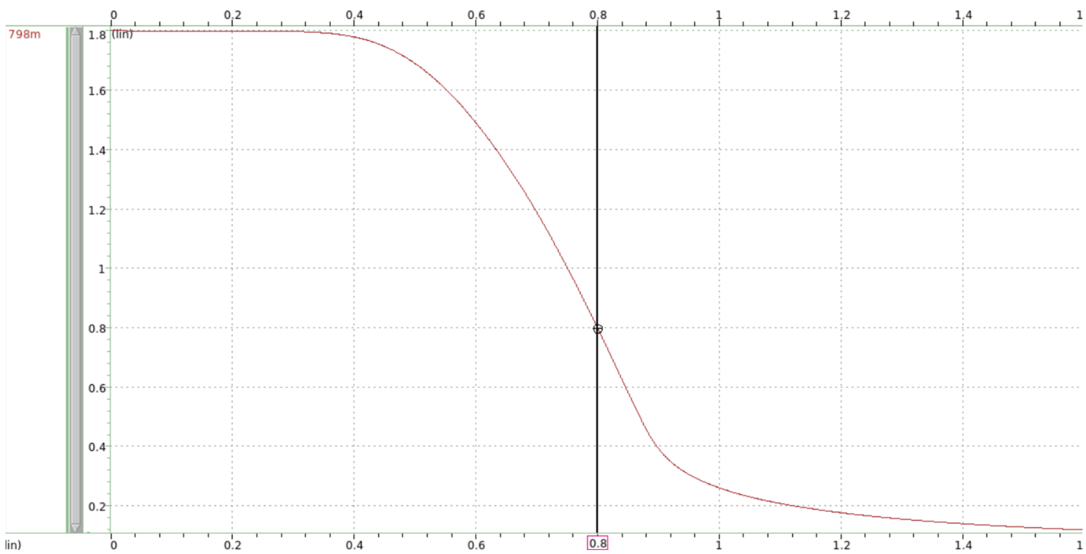
Analog Integrated Circuit Analysis and Design I

Homework 2

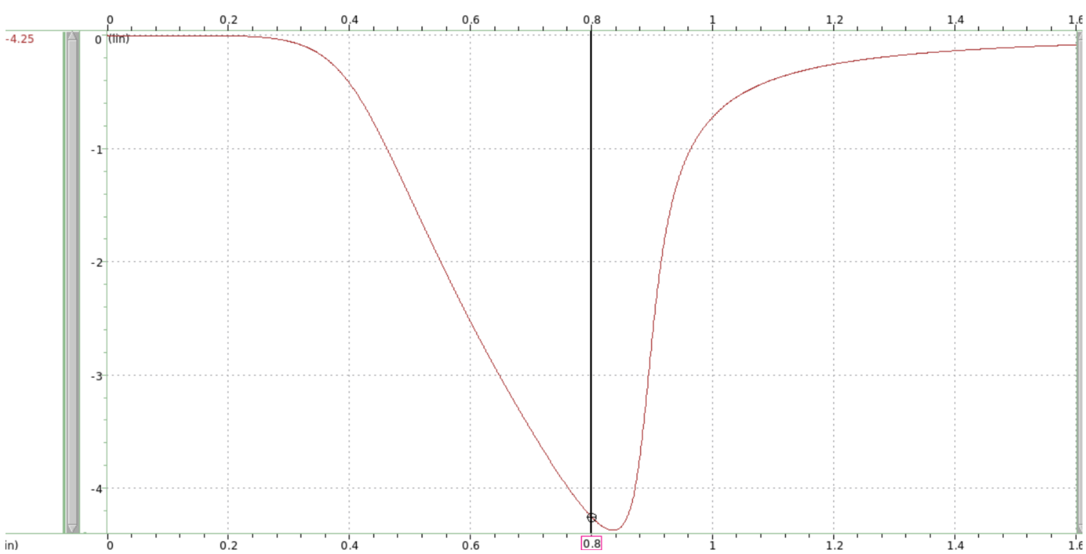
110061217 王彥智

- Part 1
  - DC sweep:

    We can see when Vin is 0.8V, $Vout$ is 0.798V(error: 0.25%) and the derivative of $Vout$ is -4.25.



X axis: Vin(V)-Y axis: $Vout$ (V)



X axis: Vin(V)-Y axis: derivative of Vout(V)

- TF analysis

  The following table is the TF analysis result, we can see Av is -4.2563 when Vin is 0.8V. We can compare the result of DC sweep and TF analysis. In DC sweep, the meaning $\frac{\partial Vout}{\partial Vin}$ is "how $Vout$ change when Vin change a little bit." In TF analysis, we give some AC small signal on the DC operating point to see the output change. Therefore, the result of two analyses are basically the same, since the meaning of two operation are the same.

