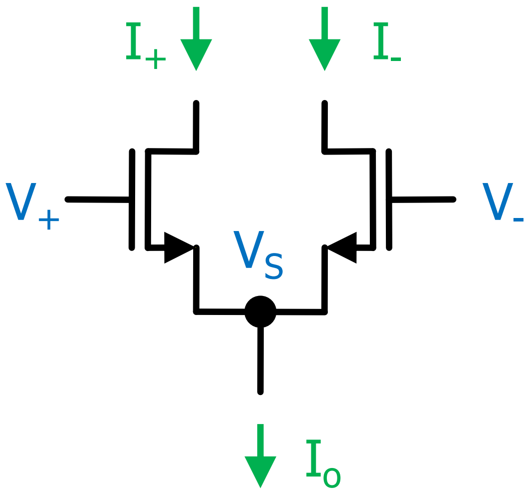
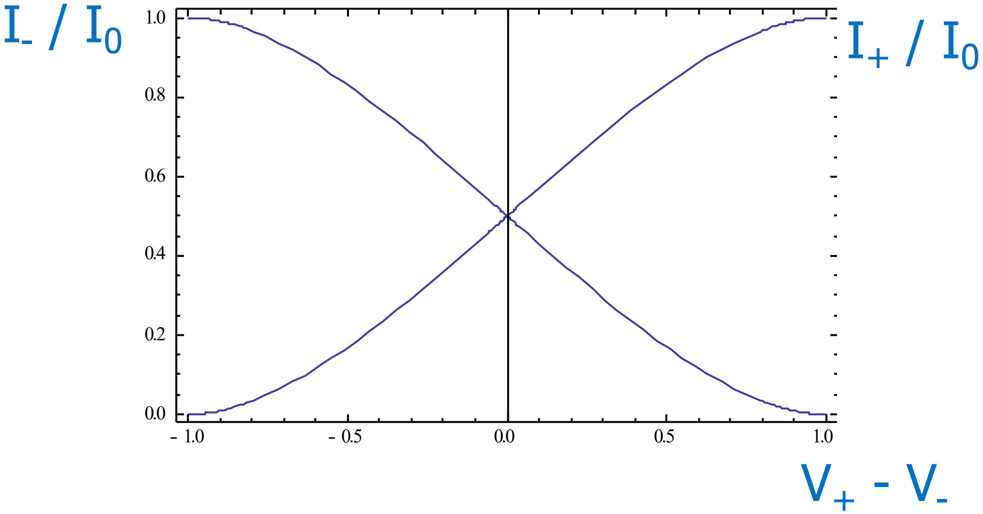
The Differential Pair

The (Differential) Pair – The Principle

- Very often, the *difference* of voltages must be amplified
- The basic circuit are two MOS with ***connected sources***:





- Assume $V_+ = V_-$
  - $\rightarrow$ $V_{GS,left} = V_{GS,right}$ $\rightarrow$ $I_+ = I_- = I_0 / 2$
- Assume $V_+ > V_-$
  - $\rightarrow V_{GS,left} > V_{GS,right}$
  - $\rightarrow I_+ > I_-$
- Assume $V_+ \gg V_-$ $\rightarrow$ $I_+ \sim I_0$, $I_- \sim 0$

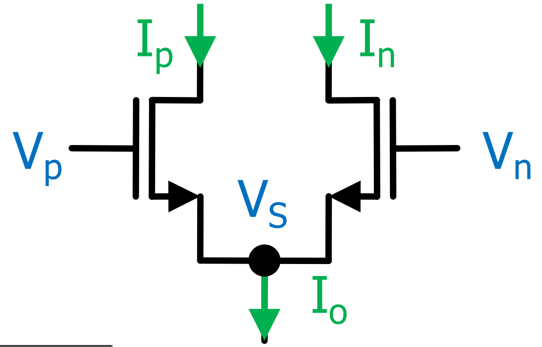
What is V_S ?

- V_S is (roughly) one threshold voltage below the ***higher*** input voltage
- It is often called the ‘tail’ voltage V_{tail}.
- The pair only works for input voltages > V_{TH}
- The tail current is normally provided by a current source which needs additional (saturation) voltage headroom

The Switching Voltage in ***Strong*** Inversion

- We have `ID[VGS_] = β (VGS - VTH)^2;` with $\beta = K/2\ W/L$
- We have 3 equations for 3 unknowns (I_P, I_N, V_S):

