Neuromorphic engineering I

Lab 5: Static Circuits: Transconductance Amplifier

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Group number:

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Lab objectives

The objectives of this lab are to understand and characterize one of the most important circuit in analog IC design.

The experimental objectives are as follows:

1. To characterize a simple differential transconductance amplifier and understand its operation in terms of the behavior of the differential pair and the current mirror. Specifically, to understand the dependence of the output current on the differential input voltages.
2. To characterize single-stage 2-transistor “common-source” amplifier gain, and how it arises from transconductance and output impedance.

1 Prelab

1.1 Transconductance amplifier

- Now consider a simple differential transconductance amplifier which is built from a differential pair and a current mirror. The output current should be equal to the the difference of the two differential pair currents, i. e. $I_{out} = I_1 - I_2$. Is this statement true? Justify your answer by stating your assumptions about transistor saturation and drain conductance.

Yes, as long as all MOSFETs are in saturation ($V_s > 4U_T$) and the diff. pair is operated below threshold. This restricts our output voltage range to:

$$V_s + 4U_T < V_{OUT} < V_{dd} - 4U_T \tag{1}$$

If we have a look at the case where $V_1 = V_2$, the current flowing through each branch will be $\frac{I_b}{2}$ The drain conductance ($g_{md} = \frac{-\delta I_{out}}{\delta V_{out}}$) in these conditions (saturation, subthreshold and assuming V_E is the same for every MOSFET) can be written as:

$$g_{md} = g_{ds} = \frac{I_4}{V_E} + \frac{I_2}{V_E} \tag{2}$$

$$g_{ds} = \frac{I_b}{2V_E} + \frac{I_b}{2V_E} \tag{3}$$

$$g_{ds} = \frac{I_b}{V_E} \tag{4}$$

Where V_E is the early voltage.

Also by appyling KCL we can verify this statement .

- Now consider the transconductance amplifier with the output open-circuited (i.e. no current flows into or out of the output node). Say V_2 is fixed at some voltage in the middle of the rails, e.g., $\frac{Vdd}{2}$. Explain what happens to the output voltage as V_1 is swept from below V_2 to above V_2 for a subthreshold bias. Discuss the current through the differential pair transistors and the current mirror, and the voltage on the internal node common to the differential pair transistors. Try to keep the discussion concise.

The equation for V_{out} in a transconductance amplifier is the following:

$$V_{out} = A(V_1 - V_2) \tag{5}$$

In subthreshold,

$$A \approx \frac{\kappa V_E}{2U_T} \tag{6}$$

- For V1<V2:

  I_2 is equal to I_b and I_1 is 0, therefore the current in the current mirror is also 0. Which will lead to a discharge in the "node capacitor" and the M2 NFET voltage will drop to 0 and as M2 goes out of saturation, $V_{out} \approx V_s$.

- For V1>V2:

  I_1 is equal to I_b and I_2 is 0, therefore the current in the mirror is I_b which will lead to charging of the "node capacitor" and eventually M5 will go out of saturation as V_{out} will go up to Vdd.

- What is the transconductance $g_m = \frac{\mathrm{d}I_{out}}{\mathrm{d}V_{in}}$, where $V_{in} \equiv V_1 - V_2$, in sub-threshold? How does it change if the circuit is operated super-threshold?

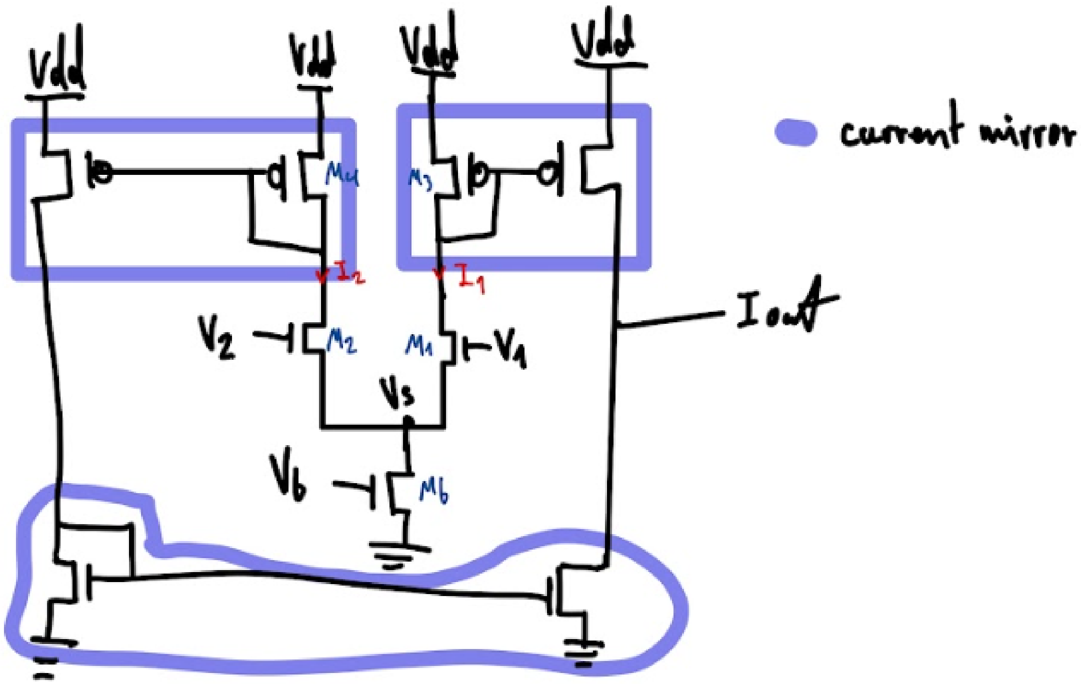
> In sub-threshold: $g_m = \frac{I_b \kappa}{2U_T}$
>
> In super-threshold: $g_m = \sqrt{\beta I_b}$ for $|V_1 - V_2| < \sqrt{2I_b/\beta}$

- Quantitatively, what is the relationship between transconductance, output resistance r_o, and voltage gain A of a transconductance amplifier?

$$gd = \frac{Ib}{V_E} \tag{7}$$
$$r_o = \frac{1}{g_d} = \frac{V_E}{I_b} \tag{8}$$
$$A = \frac{dV_{out}}{d(v_1 - V_2)} = \frac{dI_{out}}{d(v_1 - V_2)} \frac{dV_{out}}{dI_{out}} = \frac{g_m}{g_d} = g_m r_o = \frac{I_b \kappa}{2U_T} r_o \tag{9}$$

1.2 Wide-Range Transamp

- Draw the schematic of a wide-range transconductance amplifier and explain why it does not have the simple 5-transistor transamp restriction on allowable output voltage. You can either draw the schematic directly on the Jupyter notebook using the *schemdraw* , or sketch it with pen and paper and paste a picture in a Markdown cell.



