General Inverter





Parameters

V_{OH}: Output High Voltage: $V_{OH} = v_{OUT}(0)$

V_{OL}: Output Low Voltage: $V_{OL} = v_{OUT}(V_{DD})$

V_{IL}: Input Low Voltage: 1st point where $v_{OUT}'(v_{IN}) = -1$

V_{IH}: Input High Voltage: 2nd point where $v_{OUT}'(v_{IN}) = -1$

VIL and VIH can also be interpreted as values of v_{IN} that define the edges of the transition region, $v_{OUT}'(v_{IN})$ crosses -1.

Implementation
NMOS Inverter

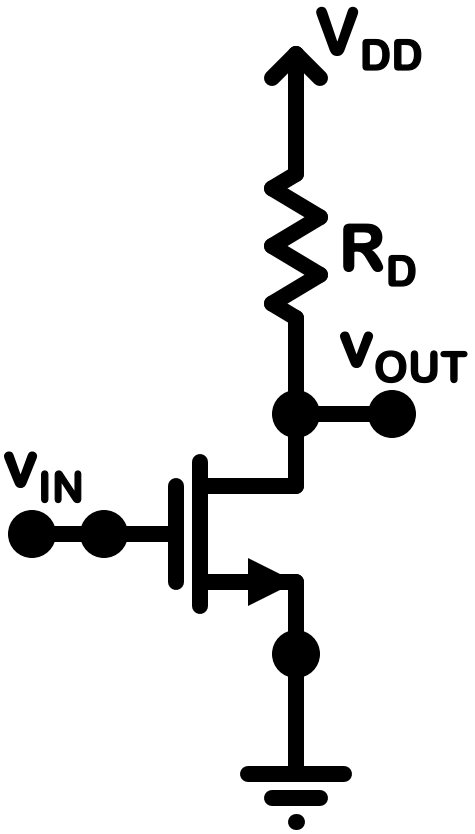
Parameters

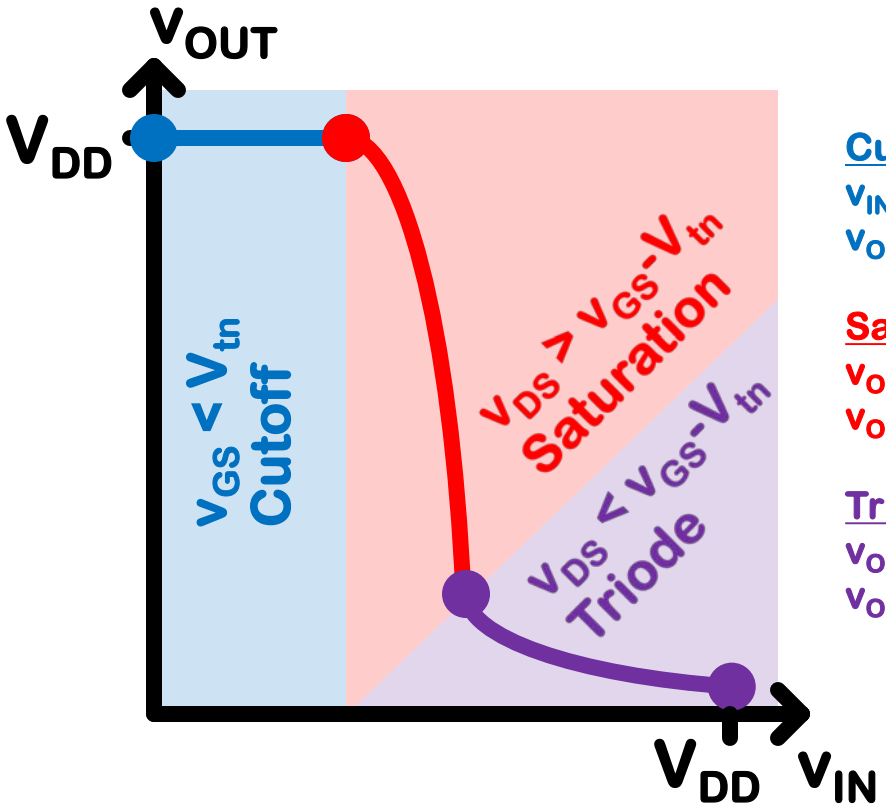
$V_{OH} = v_{OUT}(0) = V_{DD}$

$V_{OL} = v_{OUT}(V_{DD})$

$v_{OUT}'(V_{IL}) = -1$

$v_{OUT}'(V_{IH}) = -1$





Cutoff

$v_{IN} < V_{tn}$

$v_{OUT} = V_{DD}$

Saturation

$v_{OUT} > v_{IN} - V_{tn}$

$v_{OUT} = V_{DD} - 0.5 R_D k_n (v_{IN} - V_{tn})^2$

Triode (small v_{SD})