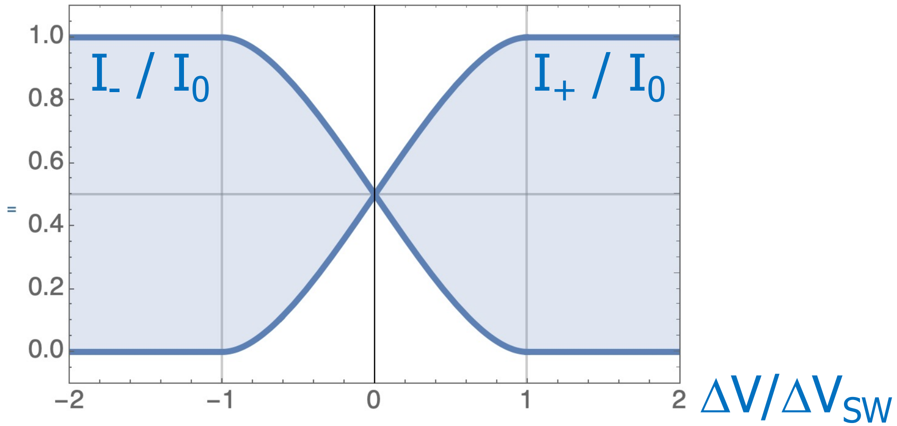
```
IP == ID[VP - VS];
IN == ID[VN - VS];
IP + IN == I0;
```



- We get $I_P = \frac{1}{2}\left(I0 + \sqrt{\beta\,\Delta V^2\,(2\,I0 - \beta\,\Delta V^2)}\right)$ with $\Delta V = V_P - V_N$

- We switch ***completely*** for

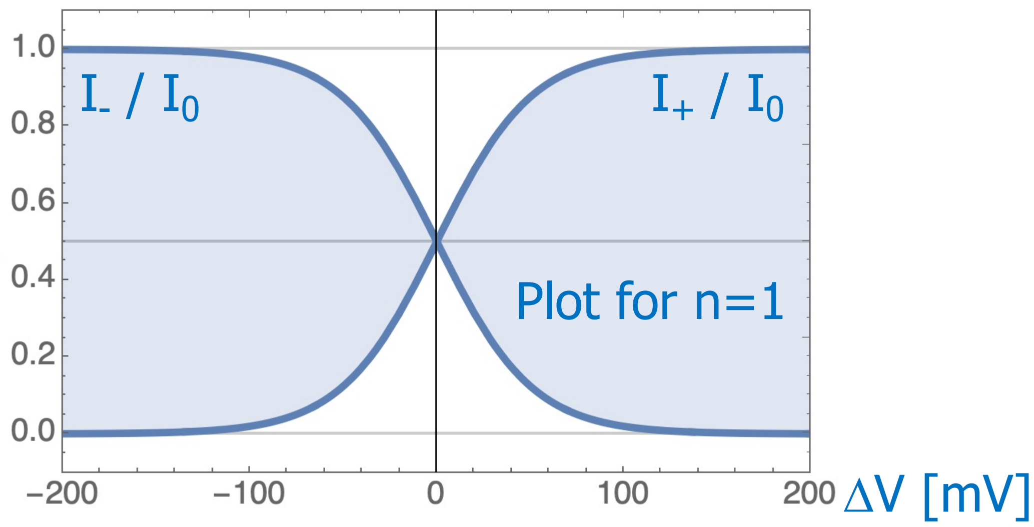
$$\Delta V_{SW} = \frac{\sqrt{I0}}{\sqrt{\beta}}$$



- Conclusion: In *strong inversion*, pair can be *fully* switched!

