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?

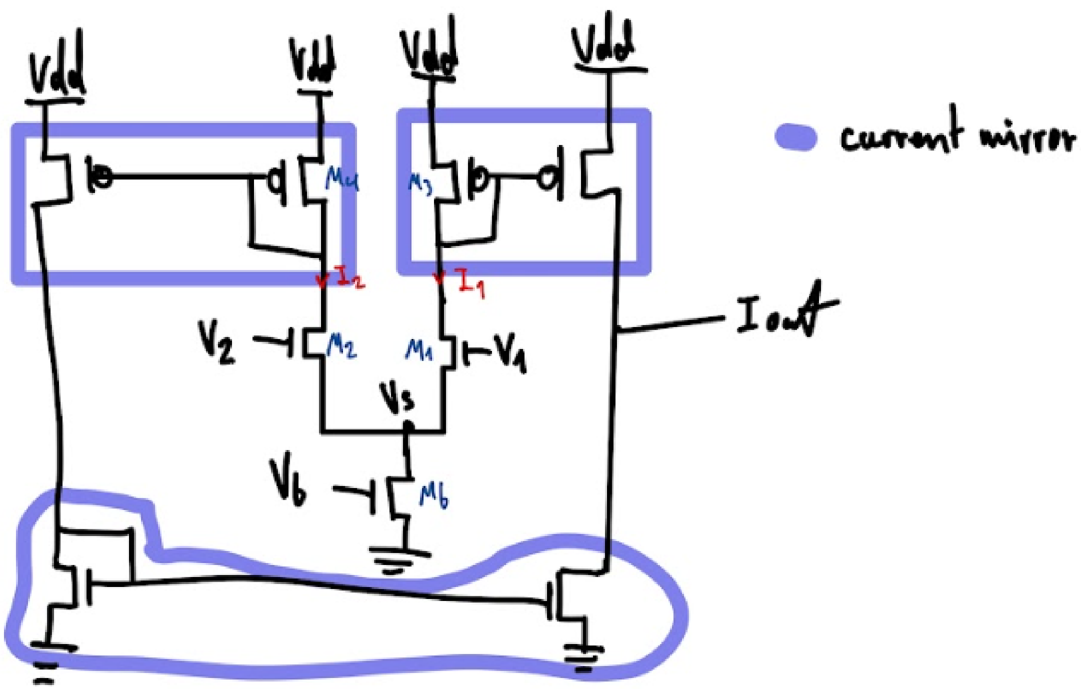
> In sub-threshold: $g_m = \frac{I_b\kappa}{2U_T}$
>
> In super-threshold: $g_m = \sqrt{\beta I_b}$ for $|V_1 - V_2| < \sqrt{2I_b/\beta}$

- 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, 6)
```

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[ ]:
```
8.862304667900389e-08
```

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

# del p
```

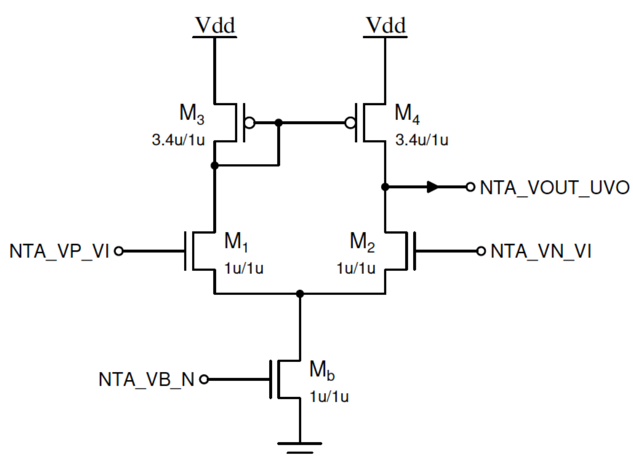
2.2 Setup C2F and voltage output buffer

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)

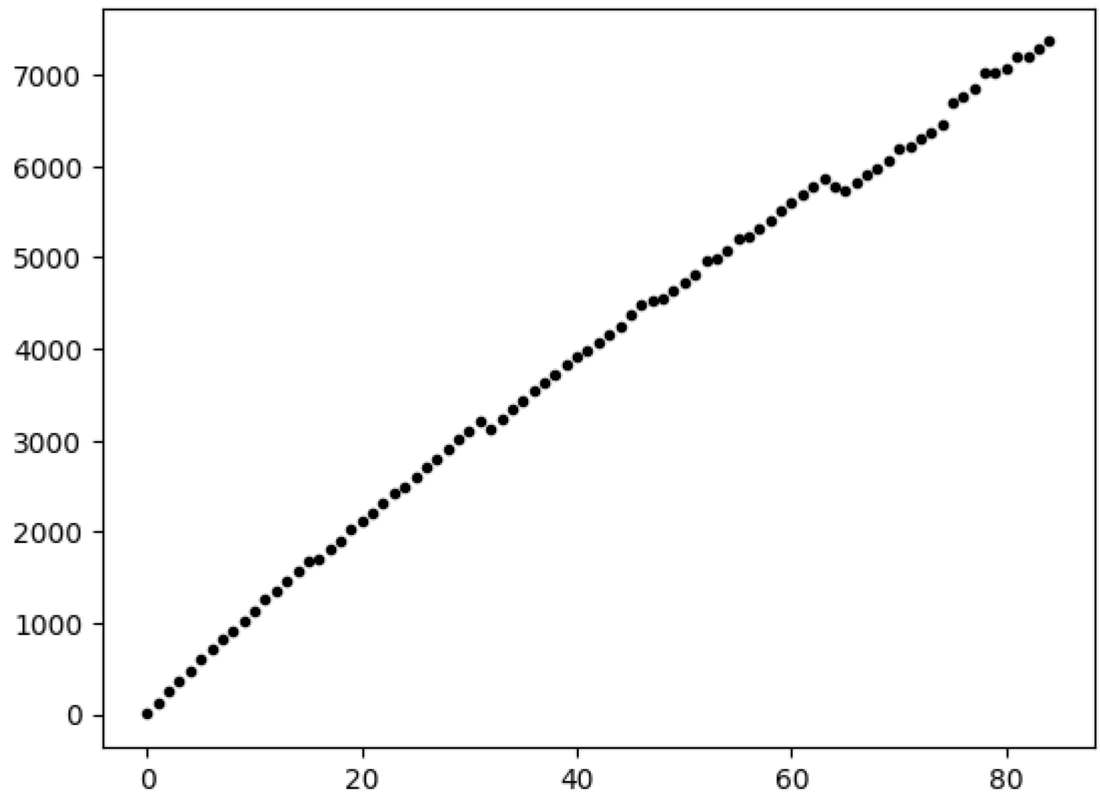
In [ ]:
```
import numpy as np
import time

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)
```

```
[4, 128, 249, 372, 479, 599, 714, 831, 911, 1029, 1140, 1255, 1353, 1465, 1575, 1686,
1694, 1806, 1906, 2020, 2112, 2215, 2325, 2428, 2498, 2606, 2705, 2802, 2915, 3008, 3
100, 3207, 3130, 3232, 3338, 3433, 3531, 3638, 3722, 3821, 3909, 3977, 4076, 4160, 42
42, 4380, 4476, 4536, 4547, 4633, 4726, 4818, 4959, 4996, 5084, 5197, 5238, 5324, 541
2, 5514, 5598, 5681, 5765, 5859, 5775, 5724, 5820, 5899, 5982, 6062, 6196, 6219, 629
2, 6369, 6456, 6687, 6761, 6853, 7013, 7020, 7058, 7193, 7197, 7295, 7363]
```

- 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()
```

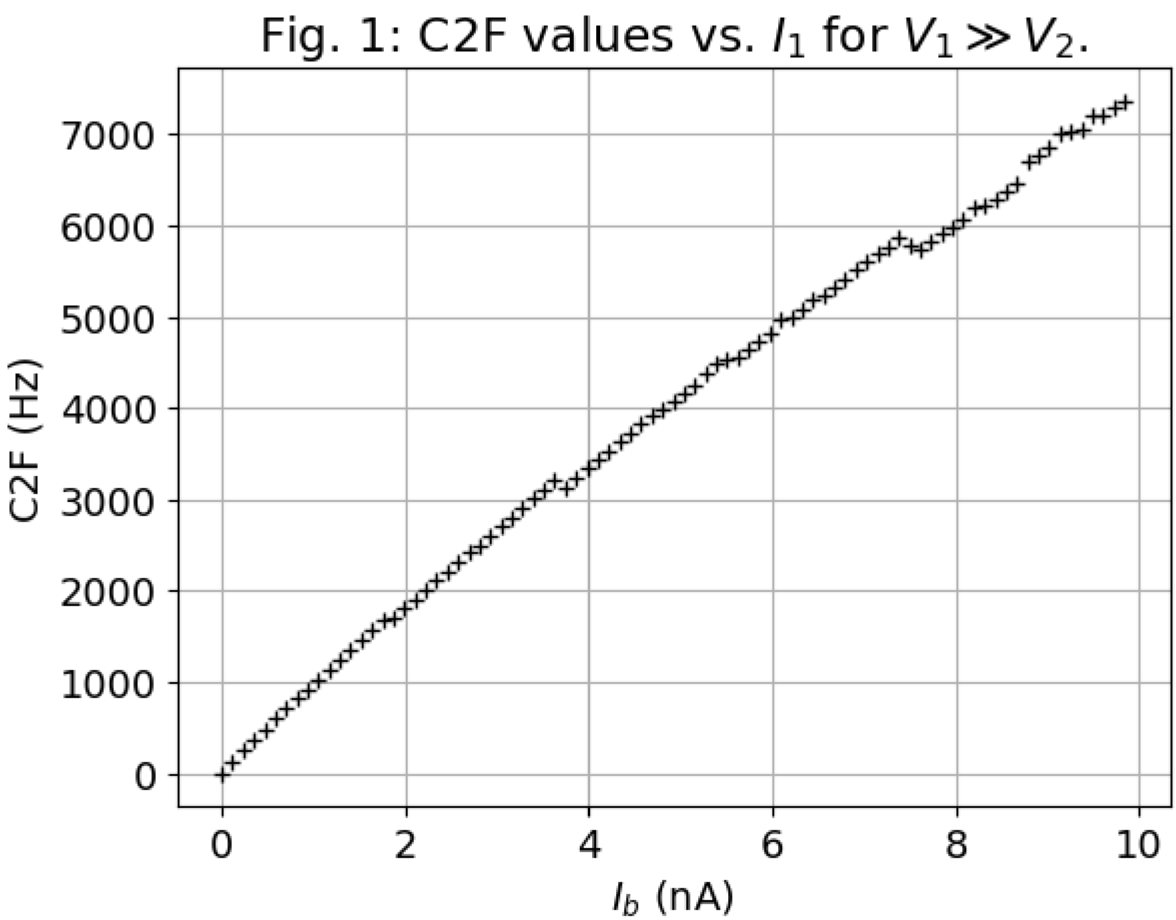


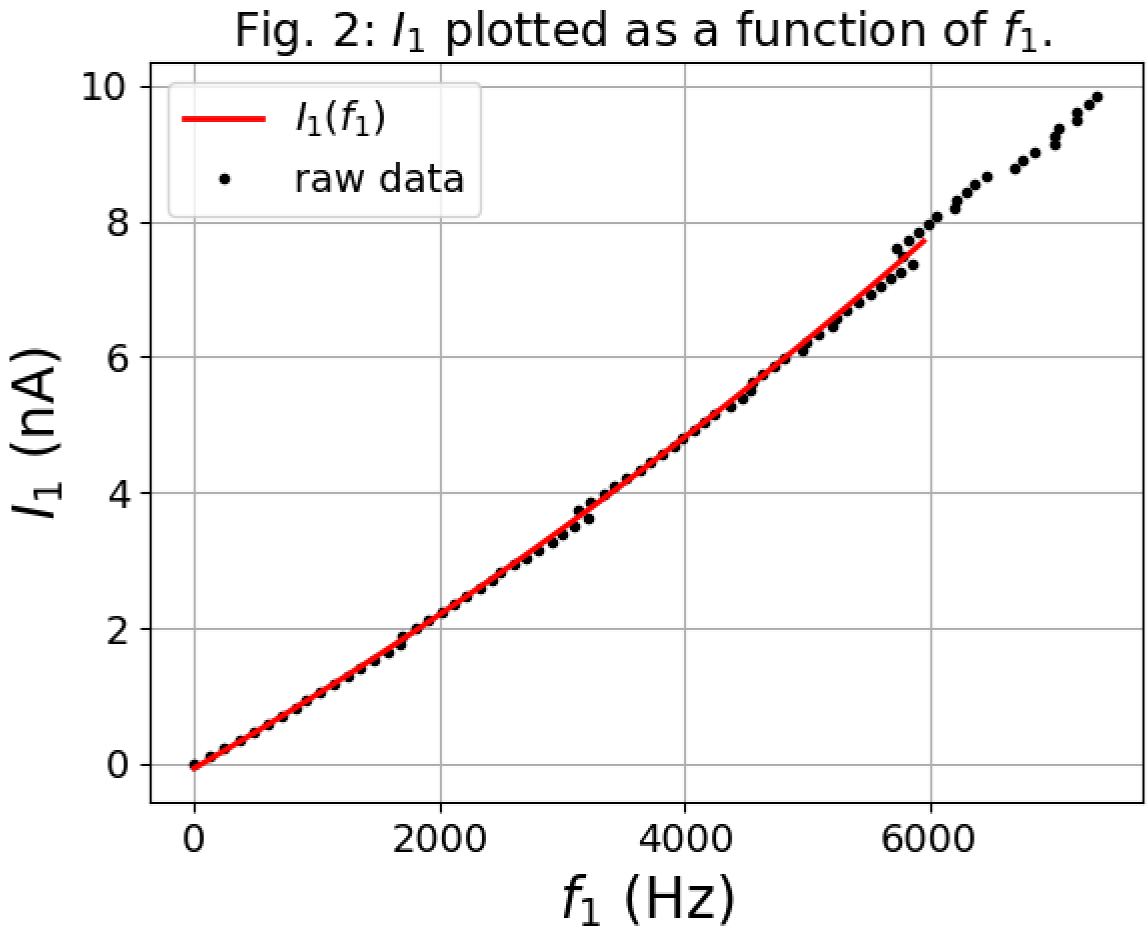
Fig. 1 shows the C2F values obtained by sweeping the bias current over the range $I_b \in [0\mathrm{nA}, 10\mathrm{nA}]$, whereas $V_1 = 0.8\mathrm{V}$ and $V_2 = 0.2\mathrm{V}$.

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 $I_+(f_+)$ (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_bc
# 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 I2(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)

I2 = 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
4.409e-08 x + 0.001044 x - 0.06894
```



