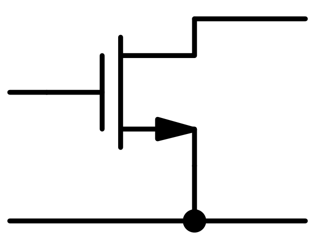
The "Atoms" of Analog Circuit Design

C. Talarico
Gonzaga University

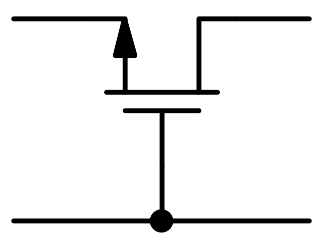
Elementary Amplifier Configurations

One-Transistor Stages



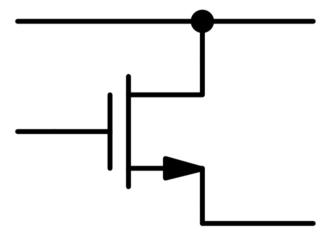
Common Source

Transconductance Stage



Common Gate

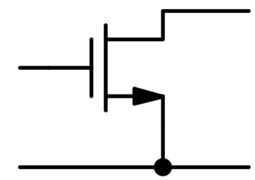
Current Buffer



Common Drain

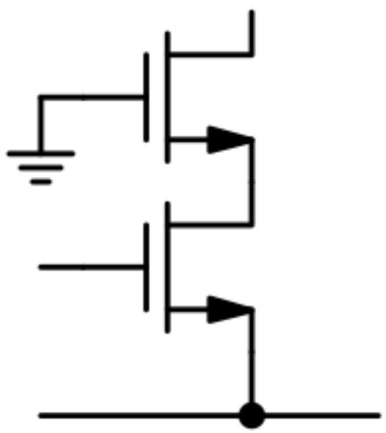
Voltage Buffer

Common Source Stage

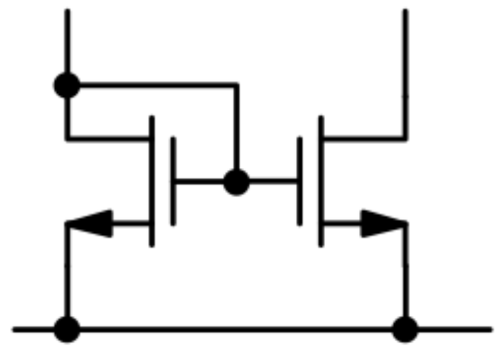


- A common source stage is sufficient for building a simple amplifier.
  - How about the other two possible single-transistor configurations?
- We'll find that common gate and common drain stages can be incorporated as valuable add-ons, for building "better" amplifiers
- Interestingly, many analog circuits can be decomposed into a combination of the above three fundamental building blocks

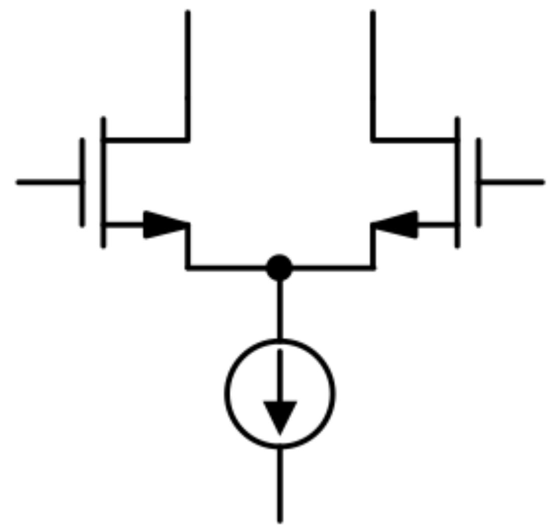
Widely Used Two-Transistor Stages



Cascode Stage



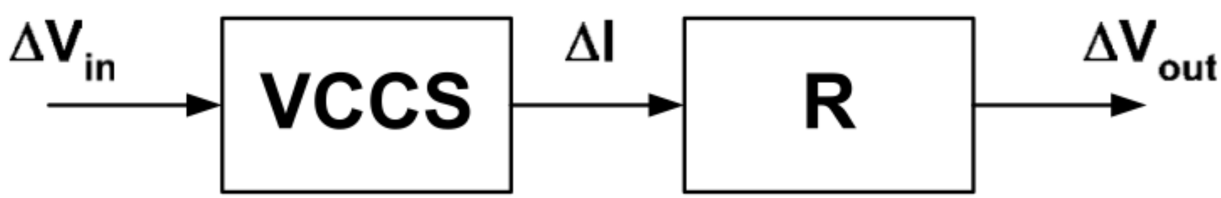
Current Mirror



Differential Pair

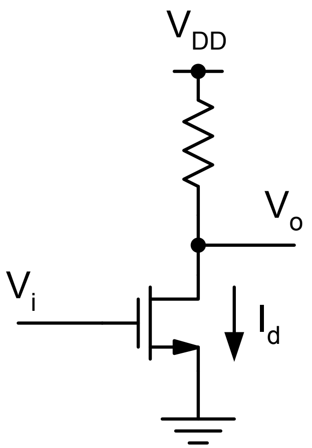
Let's Build Our First Amplifier (CS Amplifier)

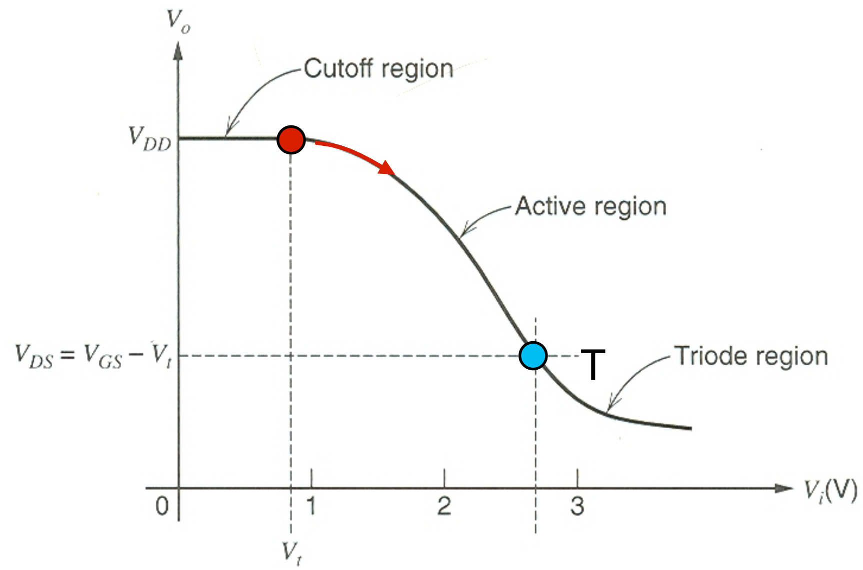
- One way to amplify
  - Convert input voltage to current using voltage controlled current source (VCCS)
  - Convert back to voltage using a resistor (R)
- "Voltage gain" = $\Delta V_{out}/\Delta V_{in}$
  - Product of the V-I and I-V conversion factors