$v_{OUT} < v_{IN} - V_{tn}$

$v_{OUT} = V_{DD}/(1 + R_D k_n (v_{IN} - V_{tn}))$

Implementation NMOS Inverter

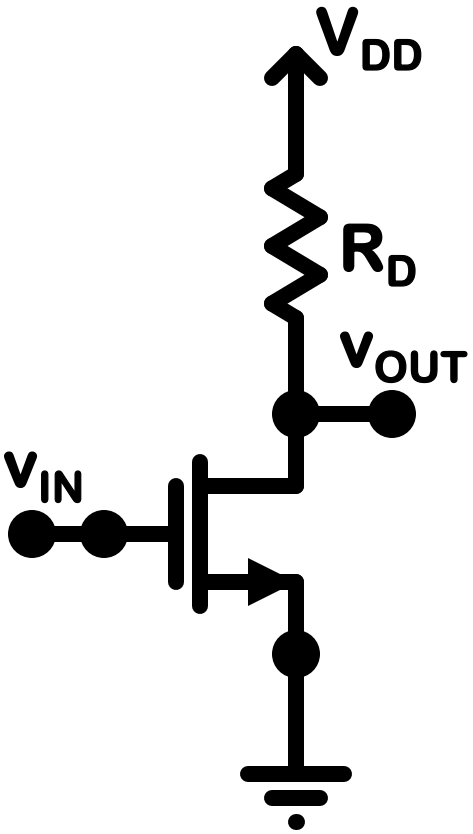
Parameters

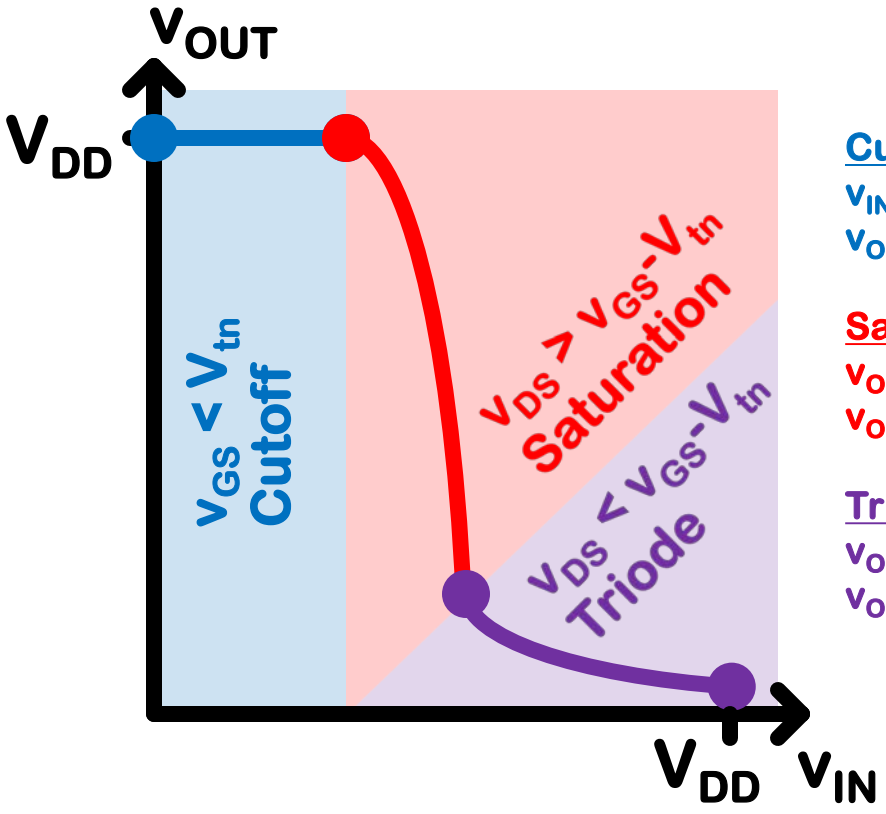
$V_{OH} = v_{OUT}(0) = V_{DD}$

$V_{OL} = v_{OUT}(V_{DD}) = V_{DD}/(1+R_D k_n(V_{DD}-V_{tn}))$

$v_{OUT}'(V_{IL}) = -R_D k_n(V_{IL}-Vtn) = -1;\ V_{IL} = (1/R_D k_n) + V_{tn}$

$v_{OUT}'(V_{IH}) = -1$; Triode (small v_{DS}) is not applicable





Cutoff

$v_{IN} < V_{tn}$

$v_{OUT} = V_{DD}$

Saturation

$v_{OUT} > v_{IN}-V_{tn}$

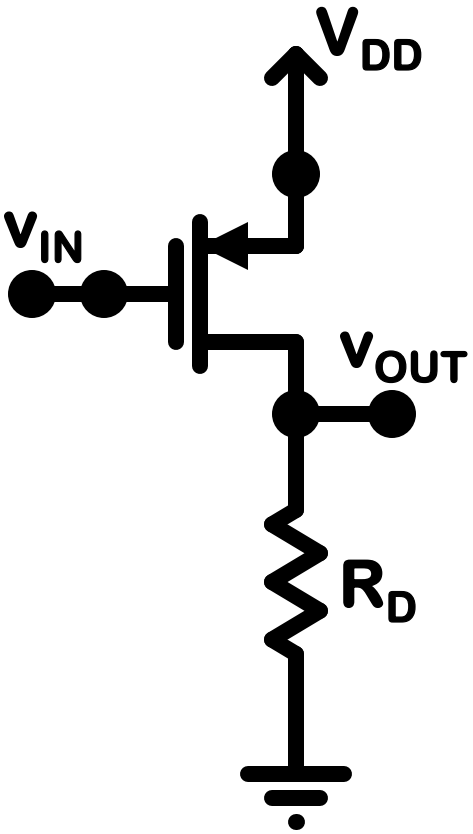
$v_{OUT} = V_{DD}-0.5R_D k_n(v_{IN}-V_{tn})^2$

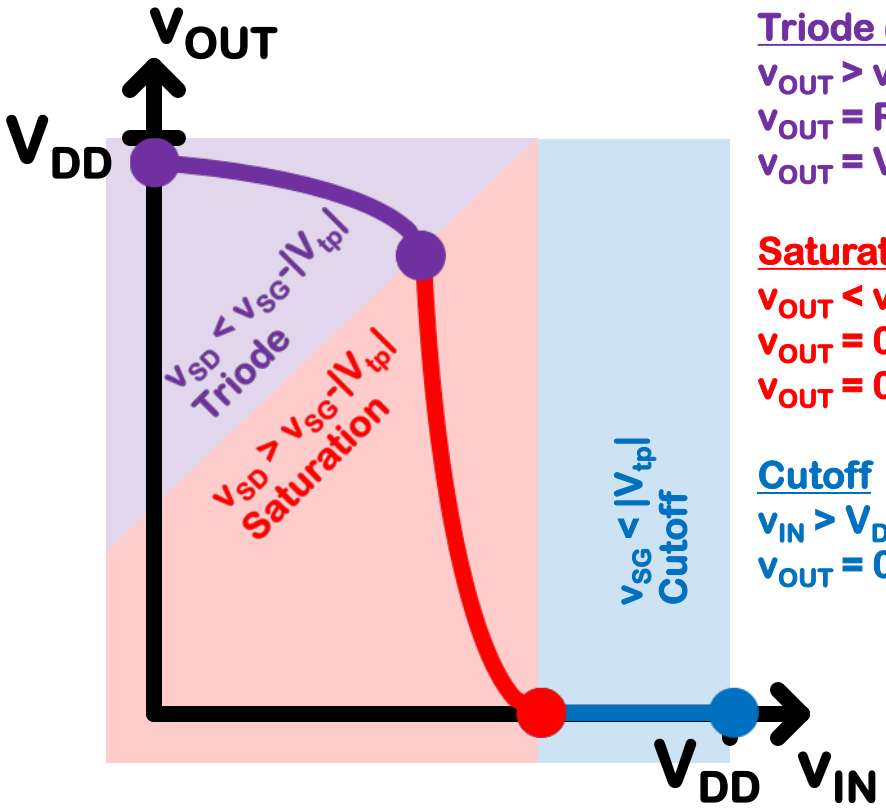
Triode (small v_{SD})

$v_{OUT} < v_{IN}-V_{tn}$

$v_{OUT} = V_{DD}/(1+R_D k_n(v_{IN} - V_{tn}))$

PMOS Inverter





Triode (small v_{SD})

$v_{OUT} > v_{IN}+|V_{tp}|$

$v_{OUT} = R_D k_p (V_{DD}-v_{IN}-|V_{tp}|)(V_{DD}-v_{OUT})$

$v_{OUT} = V_{DD}/(1+1/(R_D k_p (V_{DD}-v_{IN}-|V_{tp}|)))$

Saturation

$v_{OUT} < v_{IN}+|V_{tp}|$

$v_{OUT} = 0.5 R_D k_p ((V_{DD}-|V_{tp}|)-v_{IN})^2$

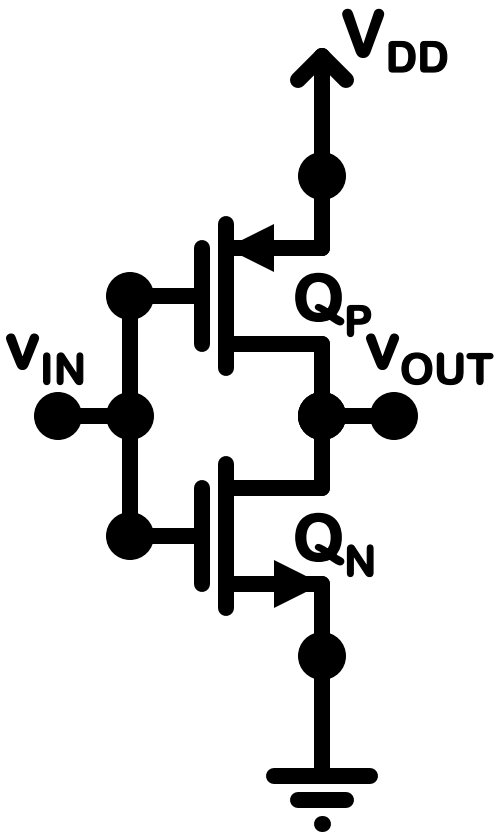
$v_{OUT} = 0.5 R_D k_p (v_{IN}-(V_{DD}-|V_{tp}|))^2$

