

# Lecture 21 - Multistage Amplifiers (I)

## MULTISTAGE AMPLIFIERS

November 22, 2005

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### Reading assignment:

Howe and Sodini, Ch. 9, §§9.1-9.3

## Key questions

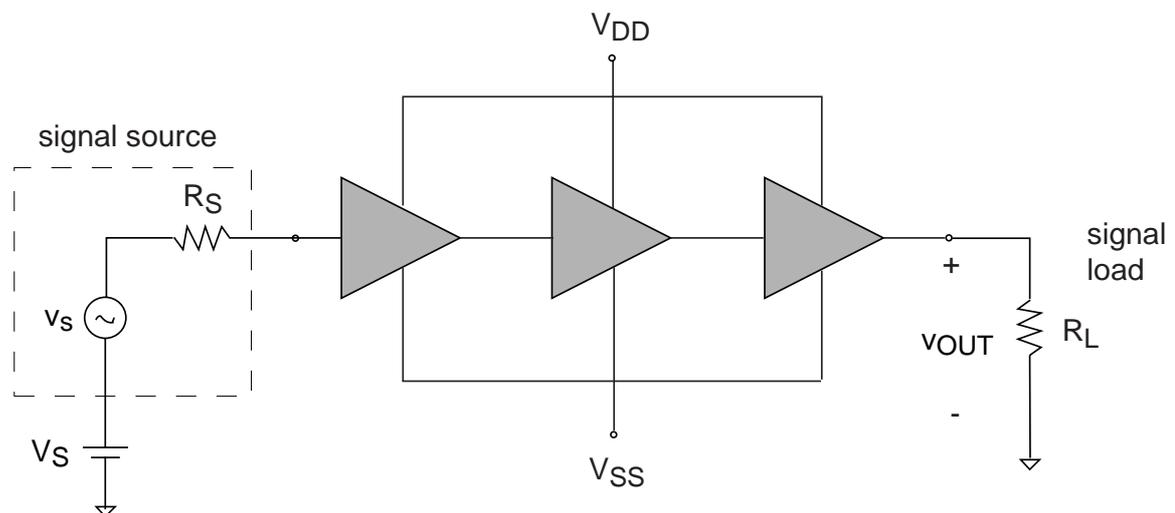
- How can one build a wide range of high-performance amplifiers using the single-transistor stages studied so far?
- What are the most important considerations when assembling multistage amplifiers:
  - regarding interstage loading?
  - regarding interstage biasing?

# 1. Introduction

Amplifier requirements are often demanding:

- must adapt to specific kinds of signal source and load,
- must deliver sufficient gain

Single-transistor amplifier stages are very limited in what they can accomplish  $\Rightarrow$  *multistage amplifier*.



Issues:

- What amplifying stages should be used and in what order?
- What devices should be used, BJT or MOSFET?
- How is biasing to be done?

□ Summary of single stage characteristics:

stage	$A_{vo}, G_{mo}, A_{io}$	$R_{in}$	$R_{out}$	key function
CS	$G_{mo} = g_m$	$\infty$	$r_o // r_{oc}$	transcond. amp.
CD	$A_{vo} \simeq \frac{g_m}{g_m + g_{mb}}$	$\infty$	$\frac{1}{g_m + g_{mb}}$	voltage buffer
CG	$A_{io} \simeq -1$	$\frac{1}{g_m + g_{mb}}$	$r_{oc} // [r_o(1 + g_m R_S)]$	current buffer
CE	$G_{mo} \simeq g_m$	$r_\pi$	$r_o // r_{oc}$	transcond. amp.
CC	$A_{vo} \simeq 1$	$r_\pi + \beta(r_o // r_{oc} // R_L)$	$\frac{1}{g_m} + \frac{R_S}{\beta}$	voltage buffer
CB	$A_{io} \simeq -1$	$\frac{1}{g_m}$	$r_{oc} // \{r_o[1 + g_m(r_\pi // R_S)]\}$	current buffer

□ Key differences between BJT's and MOSFETs:

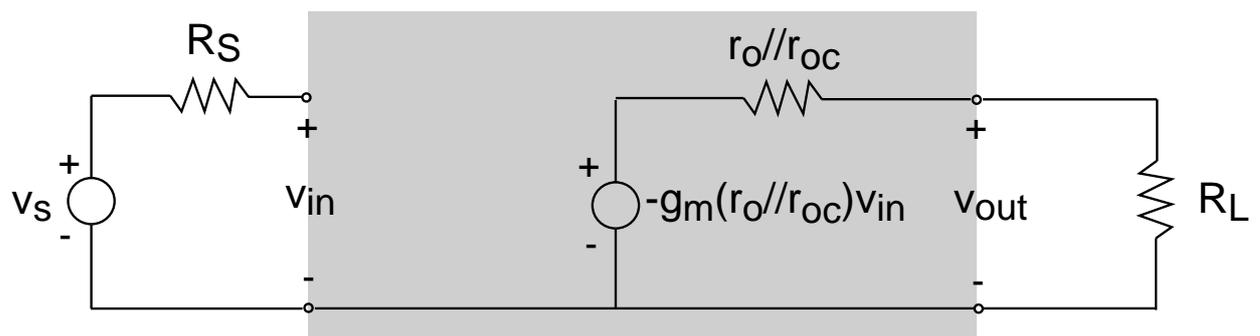
BJT	MOSFET
$I_B = \frac{I_C}{\beta}$	$I_G = 0$
$g_m = \frac{qI_C}{kT}$	$g_m = \sqrt{2\frac{W}{L}\mu C_{ox}I_D}$
$r_o = \frac{V_A}{I_C}$	$r_o = \frac{1}{\lambda I_D}$

## 2. CMOS multistage voltage amplifier

□ Goals:

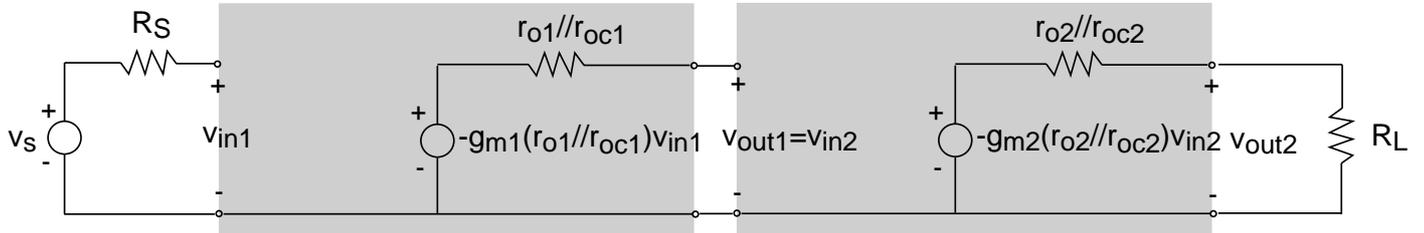
- high voltage gain
- high  $R_{in}$
- low  $R_{out}$

□ Good starting point: CS stage



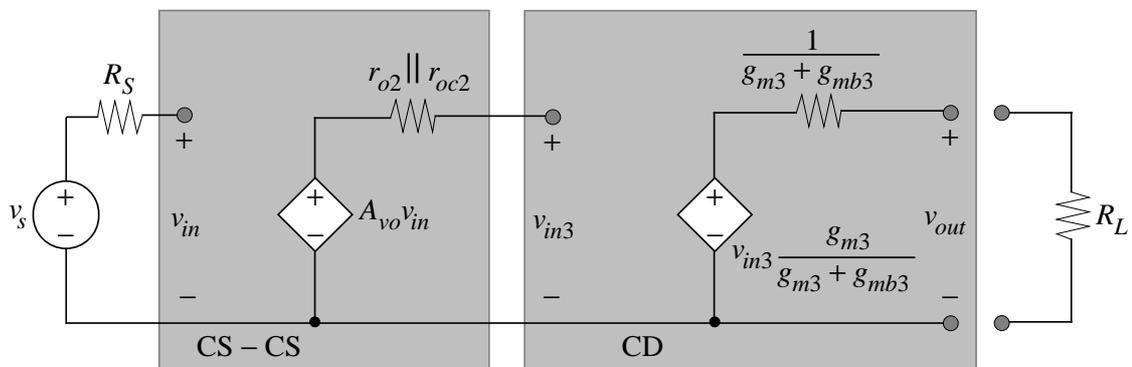
- $R_{in} = \infty$
- $A_{vo} = -g_m(r_o // r_{oc})$ , probably insufficient
- $R_{out} = r_o // r_{oc}$ , too high