Common Source Amplifier

- MOS device acts as VCCS



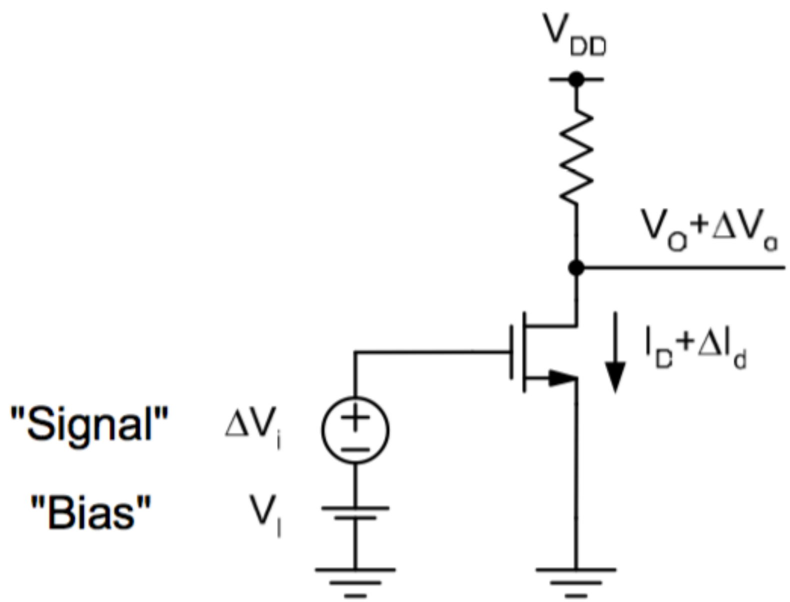


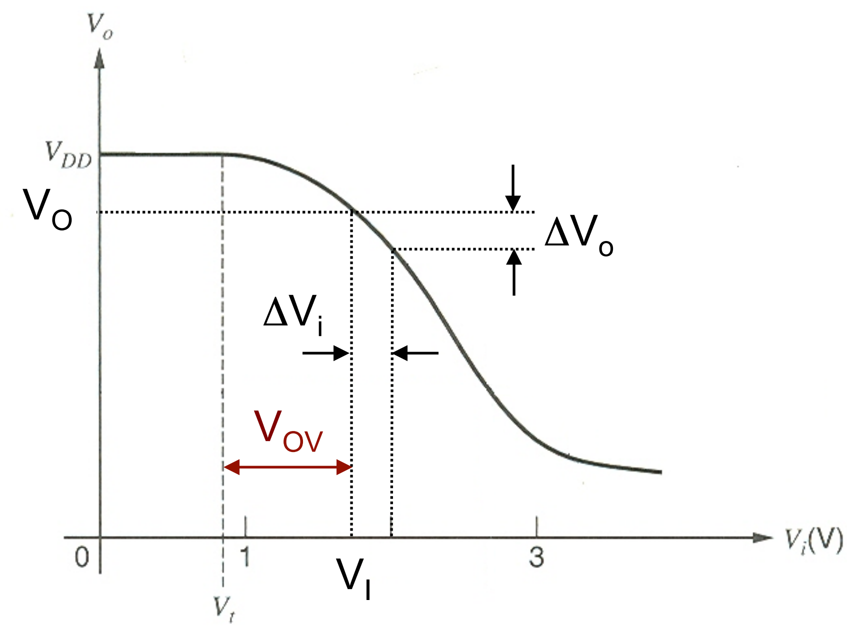
$$I_d = \frac{1}{2}\mu C_{ox}\frac{W}{L}\left(V_i - V_t\right)^2$$

$$V_o = V_{DD} - \frac{1}{2}\mu C_{ox}\frac{W}{L}\left(V_i - V_t\right)^2 \cdot R$$

Biasing

- Need some sort of "battery" that brings input voltage into useful operating region
- Define **V_{OV}**$=V_I-V_t$, "quiescent point gate overdrive" (no input signal applied)
  - with no input signal applied $V_{OV}=V_{GS}-V_t$





Relationship Between Incremental Voltages

- What is ΔV_o as a function of ΔV_i?

Note: $V_{gs}=V_i=(V_I+\Delta V_i)$

$$V_O + \Delta V_o = V_{DD} - \frac{1}{2}\mu C_{ox}\frac{W}{L}\left(V_{OV} + \Delta V_i\right)^2 \cdot R$$

$$\Delta V_o = -\frac{1}{2}\mu C_{ox}\frac{W}{L}R\cdot\left[\left(V_{OV} + \Delta V_i\right)^2 - V_{OV}^2\right]$$

$$= -\frac{1}{2}\mu C_{ox}\frac{W}{L}R\cdot\left[2V_{OV}\Delta V_i + \Delta V_i^2\right]$$

$$= -\frac{2I_D}{V_{OV}}\cdot R\cdot\Delta V_i\left[1 + \frac{\Delta V_i}{2V_{OV}}\right]$$

- As expected, this is a nonlinear relationship
- Nobody likes nonlinear equations; we need a simpler model
  - Fortunately, a (1st order) linear approximation to the above expression is sufficient for 90% of all analog circuit analysis

Small Signal Approximation (1)

$$\Delta V_o = -\frac{2I_D}{V_{OV}} \cdot R \cdot \Delta V_i \left[1 + \frac{\Delta V_i}{2V_{OV}}\right]$$