The Switching Voltage in ***Weak*** Inversion

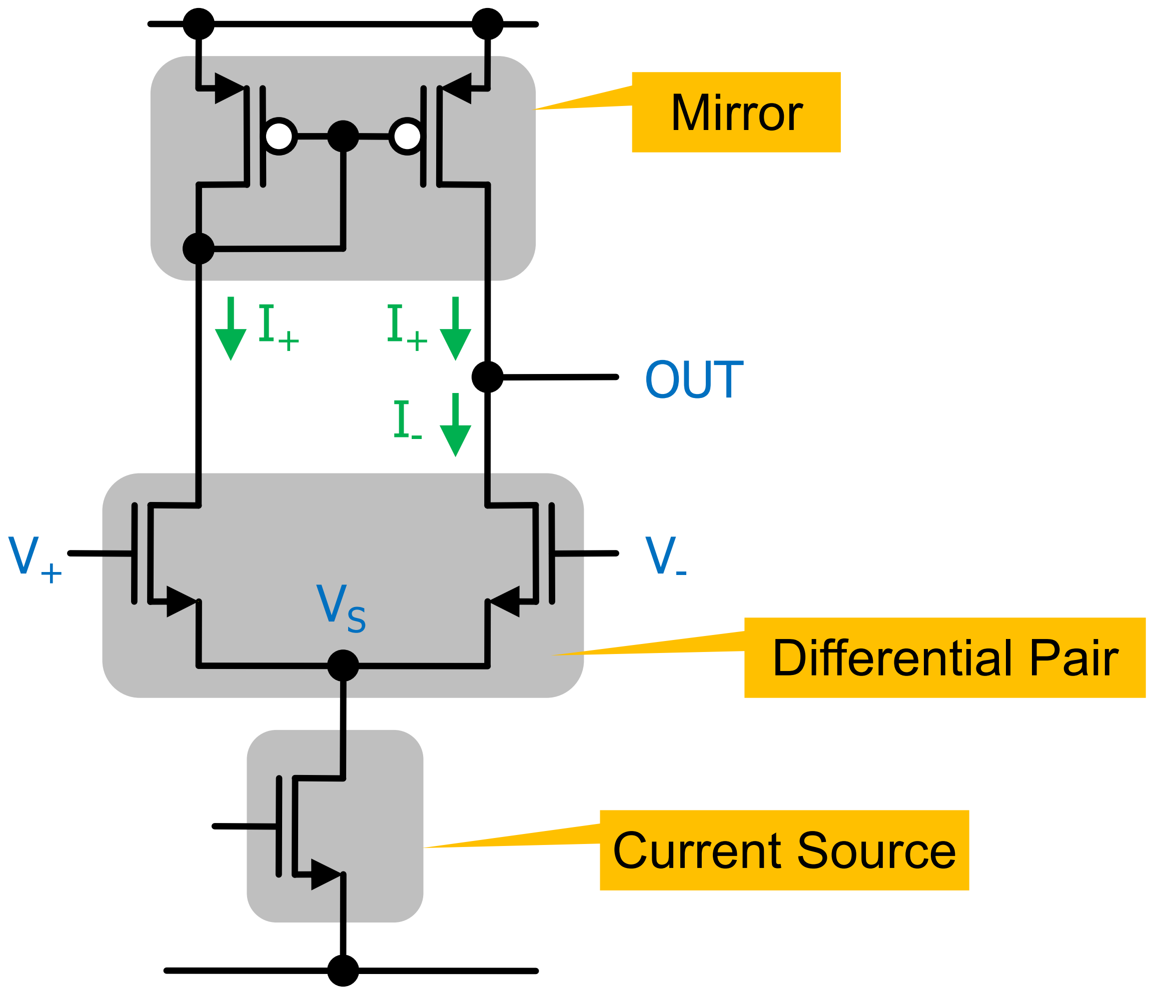
- We have `ID[VGS_] = β Exp[VGS/(n UT)];`
- We get $I_P = \dfrac{I0}{1 + e^{\frac{\Delta V}{n\,UT}}}$ with $\Delta V = V_P - V_N$ and UT = 25.6 mV
- We switch in a few UT, but ***never*** switch 'really' completely



- Conclusion: In *weak inversion*, pair switches at *small voltages*, but never fully!