Vin(V)	Rin(Ω)	Rout(Ω)	Av(V/V)
797.0000m	1.000e+20	43.8850k	-4.2394
798.0000m	1.000e+20	43.8627k	-4.2451
799.0000m	1.000e+20	43.8400k	-4.2507
800.0000m	1.000e+20	43.8168k	-4.2563
801.0000m	1.000e+20	43.7931k	-4.2617
802.0000m	1.000e+20	43.7689k	-4.2671
803.0000m	1.000e+20	43.7442k	-4.2724

TF Analysis

- Hand Calculation and Discussion

```
 **info** dc convergence successful at Newton-Raphson method
1****** PrimeSim HSPICE -- R-2020.12-SP2 linux64 (May 24 2021 7074677) ******
 ******
 ** 110061217 hw2 part1

 ****** operating point information tnom=  25.000 temp=  25.000 ******
 ****** operating point status is all       simulation time is     0.
    node    =voltage      node    =voltage      node    =voltage

 +0:vdd     =   1.8000  0:vin     = 800.0000m 0:vout    = 798.3265m


 **** voltage sources

 subckt
 element  0:vin      0:vdd
  volts    800.0000m    1.8000
  current    0.       -21.3122u
  power      0.        38.3620u

     total voltage source power dissipation=   38.3620u       watts


 **** resistors

 subckt
 element  0:rd
  r value   47.0000k
  v drop     1.0017
  current   21.3122u
  power     21.3479u
```

Operating point

```
subckt
element  0:mn
model    0:n_18.1
region   Saturation
 id        21.3122u
 ibs      -6.353e-21
 ibd      -114.4098a
 vgs       800.0000m
 vds       798.3265m
 vbs         0.
 vth       398.5086m
 vdsat     332.9477m
 vod       401.4914m
 beta      308.1817u
 gam eff   507.4472m
 gm         97.1615u
 gds         1.5461u
 gmb        18.3993u
 cdtot       1.4212f
 cgtot       6.8826f
 cstot       7.8613f
 cbtot       3.8609f
 cgs         6.0654f
 cgd       358.0754a
```

NMOS

Working item	SPEC	Your Design	Hand Calculation
V_{DD}	1.8V	1.8V	1.8V
$V_{in,DC}$	0.8V	0.8V	0.8V
$V_{out,DC}$	0.8V	798.3265mV	798.3266V
$Gain\ A_V$	>3.2(V/V)	4.2563(V/V)	4.2572(V/V)
R_D	<90k Ω	47k Ω	
I_D	<30uA	21.3122uA	
$M_b\ W/L$		1um/1um	

COMMON SOURCE PERFORMANCE TABLE

$$V_{out} = V_{DD} - I_d * R_D \ = \ 1.8 - 21.3122uA * 47k\Omega = 0.7983266V$$

$$Error = \frac{(0.7983265 - 0.7983266)}{0.7983266} * \ 100\% \ = \ -1.252 * 10\text{^}(-3)\%$$

$$A_V \ = \ \frac{\partial Vout}{\partial Vin} = \ -g_m R_D \ = -97.1615u\left(\frac{1}{\Omega}\right) * 47k\Omega = -4.5665(V/V)$$

$$Error = \frac{(4.2563 - 4.5665)}{4.5665} * \ 100\% \ = \ -7.28\%$$

$$R_{out} \ = \ \ (R_D \parallel \frac{1}{g_{ds}}) = \ (47\text{K} \,||\, 646788.6941) = 43816.0334\Omega$$

Error = (43.8168 – 43.8160) / 43.8160 $*$ 100% = 0.0017%

- Discussion
  - How I design the amplifier?

    First, I choose L = 1um, since it should not be too small, or it will have short-channel effect. Also, I don't want L to be too large, or it will waste the space of circuit. Second, I use a random W, L and R_D value to run hspice , I can get beta value($\frac{beta}{W/L} = u_n C_{ox}$), and Vth value. Third, I use W/L = 1 , since $I_D = \frac{\frac{1}{2}\mu_n C_{ox} W}{L(V_{in}-V_{th})^2} < 30uA$. Then, I use R_D = 50k Ω to run hspice, and use $Id = \frac{1}{2} * \frac{u_n C_{ox} W}{L} * (V_{gs} - V_{th})$ and $V_{out} = V_{DD} - I_d * R_D$ to find correct R_D. Finally, use new R_D to run hspice again, since I don't consider r_o, there will be some error, so I adjust it a little bit. The final R_D is 47k Ω.

