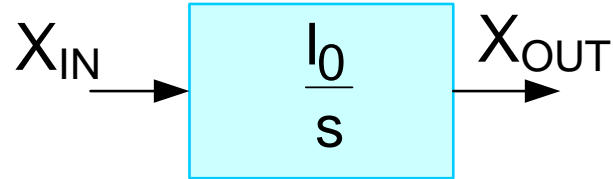


EE 508  
Lecture 23

**Integrator Design**

TA-C Integrators  
Other Integrator Structures

# Integrator Characteristics of Interest



$$I(s) = \frac{I_0}{s}$$

Properties of an ideal integrator:

$$|I(j\omega)| = \frac{I_0}{\omega}$$

Gain decreases with  $1/\omega$

$$\angle I(j\omega) = -90^\circ$$

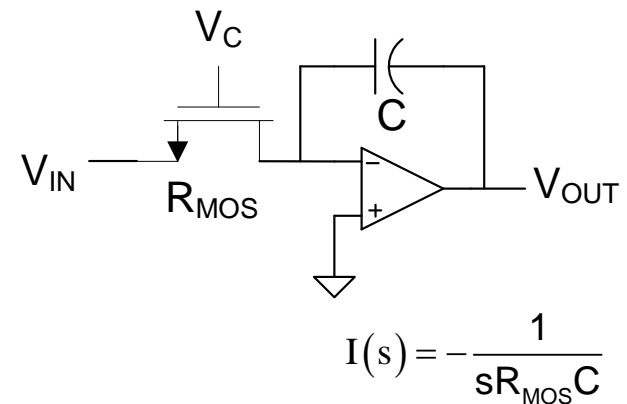
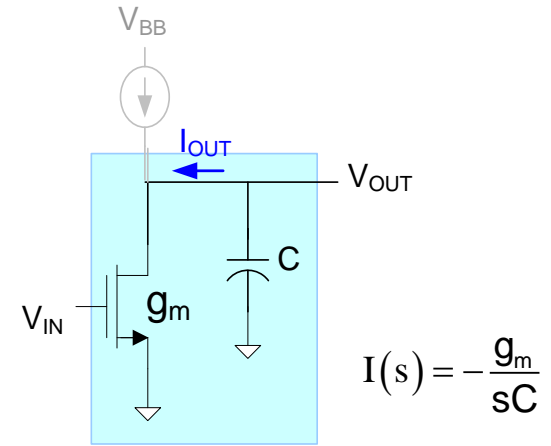
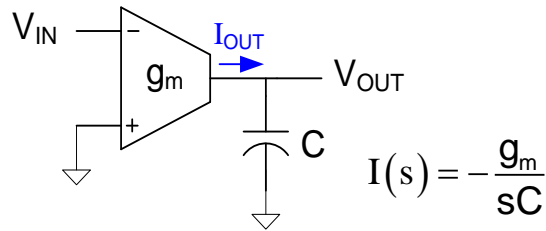
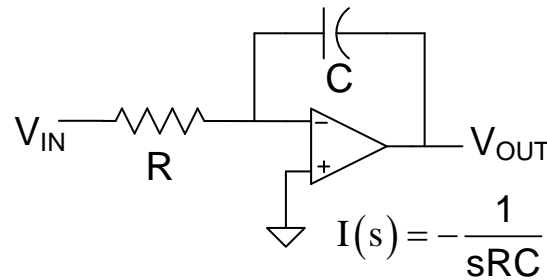
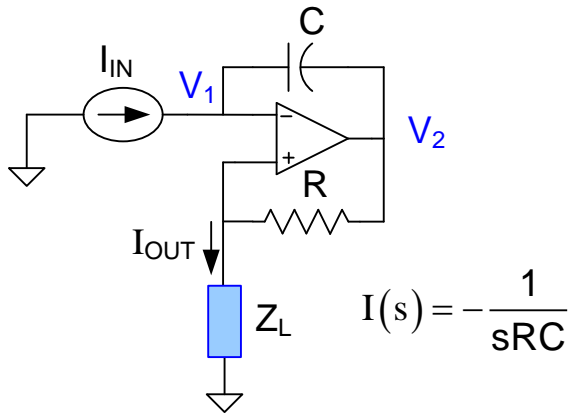
Phase is a constant  $-90^\circ$

$$|I(jI_0)| = 1$$

Unity Gain Frequency = 1

How important is it that an integrator have all 3 of these properties?

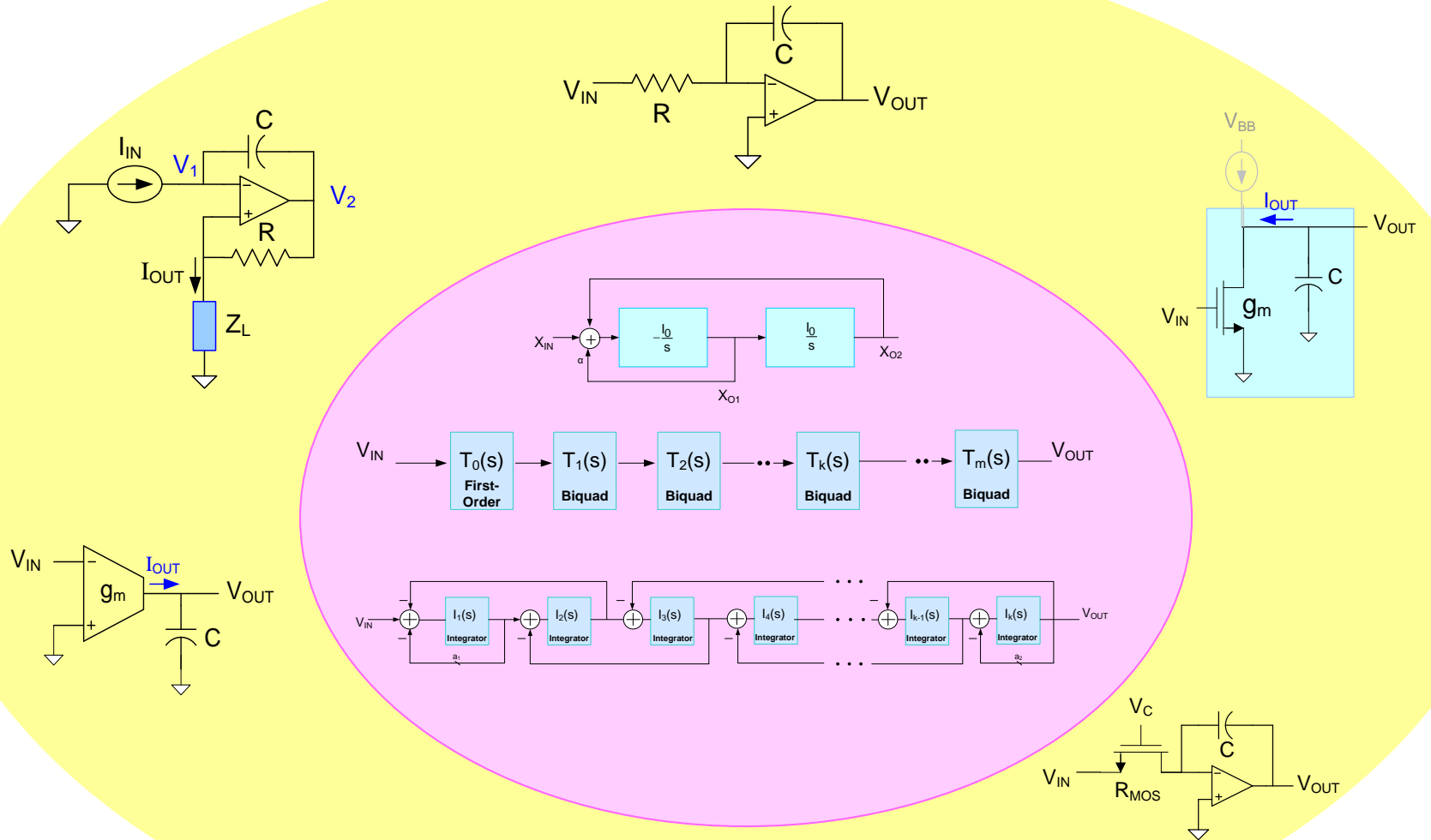
# Some integrator structures



There are other useful integrator structures (some will be introduced later)

There are many different ways to build an inverting integrator

# Integrator-Based Filter Design



Any of these different types of integrators can be used to build integrator-based filters

# Are new integrators still being invented?

## USPTO PATENT FULL-TEXT AND IMAGE DATABASE

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AND  
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Searching US Patent Collection...

Results of Search in US Patent Collection db for:

**TTL/integrator** - 531 patents.

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Oct 16 2018

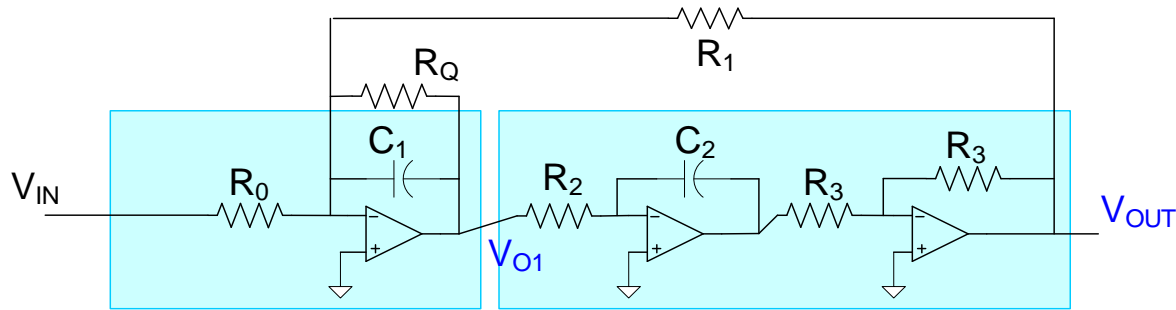
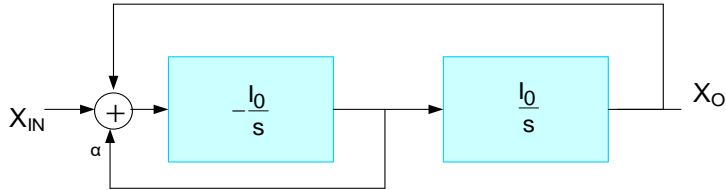
# Review from last time