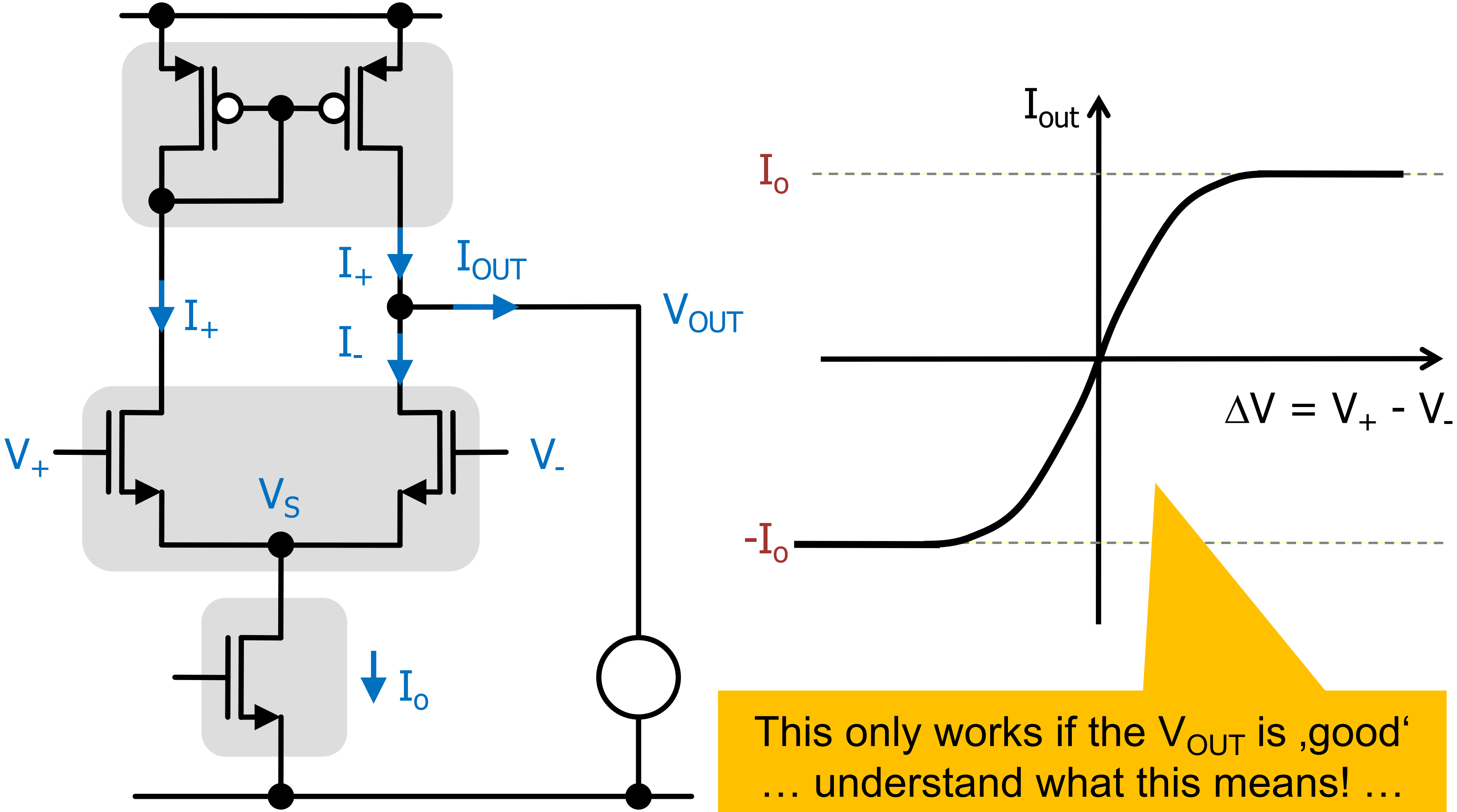
The Differential Amplifier

- One 'output' current (I_+) is often mirrored and added to the current of the other side (I_-):



Output *Current* of the Differential Amplifier

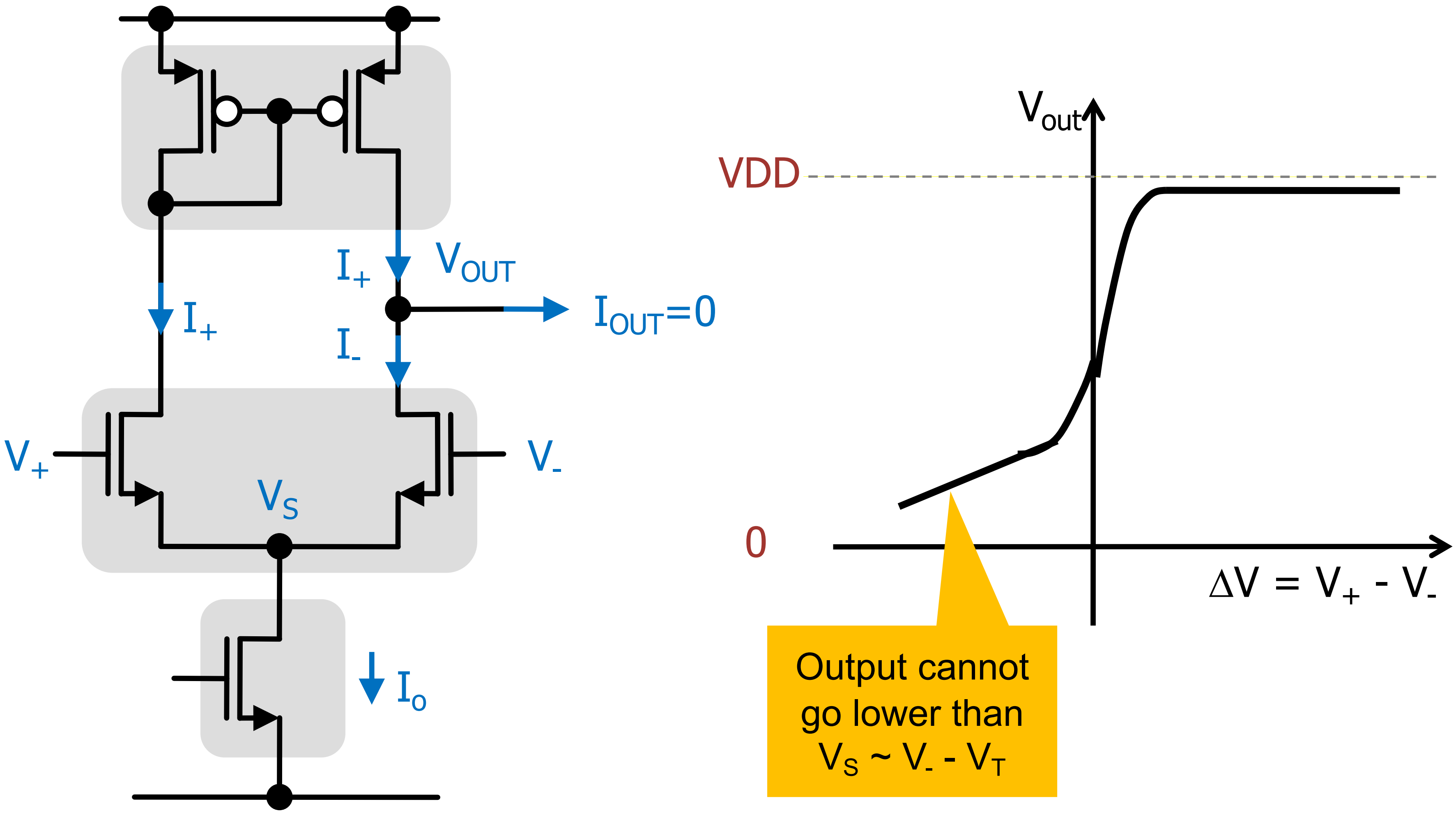
- If the output voltage is *fixed*, the *output current* is just I_+ - I_-
- The circuit is a ‚*Transconductor*' (it converts ΔU → I)