> The current mirror transistors, in order be in saturation need a V_g that is lower than $V_{dd} - 4U_T$ so V_s must satisfy this condition as well. V_s must also keep M3 in saturation and must therefore be greater than $4U_T$. We end up with I_1 charging the "capacitor node" at I_{out} and I_2 discharging it. And the only boundary on Vout is then $4U_T$

2 Setup

2.1 Connect the device

In [ ]:
```
# import the necessary library to communicate with the hardware
import pyplane

import time
import numpy as np
import matplotlib.pyplot as plt
```

In [ ]:
```
# create a Plane object and open the communication
if 'p' not in locals():
    p = pyplane.Plane()
    try:
        p.open('/dev/ttyACM0')
    except RuntimeError as e:
        del p
        print(e)
```

In [ ]:
```
p.get_firmware_version()
```

Out[ ]:
```
(1, 8, 4)
```

In [ ]:
```
# Send a reset signal to the board, check if the LED blinks
p.reset(pyplane.ResetType.Soft)

time.sleep(0.5)
# NOTE: You must send this request events every time you do a reset operetion, otherwi
# Because the class chip need to do handshake to get the communication correct.
p.request_events(1)
```

In [ ]:
```
# Try to read something, make sure the chip responses
p.read_current(pyplane.AdcChannel.GO0_N)
```

Out[ ]:
```
1.7724609335800778e-07
```

In [ ]:
```
# If any of the above steps fail, delete the object, and restart the kernel

# del p
```

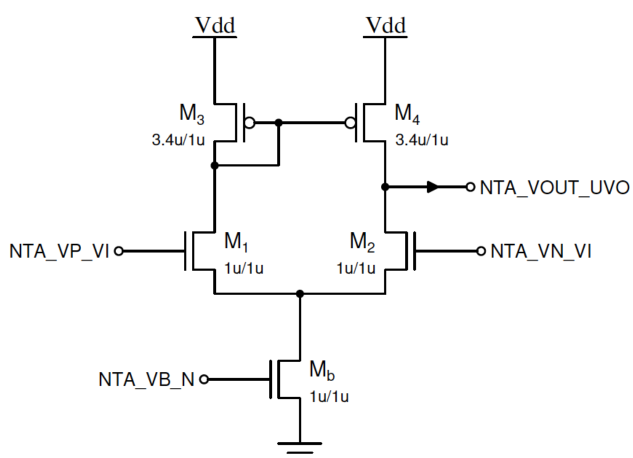
2.2 Setup C2F and voltage output buffer

In [ ]:
```
# setup C2F
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.C2F_HYS_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 100)])

time.sleep(0.2)
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.C2F_BIAS_P, \
    pyplane.Coach.BiasType.P, \
```

```
    pyplane.Coach.BiasGenMasterCurrent.I240nA, 255)])

time.sleep(0.2)
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.C2F_PWLK_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I240nA, 255)])

time.sleep(0.2)
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.C2F_REF_L, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])

time.sleep(0.2)
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.C2F_REF_H, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])

time.sleep(0.2)
# setup output rail-to-rail buffer
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.RR_BIAS_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I240nA, 255)])
```

3 N-Type 5T Transamp

3.0 Schematic and pin map



V_1 = V_p = **NTA_VP_VI = AIN3**

V_2 = V_n = **NTA_VN_VI = AIN4**

V_{out} = **NTA_VOUT_UVO = ADC[13]**

I_{out} = $I_+ - I_-$ = **NTA_IOUT_UO - NTA_IOUT_UBO = C2F[11] - C2F[12]**; **Note that** I_+ **and** I_- **is not** I_1 **and** I_2**.**

Note: There are three identical NTA circuits with the same bias and input voltages, one with the output open-circuited and routed out at NTA_VOUT*UVO, the other two with* $V{out}$fixedto1VbutI_{out}$ routed out through N- and P- type current mirror at NTA_IOUT_UO and NTA_IOUT_UBO.

3.1 Chip configuration

In [ ]:
```
# configure N type TransAmp
p.send_coach_events([pyplane.Coach.generate_aerc_event( \
    pyplane.Coach.CurrentOutputSelect.SelectLine5, \
    pyplane.Coach.VoltageOutputSelect.SelectLine1, \
    pyplane.Coach.VoltageInputSelect.SelectLine2, \
    pyplane.Coach.SynapseSelect.NoneSelected, 0)])
```

3.2 Calibration of C2F channels

Here you need to calibrate NTA_IOUT_UO and NTA_IOUT_UBO in the same way as the last lab