Nov 2017

Nov 2016

PAT. NO.	Title
1 10,082,922	<a href="#">Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit</a>
2 10,074,004	<a href="#">Capacitive fingerprint sensor with integrator</a>
3 10,070,089	<a href="#">Inverting amplifier, integrator, sample hold circuit, ad converter, image sensor, and imaging apparatus</a>
4 9,985,594	<a href="#">Gated CDS integrator</a>
5 9,972,003	<a href="#">Pregame electronic commerce integrator</a>
6 9,954,514	<a href="#">Output range for interpolation architectures employing a cascaded integrator-comb (CIC) filter with a multiplier</a>
7 9,885,959	<a href="#">Illumination optical apparatus having deflecting member, lens, polarization member to set polarization in circumference direction, and optical integrator</a>
8 9,885,872	<a href="#">Illumination optical apparatus, exposure apparatus, and exposure method with optical integrator and polarization member that changes polarization state of light</a>
9 9,866,237	<a href="#">Low power switched capacitor integrator, analog-to-digital converter and switched capacitor amplifier</a>
10 9,852,283	<a href="#">Confirming the identity of integrator applications</a>
11 9,825,646	<a href="#">Integrator and A/D converter using the same</a>
12 9,817,917	<a href="#">System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems</a>
13 9,806,552	<a href="#">Analog/digital converter with charge rebalanced integrator</a>
14 9,800,256	<a href="#">Semiconductor device including integrator and successive approximation register analog-to-digital converter and driving method of the same</a>
15 9,753,559	<a href="#">Feedback integrator current source, transistor, and resistor coupled to input</a>
16 9,726,521	<a href="#">Signal processing apparatus for processing time variant signal with first and second input signals comprising a weighting integrator, a magnitude detector and a gain-adjustable amplifier</a>
17 9,709,242	<a href="#">Shell integrator</a>
18 9,703,178	<a href="#">Projector having a rod integrator with an entrance plane smaller than an area light source</a>
19 9,680,496	<a href="#">Apparatus for overload recovery of an integrator in a sigma-delta modulator</a>
20 9,671,916	<a href="#">Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit</a>
21 9,647,677	<a href="#">Integrator, AD converter, and radiation detection device</a>
22 9,634,688	<a href="#">Integrator, delta-sigma modulator, and communications device</a>
23 9,628,103	<a href="#">Multi-mode discrete-time delta-sigma modulator power optimization using split-integrator scheme</a>
24 9,608,598	<a href="#">Cascaded integrator-comb filter as a non-integer sample rate converter</a>
25 9,588,147	<a href="#">Electronic integrator for Rogowski coil sensors</a>
26 9,574,735	<a href="#">Shell integrator</a>
27 9,558,845	<a href="#">Sampling network and clocking scheme for a switched-capacitor integrator</a>
28 9,531,718	<a href="#">Confirming the identity of integrator applications</a>
29 9,524,054	<a href="#">Integrator and touch sensing system using the same</a>
30 9,519,462	<a href="#">System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems</a>
31 9,496,969	<a href="#">Double integrator pulse wave shaper apparatus, system and method</a>
32 9,495,563	<a href="#">Analog integrator system and method</a>
33 9,473,075	<a href="#">Dynamic current source for amplifier integrator stages</a>
34 9,467,153	<a href="#">Low power and compact area digital integrator for a digital phase detector</a>
35 9,461,595	<a href="#">Integrator for class D audio amplifier</a>
36 9,454,069	<a href="#">Illumination system having first and second lens arrays including plano-convex lenses wherein some lenses in the second array include a first and a second lens element, projection-type display apparatus, and optical integrator</a>
37 9,405,800	<a href="#">Apparatuses, methods and systems for a universal payment integrator</a>
38 9,389,625	<a href="#">DC-DC converter controller apparatus with dual-counter digital integrator</a>
39 9,383,395	<a href="#">Charge balancing converter using a passive integrator circuit</a>
40 9,379,732	<a href="#">Delta-sigma modulator with reduced integrator requirements</a>
41 9,362,890	<a href="#">Compensation filter for cascaded-integrator-comb decimator</a>
42 9,354,953	<a href="#">System integrator and system integration method with reliability optimized integrated circuit chip selection</a>
43 9,314,389	<a href="#">Therapeutic integrator apparatus</a>
44 9,310,924	<a href="#">Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit</a>
45 9,268,441	<a href="#">Active integrator for a capacitive sense array</a>
46 9,225,351	<a href="#">Current amplifier circuit, integrator, and ad converter</a>
47 9,218,514	<a href="#">Apparatuses and method of switched-capacitor integrator</a>
48 9,171,189	<a href="#">Systems and methods for preventing saturation of analog integrator output</a>
49 9,152,387	<a href="#">System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems</a>
50 9,139,096	<a href="#">One-sided detection and disabling of integrator wind up for speed control in a vehicle</a>

# Example – Active RC Feedback Tow Thomas Biquad



$$\left. \begin{aligned} V_{OUT} &= \frac{1}{sR_2C_2} V_{O1} \\ V_{IN}G_0 + V_{O1}(sC_1 + G_Q) + G_1V_{OUT} &= 0 \end{aligned} \right\}$$

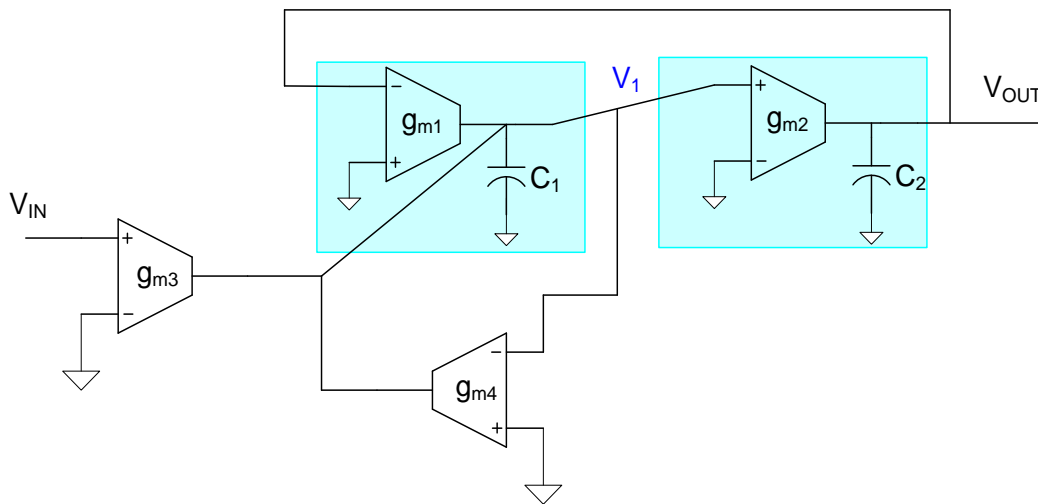
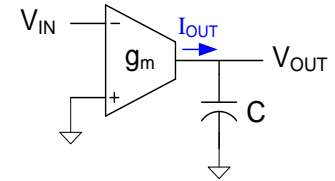
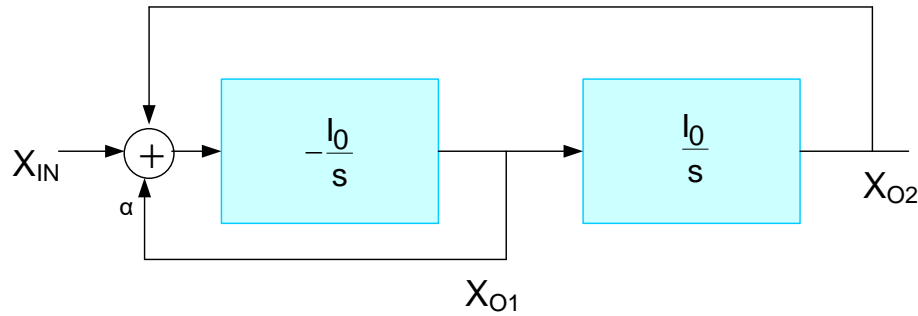
$$\frac{V_{OUT}}{V_{IN}} = - \frac{1}{s^2 + s \frac{1}{R_Q C_1} + \frac{1}{C_1 R_1 R_2 C_2}}$$

If  $R_1 = R_2 = R$  and  $C_1 = C_2 = C$

$$\omega_0 = \frac{1}{RC}$$

$$Q = \frac{R_Q}{R}$$

# Example – OTA-C Tow Thomas Biquad



$$\left. \begin{aligned} V_{OUT} s C_2 &= g_{m2} V_1 \\ V_1 s C_1 &= -g_{m1} V_{OUT} + g_{m3} V_{IN} - g_{m4} V_1 \end{aligned} \right\}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{g_{m3} g_{m2}}{(s^2 C_1 C_2 + s g_{m4} C_2 + g_{m1} g_{m2})}$$

Assume  $g_{m1} = g_{m2} = g_m$ ,  $C_1 = C_2 = C$

$$\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{g_{m3}}{g_m}\right) \frac{g_m^2}{C^2}}{\left(s^2 + s \left(\frac{g_{m4}}{g_m}\right) \frac{g_m}{C} + \frac{g_m^2}{C^2}\right)}$$

express as

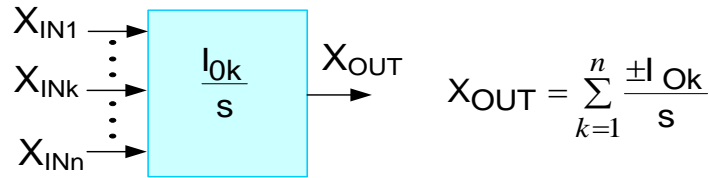
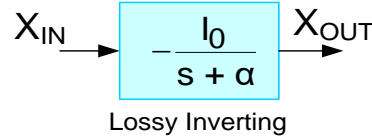
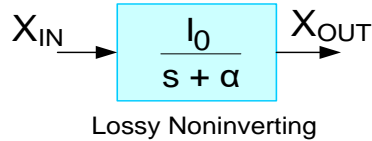
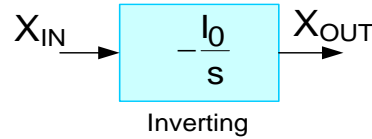
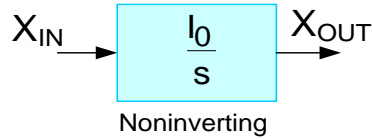
$$\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{g_{m3}}{g_m}\right) \omega_0^2}{\left(s^2 + s \frac{\omega_0}{Q} + \omega_0^2\right)}$$

where

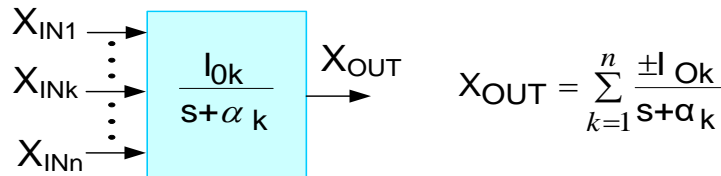
$$\omega_0 = \frac{g_m}{C} \quad Q = \frac{g_m}{g_{m4}}$$



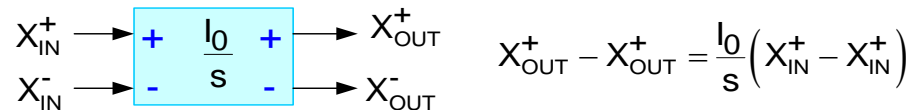
# Basic Integrator Functionality



Summing (Multiple-Input) Inverting/Noninverting



Summing (Multiple-Input) Lossy Inverting/Noninverting

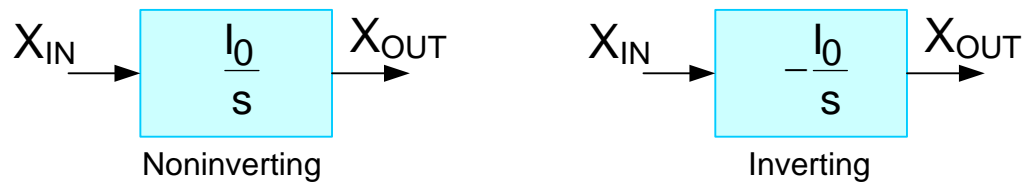


Balanced Differential



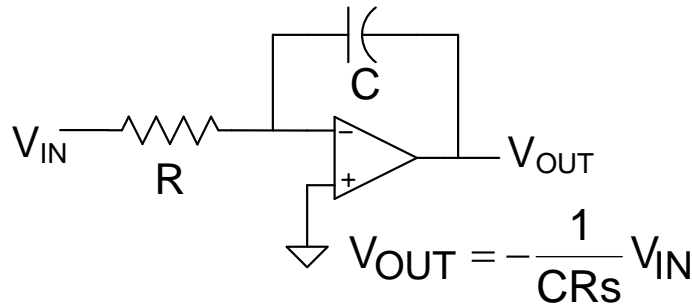
Fully Differential

# Basic Integrator Functionality

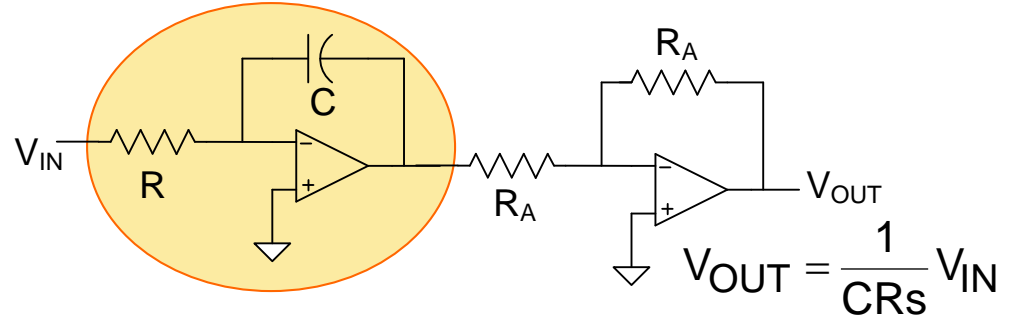


- An inverting/noninverting integrator pair define a family of integrators
- All integrator functional types can usually be obtained from the inverting/noninverting integrator pair
- Suffices to focus primarily on the design of the inverting/noninverting integrator pair since properties of class primarily determined by properties of integrator pair