This only works if the V_{OUT} is ‚good'
… understand what this means! …

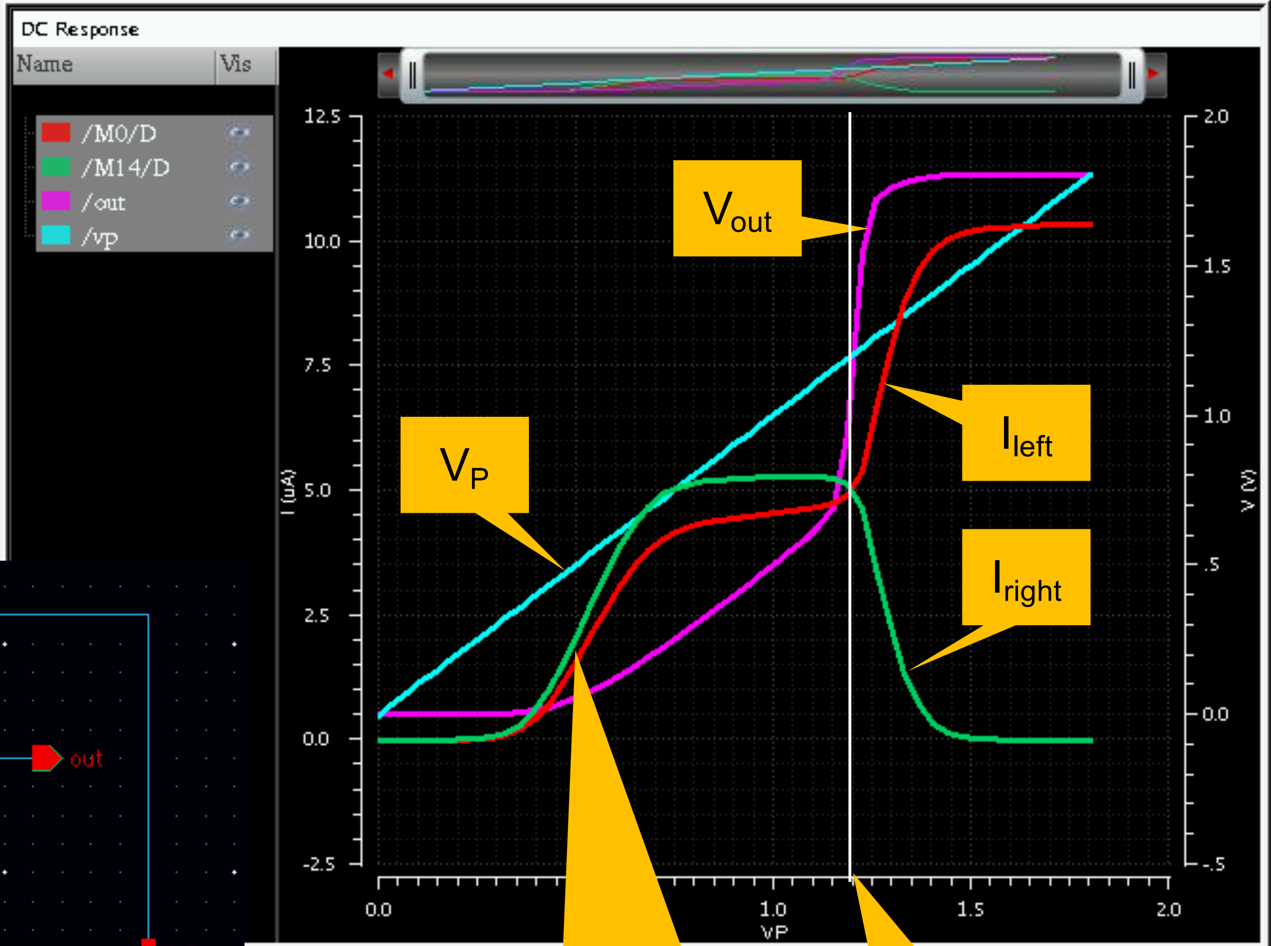
Output *Voltage* of the Differential Amplifier