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
```

Out[ ]:
```
0.798827052116394
```

Set voltages such that $V_1 \ll V_2$.

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

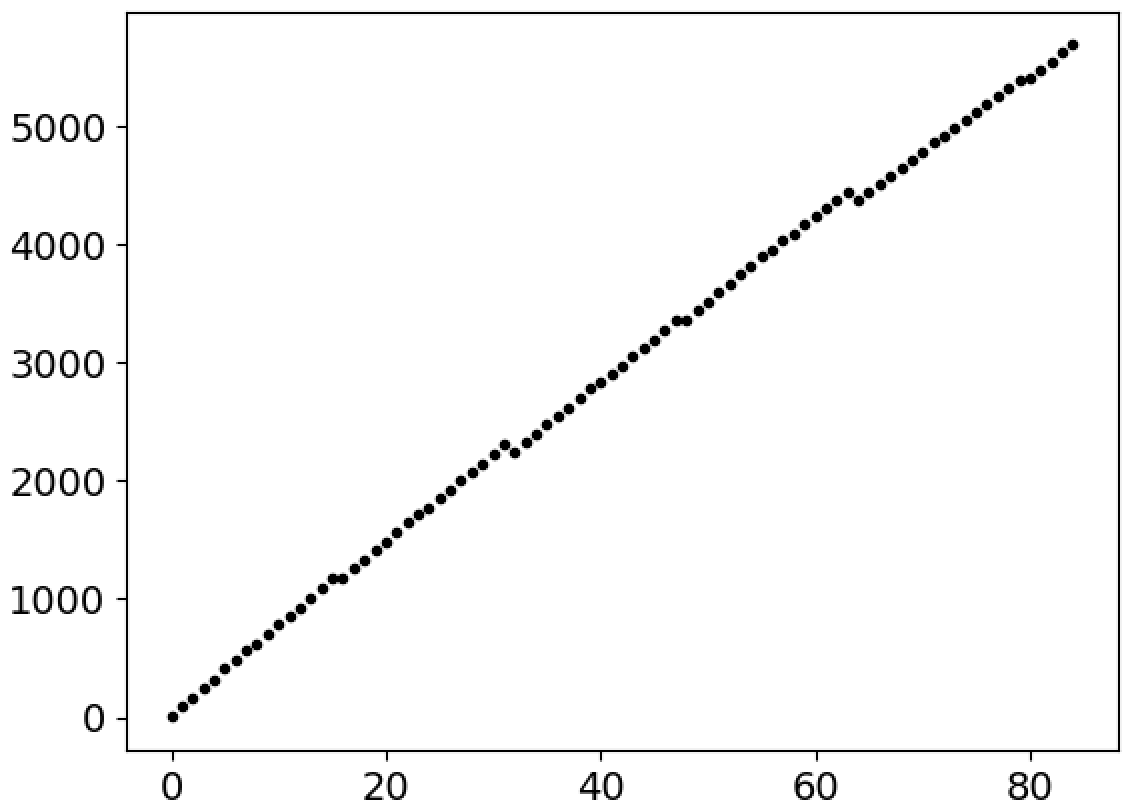
In [ ]:
```
import numpy as np
import time

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)
```

```
[2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,
2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,
2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,
2]
```

- Plot

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



- Save data

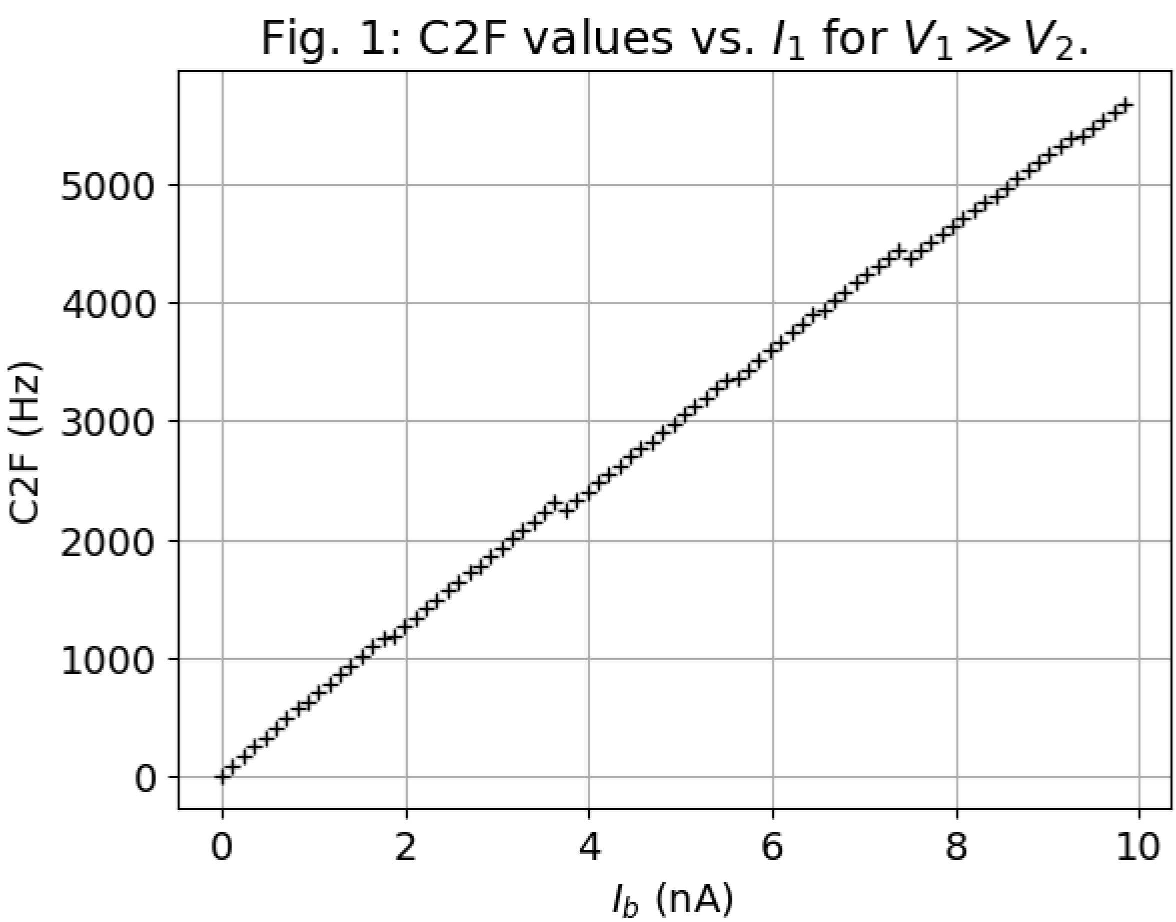
In [ ]:
```
# if the data looks nice, save it!
data_Iout_UBO_ex3_cal= [c2f_Iout_UBO_ex3, calIout_UBO_ex3]
# save to csv file
np.savetxt('./data/c2f_Iout_UBO_ex3_cal.csv', data_Iout_UBO_ex3_cal, delimiter=',')
```

- Load data you saved

In [ ]:
```
# load the saved data
c2f_Iout_UBO_ex3_save,calIout_UBO_ex3_save = np.loadtxt('./data/c2f_Iout_UBO_ex3_cal.c
```

- C2F plot

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

Iout_UBO_ex3 = calIout_UBO_ex3_save/256*30

plt.plot(Iout_UBO_ex3,c2f_Iout_UBO_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()
```

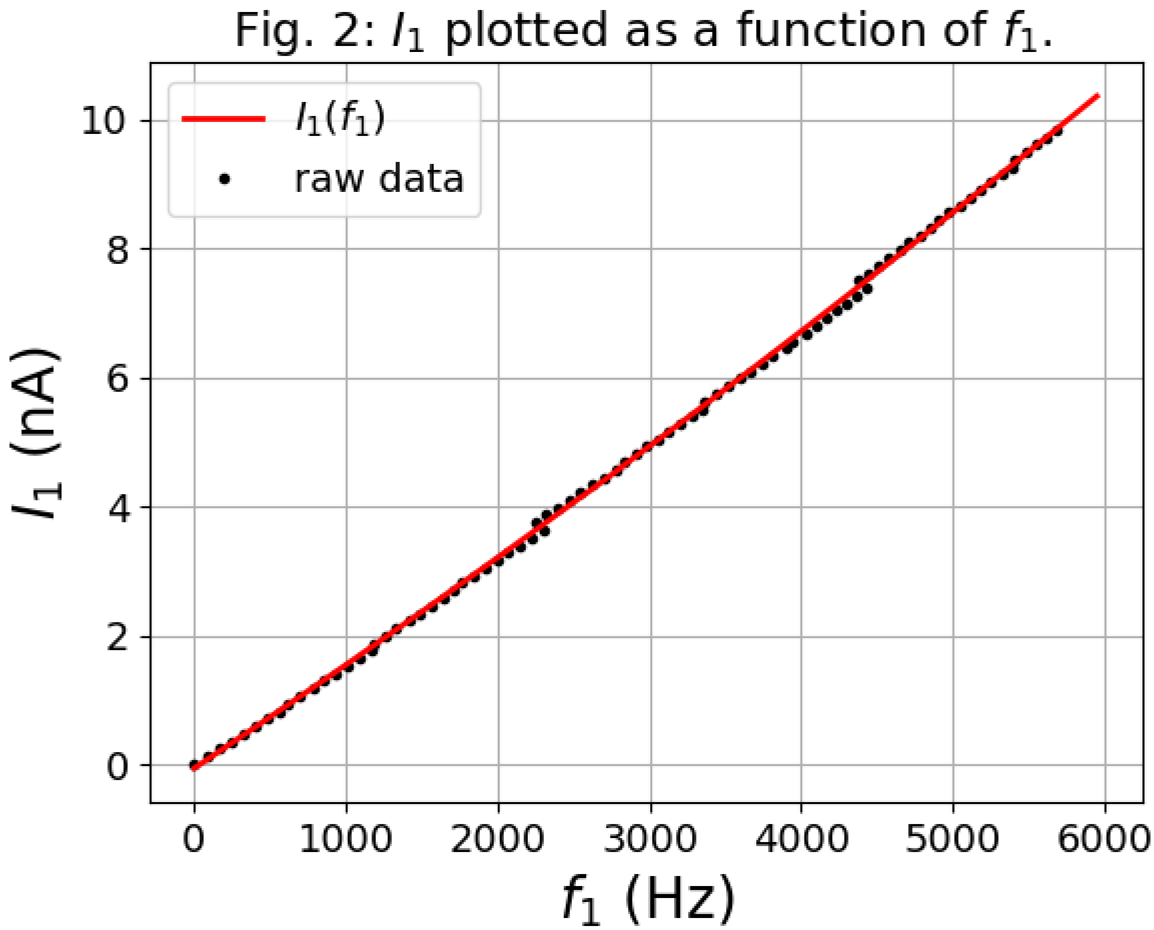


- Extract the function $I_-(f_-)$ (Hint: use second-order polynomial to increase accuracy)

In [ ]:
```
# plot the raw data
```

```
raw_UO, = plt.plot(c2f_Iout_UBO_ex3_save, Iout_UBO_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_UBO_ex3_save[low_bound:high_bound], Iout_UBO_ex3[low_
# print(a0)
# print(a1)
# print(a2)

# Print out the function I(f) you got
I_freq = np.polyfit(c2f_Iout_UBO_ex3_save[low_bound:high_bound], Iout_UBO_ex3[low_bour
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
2.977e-08 x + 0.001575 x - 0.06453
```



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, 51)])  #for  about 6  nA
```

The bias current is set to

$$I_b = w\frac{BG_{\text{fine}}}{256}I_{BG_{\text{master}}} = \frac{51}{256} \cdot 30\text{nA} \approx 5.9\text{nA}.$$

- 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, 0.8) # V2 = ?
v2_real = p.get_set_voltage(pyplane.DacChannel.AIN4)
print("V2 is set to {} V".format(v2_real))
```

```
V2 is set to 0.798827052116394 V
```

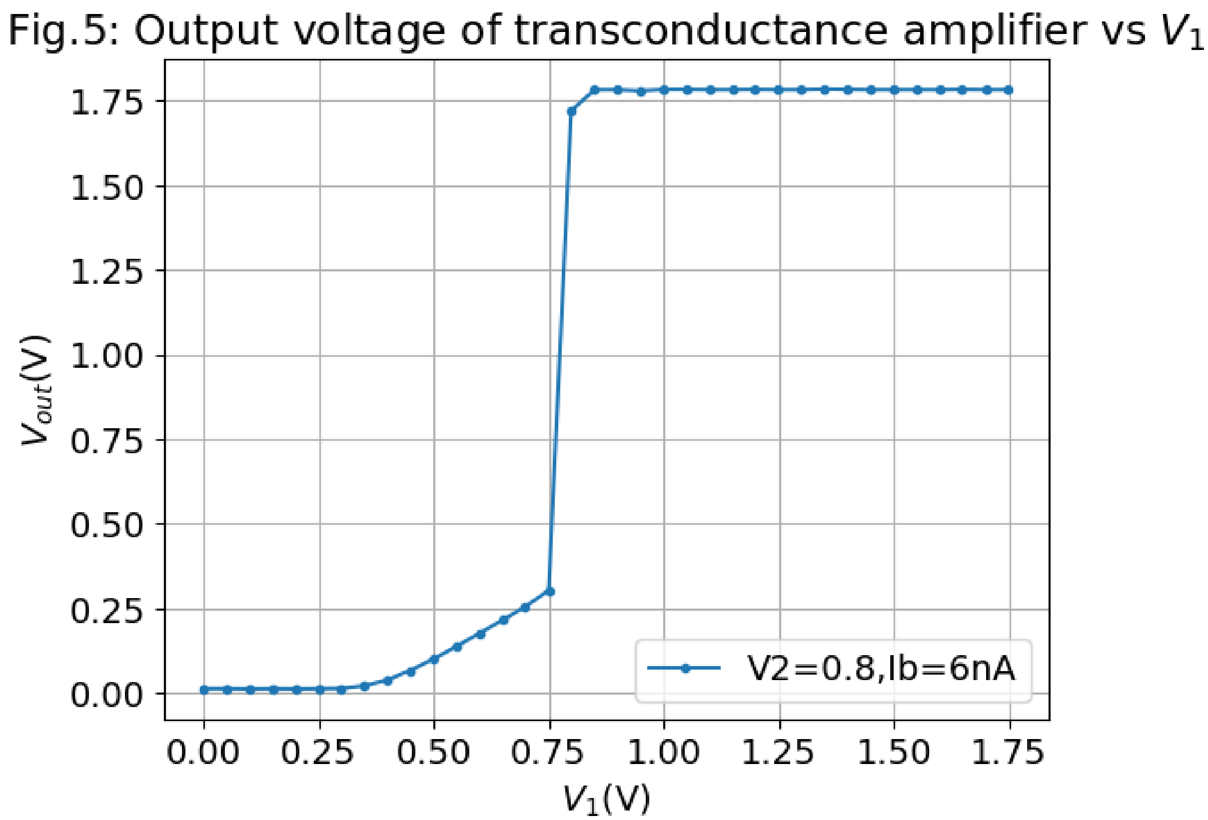
- Sweep V_1 and measure V_{out} (Hint: use get_set_voltage to get the real value set on the DAC)

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

V1_sweep_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 [ ]:
```
plt.plot(V1_sweep_ex3_getset,Vout_V1_sweep_ex3, ".-",label="V2=0.8,Ib=6nA")
plt.grid()
plt.title("Fig.5: Output voltage of transconductance amplifier vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of transconductance amplifier
for V2=0.8V,$I_b=0.8 nA$''')
plt.ylabel('''$V_{out}$(V)''')
plt.legend()
```

Out[ ]:
```
<matplotlib.legend.Legend at 0x7fad899327c0>
```



Output voltage of transconductance amplifier
for V2=0.8V,$I_b = 0.8nA$

- Save raw data

In [ ]:
```
# if the data looks nice, save it!
data_Vout_V1_sweep_ex3 = [V1_sweep_ex3_getset,Vout_V1_sweep_ex3,]
# save to csv file
np.savetxt('./data/data_Vout_V1_sweep_ex3.csv', data_Vout_V1_sweep_ex3, delimiter=',')
```

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 $I_b \approx 5.9\mathrm{nA}$ to $I_b \approx 2.3\mathrm{nA}$.

In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 20)])
```

In [ ]:
```
# your codes
import numpy as np
import time

V1_sweep_ex3_ib1 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex3_getset_ib1 = p.get_set_voltage(pyplane.DacChannel.AIN4)
```

```
Vout_V1_sweep_ex3_ib1 = []
V1_sweep_ex3_getset_ib1 = []

for n in range(len(V1_sweep_ex3_ib1)):

    p.set_voltage(pyplane.DacChannel.AIN3,V1_sweep_ex3_ib1[n]) #

    time.sleep(0.3) # settle time

    V1_sweep_ex3_getset_ib1.append(p.get_set_voltage(pyplane.DacChannel.AIN3))
#     Vout_V1_sweep_ex3.append(p.read_adc_instantaneous(13))
    Vout_V1_sweep_ex3_ib1.append(p.read_voltage(pyplane.AdcChannel.AOUT13))

data_Vout_V1_sweep_ex3_ib1 = [V1_sweep_ex3_getset_ib1,Vout_V1_sweep_ex3_ib1]
# save to csv file
np.savetxt('./data/data_Vout_V1_sweep_ex3_ib1.csv', data_Vout_V1_sweep_ex3_ib1, delimi
```

The bias current was switched from $I_b \approx 5.9\mathrm{nA}$ to $I_b \approx 1.1\mathrm{nA}$.

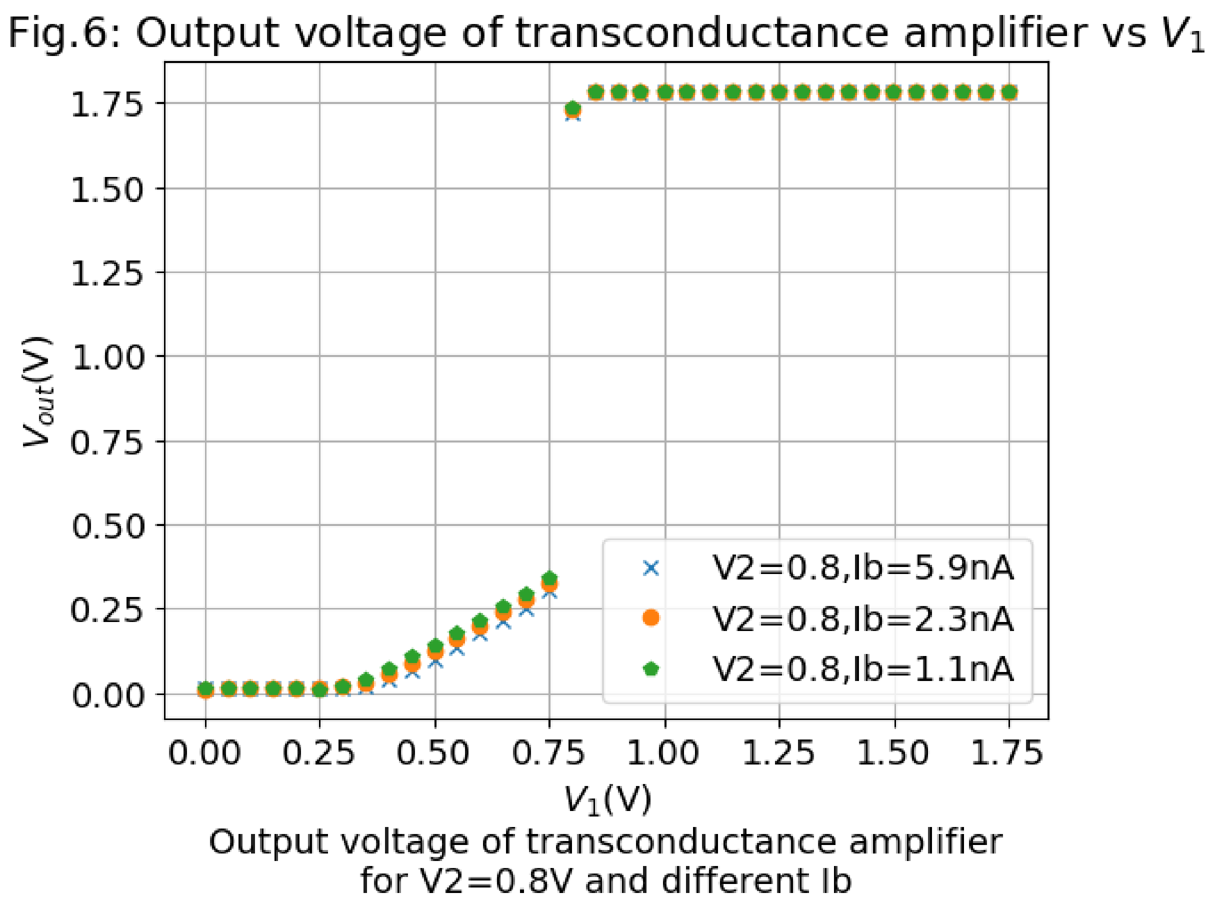
In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 10)])
```

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

V1_sweep_ex3_ib2 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex3_getset_ib2 = p.get_set_voltage(pyplane.DacChannel.AIN4)

Vout_V1_sweep_ex3_ib2 = []
V1_sweep_ex3_getset_ib2 = []

for n in range(len(V1_sweep_ex3_ib2)):

    p.set_voltage(pyplane.DacChannel.AIN3,V1_sweep_ex3_ib2[n]) #

    time.sleep(0.3) # settle time

    V1_sweep_ex3_getset_ib2.append(p.get_set_voltage(pyplane.DacChannel.AIN3))
#     Vout_V1_sweep_ex3.append(p.read_adc_instantaneous(13))
    Vout_V1_sweep_ex3_ib2.append(p.read_voltage(pyplane.AdcChannel.AOUT13))

data_Vout_V1_sweep_ex3_ib2 = [V1_sweep_ex3_getset_ib2,Vout_V1_sweep_ex3_ib2]
# save to csv file
np.savetxt('./data/data_Vout_V1_sweep_ex3_ib2.csv', data_Vout_V1_sweep_ex3_ib2, delimi
```

In [ ]:
```
# plot the three curves on one figure to compare
sweep0, Ib0 = np.loadtxt('./data/data_Vout_V1_sweep_ex3.csv',delimiter=',')
sweep1, Ib1 = np.loadtxt('./data/data_Vout_V1_sweep_ex3_ib1.csv',delimiter=',')
sweep2, Ib2 = np.loadtxt('./data/data_Vout_V1_sweep_ex3_ib2.csv',delimiter=',')

plt.plot(sweep0,Ib0, "x",label="V2=0.8,Ib=5.9nA")
plt.plot(sweep0,Ib1, "o",label="V2=0.8,Ib=2.3nA")
plt.plot(sweep0,Ib2, "p",label="V2=0.8,Ib=1.1nA")
plt.grid()
```

```
plt.title("Fig.6: Output voltage of transconductance amplifier vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of transconductance amplifier
for V2=0.8V and different Ib''')
plt.ylabel('''$V_{out}$(V)''')
plt.legend()
```

Out[ ]: <matplotlib.legend.Legend at 0x7fad83735370>



To conclude your observations:

> The biais current I_b does not seem to influence very much V_out as a function as V_1. However, we observe a slight delay in the beggining of the rise of V_{out} as I_b increases.

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 $V_2 = 0.8\mathrm{V}$ to $V_2 = 0.4\mathrm{V}$. The bias current was $I_b = 5.9\mathrm{nA}$

In [ ]:
```
# Set V2 = 0.4
p.set_voltage(pyplane.DacChannel.AIN4, 0.4) # V2 = ?
v2_real = p.get_set_voltage(pyplane.DacChannel.AIN4)
print("V2 is set to {} V".format(v2_real))
```

```
V2 is set to 0.399413526058197 V
```

In [ ]:
```
# Set Ib = 5.9
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
   pyplane.Coach.BiasAddress.NTA_VB_N, \
   pyplane.Coach.BiasType.N, \
   pyplane.Coach.BiasGenMasterCurrent.I30nA, 51)])  #for  about 6  nA
```

In [ ]:
```
# your codes
import numpy as np
import time

V1_sweep_ex3_v0 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex3_getset_v0 = p.get_set_voltage(pyplane.DacChannel.AIN4)

Vout_V1_sweep_ex3_v0 = []
V1_sweep_ex3_getset_v0 = []

for n in range(len(V1_sweep_ex3_v0)):

    p.set_voltage(pyplane.DacChannel.AIN3,V1_sweep_ex3_v0[n]) #

    time.sleep(0.3) # settle time

    V1_sweep_ex3_getset_v0.append(p.get_set_voltage(pyplane.DacChannel.AIN3))
#     Vout_V1_sweep_ex3.append(p.read_adc_instantaneous(13))
    Vout_V1_sweep_ex3_v0.append(p.read_voltage(pyplane.AdcChannel.AOUT13))

data_Vout_V1_sweep_ex3_v0 = [V1_sweep_ex3_getset_v0,Vout_V1_sweep_ex3_v0]
# save to csv file
np.savetxt('./data/data_Vout_V1_sweep_ex3_v0.csv', data_Vout_V1_sweep_ex3_v0, delimite
```

Switch voltage from $V_2 = 0.8\mathrm{V}$ to $V_2 = 1.6\mathrm{V}$. The bias current was $I_b = 5.9\mathrm{nA}$

In [ ]:
```
# Set V2 = 1.2
p.set_voltage(pyplane.DacChannel.AIN4, 1.6) # V2 = 1.6
v2_real = p.get_set_voltage(pyplane.DacChannel.AIN4)
print("V2 is set to {} V".format(v2_real))
```

```
V2 is set to 1.5994136333465576 V
```

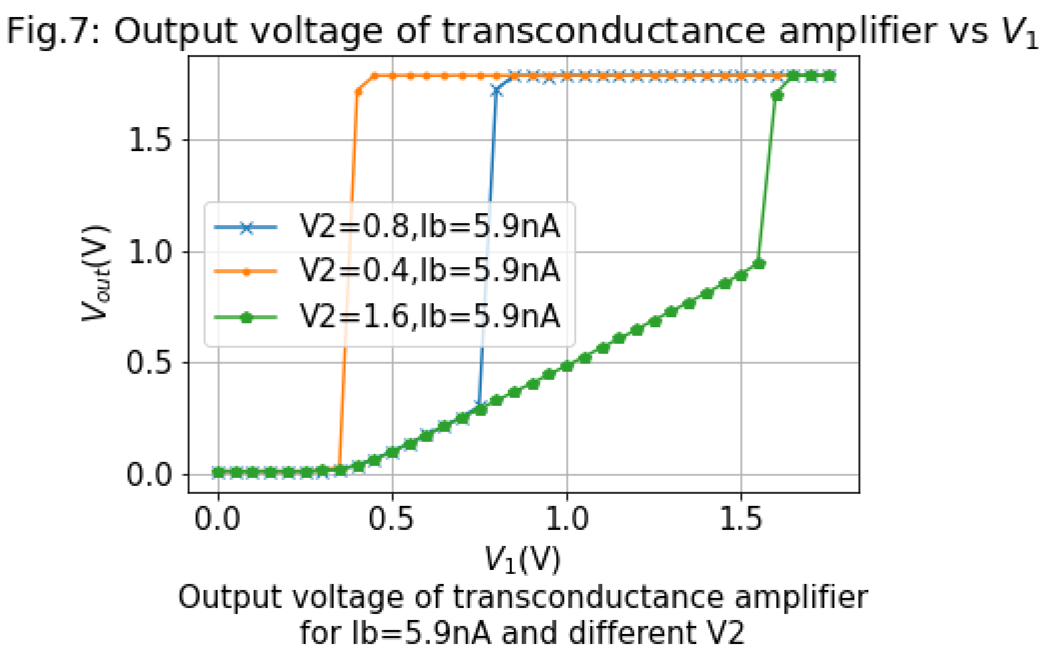
In [ ]:
```
import numpy as np
import time

V1_sweep_ex3_v1 = np.arange(0,1.8,0.05) # voltage V1 sweep range

V2_ex3_getset_v1 = p.get_set_voltage(pyplane.DacChannel.AIN4)

Vout_V1_sweep_ex3_v1 = []
V1_sweep_ex3_getset_v1 = []

for n in range(len(V1_sweep_ex3_v1)):

    p.set_voltage(pyplane.DacChannel.AIN3,V1_sweep_ex3_v1[n]) #

    time.sleep(0.3) # settle time

    V1_sweep_ex3_getset_v1.append(p.get_set_voltage(pyplane.DacChannel.AIN3))
```

```
#     Vout_V1_sweep_ex3.append(p.read_adc_instantaneous(13))
    Vout_V1_sweep_ex3_v1.append(p.read_voltage(pyplane.AdcChannel.AOUT13))

data_Vout_V1_sweep_ex3_v1 = [V1_sweep_ex3_getset_v1,Vout_V1_sweep_ex3_v1]
# save to csv file
np.savetxt('./data/data_Vout_V1_sweep_ex3_v1.csv', data_Vout_V1_sweep_ex3_v1, delimite
```

In [ ]:

```
# plot the three curves on one figure to compare
# plot the three curves on one figure to compare
sweepv0, Ib0 = np.loadtxt('./data/data_Vout_V1_sweep_ex3.csv',delimiter=',')
sweepv1, v1 = np.loadtxt('./data/data_Vout_V1_sweep_ex3_v0.csv',delimiter=',')
sweepv2, v2 = np.loadtxt('./data/data_Vout_V1_sweep_ex3_v1.csv',delimiter=',')

plt.plot(sweepv0,Ib0, "x-",label="V2=0.8,Ib=5.9nA")
plt.plot(sweepv0,v1, ".-",label="V2=0.4,Ib=5.9nA")
plt.plot(sweepv0,v2, "p-",label="V2=1.6,Ib=5.9nA")
plt.grid()
plt.title("Fig.7: Output voltage of transconductance amplifier vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of transconductance amplifier
for Ib=5.9nA and different V2''')
plt.ylabel('''$V_{out}$(V)''')
plt.legend()
```

Out[ ]: <matplotlib.legend.Legend at 0x283d45f6fd0>



To conclude your observations:

> Varying V2 highly influences when V_{out} will make the switch (of course), we can also see that the bigger V_2, the longer V_{out} increases linearly with V_1 (with a slope of kappa).

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, 51)])
```

Switch bias current back to $I_b = 5.9\mathrm{nA}$.

- Assign common mode voltage V_{cm}

In [ ]:
```
Vcm_ex3 = 0.9 # Vcm = 0.9V
```

- 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)
```

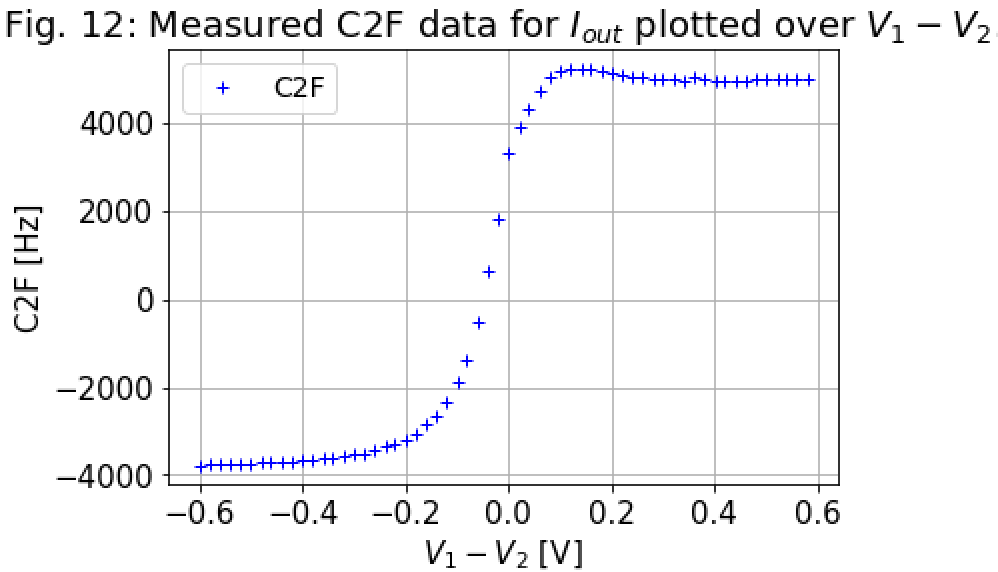
- Save raw data

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. $Vdiff$)

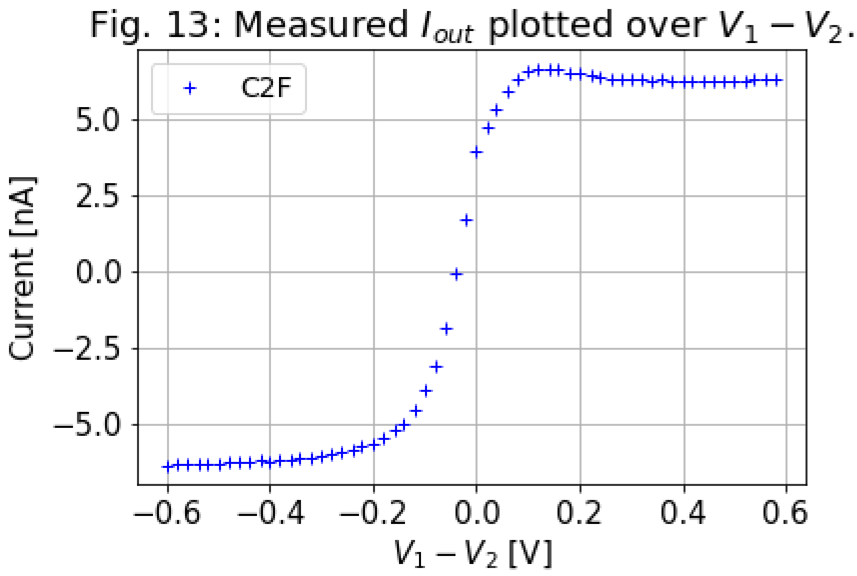
In [ ]:
```
import matplotlib.pyplot as plt
import numpy as np
plt.rcParams.update({'font.size': 15})

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]
[-3775. -3757. -3754. -3753. -3743. -3742. -3725. -3716. -3696. -3684.
 -3681. -3654. -3631. -3602. -3577. -3533. -3506. -3433. -3362. -3280.
 -3188. -3048. -2856. -2660. -2344. -1881. -1363.  -516.   633.  1819.
  3311.  3896.  4324.  4740.  5026.  5162.  5228.  5228.  5233.  5159.
  5117.  5072.  5055.  5021.  5013.  4995.  4988.  4970.  5025.  4976.
  4966.  4965.  4975.  4975.  4976.  4978.  4982.  4984.  4989.  5004.]
```



- 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 [ ]:
```
a2_1 = 4.409e-08
a1_1 = 0.001044
a0_1 = -0.06894

a2_2 = 2.977e-08
a1_2 = 0.001575
a0_2 = -0.06453

I_plus = a2_1*c2f_Iout_UO_Vcm09_ex3**2+a1_1*c2f_Iout_UO_Vcm09_ex3+a0_1
I_minus = a2_2*c2f_Iout_UBO_Vcm09_ex3**2+a1_2*c2f_Iout_UBO_Vcm09_ex3+a0_2

plt.plot(Vdiff_Vcm09,I_plus-I_minus,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 13: Measured $I_{out}$ plotted over $V_1-V_2$.')
plt.grid()
plt.show()
```



- Compute transconductance

In [ ]:
```
#gm = Ib*kappa / 2 UT
Ib = 5.9e-9
kappa = (v2[20]-v2[15])/(sweepv0[20]-sweepv0[15]) #kappa is the slope of vout vs (v1-v
UT = 0.025
gm = Ib*kappa/UT
print("kappa: ",np.round(kappa,3))
print('g_m: ',gm)
```

```
kappa:  0.784
g_m:  1.849213103060824e-07
```

- 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.

> Transistor mismatch will cause the flow of current to be different in the mirror (and differential) parts of the circuit thus the current "generated" by M4 may not be exactly I1, which would explain any assymetries in the graph. weprobably could not distinguish between mismatch in the mirror and differential pair. In Fig.13, we can see that the sigmoid is not centered at x=0 and has a slight overshoot at x=0.1.

3.4.2 Different bias currents

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

In [ ]:
```
# Set Ib = ?
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 90)])
```

The bias current was switched from $I_b \approx 5.9\mathrm{nA}$ to $I_b \approx 10.5\mathrm{nA}$.

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)

# if the data looks nice, save it!
data_Iout_Vcm09_ex3_I1 = [V1_sweep_ex3_getset,V2_ex3_getset,c2f_Iout_UO_Vcm_ex3,c2f_Io
# save to csv file
np.savetxt('./data/V1_sweep_Iout_Vcm09_ex3_I1.csv', data_Iout_Vcm09_ex3_I1, delimiter=
```

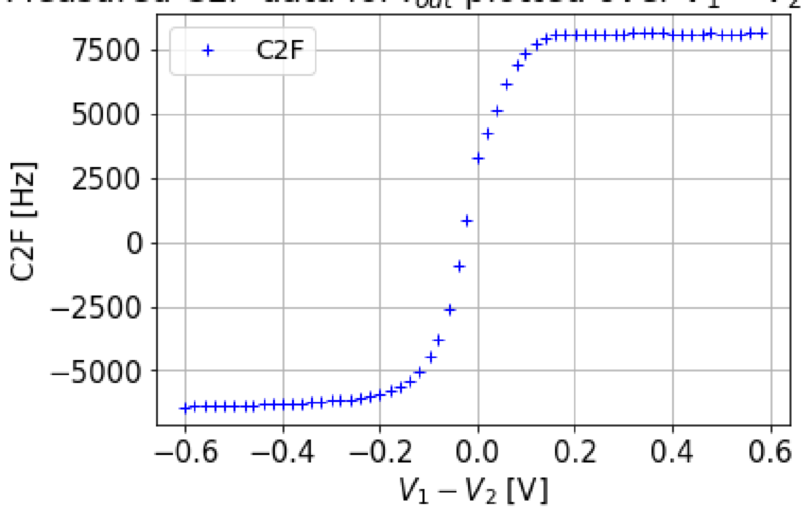
Plot raw data

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

V1_sweep_Iout_Vcm09_ex3_getset_I1,V2_Iout_Vcm09_ex3_getset_I1,c2f_Iout_UO_Vcm09_ex3_I1

Vdiff_Vcm09_I1 = V1_sweep_Iout_Vcm09_ex3_getset_I1-V2_Iout_Vcm09_ex3_getset_I1
```

```
print(Vdiff_Vcm09_I1)
c2f_Iout_Vcm09_I1 = c2f_Iout_UO_Vcm09_ex3_I1 - c2f_Iout_UBO_Vcm09_ex3_I1
print(c2f_Iout_Vcm09_I1)

plt.plot(Vdiff_Vcm09_I1,c2f_Iout_Vcm09_I1,'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 $V_1-V_2$, for Ib=10.
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]
[-6415. -6407. -6391. -6380. -6374. -6367. -6357. -6347. -6336. -6324.
 -6313. -6296. -6282. -6258. -6228. -6191. -6162. -6123. -6064. -6001.
 -5907. -5779. -5602. -5396. -5023. -4470. -3789. -2627.  -928.   873.
  3267.  4275.  5158.  6201.  6915.  7367.  7721.  7991.  8079.  8135.
  8078.  8081.  8090.  8092.  8092.  8091.  8177.  8176.  8175.  8151.
  8102.  8107.  8106.  8120.  8191.  8131.  8132.  8138.  8146.  8151.]
```

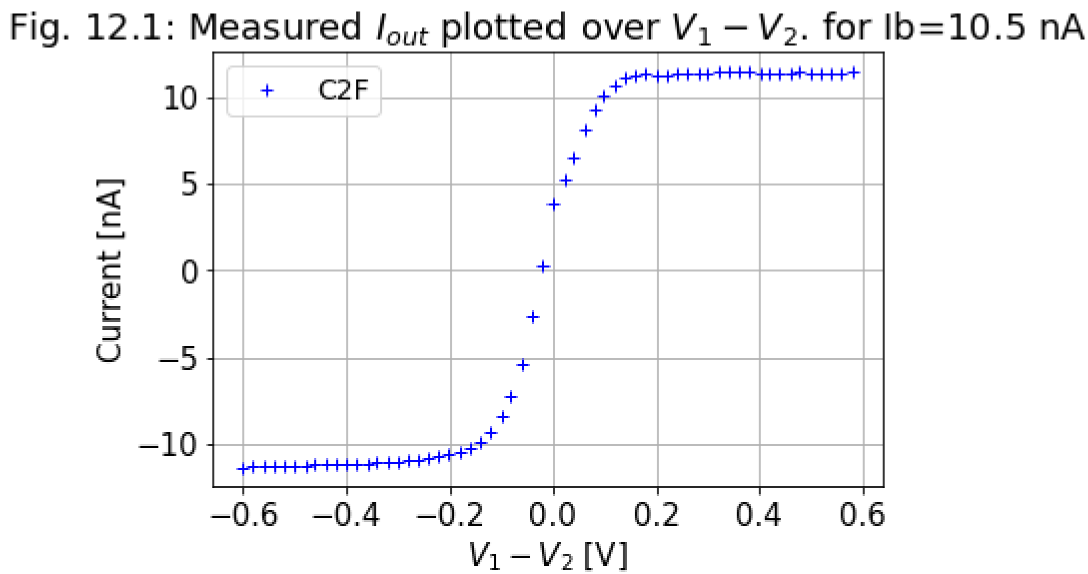
Fig. 12: Measured C2F data for I_{out} plotted over $V_1 - V_2$, for Ib=10.5 nA



Convert frequency

In [ ]:
```
a2_1 = 4.409e-08
a1_1 = 0.001044
a0_1 = -0.06894

a2_2 = 2.977e-08
a1_2 = 0.001575
a0_2 = -0.06453

I_plus_I1 = a2_1*c2f_Iout_UO_Vcm09_ex3_I1**2+a1_1*c2f_Iout_UO_Vcm09_ex3_I1+a0_1
I_minus_I1 = a2_2*c2f_Iout_UBO_Vcm09_ex3_I1**2+a1_2*c2f_Iout_UBO_Vcm09_ex3_I1+a0_2
```

```
plt.plot(Vdiff_Vcm09_I1,I_plus_I1-I_minus_I1,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 12.1: Measured $I_{out}$ plotted over $V_1-V_2$. for Ib=10.5 nA')
plt.grid()
plt.show()
```



In [ ]:
```
# Set Ib = 2.3 nA
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 20)])
```

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)

# if the data looks nice, save it!
data_Iout_Vcm09_ex3_I2 = [V1_sweep_ex3_getset,V2_ex3_getset,c2f_Iout_UO_Vcm_ex3,c2f_Io
# save to csv file
np.savetxt('./data/V1_sweep_Iout_Vcm09_ex3_I2.csv', data_Iout_Vcm09_ex3_I2, delimiter=
```

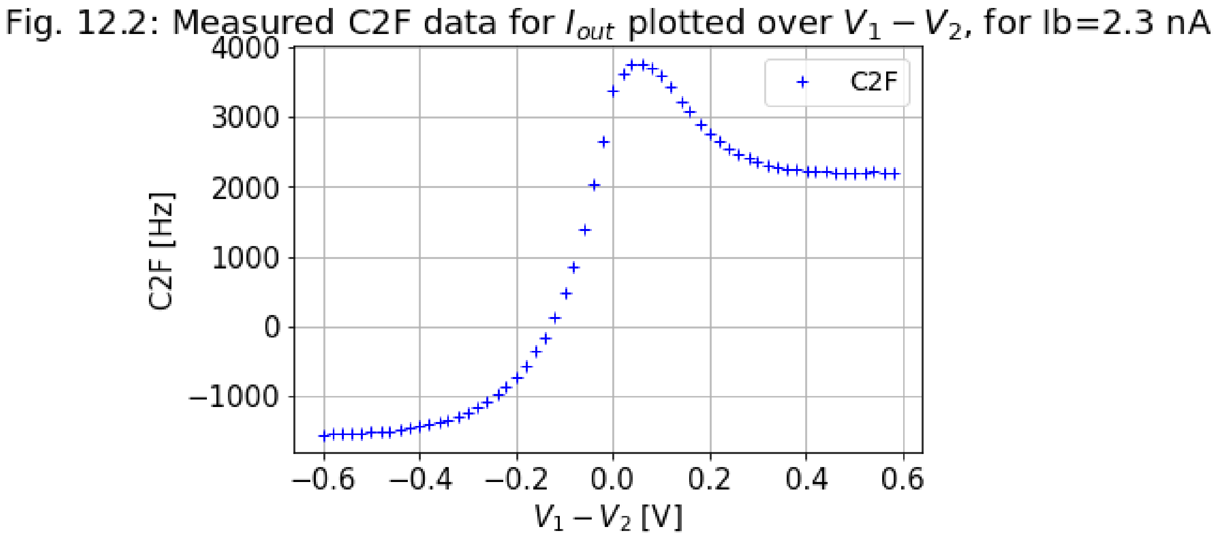
The bias current was switched from $I_b \approx 5.9\mathrm{nA}$ to $I_b \approx 2.3\mathrm{nA}$.

Plot raw data

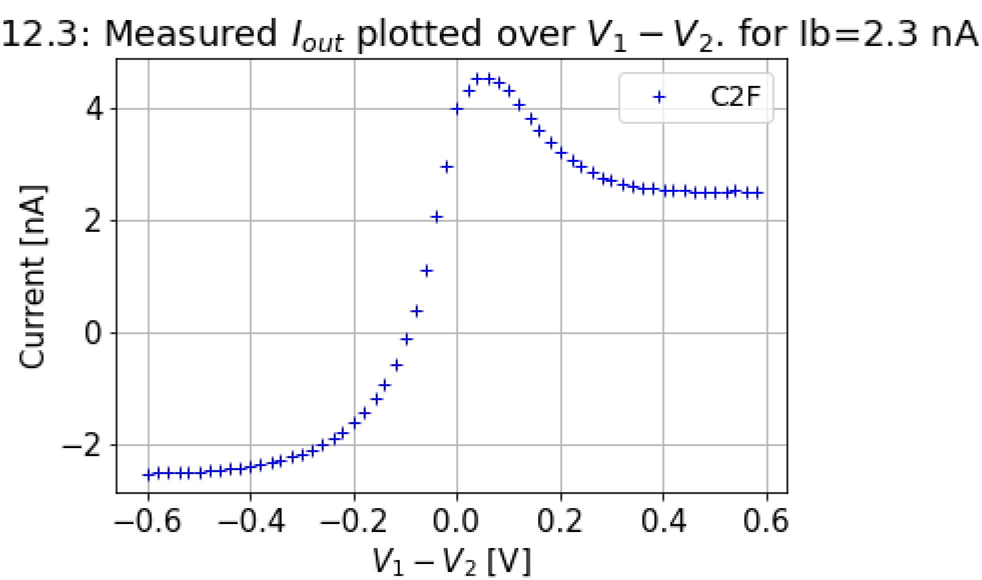
In [ ]:

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

V1_sweep_Iout_Vcm09_ex3_getset_I2,V2_Iout_Vcm09_ex3_getset_I2,c2f_Iout_UO_Vcm09_ex3_I2

Vdiff_Vcm09_I2 = V1_sweep_Iout_Vcm09_ex3_getset_I2-V2_Iout_Vcm09_ex3_getset_I2
print(Vdiff_Vcm09_I2)
c2f_Iout_Vcm09_I2 = c2f_Iout_UO_Vcm09_ex3_I2 - c2f_Iout_UBO_Vcm09_ex3_I2
print(c2f_Iout_Vcm09_I2)

plt.plot(Vdiff_Vcm09_I2,c2f_Iout_Vcm09_I2,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('C2F [Hz]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 12.2: Measured C2F data for $I_{out}$ plotted over $V_1-V_2$, for Ib=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]
[-1544. -1539. -1536. -1529. -1523. -1513. -1501. -1491. -1476. -1454.
 -1434. -1405. -1367. -1334. -1282. -1223. -1160. -1076.  -974.  -872.
  -730.  -559.  -357.  -156.   133.   488.   856.  1386.  2040.  2657.
  3364.  3608.  3744.  3756.  3698.  3589.  3419.  3220.  3070.  2905.
  2764.  2642.  2558.  2470.  2406.  2360.  2315.  2281.  2259.  2241.
  2227.  2217.  2211.  2203.  2200.  2197.  2196.  2213.  2195.  2195.]
```



In [ ]:
```
a2_1 = 4.409e-08
a1_1 = 0.001044
a0_1 = -0.06894

a2_2 = 2.977e-08
a1_2 = 0.001575
a0_2 = -0.06453

I_plus_I2 = a2_1*c2f_Iout_UO_Vcm09_ex3_I2**2+a1_1*c2f_Iout_UO_Vcm09_ex3_I2+a0_1
I_minus_I2 = a2_2*c2f_Iout_UBO_Vcm09_ex3_I2**2+a1_2*c2f_Iout_UBO_Vcm09_ex3_I2+a0_2

plt.plot(Vdiff_Vcm09_I2,I_plus_I2-I_minus_I2,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 12.3: Measured $I_{out}$ plotted over $V_1-V_2$. for Ib=2.3 nA')
plt.grid()
plt.show()
```

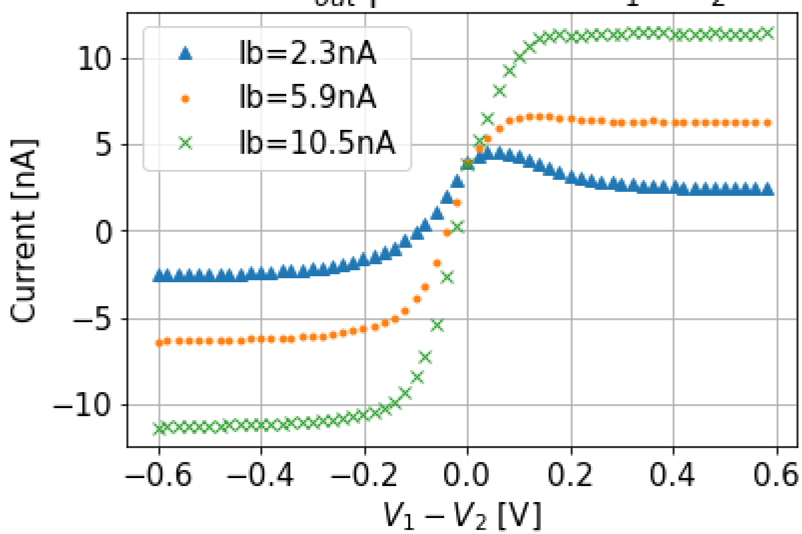


To conclude your observations:

We can plot the three curves in one plot:

In [ ]:
```
plt.plot(Vdiff_Vcm09,I_plus_I2-I_minus_I2,"^",label="Ib=2.3nA")
plt.plot(Vdiff_Vcm09,I_plus-I_minus,".",label="Ib=5.9nA")
plt.plot(Vdiff_Vcm09,I_plus_I1-I_minus_I1,"x",label="Ib=10.5nA")


plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend()
plt.title('Fig. 12.4: Measured $I_{out}$ plotted over $V_1-V_2$. for various Ib')
plt.grid()
plt.show()
```

Fig. 12.4: Measured I_{out} plotted over $V_1 - V_2$. for various Ib



> We can observe that the maximum output current is proportional to Ib (makes sense when considering the equations), and that at low Ib values the linear range seems to overshoot a little. The linear range and slope of the linear range is also proportional to Ib. All three curves seem to intersect at the same point ($V_1 - V_2 = 0$)...

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_ex3 = 0.4
```

In [ ]:
```
# Set Ib = ?
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.NTA_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 90)])
```

The bias current was switched back to $I_b \approx 10.5\mathrm{nA}$.

In [ ]:
```
# your code, data aquisition
import numpy as np
import time

V1_sweep_ex3 = np.arange(0.2, 0.7, 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)

# if the data looks nice, save it!
data_Iout_Vcm09_ex3_Vcm1 = [V1_sweep_ex3_getset,V2_ex3_getset,c2f_Iout_UO_Vcm_ex3,c2f_
# save to csv file
np.savetxt('./data/V1_sweep_Iout_Vcm09_ex3_V_CM1.csv', data_Iout_Vcm09_ex3_Vcm1, delim
```

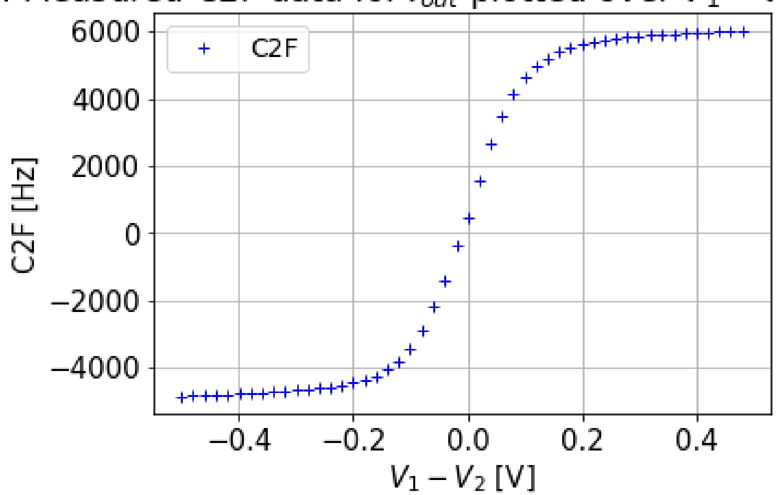
plot raw

In [ ]:
```
plt.rcParams.update({'font.size': 15})

V1_sweep_Iout_Vcm09_ex3_getset_Vcm1,V2_Iout_Vcm09_ex3_getset_Vcm1,c2f_Iout_UO_Vcm09_ex

Vdiff_Vcm09_Vcm1 = V1_sweep_Iout_Vcm09_ex3_getset_Vcm1-V2_Iout_Vcm09_ex3_getset_Vcm1
print(Vdiff_Vcm09_Vcm1)
c2f_Iout_Vcm09_Vcm1 = c2f_Iout_UO_Vcm09_ex3_Vcm1 - c2f_Iout_UBO_Vcm09_ex3_Vcm1
print(c2f_Iout_Vcm09_Vcm1)

plt.plot(Vdiff_Vcm09_Vcm1,c2f_Iout_Vcm09_Vcm1,'b+')

plt.xlabel('$V_1-V_2$ [V]')
```

```
plt.ylabel('C2F [Hz]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 13.2: Measured C2F data for $I_{out}$ plotted over $V_1-V_2$, for Vcm=
plt.grid()
plt.show()
```

```
[-0.49970684 -0.48035194 -0.45923757 -0.43988275 -0.42052792 -0.39941356
 -0.38005868 -0.36070383 -0.33958948 -0.32023466 -0.29912028 -0.27976546
 -0.26041058 -0.2392962  -0.21994138 -0.20058653 -0.17947218 -0.16011736
 -0.14076245 -0.1196481  -0.10029328 -0.0791789  -0.05982405 -0.04046923
 -0.01935485  0.          0.01935485  0.04046923  0.05982405  0.0791789
  0.10029328  0.1196481   0.14076245  0.16011736  0.17947218  0.20058653
  0.21994138  0.2392962   0.26041058  0.27976546  0.29912028  0.32023466
  0.33958948  0.36070383  0.38005868  0.39941356  0.42052792  0.43988275
  0.45923757  0.48035194]
[-4842. -4830. -4817. -4803. -4790. -4778. -4755. -4737. -4719. -4700.
 -4672. -4646. -4613. -4568. -4525. -4453. -4357. -4238. -4060. -3803.
 -3461. -2890. -2204. -1394.  -359.   443.  1574.  2657.  3473.  4118.
  4628.  4949.  5205.  5384.  5496.  5602.  5681.  5728.  5782.  5821.
  5841.  5872.  5894.  5919.  5941.  5958.  5972.  5987.  6005.  6017.]
```

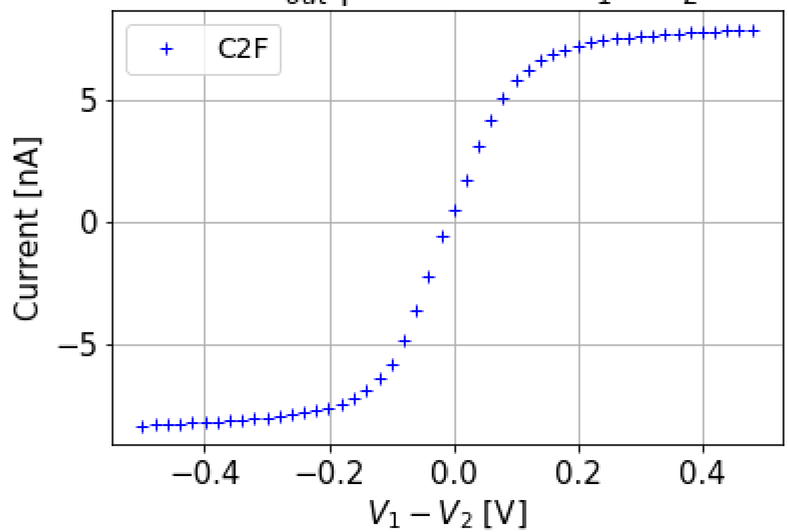
Fig. 13.2: Measured C2F data for I_{out} plotted over $V_1 - V_2$, for Vcm=0.4 V



Convert to current

In [ ]:
```
a2_1 = 4.409e-08
a1_1 = 0.001044
a0_1 = -0.06894

a2_2 = 2.977e-08
a1_2 = 0.001575
a0_2 = -0.06453

I_plus_Vcm1 = a2_1*c2f_Iout_UO_Vcm09_ex3_Vcm1**2+a1_1*c2f_Iout_UO_Vcm09_ex3_Vcm1+a0_1
I_minus_Vcm1 = a2_2*c2f_Iout_UBO_Vcm09_ex3_Vcm1**2+a1_2*c2f_Iout_UBO_Vcm09_ex3_Vcm1+a0

plt.plot(Vdiff_Vcm09_Vcm1,I_plus_Vcm1-I_minus_Vcm1,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 13.3: Measured $I_{out}$ plotted over $V_1-V_2$. for Vcm=0.4 V')
plt.grid()
plt.show()
```

Fig. 13.3: Measured I_{out} plotted over $V_1 - V_2$. for Vcm=0.4 V



Change to Vcm = 0.2V

In [ ]:
```
# Assign common mode voltage Vcm
Vcm_ex3 = 0.2
```

In [ ]:
```
# your code, data aquisition
import numpy as np
import time

V1_sweep_ex3 = np.arange(0.1, 0.3, 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)
```

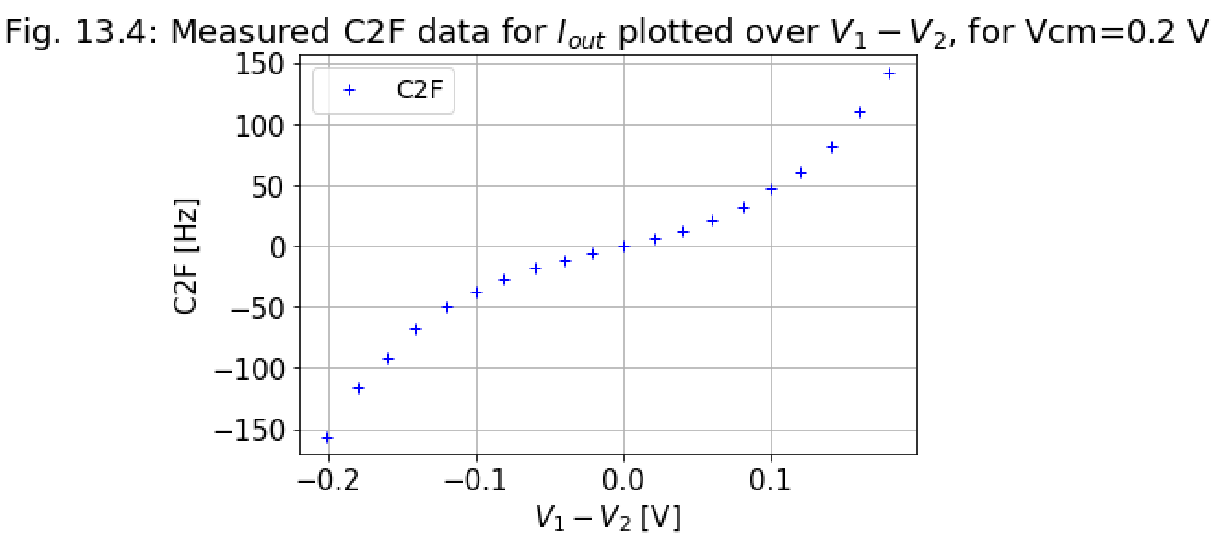
```
# print(c2f_Iout_UO_Vcm_ex3)
# print(c2f_Iout_UBO_Vcm_ex3)

# if the data looks nice, save it!
data_Iout_Vcm09_ex3_Vcm2 = [V1_sweep_ex3_getset,V2_ex3_getset,c2f_Iout_UO_Vcm_ex3,c2f_
# save to csv file
np.savetxt('./data/V1_sweep_Iout_Vcm09_ex3_Vcm2.csv', data_Iout_Vcm09_ex3_Vcm2, delimi
```

Plot raw

In [ ]:

```
plt.rcParams.update({'font.size': 15})

V1_sweep_Iout_Vcm09_ex3_getset_Vcm2,V2_Iout_Vcm09_ex3_getset_Vcm2,c2f_Iout_UO_Vcm09_ex

Vdiff_Vcm09_Vcm2 = V1_sweep_Iout_Vcm09_ex3_getset_Vcm2-V2_Iout_Vcm09_ex3_getset_Vcm2
print(Vdiff_Vcm09_Vcm2)
c2f_Iout_Vcm09_Vcm2 = c2f_Iout_UO_Vcm09_ex3_Vcm2 - c2f_Iout_UBO_Vcm09_ex3_Vcm2
print(c2f_Iout_Vcm09_Vcm2)

plt.plot(Vdiff_Vcm09_Vcm2,c2f_Iout_Vcm09_Vcm2,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('C2F [Hz]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 13.4: Measured C2F data for $I_{out}$ plotted over $V_1-V_2$, for Vcm=
plt.grid()
plt.show()
```

```
[-0.20058654 -0.17947215 -0.16011732 -0.14076249 -0.1196481  -0.10029326
 -0.08093843 -0.05982405 -0.04046921 -0.02111436  0.          0.02111436
  0.04046921  0.05982405  0.08093843  0.10029326  0.1196481   0.14076249
  0.16011732  0.17947215]
[-156. -116.  -92.  -68.  -49.  -37.  -26.  -17.  -11.   -5.    1.    6.
   13.   22.   32.   47.   61.   83.  111.  143.]
```

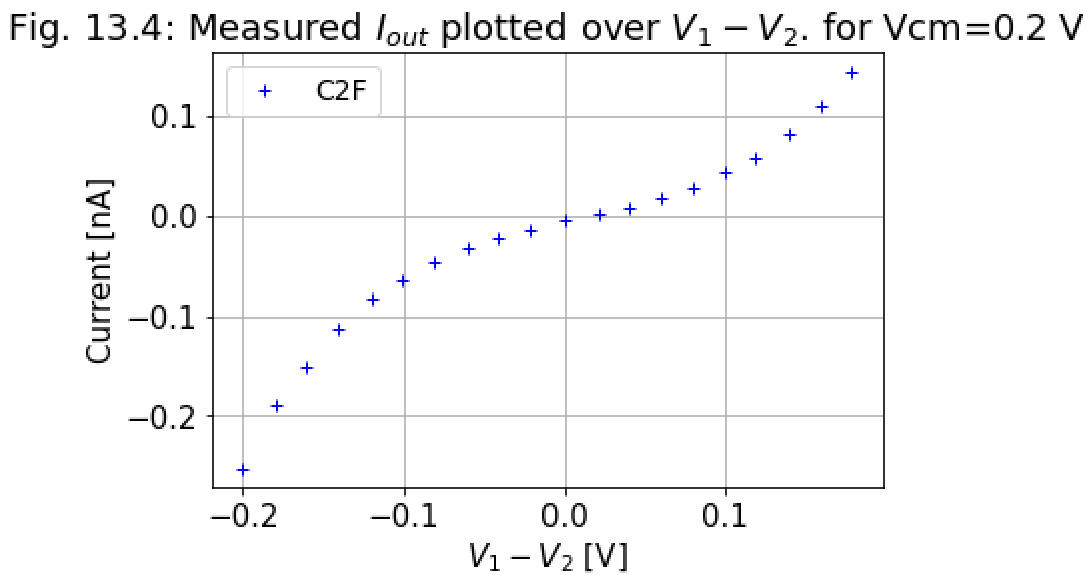


Convert to current

In [ ]:

```
a2_1 = 4.409e-08
a1_1 = 0.001044
a0_1 = -0.06894

a2_2 = 2.977e-08
```

```
a1_2 = 0.001575
a0_2 = -0.06453

I_plus_Vcm2 = a2_1*c2f_Iout_UO_Vcm09_ex3_Vcm2**2+a1_1*c2f_Iout_UO_Vcm09_ex3_Vcm2+a0_1
I_minus_Vcm2 = a2_2*c2f_Iout_UBO_Vcm09_ex3_Vcm2**2+a1_2*c2f_Iout_UBO_Vcm09_ex3_Vcm2+a0

plt.plot(Vdiff_Vcm09_Vcm2,I_plus_Vcm2-I_minus_Vcm2,'b+')

plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend(['C2F'],prop={'size': 14})
plt.title('Fig. 13.4: Measured $I_{out}$ plotted over $V_1-V_2$. for Vcm=0.2 V')
plt.grid()
plt.show()
```

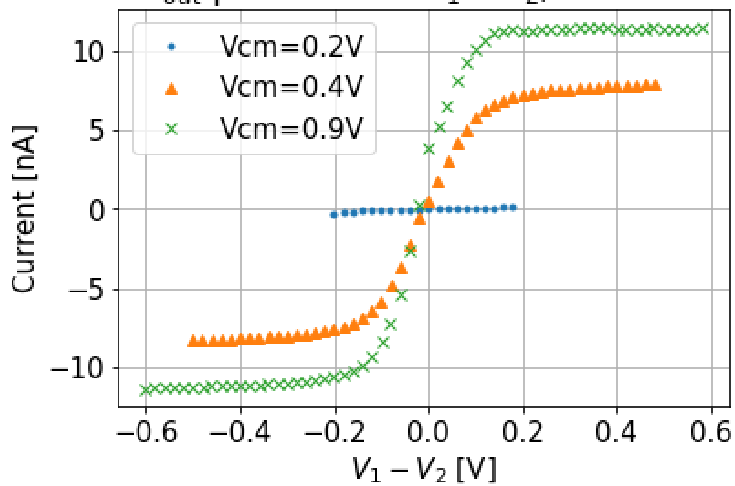


To conclude your observations:

We can plot all measures in one graph

In [ ]:
```
plt.plot(Vdiff_Vcm09_Vcm2,I_plus_Vcm2-I_minus_Vcm2,".",label="Vcm=0.2V")
plt.plot(Vdiff_Vcm09_Vcm1,I_plus_Vcm1-I_minus_Vcm1,"^",label="Vcm=0.4V")
plt.plot(Vdiff_Vcm09,I_plus_I1-I_minus_I1,"x",label="Vcm=0.9V")


plt.xlabel('$V_1-V_2$ [V]')
plt.ylabel('Current [nA]')
plt.legend()
plt.title('Fig. 13.5: Measured $I_{out}$ plotted over $V_1-V_2$, for various Vcm, Ib=1
plt.grid()
plt.show()
```

Fig. 13.5: Measured I_{out} plotted over $V_1 - V_2$, for various Vcm, Ib=10.5 nA



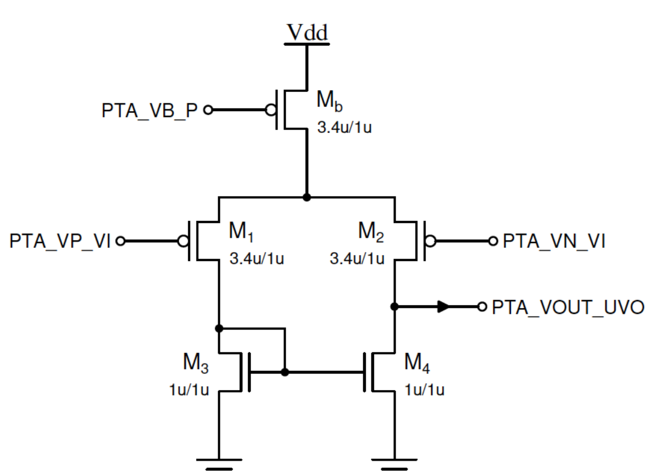
> We can see that increasing Vcm has more or less the same effect as increasing Ib on Iout. Decreasing Vm lowers the range of $V_1 - V_2$ (because: $V_m = \frac{1}{2}(V_1 - V_2)$).

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.

> When the common mode voltage is too small, the corresponding current does not have the tanh shape, but more of a sinh shape. This is because we are no more satisfying the condition $max(V_1, V_2) > V_b + \frac{4UT}{\kappa}$ and M3 is no longer in saturation (Probably why we measure a current that ressembles a transistor in triode regime).

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 $I_b = ???\text{nA}$ in the basic measurement to $I_b = ???\text{nA}$.

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 $I_b = ???\mathrm{nA}$.

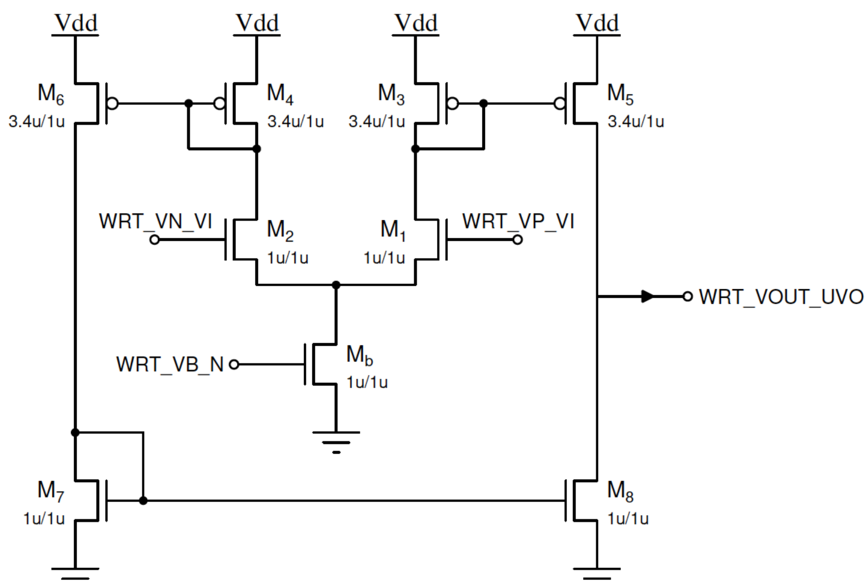
In [ ]:

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
```

Out[ ]:
```
0.8991203308105469
```

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)

data = [V1_sweep_ex5_getset,Vout_V1_sweep_ex5]
np.savetxt('./data/V1_sweep_Vout_V209_ex5.csv', data, delimiter=',')
```

```
0.8991203308105469
[0.0, 0.04926686733961105, 0.0985337346792221, 0.1495601385831833, 0.1988269984722137
5, 0.24985340237617493, 0.2991202771663666, 0.3483871519565582, 0.399413526058197, 0.
44868040084838867, 0.49970680475234985, 0.5489736795425415, 0.5982405543327332, 0.649
2669582366943, 0.698533833026886, 0.7495601773262024, 0.798827052116394, 0.8498534560
203552, 0.8991203308105469, 0.9483872056007385, 0.9994136095046997, 1.048680424690246
6, 1.0997068881988525, 1.1489737033843994, 1.1982406377792358, 1.2492669820785522, 1.
2985339164733887, 1.349560260772705, 1.3988271951675415, 1.449853539466858, 1.4991203
546524048, 1.5483872890472412, 1.5994136333465576, 1.648680567741394, 1.6997069120407
104, 1.7489738464355469]
[0.011279297061264515, 0.0120849609375, 0.012890624813735485, 0.0120849609375, 0.0120
849609375, 0.0120849609375, 0.0120849609375, 0.011279297061264515, 0.0120849609375,
0.011279297061264515, 0.0120849609375, 0.0120849609375, 0.0120849609375, 0.0120849609
375, 0.0120849609375, 0.0120849609375, 0.0120849609375, 0.02739257737994194, 1.764404
296875, 1.780517578125, 1.782934546470642, 1.782934546470642, 1.782934546470642, 1.78
37402820587158, 1.7837402820587158, 1.7837402820587158, 1.7837402820587158, 1.7829345
46470642, 1.7837402820587158, 1.7837402820587158, 1.782934546470642, 1.78535151481628
42, 1.7845458984375, 1.7837402820587158, 1.7837402820587158, 1.7837402820587158]
```

- Plot raw data

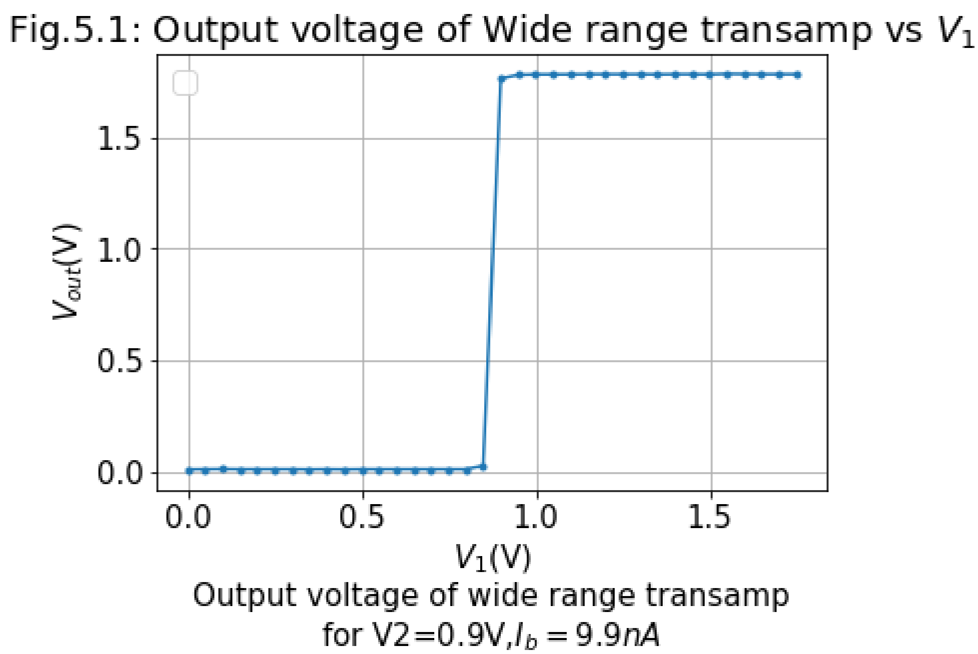
In [ ]:

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

V1_sweep_ex5_getset,Vout_V1_sweep_ex5 = np.loadtxt('./data/V1_sweep_Vout_V209_ex5.csv'

plt.plot(V1_sweep_ex5_getset,Vout_V1_sweep_ex5, ".-")
plt.grid()
plt.title("Fig.5.1: Output voltage of Wide range transamp vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.9V,$I_b=9.9 nA$''')
plt.ylabel('''$V_{out}$(V)''')
plt.legend()
```

```
No artists with labels found to put in legend.  Note that artists whose label start w
ith an underscore are ignored when legend() is called with no argument.
```

Out[ ]:

```
<matplotlib.legend.Legend at 0x283da338c10>
```



- 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 $I_b \approx 9.9\mathrm{nA}$ from $I_b \approx 4.6\mathrm{nA}$ in the basic measurement.

In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.WRT_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 40)])
```

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)

data = [V1_sweep_ex5_getset,Vout_V1_sweep_ex5]
np.savetxt('./data/V1_sweep_Vout_V209_ex5_I1.csv', data, delimiter=',')
```

```
0.8991203308105469
[0.0, 0.04926686733961105, 0.0985337346792221, 0.1495601385831833, 0.1988269984722137
5, 0.24985340237617493, 0.2991202771663666, 0.3483871519565582, 0.399413526058197, 0.
44868040084838867, 0.49970680475234985, 0.5489736795425415, 0.5982405543327332, 0.649
2669582366943, 0.698533833026886, 0.7495601773262024, 0.798827052116394, 0.8498534560
203552, 0.8991203308105469, 0.9483872056007385, 0.9994136095046997, 1.048680424690246
6, 1.0997068881988525, 1.1489737033843994, 1.1982406377792358, 1.2492669820785522, 1.
2985339164733887, 1.349560260772705, 1.3988271951675415, 1.449853539466858, 1.4991203
546524048, 1.5483872890472412, 1.5994136333465576, 1.648680567741394, 1.6997069120407
104, 1.7489738464355469]
[0.011279297061264515, 0.011279297061264515, 0.011279297061264515, 0.0112792970612645
15, 0.0120849609375, 0.0120849609375, 0.011279297061264515, 0.0120849609375, 0.012084
9609375, 0.011279297061264515, 0.012890624813735485, 0.0120849609375, 0.012084960937
5, 0.011279297061264515, 0.012890624813735485, 0.0120849609375, 0.0120849609375, 0.02
497558668255806, 1.7813231945037842, 1.7926025390625, 1.778906226158142, 1.7885742187
5, 1.778906226158142, 1.7917969226837158, 1.782934546470642, 1.794213891029358, 1.779
7119617462158, 1.795019507408142, 1.7813231945037842, 1.7958252429962158, 1.795825242
9962158, 1.790185570716858, 1.7845458984375, 1.7917969226837158, 1.780517578125, 1.79
9047827720642]
```

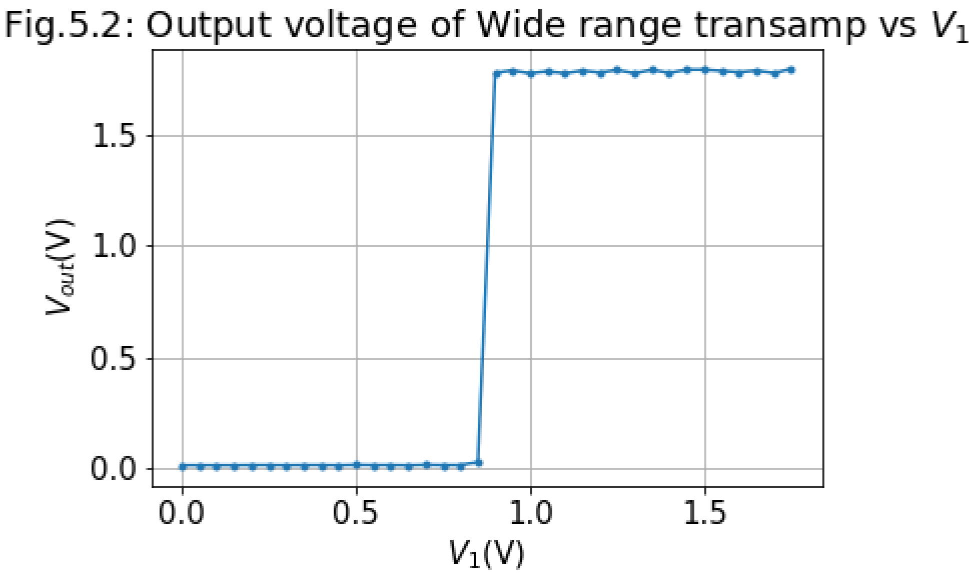
Plot

In [ ]:

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

V1_sweep_ex5_getset_I1,Vout_V1_sweep_ex5_I1 = np.loadtxt('./data/V1_sweep_Vout_V209_ex

plt.plot(V1_sweep_ex5_getset_I1,Vout_V1_sweep_ex5_I1, ".-")
plt.grid()
plt.title("Fig.5.2: Output voltage of Wide range transamp vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.9V,$I_b=4.6 nA$''')
plt.ylabel('''$V_{out}$(V)''')
```

Out[ ]:

```
Text(0, 0.5, '$V_{out}$(V)')
```



Output voltage of wide range transamp
for V2=0.9V,$I_b = 4.6nA$

In [ ]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.WRT_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 20)])
```

set I_b to $2.3nA$

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)

data = [V1_sweep_ex5_getset,Vout_V1_sweep_ex5]
np.savetxt('./data/V1_sweep_Vout_V209_ex5_I2.csv', data, delimiter=',')
```

```
0.8991203308105469
[0.0, 0.04926686733961105, 0.0985337346792221, 0.1495601385831833, 0.1988269984722137
5, 0.24985340237617493, 0.2991202771663666, 0.3483871519565582, 0.399413526058197, 0.
44868040084838867, 0.49970680475234985, 0.5489736795425415, 0.5982405543327332, 0.649
2669582366943, 0.698533833026886, 0.7495601773262024, 0.798827052116394, 0.8498534560
203552, 0.8991203308105469, 0.9483872056007385, 0.9994136095046997, 1.048680424690246
6, 1.0997068881988525, 1.1489737033843994, 1.1982406377792358, 1.2492669820785522, 1.
2985339164733887, 1.349560260772705, 1.3988271951675415, 1.449853539466858, 1.4991203
546524048, 1.5483872890472412, 1.5994136333465576, 1.648680567741394, 1.6997069120407
104, 1.7489738464355469]
[0.011279297061264515, 0.0120849609375, 0.0120849609375, 0.0120849609375, 0.012084960
9375, 0.0120849609375, 0.012890624813735485, 0.0120849609375, 0.011279297061264515,
0.0120849609375, 0.011279297061264515, 0.011279297061264515, 0.011279297061264515, 0.
011279297061264515, 0.011279297061264515, 0.010473631850290З, 0.0120849609375, 0.020
94726637005806, 1.7797119617462158, 1.7926025390625, 1.7998535633087158, 1.8014647960
662842, 1.8006591796875, 1.7974364757537842, 1.7772948741912842, 1.7813231945037842,
1.794213891029358, 1.782934546470642, 1.8006591796875, 1.799047827720642, 1.777294874
1912842, 1.7764892578125, 1.786157250404358, 1.7934081554412842, 1.778100609779358,
1.78857421875]
```

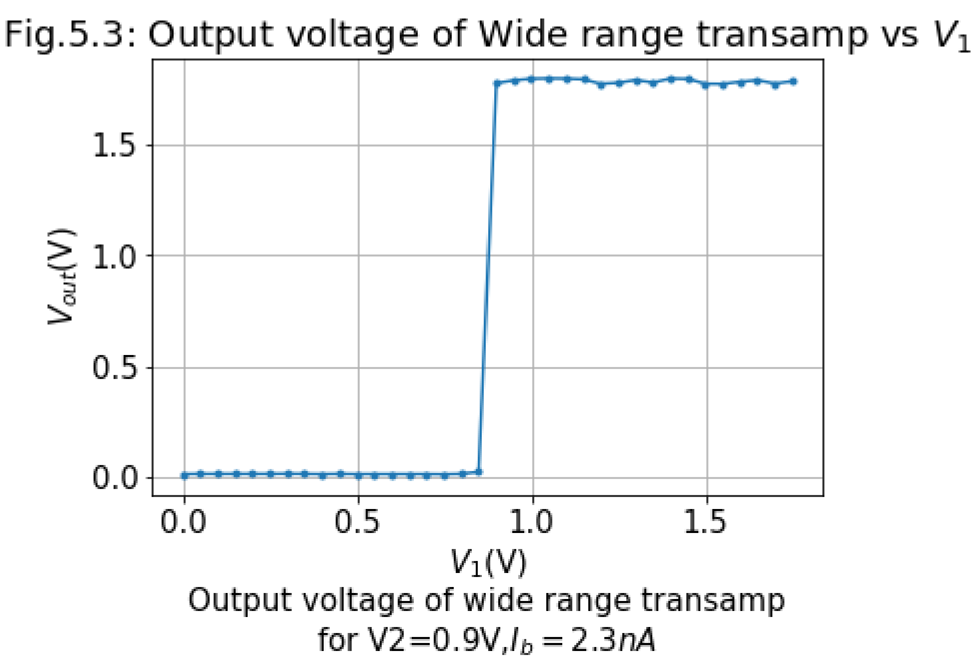
Plot

In [ ]:

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

V1_sweep_ex5_getset_I2,Vout_V1_sweep_ex5_I2 = np.loadtxt('./data/V1_sweep_Vout_V209_ex

plt.plot(V1_sweep_ex5_getset_I2,Vout_V1_sweep_ex5_I2, ".-")
plt.grid()
plt.title("Fig.5.3: Output voltage of Wide range transamp vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.9V,$I_b=2.3 nA$''')
plt.ylabel('''$V_{out}$(V)''')
```

Out[ ]:

```
Text(0, 0.5, '$V_{out}$(V)')
```

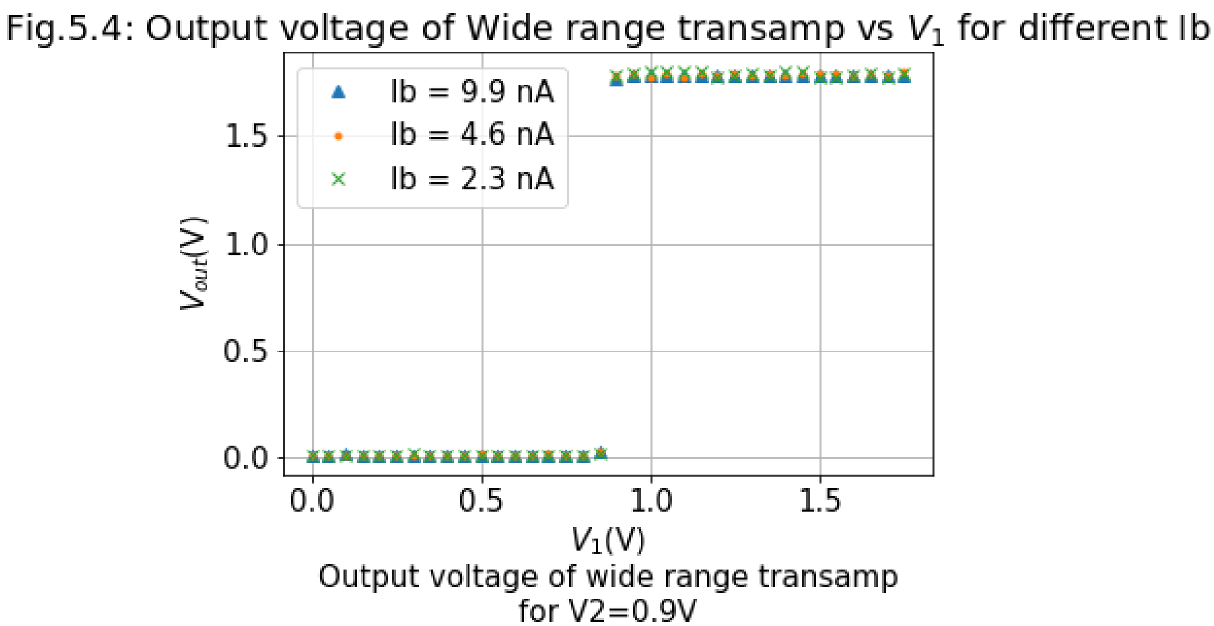


To conclude your observations:

We can plot all three conditions in one plot

In [ ]:
```
plt.plot(V1_sweep_ex5_getset,Vout_V1_sweep_ex5, "^",label="Ib = 9.9 nA")
plt.plot(V1_sweep_ex5_getset_I1,Vout_V1_sweep_ex5_I1, ".",label="Ib = 4.6 nA")
plt.plot(V1_sweep_ex5_getset_I2,Vout_V1_sweep_ex5_I2, "x",label="Ib = 2.3 nA")
plt.grid()
plt.title("Fig.5.4: Output voltage of Wide range transamp vs $V_1$ for different Ib")
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.9V''')
plt.ylabel('''$V_{out}$(V)''')
plt.legend()
```

Out[ ]: <matplotlib.legend.Legend at 0x283da981a60>



> We can see that changing the biais current does not affect the transamp behaviour.

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 $I_b \approx 2.3\mathrm{nA}$.

In [ ]:
```
# set Ib = 9.9
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.WRT_VB_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 85)])
```

In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8, 0.4)    # V2 = 0.4
```

Out[ ]:
```
0.399413526058197
```

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)

data = [V1_sweep_ex5_getset,Vout_V1_sweep_ex5]
np.savetxt('./data/V1_sweep_Vout_V209_ex5_V204.csv', data, delimiter=',')
```

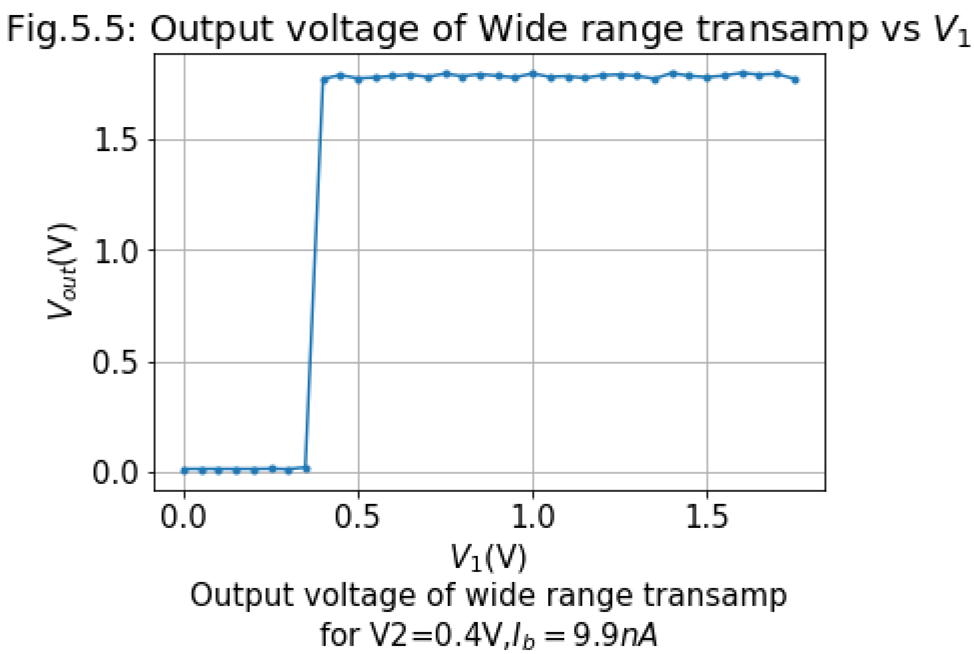
```
0.399413526058197
[0.0, 0.04926686733961105, 0.0985337346792221, 0.1495601385831833, 0.1988269984722137
5, 0.24985340237617493, 0.2991202771663666, 0.3483871519565582, 0.399413526058197, 0.
44868040084838867, 0.49970680475234985, 0.5489736795425415, 0.5982405543327332, 0.649
2669582366943, 0.698533833026886, 0.7495601773262024, 0.798827052116394, 0.8498534560
203552, 0.8991203308105469, 0.9483872056007385, 0.9994136095046997, 1.048680424690246
6, 1.0997068881988525, 1.1489737033843994, 1.1982406377792358, 1.2492669820785522, 1.
2985339164733887, 1.349560260772705, 1.3988271951675415, 1.449853539466858, 1.4991203
546524048, 1.5483872890472412, 1.5994136333465576, 1.648680567741394, 1.6997069120407
104, 1.7489738464355469]
[0.0120849609375, 0.0120849609375, 0.0120849609375, 0.0120849609375, 0.0120849609375,
0.012890624813735485, 0.011279297061264515, 0.01933593675494194, 1.7756836414337158,
1.7926025390625, 1.778100609779358, 1.782128930091858, 1.78857421875, 1.7950195074081
42, 1.7845458984375, 1.799047827720642, 1.7877686023712158, 1.796630859375, 1.7893798
351287842, 1.782128930091858, 1.7998535633087158, 1.7845458984375, 1.787768602371215
8, 1.7797119617462158, 1.7917969226837158, 1.795019507408142, 1.7893798351287842, 1.7
764892578125, 1.8014647960662842, 1.7893798351287842, 1.782934546470642, 1.7901855707
16858, 1.802270531654358, 1.795019507408142, 1.798242211341858, 1.7772948741912842]
```

raw plot

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

V1_sweep_ex5_getset_V1,Vout_V1_sweep_ex5_V1 = np.loadtxt('./data/V1_sweep_Vout_V209_ex

plt.plot(V1_sweep_ex5_getset_V1,Vout_V1_sweep_ex5_V1, ".-")
plt.grid()
plt.title("Fig.5.5: Output voltage of Wide range transamp vs $V_1$")
```

```
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.4V,$I_b=9.9 nA$''')
plt.ylabel('''$V_{out}$(V)''')
```

Out[ ]: Text(0, 0.5, 'V_{out}(V)')



In [ ]:
```
p.set_voltage(pyplane.DacChannel.AIN8, 0.2)    # V2 = 0.2
```

Out[ ]: 0.19882699847221375

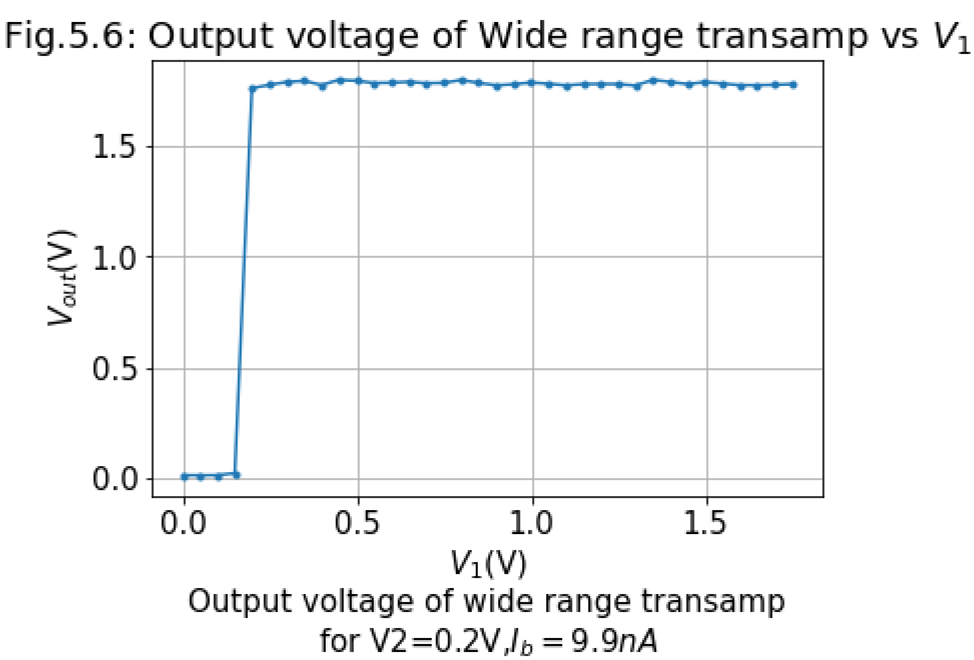
In [ ]:
```
import numpy as np
import time

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)

data = [V1_sweep_ex5_getset,Vout_V1_sweep_ex5]
np.savetxt('./data/V1_sweep_Vout_V209_ex5_V202.csv', data, delimiter=',')
```

```
0.19882699847221375
[0.0, 0.04926686733961105, 0.0985337346792221, 0.1495601385831833, 0.1988269984722137
5, 0.24985340237617493, 0.2991202771663666, 0.3483871519565582, 0.399413526058197, 0.
44868040084838867, 0.49970680475234985, 0.5489736795425415, 0.5982405543327332, 0.649
2669582366943, 0.698533833026886, 0.7495601773262024, 0.798827052116394, 0.8498534560
203552, 0.8991203308105469, 0.9483872056007385, 0.9994136095046997, 1.048680424690246
6, 1.0997068881988525, 1.1489737033843994, 1.1982406377792358, 1.2492669820785522, 1.
298533916473887, 1.349560260772705, 1.3988271951675415, 1.449853539466858, 1.4991203
546524048, 1.5483872890472412, 1.5994136333465576, 1.648680567741394, 1.6997069120407
104, 1.7489738464355469]
[0.0120849609375, 0.011279297061264515, 0.0120849609375, 0.02094726637005806, 1.76440
4296875, 1.7797119617462158, 1.7926025390625, 1.7974364757537842, 1.778906226158142,
1.802270531654358, 1.798242211341858, 1.7877686023712158, 1.7893798351287842, 1.79340
81554412842, 1.786962866783142, 1.78857421875, 1.8014647960662842, 1.78857421875, 1.7
772948741912842, 1.782128930091858, 1.790185570716858, 1.7845458984375, 1.77729487419
12842, 1.782934546470642, 1.7837402820587158, 1.782934546470642, 1.7764892578125, 1.8
02270531654358, 1.7926025390625, 1.782934546470642, 1.7926025390625, 1.78535151481628
42, 1.778100609779358, 1.778100609779358, 1.7797119617462158, 1.782934546470642]
```

Plot

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

V1_sweep_ex5_getset_V2,Vout_V1_sweep_ex5_V2 = np.loadtxt('./data/V1_sweep_Vout_V209_ex

plt.plot(V1_sweep_ex5_getset_V2,Vout_V1_sweep_ex5_V2, ".-")
plt.grid()
plt.title("Fig.5.6: Output voltage of Wide range transamp vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.2V,$I_b=9.9 nA$''')
plt.ylabel('''$V_{out}$(V)''')
```

Out[ ]:
```
Text(0, 0.5, '$V_{out}$(V)')
```

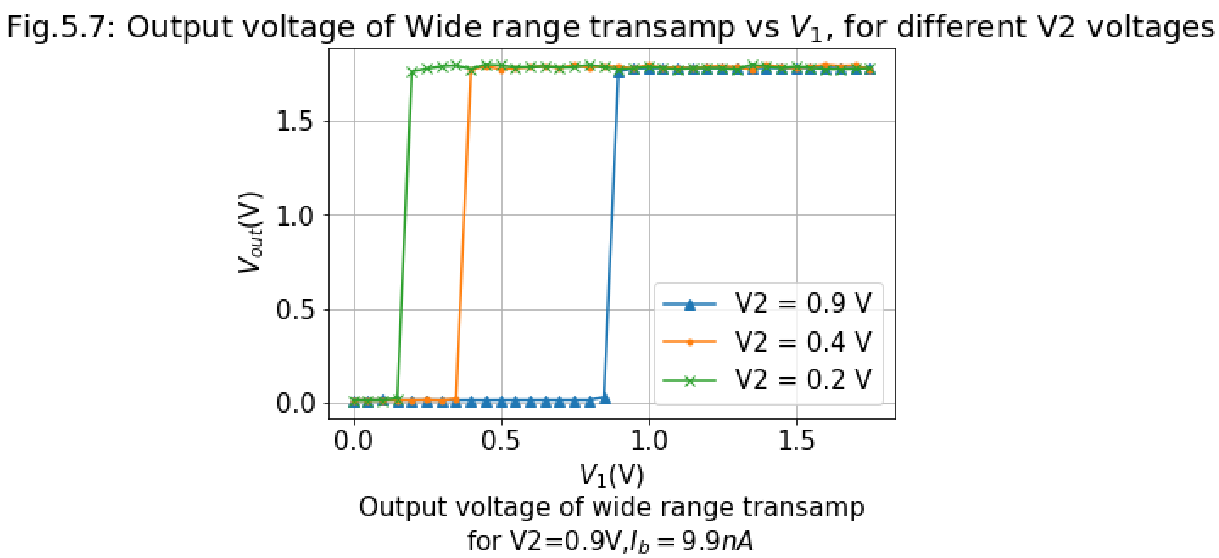


To conclude your observations:

We can plot all figures in one plot

In [ ]:
```
plt.plot(V1_sweep_ex5_getset,Vout_V1_sweep_ex5, "^-",label="V2 = 0.9 V")
plt.plot(V1_sweep_ex5_getset_V1,Vout_V1_sweep_ex5_V1, ".-",label="V2 = 0.4 V")
plt.plot(V1_sweep_ex5_getset_V2,Vout_V1_sweep_ex5_V2, "x-",label="V2 = 0.2 V")
plt.grid()
plt.title("Fig.5.7: Output voltage of Wide range transamp vs $V_1$, for different V2 v
plt.xlabel('''$V_1$(V)
Output voltage of wide range transamp
for V2=0.9V,$I_b=9.9 nA$''')
plt.ylabel('''$V_{out}$(V)''')
plt.legend()
```

Out[ ]:
```
<matplotlib.legend.Legend at 0x283dbc3f250>
```



We can now see that compared to the 5T transamp there is no more linear rise (that depended on κ) when $V_1 < V_2$ and as soon as $V_1 > V_2$, V_{out} shoots to Vdd

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)

For $V2 = 0.4V$

In [ ]:
```
# fix Vn = ??? (<0.9V), Compare Vout vs Vpos
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.AIN8,0.4) #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 = []
```

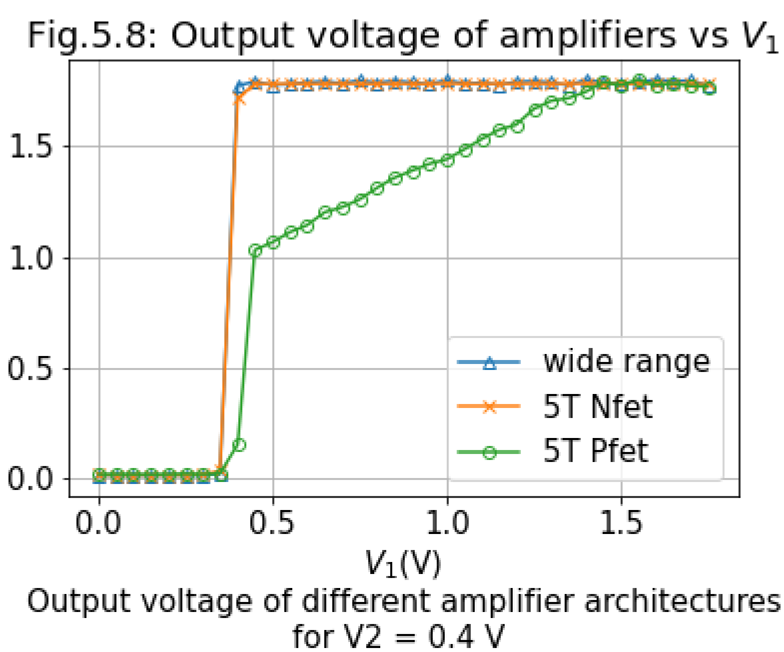
```
V1_sweep_ex5_getset = []

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

data = [V1_sweep_ex5_getset,Vout_V1_sweep_PFET]
np.savetxt('./data/ex_6_PFET_3.csv', data, delimiter=',')
# Read 5T NFET transamp


#Read wide-range transamp
```

In [ ]:

```
#load previous readings
sweep_nfet, vout_nfet = np.loadtxt('./data/data_Vout_V1_sweep_ex3_v0.csv',delimiter=',
sweep_pfet, vout_pfet = np.loadtxt('./data/ex_6_PFET_3.csv',delimiter=',')

plt.plot(V1_sweep_ex5_getset_V1,Vout_V1_sweep_ex5_V1, "^-",mfc="none", label = "wide r
plt.plot(sweep_nfet,vout_nfet, "x-",label="5T Nfet")
plt.plot(sweep_pfet,vout_pfet, "o-",mfc="none",label="5T Pfet")
plt.grid()
plt.legend()
plt.title("Fig.5.8: Output voltage of amplifiers vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of different amplifier architectures
for V2 = 0.4 V ''')
```

Out[ ]:

```
Text(0.5, 0, '$V_1$(V)\nOutput voltage of different amplifier architectures\nfor V2 =
0.4 V ')
```



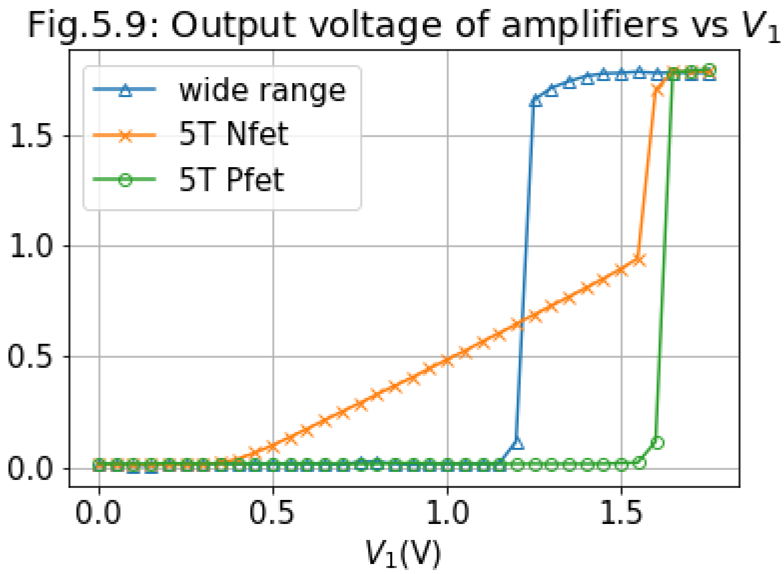
> We can see that at this voltage set, the wide range and 5T NFET have the same behaviour for V_{out}. (There is no linear range, unlike for the 5T PFET)

For $V_2\ (V_{neg}) = 1.6$

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.AIN8,1.6) #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

data = [V1_sweep_ex5_getset,Vout_V1_sweep_PFET]
np.savetxt('./data/ex_6_PFET_1.csv', data, delimiter=',')
```

In [ ]:
```
#load previous readings
sweep_nfet, vout_nfet = np.loadtxt('./data/data_Vout_V1_sweep_ex3_v1.csv',delimiter=',
sweep_pfet, vout_pfet = np.loadtxt('./data/ex_6_PFET_1.csv',delimiter=',')      #pfet
sweep_wide, vout_sweep = np.loadtxt('./data/ex_6_wide_16.csv',delimiter=',')
plt.plot(sweep_wide,vout_sweep, "^-",mfc="none", label = "wide range") #plot wide rang
plt.plot(sweep_nfet,vout_nfet, "x-",label="5T Nfet")
plt.plot(sweep_pfet,vout_pfet, "o-",mfc="none",label="5T Pfet")
plt.grid()
plt.legend()
plt.title("Fig.5.9: Output voltage of amplifiers vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of different amplifier architectures
for V2 = 1.6 V ''')
```

Out[ ]:
```
Text(0.5, 0, '$V_1$(V)\nOutput voltage of different amplifier architectures\nfor V2 =
1.6 V ')
```



Output voltage of different amplifier architectures
for V2 = 1.6 V

> Unfortunately, the measures taken for the wide range transamp were not taken at $V2 = 1.6V$ (but probably around 1.3 V) so comparisons are a little harder to make. But we can see that when $V_2 > 0.9V$ and $V_1 > V_2$ the pfet fet transamp behaves similarly to the wide range transamp. The nfet transamp increases linearly (with slope of κ) until $V_1 > V_2$ then shoots to V_{dd}.

For V_2 $(V_{neg}) = 0.9$

In [ ]:
```
# fix Vn = 0.9V, Compare Vout vs Vpos
#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.AIN8,0.9) #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

data = [V1_sweep_ex5_getset,Vout_V1_sweep_PFET]
```

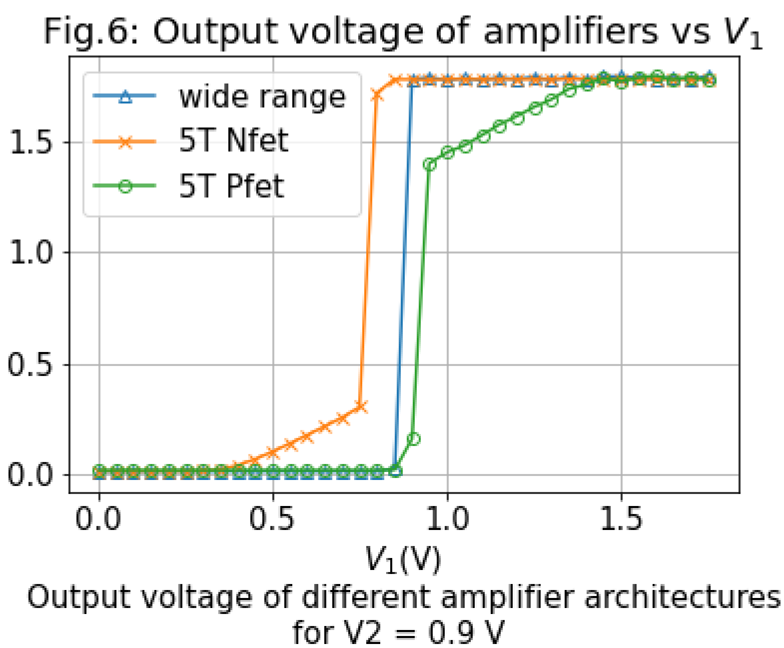
```
np.savetxt('./data/ex_6_PFET_2.csv', data, delimiter=',')
plt.show()
```

In [ ]:

```
#load previous readings
sweep_nfet, vout_nfet = np.loadtxt('./data/data_Vout_V1_sweep_ex3.csv',delimiter=',')
sweep_pfet, vout_pfet = np.loadtxt('./data/ex_6_PFET_2.csv',delimiter=',')      #pfet
sweep_wide, vout_sweep = np.loadtxt('./data/V1_sweep_Vout_V209_ex5_I1.csv',delimiter='
plt.plot(sweep_wide,vout_sweep, "^-",mfc="none", label = "wide range") #plot wide rang
plt.plot(sweep_nfet,vout_nfet, "x-",label="5T Nfet")
plt.plot(sweep_pfet,vout_pfet, "o-",mfc="none",label="5T Pfet")
plt.grid()
plt.legend()
plt.title("Fig.6: Output voltage of amplifiers vs $V_1$")
plt.xlabel('''$V_1$(V)
Output voltage of different amplifier architectures
for V2 = 0.9 V ''')
```

Out[ ]:

```
Text(0.5, 0, '$V_1$(V)\nOutput voltage of different amplifier architectures\nfor V2 =
0.9 V ')
```



Unfortunately, the measurements for the nfet were conducted at 0.8 V, but we can still make some meaningful observations. In the case where $V_2 = 0.9$, the 5T transamps (nfet and pfet) both have a linear region, until $V_1 = V_2$ then shoots to vdd. (For the nfet) And conversely for the Pfet, it is at gnd until $V_1 = V2$ then rises up instantly then increases with a slope to $V_d d$

To conclude your observations:

We can see that depending on the input voltages, V_1 and V_2 and the transamp type (pfet or nfet) we can approach a similar behaviour to the wide range transamp (over 0.9V pfet $\approx$ wide range, under 0.9V nfet $\approx$ wide range), but in the close range to 0.9V, none of the nfet or pfet behave like the wide range, as they are limited by the saturation conditions.

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.

> In order to get $I_{out} = 0$, we need to satisfy the following equation:

$$I_{out} = I_b tanh(\frac{\kappa}{2U_T}(V_1 - V_2)) = 0 \tag{10}$$

> So $V_1 = V_2$ to satisfy the equation.
>
> And for $V_1 > V_b - (4 + ln(2))U_T/\kappa$,

$$V_{out} \approx \kappa V_1 - \kappa V_b + U_T ln(2) \tag{11}$$

> So by changing the output voltage, V_1 will adjust but in order to satisfy the first equation, V_2 has to adjust as well, therefore the offset voltage will always be the same

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

> For the NFET, the saturation condition for M3 is : $V_s > 4U_T$,
>
> Therefore as $V_s \approx \kappa(max(V_1, V_2) - V_b)$, we get:

$$max(V_1, V_2) > V_b + \frac{4U_T}{\kappa} \tag{12}$$

> M_b being a PFET the saturation condition is the following, $V_s < V_{dd} - 4UT$ and so:

$$max(V_1, V_2) < V_b + \frac{4U_T}{\kappa} \tag{13}$$

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.*

Amp Type	Advantages	Disadvantages
Wide output range transamp	no linear range,voltage swing between the two power rails, higher gain	twice as many transistors needed compared to 5t layout,increased effect of mismatches

Amp Type	Advantages	Disadvantages
Standard transconductance	only 5 transistors	twice as many transistors needed compared to 5t layout, boundary conditions limit output range

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!