3.2.1 NTA_IOUT_UO

- Set fixed voltages for V_1 and V_2

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN3,0.8) # V1 = 0.8
time.sleep(0.2) # settle time
p.set_voltage(pyplane.DacChannel.AIN4,0.2) # V2 = 0.2
```

Out[ ]:
```
0.19882699847221375
```

Set voltages such that $V_1 \gg V_2$.

- Data aquisition (Hint: use master current for I_b = 30 nA)

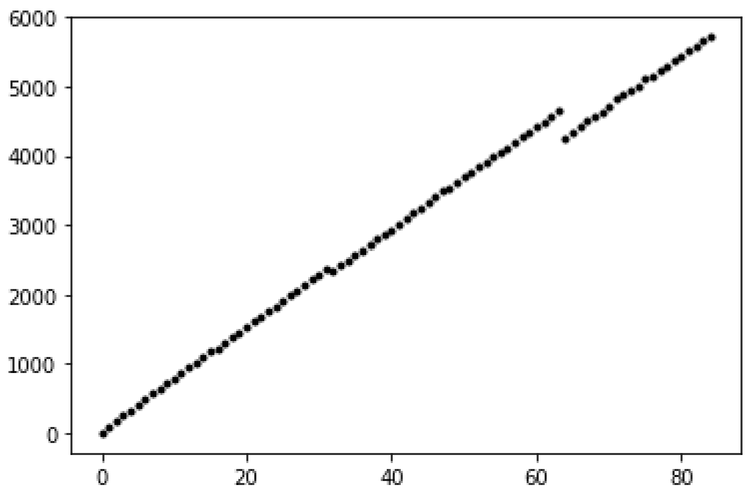
In [ ]:
```
import numpy as np
import time

calIout_UO_ex3 = np.arange(0,85,1) # bias current sweep range, fine value

c2f_Iout_UO_ex3 = []  # what you get is frequency

for n in range(len(calIout_UO_ex3)):

    # set bias
    p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, calIout_UO_ex3[n])])

    time.sleep(0.2) # settle time
```

```
    # read c2f values
    c2f_Iout_UO_ex3_temp = p.read_c2f_output(0.1)
    c2f_Iout_UO_ex3.append(c2f_Iout_UO_ex3_temp[11])

print(c2f_Iout_UO_ex3)
```

```
[2, 89, 167, 251, 325, 409, 487, 568, 627, 709, 786, 867, 943, 1022, 1097, 1180, 122
0, 1305, 1377, 1457, 1530, 1613, 1687, 1767, 1825, 1907, 1982, 2064, 2135, 2215, 229
0, 2371, 2328, 2420, 2497, 2567, 2640, 2718, 2791, 2874, 2929, 3015, 3093, 3187, 324
2, 3336, 3403, 3484, 3523, 3611, 3685, 3766, 3832, 3904, 3980, 4058, 4111, 4188, 426
5, 4344, 4412, 4487, 4565, 4639, 4259, 4338, 4413, 4494, 4561, 4635, 4710, 4815, 487
0, 4948, 4996, 5103, 5150, 5225, 5297, 5379, 5442, 5517, 5571, 5651, 5715]
```

- Plot

In [ ]:
```
plt.plot(c2f_Iout_UO_ex3, '.k')
plt.show()
```



- Save data

In [ ]:
```
# if the data looks nice, save it!
data_Iout_UO_ex3_cal= [c2f_Iout_UO_ex3, calIout_UO_ex3]
# save to csv file
np.savetxt('./data/c2f_Iout_UO_ex3_cal.csv', data_Iout_UO_ex3_cal, delimiter=',')
```

- Load data you saved

In [ ]:
```
# load the saved data
c2f_Iout_UO_ex3_save,calIout_UO_ex3_save = np.loadtxt('./data/c2f_Iout_UO_ex3_cal.csv'
```

- C2f plot

In [ ]:
```
# C2f plot
import matplotlib.pyplot as plt
import numpy as np
plt.rcParams.update({'font.size': 14})
```

```
Iout_UO_ex3 = calIout_UO_ex3_save/256*30

plt.plot(Iout_UO_ex3,c2f_Iout_UO_ex3_save,'k+')

plt.xlabel('$I_b$ (nA)')
plt.ylabel('C2F (Hz)')
# plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 1: C2F values vs. $I_1$ for $V_1 \gg V_2$.')
plt.grid()
plt.show()
```

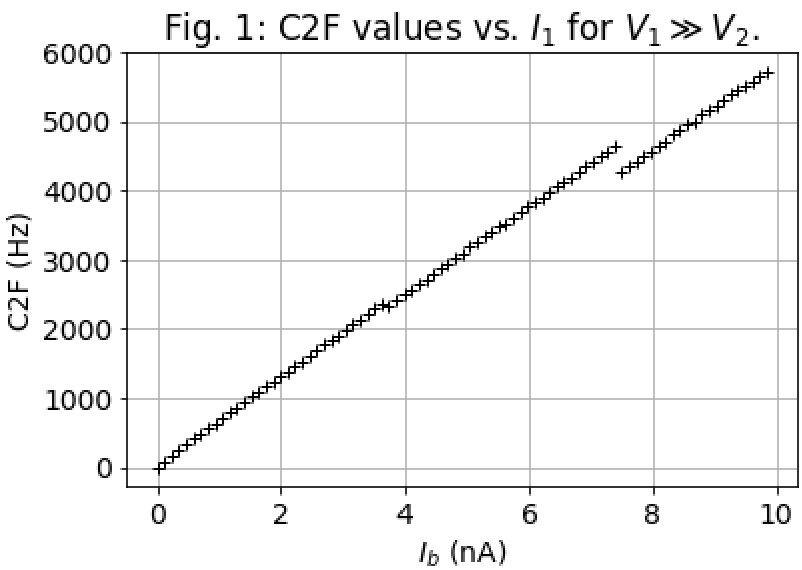


Fig. 1 shows the C2F values obtained by sweeping the bias current over the range $I_b \in [0\text{nA}, 10\text{nA}]$, whereas $V_1 = 0.8\text{V}$ and $V_2 = 0.2\text{V}$.

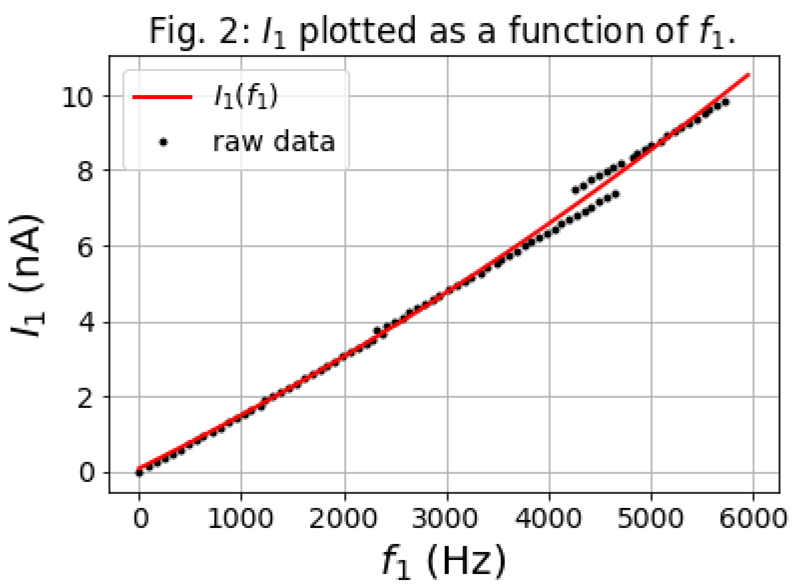
The values for V_1 and V_2 were chosen such that $V_1 \gg V_2$. For these values, the corresponding currents becomes $I_1 \approx I_b$ and $I_2 \approx 0$. The measured data can therefore be utilized to determine the mapping between $I_1 \approx I_b$ and the C2F measurements for the transconductance amplifier.

- Extract the function $I_+ \left(f_+\right)$ (Hint: use higher order polynomial to increase accuracy)

In [ ]:
```
# plot the raw data
raw_UO, = plt.plot(c2f_Iout_UO_ex3_save, Iout_UO_ex3, '.k')