Note: ΔV_i is the max excursion of the signal V_i from V_I

- Assuming $\Delta V_i << 2V_{OV}$, we have

$$\Delta V_o \cong -\frac{2I_D}{V_{OV}} \cdot R \cdot \Delta V_i$$

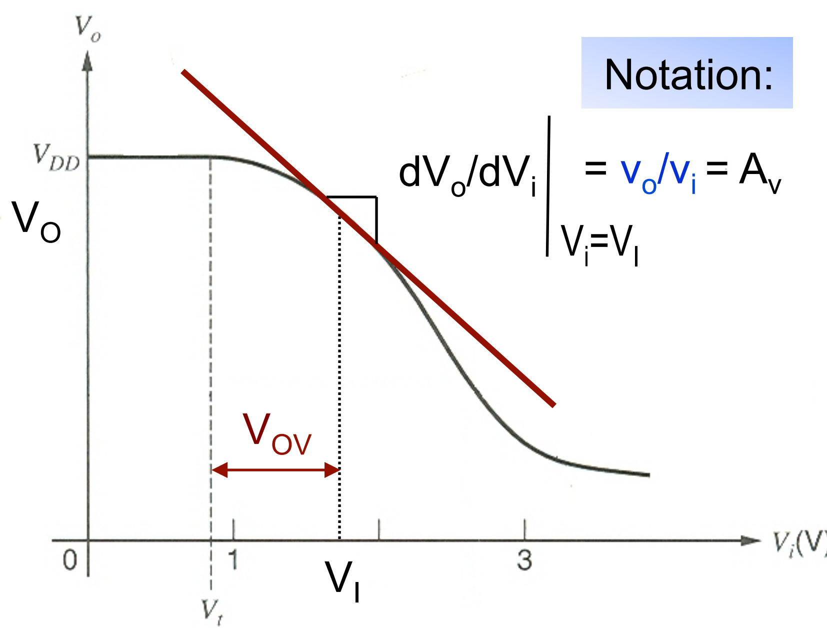
- If we further pretend that the input voltage increment is infinitely small, we can find this result directly by taking the derivative of the large signal transfer function at the "operating point" V_I

$$\left.\frac{dV_o}{dV_i}\right|_{V_i = V_I} = -\frac{2I_D}{V_{OV}} \cdot R = -\mu C_{ox} \frac{W}{L} V_{OV} \cdot R = A_v$$

small-signal voltage gain

Small Signal Approximation (2)

- Graphical illustration:



- The slope of the above tangent is the so called "small-signal voltage gain" of our amplifier (A_v)

Notation

Total quantity → V_o; Quiescent point value → V_O; Incremental change → v_o

$$V_o = V_O + \underbrace{v_o}_{\Delta V_o}$$

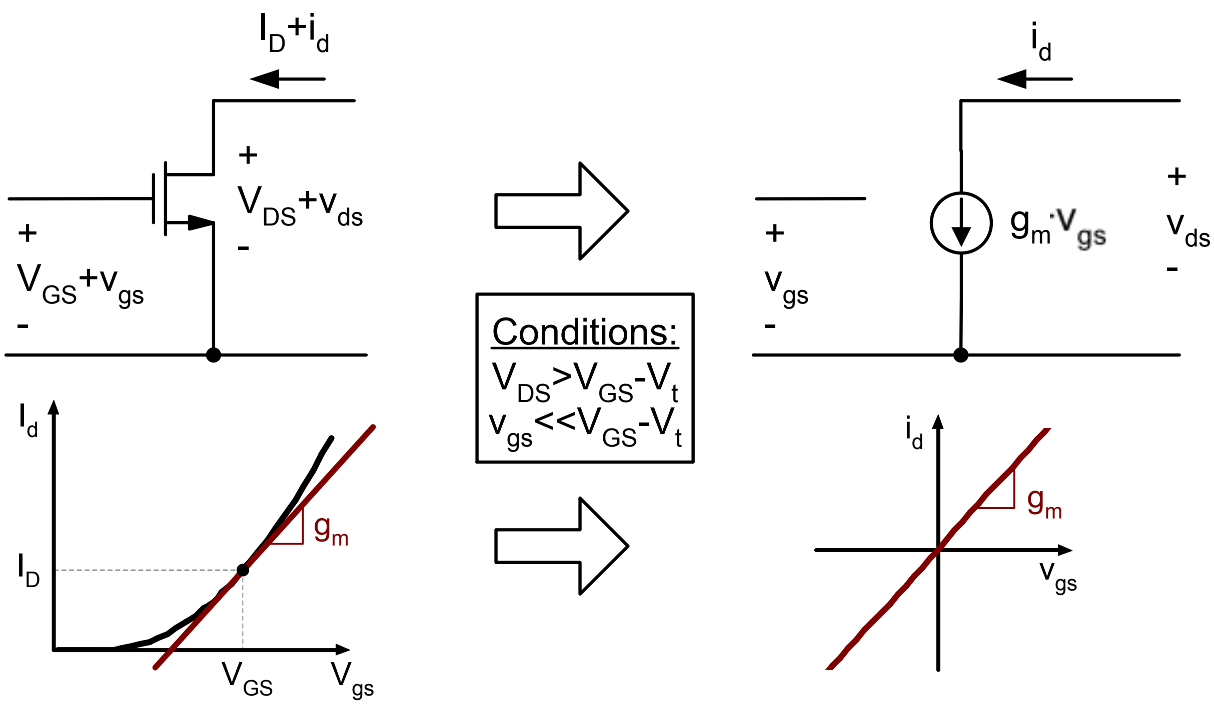
Alternatively:
(IEEE standard)

Total quantity → v_O; Quiescent point value → V_O; Incremental change → v_o

$$v_O = V_O + \underbrace{v_o}_{\Delta v_O}$$

Small Signal MOS Model

- Fortunately we don't have to repeat this analysis for every single circuit we build
- Instead, we derive a linearized circuit model for the MOS transistor and plug it into arbitrary circuits