first, set L=1u and $\frac{W}{L}=1$, R=50k

we can find beta ≅ 277.4u , Vth ≅ 0.4V

$\rightarrow \therefore U_n C_{ox} = 277.4u/1 = 277.4$

$$\begin{cases} I_d = \frac{1}{2} U_n C_{ox} \frac{W}{L} (V_{gs} - V_{th})^2 \\ g_m = u_n C_{ox} \frac{W}{L} (V_{gs} - V_{th}) \end{cases}$$

$(I_d < 30u)$

$I_d = \frac{1}{2} \times 277.4u \times \frac{W}{L} \times (0.4)^2 < 30u$ ... ok!

$V_{DS} = V_{dd} - R \times I_d$

$0.8 = 1.8 - R \times \frac{1}{2} \times 277.4u \times \frac{W}{L} \times (0.8 - 0.4)^2$

$\therefore R\frac{W}{L} = \frac{1}{2.568 \times 10^{-5}} \cong 45k\Omega$

$\rightarrow$ choose $R = 45k\Omega$, $\frac{W}{L} = 1$, $L = 1u$ ($V_{th} = 0.4V$)

代入後有誤差，我認為是沒有考慮小 r_o，

微調後用 $R_d = 47k\Omega$ 最為接近

My calculation for design

- Why the hand calculation of A_V is different from the result?

I use the following formula to calculate the result:

$$V_{out} = V_{DD} - I_d * R_D = V_{DD} - \frac{1}{2} * u_n C_{ox} \frac{W}{L} * (V_{in} - V_{th})^2 * R_D$$

$$\rightarrow \frac{\partial Vout}{\partial Vin} = -u_n C_{ox} \frac{W}{L} * (V_{in} - V_{th}) * R_D$$

$$And, when\ in\ \ saturation, g_m = \ u_n C_{ox} \frac{W}{L} (Vin - Vth)$$

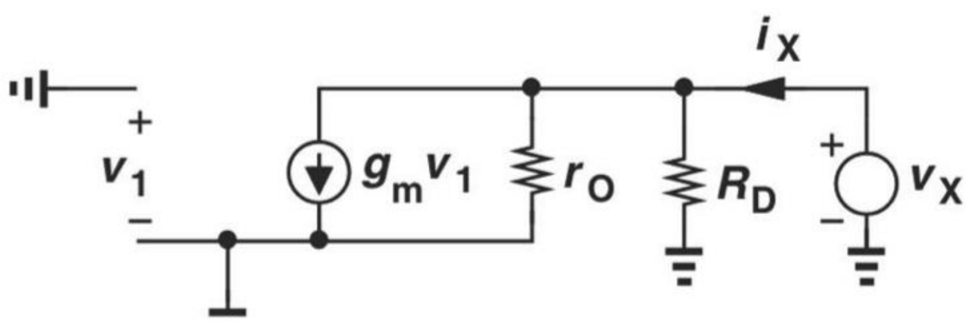
$$So, A_V = \frac{\partial Vout}{\partial Vin} = \ -g_m R_D = -97.1615u \left(\frac{1}{\Omega}\right) * 47k\Omega = -4.5665$$

However, by using small signal analysis, we should consider channel-length modulation effect, and by the following small signal module:

$$A_V = -gm * R_{out} = -gm * (R_D \parallel r_o)$$

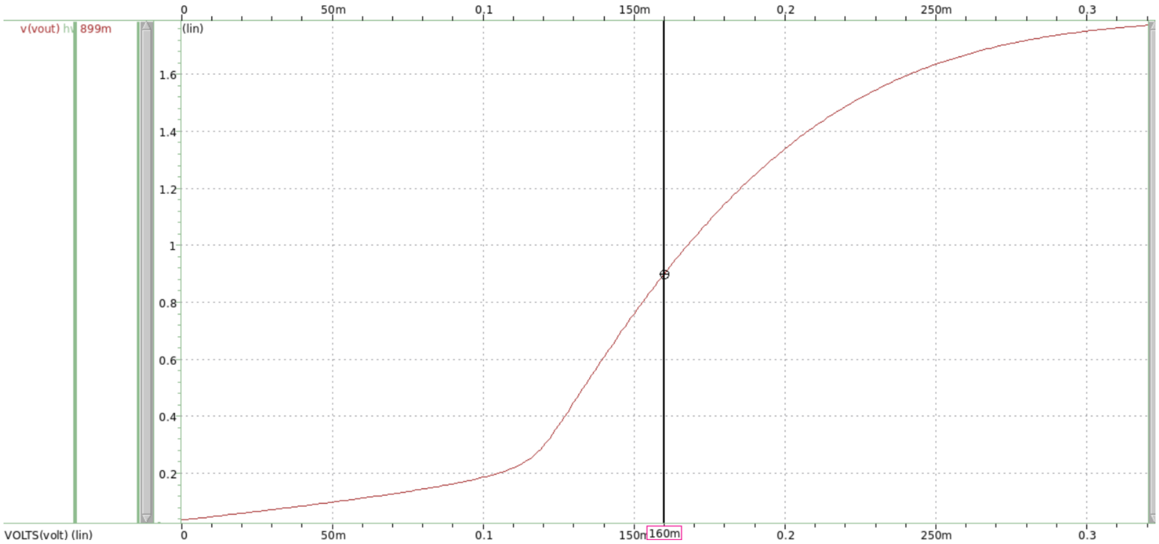
$$= -97.1615\ \mathrm{u} \left(\frac{1}{\Omega}\right) \times\ 43.8168\mathrm{k}\Omega\ =\ -4.2572 \left(\frac{\mathrm{V}}{\mathrm{V}}\right)$$