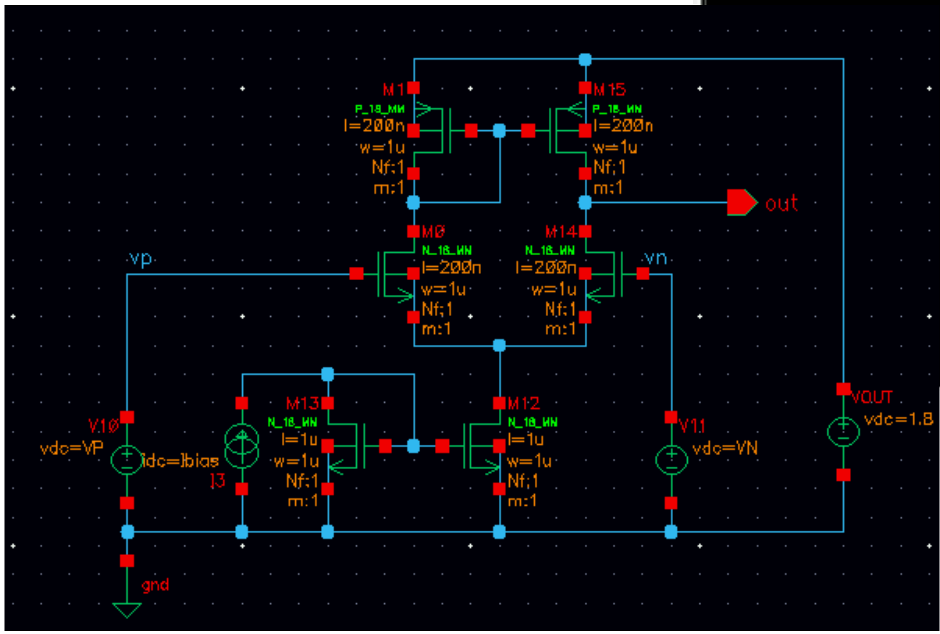
- If *no current* flows out of the circuit (the output voltage is left free), we have *voltage* gain (the current I_+-I_- pulls V_{out} hi/low)



Simulation

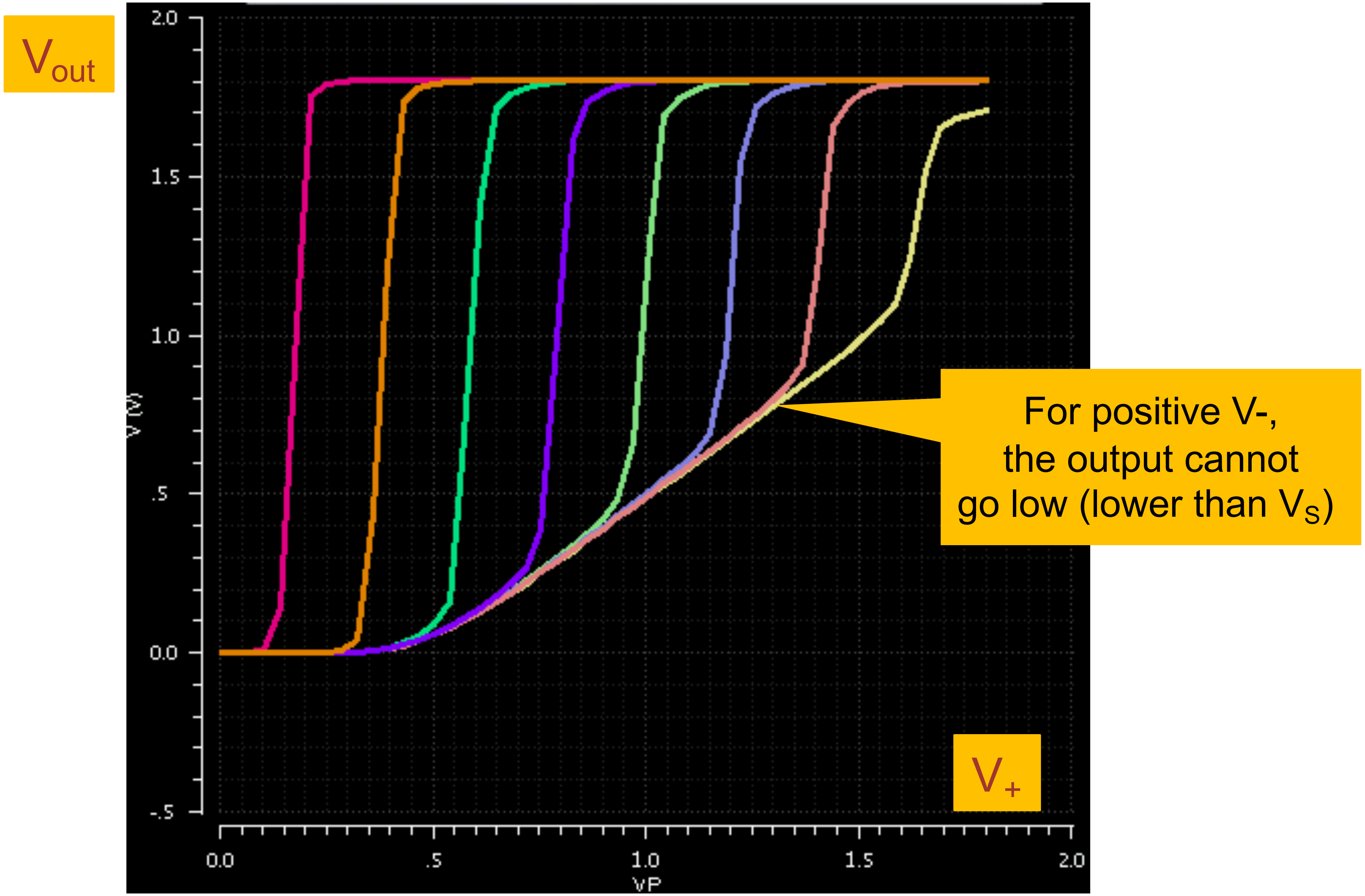
- VDD = 1.8V
- V_N = 1.2V





Sweeping V_-

- $V_N = V_- = 0.2, 0.4, \ldots 1.6$ V



Gain

- What is the (voltage) gain?

