6. OpAmp Application Examples

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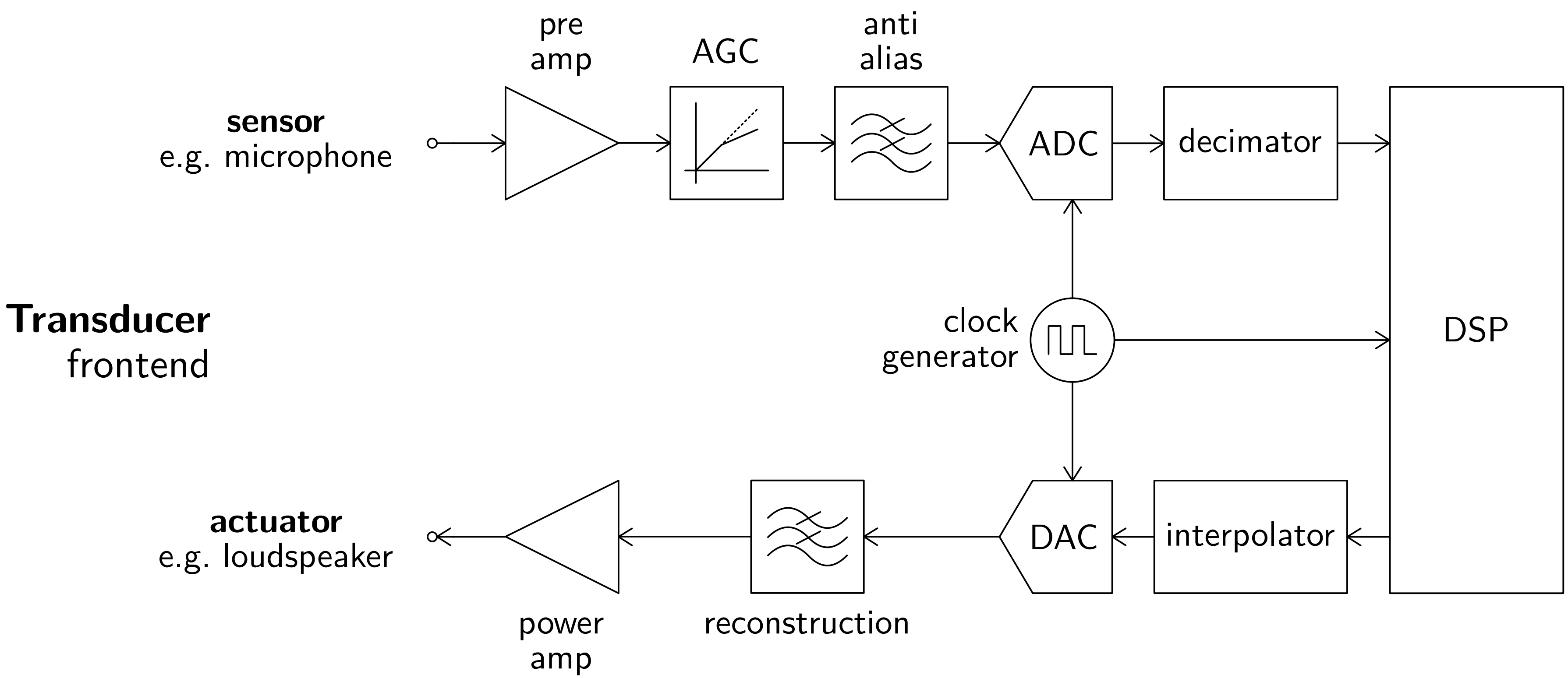
Pre-Amplification Stages

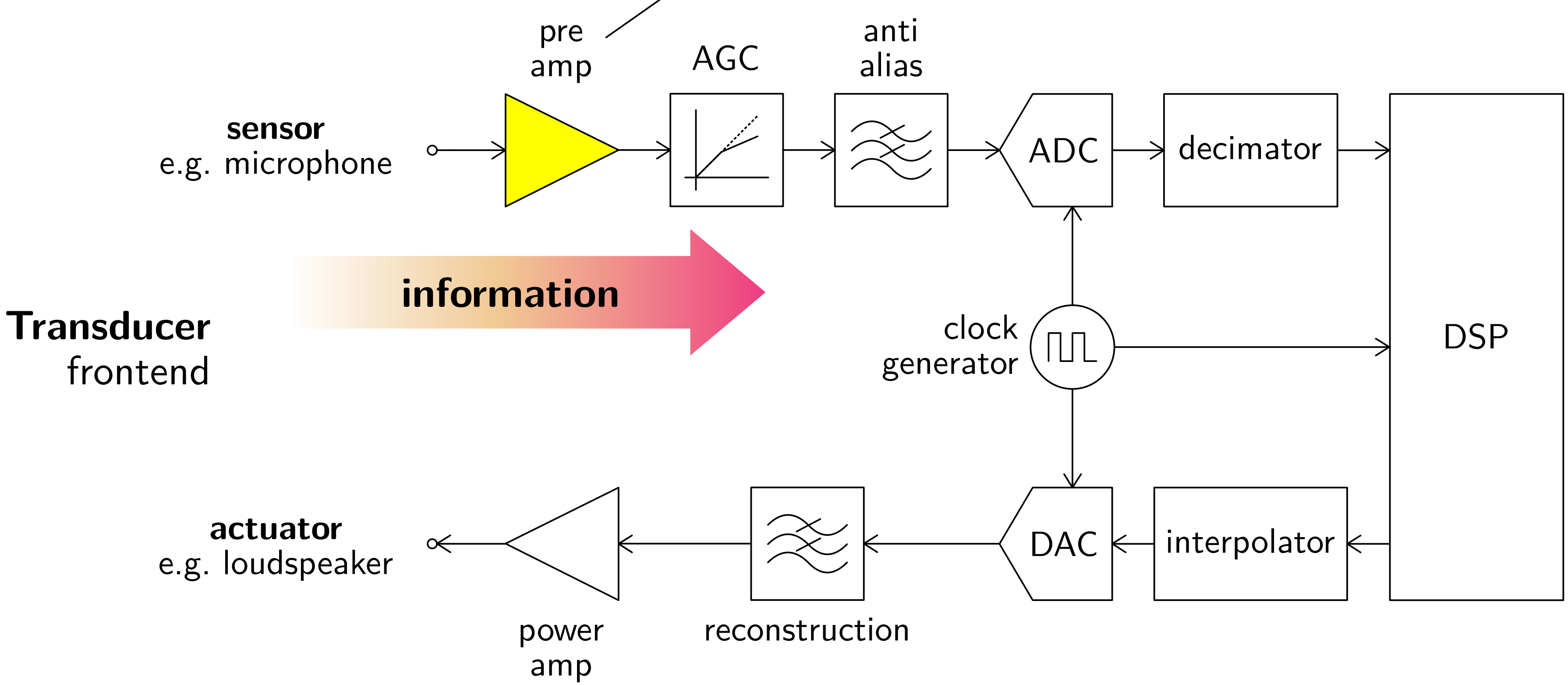
- General usage in analog **signal processing** systems:



Pre-Amplification Stages

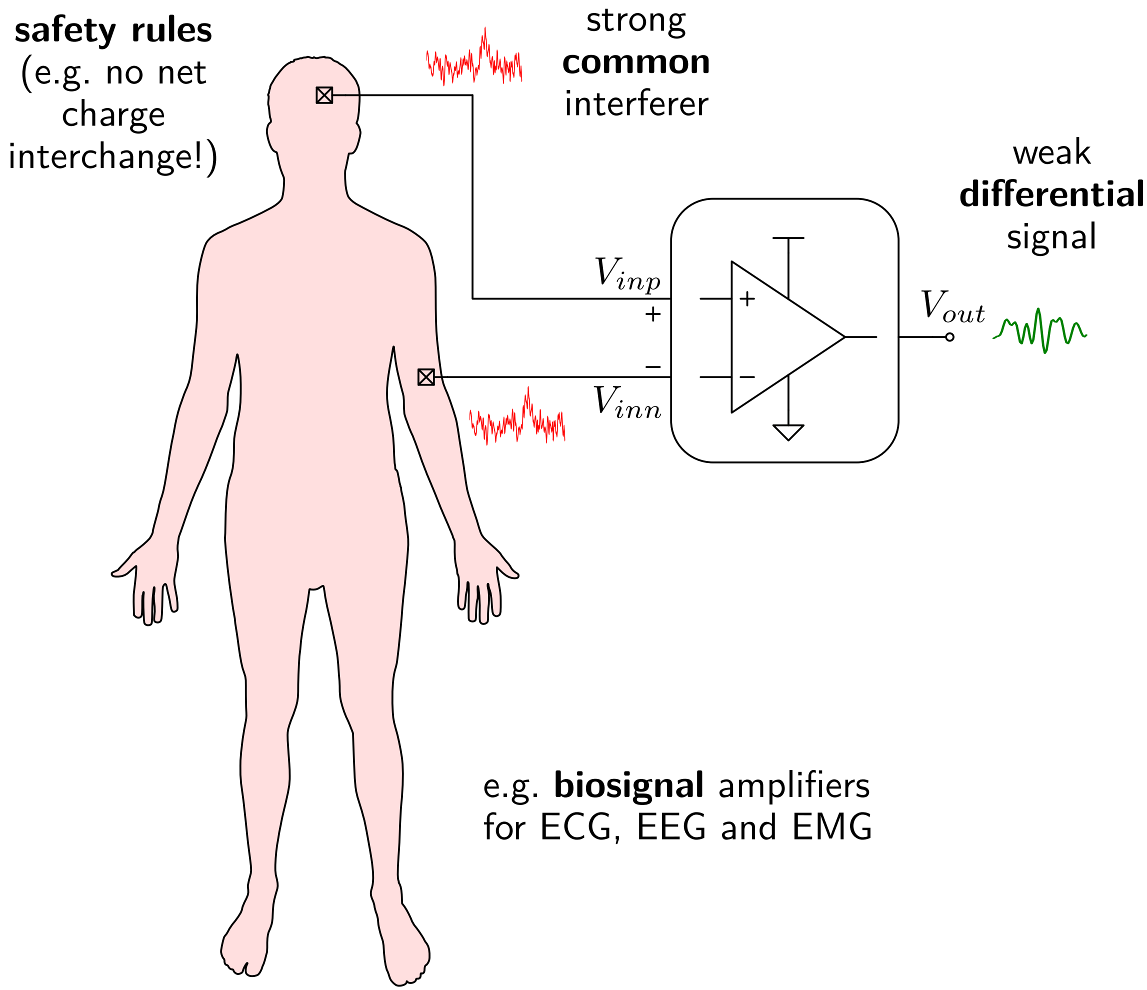
- General usage in analog **signal processing** systems:

to save source signal integrity (**SNDR**) against circuit non-idealities (e.g. noise, interference)



Instrumentation Amplifiers

- OpAmp requirements for **sensor** read-out fronteds:



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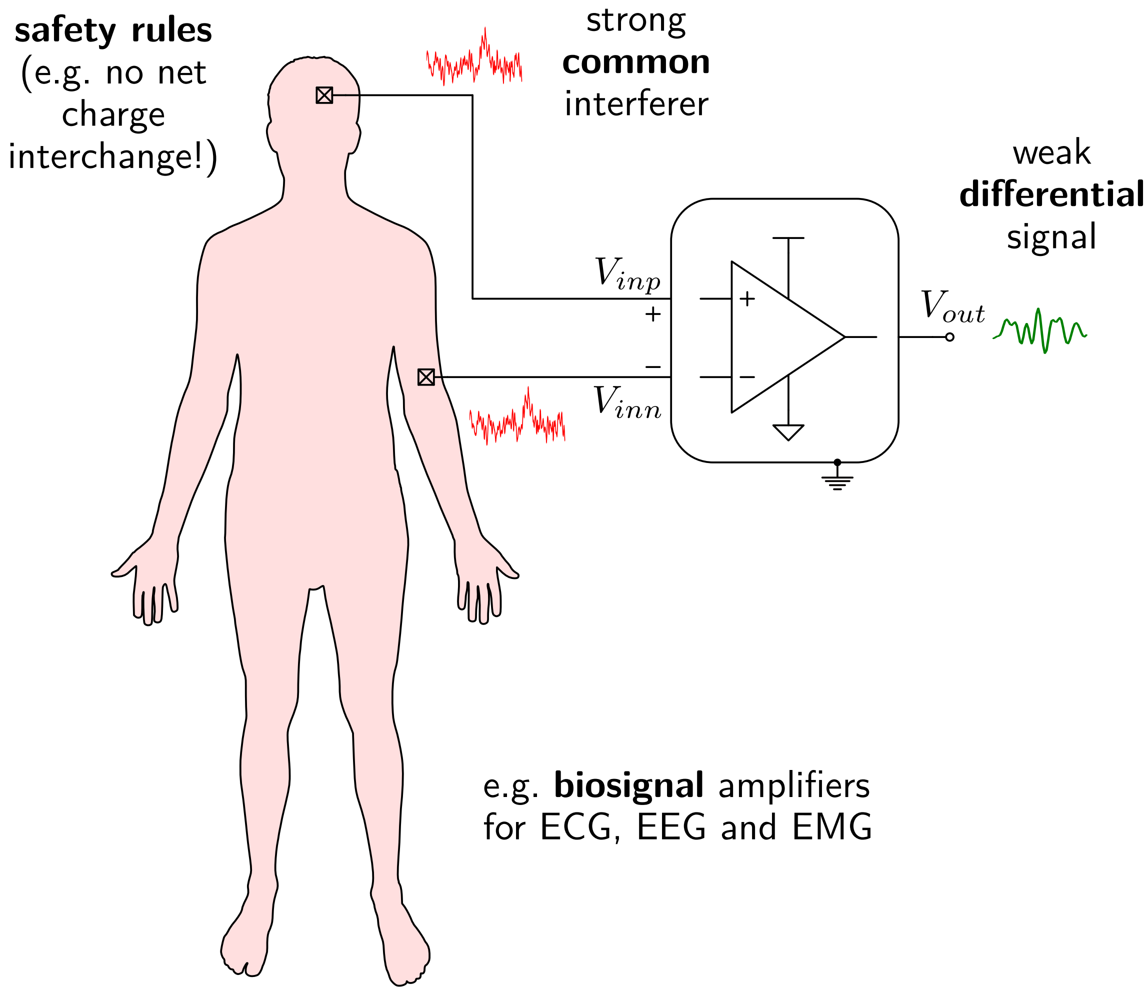
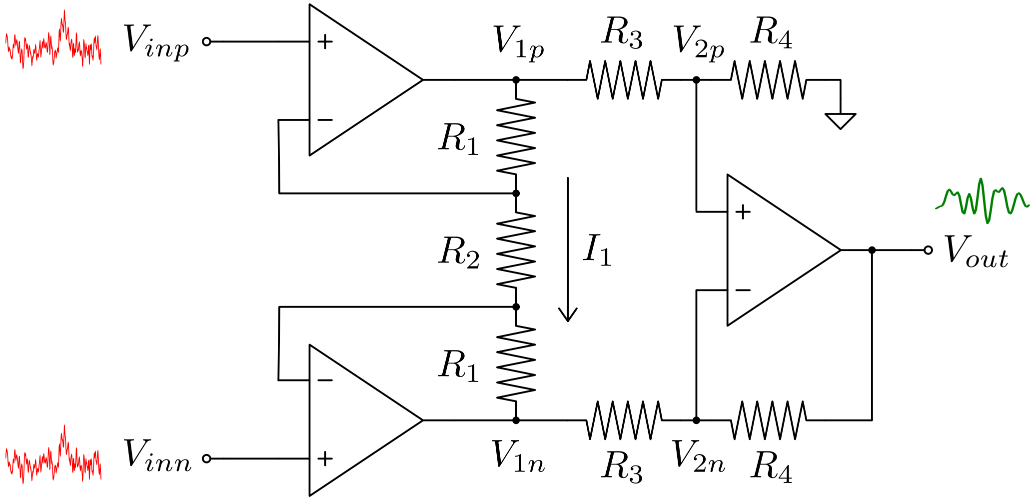


- **Shielding** and **floating** supply for external interference rejection
- Infinite DC input **impedance**
- Low equivalent input **noise** { thermal $I_{bias} \uparrow$; flicker $WL \uparrow$ }
- Very high **CMRR** { $V_{ind} \sim \mu$V ; $V_{inc} \sim$ V } 120dB!
- Reduced **bandwidth** (typ. kHz-range)
- Moderate output **full scale**

▼ **Specific** OpAmp circuits and feedback topologies

Classic Differential Preamplifiers

- **3-OpAmp** topology:



$$G_d \doteq \frac{V_{out}}{V_{inp} - V_{inn}} = \left(1 + \frac{2R_1}{R_2}\right)\frac{R_4}{R_3}$$

first stage: $I_1 = \frac{V_{inp} - V_{inn}}{R_2}$

$$\begin{cases} V_{1p} = V_{inp} + R_1 I_1 = \left(1 + \frac{R_1}{R_2}\right) V_{inp} - \frac{R_1}{R_2} V_{inn} \\ V_{1n} = V_{inn} - R_1 I_1 = \left(1 + \frac{R_1}{R_2}\right) V_{inn} - \frac{R_1}{R_2} V_{inp} \end{cases}$$

$$V_{1p} - V_{1n} \equiv \left(1 + \frac{2R_1}{R_2}\right)(V_{inp} - V_{inn})$$

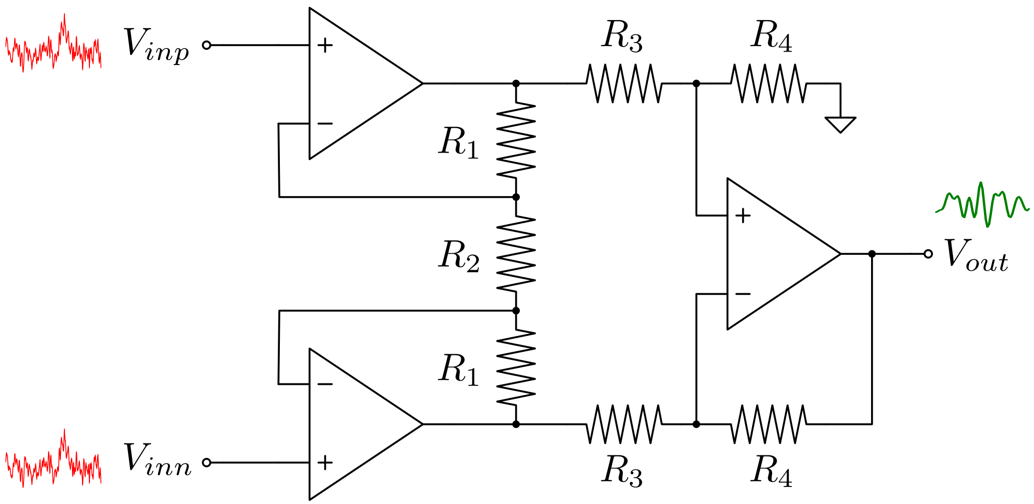
second stage: $V_{2p} \simeq V_{2n}$

$$\frac{R_4}{R_3 + R_4} V_{1p} \simeq \frac{1}{R_3 + R_4}(R_4 V_{1n} + R_3 V_{out})$$

$$V_{out} \simeq \frac{R_4}{R_3}(V_{1p} - V_{1n})$$

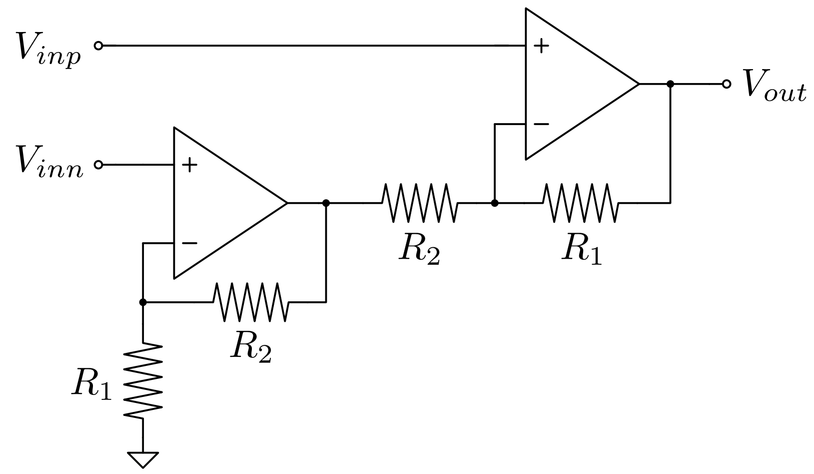
Classic Differential Preamplifiers

- **3-OpAmp** topology:



$$G_d \doteq \frac{V_{out}}{V_{inp} - V_{inn}} = \left(1 + \frac{2R_1}{R_2}\right) \frac{R_4}{R_3}$$