# data range you want to fit
low_bound = 2
high_bound = 80
# print(c2f_Iout_UO_ex3[low_bound:high_bound])

# fit polynomial to C2F (frequency) vs I data
a2, a1, a0 = np.polyfit(c2f_Iout_UO_ex3_save[low_bound:high_bound], Iout_UO_ex3[low_bo
# print(a0)
# print(a1)
# print(a2)

# Print out the function I(f) you got
I_freq = np.polyfit(c2f_Iout_UO_ex3_save[low_bound:high_bound], Iout_UO_ex3[low_bound:
```

```
print ('The I1(f1) function of NTA_IOUT_UO is :')
print (np.poly1d(I_freq))


# select frequency range that you want to plot
freq = np.arange(0, 6000, 50)
# print(freq)

I1 = a2*freq**2 + a1*freq + a0   # function I(f),
fit, = plt.plot(freq, I1, 'r-', linewidth=2)


plt.xlabel('$f_1$ (Hz)', {'size':20})
plt.ylabel('$I_1$ (nA)', {'size':20})
plt.legend([fit, raw_UO], ['$I_1(f_1)$', 'raw data'],prop={'size': 14})
plt.title('Fig. 2: $I_1$ plotted as a function of $f_1$. ')
plt.grid()
plt.show()
```

```
The I1(f1) function of NTA_IOUT_UO is :
           2
6.842e-08 x + 0.00135 x + 0.07457
```



3.2.2 NTA_IOUT_UBO

- Set fixed voltages for V_1 and V_2

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN3,0.2) # V1 = 0.8
time.sleep(0.2) # settle time
p.set_voltage(pyplane.DacChannel.AIN4,0.8) # V2 = 0.2
```

Set voltages such that $V_1 \ll V_2$.

- Data aquisition (Hint: use master current for I_b 30 nA)

In [ ]:
```
import numpy as np
import time
```

```
calIout_UBO_ex3 = np.arange(0,85,1) # bias current sweep range

c2f_Iout_UBO_ex3 = []

for n in range(len(calIout_UBO_ex3)):

    # set bias
    p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, calIout_UBO_ex3[n])])

    time.sleep(0.2) # settle time

    # read c2f values
    c2f_Iout_UBO_ex3_temp = p.read_c2f_output(0.1)
    c2f_Iout_UBO_ex3.append(c2f_Iout_UBO_ex3_temp[12])

print(c2f_Iout_UBO_ex3)
```

- Plot

In [ ]:
```
plt.plot(c2f_Iout_UBO_ex3, '.k')
plt.show()
```

- Save data

In [ ]:
```
# if the data looks nice, save it!
```

- Load data you saved

In [ ]:
```
```

- Extract the function $I_-(f_-)$ (Hint: use second-order polynomial to increase accuracy)

In [ ]:
```
```

3.3 Output voltage vs. input voltage

3.3.1 Basic measurement

- Set bias current I_b

In [ ]:
```
 p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
```

The bias current is set to

$$I_b = w\frac{BG_{\text{fine}}}{256}I_{BG_{\text{master}}} = \frac{???}{256}\cdot 30\text{nA} \approx ???\text{nA}.$$

- Set fixed value of V_2 (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN4, ...) # V2 = ?
v2_real = p.get_set_voltage(pyplane.DacChannel.AIN4)
print("V2 is set to {} V".format(v2_real))
```

- Sweep V_1 and measure V_{out} (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:
```
import numpy as np
import time

V1_sweep_ex3 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex3_getset = p.get_set_voltage(pyplane.DacChannel.AIN4)

Vout_V1_sweep_ex3 = []
V1_sweep_ex3_getset = []

for n in range(len(V1_sweep_ex3)):

    p.set_voltage(pyplane.DacChannel.AIN3,V1_sweep_ex3[n]) #

    time.sleep(0.3) # settle time

    V1_sweep_ex3_getset.append(p.get_set_voltage(pyplane.DacChannel.AIN3))
#     Vout_V1_sweep_ex3.append(p.read_adc_instantaneous(13))
    Vout_V1_sweep_ex3.append(p.read_voltage(pyplane.AdcChannel.AOUT13))

# print(V2_ex3_getset)
# print(V1_sweep_ex3_getset)
# print(Vout_V1_sweep_ex3)
```

- Plot raw data

In [ ]:
```

```

- Save raw data

In [ ]:
```
# if the data looks nice, save it!
```

3.3.2 Different bias currents

- Repeat 3.3.1 with another two bias currents and compare the three curves

The bias current was switched from $I_b \approx ???\text{nA}$ to $I_b \approx ???\text{nA}$.

In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
```

In [ ]:
```
# your codes
```

In [ ]:
```
# plot the three curves on one figure to compare
```

To conclude your observations:

xxxxxxxx

3.3.3 Different fixed voltages V_n

- Repeat 3.3.1 with another two fixed voltages V_2 and compare the three curves

Switch voltage from $V_2 = ???\mathrm{V}$ to $V_2 = ???\mathrm{V}$. The bias current was $I_b = ???\mathrm{nA}$

In [ ]:
```
# Set V2 = ?
```

In [ ]:
```
# Set Ib = ?
```

In [ ]:
```
# your codes
```

In [ ]:
```
# plot the three curves on one figure to compare
```

To conclude your observations:

xxx

3.4 Output current vs. input voltage

3.4.1 Basic measurement

- Set bias current I_b

In [ ]:
```
 p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
```

Switch bias current back to $I_b = ???\mathrm{nA}$.