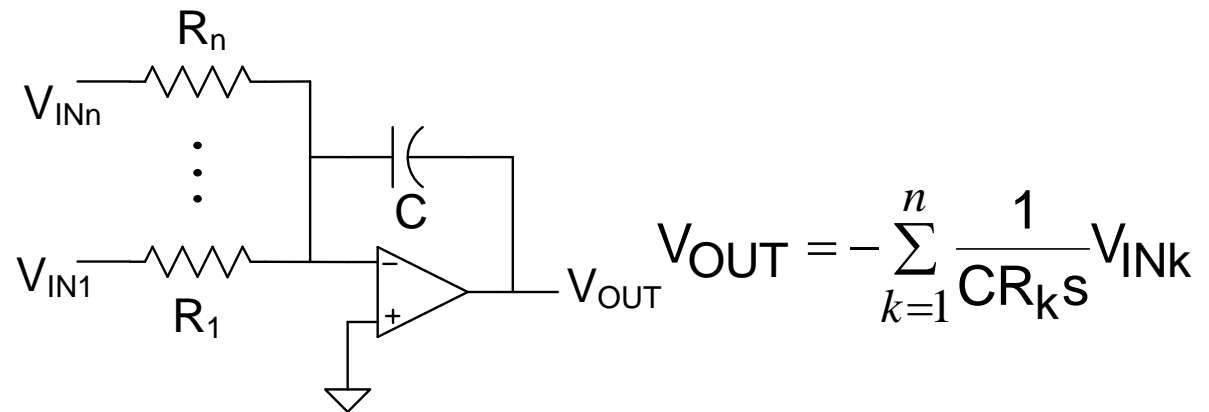
# Example – Basic Op-Amp Feedback Integrator



Inverting Integrator of Family

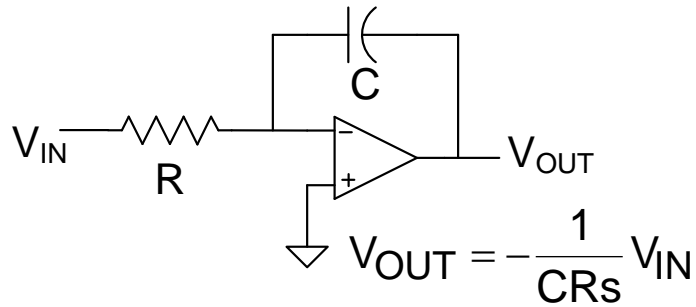


Noninverting Integrator

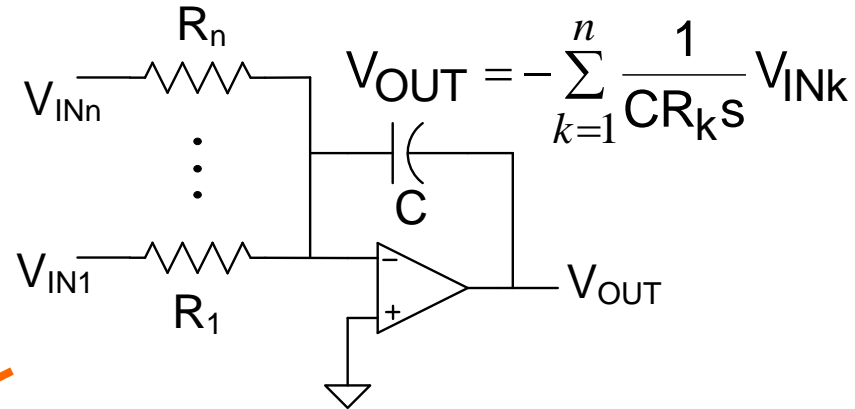


Summing Inverting Integrator

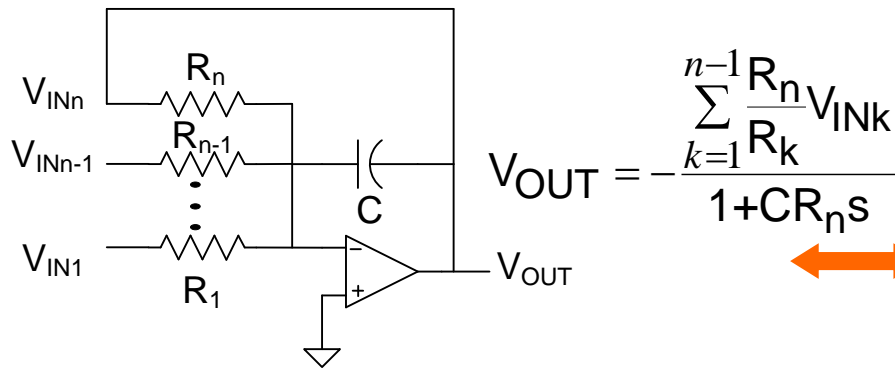
# Example – Basic Op-Amp Feedback Integrator



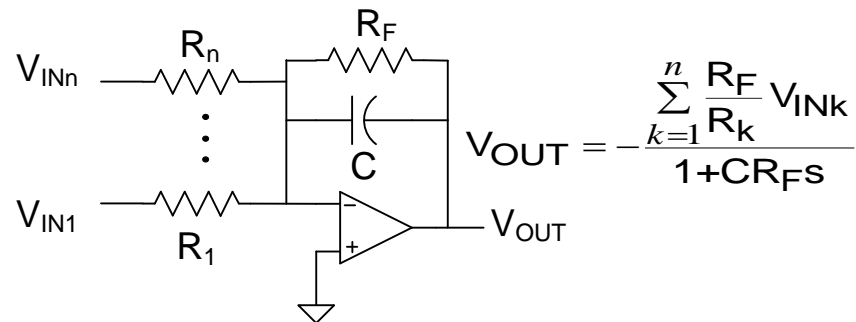
Inverting Integrator of Family



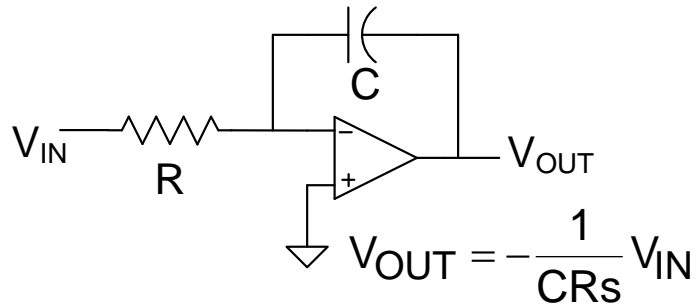
Summing Inverting Integrator



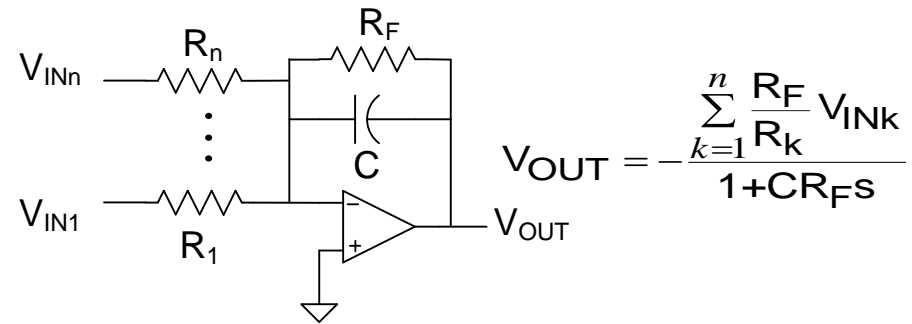
Lossy Summing Inverting Integrator



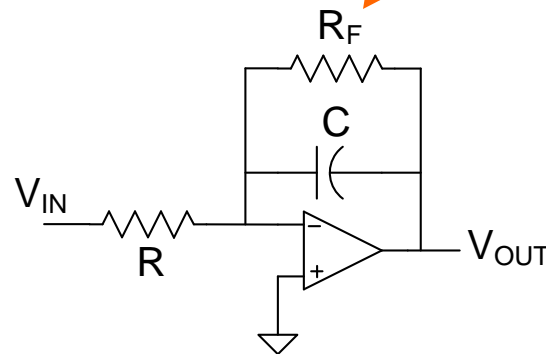
# Example – Basic Op-Amp Feedback Integrator