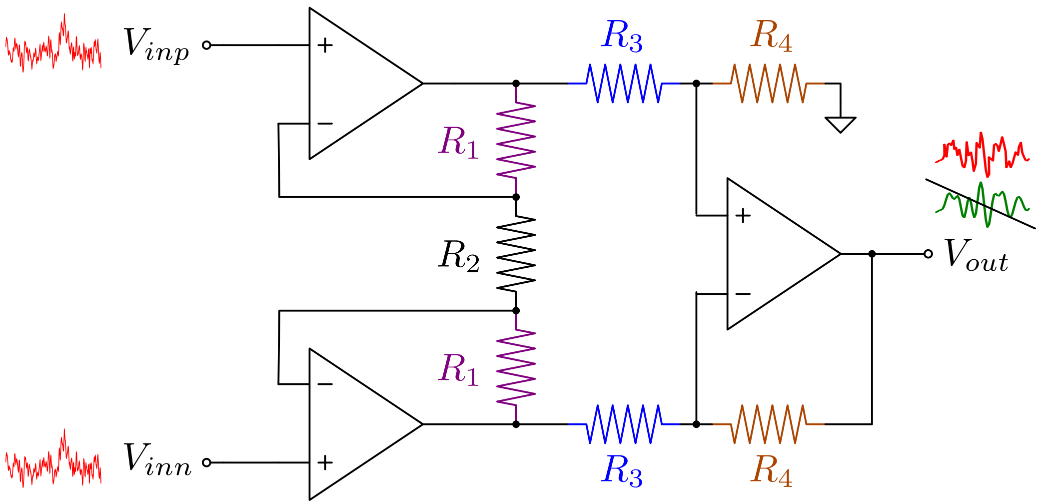
- **2-OpAmp** circuit:



$$G_d = \left(1 + \frac{R_1}{R_2}\right)$$

Classic Differential Preamplifiers

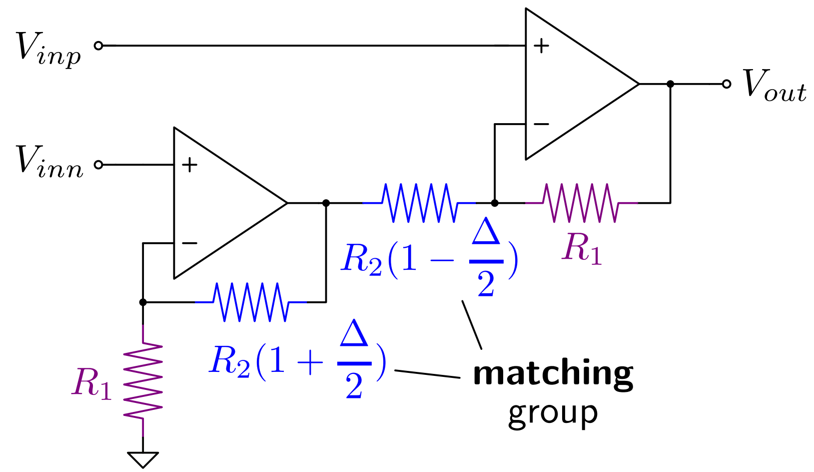
- **3-OpAmp** topology:



$$G_d \doteq \frac{V_{out}}{V_{inp}-V_{inn}} = \left(1+\frac{2R_1}{R_2}\right)\frac{R_4}{R_3}$$

- **CMRR** losses due to technology **mismatching**!

- **2-OpAmp** circuit:



$$G_d = \left(1+\frac{R_1}{R_2}\right)$$

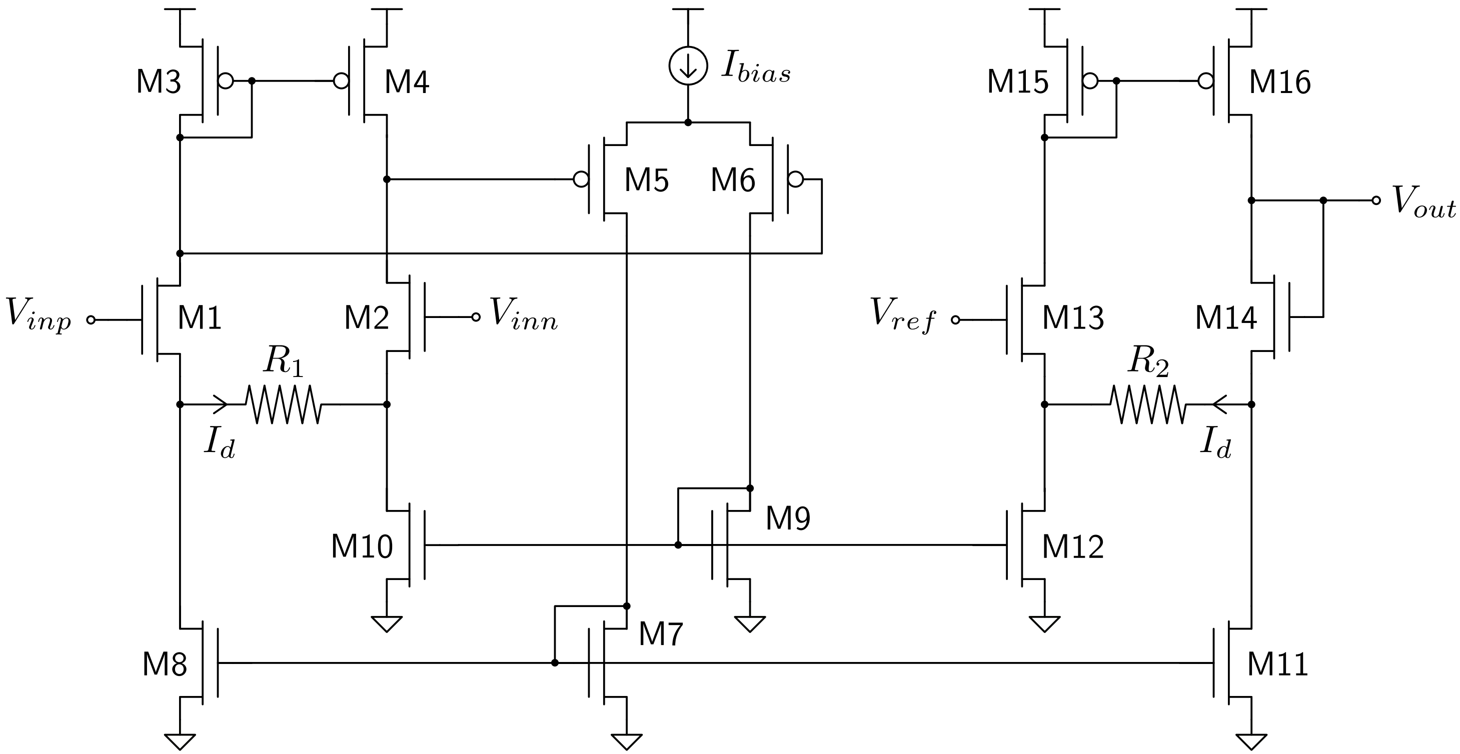
$$V_{out} = \left[1+\frac{R_1}{R_2(1-\frac{\Delta}{2})}\right]V_{inp} - \left[1+\frac{R_2(1+\frac{\Delta}{2})}{R_1}\right]\frac{R_1}{R_2(1-\frac{\Delta}{2})}V_{inn}$$

$$V_{out} = G_d V_{ind} + G_c V_{inc}$$

$V_{ind} = V_{inp} - V_{inn}$, $\quad V_{inc} = \frac{V_{inp}+V_{inn}}{2}$

Specific OpAmps for Preamplifiers

- Non-differential **floating** gain elements:



$$V_{out} = V_{ref} + G_d(V_{inp} - V_{inn}) \qquad G_d = \frac{R_2}{R_1}$$

Specific OpAmps for Preamplifiers

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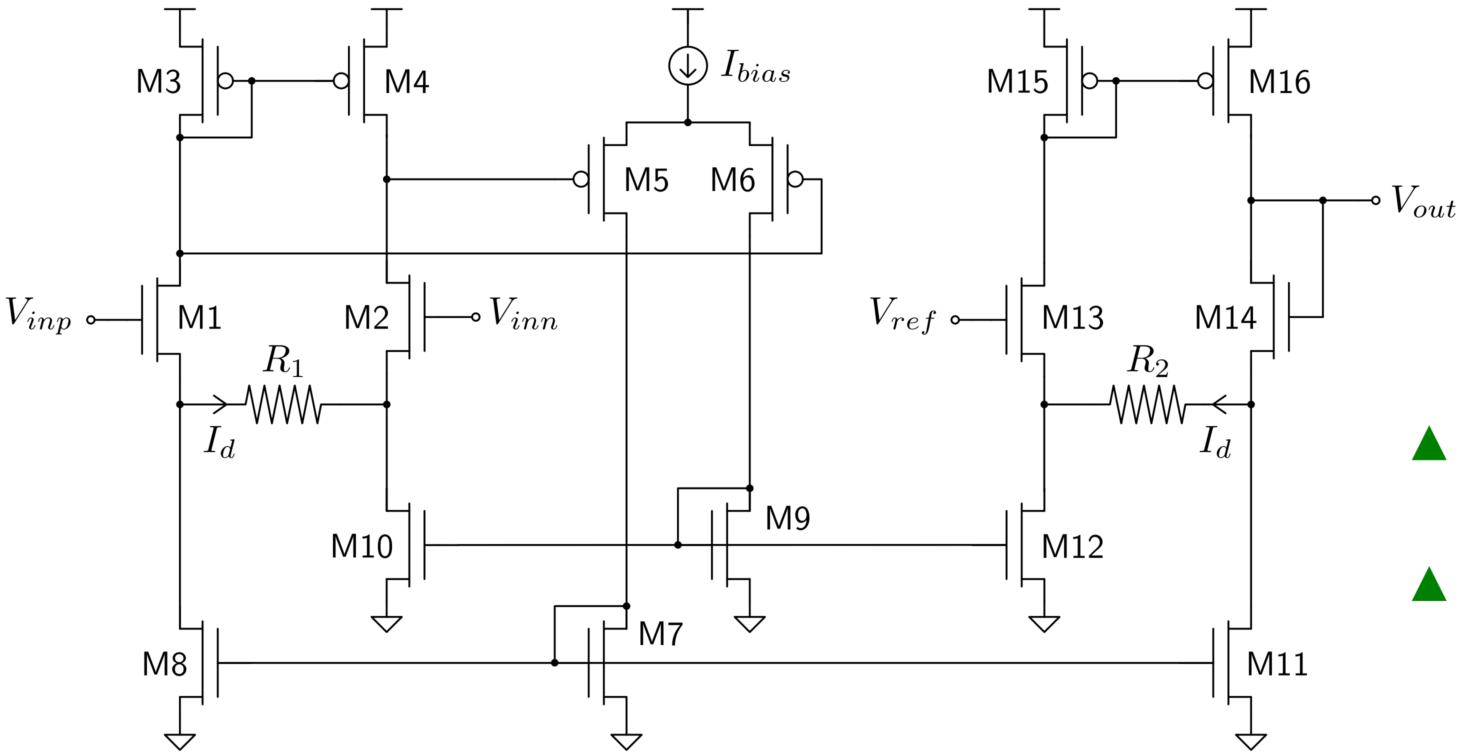