Transconductance

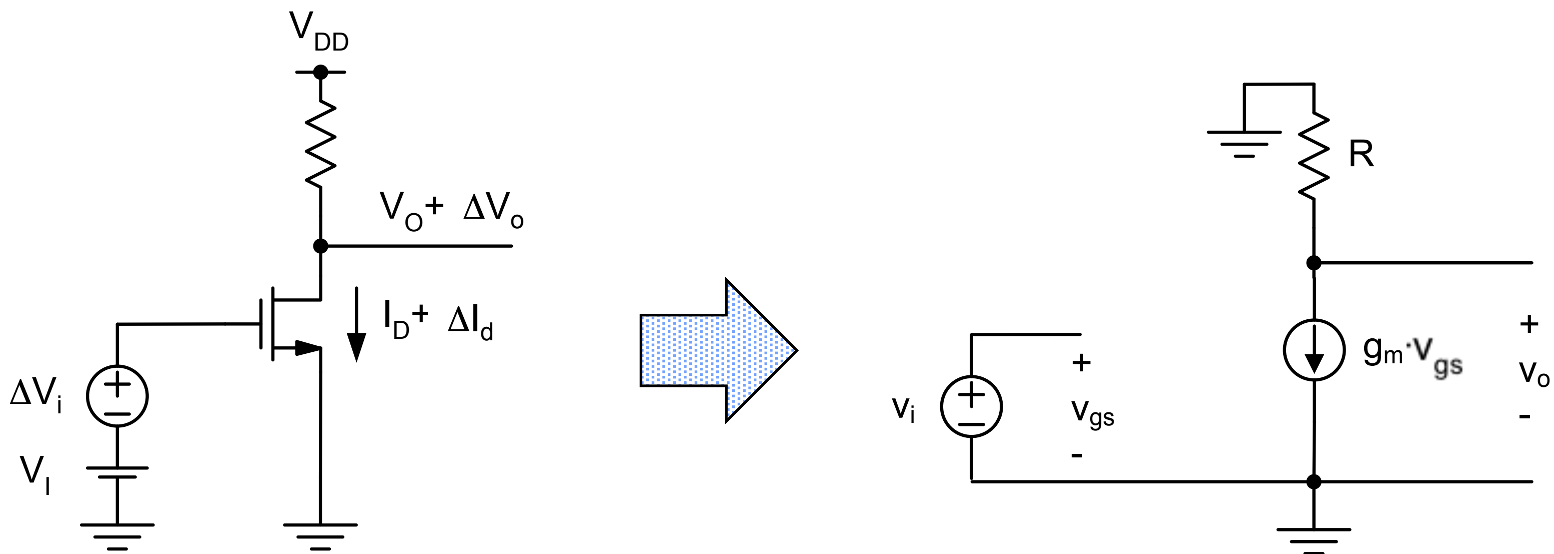
- The parameter that relates small signal gate voltage to drain current is called transconductance (g_m)
- The transconductance is found by differentiating the large signal I-V characteristic of the transistor at its operating point

$$I_d = \frac{1}{2}\mu C_{ox}\frac{W}{L}\left(V_{gs} - V_t\right)^2$$

$$g_m = \frac{i_d}{v_{gs}} = \left.\frac{dI_d}{dV_{gs}}\right|_{V_{gs}=V_{GS}} = \mu C_{ox}\frac{W}{L}\left(V_{GS} - V_t\right) = \mu C_{ox}\frac{W}{L}V_{OV}$$

$$\boxed{g_m = \frac{2I_D}{V_{OV}}}$$

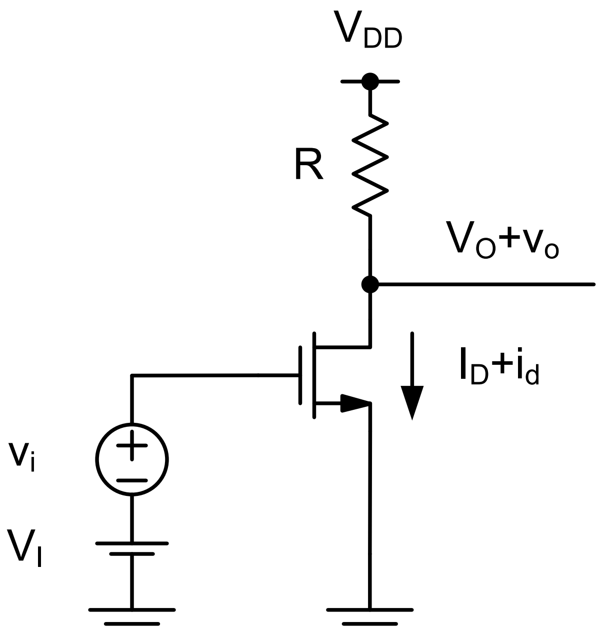
Small-Signal Equivalent of CS Amplifier



- Use large signal I-V law to compute operating point (I_D, V_O, g_m)
  - Make sure device operates in proper region; consider desired "signal swing"
- Now perform rest of calculations in "small-signal land"
  - Gain, bandwidth (more later), …

Example (1)

- Given: V_I=1.5V, W=20μm, L=1μm, R=5kΩ, V_{DD}=5V
- Assume the desired signal swing ΔV_i at the input is small enough for the transistor to operate in the same region at all time
- Technology parameters: μC_{ox} = 50μA/V², V_t=0.5V
- Calculate: I_D, V_O, g_m, A_v

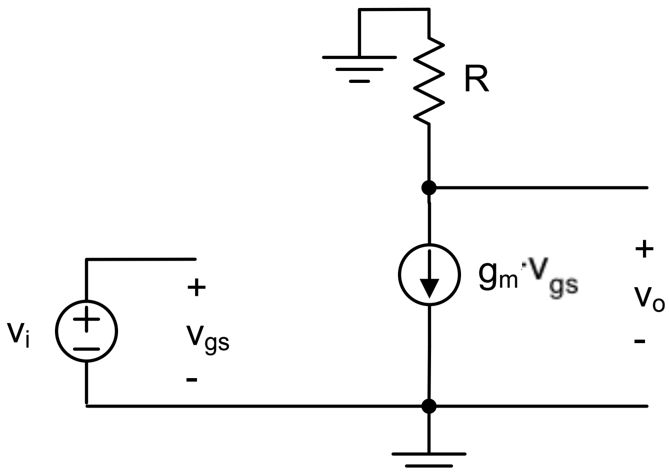


$$I_D = \frac{1}{2}\cdot 50\frac{\mu A}{V^2}\cdot\frac{20}{1}\cdot(1.5V - 0.5V)^2 = 500\mu A$$

$$V_O = 5V - 5k\Omega\cdot 500\mu A = 2.5V$$

$$\left.\begin{array}{l} V_{DS} = V_O = 2.5V \\ V_{GS} - V_t = V_I - V_t = 1V \end{array}\right\} \Rightarrow Saturation$$

Example (2)



$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \cdot 500\mu A}{1.5V - 0.5V} = 1mS$$

$$A_v = -g_m R = -1mS \cdot 5k\Omega = -5$$

Getting Started with HSpice

- The above circuit was easy to analyze
  - And it is unlikely that we made a mistake
- In general, we want to be able to compute circuit characteristics both manually and by using a circuit simulator
  - Both hand calculation and simulation is important; one does not "replace" the other
  - "Double book keeping is important in design and analysis to detect flaws in assumptions and understanding
- Let's see how we can duplicate this result using HSpice…