- To first order, it is – as before – the g_m of the *input* transistor(s) multiplied with the total impedance at the *output* (i.e. r_{ds} of the current mirror output in parallel to r_{ds} of the diff. pair)

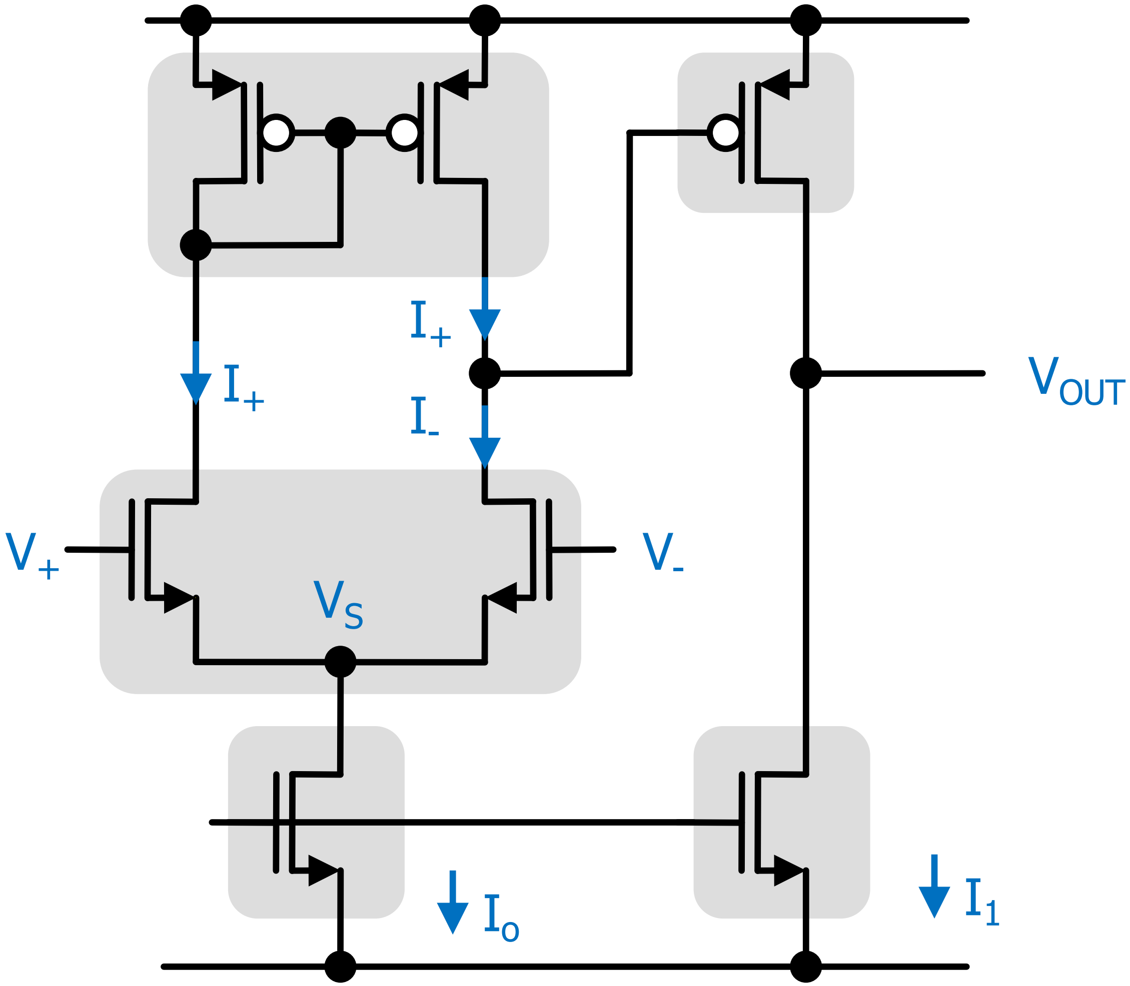
- (The output resistance on the left branch do not matter, because the voltage there is kept nearly constant by the diode connected PMOS upper left…)

Comments

- Understanding the large signal behaviour for very different V_p,V_n is important, but in practical circuits, feedback is often applied so that $V_p = V_n$.
- Another important property is the *common mode input range*. This is limited by the V_{GS} of the input pair and the compliance of the tail current source: An *NMOS* differential pair *does not work* any more at *low* (common mode) input voltage.
- Another property is *common mode gain*, i.e. the change in output voltage if both inputs are changes simultaneously. In an ideal amplifier, common mode gain is 0.
- If the amplifier is loaded with a resistive load, gain drops. (as for the gain stage).
  - A source follower is therefore sometimes added.
  - Stability in feedback circuits is then more tricky. Compensation methods are needed.