Inverting Integrator of Family



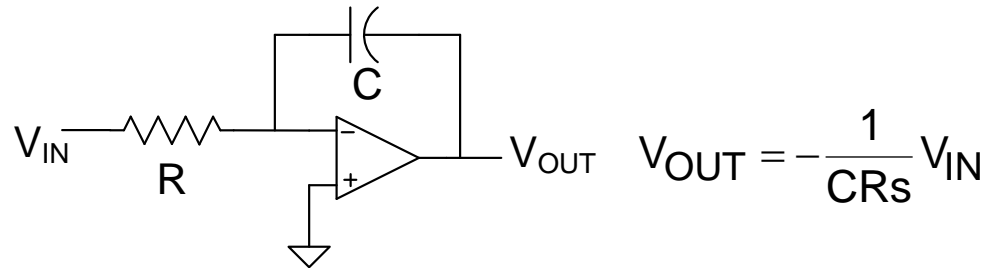
Lossy Summing Inverting Integrator



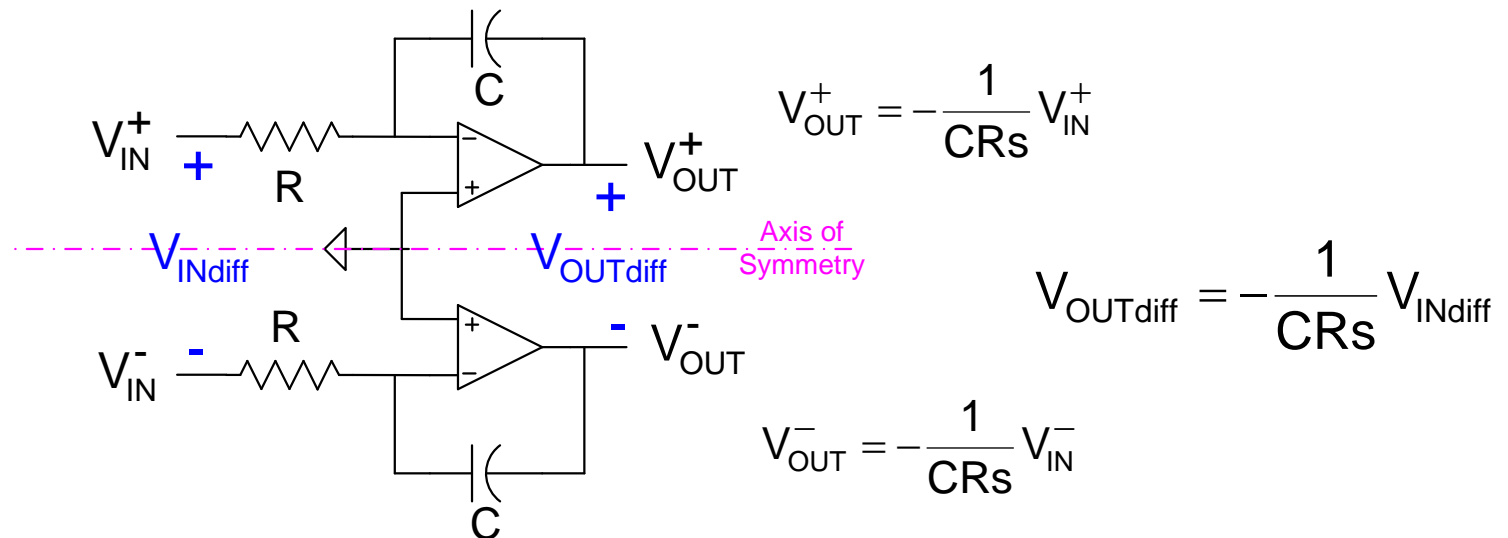
Lossy Inverting Integrator

$$V_{OUT} = -\frac{R_F/R}{1 + CR_Fs} V_{IN}$$

# Example – Basic Op-Amp Feedback Integrator

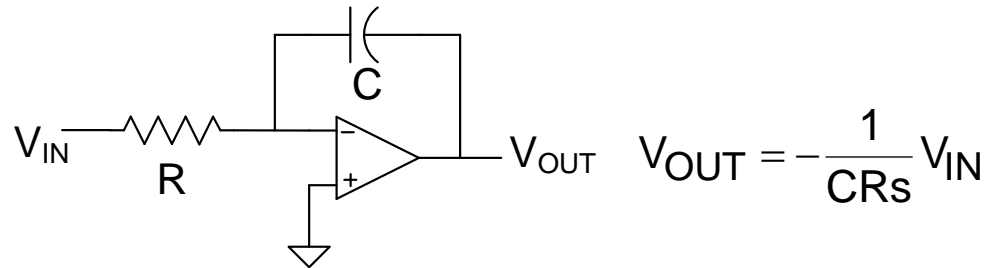


Inverting Integrator of Family

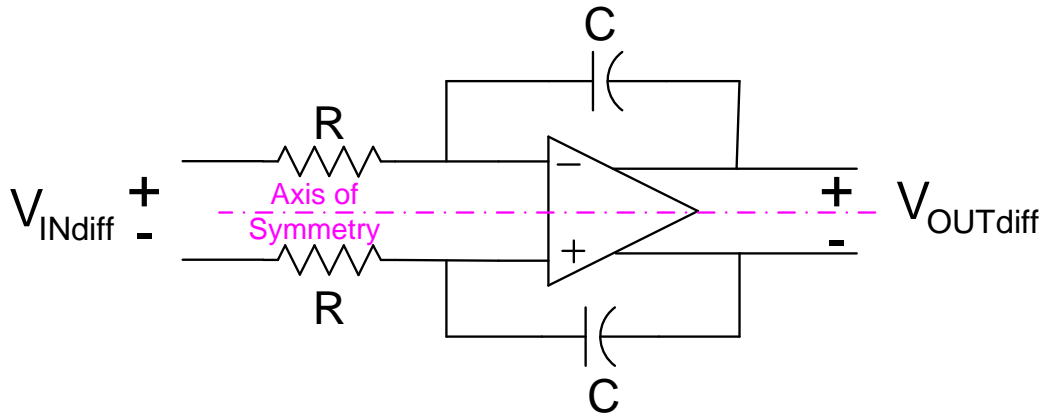


Balanced Differential Inverting Integrator

# Example – Basic Op-Amp Feedback Integrator



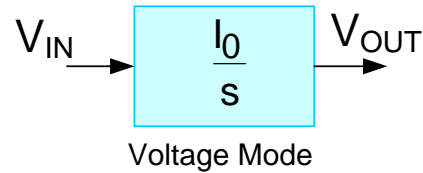
Inverting Integrator of Family



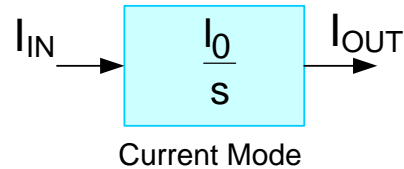
$$V_{OUTdiff} = -\frac{1}{CRs} V_{INdiff}$$

Fully Differential Inverting Integrator

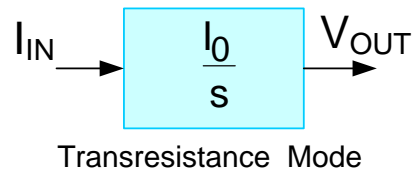
# Integrator Types



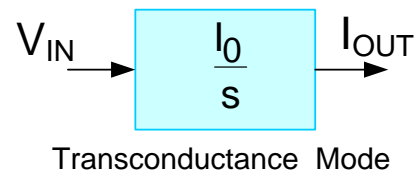
$$V_{OUT} = \frac{I_0}{s} V_{IN}$$



$$I_{OUT} = \frac{I_0}{s} I_{IN}$$



$$V_{OUT} = \frac{I_0}{s} I_{IN}$$



$$I_{OUT} = \frac{I_0}{s} V_{IN}$$

Will consider first the Voltage Mode type of integrators



# Voltage Mode Integrators

→ Active RC (Feedback-based)

- MOSFET-C (Feedback-based)

- OTA-C

- TA-C

} Sometimes termed “current mode”

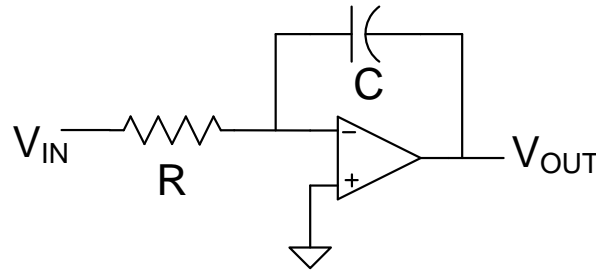
- Other Continuous-time Structures

- Switched Capacitor

- Switched Resistor

} Discrete Time

# Active RC Voltage Mode Integrator



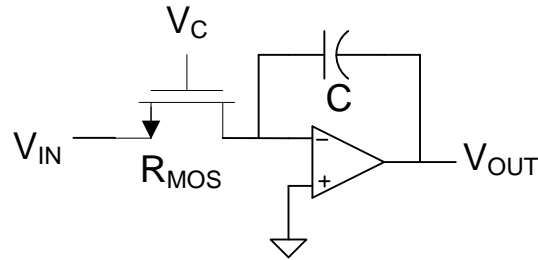
$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

- Limited to low frequencies because of Op Amp limitations
- No good resistors for monolithic implementations
  - Area for passive resistors is too large at low frequencies
  - Some recent work by Haibo Fei shows promise for some audio frequency applications
- Capacitor area too large at low frequencies for monolithic implementations
- Active devices are highly temperature dependent, proc. dependent, and nonlinear
- No practical tuning or trimming scheme for integrated applications with passive resistors

# Voltage Mode Integrators

- Active RC (Feedback-based)
  - • MOSFET-C (Feedback-based)
  - OTA-C
  - TA-C
- } Sometimes termed “current mode”
- Other Continuous-time Structures
  - Switched Capacitor
  - Switched Resistor
- } Discrete Time

# MOSFET-C Voltage Mode Integrator

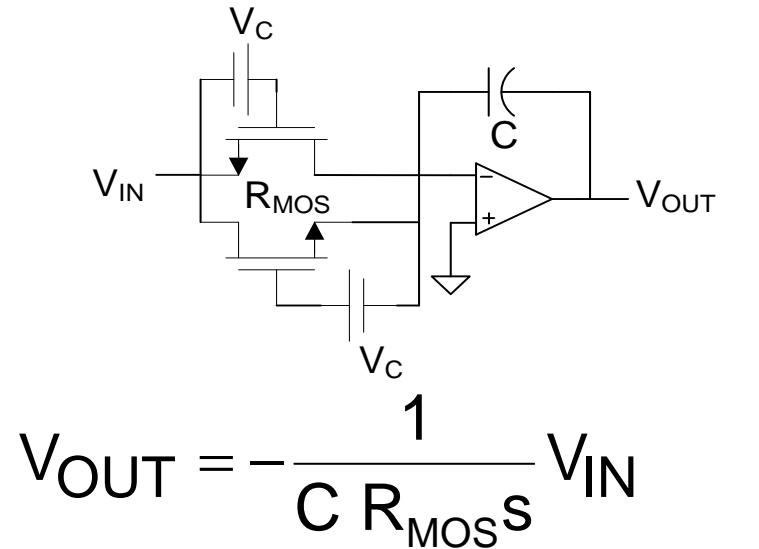
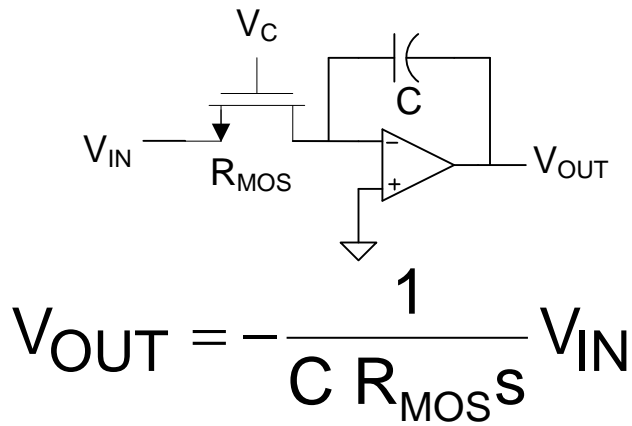


$$V_{OUT} = -\frac{1}{CR_{MOS}S} V_{IN}$$

- Limited to low frequencies because of Op Amp limitations
- Area for  $R_{MOS}$  is manageable !
- Active devices are highly temperature dependent, process dependent
- Potential for tuning with  $V_C$
- Highly Nonlinear (can be partially compensated with cross-coupled input)

**A Solution without a Problem**

# MOSFET-C Voltage Mode Integrator



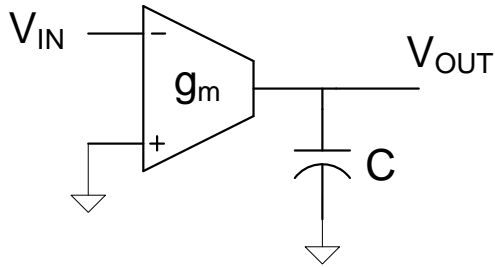
- Improved Linearity
- Some challenges for implementing  $V_C$

Still A Solution without a Problem

# Voltage Mode Integrators

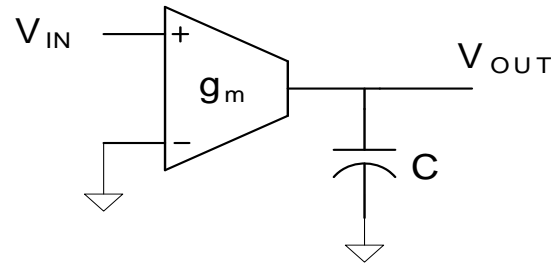
- Active RC (Feedback-based)
  - MOSFET-C (Feedback-based)
  - OTA-C
  - TA-C
- } Sometimes termed “current mode”
- Other Continuous-time Structures
  - Switched Capacitor
  - Switched Resistor
- } Discrete Time