- Assign common mode voltage V_{cm}

In [ ]:
```
Vcm_ex3 = ... # Vcm = ???V
```

- Sweep differential voltage V_{diff} and measure I_{out} (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:
```
import numpy as np
import time

V1_sweep_ex3 = np.arange(0.6, 1.2, 0.01) # voltage V1 sweep range

#V2_ex3_getset = p.get_set_voltage(pyplane.DacChannel.AIN4)

V2_ex3 = []
V1_sweep_ex3_getset = []
V2_ex3_getset = []
c2f_Iout_UO_Vcm_ex3 = []
c2f_Iout_UBO_Vcm_ex3 = []

for n in range(len(V1_sweep_ex3)):

    # calculate V2 via Vcm and V1
    V2_ex3.append(2*Vcm_ex3-V1_sweep_ex3[n])

    p.set_voltage(pyplane.DacChannel.AIN3,V1_sweep_ex3[n]) #
    p.set_voltage(pyplane.DacChannel.AIN4,V2_ex3[n]) #

    time.sleep(0.2) # settle time

    V1_sweep_ex3_getset.append(p.get_set_voltage(pyplane.DacChannel.AIN3))
    V2_ex3_getset.append(p.get_set_voltage(pyplane.DacChannel.AIN4))

    # read c2f values
    c2f_Iout_ex3_temp = p.read_c2f_output(0.1)
    c2f_Iout_UO_Vcm_ex3.append(c2f_Iout_ex3_temp[11])
    c2f_Iout_UBO_Vcm_ex3.append(c2f_Iout_ex3_temp[12])

# print(V1_sweep_ex3_getset)
# print(V2_ex3_getset)
# print(c2f_Iout_UO_Vcm_ex3)
# print(c2f_Iout_UBO_Vcm_ex3)
```

- Save raw data

In [ ]:
```
# if the data looks nice, save it!
data_Iout_Vcm09_ex3 = [V1_sweep_ex3_getset,V2_ex3_getset,c2f_Iout_UO_Vcm_ex3,c2f_Iout_
# save to csv file
np.savetxt('./data/V1_sweep_Iout_Vcm09_ex3.csv', data_Iout_Vcm09_ex3, delimiter=',')
```

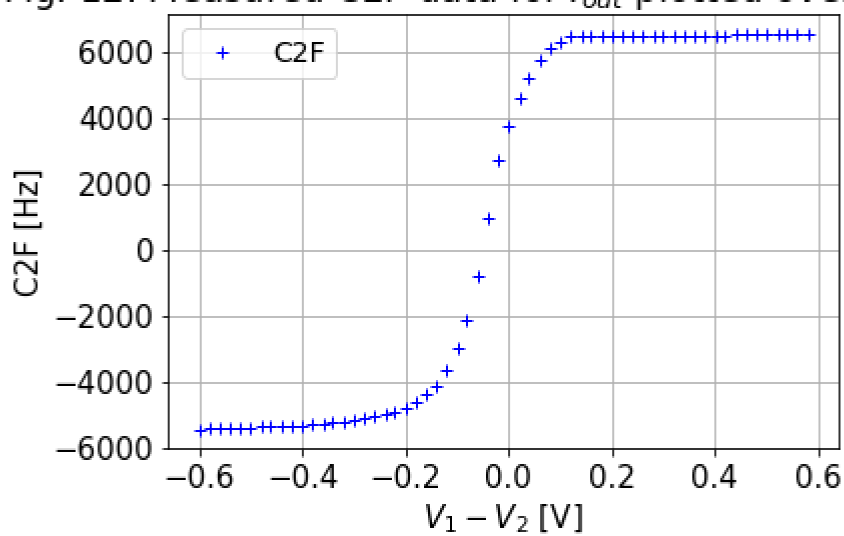
- Plot raw data (C2F frequncy vs. $Vdiff$)

In [ ]:
```
import matplotlib.pyplot as plt
import numpy as np
plt.rcParams.update({'font.size': 15})
```

```
V1_sweep_Iout_Vcm09_ex3_getset,V2_Iout_Vcm09_ex3_getset,c2f_Iout_UO_Vcm09_ex3,c2f_Iout

Vdiff_Vcm09 = V1_sweep_Iout_Vcm09_ex3_getset-V2_Iout_Vcm09_ex3_getset
print(Vdiff_Vcm09)
c2f_Iout_Vcm09 = c2f_Iout_UO_Vcm09_ex3 - c2f_Iout_UBO_Vcm09_ex3
print(c2f_Iout_Vcm09)

plt.plot(Vdiff_Vcm09,c2f_Iout_Vcm09,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('C2F [Hz]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 12: Measured C2F data for $I_{out}$ plotted over $V_1-V_2$.')
plt.grid()
plt.show()
```

```
[-0.60000008 -0.58064526 -0.55953091 -0.53841656 -0.52082115 -0.49970675
 -0.4785924  -0.4609971  -0.43988276 -0.41876841 -0.40117306 -0.38005871
 -0.35894436 -0.34134907 -0.32023472 -0.29912025 -0.2815249  -0.26041055
 -0.2392962  -0.22170091 -0.20058656 -0.17947215 -0.1583578  -0.14076245
 -0.1196481  -0.09853375 -0.08093846 -0.05982405 -0.0387097  -0.02111435
  0.          0.02111435  0.0387097   0.05982405  0.08093846  0.09853375
  0.1196481   0.14076245  0.1583578   0.17947215  0.20058656  0.22170091
  0.2392962   0.26041055  0.2815249   0.29912025  0.32023472  0.34134907
  0.35894436  0.38005871  0.40117306  0.41876841  0.43988276  0.4609971
  0.4785924   0.49970675  0.52082115  0.53841656  0.55953091  0.58064526]
[-5423. -5417. -5408. -5397. -5387. -5373. -5361. -5351. -5337. -5321.
 -5303. -5283. -5256. -5228. -5199. -5157. -5116. -5053. -4982. -4903.
 -4782. -4608. -4387. -4121. -3654. -2955. -2144.  -784.   998.  2749.
  3791.  4606.  5209.  5783.  6154.  6347.  6469.  6512.  6524.  6524.
  6524.  6511.  6511.  6502.  6504.  6493.  6497.  6506.  6507.  6513.
  6520.  6524.  6532.  6537.  6543.  6544.  6554.  6556.  6565.  6569.]
```

Fig. 12: Measured C2F data for I_{out} plotted over $V_1 - V_2$.



- Convert c2f frenquncy to current and plot. You may need the factors a2, a1, a0 that you get when fitting the I(f) function in section 3 to convert frequency to current.

In [ ]:

- Compute transconductance

In [ ]:

- Explain any asymmetries in the amplifier's I-V curve and the offset voltage in terms of mismatch between devices in the mirror and differential pair. Do you think we can distinguish the effects of mismatch in the current mirror and in the differential pair? The main point here is to recognize that there will be non-idealities, to understand where they arise.

3.4.2 Different bias currents

- Repeat 3.4.1 with another two bias currents and compare the three curves

In [ ]:
```
# Set Ib = ?
```

The bias current was switched from $I_b \approx ???\mathrm{nA}$ to $I_b \approx ???\mathrm{nA}$.

In [ ]:

To conclude your observations:

xxx

3.4.3 Different common mode voltages

- Repeat 3.4.1 with another two common mode voltages and compare the three curves

In [ ]:
```
# Assign common mode voltage Vcm
Vcm_xxx = ???
```

In [ ]:
```
# Set Ib = ?
```

The bias current was switched back to $I_b \approx ???\mathrm{nA}$.

In [ ]:
```
# your code, data aquisition
```

To conclude your observations:

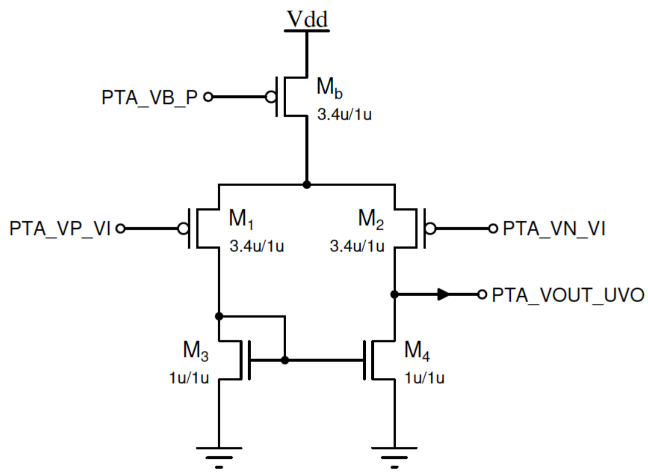
xxxxxxxx

What do you observe when the common mode voltage V_{cm} is too small (e.g. 0.2V or 0.3V)? Does it have a sigmoid shape? If not, try to explain why.

xxxxxx

4 P-Type 5T Transamp (**OPTIONAL**)

4.0 Schematic and pin map



V_1 = V_p = **PTA_VP_VI = AIN7**

V_2 = V_n = **PTA_VN_VI = AIN8**

V_{out} = **PTA_VOUT_UVO = ADC[12]**

I_{out} = $I_+ - I_-$ = **PTA_IOUT_UO - PTA_IOUT_UBO = C2F[13] - C2F[14]**

Note: There are three identical PTA circuits with the same bias and input voltages, one with the output open-circuited and routed out at PTA_VOUT*UVO, the other two with $V{out}*$fixedto1VbutI_{out} routed out through N- and P- type current mirror at PTA_IOUT_UO and PTA_IOUT_UBO.

4.1 Chip configuration

In [ ]:
```
# configure P type TransAmp
p.send_coach_events([pyplane.Coach.generate_aerc_event( \
    pyplane.Coach.CurrentOutputSelect.SelectLine5, \
    pyplane.Coach.VoltageOutputSelect.SelectLine1, \
    pyplane.Coach.VoltageInputSelect.SelectLine1, \
    pyplane.Coach.SynapseSelect.NoneSelected, 0)])
```

4.2 Calibration of C2F channels

Here you need to calibrate PTA_IOUT_UO and PTA_IOUT_UBO in the same way as the last lab. **Notice the W/L ratio of 3.4 of Mb**.

4.2.1 PTA_IOUT_UO

- Set fixed voltages for V_1 and V_2

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN7, ???) # V1 = ???
p.set_voltage(pyplane.DacChannel.AIN8, ???) # V2 = ???
```

Set $V_1 \gg V_2$.

- Data aquisition (Hint: use master current 30 nA)

In [ ]:
```
...
...

# Notice the W/L ratio of 3.4 of Mb when setting Ib.
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.PTA_VB_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
...
```

- Plot

In [ ]:
```

```

- Save data

In [ ]:
```
# if the data looks nice, save it!
```

- Extract the function $I_+(f_+)$ (Hint: use higher order polynomial to increase accuracy)

In [ ]:
```

```

4.2.2 PTA_IOUT_UBO

- Set fixed voltages for V_1 and V_2

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN7, ???) # V1 = ??
p.set_voltage(pyplane.DacChannel.AIN8, ???) # V2 = ??
```

Set $V_1 \ll V_2$.

- Data aquisition (Hint: use master current 30 nA)

In [ ]:
```
# Notice the W/L ratio of 3.4 of Mb when setting Ib.
```

- Plot

In [ ]:

- Save data

In [ ]:
```
# if the data looks nice, save it!
```

- Extract the function $I_-(f_-)$ (Hint: use higher order polynomial to increase accuracy)

In [ ]:

4.3 Output voltage vs. input voltage

4.3.1 Basic measurement

- Set bias current I_b

In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.PTA_VB_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
```

The bias current is set to (Notice the W/L ratio of 3.4 of Mb.)

$$I_b = w\frac{BG_{\text{fine}}}{256}I_{BG_{\text{master}}} = 3.4\frac{???}{256} \cdot 30\text{nA} = ???\text{nA}.$$

- Set fixed value of V_2 (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8, ???) # V2 = ???
```

Set $V_2 = ???\text{V}$.

- Sweep V_1 and measure V_{out} (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:

- Plot raw data

In [ ]:

- Save raw data

In [ ]:
```
# if the data looks nice, save it!
```

4.3.2 Different bias currents (**optional**)

- Repeat 4.3.1 with another two bias currents and compare the three curves

In [ ]:
```
```

Switch bias current from $I_b = ???\mathrm{nA}$ in the basic measurement to $I_b = ???\mathrm{nA}$.

In [ ]:
```
```

To conclude your observations:

xxxxxxxx

4.3.3 Different fixed voltages V_n (**optional**)

- Repeat 4.3.1 with another two fixed voltages V_2 and compare the three curves

In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
   pyplane.Coach.BiasAddress.PTA_VB_P, \
   pyplane.Coach.BiasType.P, \
   pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
```

Switch bias current back to $I_b = ???\mathrm{nA}$.

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8, ???) # V2 = ???
```

- Repeat 4.3.1 with another two fixed voltages V_2 and compare the three curves

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8, ???) # V2 = ??
```

Switch input voltage from $V_2 = ???\mathrm{V}$ in the basic measurement to $V_2 = \mathrm{V}$.

Switch bias current back to $I_b = 7.5\mathrm{nA}$.

In [ ]:
```
import numpy as np
import time

V1_sweep_ex4 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex4_getset = p.get_set_voltage(pyplane.DacChannel.AIN8)

Vout_V1_sweep_ex4 = []
V1_sweep_ex4_getset = []

for n in range(len(V1_sweep_ex4)):
```

```
    p.set_voltage(pyplane.DacChannel.AIN7,V1_sweep_ex4[n]) #

    time.sleep(0.5) # settle time

    V1_sweep_ex4_getset.append(p.get_set_voltage(pyplane.DacChannel.AIN7))
    Vout_V1_sweep_ex4.append(p.read_adc_instantaneous(12))

print(V2_ex4_getset)
print(V1_sweep_ex4_getset)
print(Vout_V1_sweep_ex4)
```

In [ ]:

```

```

To conclude your observations:

xxxxxxxx

4.4 Output current vs. input voltage

4.4.1 Basic measurement

- Set bias current I_b

In [ ]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.PTA_VB_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, ???)])
```

Bias current is switched back to $I_b = ????\mathrm{nA}$.

- Assign common mode voltage V_{cm}

In [ ]:

```
Vcm_ex4 = ??
```

Common mode voltage is set to $V_{cm} = ???\mathrm{V}$.

- Sweep differential voltage V_{diff} and measure I_{out} (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:

```

```

- Plot raw data (C2F)

In [ ]:

```

```

- Save raw data

In [ ]:
```
# if the data looks nice, save it!
```

- Convert rate to current and plot

In [ ]:
```
```

- Compute transconductance

- Explain any asymmetries in the amplifier's I-V curve and the offset voltage in terms of mismatch between devices in the mirror and differential pair, and the Early effect.

4.4.2 Different bias currents (**optional**)

- Repeat 4.4.1 with another two bias currents and compare the three curves

Switch bias current from $I_b = ???\mathrm{nA}$ in the basic measurement to $I_b = ???\mathrm{nA}$.

In [ ]:
```
```

To conclude your observations:

xxxxxxxx

4.4.3 Different common mode voltages (**optional**)

- Repeat 4.4.1 with another two common mode voltages and compare the three curves

The common mode voltage was changed from $V_{cm} = ???\mathrm{V}$ to $V_{cm} = ???\mathrm{V}$.

In [ ]:
```
```

Switch bias current back to $I_b = ???\mathrm{nA}$.

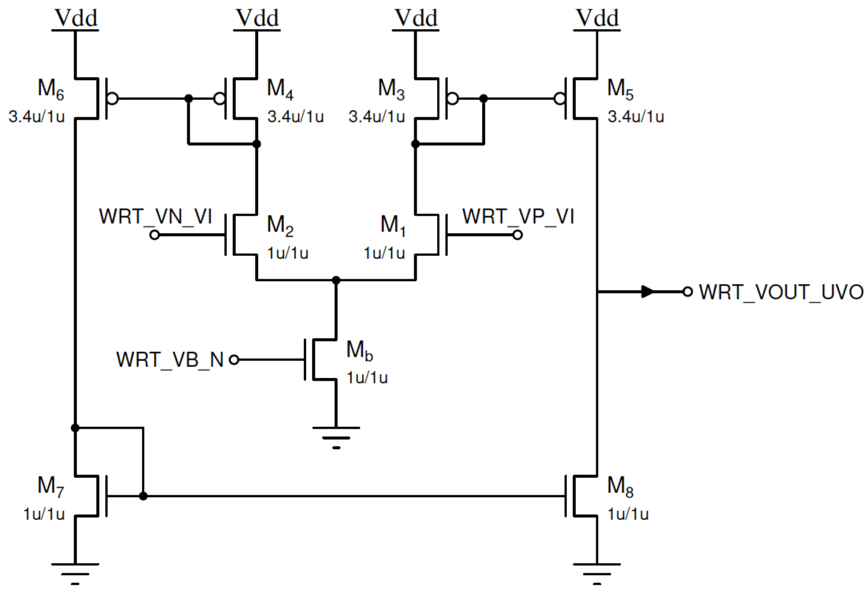
In [ ]:
```
```

To conclude your observations:

xxxxxxxx

5 Wide-range Transamp

5.0 Schematic and pin map



V_1 = V_p = **WRT_VP_VI = AIN7**

V_2 = V_n = **WRT_VN_VI = AIN8**

V_{out} = **WRT_VOUT_UVO = ADC[11]**

5.1 Chip configuration

In [ ]:
```
# configure wide-range TransAmp
p.send_coach_events([pyplane.Coach.generate_aerc_event( \
    pyplane.Coach.CurrentOutputSelect.SelectLine5, \
    pyplane.Coach.VoltageOutputSelect.SelectLine1, \
    pyplane.Coach.VoltageInputSelect.SelectLine2, \
    pyplane.Coach.SynapseSelect.NoneSelected, 0)])
```

5.2 Output voltage vs. input voltage

5.2.1 Basic measurement

- Set bias current I_b

In [ ]:
```
 p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.WRT_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 85)])
```

The bias current is set to

$$I_b = w\frac{BG_{\text{fine}}}{256}I_{BG_{\text{master}}} = \frac{85}{256}\cdot 30\text{nA} \approx 9.961\text{nA}.$$

- Set fixed value of V_2 (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8,0.9) # V2 = 0.9
```

The input voltage is set to $V_2 = 0.9\text{V}$.

- Sweep V_1 and measure V_{out} (Hint: use get_set_voltage to get the real value set on the DAC)

In [ ]:
```
import numpy as np
import time

V1_sweep_ex5 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex5_getset = p.get_set_voltage(pyplane.DacChannel.AIN8)

Vout_V1_sweep_ex5 = []
V1_sweep_ex5_getset = []

for n in range(len(V1_sweep_ex5)):

    p.set_voltage(pyplane.DacChannel.AIN7,V1_sweep_ex5[n]) #

    time.sleep(0.2) # settle time

    V1_sweep_ex5_getset.append(p.get_set_voltage(pyplane.DacChannel.AIN7))
    Vout_V1_sweep_ex5.append(p.read_voltage(pyplane.AdcChannel.AOUT11))

print(V2_ex5_getset)
print(V1_sweep_ex5_getset)
print(Vout_V1_sweep_ex5)
```

- Plot raw data

In [ ]:

- Save raw data

In [ ]:
```
# if the data looks nice, save it!
```

5.2.2 Different bias currents

- Repeat 5.2.1 with another two bias currents and compare the three curves

The bias current is switched to $I_b \approx ???\text{nA}$ from $I_b \approx ???\text{nA}$ in the basic measurement.

In [ ]:

To conclude your observations:

xxxxxxxx

5.2.3 Different fixed voltages V_n

- Repeat 5.2.1 with another two fixed voltages V_2 and compare the three curves

The bias current is switched back to $I_b \approx ???\mathrm{nA}$.

In [ ]:
```
# set Ib = ???
```

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8, ???)    # V2 = ???
```

In [ ]:
```
```

To conclude your observations:

xxxxxxxx

5.3 Comparison with 5T transamps

Compare the V_{out} vs V_{pos} (V_1) curves of the three transamps with different V_{neg} (V_2)

In [ ]:
```
# fix Vn = ??? (<0.9V), Compare Vout vs Vpos

# Read 5T NFET transamp


#Read wide-range transamp
```

In [ ]:
```
#Read 5T PFET transamp
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.PTA_VB_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA,25)])

p.set_voltage(pyplane.DacChannel.AIN8,1.1) #Set Vneg (V2)

V1_sweep_ex5 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex5_getset = p.get_set_voltage(pyplane.DacChannel.AIN8)

Vout_V1_sweep_PFET = []
V1_sweep_ex5_getset = []

for n in range(len(V1_sweep_ex5)):

    p.set_voltage(pyplane.DacChannel.AIN7,V1_sweep_ex5[n]) #Set Vpos(V1)

    time.sleep(0.3) # settle time
```

```
    V1_sweep_ex5_getset.append(p.get_set_voltage(pyplane.DacChannel.AIN7))
    Vout_V1_sweep_PFET.append(p.read_voltage(pyplane.AdcChannel.AOUT12)) #Read Vout
```

In [ ]:
```
# fix Vn = 0.9V, Compare Vout vs Vpos

plt.show()
```

In [ ]:
```
#PFET configuration
p.send_coach_events([pyplane.Coach.generate_aerc_event( \
    pyplane.Coach.CurrentOutputSelect.SelectLine5, \
    pyplane.Coach.VoltageOutputSelect.SelectLine1, \
    pyplane.Coach.VoltageInputSelect.SelectLine1, \
    pyplane.Coach.SynapseSelect.NoneSelected, 0)])
```

In [ ]:
```
# fix Vn = ??? (>0.9V), Compare Vout vs Vpos

plt.show()
```

To conclude your observations:

xxxxxxxx

6 Postlab

1. When we set the output voltage of the transconductance amplifier to a certain value between gnd and Vdd and measured its output current, we found that at some nonzero input voltage (the offset voltage) the output current was zero. Will we get a different input offset voltage if we change the output voltage? Explain why.

1. What are the conditions for keeping M_b in saturation for the P-type transamp? Do they differ from the N-type transamp?

1. What are the advantages and disadvantages of the wide-output-range transconductance amplifier vs. a standard transconductance amplifier? Consider layout area, output voltage swing, offset voltage, current asymmetries, and the gain A. Why is the wide-output-range transamp better suited for construction of a high-gain single-stage amplifier? *Hint: think about the necessary symmetries between pairs of transistors.*

7 What we expect after lab 4 and lab5

Can you sketch a transamp, a wide range transamp, a current correlator, and a bump circuit in both n- and p-type varieties?

How does a differential pair work? How does the common-node voltage change with the input voltages? How can you compute the differential tail currents from the subthreshold equations, and how do you obtain the result in terms of the differential input voltage? How does a current-correlator work? How does a bump circuit work?

The I-V characteristics of a transconductance amplifier below threshold. What’s the functional difference between simple and wide-output-range transamp? The subthreshold transconductance gm. The relation between gain A, transistor drain conductances gd, and transconductances gm.

Can you reason through all the node voltages in these circuits? I.e., if we draw the circuit and provide specific power supply and input voltages, can you reason to estimate all the other node voltages, at least to first order approximations, assuming κ = 1?

8 Congratulations

Wish you joy when you look back on your works, beautiful plots and all your efforts!