$$Error\ can\ be\ reduce\ to \frac{(4.2563 - 4.2572)}{4.2572}\ *\ 100\%\ =\ -0.0211\%$$

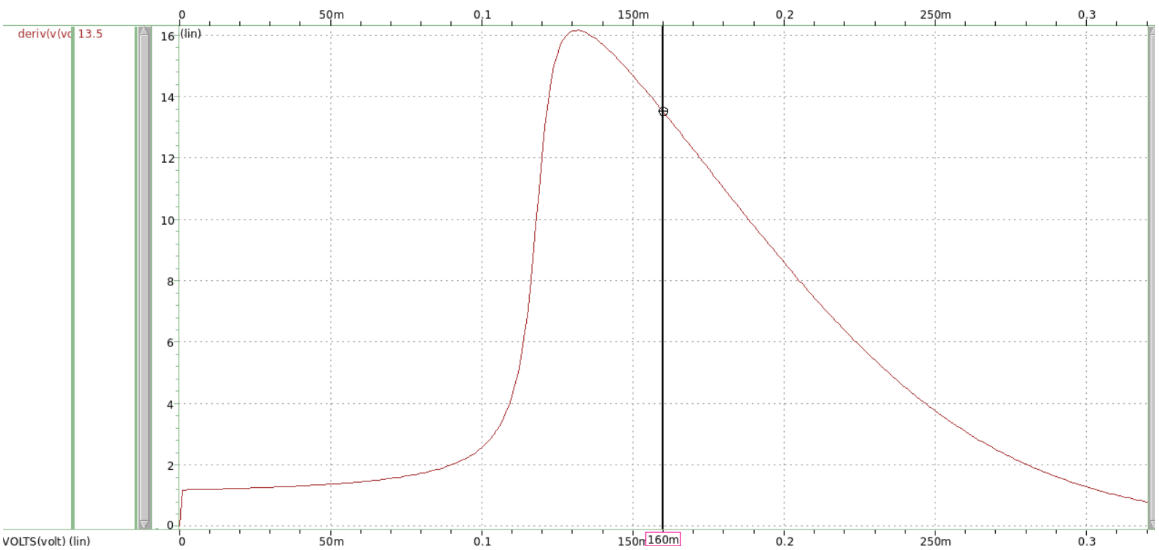


Small signal Model of Common Source Amplifier

- Part 2
  - DC sweep
    We can see when Vin is 0.16V, $Vout$is 0.899V(error: 0.11%) and the derivative of $Vout$is 13.5.



X axis: Vin(V)-Y axis: $Vout$ (V)



X axis: Vin(V)-Y axis: derivative of $Vout$ (V)

- TF analysis

  The following table is the TF analysis result, we can see Av is 13.4464 when Vin is 0.16V. Comparing the result of DC sweep and TF analysis, we can see the result of two analyses are basically the same.