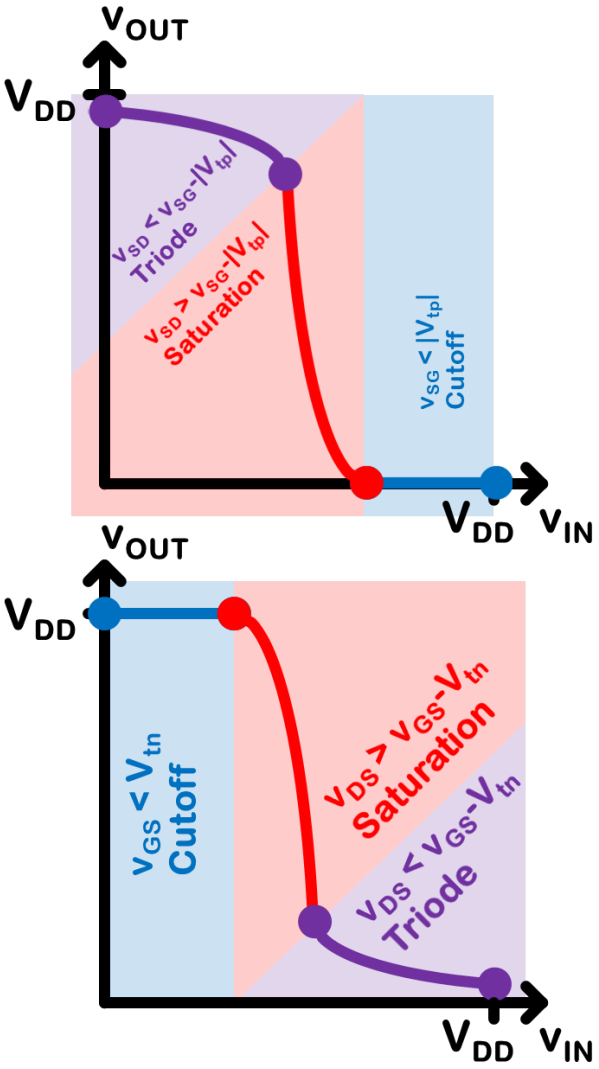
Cutoff

$v_{IN} > V_{DD}-|V_{tp}|$

$v_{OUT} = 0$

CMOS Inverter



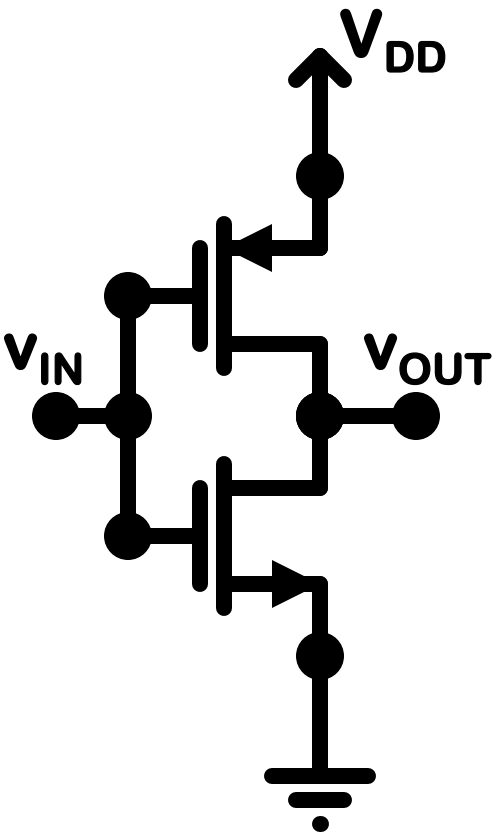


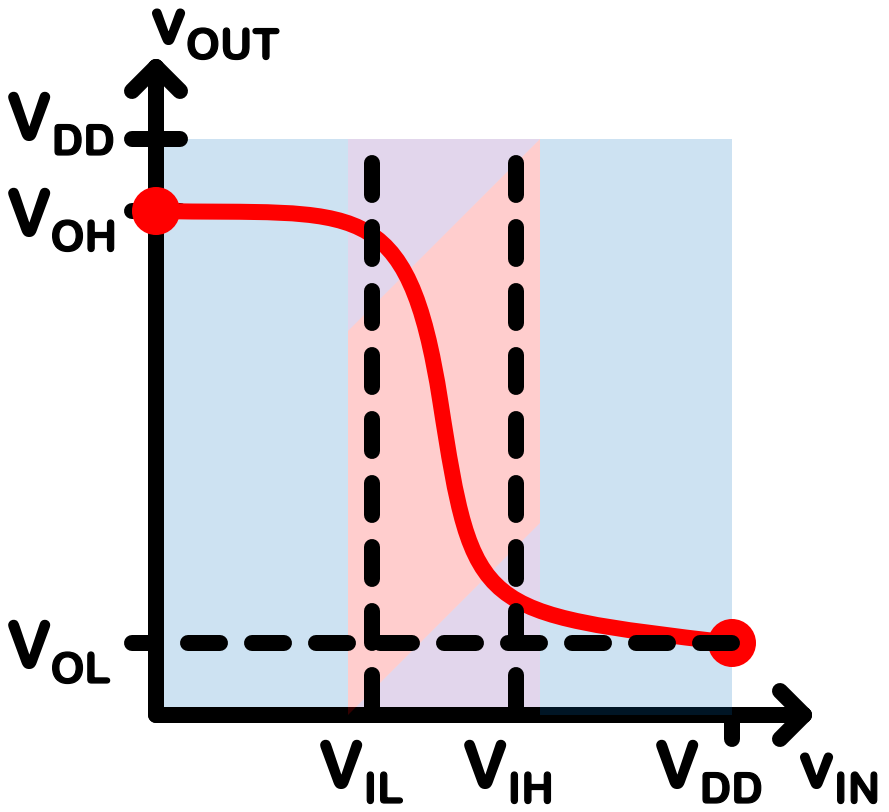
*devices are matched.

*$V_{DD} > 2V_t$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

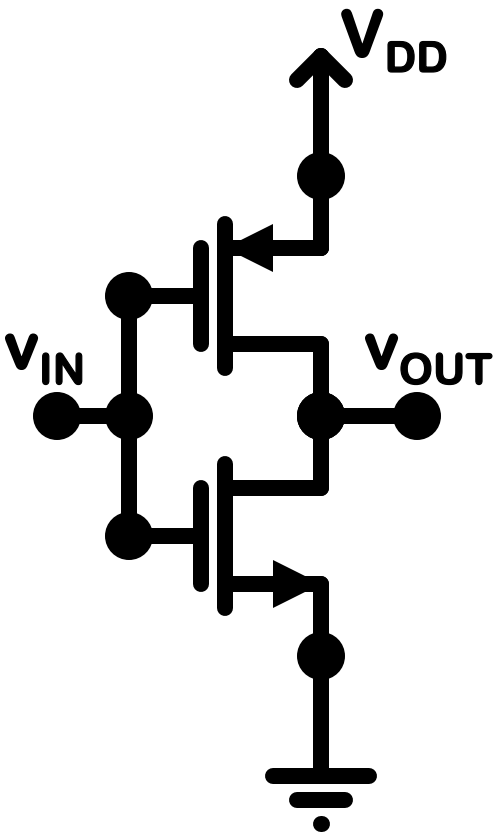
CMOS Inverter





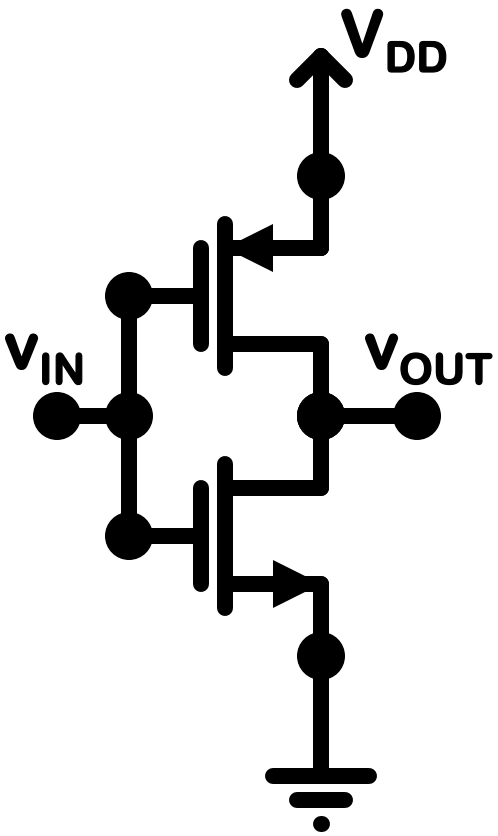
V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter



V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter



Cutoff

$i_D = 0$

Triode

$i_D = k_n(v_{GS} - V_{tn} - 0.5v_{DS})v_{DS}$

$v_{GS} = v_{IN}$

$v_{DS} = v_{OUT} = 0$

$v_{SG} < |V_{tp}|$

$V_{DD} - v_{IN} < |V_{tp}|$

$v_{IN} > V_{DD} - |V_{tp}|$

$v_{GS} > V_{tn}$

$v_{IN} > V_{tn}$

$v_{DS} < v_{GS} - V_{tn}$

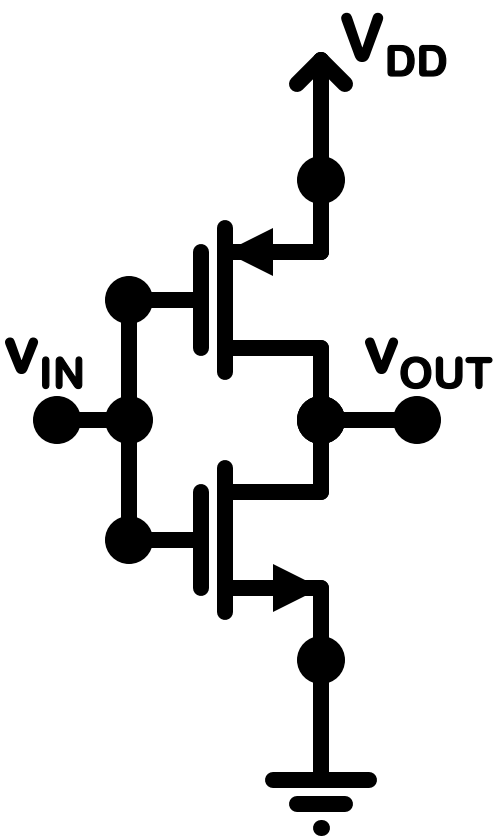
$v_{OUT} < v_{IN} - V_{tn}$

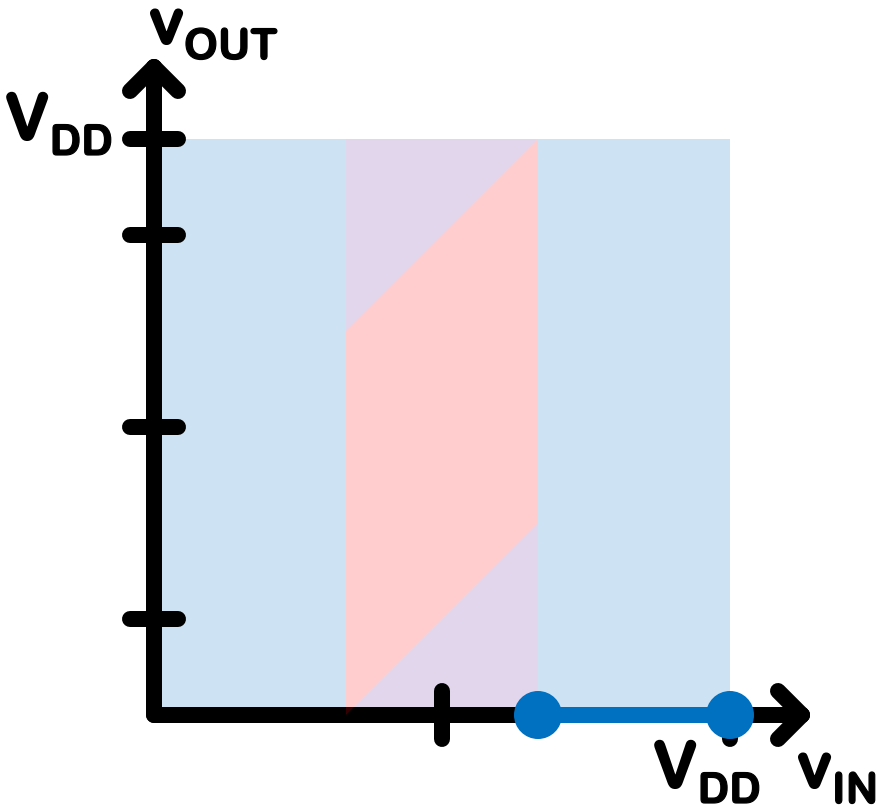
$0 < v_{IN} - V_{tn}$

$v_{IN} > V_{tn}$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

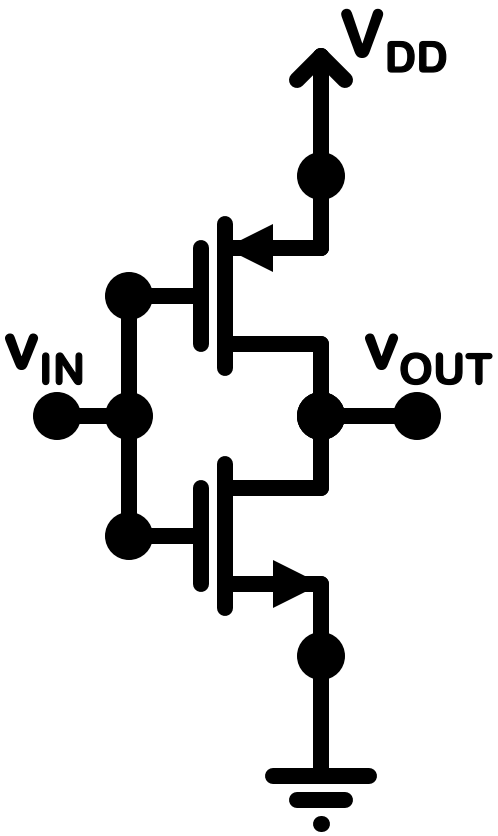
CMOS Inverter





V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter



Cutoff

$i_D = 0$

Triode

$i_D = k_p(v_{SG} - |V_{tp}| - 0.5v_{SD})v_{SD}$

$v_{SG} = V_{DD} - v_{IN}$

$v_{SD} = V_{DD} - v_{OUT} = 0$

$v_{OUT} = V_{DD}$

$v_{GS} < V_{tn}$

$v_{IN} < V_{tn}$

$v_{SG} > V_{tn}$

$V_{DD} - v_{IN} > |V_{tp}|$

$v_{IN} < V_{DD} - |V_{tp}|$

$v_{SD} < v_{SG} - |V_{tp}|$

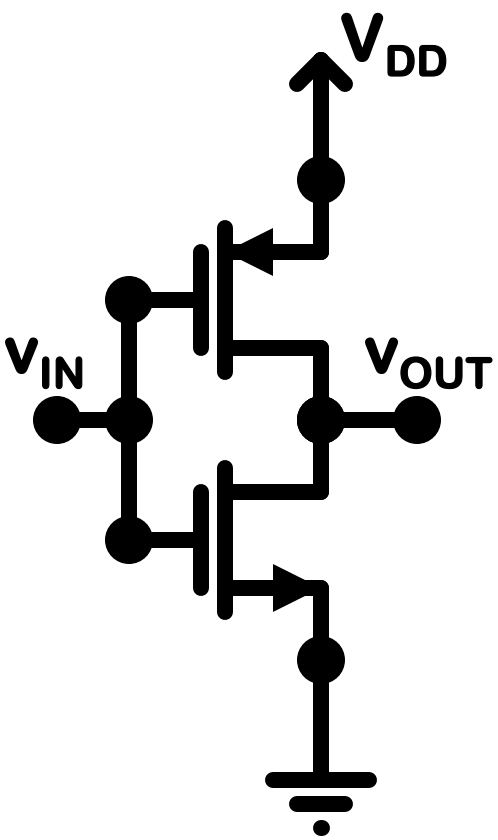
$V_{DD} - v_{OUT} < V_{DD} - v_{IN} - |V_{tp}|$