More Gain: Diff-Amp with Gain Stage

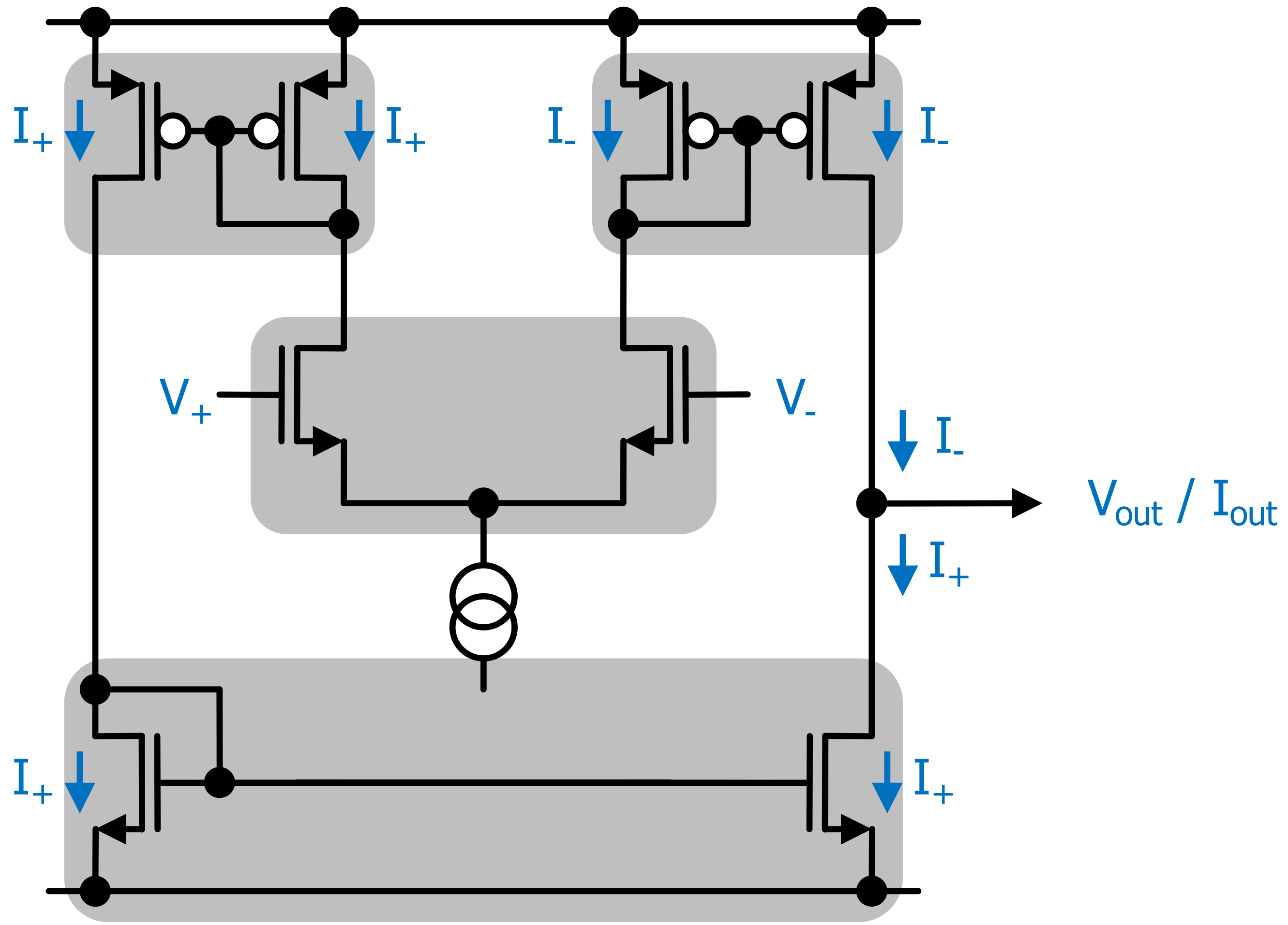
- The differential amplifier is often followed by a gain stage
  - This two-stage design has two ‚main' poles and may need compensation if used in feedback configuration



- The 'steep' part of the transfer function of the first (differential) stage should coincide with the 'steep' part of the second stage!
- This can be achieved (for 3x equal PMOS) with $I_0 = 2 \times I_1$, so that $I_+ = I_- = I_1$ at the switching point.

Differential Pair + Current Mirror

- The problem of limited output voltage swing for high input common mode can be solved by mirroring the currents:



Alternative topologies

- Many topologies are possible, using mirrors and cascodes
- For instance, this ‘folded cascode’ configuration: