Lab 7: Winner-Take-All circuit

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Group Number: 4.5

Date:

The winner-take-all (WTA) circuit models a neural network consisting of n excitatory cells and one inhibitory cell. When the excitatory cells are active, they excite the inhibitory cell which in turn inhibits all excitatory cells. The inhibitory cell's activity will increase until it silences all excitatory cells but one. If the network loop gain is high enough, this excitatory cell is able to maintain the required inhibitory cell activity by itself. Naturally, the excitatory cell that survives is the one with the largest extrinsic input.

A useful extension of the WTA network is the introduction of positive feedback and lateral coupling through both excitatory and (local) inhibitory nearest neighbor interactions. The positive feedback variant of the classical WTA network shows a hysteretic behavior in the selection/de-selection mechanism, and is therefore denoted the hysteretic winner-take-all (HWTA) network.

In this lab, we will investigate properties of both the classical WTA and HWTA circuits. Circuit schematics of a single cell in the WTA and HWTA networks are shown in Fig. 1. We will first characterize the response properties of the classical WTA circuit and then compare the effect of the various circuit additions to the HWTA circuit. Furthermore we will investigate the effect of the coupling diffusor circuits in the HWTA circuit. These diffusors implement both lateral excitatory and inhibitory coupling between the cells.

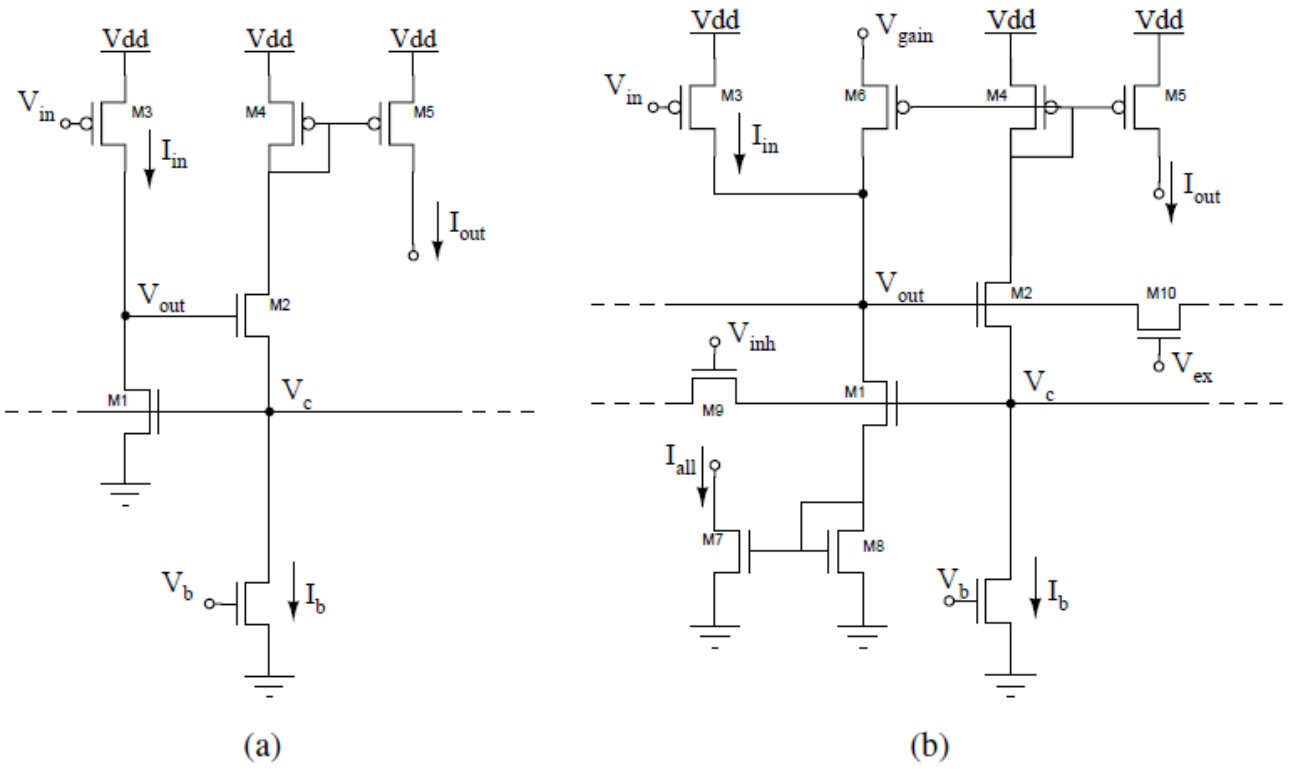


Figure 1: (a) Schematic of a single cell of a classical WTA network. (b) Schematic of a single cell of a HWTA network.

1 Reading

Study the handouts and read the papers:

Indiveri, 2001 A current-mode hysteretic winner-take-all network, with excitatory and inhibitory coupling

Douglas, Martin 2007 Recurrent neuronal circuits in the neocortex \end{description}

2 Prelab

This prelab will help you develop intuition for the input-output current relationship of the network. We suggest you read the entire Prelab to understand the chain of reasoning before attempting to answer the questions. Assume subthreshold operation unless otherwise stated.

1. To begin, let's consider the 2-node WTA network in Fig. 2. Note that the WTA bias current I_b is identical for both cells (they share the same bias voltage V_b). Also note that node V_c is common to both cells. This common node is crucial, as it is through this node that the global competition takes place.

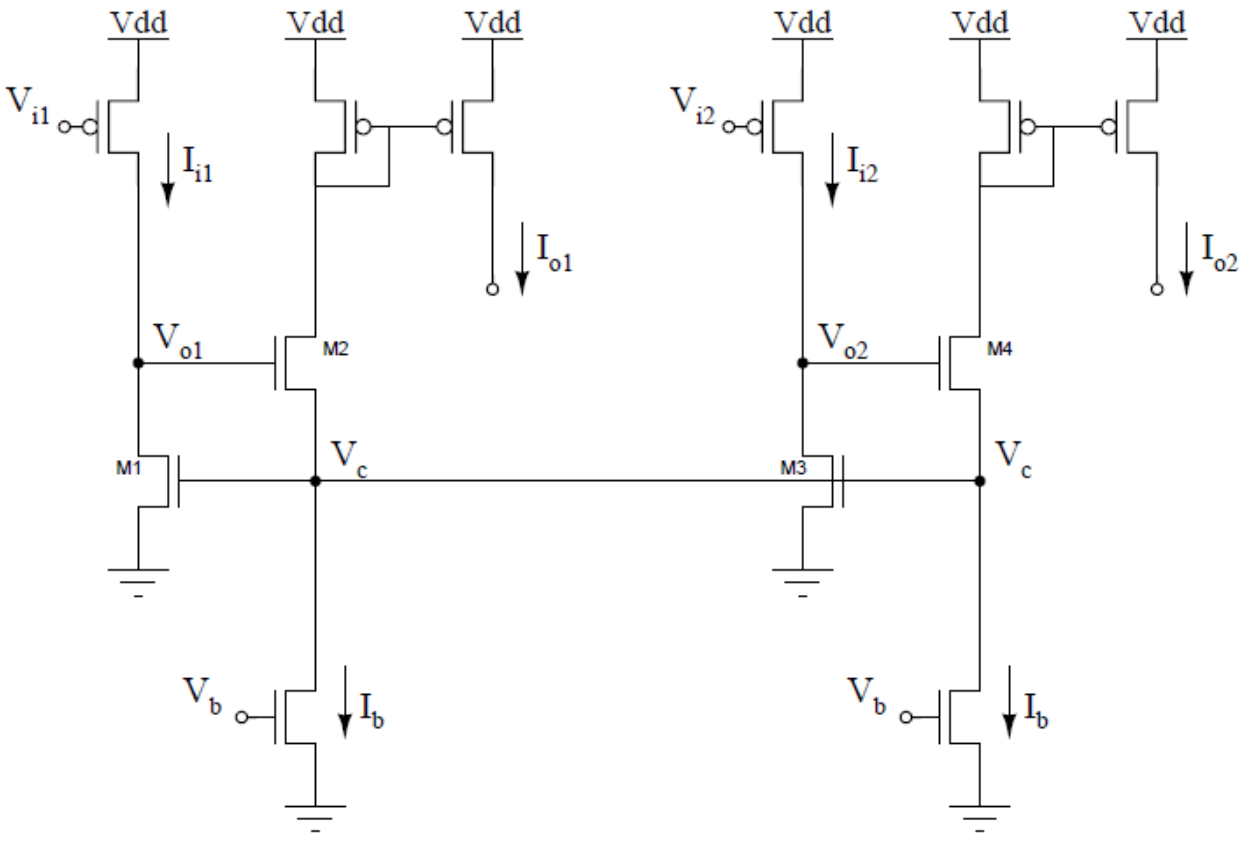


Figure 2: Schematic of a 2-node WTA network.

Write down the equations for the (subthreshold) currents flowing through transistors M1 and M3, as a function of their gate, source and drain voltages, separating their *forward* and *reverse* components. Don't take into account, for the time being, the Early effect in the equations.

The equations for the subtreshold currents through transistors M1 and M3 are

> $I_1 = I_0 e^{\frac{\kappa V_c}{U_T}}$
>
> $I_3 = I_1 = I_0 e^{\frac{\kappa V_c}{U_T}}$

Given that the gate voltages of M1 and M3 are the same, under the different conditions given below, what is V_c, what happens to V_{o1} and V_{o2}, I_{o1} and I_{o2}:

- $I_{i1} = I_{i2} = I_{in}$.

  > - $I_{o1} = I_{o2} = I_b$
  > - $V_{o1} = V_{o2} \approx V_c + V_b$
  > - $V_c = \frac{U_T}{\kappa} \ln \frac{I_{in}}{I_0}$

- $I_{i1} \gg I_{i2}$

  > - $I_{o1} = 2I_b$
  > - $I_{o2} = 0$
  > - $V_{o1} = V_c + V_b$
  > - $V_{o2} = 0$
  > - $V_c = \frac{U_T}{\kappa} \ln \frac{I_{i1}}{I_0}$

Generalize your results to an n-input WTA circuit.

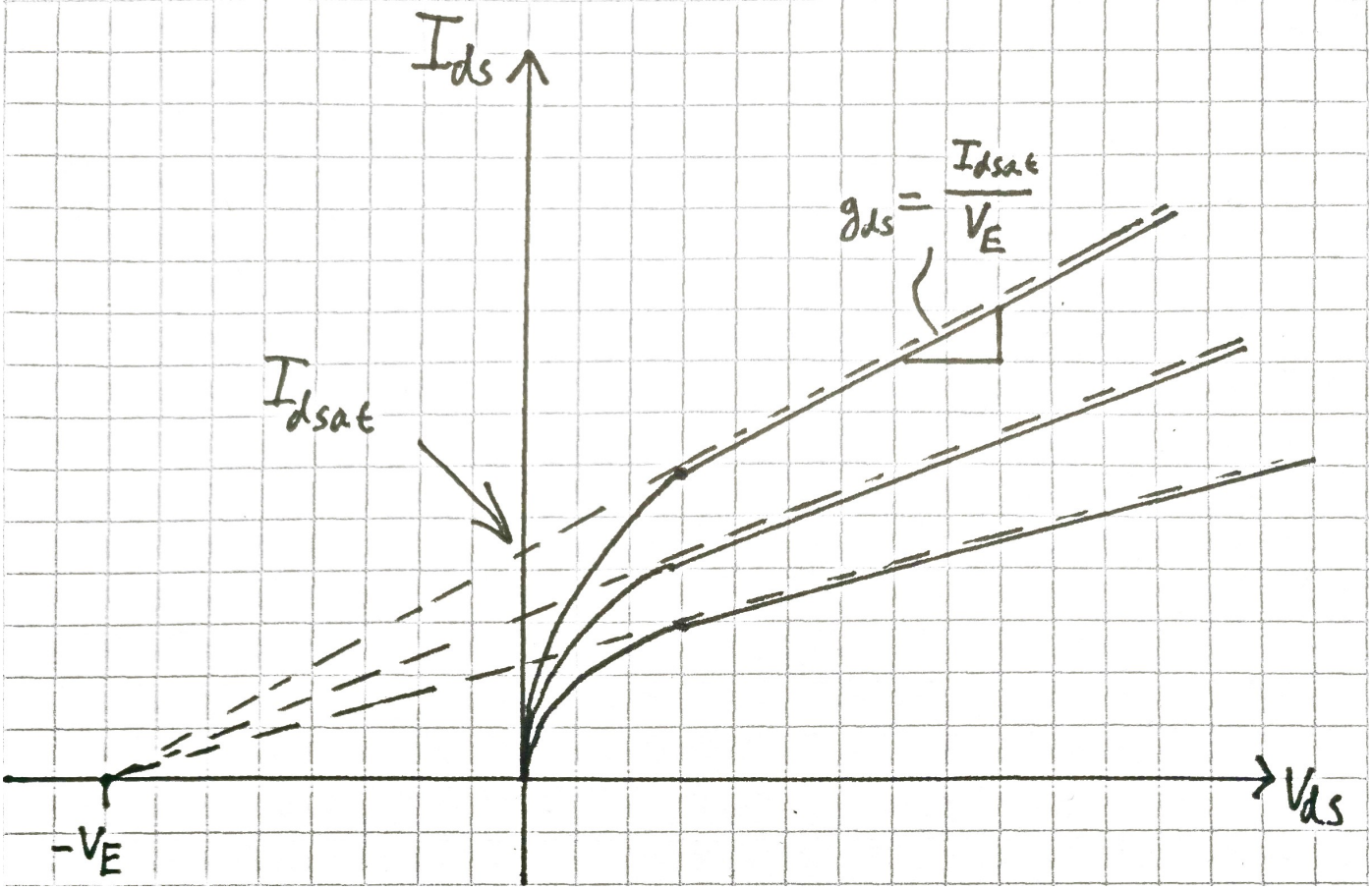
> If $I_{ia} \gg I_{ib} \; \forall \; b \in \{x \in \mathbb{N} \mid 0 \leq x \leq n \wedge x \neq a\}$:
>
> - $I_{oa} = nI_b$
> - $I_{ob} = 0$
> - $V_{oa} = V_c + V_b$
> - $V_{ob} = 0$
> - $V_c = \frac{U_T}{\kappa} \ln \frac{I_{ia}}{I_0}$

1. The analysis above applies when the input currents are sufficiently different. To understand what happens when the inputs are very similar, we have to take into account the Early effect on devices M1 and M3. Let's do a small-signal analysis.

Initially, the input currents are equal, $I_{i1} = I_{i2} = I_u$, and therefore the outputs are equal, $I_{o1} = I_{o2} = I_b$. A small differential input ΔI_{in} is then applied, i.e. the inputs are now $I_u \pm \frac{1}{2}\Delta I_{in}$. What is the differential output, ΔV_{out}?

Proceed as follows:

- To help you in your reasoning, draw a transistor's subthreshold I_{ds} vs. V_{ds} curve.



- Assume that V_c does not change. Given that the drain conductance of M1 and M3 is g_{d}, figure out how much V_{o1} and V_{o2} must change to accomodate the change in current.

> $$\Delta V_o = \pm\frac{\Delta I_{in}}{2g_d} = \pm\frac{1}{2} I_{in} V_e$$

- Given these changes, use the small-signal transconductance g_{m} of M2 and M4 to figure out how much the output currents will change? Assuming that $I_{i1} = I_{i2} = I_u$ and I_b are in the same order of currents (e.g. $I_u / I_b \approx 1$), early voltage of M1 and M3 is V_e = 25V, U_T = 25mV, κ = 1. (This is to have an intuitive understanding that how sensitive is the change of output currents conrresponding to the change of input current.)

> $$\Delta I_o = \pm\frac{g_m \Delta I_{in}}{2g_d} = \pm\frac{1}{2}\Delta I_{in} A$$
> $$\Rightarrow\ \Delta I_o = \pm\frac{\kappa V_E}{U_T}\frac{1}{2}\Delta I_{in} = \pm 500 \Delta I_{in}$$

- Express the drain conductance and transconductance in terms of I_u and I_b and obtain a relationship between the normalized input and output signals, $\Delta I_{in}/I_u$ and $\Delta I_{out}/I_b$.

> - $\frac{\Delta I_{out}}{I_b} = \frac{2I_b}{AI_u}\frac{\Delta I_{in}}{I_u}$
> - $\frac{g_m}{g_d} = \frac{2I_b^2 \Delta I_{in}}{I_u^2 \Delta I_{out}}$

1. The circuit on the CoACH chip has the circuit of Fig. 1 (b), which has four differences from Fig. 1 (a). In order to conduct the experiment, you need to answer the following questions:

- M6

What function does it implement?

> Local excitatory feedback

What should V_{gain} be in order to disable this function?

> $V_{gain} < 4U_T + V_{out}$
> $\Rightarrow V_{gain} \ll V_{dd}$

What should V_{gain} be in order to enable this function, and what is the effect?

> $V_{gain} > 4U_T + V_{out}$
> $\Rightarrow V_{gain} \approx V_{dd}$
> This activates a current mirror to M4

- M7 and M8

What function does it implement?

> Diode-source degeneration

(Optional) What other effect does it introduce? (Hint: Discuss the changes in V_c, V_o and I_o in two cases for a 2-WTA: $I_{i1} = I_{i2}$ and $I_{i1} \gg I_{i2}$)

- M9

What function does it implement?

> Inhibitory lateral coupling

What should V_{inh} be in order to turn off this function?

> $V_{inh} < V_c - V_t$
> $\Rightarrow V_{inh} \ll V_{dd}$

What should V_{inh} be in order to turn on this function, and what is the effect?

> $V_{inh} \approx V_{dd}$
> It decreases I_{in} via a current mirror, inhibiting a cell when other cells are firing.

- M10

What function does it implement?

> Excitatory lateral coupling

What should V_{ex} be in order to turn off this function?

> $V_{ex} < V_c - V_t \Rightarrow V_{ex} \ll V_{dd}$

What should V_{ex} be in order to turn on this function, and what is the effect?

> $V_{ex} \approx V_{dd}$
> It increases I_{in} via a current mirror. This "shares" output, smoothing the curves.

3 Setup

3.1 Connect the device

In [8]:
```
# import the necessary libraries
import pyplane
import time
import numpy as np
import matplotlib.pyplot as plt
from scipy import interpolate
```

In [9]:
```
# 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 [10]:
```
p.get_firmware_version()
```

Out[10]:
```
(1, 8, 6)
```

In [11]:
```
# 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, otherwise t
# Because the class chip need to do handshake to get the communication correct.
p.request_events(1)
```

In [12]:
```
# Try to read something, make sure the chip responses
p.read_current(pyplane.AdcChannel.GO0_N)
```

Out[12]:
```
4.99511713769607e-07
```

In [13]:
```
# If any of the above steps fail, delete the object, and restart the kernel

# del p
```

3.1 Chip configuration

To measure I_{out}, use:

In [14]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
```

```
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine2,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

To measure I_{all}, use:

In [15]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine3,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

3.2 Bias Generator (BiasGen or BG)

In a simplified form, the output of a branch of the BiasGen will be the gate voltage V_b for the bias current I_b, and if the current mirror has a ratio of w and the bias transistor operates in subthreshold-saturation:

$$I_b = w\frac{BG_{fine}}{256}I_{BG_{master}} \tag{1}$$

Where $I_{BG_{master}}$ is the `BiasGenMasterCurrent` $\in \{60\text{ pA}, 460\text{ pA}, 3.8\text{ nA}, 30\text{ nA}, 240\text{ nA}\}$, BG_{fine} is the integer fine value $\in [0, 256)$

To set a bias, use the function similar to the following:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.BIAS_NAME, \
    pyplane.Coach.BiasType.BIAS_TYPE, \
    pyplane.Coach.BiasGenMasterCurrent.MASTER_CURRENT, FINE_VALUE)])
```

You may have noticed that there are some biases that are not used to directly generate a current, but rather what matters is the voltage, e.g. V_{gain}, V_{ex} and V_{inh} in our HWTA circuit. Even though they may have a `BIAS_NAME` ending with `_N` or `_P` it only indicates that they are connected to the gate of an N- or a P-FET, but the `BIAS_TYPE` parameter can be both `_N` or `_P` . For example, setting a `_N` bias to `BIAS_TYPE = P` in the case of Ib=0 will only make this voltage very close to VDD, which *is* sometimes the designed use case.

3.3 Setup C2F and voltage output buffer

In [16]:
```
# # 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)])
```

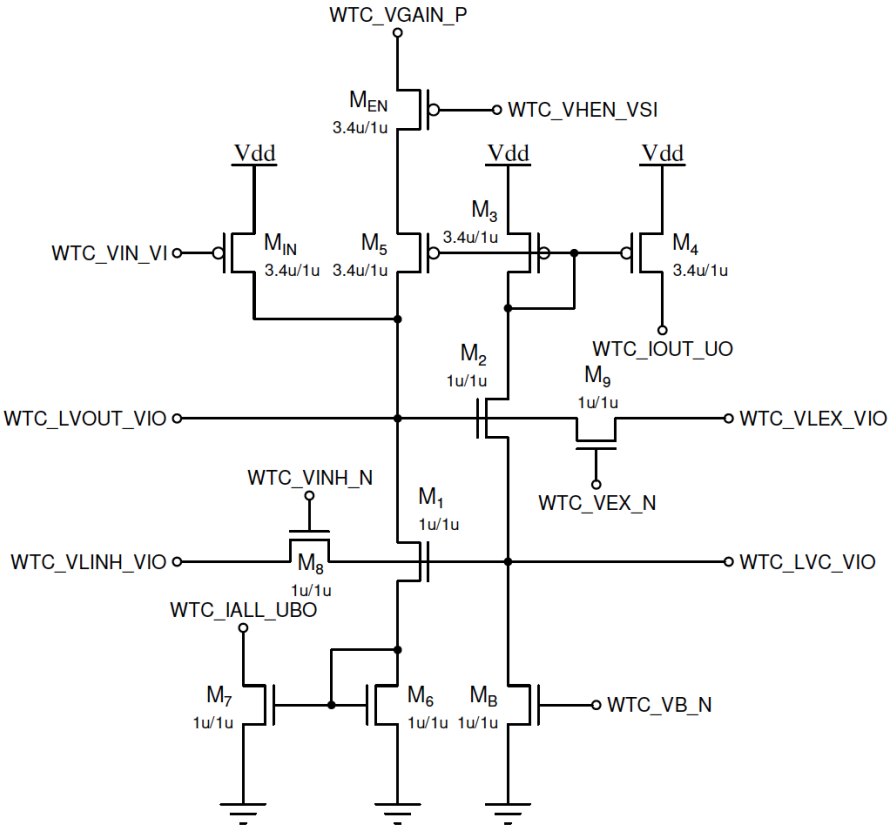
3.4 Schematic and pin map

In this Lab you will work with the WTA circuits on the CoACH chip.

The winner-take-all circuit comprises 16 cells, with the first cell connected to the last cell by "wrap-around lines", VO & VC. There are four circuit biases parameters, shared by all cells: V_b, V_{ex}, V_{inh} and V_{gain}.

As this circuit is known to be sensitive to mismatch, dummies were used extensively: both within the cells to ensure cell devices are surrounded by same geometries, as well as by placing dummy cells on either side of the array to mitigate corner effects on Cell 1 and Cell 16. (No need to know the details)

Schematic of each cell of the WTA circuit is shown below (It should be WTA instead of WTC). Hysteresis is enabled (`VHEN_VSI = 0`) by default, but you can easily set V_{gain} to disable it.



For cell x $(0 \leq x < 16)$:

- `WTC_VIN_VI[x]` = $V_{in,x}$ = AINx
- `WTC_LVOUT_VIO[x]` = $V_{out,x}$ = ADC[15-x]
- `WTC_IOUT_UO[x]` = $I_{out,x}$ = C2F[x] (CurrentOutputSelect = SelectLine2)
- `WTC_IALL_UBO[x]` = $I_{all,x}$ = C2F[x] (CurrentOutputSelect = SelectLine3)

4 Calibration

4.1 Calibration of C2F channels for I_{out}

In order to calibrate each C2F channel more accurately, we construct a case when only the calibrated cell wins, so that all 16 I_b flow through the winning channel.

4.1.1 Chip configuration

In [17]:
```
# Select Line2 to read Iout
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine2,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

4.1.2 Set fixed voltages

- What value should bias `WTA_VGAIN_P` take?

In [18]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VGAIN_P,\
```

```
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])  # ??? = 0 ~ 255
```

Hint: The output feedback has been turned off by setting $V_{gain} \ll V_{dd}$.

- What value should bias `WTA_VEX_N` take?

In [19]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VEX_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 0)])  # ??? = 0 ~ 255
```

The excitatory lateral coupling has been turned OFF by setting $V_{ex} = 0\text{V}$.

- What value should bias `WTA_VINH_N` take?

In [20]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VINH_N,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 0)])  # ??? = 0 ~ 255
```

The inhibitory lateral coupling has been turned ON by setting $V_{inh} = V_{dd}$ (Bias current is 0 because it's pFET).

- What value should the V_{in} of the non-winning cells take?

In [21]:
```
V_lose = 1.8  # ??? V
for i in range(16):
    p.set_voltage(eval('pyplane.DacChannel.AIN' + str(i)), V_lose)
    time.sleep(0.2)
```

(the input transistors are pFETs)

$V_{in,lose} = 0.0\text{V}$.

- What value should the V_{in} of the winning cell take?

In [14]:
```
V_win = 0.0
```

$V_{in,win} = 0.8\text{V}$.

Why?

> We just want one winner for the calibration, so only one cell is turned on.

4.1.3 Data aquisition

- For each cell, sweep the total bias current ($16I_b$ from 0 to 10 nA). Because we don't need too high precision, and it takes 16x the time, only 6 points (including 0) per channel is enough.