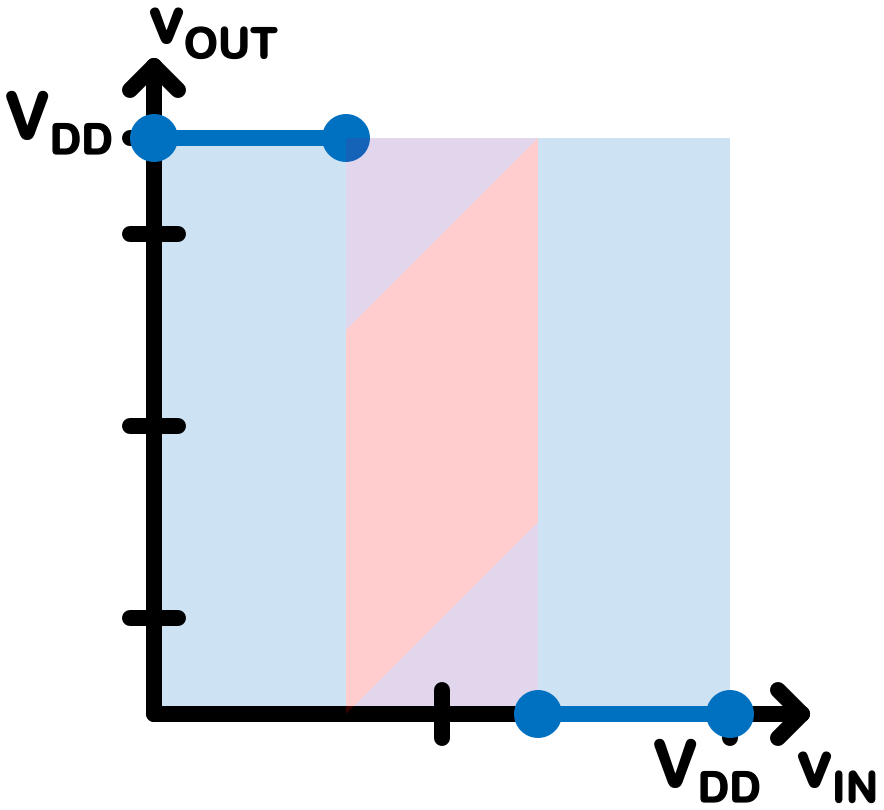
$0 < V_{DD} - v_{IN} - |V_{tp}|$

$v_{IN} < V_{DD} - |V_{tp}|$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

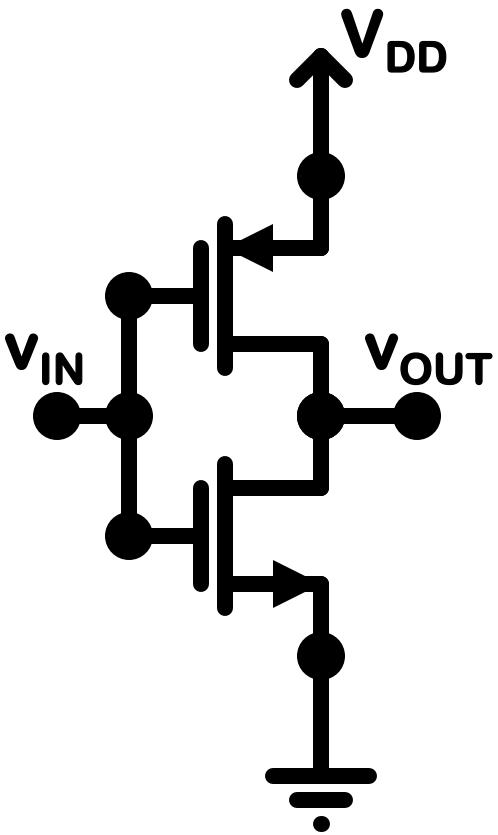
CMOS Inverter





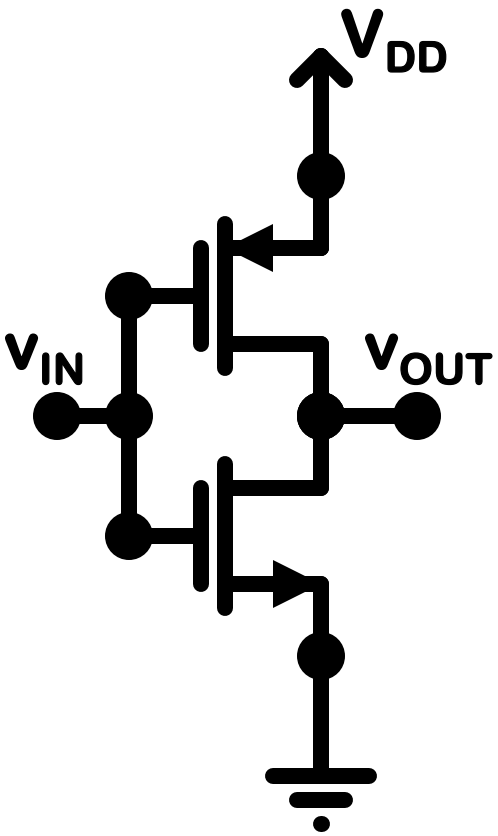
V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter



V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter



Saturation

$v_{OUT} > v_{IN} - V_{tn}$

$i_D = 0.5k_n(v_{GS} - V_{tn})^2$

$i_D = 0.5k_P(v_{SG} - |V_{tp}|)^2$

$0.5k_n(v_{GS} - V_{tn})^2 = 0.5k_P(v_{SG} - |V_{tp}|)^2$

$(v_{GS}) = (v_{SG})$

$v_{IN} = V_{DD} - v_{IN}$

$v_{IN} = V_{DD}/2$

$v_{GS} > V_{tn}$ $v_{IN} > V_{tn}$

$v_{SG} > |V_{tp}|$ $v_{IN} < V_{DD} - |V_{tp}|$

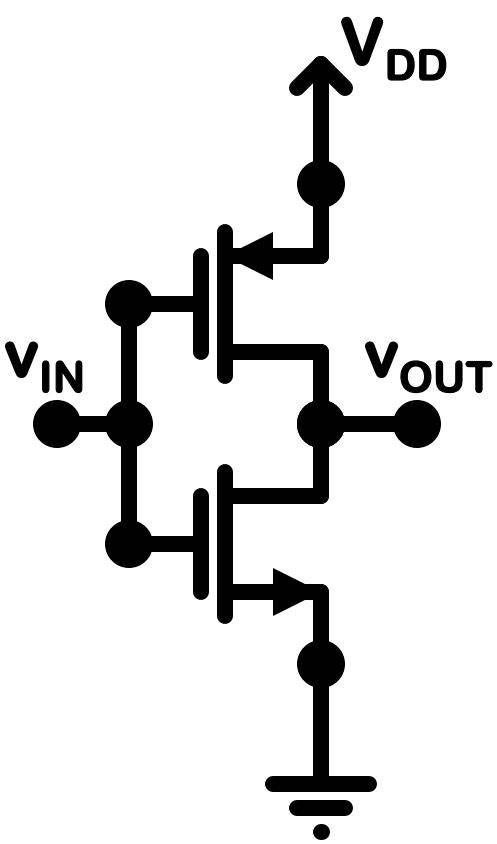
$v_{DS} > v_{GS} - V_{tn}$

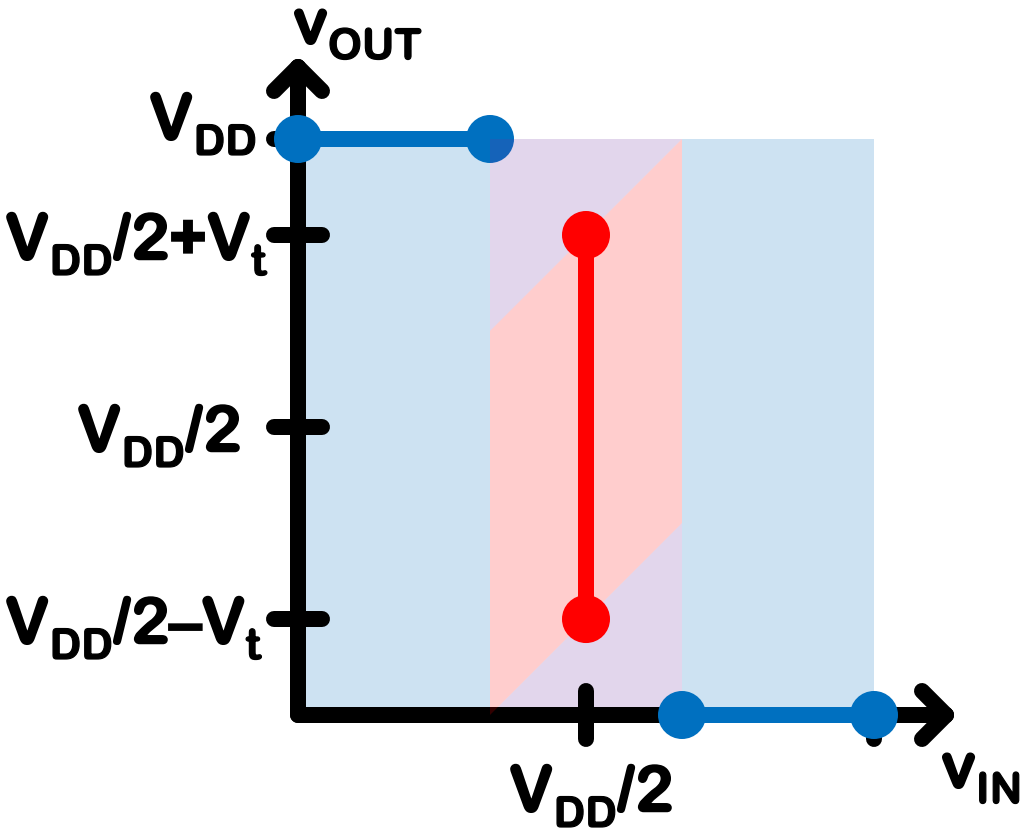
$v_{OUT} > v_{IN} - V_{tn}$ $v_{OUT} > V_{DD}/2 - V_{tn}$

$v_{OUT} < V_{DD}/2 + V_{tn}$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	**Saturation**	Saturation	Cutoff
NMOS:	Cutoff	Saturation	**Saturation**	Triode	Triode

CMOS Inverter

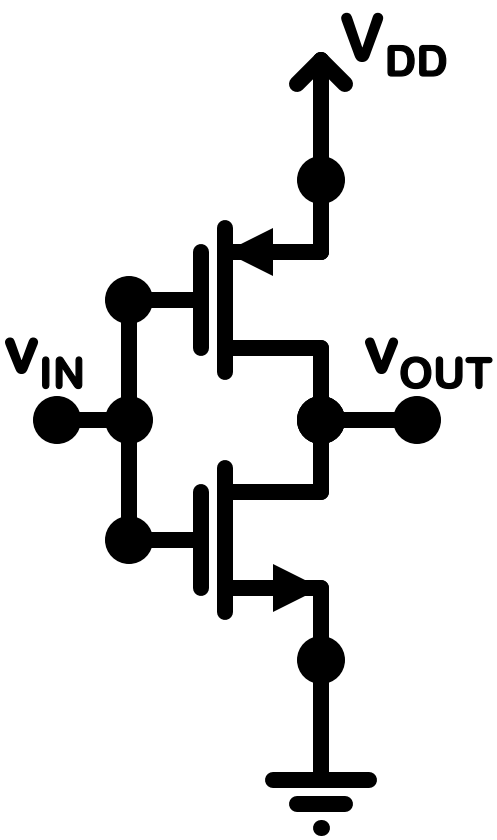


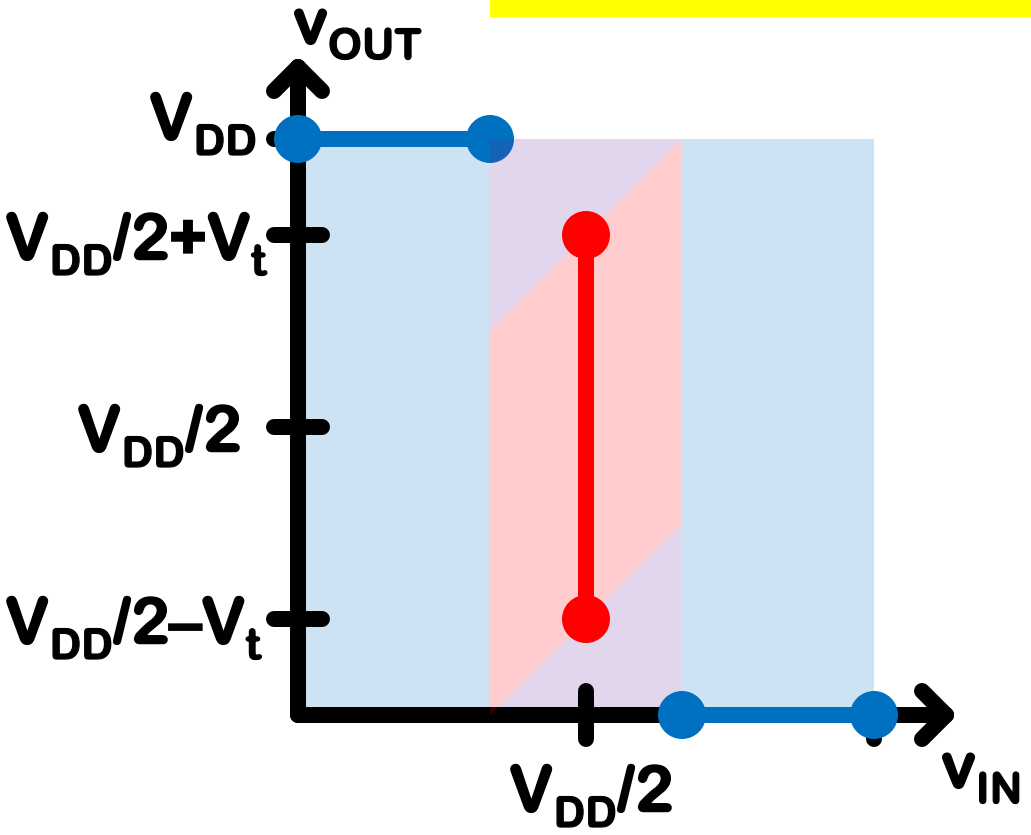


V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter

As V_t approaches $V_{DD}/2$ the transfer function resembles an ideal inverter.

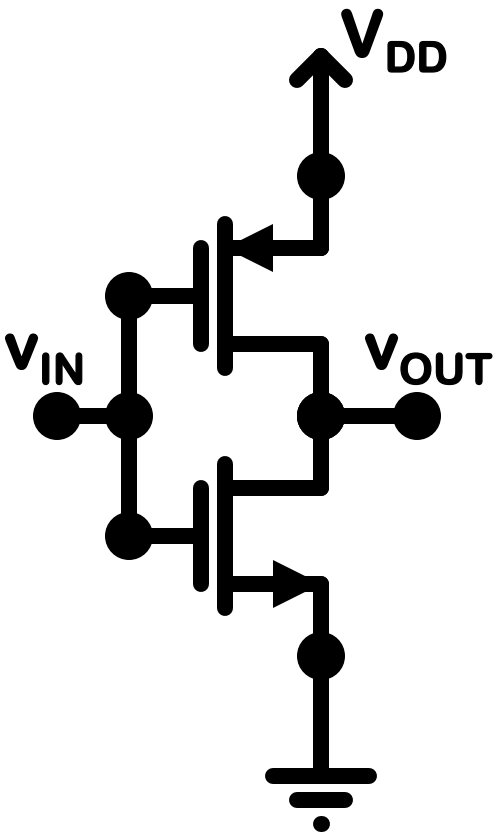




Not really vertical, we did not include λ, V_A, r_o.

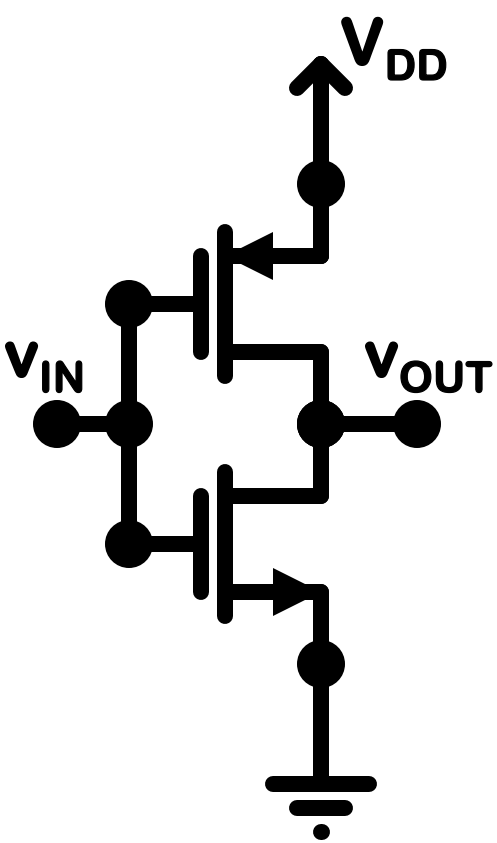
V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