□ Add second CS stage to get more gain:



- $R_{in} = \infty$
- $A_{vo} = g_{m1}(r_{o1} // r_{oc1})g_{m2}(r_{o2} // r_{oc2})$
- but  $R_{out} = r_{o2} // r_{oc2}$ , still high

□ Add CD stage at output:



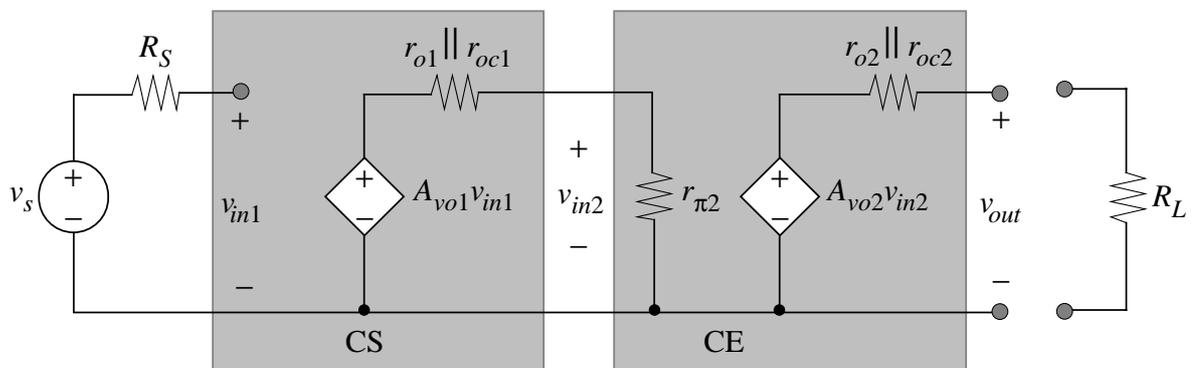
- $R_{in} = \infty$
- $A_{vo} = g_{m1}(r_{o1} // r_{oc1})g_{m2}(r_{o2} // r_{oc2}) \frac{g_{m3}}{g_{m3} + g_{mb3}}$ , still high
- $R_{out} = \frac{1}{g_{m3} + g_{mb3}}$ , now small

### 3. BiCMOS multistage voltage amplifier

□  $A_{vo}(CE) > A_{vo}(CS)$  because  $r_o(BJT) > r_o(MOSFET)$  and  $g_m(BJT) > g_m(MOSFET)$  but...

CS stage is best first stage, since  $R_{in} = \infty$ .

□ Add CE stage following CS stage?



Trouble is interstage loading degrades gain:

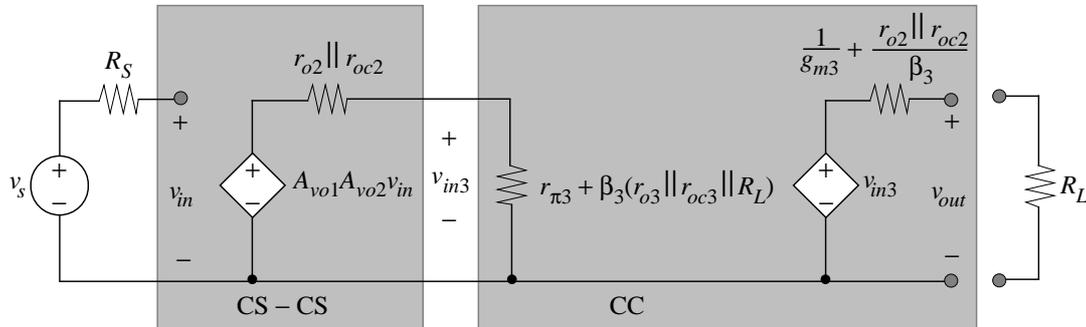
$$R_{out1} = r_{o1} \parallel r_{oc1} \gg R_{in2} = r_{\pi 2}$$

Voltage divider between stages:

$$\frac{R_{in2}}{R_{out1} + R_{in2}} = \frac{r_{\pi 2}}{r_{o1} \parallel r_{oc1} + r_{\pi 2}} \simeq \frac{r_{\pi 2}}{r_{o1} \parallel r_{oc1}} \ll 1$$

Additional gain provided by CE stage more than lost in interstage loading.