HSpice Input File (1)

```
* Common source amplifier
* Filename: one.sp
* C. Talarico, Fall 2014

*** device model
.model simple_nmos nmos kp=50u vto=0.5
*** useful options
.option post brief nomod

*** Supply voltage
vdd vdd 0  5

*** input voltage
vi  vi  0   dc  1.5         *** value for .op analysis
+           ac  0.1         *** amplitude for .ac analysis
+           sin 1.5 0.1 1k  *** sinewave for .tran: V_I=1.5V, v_i=0.1V, f=1kHz
```

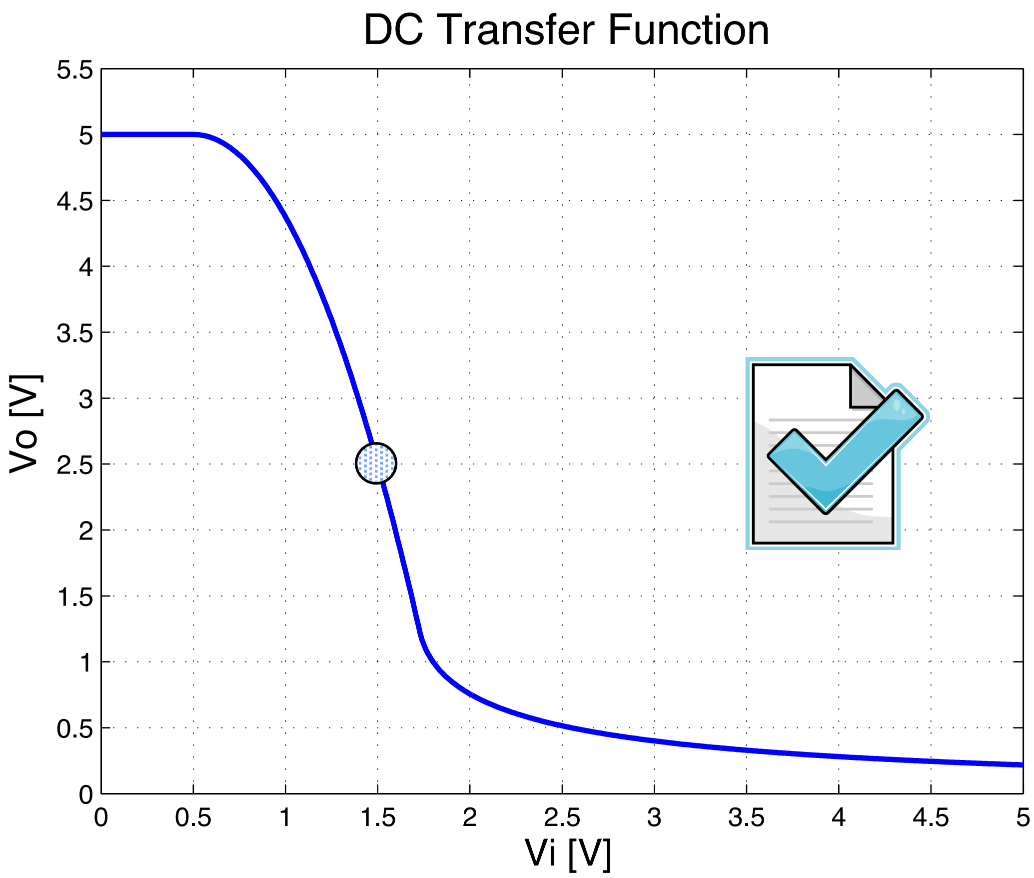
HSpice Input File (2)

```
*** Circuit
*** d   g   s   b
mn1 vo  vi  0   0   simple_nmos   w=20u  l=1u
R1  vdd vo  5k

*** calculate operating point
.op

*** large signal analysis (sweep Vi)
.dc vi 0 5 0.01

*** small signal analysis (sweep frequency)
.ac dec 10 100 1k

*** transient analysis (sweep time)
.tran 1u 5m
.end
```

.op Output

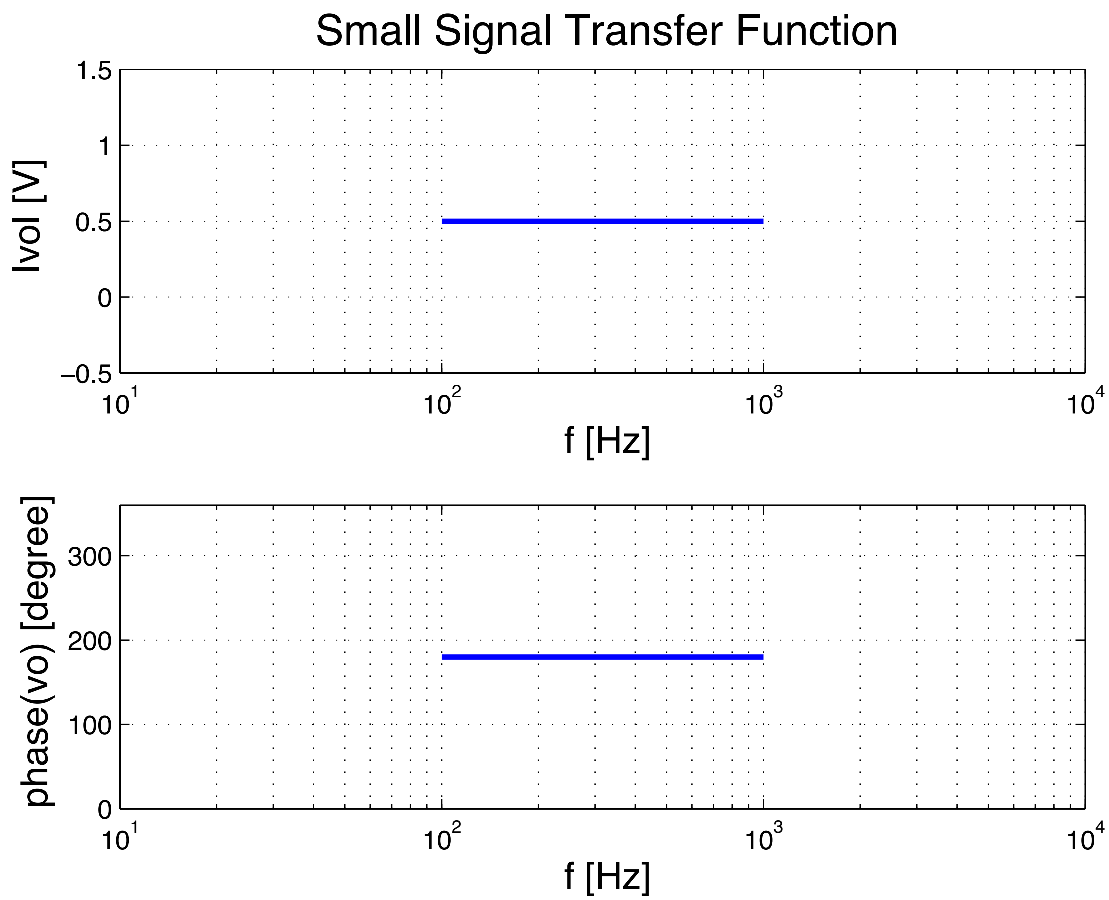
```
**** mosfets
element  0:mn1
 model    0:simple_nmos
 region     Saturati
  id        500.0000u
  vgs          1.5000
  vds          2.5000
  vbs          0.
  vth       500.0000m
  vdsat        1.0000
  vod          1.0000
  beta         1.0000m
  gam eff   527.6252m
  gm           1.0000m
  gds          0.
  …
```