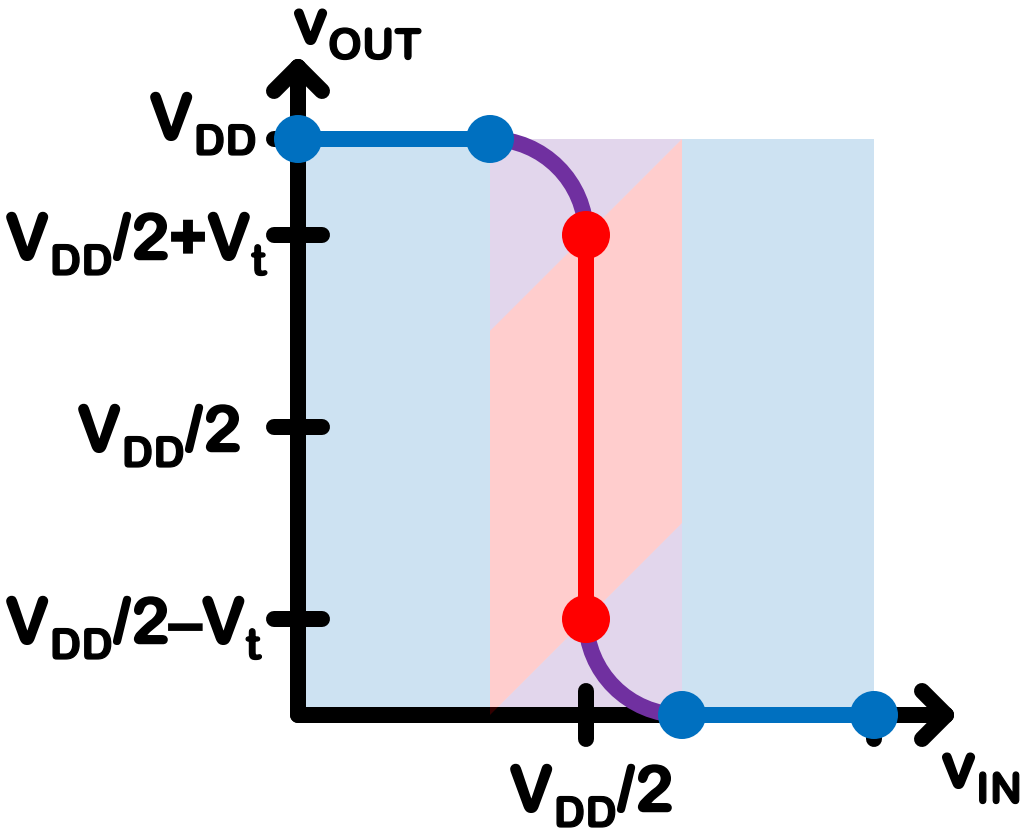
CMOS Inverter



V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

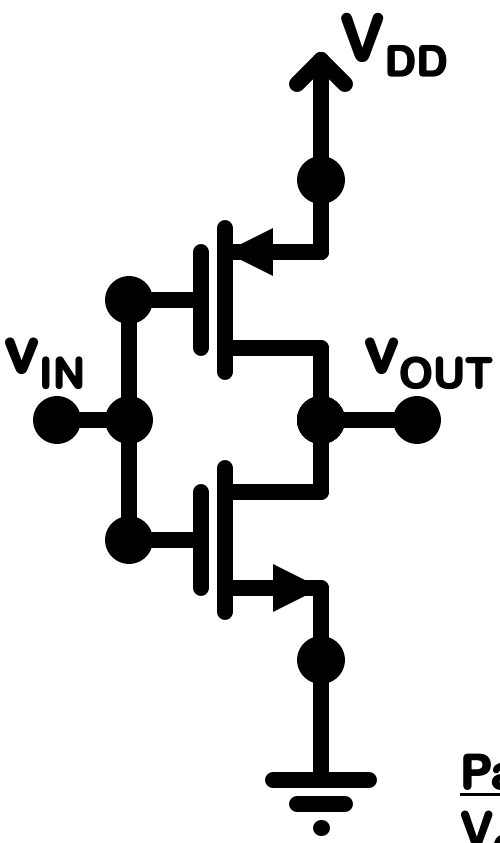
CMOS Inverter

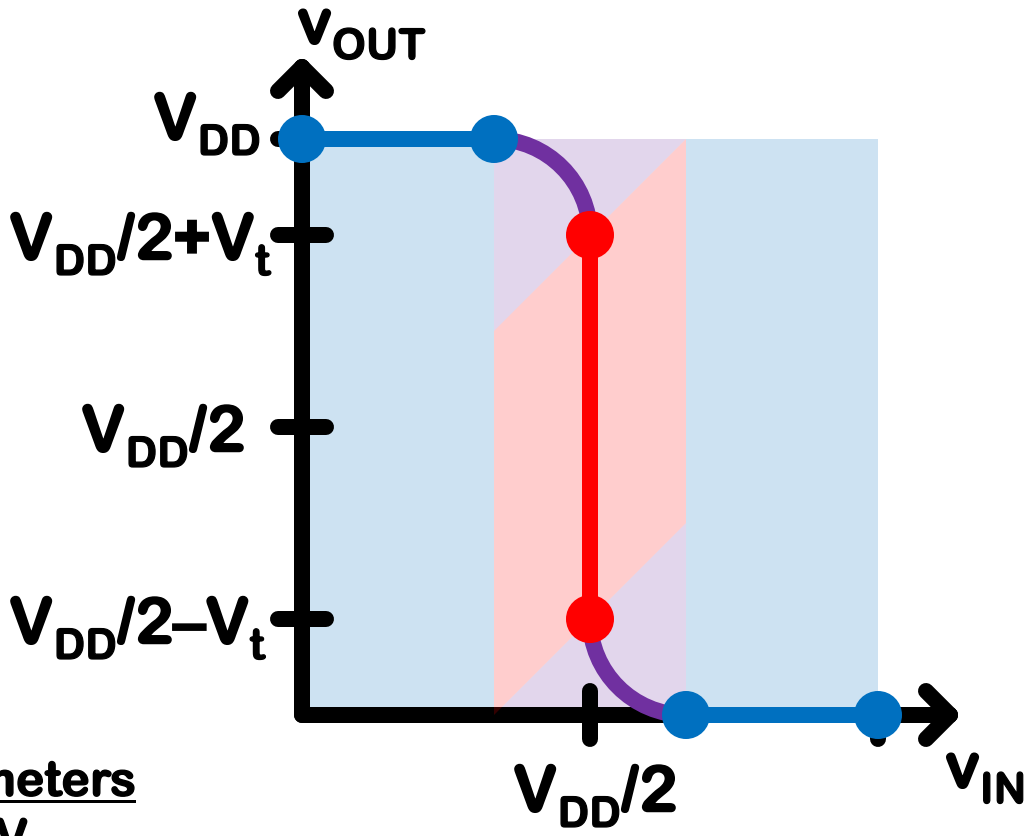




V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	**Saturation**	Cutoff
NMOS:	Cutoff	Saturation	Saturation	**Triode**	Triode