Vin(V)	Rin(Ω)	Rout(Ω)	Av(V/V)
155.0000m	5.1964k	61.9412k	14.0483
156.0000m	5.2408k	62.0637k	13.9293
157.0000m	5.2862k	62.1844k	13.8095
158.0000m	5.3327k	62.3034k	13.6891
159.0000m	5.3803k	62.4209k	13.5680
160.0000m	5.4290k	62.5370k	13.4464
161.0000m	5.4787k	62.6518k	13.3242
162.0000m	5.5296k	62.7654k	13.2016
163.0000m	5.5817k	62.8779k	13.0786
164.0000m	5.6348k	62.9893k	12.9552
165.0000m	5.6892k	63.0998k	12.8314

TF Analysis

- Hand Calculation

```
 **info** dc convergence successful at Newton-Raphson method
1****** PrimeSim HSPICE -- R-2020.12-SP2 linux64 (May 24 2021 7074677) ******
 ******
 ** 110061217 hw2 part2

 ****** operating point information tnom=  25.000 temp=  25.000 ******
 ****** operating point status is all       simulation time is     0.
    node    =voltage      node    =voltage      node    =voltage

 +0:vb      = 600.0000m 0:vdd     =   1.8000  0:vin     = 160.0000m
 +0:vout    = 899.3692m


 **** voltage sources

 subckt
 element  0:vin      0:vb       0:vdd
  volts    160.0000m  600.0000m    1.8000
  current   12.3374u    0.       -12.3374u
  power     -1.9740u    0.        22.2073u

     total voltage source power dissipation=   20.2333u       watts


 **** resistors

 subckt
 element  0:rd
  r value   73.0000k
  v drop   900.6308m
  current   12.3374u
  power     11.1115u
```

Operating point

```
**** mosfets


subckt
element  0:mn
model    0:n_18.1
region   Saturation
 id         12.3374u
 ibs       -1.965e-21
 ibd       -679.5079a
 vgs        440.0000m
 vds        739.3692m
 vbs          0.
 vth        383.9824m
 vdsat       90.5847m
 vod         56.0176m
 beta         3.7299m
 gam eff    507.4460m
 gm         212.7323u
 gds          2.2920u
 gmb         43.5106u
 cdtot       15.8434f
 cgtot       76.5866f
 cstot       84.6477f
 cbtot       44.7636f
 cgs         64.4158f
 cgd          4.2951f
```

NMOS

Working item	SPEC	Your Design	Hand Calculation
V_{DD}	1.8V	1.8V	1.8V
$V_{in,DC}$	0.16V	0.16V	0.16V
$V_{out,DC}$	0.9V	899.3692mV	899.3698mV
$Gain\ A_V$	>10(V/V)	13.4464(V/V)	13.448 (V/V)
R_D	<90k Ω	73k Ω	
I_D	<30uA	13.3374uA	
V_b		0.6V	
$M_b\ W/L$		12um/1um	

COMMON GATE PERFORMANCE TABLE

$$V_{out} = V_{DD} - I_d * R_D = 1.8 - 12.3374uA * 73k\Omega = 0.8993698V$$

$$Error = \frac{899.3692 - 899.3698}{899.3698} * 100\% = -6.67 * 10^\wedge(-4)\%$$

$$A_V = \frac{\partial Vout}{\partial Vin} = g_m R_D = 212.7323u\left(\frac{1}{\Omega}\right) * 73k\Omega = 15.5294(V/V)$$

$$Error = \frac{13.4464 - 15.5294}{15.5294} * 100\% = -13.41\%$$

$$R_{out} = (R_D \parallel \frac{1}{g_{ds}}) = (73K \parallel 436300.1745) = 62536.622\Omega$$

$$\text{Error} = \frac{(62537 - 62536.622)}{62536.622} * 100\% = 2.5 * 10^\wedge(-8)\%$$

$$R_{in} = = \frac{R_D + \frac{1}{g_{ds}}}{g_m ro + 1} = \frac{73000 + 436300}{212.7323u * 436300 + 1} = 5428.763\Omega$$

$$\text{Error} = \frac{(5429 - 5428.763)}{5428.763} * 100\% = 0.00435\%$$

- Discussion
  - How I design the amplifier?
    First, I choose L = 1um, since it should not be too small, or it will have short-channel effect. Also, I don't want L to be too large, or it will waste the space of circuit. Second, I use a random W, L and R_D value to run hspice, I can get beta value($\frac{beta}{W/L} = u_n C_{ox}$), and Vth value. Third, to let NMOS operated in saturation region, $V_b > V_{th} + V_{in} \approx 0.56V$, I use $V_b = 0.6V$ to bias the NMOS. Third, since $I_D = \frac{1}{2}\mu_n C_{ox}\frac{\mathrm{W}}{\mathrm{L}}(V_{in} - V_{th})^2 = \frac{1}{2}400\frac{\mathrm{W}}{\mathrm{L}}(0.04)^2 < 30uA$, and the required gain is large, so I use W/L = 12. Then, I use random R_D to run hspice, and use $Id = \frac{1}{2} * \frac{u_n C_{ox} W}{L} * (V_{gs} - V_{th})$ and $V_{out} = V_{DD} - I_d * R_D$ to find correct R_D. Finally, use new R_D to run hspice again, since I don't consider r_o, there will be some error, so I adjust it a little bit. The final R_D is 73k Ω.
    *I connect the source and body here since I don't want to have body effect.
    *I choose $V_b = 0.6v$ since I don't want NMOS enter subthreshold region. Also, leg room can be lower(more space to operate).

  - Why the hand calculation of A_V is different from the result?

    I use the following formula to calculate the result:

$$V_{out} = V_{DD} - I_d * R_D = V_{DD} - \frac{1}{2} * u_n C_{ox} \frac{W}{L} * (V_b - V_{in} - V_{th})^2 * R_D$$

$$\rightarrow \frac{\partial Vout}{\partial Vin} = -u_n C_{ox} \frac{W}{L} * (V_b - V_{in} - V_{th}) * R_D$$

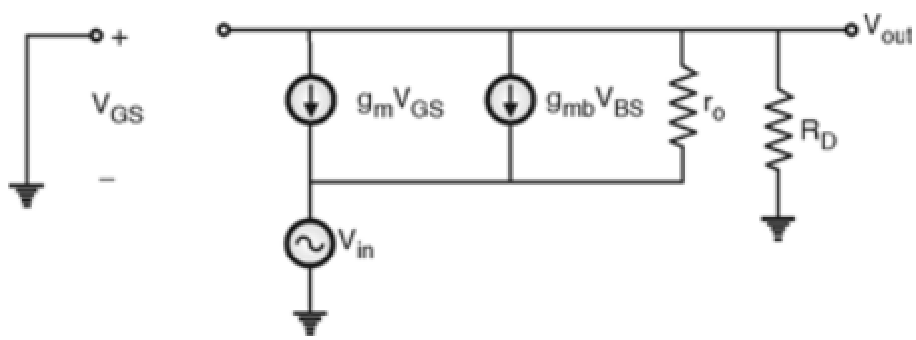
$$And, when\ in\ saturation, g_m = u_n C_{ox} \frac{W}{L}(V_b - Vin - Vth)$$

$$So, A_V = \frac{\partial Vout}{\partial Vin} = g_m R_D = 212.7323u \left(\frac{1}{\Omega}\right) * 73k\Omega = 15.5294$$

However, by using small signal analysis, we should consider channel-length modulation effect and Rin (neglect g_{mb} here, since I connect body and source so V_{bs} is 0 here). By the following small signal module:

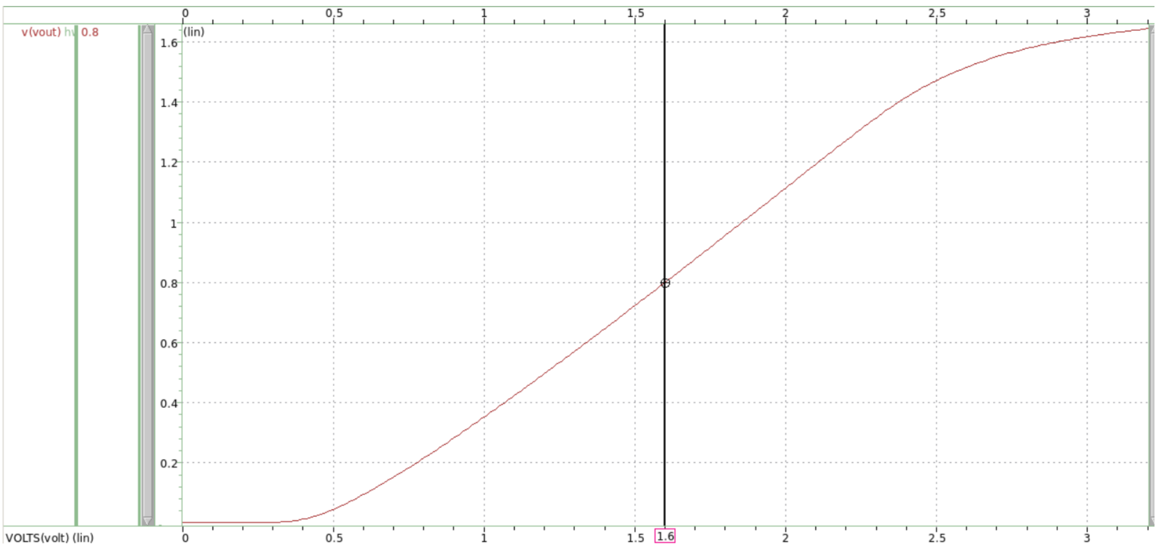
$$A_V = \frac{V_{out}}{V_{in}} = \frac{1+g_m r_o}{R_{in}(1+g_m r_o)} * R_D = 13.448(\text{V/V})$$

$$Error\ can\ be\ reduce\ to\ \frac{(13.4464 - 13.448)}{13.448} * 100\% = -6.5 * 10\text{^}(-5)\%$$