.dc Output



DC Transfer Function
Vo [V]
Vi [V]
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

.ac Output

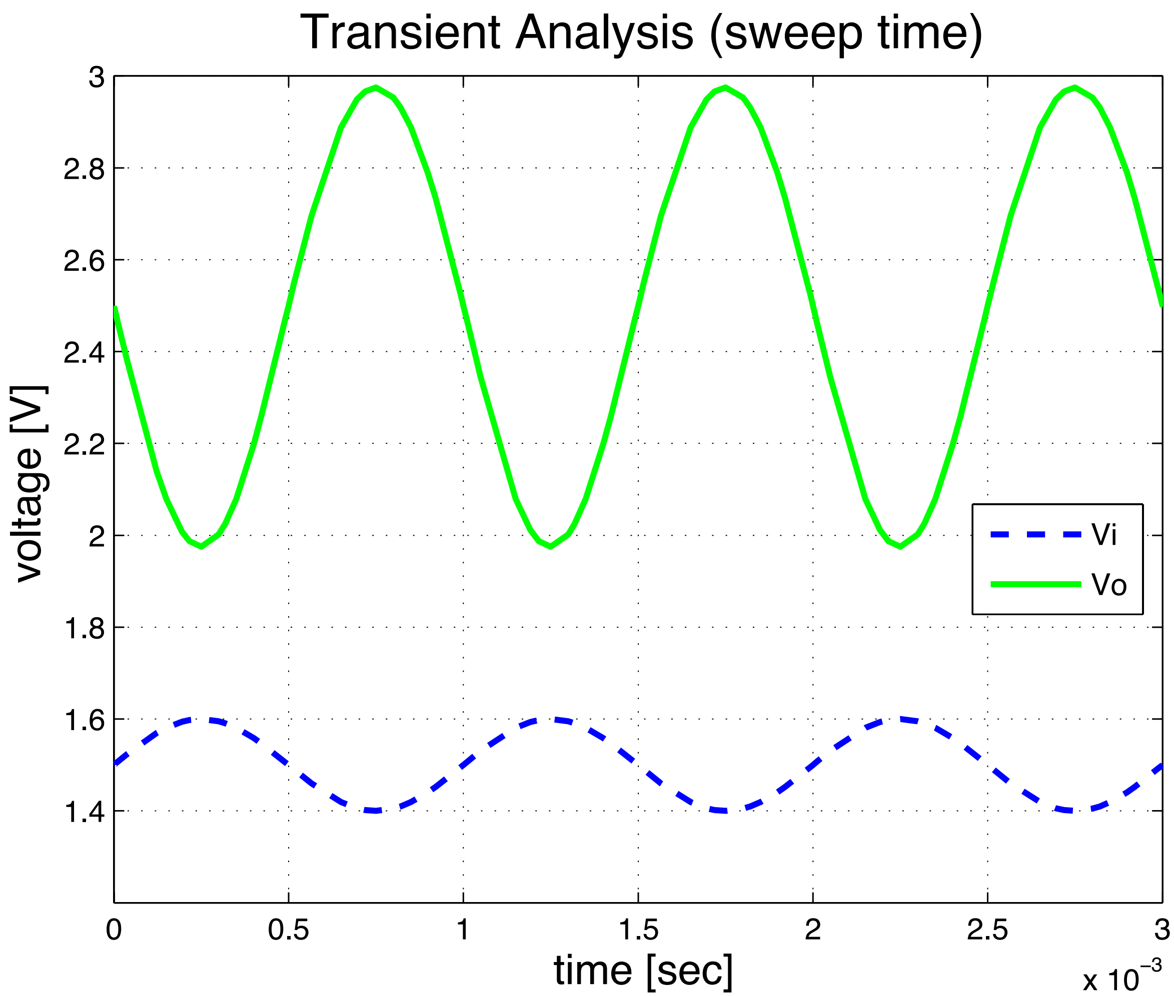


$A_v = v_o/v_i$

$= -0.5V/0.1V$

$= -5$

.tran Output



NOTE:
V_o is slightly above 2V and slightly below 3V.
The discrepancy with hand calculation is due to the fact that the MOS behavior is not linear (the small signal model is an approximation !)

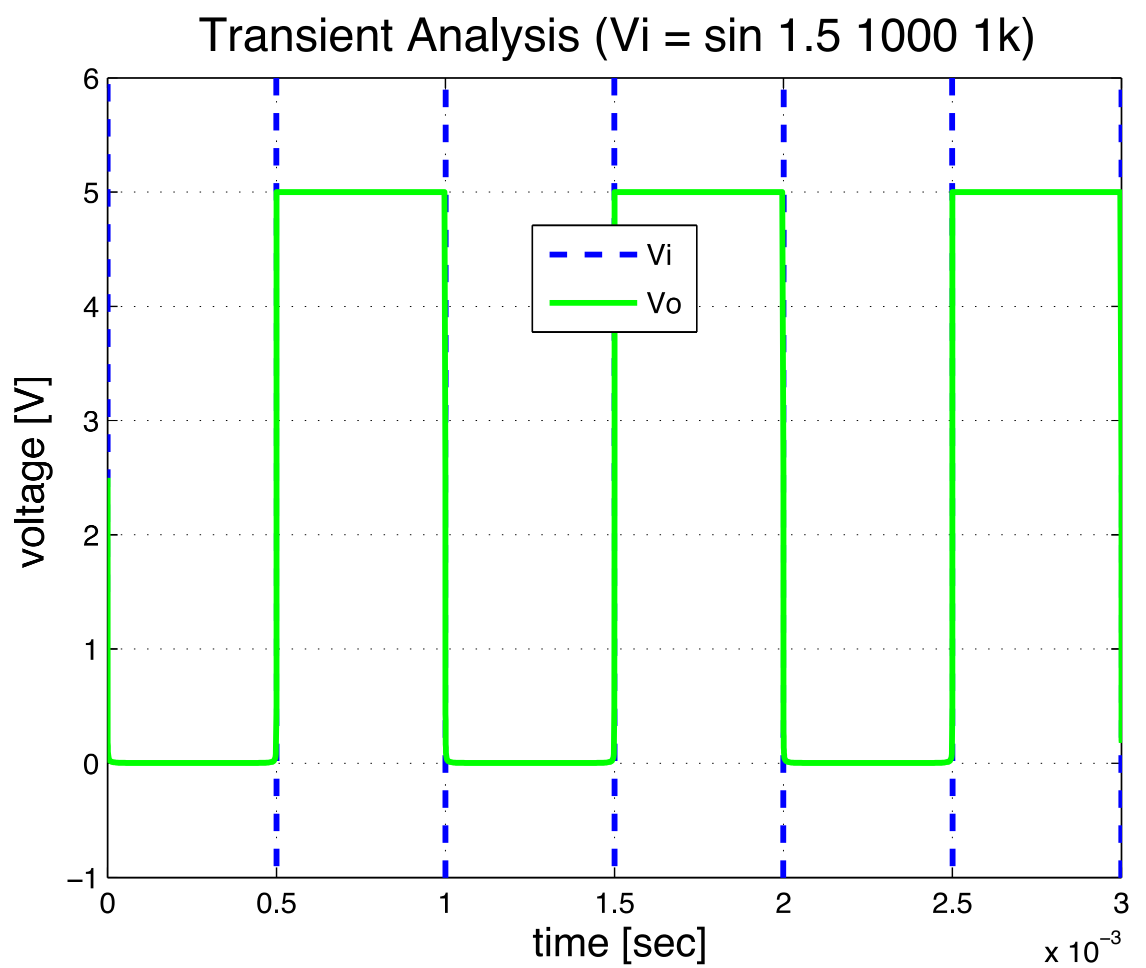
Another Run

- Now with the following stimulus

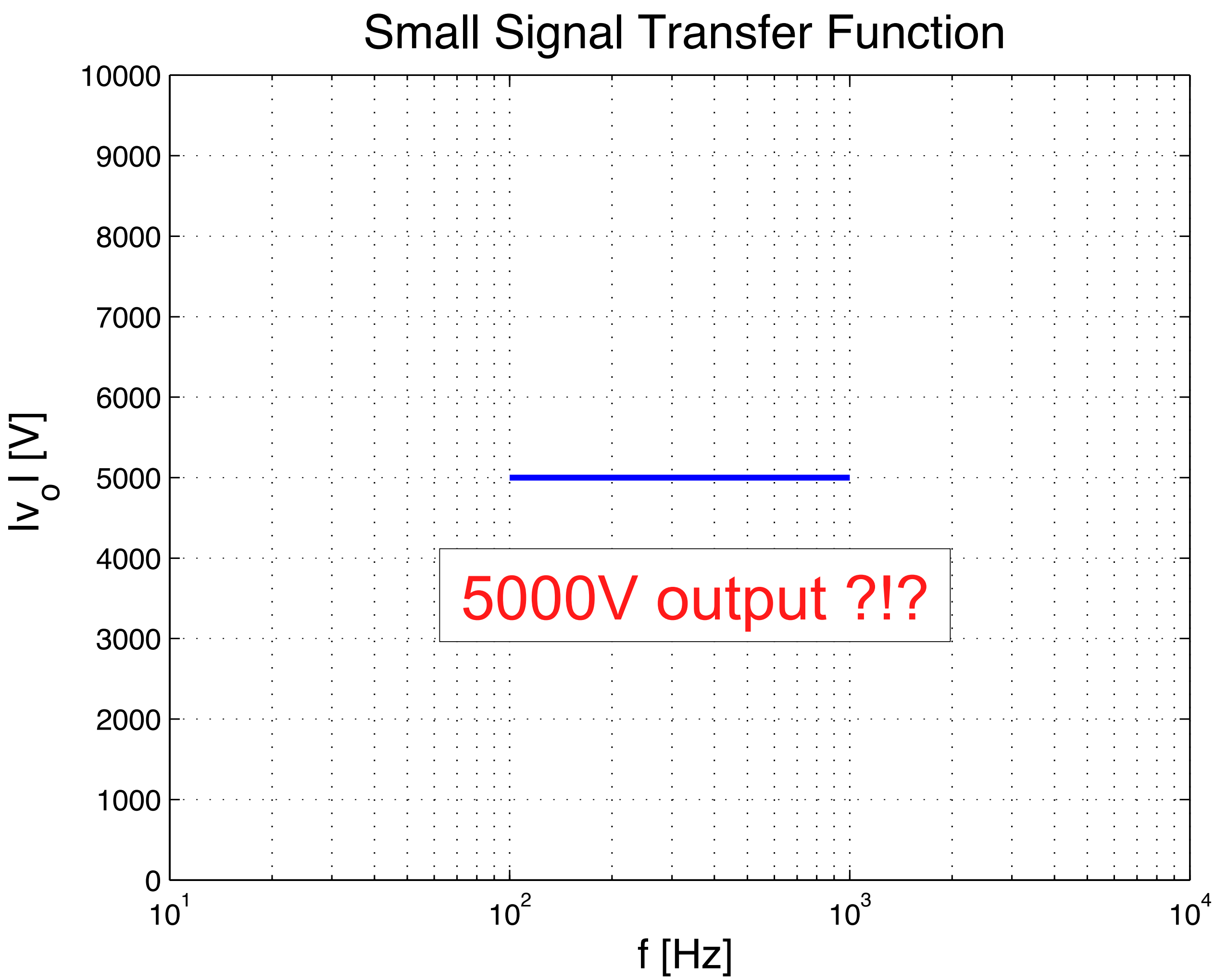
```
*** input voltage
vi  vi  0   dc  1.5  *** value for .op analysis
+           ac  1000  *** amplitude for .ac analysis
+           sin 1.5 1000 1k  *** sinewave for .tran: V_I=1.5V, v_i=1000V, f=1kHz
```

- 1000V input amplitude applied to the circuit!

.tran Output


Transient Analysis (Vi = sin 1.5 1000 1k)
voltage [V]
time [sec]
x 10^−3
Vi
Vo
6
5
4
3
2
1
0
−1
0
0.5
1
1.5
2
2.5
3

.ac Output



Small Signal Transfer Function
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
|v_o| [V]
10^1
10^2
10^3
10^4
f [Hz]
5000V output ?!?

Important to Remember

- Once a small-signal model of the circuit is constructed, all large signal information is lost
  - The small-signal (.ac) circuit transfer function is linear and extends from $-\infty$ to $+\infty$
  - Features such as finite voltage range, signal clipping, etc. are lost and completely meaningless in a small-signal analysis (or .ac simulation)
- The input amplitude in the .ac statement is irrelevant and can be set to any number (other than 0)
  - Best to use 1V, in which case the output amplitude corresponds to the circuit gain

HSPICE Deck (1)

```
* Common source amplifier
* filename: one.sp
* C. Talarico, Fall 2014
*** device model
.model simple_nmos nmos kp=50u vto=0.5
*** useful options
.option post brief nomod
*** supply voltage
vdd vdd 0  5
*** input voltage
vi  vi  0   dc  1.5         *** value for .op analysis
+           ac  0.1         *** amplitude for .ac analysis
+           sin 1.5 0.1 1k  *** sinewave for .tran: V_I=1.5V, v_i=0.1V, f=1kHz
*** circuit
*** d   g   s   b
mn1 vo  vi  0   0   simple_nmos   w=20u  l=1u
R1  vdd vo  5k
```

HSPICE Deck (2)

```
*** calculate operating point
.op
*** large signal analysis (sweep Vi)
.dc vi 0 5 0.01
*** small signal analysis (sweep frequency)
.ac dec 10 100 1k
*** transient analysis (sweep time)
.tran 1u 5m

.alter another_run
*** input voltage
vi  vi  0   dc  1.5  *** value for .op analysis
+           ac  1000  *** amplitude for .ac analysis
+           sin 1.5 1000 1k  *** sinewave for .tran: V_I=1.5V, v_i=1000V, f=1kHz
.end
```

MATLAB script

```
%
% one_plot.m
%
clear all; close all;
format short eng
addpath('/usr/local/MATLAB/personal/HspiceToolbox');
x = loadsig('./one.sw0');
lssig(x)
y = loadsig('./one.ac0');
lssig(y)
z = loadsig('./one.tr0');
lssig(z)


figure(1);
Vi = evalsig(x,'v_vi');
Vo = evalsig(x,'v_vo');
plot(Vi, Vo, 'linewidth',2, 'color', 'b', 'linestyle', '-');
grid on;
ylabel(' Vo [V]', 'Fontsize', 14);
xlabel(' Vi [V]', 'Fontsize', 14);
title('DC Transfer Function', 'Fontsize', 16);
ymax = 5.5;
ymin = 0;
ylim([ ymin ymax]);

figure(2);
subplot(2,1,1);
freq = evalsig(y,'HERTZ');
vo = evalsig(y,'v_vo');
mag = abs(vo);
phase = 180*unwrap(angle(vo))/pi;
semilogx(freq, mag,'linewidth',2, 'color', 'b', 'linestyle', '-');
grid on;
ylabel(' |v_o| [V]', 'Fontsize', 14);
xlabel(' f [Hz]', 'Fontsize', 14);
title('Small Signal Transfer Function', 'Fontsize', 16);
xmin = 1e1;
xmax = 1e4;
xlim([xmin xmax]);
subplot(2,1,2);
semilogx(freq, phase,'linewidth',2, 'color', 'b', 'linestyle', '-');
grid on;
ylabel(' phase(v_o) [degree]', 'Fontsize', 14);
xlabel(' f [Hz]', 'Fontsize', 14);
xmin = 1e1;
xmax = 1e4;
xlim([xmin xmax]);
ymax = 360;
ymin = 0;
ylim([ ymin ymax]);
```

```
figure(3);
time = evalsig(z,'TIME');
Vi = evalsig(z,'v_vi');
Vo = evalsig(z,'v_vo');
plot(time, Vi, 'linewidth',2, 'color', 'b', 'linestyle', '--');
grid on;
xlabel(' time [sec]', 'Fontsize', 14);
ylabel(' voltage [V]', 'Fontsize', 14);
title('Transient Analysis (sweep time)', 'Fontsize', 16);
xmin = 0;
xmax = 3e-3;
xlim([ xmin xmax]);
hold;
plot(time, Vo, 'linewidth',2, 'color', 'g', 'linestyle', '-');
legend('Vi','Vo','location', 'best');

% another run
z = loadsig('./one.tr1');
lssig(z)
figure(4);
time = evalsig(z,'TIME');
Vi = evalsig(z,'v_vi');
Vo = evalsig(z,'v_vo');
plot(time, Vi, 'linewidth',2, 'color', 'b', 'linestyle', '--');
grid on;
xlabel(' time [sec]', 'Fontsize', 14);
ylabel(' voltage [V]', 'Fontsize', 14);
title('Transient Analysis (Vi = sin 1.5 1000 1k)', 'Fontsize', 16);
xmin = 0;
xmax = 3e-3;
xlim([ xmin xmax]);
ymin = -1;
ymax = 6;
ylim([ ymin ymax]);
hold;
plot(time, Vo, 'linewidth',2, 'color', 'g', 'linestyle', '-');
legend('Vi','Vo','location', 'best');


figure(5);
y = loadsig('./one.ac1');
lssig(y)
freq = evalsig(y,'HERTZ');
vo = evalsig(y,'v_vo');
mag = abs(vo);
semilogx(freq, mag,'linewidth',2, 'color', 'b', 'linestyle', '-');
grid on;
ylabel(' |v_o| [V]', 'Fontsize', 14);
xlabel(' f [Hz]', 'Fontsize', 14);
title('Small Signal Transfer Function', 'Fontsize', 16);
xmin = 1e1;
xmax = 1e4;
xlim([xmin xmax]);
ymin = 0;
ymax = 10000;
ylim([ymin ymax]);
```