CMOS Inverter





Parameters

$V_{OH} = V_{DD}$

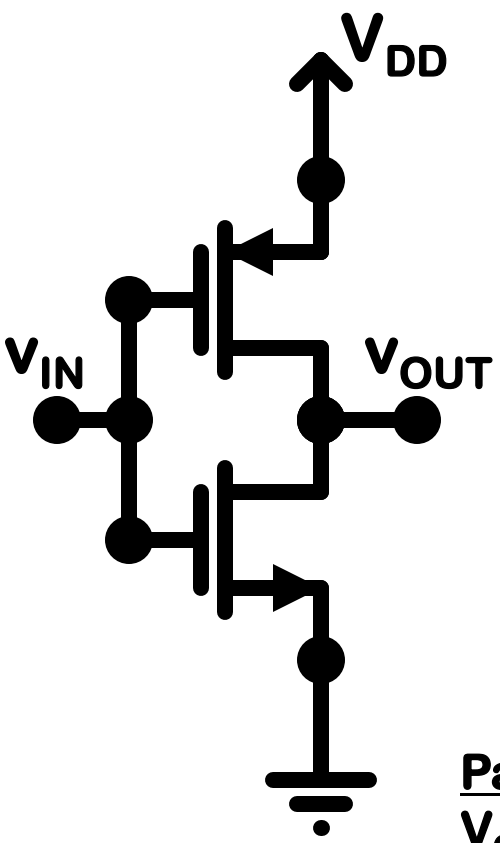
$V_{OL} = 0$

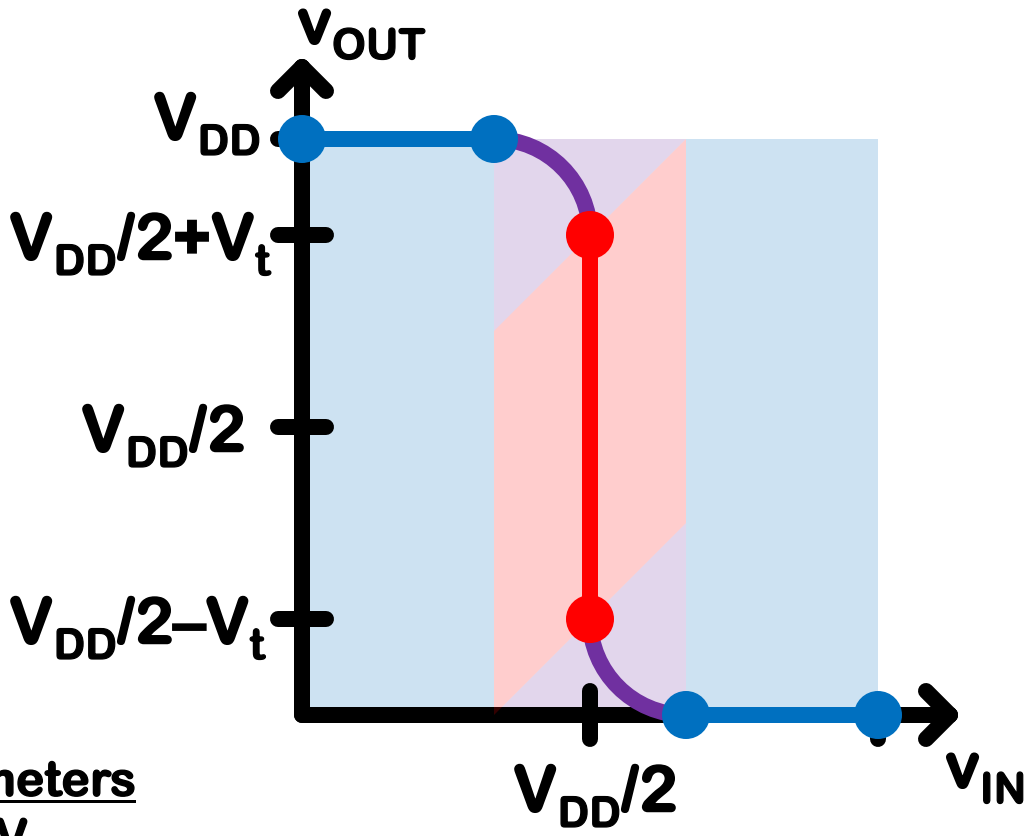
$v_{IH} = ?$

$V_{IL} = ?$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter





Parameters

$V_{OH} = V_{DD}$

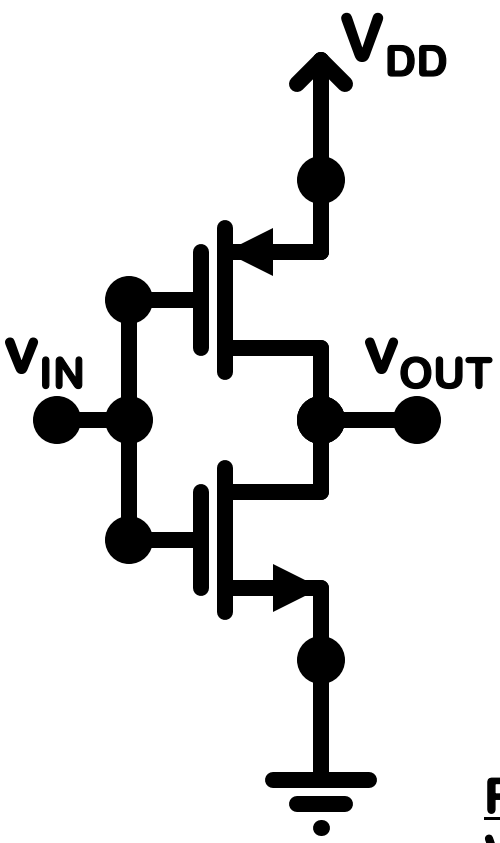
$V_{OL} = 0$

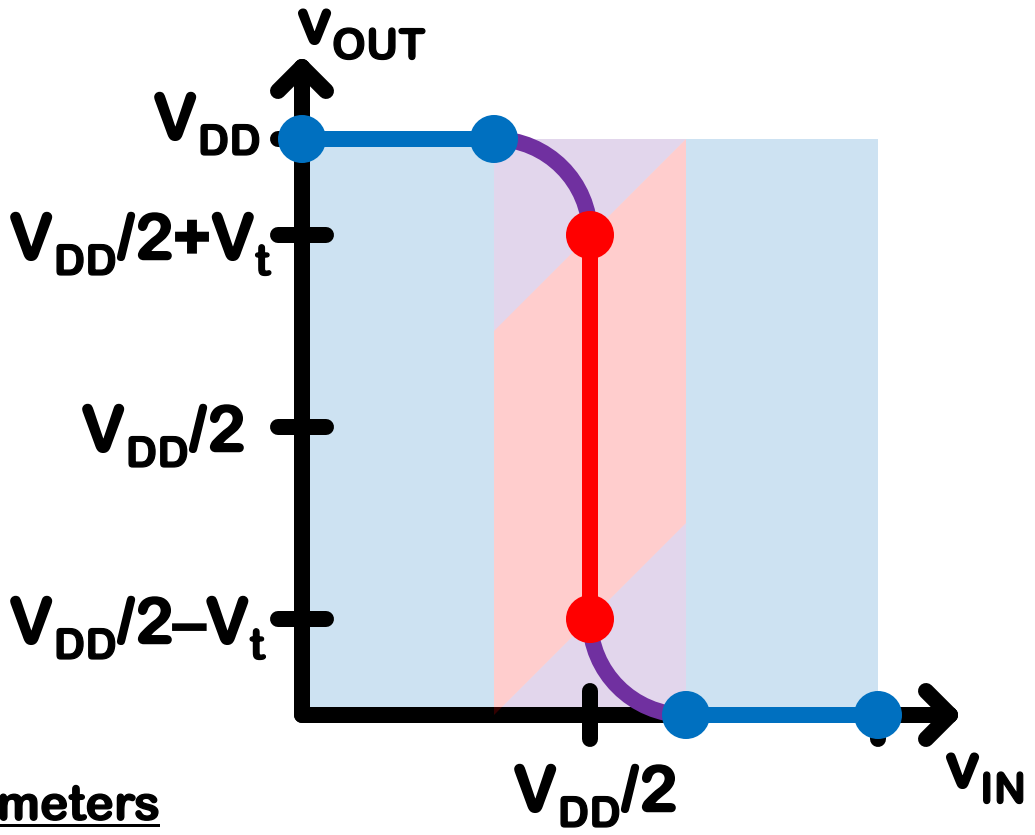
$v_{IH} = (5V_{DD}-2V_t)/8$

$V_{IL} = (3V_{DD}+2V_t)/8$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode

CMOS Inverter





Parameters

$V_{OH} = V_{DD}$

$V_{OL} = 0$

$v_{IH} = (5V_{DD}-2V_t)/8$

$V_{IL} = (3V_{DD}+2V_t)/8$

$NM_H = NM_L = NM = (3V_{DD}+2V_t)/8$

V_{IN}:	0				V_{DD}
PMOS:	Triode	Triode	Saturation	Saturation	Cutoff
NMOS:	Cutoff	Saturation	Saturation	Triode	Triode