# OTA-C Voltage Mode Integrator



$$V_{OUT} = -\frac{g_m}{sC} V_{IN}$$

Inverting



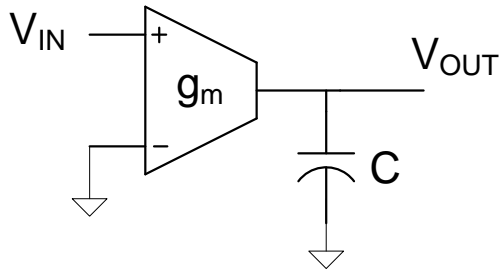
$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

Noninverting

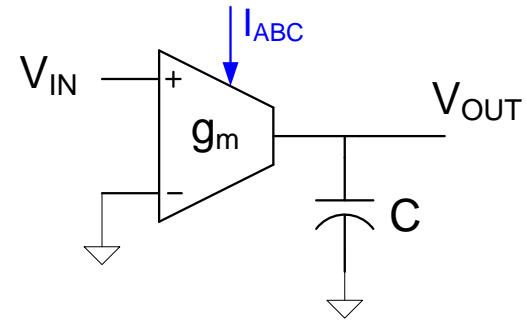
- Requires only two components
- Inverting and Noninverting structures of same complexity
- Good high-frequency performance
- Small area
- Linearity is limited (no feedback in integrator)
- Susceptible to process and temperature variations
- Tuning control can be readily added

Widely used in high frequency applications

# OTA-C Voltage Mode Integrator



$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$



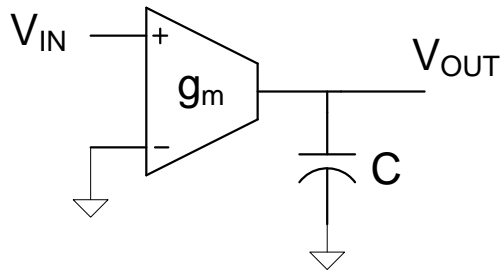
$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

$$g_m = f(I_{ABC})$$

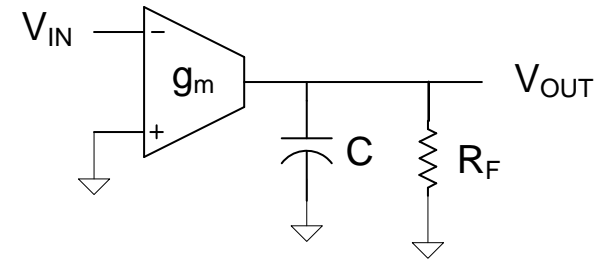
Programmable Integrator



# OTA-C Voltage Mode Integrator



$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

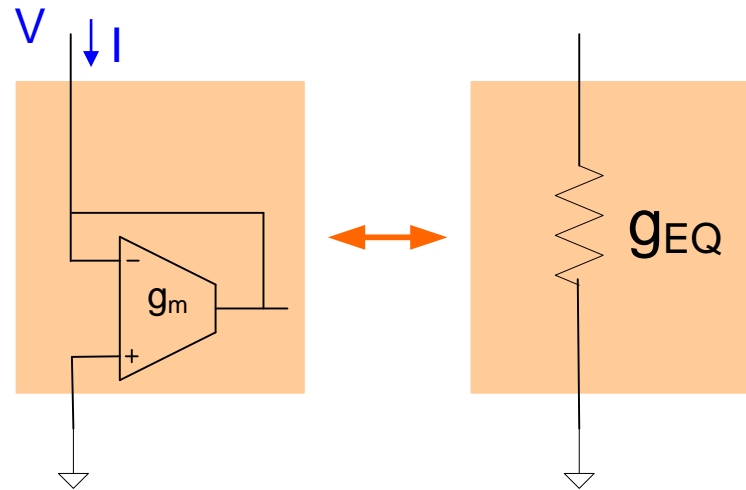


$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m R_F}{1 + s(R_F C)}$$

Lossy Integrator

But  $R_F$  is typically too large for integrated applications

# OTA-C Voltage Mode Integrator



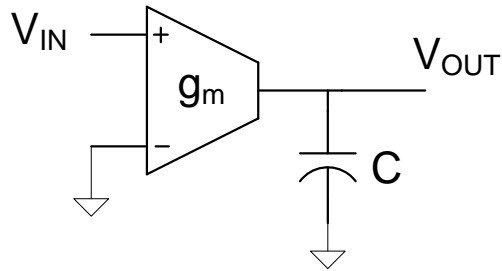
$$I = -g_m V$$

$$g_{EQ} = \frac{I}{V}$$

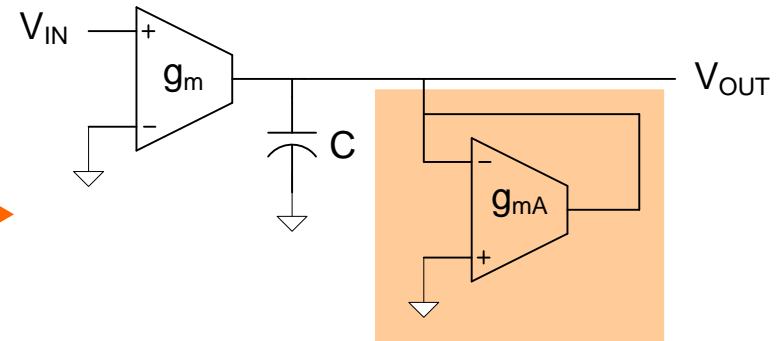
$$g_{EQ} = g_m$$

OTA is generally much smaller than a resistor

# OTA-C Voltage Mode Integrator



$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

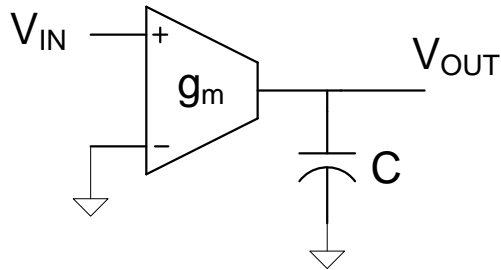


$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m/g_{mA}}{1+s(C/g_{mA})}$$

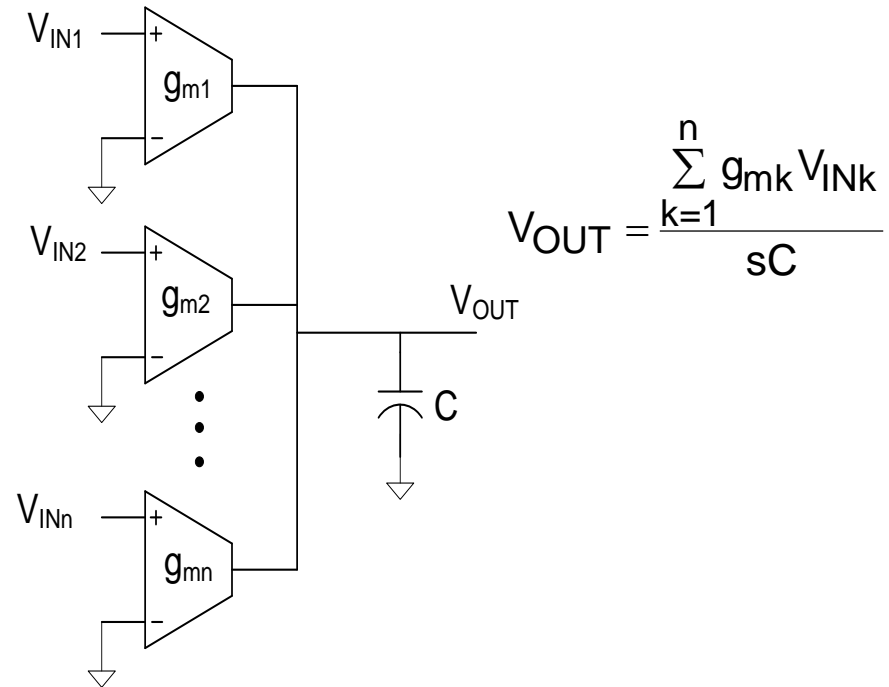
Lossy Integrator

- Practical implementation
- Both OTAs can be readily programmable

# OTA-C Voltage Mode Integrator



$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

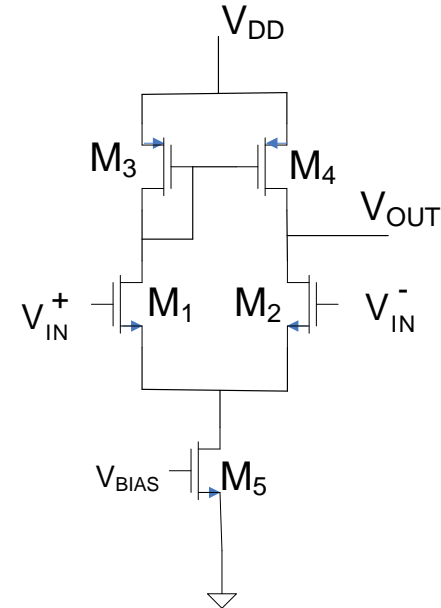
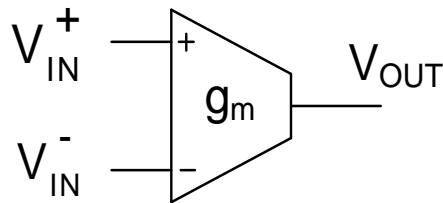


$$V_{OUT} = \frac{\sum_{k=1}^n g_{mk} V_{INk}}{sC}$$

Summing Integrator

- Inverting and noninverting functions can be combined in single summer
- All transconductance gains can be programmable

# OTA Architecture



Mid-complexity OTA

- $M_1$  and  $M_2$  matched
- $M_2$  and  $M_4$  matched
- Define  $M$  to be the gain of the current mirror formed with  $M_2$  and  $M_4$
- $g_m$  programmable with  $V_{BIAS}$

$$g_m = \frac{g_{m1}}{2} (1+M)$$

Often  $M=1$

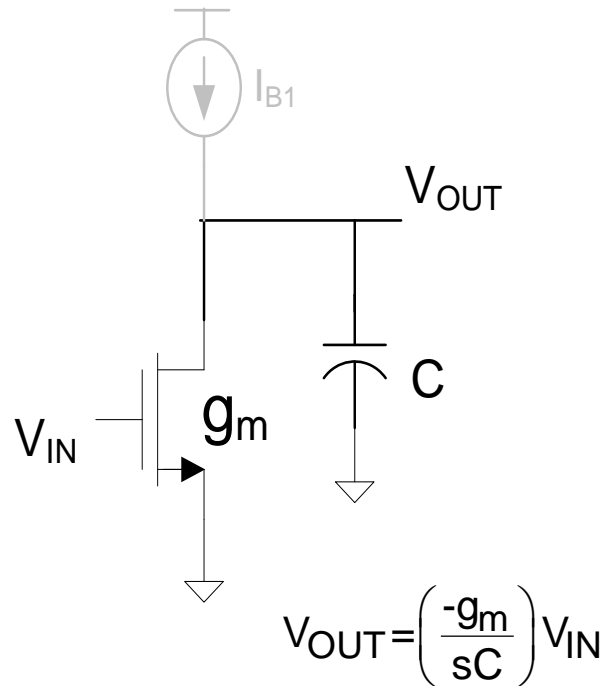
$$g_m = g_{m1}$$

Other OTAs exist, considerable effort expended over past two decades on OTA design