In [15]:
```
N_samples = 6
Ib = np.linspace(0, 10e-9, N_samples)
fine = np.round((Ib/16/460e-12)/3 * 256).astype(int)  # think about this equation, underst
```

```
c2f = np.zeros([16, N_samples])

for i in range(16):
    VC_win = eval('pyplane.DacChannel.AIN' + str(i))
    p.set_voltage(VC_win, V_win)
    for j in range(N_samples):
        p.send_coach_events([pyplane.Coach.generate_biasgen_event(
            pyplane.Coach.BiasAddress.WTA_VB_N, pyplane.Coach.BiasType.N,
            pyplane.Coach.BiasGenMasterCurrent.I460pA, fine[j])])
        time.sleep(0.2)

        # read c2f values
        c2f_temp = p.read_c2f_output(0.1)
        c2f[i][j] = c2f_temp[i]
#         print(c2f_temp)   # debug
        print(c2f)  # debug

    p.set_voltage(VC_win, V_lose)
```

```
[[9. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0. 0.]]
[[  9. 958.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]
 [  0.   0.   0.   0.   0.   0.]]
[[   9.  958. 1837.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
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 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]]
```

```
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]]
[[   9.  958. 1837. 2695.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]]
[[   9.  958. 1837. 2695. 3582.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]]
[[   9.  958. 1837. 2695. 3582. 4389.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
 [   0.    0.    0.    0.    0.    0.]
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 [4.000e+00 6.760e+02 1.276e+03 1.858e+03 2.455e+03 3.010e+03]
 [4.000e+00 7.460e+02 1.418e+03 2.078e+03 2.747e+03 3.360e+03]
 [4.000e+00 7.010e+02 1.342e+03 1.986e+03 2.655e+03 3.267e+03]
 [6.000e+00 1.520e+03 2.884e+03 4.244e+03 5.610e+03 6.896e+03]
 [4.000e+00 6.390e+02 1.221e+03 1.789e+03 2.387e+03 2.945e+03]
 [5.000e+00 7.100e+02 1.343e+03 1.971e+03 2.605e+03 3.194e+03]
```

```
 [5.000e+00 8.970e+02 1.703e+03 2.498e+03 3.316e+03 4.056e+03]
 [5.000e+00 9.690e+02 1.845e+03 2.702e+03 3.581e+03 4.371e+03]
 [4.000e+00 5.490e+02 1.054e+03 1.554e+03 2.051e+03 2.523e+03]
 [3.000e+00 4.420e+02 8.550e+02 1.268e+03 1.714e+03 2.126e+03]
 [4.000e+00 7.370e+02 1.404e+03 2.059e+03 2.720e+03 3.354e+03]
 [6.000e+00 1.494e+03 2.836e+03 4.156e+03 5.509e+03 6.742e+03]
 [5.000e+00 9.250e+02 1.751e+03 2.568e+03 0.000e+00 0.000e+00]]
[[9.000e+00 9.580e+02 1.837e+03 2.695e+03 3.582e+03 4.389e+03]
 [4.000e+00 7.920e+02 1.479e+03 2.151e+03 2.822e+03 3.493e+03]
 [5.000e+00 8.460e+02 1.596e+03 2.366e+03 3.134e+03 3.842e+03]
 [4.000e+00 6.760e+02 1.276e+03 1.858e+03 2.455e+03 3.010e+03]
 [4.000e+00 7.460e+02 1.418e+03 2.078e+03 2.747e+03 3.360e+03]
 [4.000e+00 7.010e+02 1.342e+03 1.986e+03 2.655e+03 3.267e+03]
 [6.000e+00 1.520e+03 2.884e+03 4.244e+03 5.610e+03 6.896e+03]
 [4.000e+00 6.390e+02 1.221e+03 1.789e+03 2.387e+03 2.945e+03]
 [5.000e+00 7.100e+02 1.343e+03 1.971e+03 2.605e+03 3.194e+03]
 [5.000e+00 8.970e+02 1.703e+03 2.498e+03 3.316e+03 4.056e+03]
 [5.000e+00 9.690e+02 1.845e+03 2.702e+03 3.581e+03 4.371e+03]
 [4.000e+00 5.490e+02 1.054e+03 1.554e+03 2.051e+03 2.523e+03]
 [3.000e+00 4.420e+02 8.550e+02 1.268e+03 1.714e+03 2.126e+03]
 [4.000e+00 7.370e+02 1.404e+03 2.059e+03 2.720e+03 3.354e+03]
 [6.000e+00 1.494e+03 2.836e+03 4.156e+03 5.509e+03 6.742e+03]
 [5.000e+00 9.250e+02 1.751e+03 2.568e+03 3.410e+03 0.000e+00]]
[[9.000e+00 9.580e+02 1.837e+03 2.695e+03 3.582e+03 4.389e+03]
 [4.000e+00 7.920e+02 1.479e+03 2.151e+03 2.822e+03 3.493e+03]
 [5.000e+00 8.460e+02 1.596e+03 2.366e+03 3.134e+03 3.842e+03]
 [4.000e+00 6.760e+02 1.276e+03 1.858e+03 2.455e+03 3.010e+03]
 [4.000e+00 7.460e+02 1.418e+03 2.078e+03 2.747e+03 3.360e+03]
 [4.000e+00 7.010e+02 1.342e+03 1.986e+03 2.655e+03 3.267e+03]
 [6.000e+00 1.520e+03 2.884e+03 4.244e+03 5.610e+03 6.896e+03]
 [4.000e+00 6.390e+02 1.221e+03 1.789e+03 2.387e+03 2.945e+03]
 [5.000e+00 7.100e+02 1.343e+03 1.971e+03 2.605e+03 3.194e+03]
 [5.000e+00 8.970e+02 1.703e+03 2.498e+03 3.316e+03 4.056e+03]
 [5.000e+00 9.690e+02 1.845e+03 2.702e+03 3.581e+03 4.371e+03]
 [4.000e+00 5.490e+02 1.054e+03 1.554e+03 2.051e+03 2.523e+03]
 [3.000e+00 4.420e+02 8.550e+02 1.268e+03 1.714e+03 2.126e+03]
 [4.000e+00 7.370e+02 1.404e+03 2.059e+03 2.720e+03 3.354e+03]
 [6.000e+00 1.494e+03 2.836e+03 4.156e+03 5.509e+03 6.742e+03]
 [5.000e+00 9.250e+02 1.751e+03 2.568e+03 3.410e+03 4.148e+03]]
```

- Save data

In [30]:

```
np.savetxt('./data/data_ex_4_1_3.csv', c2f, delimiter=',')
```

- Plot data (Hint: `np.transpose`)

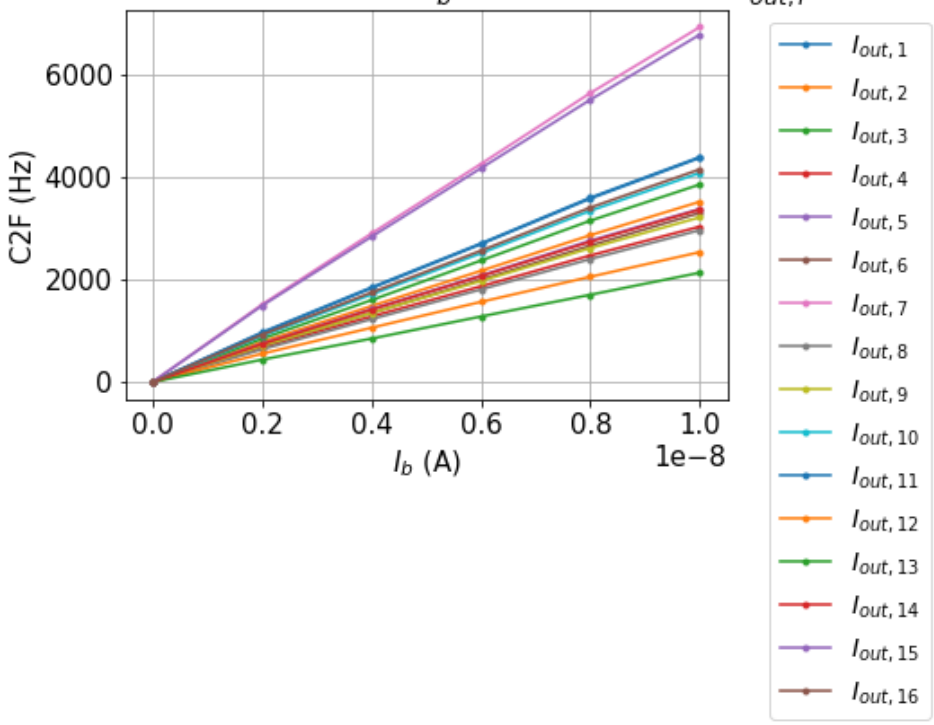
In [12]:

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

N_samples = 6
Ib = np.linspace(0, 10e-9, N_samples)
c2f = np.loadtxt('./data/data_ex_4_1_3.csv',delimiter=',')
plt.plot(Ib,np.transpose(c2f),'.-')

plt.xlabel('$I_b$ (A)')
plt.ylabel('C2F (Hz)')
plt.legend(['${I_{out,1}}$','${I_{out,2}}$','${I_{out,3}}$','${I_{out,4}}$','${I_{out,5}}$
plt.title('Fig. 1: Measured C2F values as function of $I_b$ for calibration of $I_{out,i}$
plt.grid()
plt.show()
```

Fig. 1: Measured C2F values as function of I_b for calibration of $I_{out,i}$ of all 16 WTA cells.



- Fit data

In [39]:

```
c2f = np.loadtxt('./data/data_ex_4_1_3.csv',delimiter=',')
N_samples = 6
Ib = np.linspace(0, 10e-9, N_samples)
c2f_ch1 = np.polyfit(c2f[0],Ib,2)
c2f_ch2 = np.polyfit(c2f[1],Ib,2)
c2f_ch3 = np.polyfit(c2f[2],Ib,2)
c2f_ch4 = np.polyfit(c2f[3],Ib,2)
c2f_ch5 = np.polyfit(c2f[4],Ib,2)
c2f_ch6 = np.polyfit(c2f[5],Ib,2)
c2f_ch7 = np.polyfit(c2f[6],Ib,2)
c2f_ch8 = np.polyfit(c2f[7],Ib,2)
c2f_ch9 = np.polyfit(c2f[8],Ib,2)
c2f_ch10 = np.polyfit(c2f[9],Ib,2)
c2f_ch11 = np.polyfit(c2f[10],Ib,2)
c2f_ch12 = np.polyfit(c2f[11],Ib,2)
c2f_ch13 = np.polyfit(c2f[12],Ib,2)
c2f_ch14 = np.polyfit(c2f[13],Ib,2)
c2f_ch15 = np.polyfit(c2f[14],Ib,2)
c2f_ch16 = np.polyfit(c2f[15],Ib,2)

print(c2f_ch1)
print ('The I1(f1) function is :')
print (np.poly1d(c2f_ch1))
```

```
[ 3.92755152e-17  2.11525298e-12 -2.65304024e-11]
The I1(f1) function is :
           2
3.928e-17 x + 2.115e-12 x - 2.653e-11
```

4.2 Calibration of input current I_{in} vs input voltage V_{in}

The input is given as voltage (`WTC_VIN_VI` = V_{in}), so we want to know the exact current $I_{in}(= I_{all})$ first.

4.2.1 Chip configuration

In [11]:
```
# Select Line3 to read Iin (when Iall=Iin)
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine3,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

4.2.2 Set fixed voltages

- What value should bias `WTA_VGAIN_P` take?

In [12]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VGAIN_P,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])
```

- What value should bias `WTA_VEX_N` take?

In [13]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VEX_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 0)])
```

The excitatory lateral coupling has been turned OFF by setting $V_{ex} = 0\mathrm{V}$.

- What value should bias `WTA_VINH_N` take?

In [14]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VINH_N,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])
```

The inhibitory lateral coupling has been turned OFF by setting $V_{inh} = 0V$.

- What value should bias `WTA_VB_N` take?

In [15]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VB_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])
```

The bias current has been set to $I_b = 89.65\mathrm{nA}$.

4.2.3 Data aquisition

Assume that the c2f calibration in 4.1 is accurate, then if we sweep V_{in} and measure the c2f response (which is connected to I_{all} now, we can obtain the bijection between V_{in} and I_{in}.

- What is the model of $I_{in}(V_{in})$ in subthreshold? (PFET)

Assuming that the input transistor is in saturation, the input current in subtreshold can be determined by the equation

$$I_{in} = I_0 e^{\frac{V_{dd} - \kappa V_{in}}{U_T}}.$$

- Now sweep V_{in} for all 16 channels at the same time to get the missing parameter in the model.