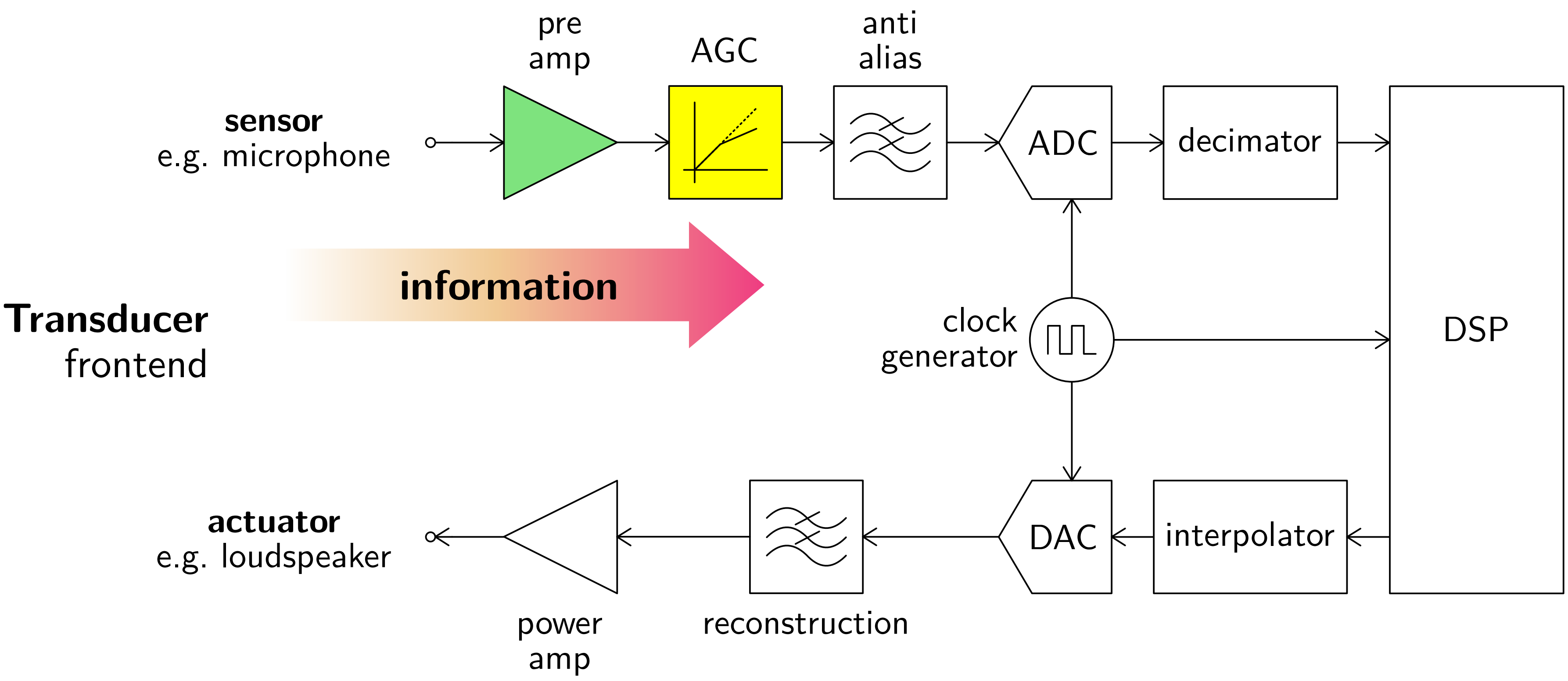
$$V_{out} = V_{ref} + G_d(V_{inp} - V_{inn}) \qquad G_d = \frac{R_2}{R_1}$$

- ▲ Null contributions of resitors to **CMRR**
- ▲ Input stage technology mismatching seen as static **offset**
- ▼ Input stage **noise**
- ▼ Output **full-scale**

Automatic Gain Control

Also known as programmable/variable gain amplifier (**PGA**/**VGA**)

- General usage in analog **signal processing** systems:



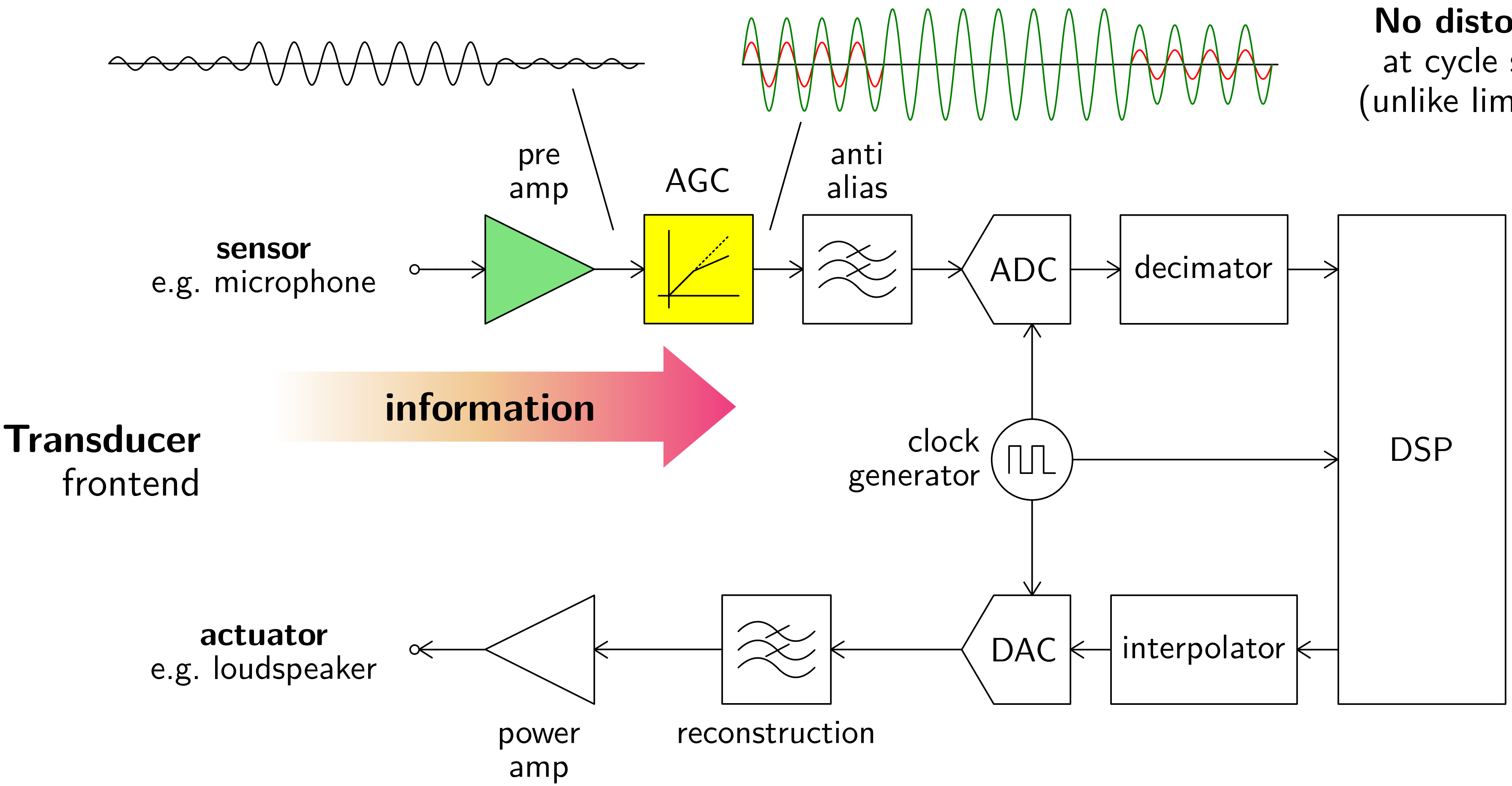
Automatic Gain Control

Also known as programmable/variable gain amplifier (**PGA**/**VGA**)

- General usage in analog **signal processing** systems:

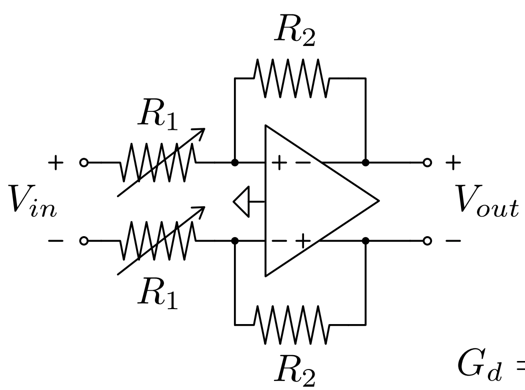
Amplitude matching with **ADC full-scale**:

No distortion at cycle scale (unlike limiters)!

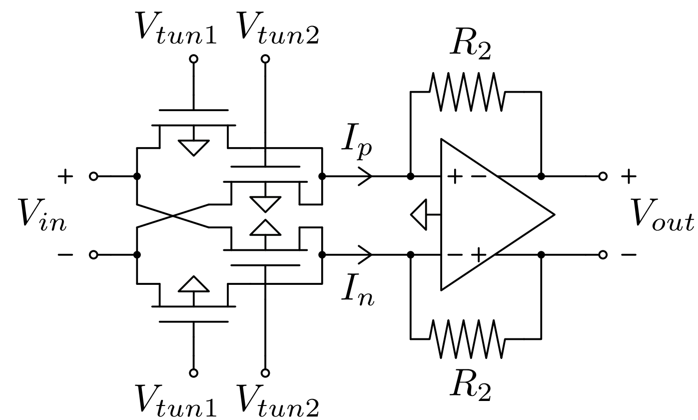


Programmable Gain

- Based on MOS resistive circuits (**MRC**):



$$G_d = -\frac{R_2}{R_1}$$



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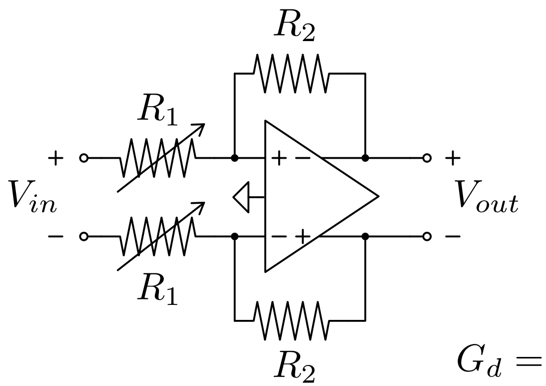

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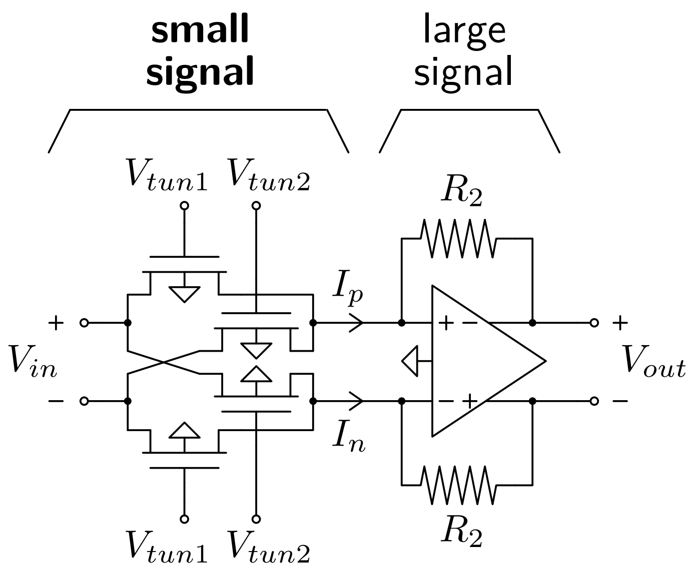