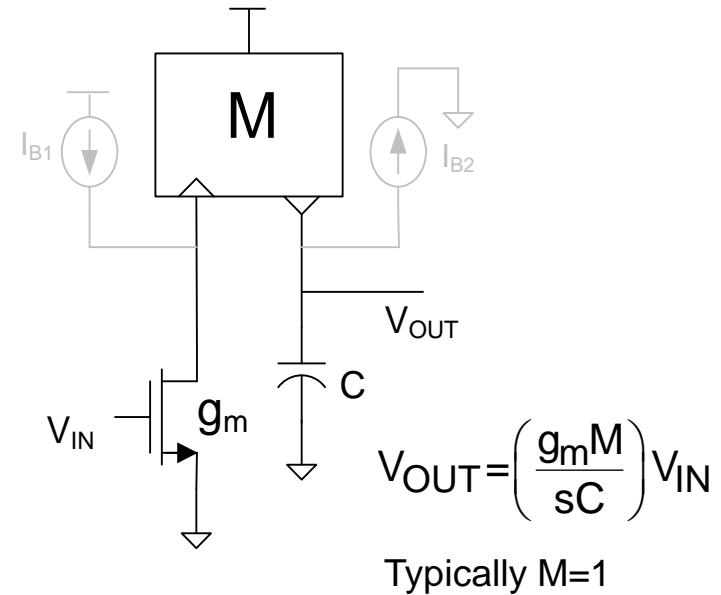
# Voltage Mode Integrators

- Active RC (Feedback-based)
  - MOSFET-C (Feedback-based)
  - OTA-C
  - TA-C
- } Sometimes termed “current mode”
- Other Continuous-time Structures
  - Switched Capacitor
  - Switched Resistor
- } Discrete Time

# TA-C Voltage Mode Integrator



Inverting Integrator

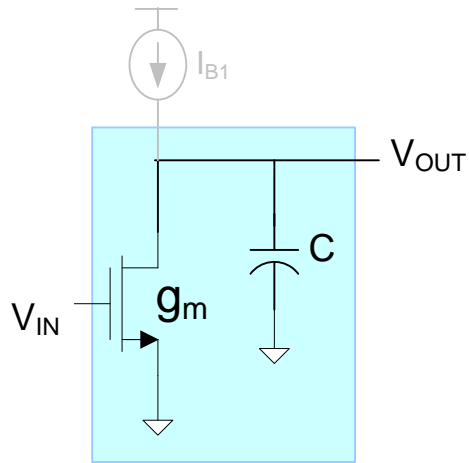


Noninverting Integrator

- Can operate at very high frequencies
- Low device count circuit
- Simplicity is important for operating at very high frequencies
- $I_0$  is process and temperature dependent
- Linearity is limited

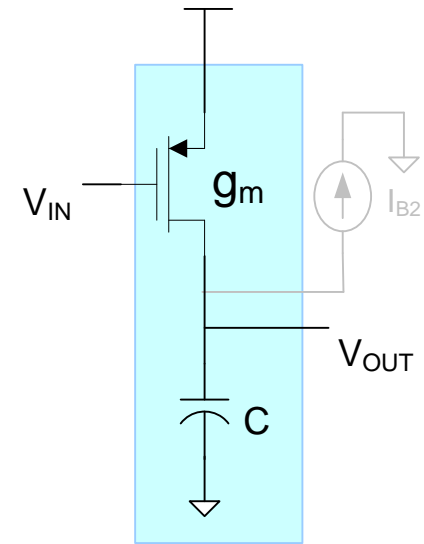
# TA-C Voltage Mode Integrator

Some other perspectives



n-channel input

$$V_{OUT} = \left( \frac{-g_m}{sC} \right) V_{IN}$$



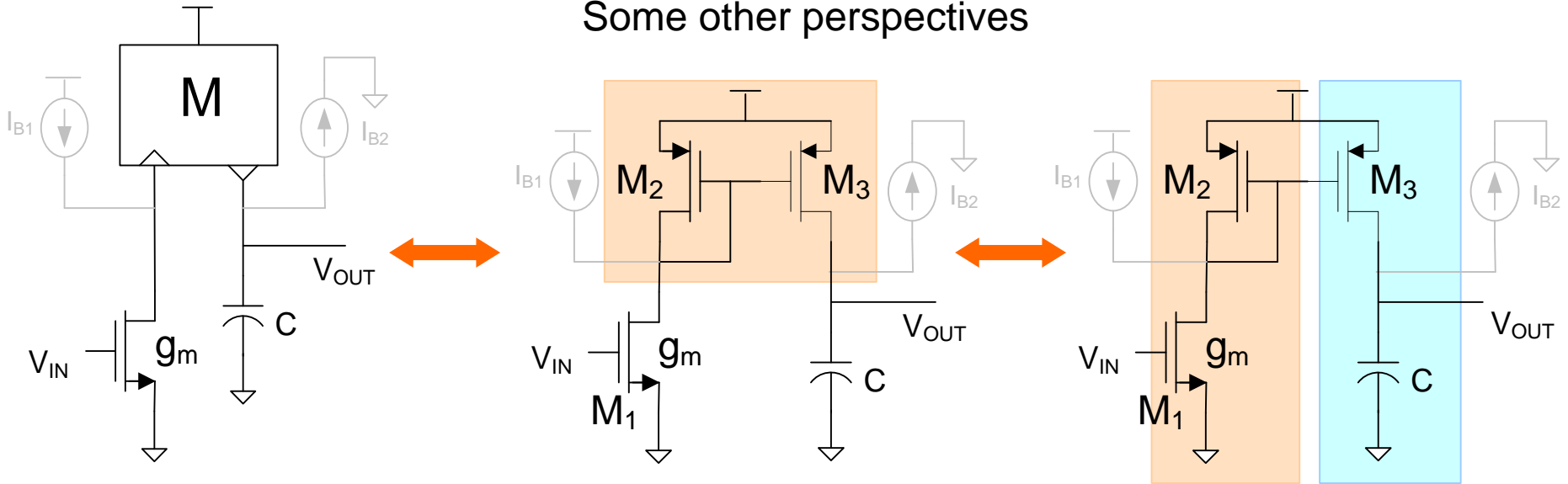
p-channel input

Inverting Integrators



# TA-C Voltage Mode Integrator

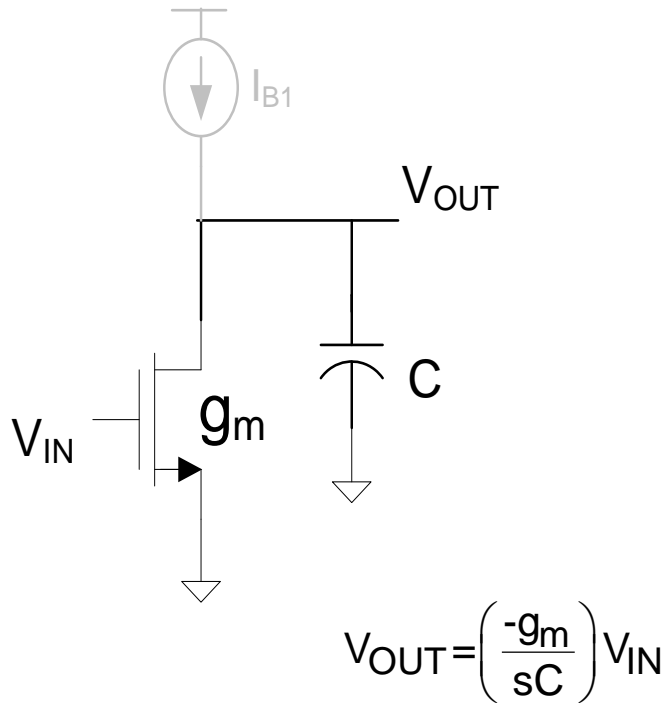
Some other perspectives



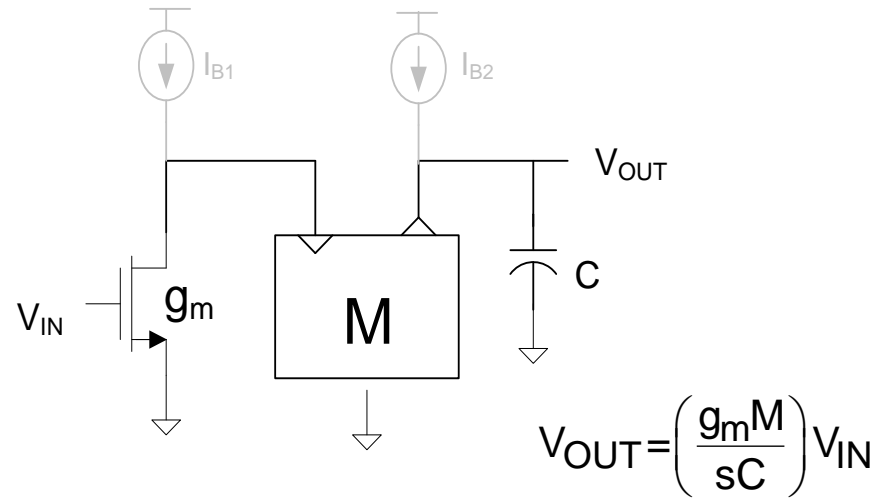
Noninverting Integrator

Can be viewed either as n-channel input with current mirror or as low-gain inverter driving a p-channel input inverting integrator

# TA-C Voltage Mode Integrator



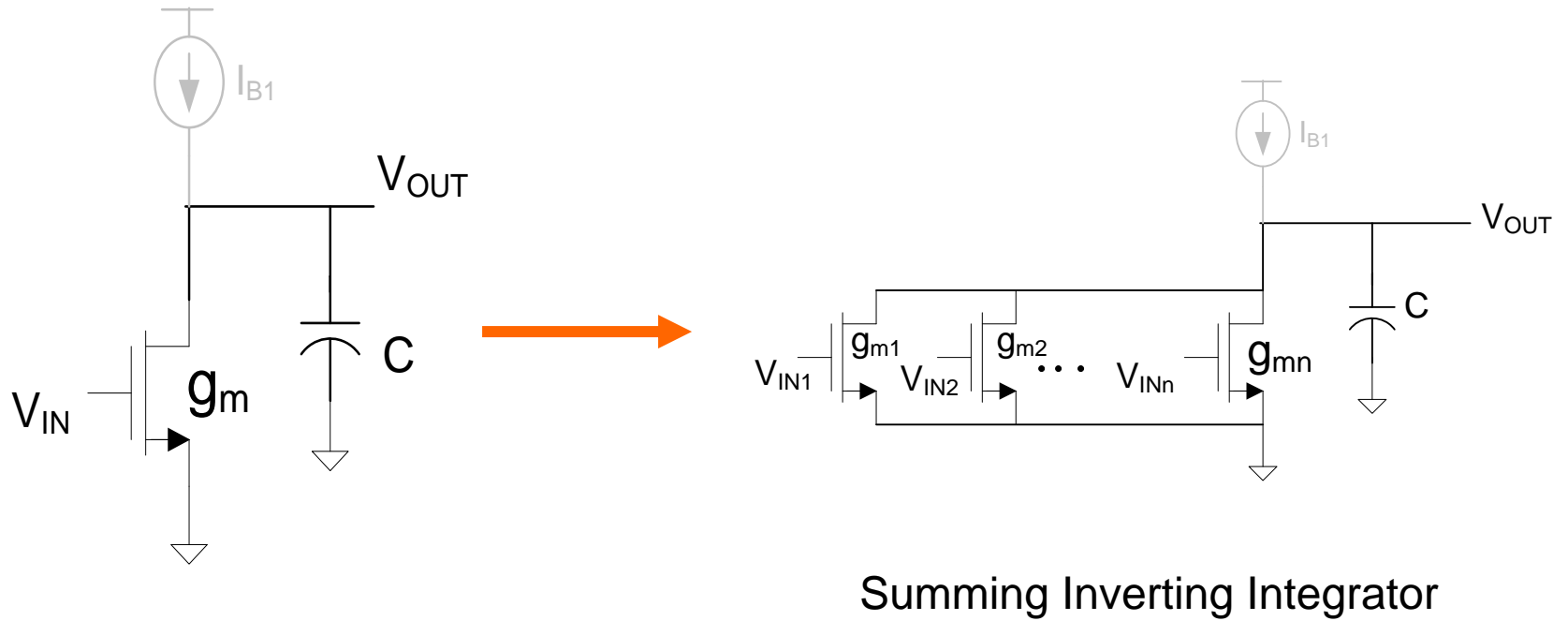
Inverting Integrator



Typically  $M=1$

Alternate noninverting Integrator

# TA-C Voltage Mode Integrator



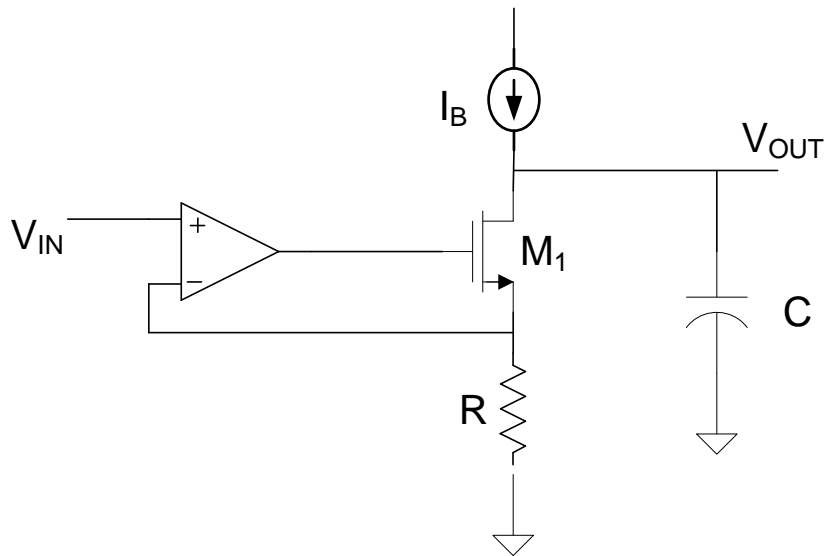
# Voltage Mode Integrators

- Active RC (Feedback-based)
  - MOSFET-C (Feedback-based)
  - OTA-C
  - TA-C
- } Sometimes termed “current mode”

## → Other Continuous-time Structures

- Switched Capacitor
  - Switched Resistor
- } Discrete Time

# Another Voltage Mode Integrator

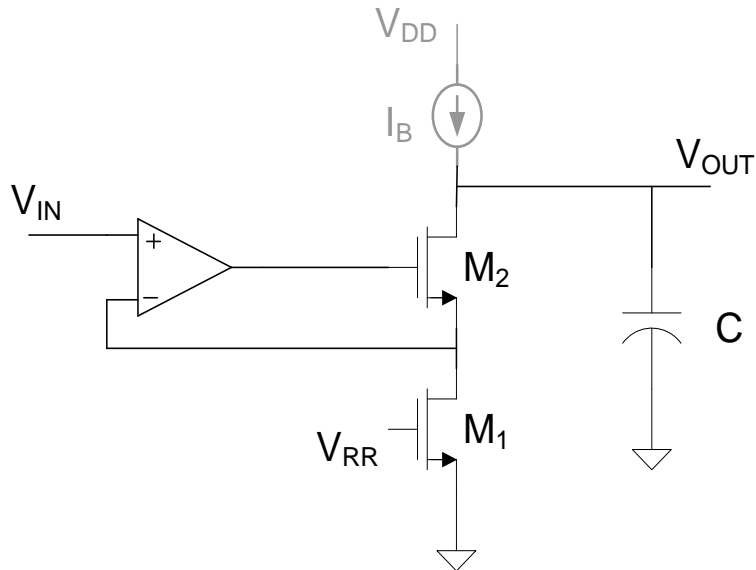


$$V_{OUT} = \left( \frac{-1}{sRC} \right) V_{IN}$$

Inverting Integrator

- **Infinite input impedance (in contrast to basic Active RC Integrator)**
- **Both R and C have one terminal grounded**
- **Requires integrated process**
- **Accuracy limited by process and temperature**
- **Size limitations same as basic Active RC Integrator**
- **Limited to lower frequencies because of Op Amp**
- **Good linearity**

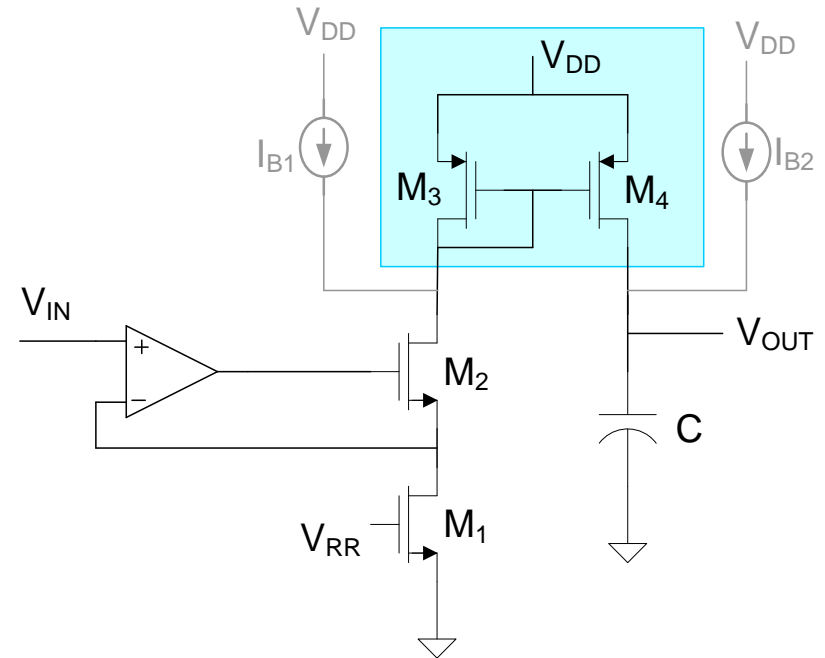
# Another Voltage Mode Integrator



Inverting Integrator

$$V_{OUT} = \left( \frac{-1}{sR_{FET}C} \right) V_{IN}$$

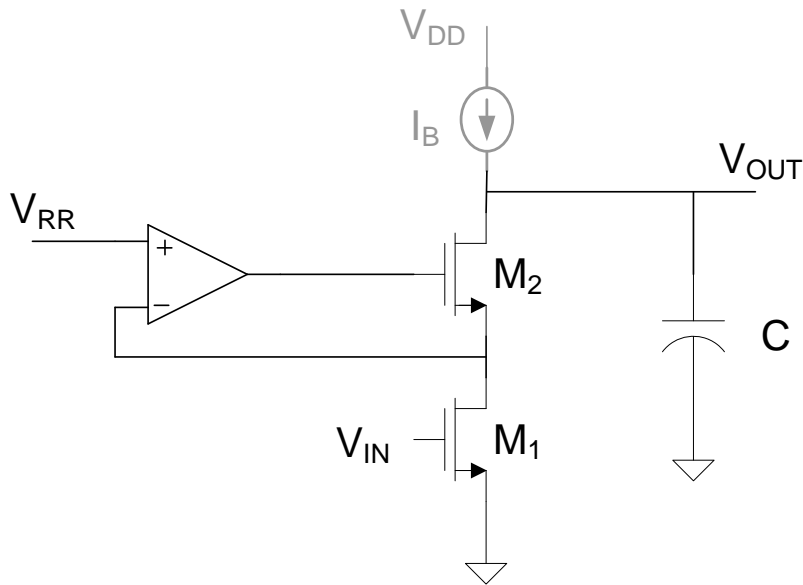
- $M_1$  in triode region
- Reduces Area Concerns but Loss of Linearity
- $I_0$  is programmable with  $V_{RR}$
- Accurate control of  $I_B$  critical



Noninverting Integrator

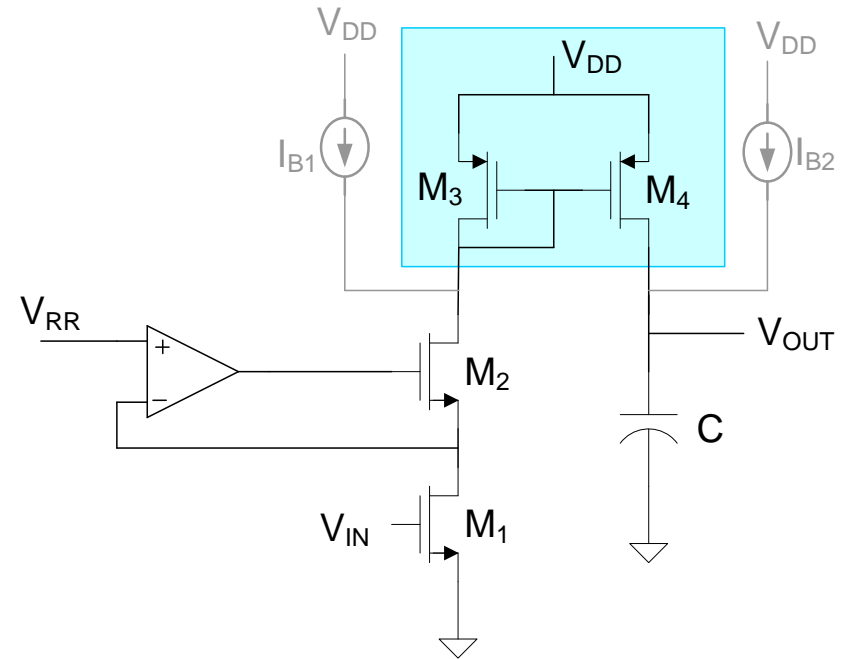
$$V_{OUT} = \left( \frac{1}{sR_{FET}C} \right) V_{IN}$$

# Regulated Cascode Voltage Mode Integrator



Inverting Integrator

$$V_{OUT} = \left( \frac{-g_{mT}}{sC} \right) V_{IN}$$



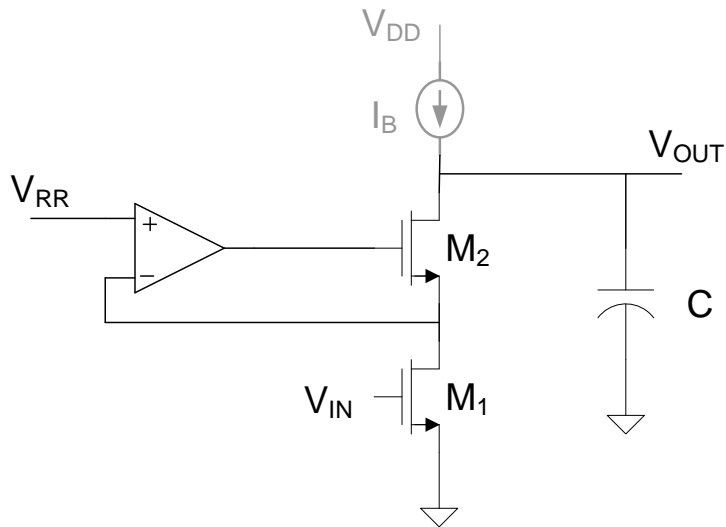
Noninverting Integrator

$$V_{OUT} = \left( \frac{g_{mT}}{sC} \right) V_{IN}$$

$g_{mT}$  is triode region transconductance of  $M_1$

- $M_1$  operating in triode region
- $R_{FET}$  programmable with  $V_{RR}$
- Very good linearity properties
- Input impedance still infinite

# Regulated Cascode Voltage Mode Integrator



$$V_{OUT} = \left( \frac{-g_{mT}}{sC} \right) V_{IN}$$

Linearity Properties:

Assuming square-law triode model

$$I_{D1} = \frac{\mu C_{OX} W}{L} \left( V_{GS} - V_T - \frac{V_{RR}}{2} \right) V_{RR}$$

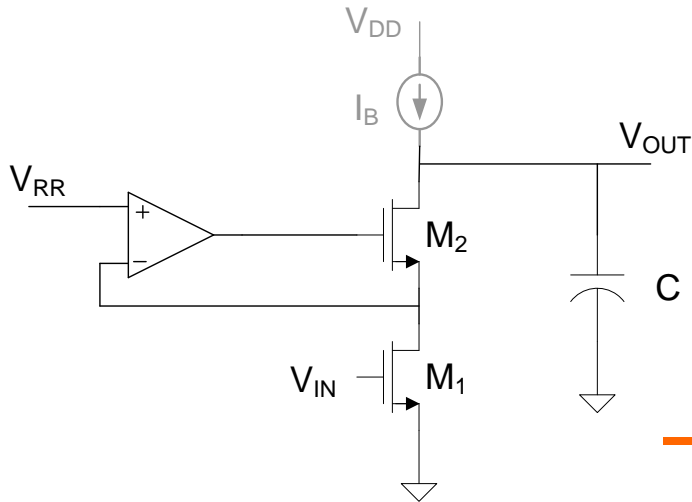
$$I_{D1} = \left[ \frac{\mu C_{OX} W}{L} V_{RR} \right] V_{IN} + \left[ \frac{\mu C_{OX} W}{L} \left( V_T + \frac{V_{RR}}{2} \right) V_{RR} \right]$$

Note linear dependence on  $V_{IN}$

$$g_{mT} = \left[ \frac{L}{\mu C_{OX} W V_{RR}} \right]$$

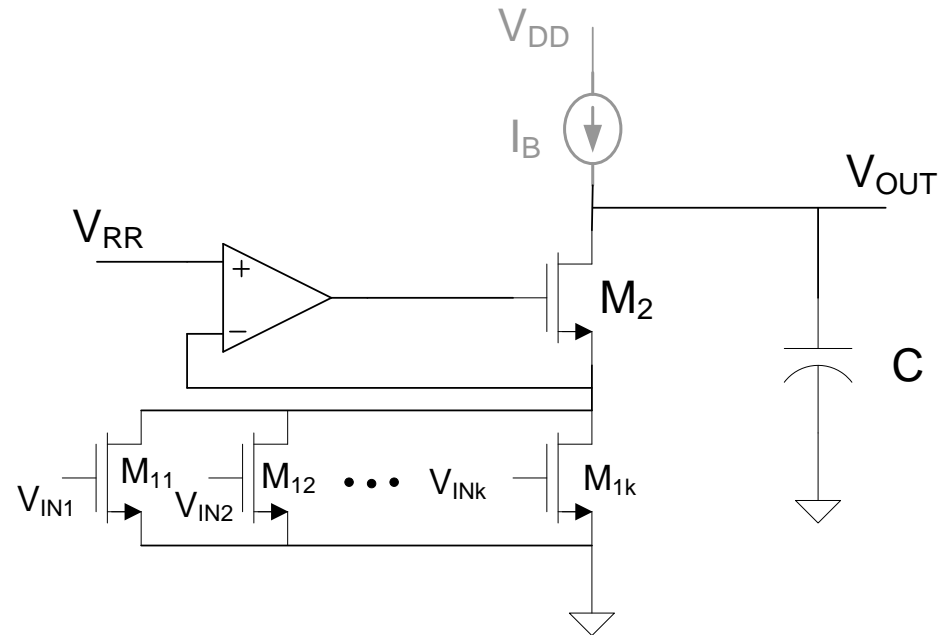


# Regulated Cascode Voltage Mode Integrator



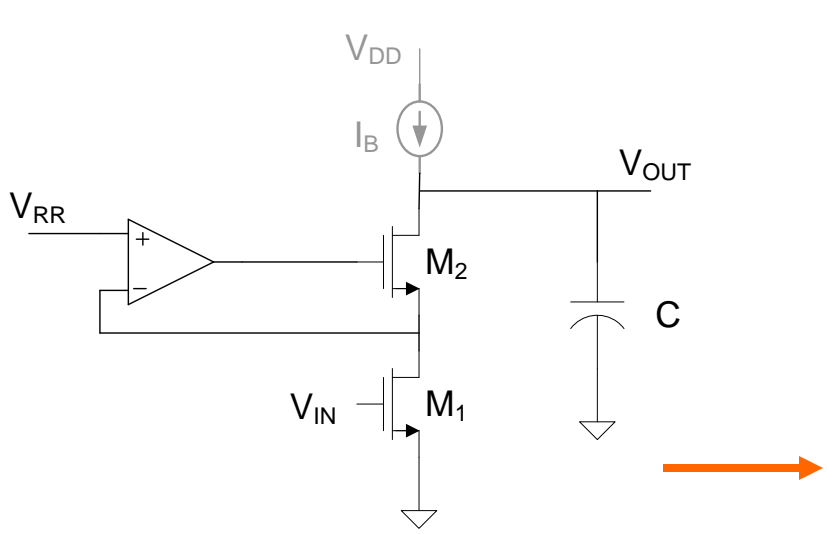
Inverting Integrator

$$V_{OUT} = \left( \frac{-1}{sR_{FET}C} \right) V_{IN}$$



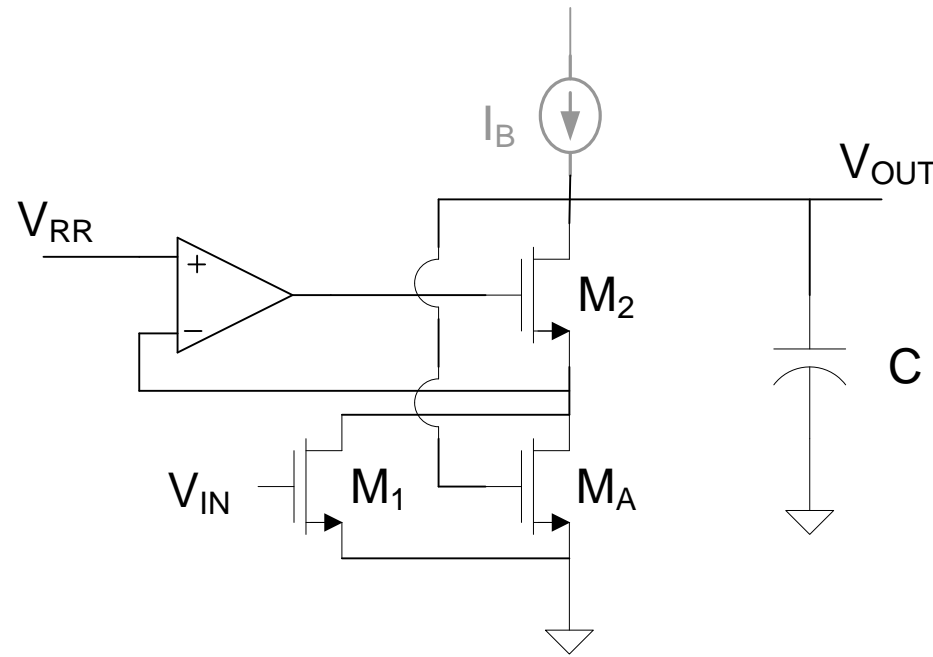
- **Multiple inputs require single additional transistor**
- **Accurate ratioing of gains practical**
- **Can also sum currents on C**

# Regulated Cascode Voltage Mode Integrator



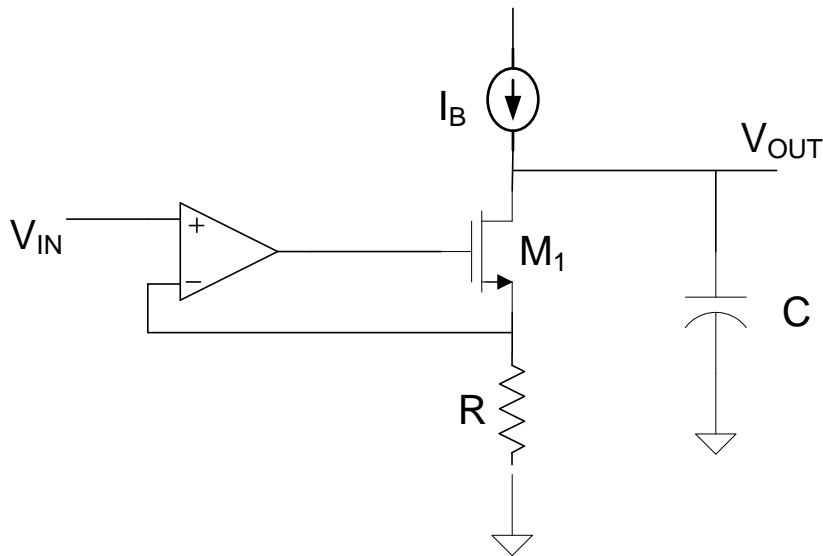
Inverting Integrator

$$V_{OUT} = \left( \frac{-1}{sR_{FET}C} \right) V_{IN}$$



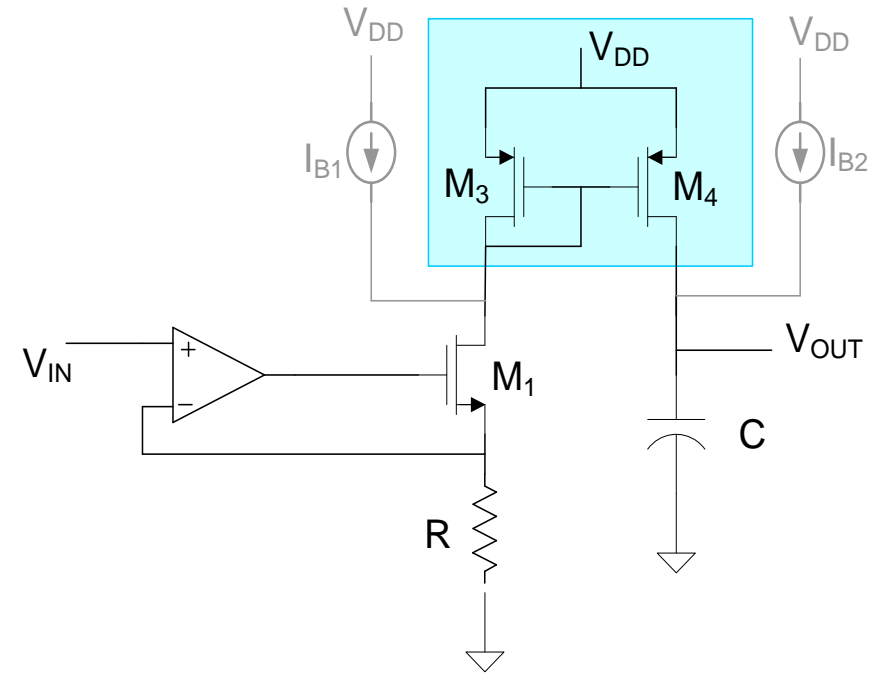
Inverting Lossy Integrator

# Another Voltage Mode Integrator



Inverting Integrator

$$V_{OUT} = \left( \frac{-1}{sRC} \right) V_{IN}$$



Noninverting Integrator

$$V_{OUT} = \left( \frac{1}{sRC} \right) V_{IN}$$



Stay Safe and Stay Healthy !

**End of Lecture 23**