Important: Because all 16 channels are monitored by the c2f at the same time, if each channels has 50k events per second (this is the value everyone achieved in the last labs), it will result in almost 1M events per second in total, which is beyond the microcontroller's ability to handle and it will halt (and we have to repower it manually!). So in order to prevent this situation, **please never set any V_{in} below 1.5V!**

In [16]:

```python
N_samples = 25
Vi_set = np.linspace(1.8, 1.5, N_samples)
Vi = np.zeros(N_samples)
c2f = np.zeros([16, N_samples])
for j in range(N_samples):
    for i in range(16):
        p.set_voltage(eval('pyplane.DacChannel.AIN' + str(i)), Vi_set[j])
    Vi[j] = p.get_set_voltage(pyplane.DacChannel.AIN0)
    time.sleep(0.3)
    c2f[:,j] = p.read_c2f_output(0.1) #p.read_all_sampled_c2fs()
    print(c2f)
```

```
[[4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [2. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [2. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [2. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]]
[[4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [2. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
 [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
  0.]
```

```
  [4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]]
 [[4. 4. 5. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]]
 [[4. 4. 5. 5. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
```

```
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]]
 [[4. 4. 5. 5. 5. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [4. 4. 4. 4. 4. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [2. 3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
  [3. 3. 3. 3. 3. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
   0.]
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   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  5.  5.  6.  7.  9. 11.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 10. 12.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7. 10.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  6.  6.  8. 12. 14. 18.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  4.  4.  4.  4.  5.  6.  8. 10. 12.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 11. 14.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  7.  9. 11.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  6.  6.  6.  8. 10. 14. 18. 24.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13.  0.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]]
[[ 4.  4.  5.  5.  5.  5.  6.  6.  7.  8. 10. 12. 15. 19.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  4.  4.  4.  4.  5.  6.  6.  7.  9. 11. 14. 18.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  5.  5.  6.  7.  9. 11. 14.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 10. 12. 16.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7. 10. 13.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 21.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  6.  6.  8. 12. 14. 18. 26.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  4.  4.  4.  4.  5.  6.  8. 10. 12. 16.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 11. 14. 19.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13.  0.  0.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
```

```
[ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  7.  9. 11. 16.  0.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 14.  0.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  6.  6.  6.  8. 10. 14. 18. 24. 34.  0.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17.  0.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]]
[[ 4.  4.  5.  5.  5.  5.  6.  6.  7.  8. 10. 12. 15. 19. 25.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  4.  4.  4.  4.  5.  6.  6.  7.  9. 11. 14. 18. 24.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  5.  5.  6.  7.  9. 11. 14. 19.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 10. 12. 16. 22.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7. 10. 13. 16.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 21. 29.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  6.  6.  8. 12. 14. 18. 26. 34.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 22.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  4.  4.  4.  4.  5.  6.  8. 10. 12. 16. 22.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 23.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 11. 14. 19. 26.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  7.  9. 11. 16. 19.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 14. 18.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  6.  6.  6.  8. 10. 14. 18. 24. 34. 46.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 23.  0.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]]
[[ 4.  4.  5.  5.  5.  5.  6.  6.  7.  8. 10. 12. 15. 19. 25. 34.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  4.  4.  4.  4.  5.  6.  6.  7.  9. 11. 14. 18. 24. 33.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  5.  5.  6.  7.  9. 11. 14. 19. 27.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 10. 12. 16. 22. 29.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7. 10. 13. 16. 22.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 21. 29. 40.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  6.  6.  8. 12. 14. 18. 26. 34. 46.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 22. 30.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  4.  4.  4.  4.  5.  6.  8. 10. 12. 16. 22. 29.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 23. 30.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 11. 14. 19. 26. 36.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 22.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  7.  9. 11. 16. 19. 26.  0.  0.
  0.  0.  0.  0.  0.  0.  0.]
```

```
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 14. 18. 24.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  6.  6.  6.  8. 10. 14. 18. 24. 34. 46. 64.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 23. 31.  0.  0.
   0.  0.  0.  0.  0.  0.  0.]]
[[ 4.  4.  5.  5.  5.  5.  6.  6.  7.  8. 10. 12. 15. 19. 25. 34. 45.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  4.  4.  4.  4.  5.  6.  6.  7.  9. 11. 14. 18. 24. 33. 44.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  5.  5.  6.  7.  9. 11. 14. 19. 27. 34.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 10. 12. 16. 22. 29. 40.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7. 10. 13. 16. 22. 29.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 21. 29. 40. 55.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  4.  4.  6.  6.  8. 12. 14. 18. 26. 34. 46. 64.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  7.  9. 12. 16. 22. 30. 41.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  4.  4.  4.  4.  5.  6.  8. 10. 12. 16. 22. 29. 39.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 23. 30. 42.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  4.  4.  4.  5.  6.  8. 11. 14. 19. 26. 36. 49.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 22. 30.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  7.  9. 11. 16. 19. 26. 35.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 2.  3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 14. 18. 24. 32.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 4.  4.  4.  4.  4.  6.  6.  6.  8. 10. 14. 18. 24. 34. 46. 64. 87.  0.
   0.  0.  0.  0.  0.  0.  0.]
 [ 3.  3.  3.  3.  3.  3.  4.  4.  5.  6.  8. 10. 13. 17. 23. 31. 43.  0.
   0.  0.  0.  0.  0.  0.  0.]]
[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
   25.  34.  45.  62.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
   24.  33.  44.  60.   0.   0.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
   19.  27.  34.  47.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
   22.  29.  40.  56.   0.   0.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
   16.  22.  29.  40.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
   29.  40.  55.  75.   0.   0.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
   34.  46.  64.  88.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
   22.  30.  41.  55.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
   22.  29.  39.  54.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
   23.  30.  42.  57.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
   26.  36.  49.  68.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
   17.  22.  30.  41.   0.   0.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
   19.  26.  35.  48.   0.   0.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
   18.  24.  32.  44.   0.   0.   0.   0.   0.   0.   0.]
```

```
[  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
  46.  64.  87. 122.   0.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  31.  43.  58.   0.   0.   0.   0.   0.   0.   0.]]
[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
  25.  34.  45.  62.  83.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
  24.  33.  44.  60.  82.   0.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
  19.  27.  34.  47.  62.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  40.  56.  74.   0.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
  16.  22.  29.  40.  54.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
  29.  40.  55.  75. 104.   0.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
  34.  46.  64.  88. 119.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
  22.  30.  41.  55.  77.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  39.  54.  72.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  30.  42.  57.  77.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
  26.  36.  49.  68.  94.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
  17.  22.  30.  41.  56.   0.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
  19.  26.  35.  48.  66.   0.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
  18.  24.  32.  44.  59.   0.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
  46.  64.  87. 122. 170.   0.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  31.  43.  58.  79.   0.   0.   0.   0.   0.   0.]]
[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
  25.  34.  45.  62.  83. 114.   0.   0.   0.   0.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
  24.  33.  44.  60.  82. 114.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
  19.  27.  34.  47.  62.  86.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  40.  56.  74. 103.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
  16.  22.  29.  40.  54.  73.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
  29.  40.  55.  75. 104. 145.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
  34.  46.  64.  88. 119. 161.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
  22.  30.  41.  55.  77. 107.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  39.  54.  72. 100.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  30.  42.  57.  77. 105.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
  26.  36.  49.  68.  94. 130.   0.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
  17.  22.  30.  41.  56.  77.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
  19.  26.  35.  48.  66.  91.   0.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
  18.  24.  32.  44.  59.  81.   0.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
  46.  64.  87. 122. 170. 232.   0.   0.   0.   0.   0.]
```

```
[  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  31.  43.  58.  79. 109.   0.   0.   0.   0.   0.]]
[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
  25.  34.  45.  62.  83. 114. 162.   0.   0.   0.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
  24.  33.  44.  60.  82. 114. 162.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
  19.  27.  34.  47.  62.  86. 123.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  40.  56.  74. 103. 149.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
  16.  22.  29.  40.  54.  73. 104.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
  29.  40.  55.  75. 104. 145. 209.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
  34.  46.  64.  88. 119. 161. 227.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
  22.  30.  41.  55.  77. 107. 155.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  39.  54.  72. 100. 143.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  30.  42.  57.  77. 105. 151.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
  26.  36.  49.  68.  94. 130. 190.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
  17.  22.  30.  41.  56.  77. 109.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
  19.  26.  35.  48.  66.  91. 130.   0.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
  18.  24.  32.  44.  59.  81. 116.   0.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
  46.  64.  87. 122. 170. 232. 339.   0.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  31.  43.  58.  79. 109. 158.   0.   0.   0.   0.]]
[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
  25.  34.  45.  62.  83. 114. 162. 218.   0.   0.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
  24.  33.  44.  60.  82. 114. 162. 227.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
  19.  27.  34.  47.  62.  86. 123. 164.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  40.  56.  74. 103. 149. 207.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
  16.  22.  29.  40.  54.  73. 104. 145.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
  29.  40.  55.  75. 104. 145. 209. 291.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
  34.  46.  64.  88. 119. 161. 227. 322.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
  22.  30.  41.  55.  77. 107. 155. 215.   0.   0.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
  22.  29.  39.  54.  72. 100. 143. 197.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  30.  42.  57.  77. 105. 151. 206.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
  26.  36.  49.  68.  94. 130. 190. 263.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
  17.  22.  30.  41.  56.  77. 109. 148.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
  19.  26.  35.  48.  66.  91. 130. 181.   0.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
  18.  24.  32.  44.  59.  81. 116. 159.   0.   0.   0.]
 [  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
  46.  64.  87. 122. 170. 232. 339. 476.   0.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
  23.  31.  43.  58.  79. 109. 158. 217.   0.   0.   0.]]
```

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[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
   25.  34.  45.  62.  83. 114. 162. 218. 300.   0.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
   24.  33.  44.  60.  82. 114. 162. 227. 312.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
   19.  27.  34.  47.  62.  86. 123. 164. 230.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
   22.  29.  40.  56.  74. 103. 149. 207. 290.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
   16.  22.  29.  40.  54.  73. 104. 145. 200.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
   29.  40.  55.  75. 104. 145. 209. 291. 407.   0.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
   34.  46.  64.  88. 119. 161. 227. 322. 438.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
   22.  30.  41.  55.  77. 107. 155. 215. 297.   0.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
   22.  29.  39.  54.  72. 100. 143. 197. 273.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
   23.  30.  42.  57.  77. 105. 151. 206. 284.   0.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
   26.  36.  49.  68.  94. 130. 190. 263. 362.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
   17.  22.  30.  41.  56.  77. 109. 148. 205.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
   19.  26.  35.  48.  66.  91. 130. 181. 247.   0.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
   18.  24.  32.  44.  59.  81. 116. 159. 219.   0.   0.]
 [  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
   46.  64.  87. 122. 170. 232. 339. 476. 643.   0.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
   23.  31.  43.  58.  79. 109. 158. 217. 299.   0.   0.]]
[[  4.   4.   5.   5.   5.   5.   6.   6.   7.   8.  10.  12.  15.  19.
   25.  34.  45.  62.  83. 114. 162. 218. 300. 409.   0.]
 [  3.   3.   4.   4.   4.   4.   5.   6.   6.   7.   9.  11.  14.  18.
   24.  33.  44.  60.  82. 114. 162. 227. 312. 430.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   5.   5.   6.   7.   9.  11.  14.
   19.  27.  34.  47.  62.  86. 123. 164. 230. 317.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  10.  12.  16.
   22.  29.  40.  56.  74. 103. 149. 207. 290. 410.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.  10.  13.
   16.  22.  29.  40.  54.  73. 104. 145. 200. 273.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.  21.
   29.  40.  55.  75. 104. 145. 209. 291. 407. 555.   0.]
 [  4.   4.   4.   4.   4.   4.   4.   6.   6.   8.  12.  14.  18.  26.
   34.  46.  64.  88. 119. 161. 227. 322. 438. 603.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   7.   9.  12.  16.
   22.  30.  41.  55.  77. 107. 155. 215. 297. 409.   0.]
 [  3.   3.   3.   3.   4.   4.   4.   4.   5.   6.   8.  10.  12.  16.
   22.  29.  39.  54.  72. 100. 143. 197. 273. 377.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
   23.  30.  42.  57.  77. 105. 151. 206. 284. 396.   0.]
 [  3.   3.   3.   3.   3.   4.   4.   4.   5.   6.   8.  11.  14.  19.
   26.  36.  49.  68.  94. 130. 190. 263. 362. 506.   0.]
 [  3.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.
   17.  22.  30.  41.  56.  77. 109. 148. 205. 282.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   7.   9.  11.  16.
   19.  26.  35.  48.  66.  91. 130. 181. 247. 340.   0.]
 [  2.   3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  14.
   18.  24.  32.  44.  59.  81. 116. 159. 219. 301.   0.]
 [  4.   4.   4.   4.   4.   6.   6.   6.   8.  10.  14.  18.  24.  34.
   46.  64.  87. 122. 170. 232. 339. 476. 643. 921.   0.]
 [  3.   3.   3.   3.   3.   3.   4.   4.   5.   6.   8.  10.  13.  17.
   23.  31.  43.  58.  79. 109. 158. 217. 299. 409.   0.]]
[[   4.    4.    5.    5.    5.    5.    6.    6.    7.    8.   10.   12.
    15.   19.   25.   34.   45.   62.   83.  114.  162.  218.  300.  409.
```

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  572.]
[   3.    3.    4.    4.    4.    4.    5.    6.    6.    7.    9.   11.
   14.   18.   24.   33.   44.   60.   82.  114.  162.  227.  312.  430.
  596.]
[   4.    4.    4.    4.    4.    4.    4.    5.    5.    6.    7.    9.
   11.   14.   19.   27.   34.   47.   62.   86.  123.  164.  230.  317.
  437.]
[   3.    3.    3.    3.    3.    4.    4.    4.    5.    6.    8.   10.
   12.   16.   22.   29.   40.   56.   74.  103.  149.  207.  290.  410.
  551.]
[   2.    3.    3.    3.    3.    3.    3.    4.    4.    5.    6.    7.
   10.   13.   16.   22.   29.   40.   54.   73.  104.  145.  200.  273.
  378.]
[   3.    3.    3.    3.    3.    4.    4.    5.    6.    7.    9.   12.
   16.   21.   29.   40.   55.   75.  104.  145.  209.  291.  407.  555.
  775.]
[   4.    4.    4.    4.    4.    4.    4.    6.    6.    8.   12.   14.
   18.   26.   34.   46.   64.   88.  119.  161.  227.  322.  438.  603.
  821.]
[   3.    3.    3.    3.    3.    3.    4.    4.    5.    6.    7.    9.
   12.   16.   22.   30.   41.   55.   77.  107.  155.  215.  297.  409.
  573.]
[   3.    3.    3.    3.    4.    4.    4.    4.    5.    6.    8.   10.
   12.   16.   22.   29.   39.   54.   72.  100.  143.  197.  273.  377.
  522.]
[   3.    3.    3.    3.    3.    3.    4.    4.    5.    6.    8.   10.
   13.   17.   23.   30.   42.   57.   77.  105.  151.  206.  284.  396.
  548.]
[   3.    3.    3.    3.    3.    4.    4.    4.    5.    6.    8.   11.
   14.   19.   26.   36.   49.   68.   94.  130.  190.  263.  362.  506.
  701.]
[   3.    3.    3.    3.    3.    3.    3.    4.    4.    5.    6.    8.
   10.   13.   17.   22.   30.   41.   56.   77.  109.  148.  205.  282.
  391.]
[   2.    3.    3.    3.    3.    3.    3.    4.    4.    5.    7.    9.
   11.   16.   19.   26.   35.   48.   66.   91.  130.  181.  247.  340.
  470.]
[   2.    3.    3.    3.    3.    3.    3.    4.    4.    5.    6.    8.
   10.   14.   18.   24.   32.   44.   59.   81.  116.  159.  219.  301.
  410.]
[   4.    4.    4.    4.    4.    6.    6.    6.    8.   10.   14.   18.
   24.   34.   46.   64.   87.  122.  170.  232.  339.  476.  643.  921.
 1264.]
[   3.    3.    3.    3.    3.    3.    4.    4.    5.    6.    8.   10.
   13.   17.   23.   31.   43.   58.   79.  109.  158.  217.  299.  409.
  574.]]
```