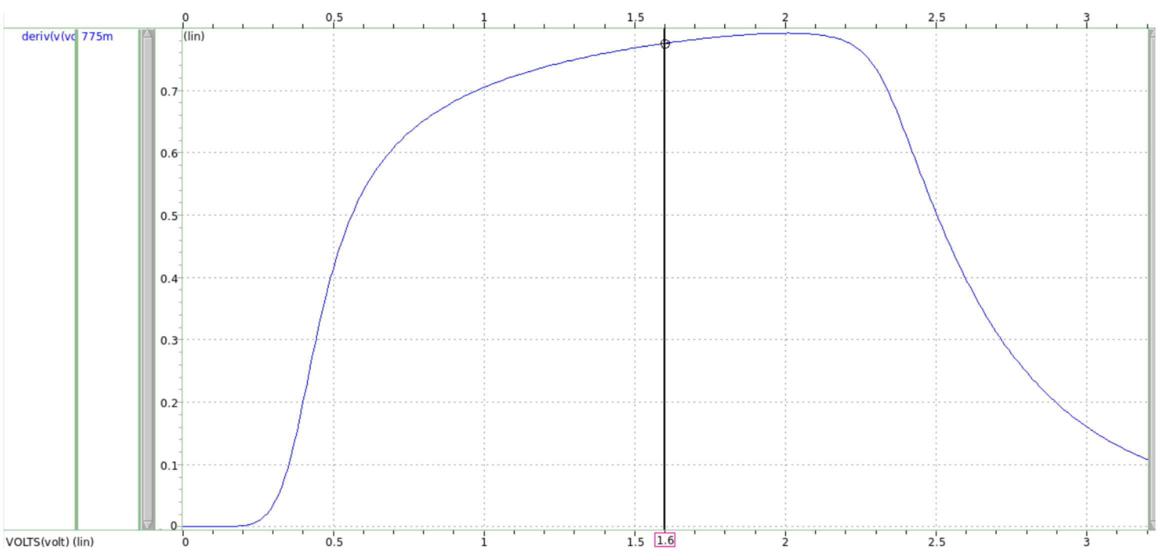


Small signal Model of Common Gate Amplifier

- Part 3
    - DC sweep
      We can see when Vin is 1.6V, $Vout$is 0.8V(error: almost 0%) and the derivative of $Vout$is 0.775.



X axis: Vin(V)-Y axis: $Vout$ (V)



X axis: Vin(V)-Y axis: derivative of $Vout$ (V)

    - TF analysis
      The following table is the TF analysis result, we can see Av is 0.7757681 when Vin is 1.6V. Comparing the result of DC sweep and TF analysis, we can see the result of two analyses are basically the same.

Vin(V)	Rin(Ω)	Rout(Ω)	Av(V/V)
1.5500	1.000e+20	8.0436k	772.2784m
1.5600	1.000e+20	8.0144k	772.9999m
1.5700	1.000e+20	7.9855k	773.7096m
1.5800	1.000e+20	7.9570k	774.4074m
1.5900	1.000e+20	7.9289k	775.0936m
1.6000	1.000e+20	7.9011k	775.7681m
1.6100	1.000e+20	7.8737k	776.4311m
1.6200	1.000e+20	7.8466k	777.0826m
1.6300	1.000e+20	7.8198k	777.7226m
1.6400	1.000e+20	7.7934k	778.3513m
1.6500	1.000e+20	7.7673k	778.9685m

TF Analysis

- Hand Calculation

```
 **info** dc convergence successful at Newton-Raphson method
1****** PrimeSim HSPICE -- R-2020.12-SP2 linux64 (May 24 2021 7074677) ******
 ******
 ** 110061217 hw2 part3

 ****** operating point information tnom=  25.000 temp=  25.000 ******
 ****** operating point status is all       simulation time is     0.
    node    =voltage      node    =voltage      node    =voltage

 +0:vdd     =   1.8000  0:vin     =   1.6000  0:vout    = 799.8416m


 **** voltage sources

 subckt
 element  0:vin      0:vdd
  volts      1.6000     1.8000
  current    0.       -21.6173u
  power      0.        38.9112u

     total voltage source power dissipation=   38.9112u       watts


 **** resistors

 subckt
 element  0:rs
  r value   37.0000k
  v drop   799.8416m
  current   21.6173u
  power     17.2905u
```

Operating point

```
**** mosfets

subckt
element  0:mn
model    0:n_18.1
region   Saturation
 id        21.6173u
 ibs      -6.444e-21
 ibd      -143.3363a
 vgs       800.1584m
 vds         1.0002
 vbs         0.
 vth       396.9768m
 vdsat     334.1528m
 vod       403.1816m
 beta      308.2048u
 gam eff   507.4472m
 gm         98.2088u
 gds         1.3530u
 gmb        18.4990u
 cdtot       1.3716f
 cgtot       6.8796f
 cstot       7.8579f
 cbtot       3.8176f
 cgs         6.0601f
 cgd       355.4636a
```

NMOS

Working item	SPEC	Your Design	Hand Calculation
V_{DD}	1.8V	1.8V	1.8V
$V_{in,DC}$	1.6V	1.6V	1.6V
$V_{out,DC}$	0.8V	799.8416mV	799.8401mV
$Gain\ A_V$	>0.75(V/V)	775.7681m(V/V)	784.1909m(V/V)
R_s	<90k Ω	37k Ω	
I_D	<30uA	13.3374uA	
$M_b\ W/L$		1um/1um	

SOURCE FOLLOWER PERFORMANCE TABLE

$$V_{out} = I_d * R_s \ = \ 21.6173uA * 37k\Omega = 0.7998401V$$

$$\text{Error} = \frac{(799.8416 - 799.8401)}{799.8401} * \ 100\% \ = \ 1.8753 * 10\text{^}(-4)\%$$

$$A_V = \frac{\partial Vout}{\partial Vin} = \frac{g_m R_S}{1 + g_m R_S} = \frac{37K\Omega}{1 + 98.2088u * 37K\Omega} = 0.7984935(V/V)$$

$$\text{Error} = \frac{(799.8416 - 798.4935)}{798.4935} * \ 100\% \ = \ 0.16\%$$

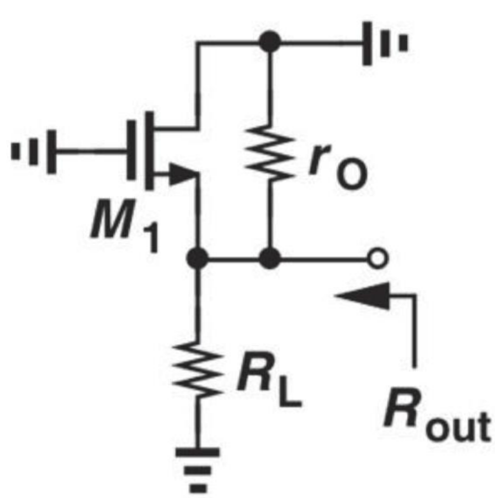
$$R_{out} = \frac{1}{g_m} || R_s = \frac{1}{98.2088u + \frac{1}{37\text{k}}} = 8386.741\Omega$$

$$\text{Error} = \frac{(7901 - 8386.741)}{8386.741} * 100\% = -6.1384\%$$

- Discussion
  - How I design the amplifier?
    First, I choose L = 1um, since it should not be too small, or it will have short-channel effect. Also, I don't want L to be too large, or it will waste the space of circuit. Second, I use a random W, L and R_D value to run hspice, I can get beta value($\frac{beta}{W/L} = u_n C_{ox}$), and Vth value. Third, since $I_D = \frac{1}{2}\mu_n C_{ox}\frac{\mathrm{W}}{\mathrm{L}}(V_{in} - V_{th})^2 < 30uA$, and the required gain is not large, so I use W/L = 1. Then, I use random R_D to run hspice, and use $Id = \frac{1}{2} * \frac{u_n C_{ox} W}{L} * (V_{gs} - V_{th})$ and $V_{out} = I_d * R_s$ to find correct R_s. Finally, use new R_s to run hspice again, since I don't consider r_o, there will be some error, so I adjust it a little bit. The final R_D is 37k Ω.
    *I connect the body and source here since I don't want to have body effect.
  - Why the hand calculation of R_{out} is different from the result?
    We should also consider R_s in the circuit(channel length modulation), so by the following circuit which is in the course materials:

$$R_{out} = \frac{1}{g_m}||\, r_o\, ||R_s = \frac{1}{\frac{1}{\frac{1}{98.2088u}} + \frac{1}{\frac{1}{1.3530u}} + \frac{1}{37000}} = 7899.4\Omega$$

$$Error\ can\ be\ reduce\ to \frac{(7901 - 7899.4)}{7899.4} * 100\% = 0.0205\%$$



Source follower output impedance