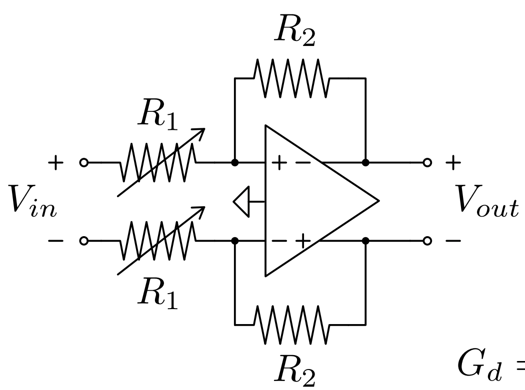
matched devices operating in strong inversion **conduction** (non-saturation):

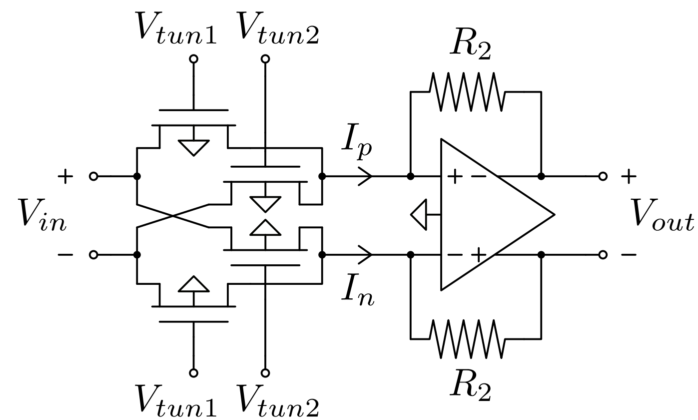
$$I_p = \beta \left[V_{tun1} - V_{TH} - \frac{n}{2}\left(\frac{V_{in}}{2}\right)\right]\left(\frac{V_{in}}{2}\right) + \beta \left[V_{tun2} - V_{TH} - \frac{n}{2}\left(-\frac{V_{in}}{2}\right)\right]\left(-\frac{V_{in}}{2}\right)$$

$$\left.\begin{aligned} I_p &= \beta\left(V_{tun1} - V_{tun2} - n\frac{V_{in}}{2}\right)\frac{V_{in}}{2} \\ I_n &= \beta\left(V_{tun2} - V_{tun1} - n\frac{V_{in}}{2}\right)\frac{V_{in}}{2} \end{aligned}\right\} \quad I_d = I_p - I_n = \beta\left(V_{tun1} - V_{tun2}\right)V_{in} \qquad R_1 \equiv \frac{1}{2\beta\left(V_{tun1} - V_{tun2}\right)}$$

Programmable Gain

- Based on MOS resistive circuits (**MRC**):





$$G_d = -\frac{R_2}{R_1}$$

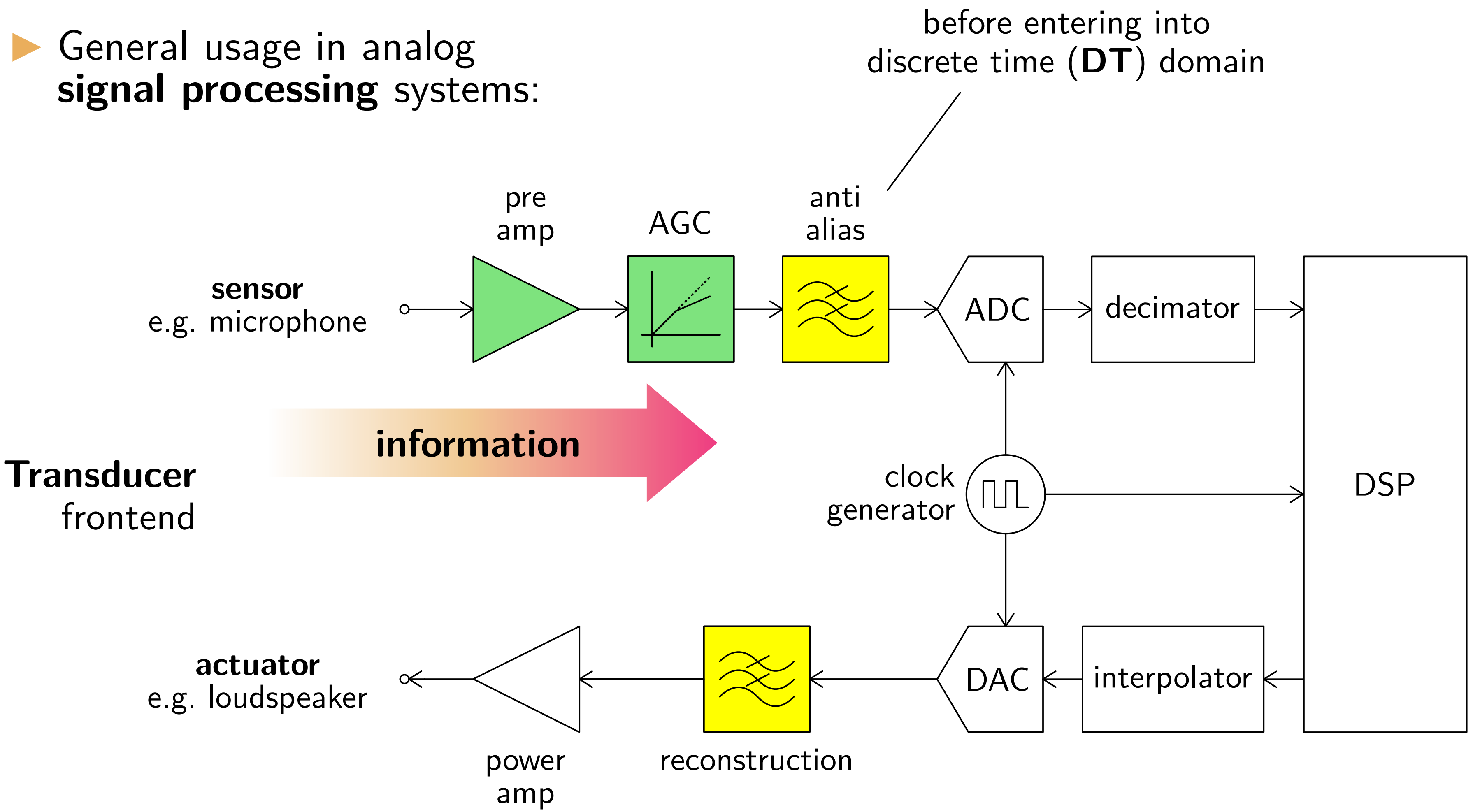
- ▲ **Compact** area
- ▲ **Electronically tunable** gain
- ▼ Technology **sensitivity**
- ▼ MOSFET flicker **noise**
- ▼ Distortion due to larger device **mismatching**

$$R_1 \equiv \frac{1}{2\beta\,(V_{tun1} - V_{tun2})}$$

$$G_d \propto (V_{tun1} - V_{tun2})$$

Continuous-Time Filters

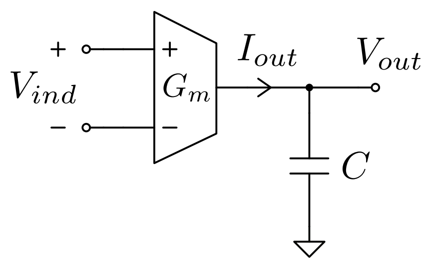
- General usage in analog **signal processing** systems:



Also common in **high-frequency** filters...

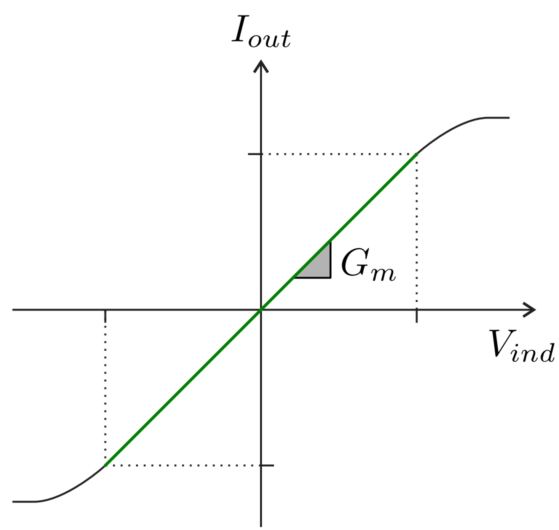
Gm-C Integrator

- Based on **wide-range** input MOS transconductors:



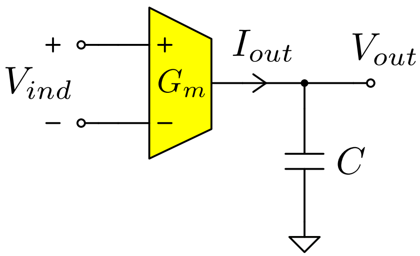
$$H(s) \doteq \frac{V_{out}}{V_{ind}} = \frac{G_m}{C}\frac{1}{s}$$

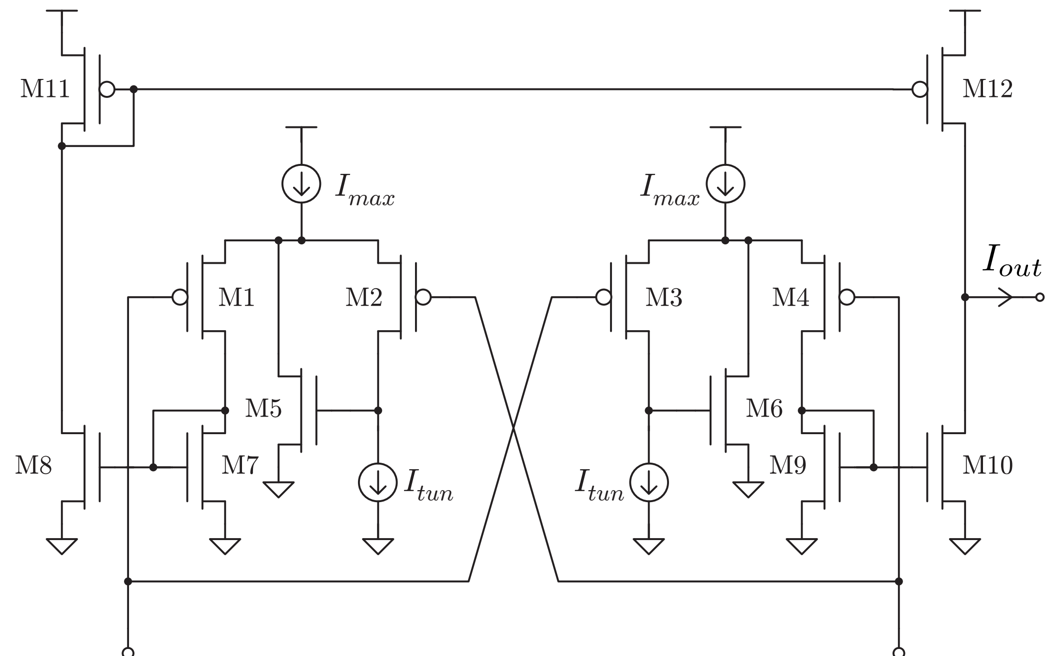
not **O**TA!
(**finite** Gm)



Gm-C Integrator

- **Cross-coupled** CMOS circuit realization:





$$V_{inn} \doteq V_{inc} - \frac{V_{ind}}{2} \qquad V_{inp} \doteq V_{inc} + \frac{V_{ind}}{2}$$

matched devices operating in **strong inversion** saturation:

$$I_{D1} = \frac{\beta}{2n}\left[\left(V_{inc} - \frac{V_{ind}}{2}\right) - V_{TH} - \left(V_{inc} + \frac{V_{ind}}{2} - V_{TH} - \sqrt{\frac{2nI_{tun}}{\beta}}\right)\right]^2$$

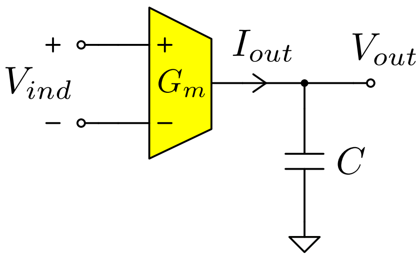
$$G_m \doteq \frac{I_{out}}{V_{ind}} = 2\sqrt{\frac{2\beta I_{tun}}{n}}$$

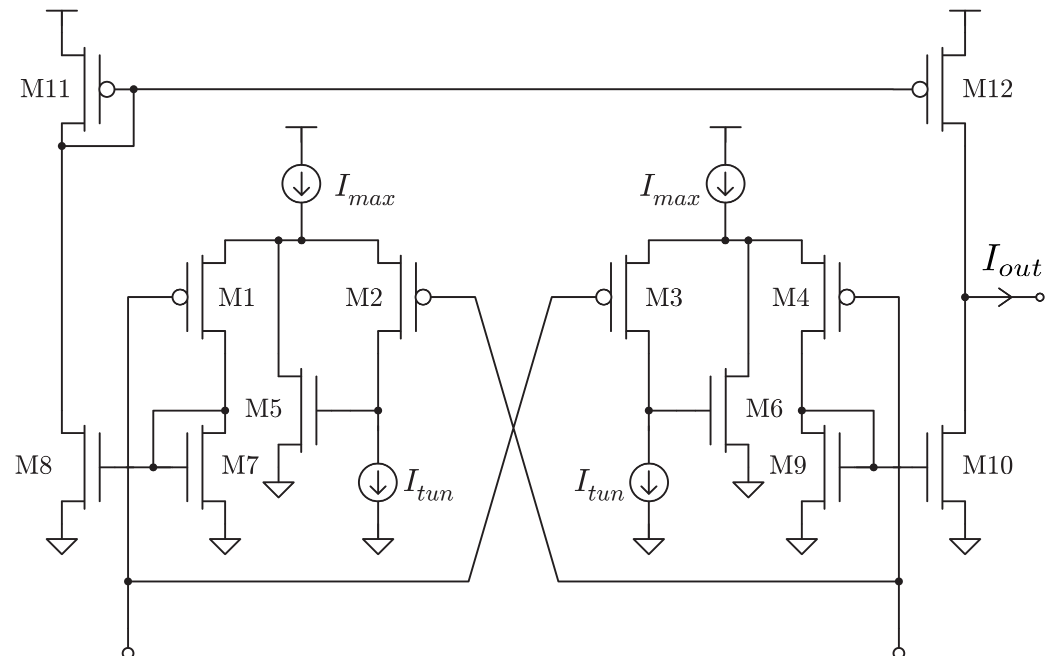
$$I_{D4} = \frac{\beta}{2n}\left[\left(V_{inc} + \frac{V_{ind}}{2}\right) - V_{TH} - \left(V_{inc} - \frac{V_{ind}}{2} - V_{TH} - \sqrt{\frac{2nI_{tun}}{\beta}}\right)\right]^2$$

$$I_{out} = I_{D4} - I_{D1} = \frac{\beta}{2n}\left[\left(V_{ind} + \sqrt{\frac{2nI_{tun}}{\beta}}\right)^2 - \left(-V_{ind} + \sqrt{\frac{2nI_{tun}}{\beta}}\right)^2\right]$$

Gm-C Integrator

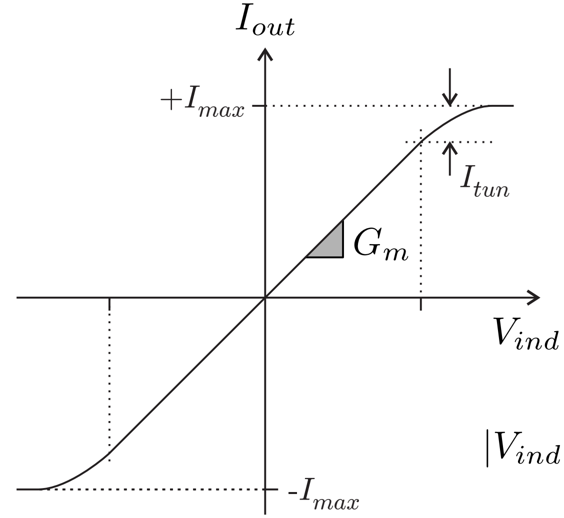
- **Cross-coupled** CMOS circuit realization:





$$V_{inn} \doteq V_{inc} - \frac{V_{ind}}{2} \qquad V_{inp} \doteq V_{inc} + \frac{V_{ind}}{2}$$

$$G_m \doteq \frac{I_{out}}{V_{ind}} = 2\sqrt{\frac{2\beta I_{tun}}{n}}$$

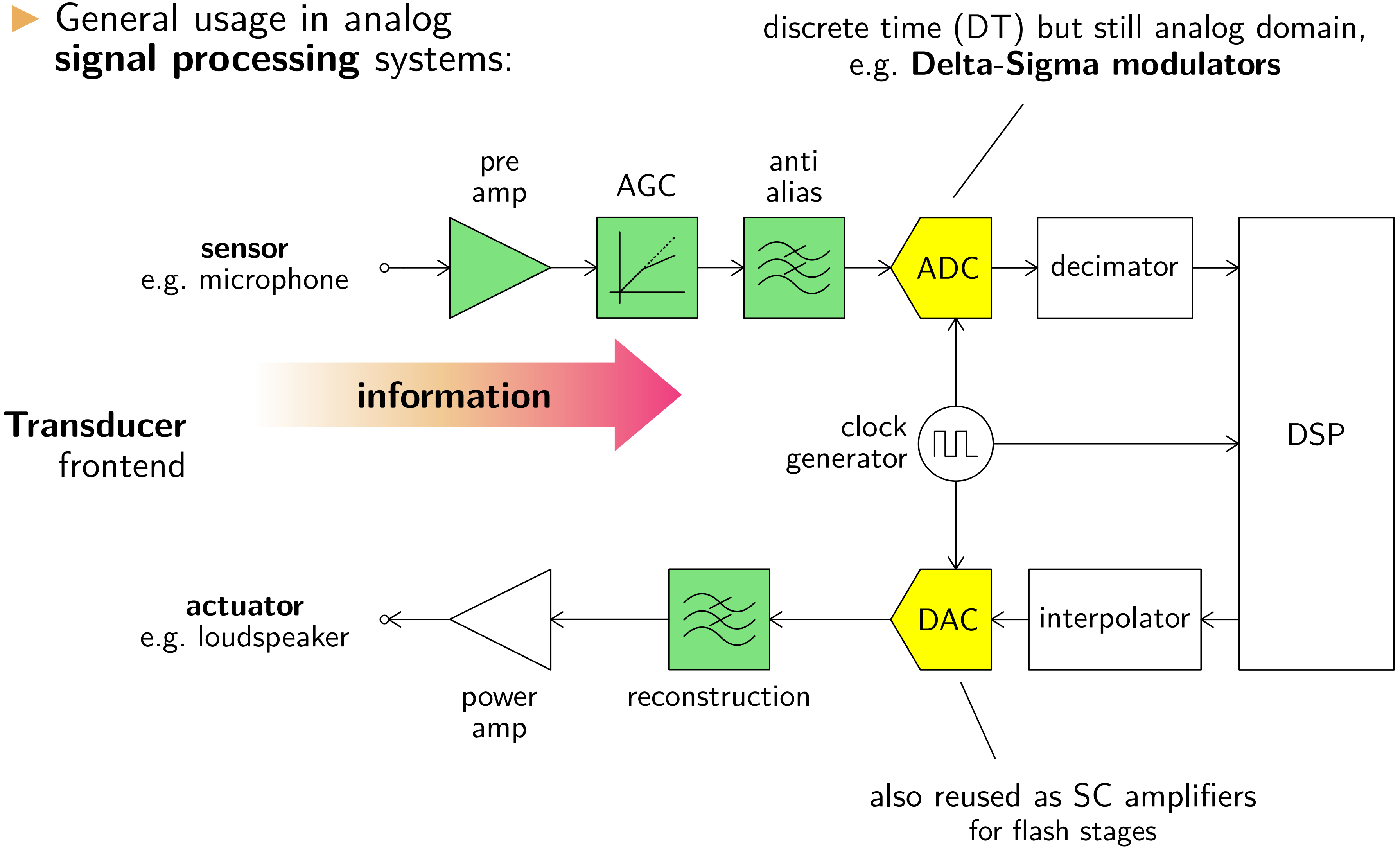


$$|V_{ind}| \leq \frac{I_{max} - I_{tun}}{G_m}$$

- ▲ **Linear** differential transconductance
- ▲ Built-in **limiter**
- ▼ **Technology** dependence

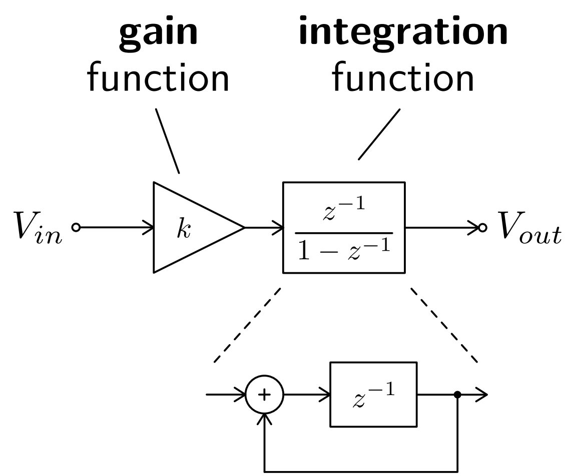
Switched-Capacitor Filters

- General usage in analog **signal processing** systems:



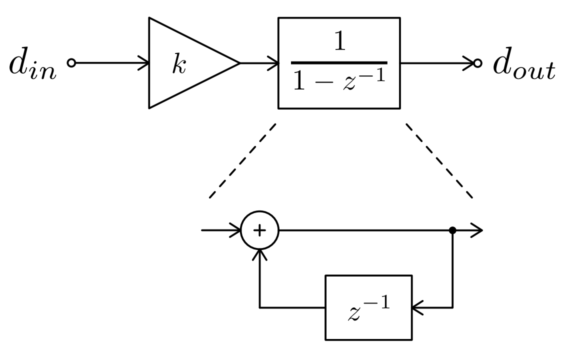
SC Integrator

- The very basic building **block**:



Analog circuit realization (ADC)

Digital circuit realization (DAC)



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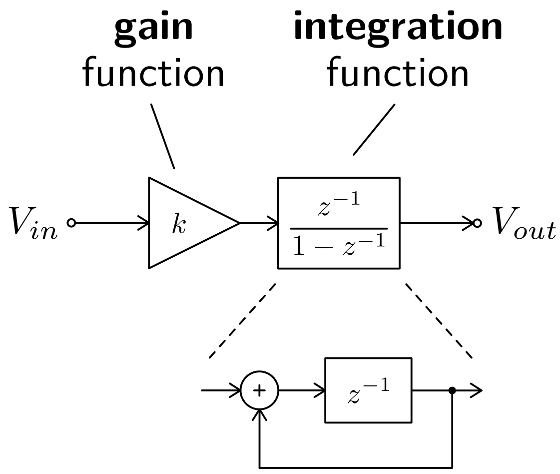
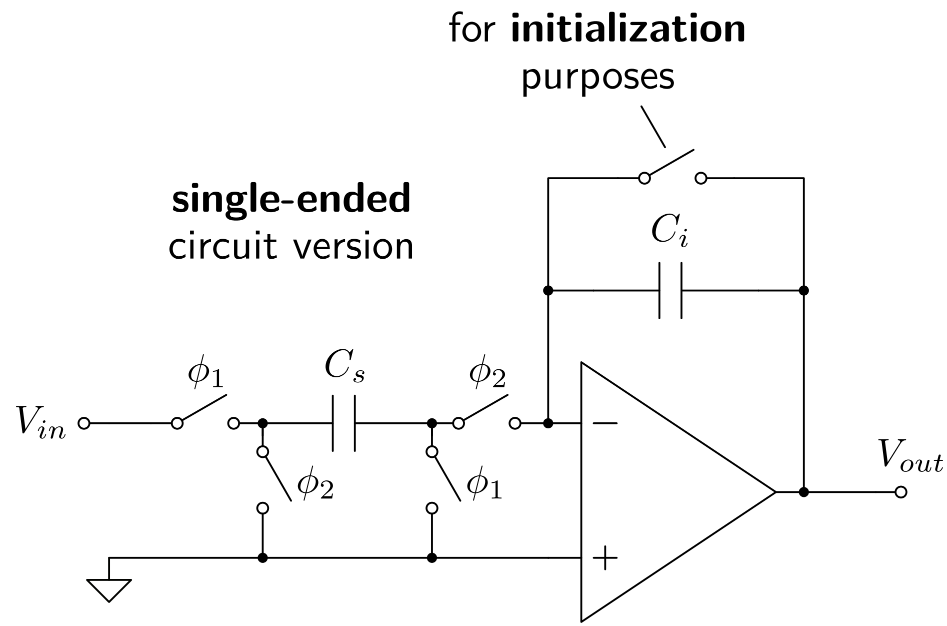
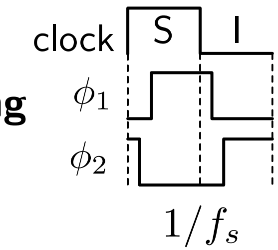


Analog circuit realization (ADC)

- SC-OpAmp **compact** implementation:

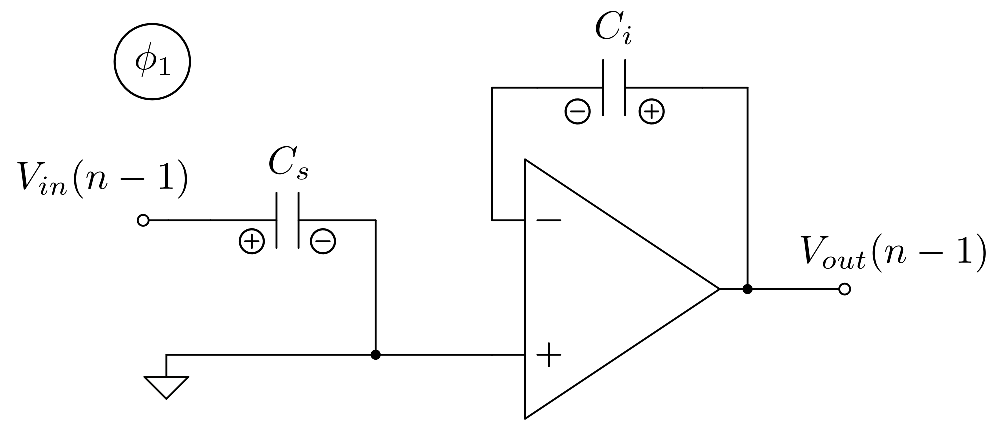


non-overlapping phases



$$\phi_x = \begin{cases} \text{H} & \text{closed} \\ \text{L} & \text{open} \end{cases}$$

SC Integrator



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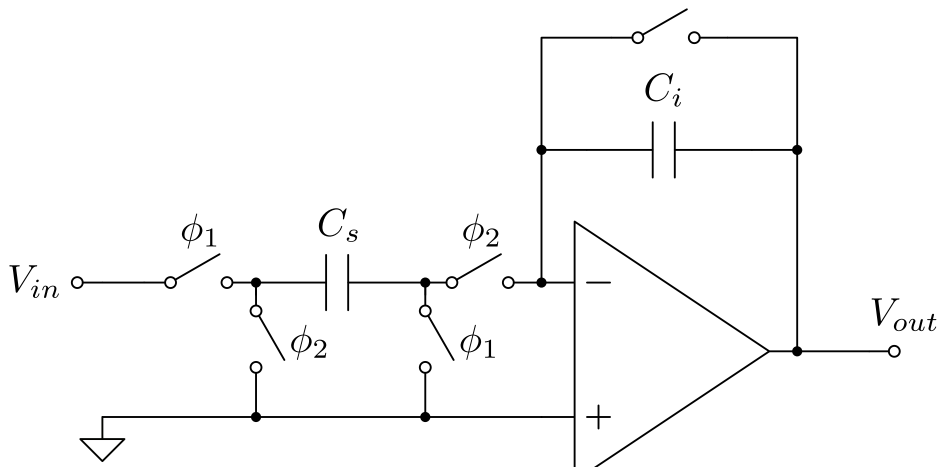

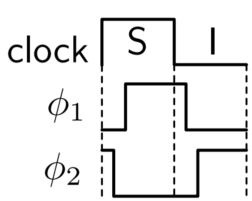

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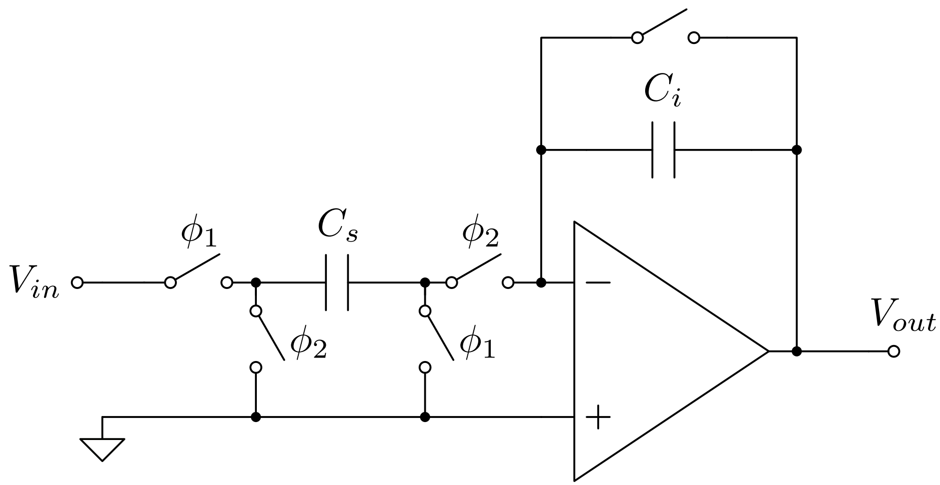

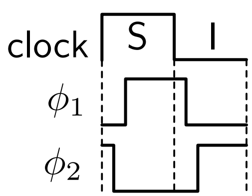

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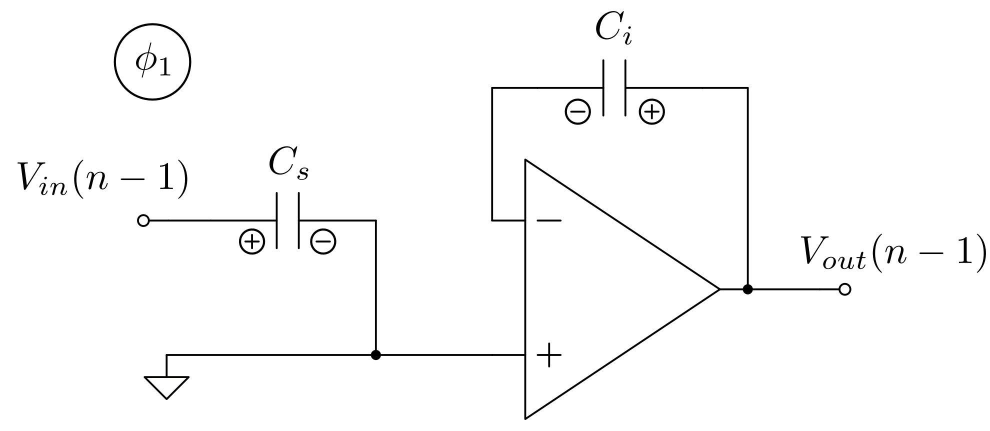
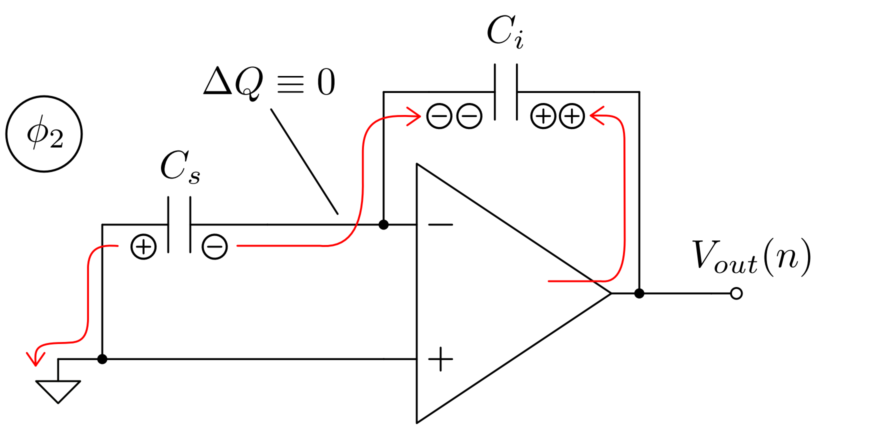


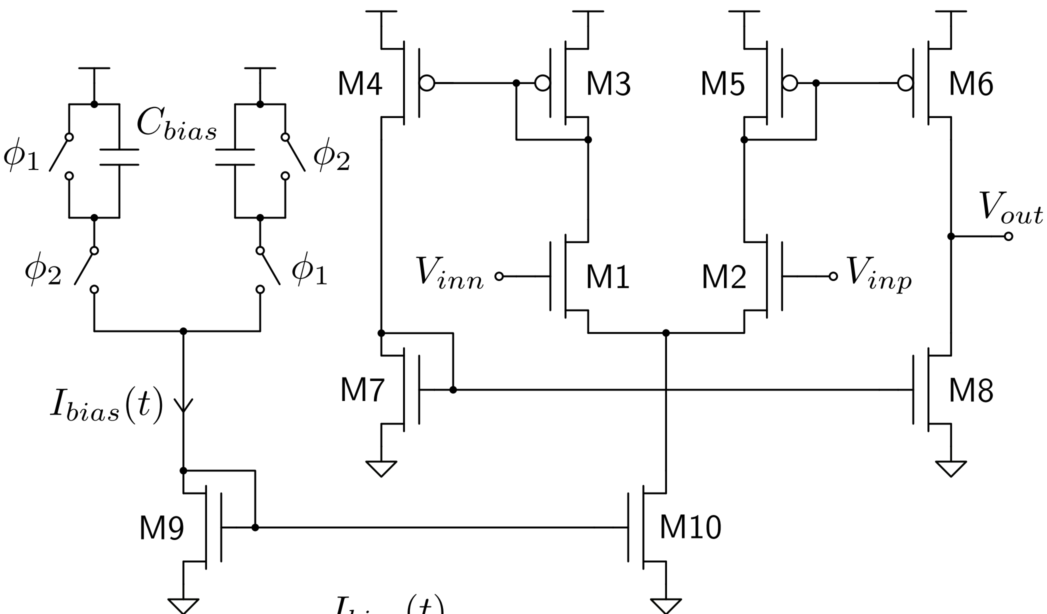


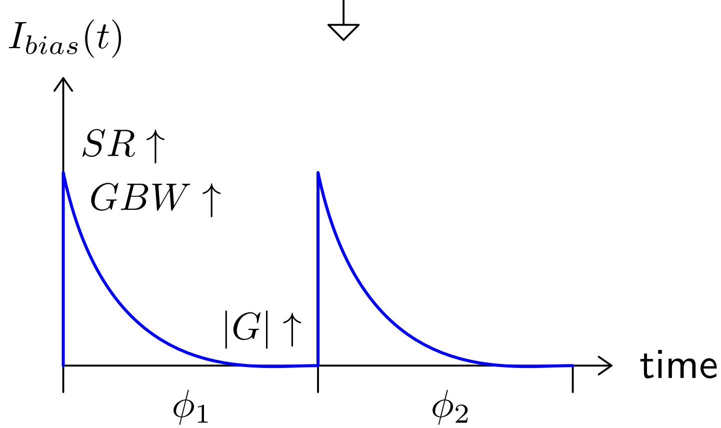
$$V_{out}(n) = V_{out}(n-1) + \frac{C_s}{C_i} V_{in}(n-1)$$

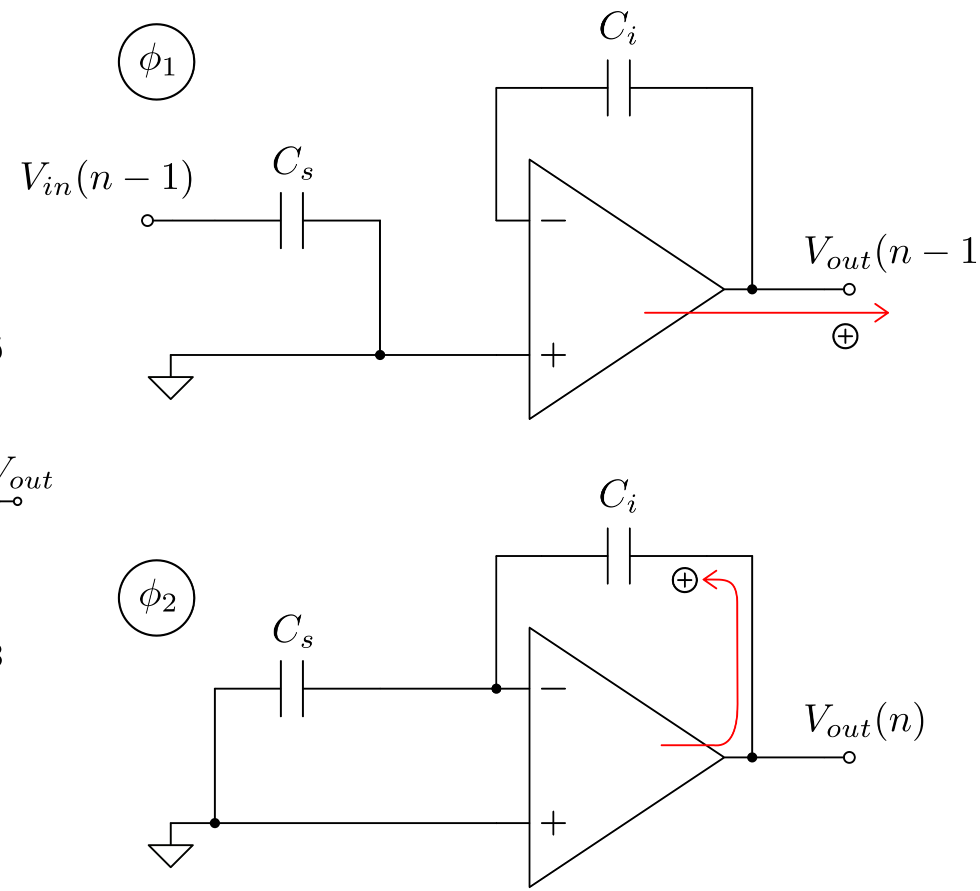
$$\frac{V_{out}}{V_{in}}(z) = k\frac{z^{-1}}{1-z^{-1}} \qquad k \doteq \frac{C_s}{C_i}$$

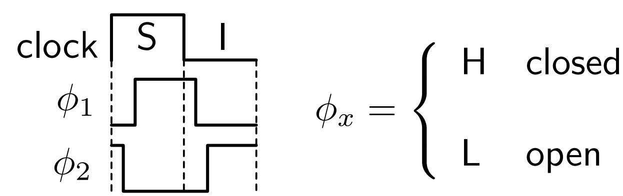
SC OpAmp Optimization

- Discrete time **dynamic biasing**:









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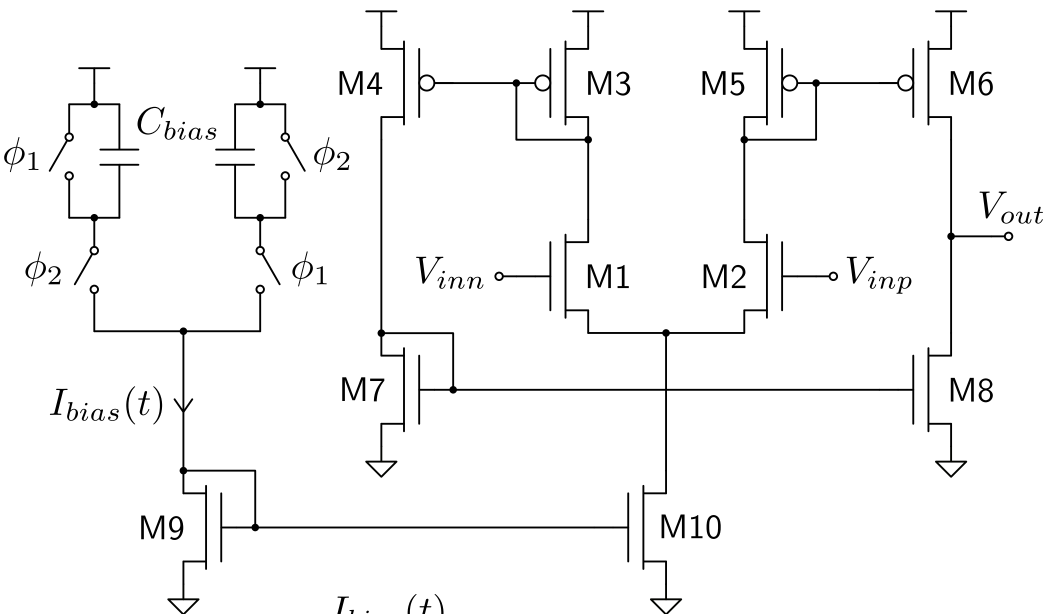

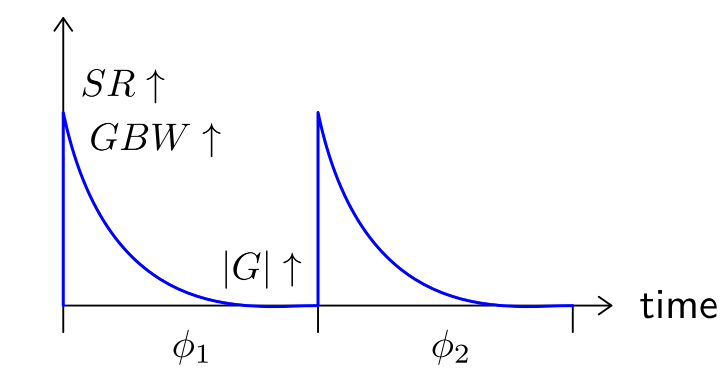

- ▲ Synchronous **Class-AB** operation
- ▲ Static **power** savings
- ▼ OpAmp fast on/off **recovery** time required
- ▼ Biasing **peak** value is technology dependent
- ▼ **Ripple** induced in the power rails (digital-like)