- Save data

In [17]:

```
np.savetxt('./data/Vi_ex_4_2_3.csv', Vi, delimiter=',')
np.savetxt('./data/c2f_ex_4_2_3.csv', c2f, delimiter=',')
```

- Plot data (Hint: `np.transpose`)

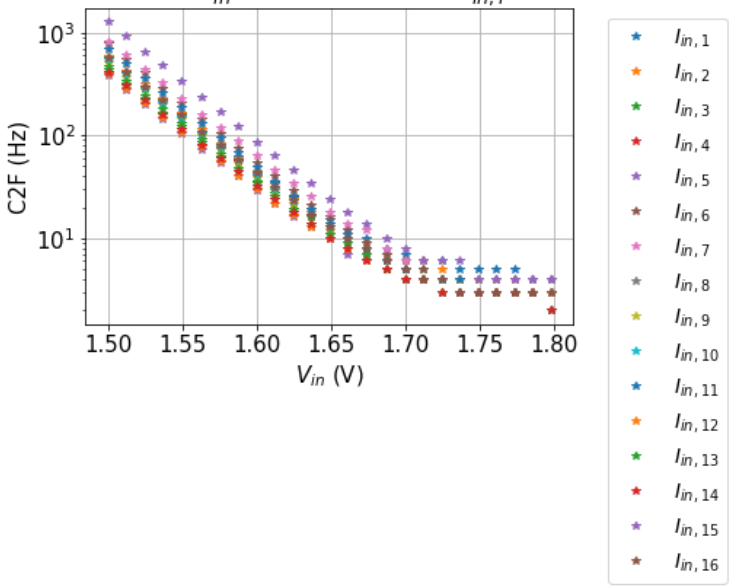
In [18]:

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

Vi = np.loadtxt('./data/Vi_ex_4_2_3.csv',delimiter=',')
c2f = np.loadtxt('./data/c2f_ex_4_2_3.csv',delimiter=',')
plt.semilogy(Vi,np.transpose(c2f),'*')
```

```
plt.xlabel('$V_{in}$ (V)')
plt.ylabel('C2F (Hz)')
plt.legend(['${I_{in,1}}$','${I_{in,2}}$','${I_{in,3}}$','${I_{in,4}}$','${I_{in,5}}$','${
plt.title('Fig. 2: Measured C2F values as function of $V_{in}$ for calibration of $I_{in,
plt.grid()
plt.show()
```

Fig. 2: Measured C2F values as function of V_{in} for calibration of $I_{in,i}$ of all 16 WTA cells on a semilogy scale.



In Fig. 2, the measured C2F values for the calibration of the input current $I_{in,i}$ of all 16 WTA cells are plotted on a semilogy scale over the input voltage in the range $V_{in} \in [1.5\text{V}, 1.8\text{V}]$.

The output feedback, excitatory lateral coupling and inhibitory lateral coupling have been turned off in this measurment, implying that $I_{in,i} = I_{all}$.

- Fit data

In [40]:

```
c2f = np.loadtxt('./data/c2f_ex_4_2_3.csv',delimiter=',')
Vi = np.loadtxt('./data/Vi_ex_4_2_3.csv',delimiter=',')

fit_from = 18

Iin_ch1 = np.polyfit(Vi[fit_from:],np.log(c2f_ch1[2]+ c2f_ch1[1]*c2f[0][fit_from:]+c2f_ch1
Iin_ch2 = np.polyfit(Vi[fit_from:],np.log(c2f_ch2[2]+ c2f_ch2[1]*c2f[1][fit_from:]+c2f_ch2
Iin_ch3 = np.polyfit(Vi[fit_from:],np.log(c2f_ch3[2]+ c2f_ch3[1]*c2f[2][fit_from:]+c2f_ch3
Iin_ch4 = np.polyfit(Vi[fit_from:],np.log(c2f_ch4[2]+ c2f_ch4[1]*c2f[3][fit_from:]+c2f_ch4
Iin_ch5 = np.polyfit(Vi[fit_from:],np.log(c2f_ch5[2]+ c2f_ch5[1]*c2f[4][fit_from:]+c2f_ch5
Iin_ch6 = np.polyfit(Vi[fit_from:],np.log(c2f_ch6[2]+ c2f_ch6[1]*c2f[5][fit_from:]+c2f_ch6
Iin_ch7 = np.polyfit(Vi[fit_from:],np.log(c2f_ch7[2]+ c2f_ch7[1]*c2f[6][fit_from:]+c2f_ch7
Iin_ch8 = np.polyfit(Vi[fit_from:],np.log(c2f_ch8[2]+ c2f_ch8[1]*c2f[7][fit_from:]+c2f_ch8
Iin_ch9 = np.polyfit(Vi[fit_from:],np.log(c2f_ch9[2]+ c2f_ch9[1]*c2f[8][fit_from:]+c2f_ch9
Iin_ch10 = np.polyfit(Vi[fit_from:],np.log(c2f_ch10[2]+ c2f_ch10[1]*c2f[9][fit_from:]+c2f_
Iin_ch11 = np.polyfit(Vi[fit_from:],np.log(c2f_ch11[2]+ c2f_ch11[1]*c2f[10][fit_from:]+c2f
Iin_ch12 = np.polyfit(Vi[fit_from:],np.log(c2f_ch12[2]+ c2f_ch12[1]*c2f[11][fit_from:]+c2f
Iin_ch13 = np.polyfit(Vi[fit_from:],np.log(c2f_ch13[2]+ c2f_ch13[1]*c2f[12][fit_from:]+c2f
Iin_ch14 = np.polyfit(Vi[fit_from:],np.log(c2f_ch14[2]+ c2f_ch14[1]*c2f[13][fit_from:]+c2f
Iin_ch15 = np.polyfit(Vi[fit_from:],np.log(c2f_ch15[2]+ c2f_ch15[1]*c2f[14][fit_from:]+c2f
Iin_ch16 = np.polyfit(Vi[fit_from:],np.log(c2f_ch16[2]+ c2f_ch16[1]*c2f[15][fit_from:]+c2f

print(Iin_ch1)
print(Iin_ch2)
print(Iin_ch3)

Vdd = 1.8
```

```
Ut  = 0.025
I0_K = np.zeros([16,2])  # store I_0 and k
for i in range(16):
    exec('I0_K['+str(i)+'][1] = -Iin_ch'+str(i+1)+'[0]*Ut')
    exec('I0_K['+str(i)+'][0] = np.exp(Iin_ch'+str(i+1)+'[1] - Vdd*I0_K['+str(i)+'][1]/Ut)
#     exec('I0_K['+str(i)+'][0] = np.exp(Iin_ch'+str(i+1)+'[1] - Vdd/Ut)')

print(I0_K)
```

```
[-27.24932389  20.30497181]
[-28.68225657  22.72318849]
[-28.31020505  21.76601547]
[[3.28640750e-13 6.81233097e-01]
 [2.79751878e-13 7.17056414e-01]
 [2.09856250e-13 7.07755126e-01]
 [2.66611974e-13 7.28465769e-01]
 [1.79574422e-13 7.18731379e-01]
 [5.22420248e-13 6.96617127e-01]
 [2.55492730e-13 6.95746647e-01]
 [3.70255924e-13 7.07112161e-01]
 [2.65205470e-13 7.18766198e-01]
 [2.65308807e-13 7.01577101e-01]
 [2.87503822e-13 7.09935357e-01]
 [3.42109313e-13 6.92306437e-01]
 [6.22835299e-13 6.78865501e-01]
 [2.07638266e-13 7.15092637e-01]
 [3.42803593e-13 7.09233213e-01]
 [2.52268945e-13 7.07698755e-01]]
```

Hint: Methods (need to understand):

By linearly fitting $\ln(I_{in})$ and referencing the equation for the input current given at the beggining of 4.2.3

PFET in saturation (**all voltages are referenced to N-well, Vwell=Vdd**):

$$I_{in} = I_0 e^{\frac{-\kappa V_g + V_s}{U_T}} = I_0 e^{\frac{-\kappa(V_{in} - V_{dd}) + (V_{dd} - V_{dd})}{U_T}} = I_0 e^{\frac{\kappa(V_{dd} - V_{in})}{U_T}},$$

the parameters κ and I_0 of all input transitors can be extracted. The corresponding relationships can be obtained by comparing the analytical description of the input current with the linearly interpolated function

$$\ln(I_{in}) = I_{in,fit}$$

$$\Rightarrow \ln(I_0) + \frac{\kappa}{U_T} V_{dd} - \frac{\kappa}{U_T} V_{in} = m_i V_{in} + b_i$$

This yields

$$m_i = -\frac{\kappa}{U_T} \Rightarrow \kappa = -m_i U_T \quad \text{and}$$

$$b_i = \ln(I_0) + \frac{\kappa}{U_T} V_{dd} \Rightarrow I_0 = e^{b_i - \frac{\kappa}{U_T} V_{dd}}.$$

Shown on the example of cell 1, you can know $I_{in} = \ldots\ldots$.

#

4.3 Calibration of the individual bias currents (optional)

If we repeat 4.1 but with V_c between cells isolated (Hint: by setting V_{inh} to proper value), we could measure individual I_b.

In [ ]:

5 Basic WTA behavior

In this experiment, we will observe the winner–take–all network in action. We will only use cell 0 and 1 and disable all other cells.

5.1 Set fixed voltages

- What value should bias `WTA_VGAIN_P` take?

In [12]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VGAIN_P,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])
```

- What value should bias `WTA_VEX_N` take?

In [13]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VEX_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 0)])
```

The excitatory lateral coupling has been turned OFF by setting $V_{ex} = 0\mathrm{V}$.

- What value should bias `WTA_VINH_N` take?

In [14]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VINH_N,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 0)])
```

The inhibitory lateral coupling has been turned ON by setting $V_{inh} = V_{dd} - 0.5V$.

- What value should bias `WTA_VB_N` take?

In [28]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VB_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 255)])
```

The bias current has been set to

$$I_b = w\frac{BG_{\text{fine}}}{256} I_{BG_{\text{master}}} = 3 \cdot \frac{255}{256} \cdot 30nA \approx 89.65nA.$$

- What value should the V_{in} of Cell 2 - Cell15 take in order to disable them?

In [29]:
```
for i in range(2, 16):
    p.set_voltage(eval('pyplane.DacChannel.AIN' + str(i)), 1.8)
    time.sleep(0.2)
```

Cells 2 - 15 can be turned off by setting their respective input voltages to ???? (as the corresponding transistors are pFETs)

5.2 Data aquisition

- Fix $V_{in,1}$ to a value and sweep $V_{in,0}$ from above $V_{in,1}$ to below $V_{in,1}$ then to above $V_{in,1}$ again and observe the two V_{out} and I_{out}.

Important: never set any V_{in} below 1.5 V

In [30]:
```
# Select Line2 to read Iout
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine2,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [38]:
```
N_samples = 50

Vin1 = 1.65  # ??? V
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.2)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))  ## 1

Vi0 = np.zeros(N_samples)
Vout0 = np.zeros(N_samples)
Vout1 = np.zeros(N_samples)
c2f_Iout = np.zeros([16, N_samples])
c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    Vi0[j] = p.get_set_voltage(pyplane.DacChannel.AIN0)

    time.sleep(0.1)

    Vout0[j] = p.read_voltage(pyplane.AdcChannel.AOUT15)  # go back 3.4 to check the note
#     time.sleep(0.1)
    Vout1[j] = p.read_voltage(pyplane.AdcChannel.AOUT14)  # go back 3.4 to check the note
#     time.sleep(0.1)

    # Measure Iout by c2f
    c2f_Iout[:,j] = p.read_c2f_output(0.1)

    #Measure Iall
    #p.send_coach_event(pyplane.Coach.generate_aerc_event(
   # pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine3,
    #pyplane.Coach.VoltageOutputSelect.SelectLine0,
    #pyplane.Coach.VoltageInputSelect.SelectLine0,
    #pyplane.Coach.SynapseSelect.NoneSelected,0))
```

- Save data

In [39]:
```
np.savetxt('./data/Vi0_ex_5_2.csv', Vi0, delimiter=',')
np.savetxt('./data/Vout0_ex_5_2.csv', Vout0, delimiter=',')
np.savetxt('./data/Vout1_ex_5_2.csv', Vout1, delimiter=',')
np.savetxt('./data/c2f_Iout_ex_5_2.csv', c2f_Iout, delimiter=',')
# np.savetxt('./data/c2f_Iall_ex_5_2.csv', c2f_Iall, delimiter=',')
```

- Plot data (you may want to plot the axes in a proper range that can zoom in the transition region)

In [41]:
```
import matplotlib.pyplot as plt
import numpy as np
plt.rcParams.update({'font.size': 15})

Vi0 = np.loadtxt('./data/Vi0_ex_5_2.csv',  delimiter=',')
Vout0 = np.loadtxt('./data/Vout0_ex_5_2.csv',  delimiter=',')
Vout1 = np.loadtxt('./data/Vout1_ex_5_2.csv',  delimiter=',')
c2f_Iout = np.loadtxt('./data/c2f_Iout_ex_5_2.csv',  delimiter=',')
# c2f_Iall = np.loadtxt('./data/c2f_Iall_ex_5_2.csv',  delimiter=',')


# I(f) function to convert frequcy to current, using factors from section 4.1
Iout0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iout[0,:]+c2f_ch1[0]*c2f_Iout[0,:]**2
Iout1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iout[1,:]+c2f_ch2[0]*c2f_Iout[1,:]**2

# Plot output current vs. the difference between input voltages
plt.plot(Vi0-Vin1,Iout0*10**9,'+-')
plt.plot(Vi0-Vin1,Iout1*10**9,'*-')

plt.xlabel('$V_{in,0}-V_{in,1}$ (V)')
plt.ylabel('$I_{out,i}$ (nA)')
plt.legend(['${I_{out,0}}$','${I_{out,1}}$'],prop={'size': 14})
plt.title('Fig. 3: Output currents of the basic WTA measurements plotted over the differer
plt.grid()
plt.show()
plt.legend(['${I_{out,0}}$','${I_{out,1}}$'],prop={'size': 14})
plt.plot(Vi0-Vin1,Vout0,'+-')
plt.plot(Vi0-Vin1,Vout1,'*-')

plt.xlabel('$V_{in,0}-V_{in,1}$ (V)')
plt.ylabel('$V_{out,i}$ (V)')
plt.legend(['${V_{out,0}}$','${V_{out,1}}$'],prop={'size': 14})
plt.title('Fig. 4: Output voltages of the basic WTA measurements plotted over the differer
plt.grid()
plt.show()
```

Fig. 3: Output currents of the basic WTA measurements plotted over the differential input voltage.

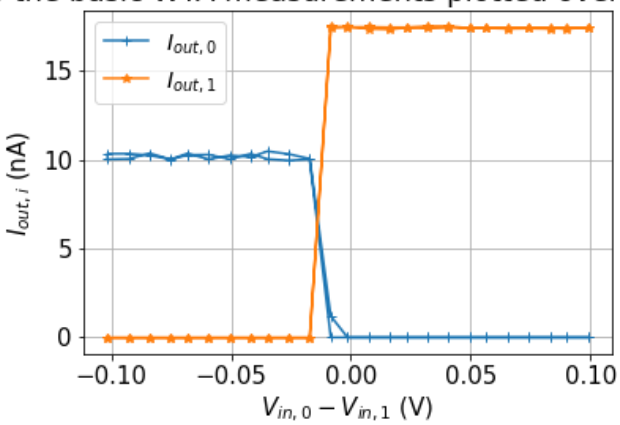
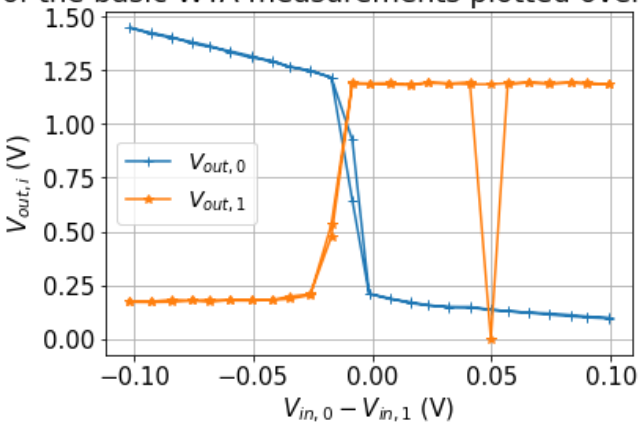


Fig. 4: Output voltages of the basic WTA measurements plotted over the differential input voltage.



Conclusion of your experiment

> $I_{out,1}$ reaches a higher maximum current than $I_{out,0}$. The V_{out} stays consistent when cell 1 is firing and decreases a bit when cell 0 is firing but starting to lose. A firing cell inhibits the other, resulting in only one cell firing most of the time. The only point where both are firing should be when $\Delta V = 0$, but this is shifted a bit because of mismatches.

5.3 Different bias currents

Question: If we change the bias current I_b, what will happen?

Answer: ???

(**Optional**) If you want to experimentally validate your answer, repeat 5.2 with two differnt bias currents and compare. The bias current was switched from $I_b \approx ???\mathrm{pA}$ to $I_b \approx ???\mathrm{pA}$.

In [ ]:

6 Hysteretic WTA behavior

In this experiment, we will observe the winner–take–all network with hysteresis. This implies a "memory" effect.

We will still use only cell 0 and 1 and disable all other cells.

6.1 Set fixed voltages

- What value should bias `WTA_VEX_N` take?

In [22]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VEX_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 50)])
```

The excitatory lateral coupling has been turned ON by setting $V_{ex} = V_{dd} - 0.5\mathrm{V}$.

- What value should bias `WTA_VINH_N` take?

In [23]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
```

```
pyplane.Coach.BiasAddress.WTA_VINH_N,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 0)])
```

The inhibitory lateral coupling has been turned ON by setting $V_{inh} = V_{dd} - 0.5V$.

- What value should bias `WTA_VB_N` take?

In [24]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VB_N,\
pyplane.Coach.BiasType.N, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 100)])
```

The bias current has been set to $I_b \approx 90nA$.

- What value should the V_{in} of Cell 2 - Cell15 take in order to disable them?

In [25]:
```
for i in range(2, 16):
    p.set_voltage(eval('pyplane.DacChannel.AIN' + str(i)), 1.8)
    time.sleep(0.2)
```

Cells 2 - 15 can be turned off by setting their respective input voltages to V_{dd} (as the corresponding transistors are pFETs)

6.2 Data aquisition

- What value should bias `WTA_VGAIN_P` take?

In [17]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VGAIN_P,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 2)])
```

- Fix $V_{in,1}$ to a value and sweep $V_{in,0}$ from above $V_{in,1}$ to below $V_{in,1}$ then to above $V_{in,1}$ again and observe the two V_{out}, I_{out} and I_{all}.

Important: never set any V_{in} below 1.5 V

In [24]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine2,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [26]:
```
N_samples = 50

Vin1 = 1.65
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.5)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))
Vi0 = np.zeros(N_samples)
Vout0 = np.zeros(N_samples)
```

```
Vout1 = np.zeros(N_samples)
c2f_Iout = np.zeros([16, N_samples])
c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    Vi0[j] = p.get_set_voltage(pyplane.DacChannel.AIN0)
    Vout0[j] = p.read_voltage(pyplane.AdcChannel.AOUT15)
#     time.sleep(0.1)
    Vout1[j] = p.read_voltage(pyplane.AdcChannel.AOUT14)
#     time.sleep(0.1)

    # Measure Iout
    c2f_Iout[:,j] = p.read_c2f_output(0.1)    #p.read_all_sampled_c2fs()
```

In [20]:

```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine3,
pyplane.Coach.VoltageOutputSelect.SelectLine0,
pyplane.Coach.VoltageInputSelect.SelectLine0,
pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [21]:

```
N_samples = 50

Vin1 = 1.65
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.5)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))

c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    #Measure Iall
    c2f_Iall[:,j] = p.read_c2f_output(0.1)  #p.read_all_sampled_c2fs()

# p.set_sampling_mode(pyplane.SamplingMode.Off)
```

- Save data

In [22]:

```
np.savetxt('./data/Vi0_ex_6_2.csv', Vi0, delimiter=',')
np.savetxt('./data/Vout0_ex_6_2.csv', Vout0, delimiter=',')
np.savetxt('./data/Vout1_ex_6_2.csv', Vout1, delimiter=',')
np.savetxt('./data/c2f_Iout_ex_6_2.csv', c2f_Iout, delimiter=',')
np.savetxt('./data/c2f_Iall_ex_6_2.csv', c2f_Iall, delimiter=',')
```

- Plot data (you may want to plot the axes in a proper range that can zoom in the transition region)

In [29]:

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

```
Vin1 = 1.65
Vi0 = np.loadtxt('./data/Vi0_ex_6_2.csv',  delimiter=',')
Vout0 = np.loadtxt('./data/Vout0_ex_6_2.csv',  delimiter=',')
Vout1 = np.loadtxt('./data/Vout1_ex_6_2.csv',  delimiter=',')
c2f_Iout = np.loadtxt('./data/c2f_Iout_ex_6_2.csv',  delimiter=',')
c2f_Iall = np.loadtxt('./data/c2f_Iall_ex_6_2.csv',  delimiter=',')

Iout0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iout[0,:]+c2f_ch1[0]*c2f_Iout[0,:]**2
Iout1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iout[1,:]+c2f_ch2[0]*c2f_Iout[1,:]**2

plt.plot((Vi0-Vin1)[:24],(Iout0[:24])*10**9,'+-')
plt.plot((Vi0-Vin1)[:24],(Iout1[:24])*10**9,'*-')
plt.plot((Vi0-Vin1)[24:],(Iout0[24:])*10**9,'+-')
plt.plot((Vi0-Vin1)[24:],(Iout1[24:])*10**9,'*-')
plt.legend(['${I_{out,0}}$ (Sweep Down)','${I_{out,1}}$ (Sweep Down)','${I_{out,0}}$ (Swee
plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$I_{out,i}$ [nA]')

plt.title('Fig. 9: Output currents of the hysteretic WTA measurements plotted over the dif
plt.grid()
plt.show()

Iall0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iall[0,:]+c2f_ch1[0]*c2f_Iall[0,:]**2
Iall1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iall[1,:]+c2f_ch2[0]*c2f_Iall[1,:]**2