□ Use two CS stages, but add CC stage at output:



Interstage loading:

$$R_{out2} = r_{o2} \parallel r_{oc2}, \quad R_{in3} = r_{\pi 3} + \beta_3(r_{o3} \parallel r_{oc3} \parallel R_L)$$

Then, interstage loss:

$$\frac{R_{in3}}{R_{out2} + R_{in3}} = \frac{r_{\pi 3} + \beta_3(r_{o3} \parallel r_{oc3} \parallel R_L)}{r_{o2} \parallel r_{oc2} + r_{\pi 3} + \beta_3(r_{o3} \parallel r_{oc3} \parallel R_L)}$$

better than trying to use a CE stage, but still pretty bad.

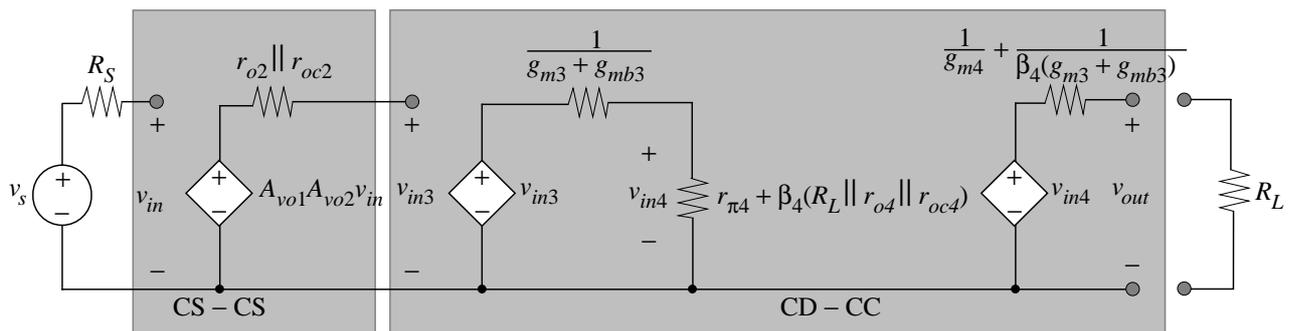
Benefit is that  $R_{out}$  has improved:

$$R_{out} = R_{out3} = \frac{1}{g_{m3}} + \frac{R_{out2}}{\beta_3} = \frac{1}{g_{m3}} + \frac{r_{o2} \parallel r_{oc2}}{\beta_3}$$

Since, in general,  $g_m(BJT) > g_m(MOSFET)$ ,  $R_{out}$  could be better than CD output stage if  $r_{o2} \parallel r_{oc2}$  is not too large. Otherwise, CD stage output is better.

□ Better voltage buffer: cascade CC and CD output stages.

What is best order? Since  $R_{in}(CD) = \infty$ , best to place CD first:



Interstage loading:

$$\frac{R_{in3}}{R_{out2} + R_{in3}} = 1$$

$$\frac{R_{in4}}{R_{out3} + R_{in4}} = \frac{r_{\pi 4} + \beta_4(r_{o4} // r_{oc4} // R_L)}{\frac{1}{g_{m3} + g_{mb3}} + r_{\pi 4} + \beta_4(r_{o4} // r_{oc4} // R_L)} \simeq 1$$

and excellent output resistance:

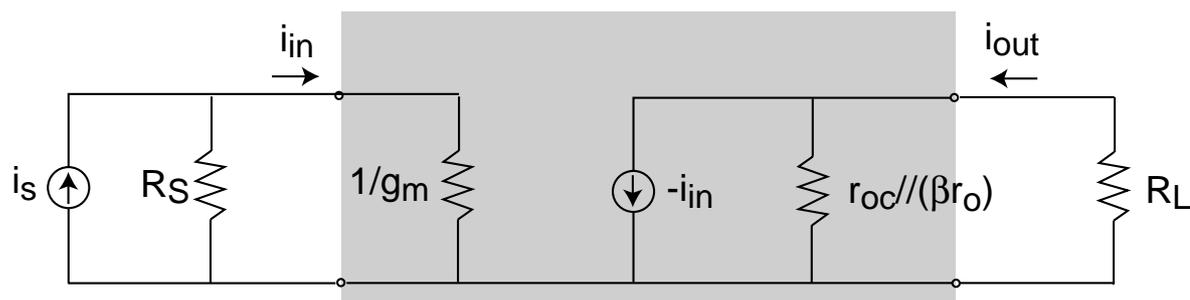
$$R_{out} = R_{out4} = \frac{1}{g_{m4}} + \frac{R_{out3}}{\beta_4} = \frac{1}{g_{m4}} + \frac{1}{\beta_4(g_{m3} + g_{mb3})}$$

## 4. BiCMOS current buffer

□ Goals:

- Unity current gain
- very low  $R_{in}$
- very high  $R_{out}$

Start with common-base stage:

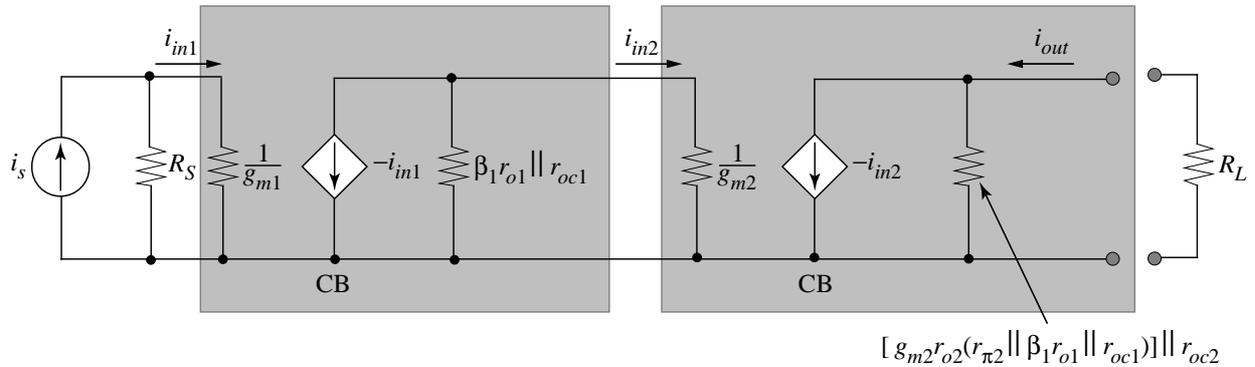


- $A_{io} = -1$
- $R_{in} = \frac{1}{g_m}$
- $R_{out} = r_{oc} // \{r_o [1 + g_m (r_\pi // R_S)]\}$

Note that if  $R_S$  is not too low,  $R_{out} \simeq r_{oc} // (\beta r_o)$ .

Can we further increase  $R_{out}$  by adding a second CB stage?

□ CB-CB current buffer:



Now

$$R_{out} = R_{out2} = r_{oc2} // \{r_{o2}[1 + g_{m2}(r_{\pi 2} // R_{out1})]\}$$

Plugging in  $R_{out1} \simeq r_{oc1} // (\beta_1 r_{o1})$ ,

$$R_{out} = r_{oc2} // \{r_{o2}[1 + g_{m2}(r_{\pi 2} // r_{oc1} // \beta_1 r_{o1})]\}$$

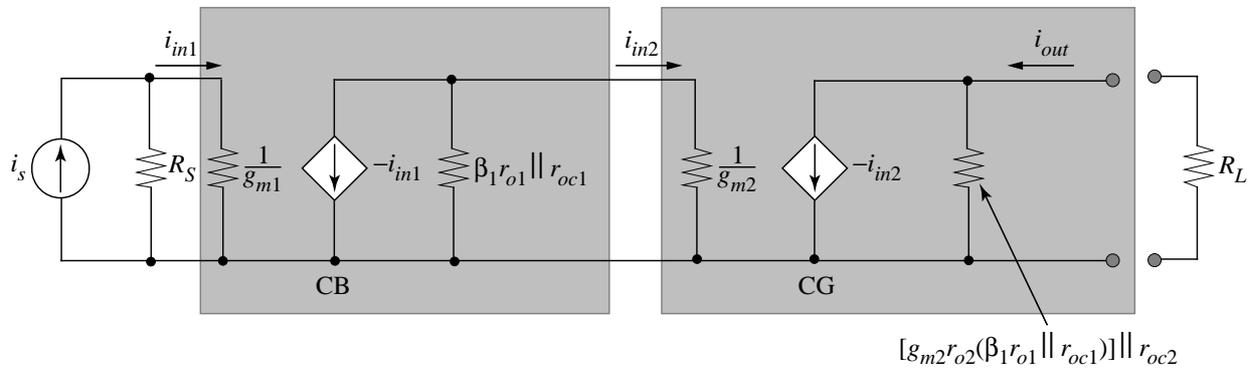
But, since  $r_{\pi 2} \ll r_{oc1} // (\beta_1 r_{o1})$ , then

$$R_{out} \simeq r_{oc2} // [r_{o2}(1 + g_{m2}r_{\pi 2})] \simeq r_{oc2} // (\beta_2 r_{o2})$$

Did not improve anything! The base current limits the number of CB stages that improve  $R_{out}$  to just one.

Since CG stage has no gate current, cascade it behind CB stage.

□ CB-CG current buffer:



$$R_{out} = R_{out2} = r_{oc2} // [r_{o2}(1 + g_{m2}R_{out1})]$$

with  $R_{out1} \simeq r_{oc1} // (\beta_1 r_{o1})$ ,

$$R_{out} = r_{oc2} // [r_{o2}g_{m2}(r_{oc1} // \beta_1 r_{o1})]$$

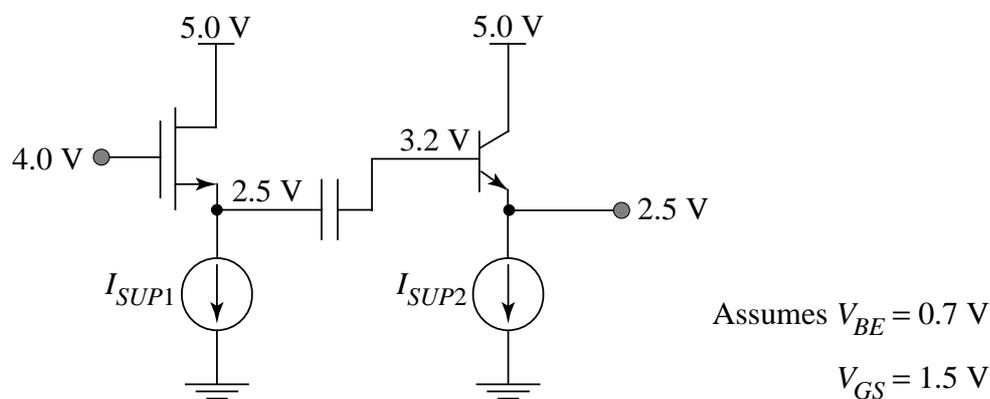
Now  $R_{out}$  has improved by about  $g_{m2}r_{o2}$ , but only to the extent that  $r_{oc2}$  is high enough...

## 5. Coupling amplifier stages

### □ CAPACITIVE COUPLING

Capacitors of large enough value behave as AC short, so signal goes through but bias is independent for each stage.

Example, CD-CC voltage buffer:



- Advantages:

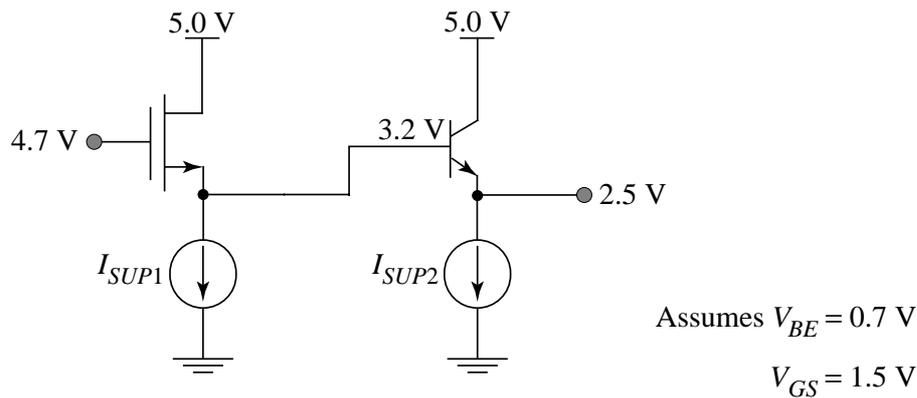
- can select bias point for optimum operation
- can select bias point close to middle of rails for maximum signal swing

- Disadvantages:

- to approximate AC short, need large capacitors that consume significant area

□ **DIRECT COUPLING:** share bias points across stages.

Example, CD-CC voltage buffer:



- Advantages:

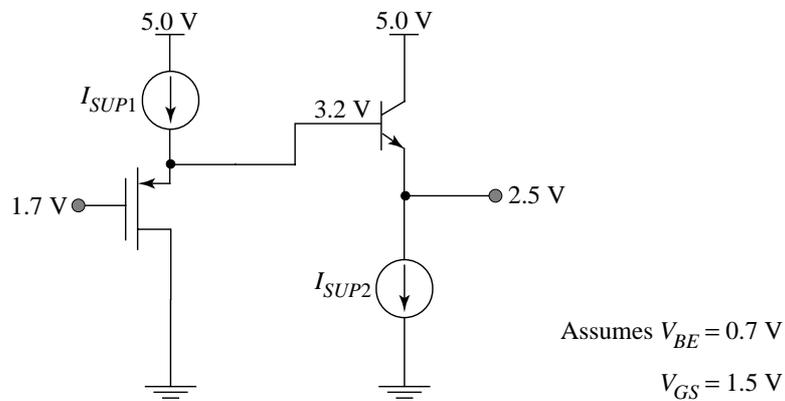
- no capacitors: compact

- Disadvantages:

- bias point shared: constrains design

- bias shifts from stage to stage and can stray too far from center of range

Solution: use PMOS CD stage:



Trade-off:  $g_m(\text{PMOS}) < g_m(\text{NMOS}) \rightarrow$  higher  $R_{out}$

In BiCMOS voltage amplifier:

$$R_{out} = \frac{1}{g_{m4}} + \frac{1}{\beta_4(g_{m3} + g_{mb3})}$$

□ Summary of DC shifts through amplifier stages:

Amplifier Type	Transistor Type			
	NMOS	PMOS	nnp	pnnp
Common Source/ Common Emitter (CS/CE)				
Common Gate/ Common Base (CG/CB)				
Common Drain/ Common Collector (CD/CC)				

Important difference in bias shift between stages in BJT and MOSFET amps:

- In BJT (for npn):

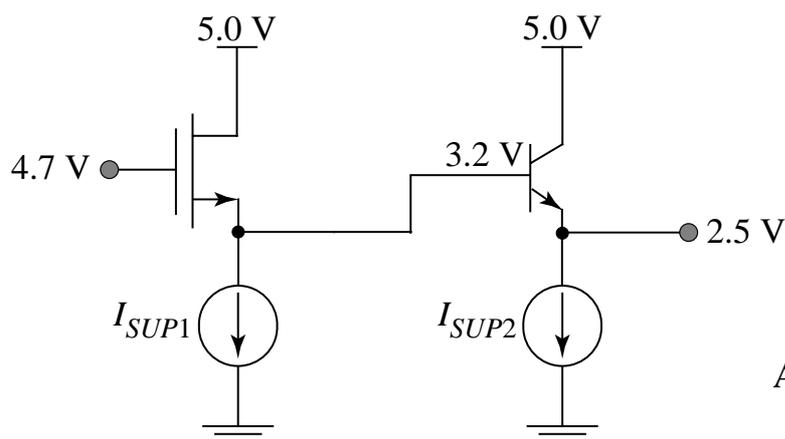
$$V_{BE} \simeq V_{BE,on}$$

rather independent of transistor size and current level.

- In MOSFET (for nMOSFET):

$$V_{GS} = V_T + \sqrt{\frac{2I_D}{\mu_n C_{ox}} \frac{L}{W}}$$

Can be engineered through bias current and transistor geometry.



Assumes  $V_{BE} = 0.7 \text{ V}$

$V_{GS} = 1.5 \text{ V}$

## Key conclusions

- To achieve amplifier design goals, several stages often needed.
- In multistage amplifiers, different stages used to accomplish different goals:
  - voltage gain: common-source, common emitter
  - voltage buffer: common-drain, common collector
  - current buffer: common-gate, common base
- In multistage amplifiers must pay attention to inter-stage loading to avoid unnecessary losses.
- In *direct-coupled* amplifiers, bias is shared between adjoining stages:
  - must select compromise bias,
  - must pay attention to bias shift from stage to stage.