# print(Iall0)

plt.semilogy((Vi0-Vin1)[:24],Iall0[:24],'+-')
plt.semilogy((Vi0-Vin1)[:24],Iall1[:24],'*-')
plt.semilogy((Vi0-Vin1)[24:],Iall0[24:],'+-')
plt.semilogy((Vi0-Vin1)[24:],Iall1[24:],'*-')

plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$I_{all,i}$ [A]')
plt.legend(['${I_{all,0}}$ (Sweep Down)','${I_{all,1}}$ (Sweep Down)','${I_{all,0}}$ (Swee
plt.title('Fig. 10: Net input currents of the hysteretic WTA measurements plotted over the
plt.grid()
plt.show()

plt.plot((Vi0-Vin1)[:24],Vout0[:24],'+-')
plt.plot((Vi0-Vin1)[:24],Vout1[:24],'*-')
plt.plot((Vi0-Vin1)[24:],Vout0[24:],'+-')
plt.plot((Vi0-Vin1)[24:],Vout1[24:],'*-')
plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$V_{out}$ [V]')
plt.legend(['${V_{out,0}}$ (Sweep Down)','${V_{out,1}}$ (Sweep Down)','${V_{out,0}}$ (Swee
plt.title('Fig. 11:  Output voltages of the hysteretic WTA measurements plotted over the
plt.grid()
plt.show()
```

Fig. 9: Output currents of the hysteretic WTA measurements plotted over the differential input voltage.

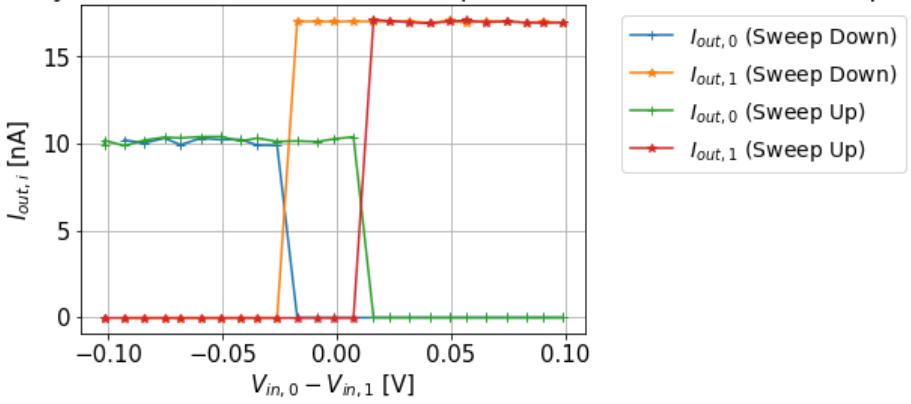


Fig. 10: Net input currents of the hysteretic WTA measurements plotted over the differential input voltage.

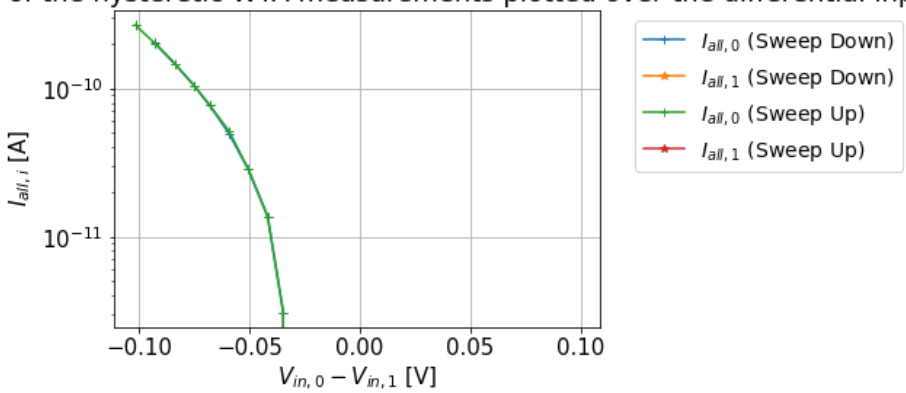
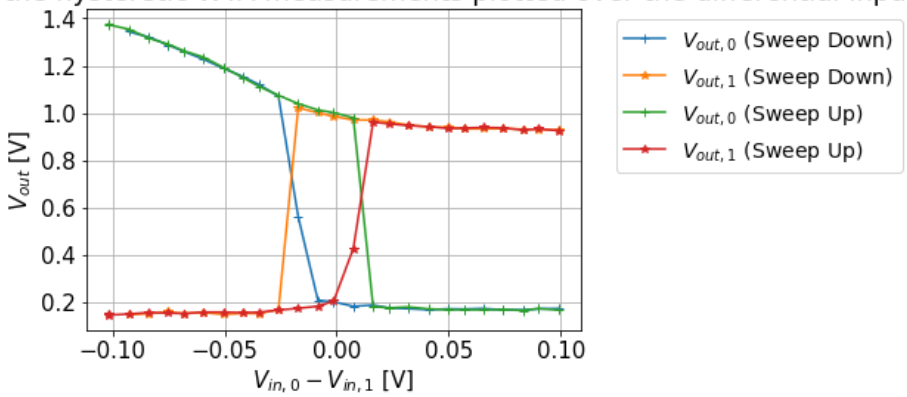


Fig. 11: Output voltages of the hysteretic WTA measurements plotted over the differential input voltage.



Conclusion of your experiment

> Because of the histerystic character of he network, a winner becomes "sticky", so the winners don't switch when $\Delta V = 0$. Instead, a new winner requires more ΔV, effectively shifting the graph. The same happens when sweeping down, only that now here is a new winner that needs to be displaced.

6.3 Different gain voltages

Repeat 6.2 with two differnt V_{gain} and compare.

- What value should bias `WTA_VGAIN_P` take?

In [26]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VGAIN_P,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 1)])
```

- Fix $V_{in,1}$ to a value and sweep $V_{in,0}$ from above $V_{in,1}$ to below $V_{in,1}$ then to above $V_{in,1}$ again and observe the two V_{out}, I_{out} and I_{all}.

Important: never set any V_{in} below 1.5 V

In [27]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine2,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [28]:
```
N_samples = 50

Vin1 = 1.65
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.5)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))
Vi0 = np.zeros(N_samples)
Vout0 = np.zeros(N_samples)
Vout1 = np.zeros(N_samples)
c2f_Iout = np.zeros([16, N_samples])
c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    Vi0[j] = p.get_set_voltage(pyplane.DacChannel.AIN0)
    Vout0[j] = p.read_voltage(pyplane.AdcChannel.AOUT15)
    time.sleep(0.1)
    Vout1[j] = p.read_voltage(pyplane.AdcChannel.AOUT14)
    time.sleep(0.1)

    # Measure Iout
    c2f_Iout[:,j] = p.read_c2f_output(0.1)    #p.read_all_sampled_c2fs()
```

In [29]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine3,
pyplane.Coach.VoltageOutputSelect.SelectLine0,
pyplane.Coach.VoltageInputSelect.SelectLine0,
pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [30]:
```
N_samples = 50

Vin1 = 1.65
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.5)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))

c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    #Measure Iall
    c2f_Iall[:,j] = p.read_c2f_output(0.1)  #p.read_all_sampled_c2fs()

# p.set_sampling_mode(pyplane.SamplingMode.Off)
```

- Save data

In [31]:
```
np.savetxt('./data/Vi0_ex_6_3_1.csv', Vi0, delimiter=',')
np.savetxt('./data/Vout0_ex_6_3_1.csv', Vout0, delimiter=',')
np.savetxt('./data/Vout1_ex_6_3_1.csv', Vout1, delimiter=',')
```

```
np.savetxt('./data/c2f_Iout_ex_6_3_1.csv', c2f_Iout, delimiter=',')
np.savetxt('./data/c2f_Iall_ex_6_3_1.csv', c2f_Iall, delimiter=',')
```

- Plot data (you may want to plot the axes in a proper range that can zoom in the transition region)

In [41]:

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

Vin1 = 1.65
Vi0 = np.loadtxt('./data/Vi0_ex_6_3_1.csv',  delimiter=',')
Vout0 = np.loadtxt('./data/Vout0_ex_6_3_1.csv',  delimiter=',')
Vout1 = np.loadtxt('./data/Vout1_ex_6_3_1.csv',  delimiter=',')
c2f_Iout = np.loadtxt('./data/c2f_Iout_ex_6_3_1.csv',  delimiter=',')
c2f_Iall = np.loadtxt('./data/c2f_Iall_ex_6_3_1.csv',  delimiter=',')

Iout0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iout[0,:]+c2f_ch1[0]*c2f_Iout[0,:]**2
Iout1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iout[1,:]+c2f_ch2[0]*c2f_Iout[1,:]**2

plt.plot((Vi0-Vin1)[:24],(Iout0[:24])*10**9,'+-')
plt.plot((Vi0-Vin1)[:24],(Iout1[:24])*10**9,'*-')
plt.plot((Vi0-Vin1)[24:],(Iout0[24:])*10**9,'+-')
plt.plot((Vi0-Vin1)[24:],(Iout1[24:])*10**9,'*-')
plt.legend(['${I_{out,0}}$ (Sweep Down)','${I_{out,1}}$ (Sweep Down)','${I_{out,0}}$ (Swee
plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$I_{out,i}$ [nA]')

plt.title('Fig. 12: Output currents of the hysteretic WTA measurements plotted over the di
plt.grid()
plt.show()

Iall0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iall[0,:]+c2f_ch1[0]*c2f_Iall[0,:]**2
Iall1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iall[1,:]+c2f_ch2[0]*c2f_Iall[1,:]**2

# print(Iall0)

plt.semilogy((Vi0-Vin1)[:24],Iall0[:24],'+-')
plt.semilogy((Vi0-Vin1)[:24],Iall1[:24],'*-')
plt.semilogy((Vi0-Vin1)[24:],Iall0[24:],'+-')
plt.semilogy((Vi0-Vin1)[24:],Iall1[24:],'*-')

plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$I_{all,i}$ [A]')
plt.legend(['${I_{all,0}}$ (Sweep Down)','${I_{all,1}}$ (Sweep Down)','${I_{all,0}}$ (Swee
plt.title('Fig. 13: Net input currents of the hysteretic WTA measurements plotted over the
plt.grid()
plt.show()

plt.plot((Vi0-Vin1)[:24],Vout0[:24],'+-')
plt.plot((Vi0-Vin1)[:24],Vout1[:24],'*-')
plt.plot((Vi0-Vin1)[24:],Vout0[24:],'+-')
plt.plot((Vi0-Vin1)[24:],Vout1[24:],'*-')
plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$V_{out}$ [V]')
plt.legend(['${V_{out,0}}$ (Sweep Down)','${V_{out,1}}$ (Sweep Down)','${V_{out,0}}$ (Swee
plt.title('Fig. 14:  Output voltages of the hysteretic WTA measurements plotted over the
plt.grid()
plt.show()
```

Fig. 12: Output currents of the hysteretic WTA measurements plotted over the differential input voltage.

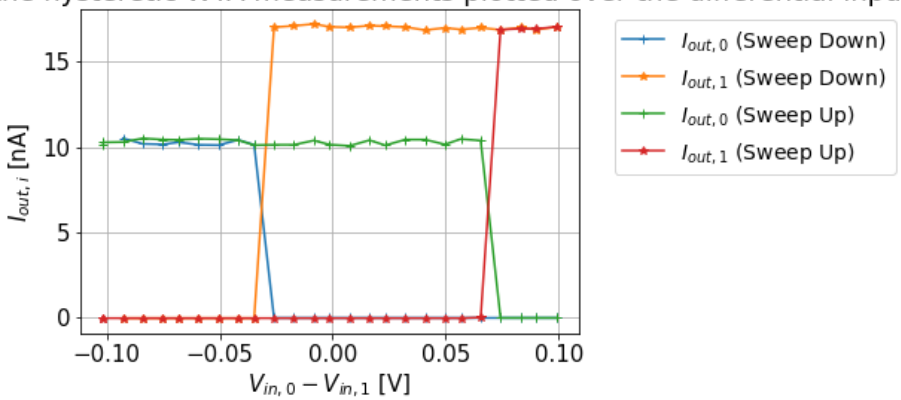


Fig. 13: Net input currents of the hysteretic WTA measurements plotted over the differential input voltage.

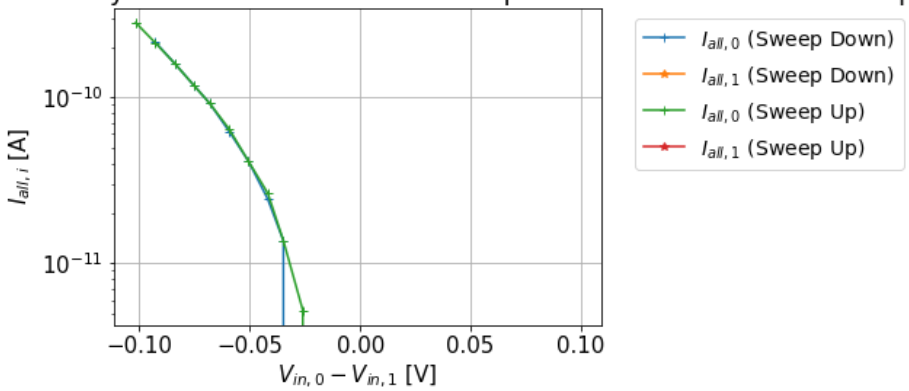
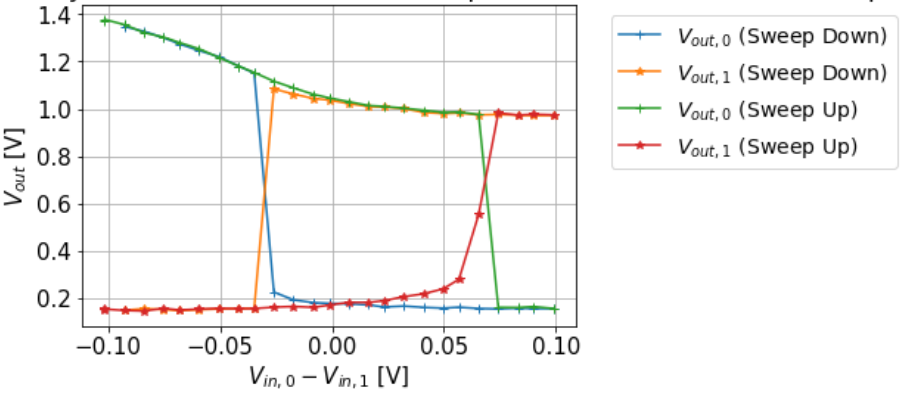


Fig. 14: Output voltages of the hysteretic WTA measurements plotted over the differential input voltage.



- What value should bias `WTA_VGAIN_P` take?

In [33]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
pyplane.Coach.BiasAddress.WTA_VGAIN_P,\
pyplane.Coach.BiasType.P, \
pyplane.Coach.BiasGenMasterCurrent.I30nA, 3)])
```

- Fix $V_{in,1}$ to a value and sweep $V_{in,0}$ from above $V_{in,1}$ to below $V_{in,1}$ then to above $V_{in,1}$ again and observe the two V_{out}, I_{out} and I_{all}.

Important: never set any V_{in} below 1.5 V

In [34]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine2,
    pyplane.Coach.VoltageOutputSelect.SelectLine0,
    pyplane.Coach.VoltageInputSelect.SelectLine0,
    pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [35]:
```
N_samples = 50

Vin1 = 1.65
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.5)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))
Vi0 = np.zeros(N_samples)
Vout0 = np.zeros(N_samples)
Vout1 = np.zeros(N_samples)
c2f_Iout = np.zeros([16, N_samples])
c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    Vi0[j] = p.get_set_voltage(pyplane.DacChannel.AIN0)
    Vout0[j] = p.read_voltage(pyplane.AdcChannel.AOUT15)
#     time.sleep(0.1)
    Vout1[j] = p.read_voltage(pyplane.AdcChannel.AOUT14)
#     time.sleep(0.1)

    # Measure Iout
    c2f_Iout[:,j] = p.read_c2f_output(0.1)    #p.read_all_sampled_c2fs()
```

In [36]:
```
p.send_coach_events([pyplane.Coach.generate_aerc_event(
pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine3,
pyplane.Coach.VoltageOutputSelect.SelectLine0,
pyplane.Coach.VoltageInputSelect.SelectLine0,
pyplane.Coach.SynapseSelect.NoneSelected,0)])
```

In [37]:
```
N_samples = 50

Vin1 = 1.65
p.set_voltage(pyplane.DacChannel.AIN1,Vin1)
time.sleep(0.5)
Vin1_actual = p.get_set_voltage(pyplane.DacChannel.AIN1)

Vin0_set = np.concatenate((np.linspace(1.75, 1.55, 25),np.linspace(1.55, 1.75, 25)))

c2f_Iall = np.zeros([16, N_samples])

for j in range(N_samples):
    p.set_voltage(pyplane.DacChannel.AIN0, Vin0_set[j])

    time.sleep(0.2)

    #Measure Iall
    c2f_Iall[:,j] = p.read_c2f_output(0.1)  #p.read_all_sampled_c2fs()

# p.set_sampling_mode(pyplane.SamplingMode.Off)
```

- Save data

In [38]:
```
np.savetxt('./data/Vi0_ex_6_3_2.csv', Vi0, delimiter=',')
np.savetxt('./data/Vout0_ex_6_3_2.csv', Vout0, delimiter=',')
np.savetxt('./data/Vout1_ex_6_3_2.csv', Vout1, delimiter=',')
```

```
np.savetxt('./data/c2f_Iout_ex_6_3_2.csv', c2f_Iout, delimiter=',')
np.savetxt('./data/c2f_Iall_ex_6_3_2.csv', c2f_Iall, delimiter=',')
```

- Plot data (you may want to plot the axes in a proper range that can zoom in the transition region)

In [42]:

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

Vin1 = 1.65
Vi0 = np.loadtxt('./data/Vi0_ex_6_3_2.csv',  delimiter=',')
Vout0 = np.loadtxt('./data/Vout0_ex_6_3_2.csv',  delimiter=',')
Vout1 = np.loadtxt('./data/Vout1_ex_6_3_2.csv',  delimiter=',')
c2f_Iout = np.loadtxt('./data/c2f_Iout_ex_6_3_2.csv',  delimiter=',')
c2f_Iall = np.loadtxt('./data/c2f_Iall_ex_6_3_2.csv',  delimiter=',')

Iout0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iout[0,:]+c2f_ch1[0]*c2f_Iout[0,:]**2
Iout1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iout[1,:]+c2f_ch2[0]*c2f_Iout[1,:]**2

plt.plot((Vi0-Vin1)[:24],(Iout0[:24])*10**9,'+-')
plt.plot((Vi0-Vin1)[:24],(Iout1[:24])*10**9,'*-')
plt.plot((Vi0-Vin1)[24:],(Iout0[24:])*10**9,'+-')
plt.plot((Vi0-Vin1)[24:],(Iout1[24:])*10**9,'*-')
plt.legend(['${I_{out,0}}$ (Sweep Down)','${I_{out,1}}$ (Sweep Down)','${I_{out,0}}$ (Swee
plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$I_{out,i}$ [nA]')

plt.title('Fig. 15: Output currents of the hysteretic WTA measurements plotted over the di
plt.grid()
plt.show()

Iall0 = c2f_ch1[2]+ c2f_ch1[1]*c2f_Iall[0,:]+c2f_ch1[0]*c2f_Iall[0,:]**2
Iall1 = c2f_ch2[2]+ c2f_ch2[1]*c2f_Iall[1,:]+c2f_ch2[0]*c2f_Iall[1,:]**2

# print(Iall0)

plt.semilogy((Vi0-Vin1)[:24],Iall0[:24],'+-')
plt.semilogy((Vi0-Vin1)[:24],Iall1[:24],'*-')
plt.semilogy((Vi0-Vin1)[24:],Iall0[24:],'+-')
plt.semilogy((Vi0-Vin1)[24:],Iall1[24:],'*-')

plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$I_{all,i}$ [A]')
plt.legend(['${I_{all,0}}$ (Sweep Down)','${I_{all,1}}$ (Sweep Down)','${I_{all,0}}$ (Swee
plt.title('Fig. 16: Net input currents of the hysteretic WTA measurements plotted over the
plt.grid()
plt.show()

plt.plot((Vi0-Vin1)[:24],Vout0[:24],'+-')
plt.plot((Vi0-Vin1)[:24],Vout1[:24],'*-')
plt.plot((Vi0-Vin1)[24:],Vout0[24:],'+-')
plt.plot((Vi0-Vin1)[24:],Vout1[24:],'*-')
plt.xlabel('$V_{in,0}-V_{in,1}$ [V]')
plt.ylabel('$V_{out}$ [V]')
plt.legend(['${V_{out,0}}$ (Sweep Down)','${V_{out,1}}$ (Sweep Down)','${V_{out,0}}$ (Swee
plt.title('Fig. 17:  Output voltages of the hysteretic WTA measurements plotted over the
plt.grid()
plt.show()
```

Fig. 15: Output currents of the hysteretic WTA measurements plotted over the differential input voltage.

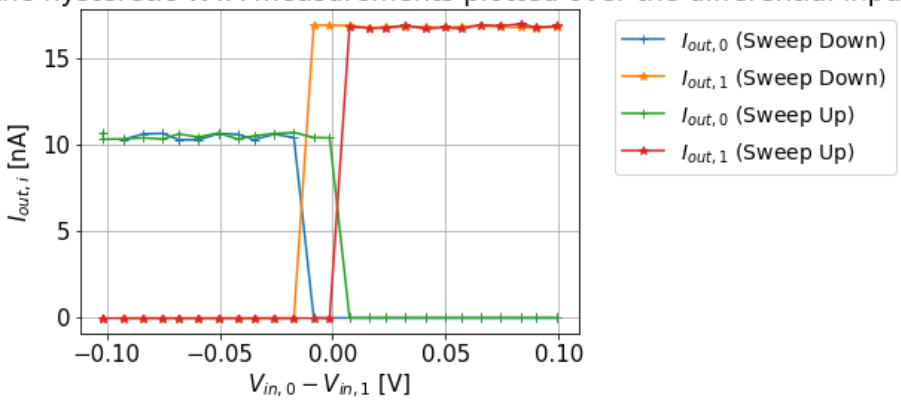


Fig. 16: Net input currents of the hysteretic WTA measurements plotted over the differential input voltage.

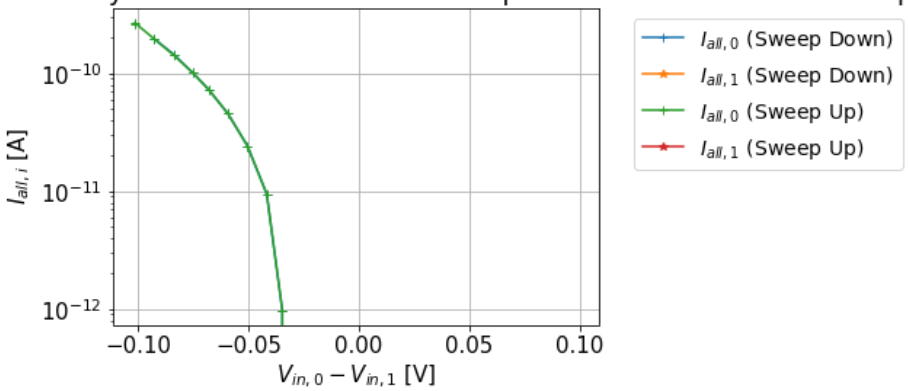
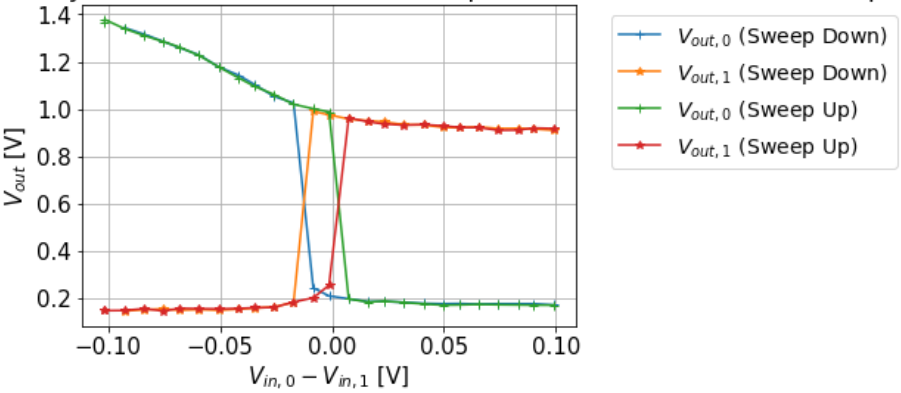


Fig. 17: Output voltages of the hysteretic WTA measurements plotted over the differential input voltage.



Conclusion of your experiment

> Increasing V_{gain} makes the winner more "sticky", increasing the amount of ΔV necessary to displace a winner. This lets the delay visible in the graph grow. The opposite happens when V_{gain} is decreased.

7 Multi-cell WTA (Optional)

In this experiment, we will use all 16 cells of the WTA circuit and see how it responds to a "bump" in the input.

7.1 No lateral interaction

Set a "bump" in V_{in} and measure V_{out}, I_{out} and I_{all}.

In [ ]:

7.2 With lateral excitation

Repeat 7.1 but with V_{ex} set to a proper value to enable lateral excitation.

In [ ]:

7.3 With lateral inhibition

Repeat 7.1 but with V_{inh} set to a proper value to enable lateral inhibition. (Hint: it may only be possible to turn it fully on/off, why?)

In [ ]:

8 Postlab

- What could be the advantages and disadvantages of doing computation in current domain vs voltage domain?

- Briefly summarize what kind of computation does the WTA circuit do?

- If you were the person to design the circuits for students for the next generation of classchip, or if you were TA of NE1 next year, what would you like to change in order to make students learn better and understand more? (e.g. what kind of codes you would provide, what should be done by students themselves?)