EE 508

Lecture 39

Current Mode Filters

Current-Mode Filters

Current-Mode Filters have become a topic of considerable interest in recent years

Consider first a brief background about filters

Recall:

John Hughes introduced the concept of the switched-current filter in 1989

This was considered a revolutionary concept since it offered potential for operating at very high frequencies with simple amplifiers (current mirrors) but no operational amplifiers. Some properties of Hughes's current-mode filters

1. **Filter parameters dependend only on geometric ratios and clock frequency**
2. **Insensitive to value of parasitic capacitors**
3. **Operates at both low and high frequencies**
4. **Very small**
5. **Can operate at very low voltages (one V_T and one V_{EB} between rails if switches are neglected)**

Others argued that these properties were inherent in the current-mode of operation and that continuous-time structures may perform even better !

A current-conveyor community had been struggling for years to get any adoption and this seemed to propel them to the forefront of the technology field

Literally hundreds of researchers jumped on the current-mode filter bandwagon

Recall:

John Hughes introduced the concept of the switched-current filter in 1989

Hughes has been recognized as a renowned filter design expert for many years and has had the benefits of an industrial research environment to support his work

Update on Hughes Work

Recall the Hughes integrator:

$$H(z) = \frac{B}{1 + Az^{-1}}$$

Hughes found the sensitivity of the parameter A was too large in his original structure to make an acceptable lossless integrator

He made some modifications to this approach to improve the sensitivity problem

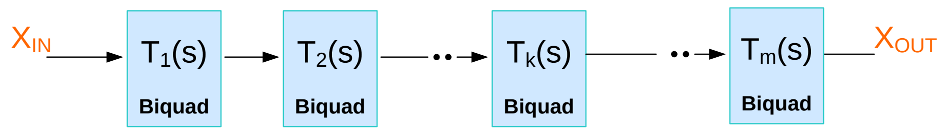
He worked for about another 10 years to develop practical switched-current filters at Phillips but struggled to get good practical experimental results. He retired several years ago

There appears to be little work going on today on the switched-current filter and there appears to be little adoption of the concept

Filter Background

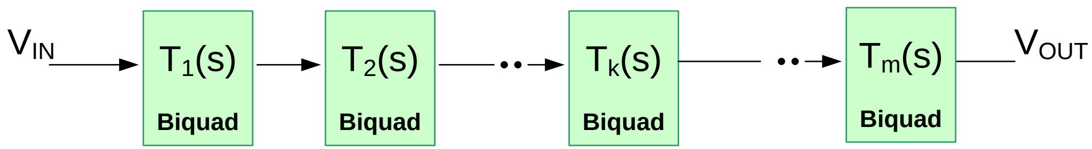
Conventional Wisdom:

- A current-mode filter is a filter where the input and output variables are currents
- A voltage-mode filter is a filter where the input and output variables are voltages



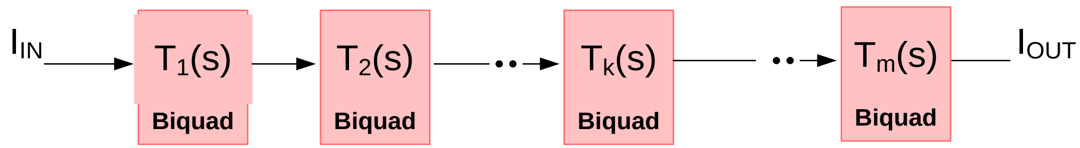
$$T(s) = T_1 T_2 \bullet\bullet T_m$$

Voltage Mode Filter



$$T(s) = \frac{V_{OUT}}{V_{IN}} = T_1 T_2 \bullet\bullet T_m$$

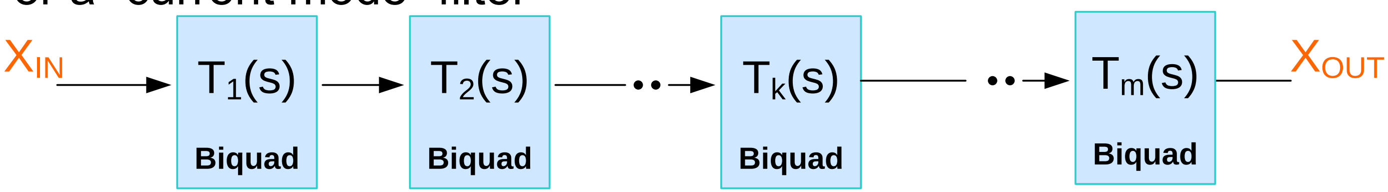
Current Mode Filter



$$T(s) = \frac{I_{OUT}}{I_{IN}} = T_1 T_2 \bullet\bullet T_m$$

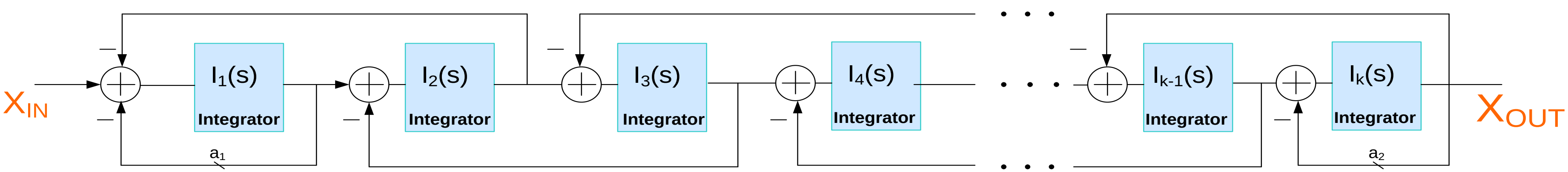
Filter Background

- Most higher-order filters today are built around one of the following architectures
- These basic structures have evolved because of their performance capabilities
  (e.g. sensitivities, component spread, …)
- These basic structures are used irrespective of whether the filter is a “voltage mode” or a “current mode” filter

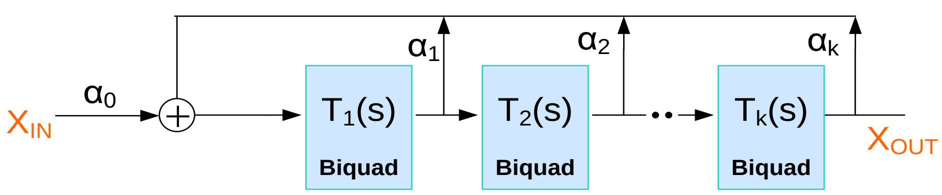


Cascaded Biquad

$$T(s) = T_1 T_2 \bullet\bullet T_m$$



Leapfrog



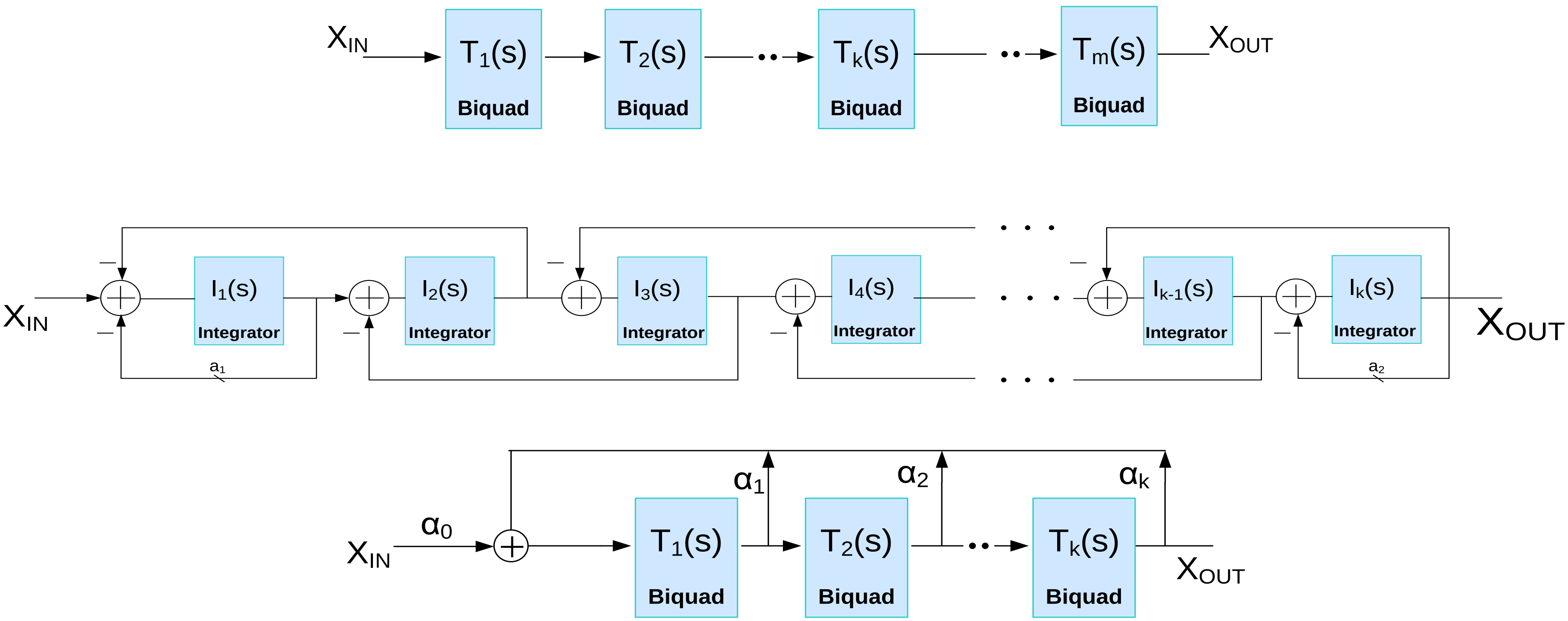
Primary Resonator Block

$$T(s) = \frac{-a_0 T_1 T_2 \bullet\bullet T_k}{1 + a_1 T_1 + a_2 T_1 T_2 + \bullet\bullet + a_k T_1 T_2 \bullet\bullet T_k}$$

$$a_k = \frac{\alpha_F}{\alpha_k}$$

Filter Background

Most filters today, particularly integrated structures, are built with integrators

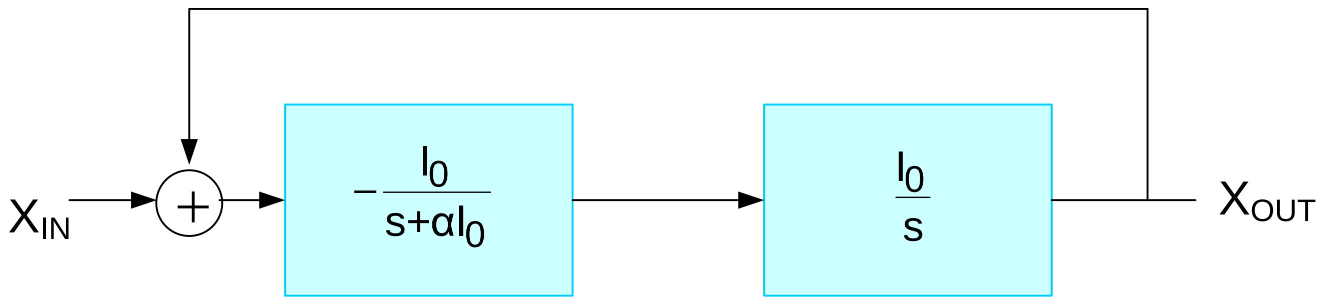


Biquads are usually built with integrators !

Filter Background

Most filters today, particularly integrated structures, are built with integrators

Typical integrator-based biquadratic structure (shown LP only)



$$T(s)=\frac{-I_0^2}{s^2+\alpha I_0 s+I_0^2}$$

Tow-Thomas Biquad

- State Variable Biquad
- Two Integrator Loop

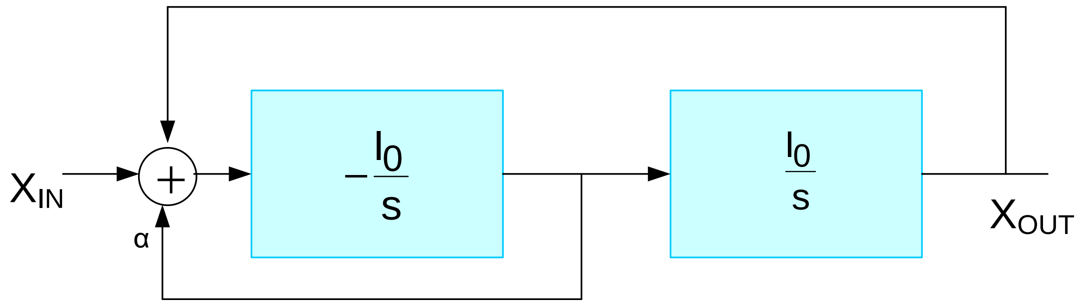
Similar to:

- KHN Biquad
- Lead and Lag in a Loop

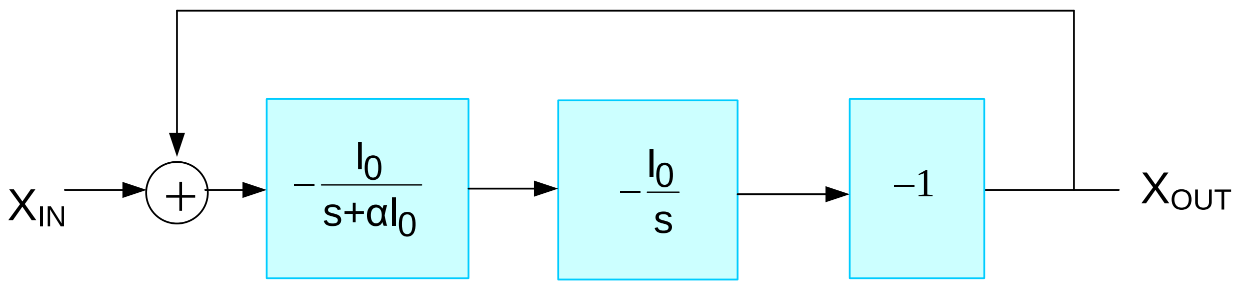
Filter Background

Most filters today, particularly integrated structures, are built with integrators

Variants of two integrator loop



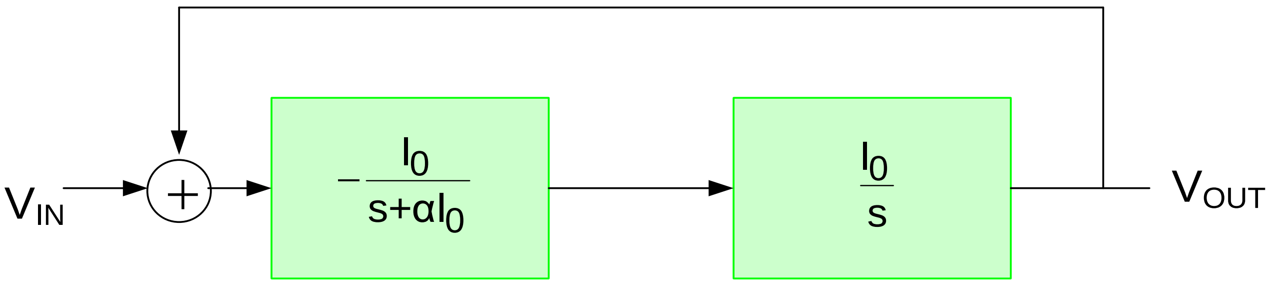
$$T(s)=\frac{-I_0^2}{s^2+\alpha I_0 s+I_0^2}$$



$$T(s)=\frac{-I_0^2}{s^2+\alpha I_0 s+I_0^2}$$

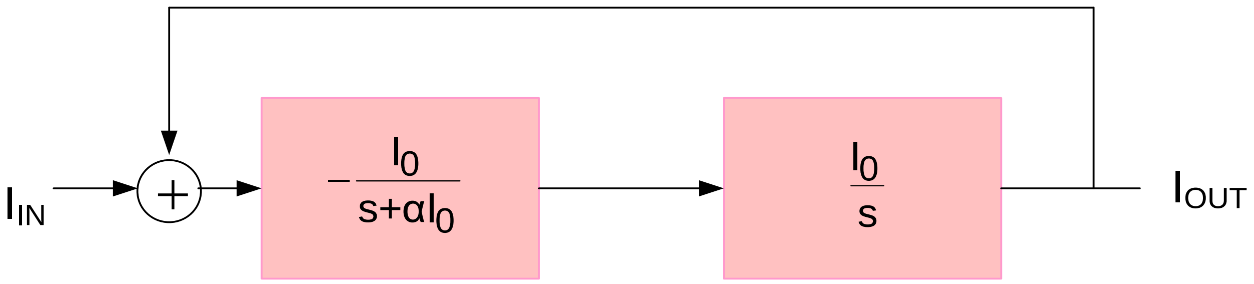
Filter Background

Voltage-Mode Biquad



$$T(s) = \frac{V_{OUT}}{V_{IN}} = \frac{-I_0^2}{s^2+\alpha I_0 s+I_0^2}$$

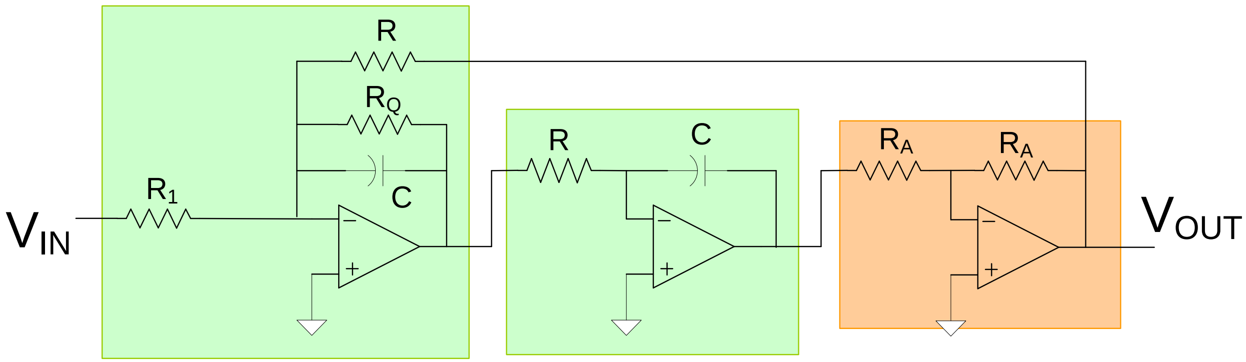
Current-Mode Biquad



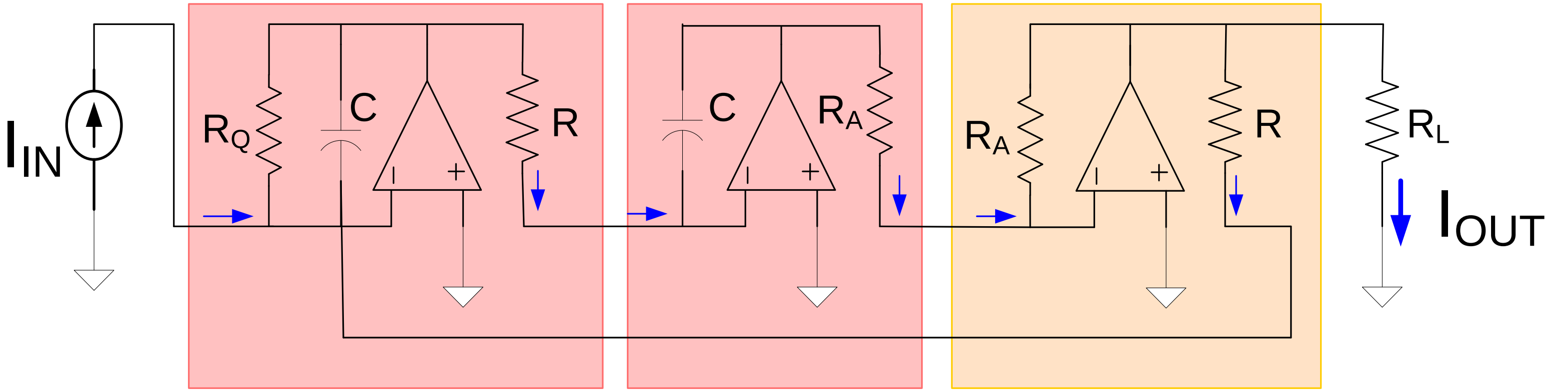
$$T(s) = \frac{I_{OUT}}{I_{IN}} = \frac{-I_0^2}{s^2+\alpha I_0 s+I_0^2}$$

Filter Background

Voltage-Mode Biquad

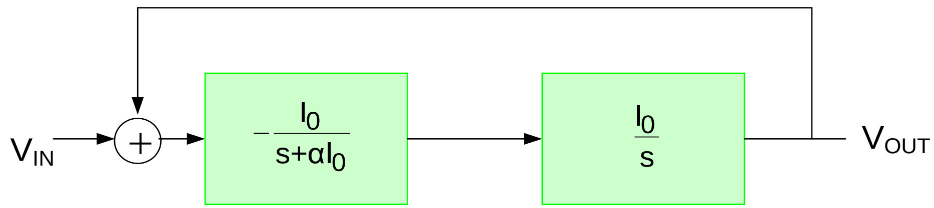


Current-Mode Biquad

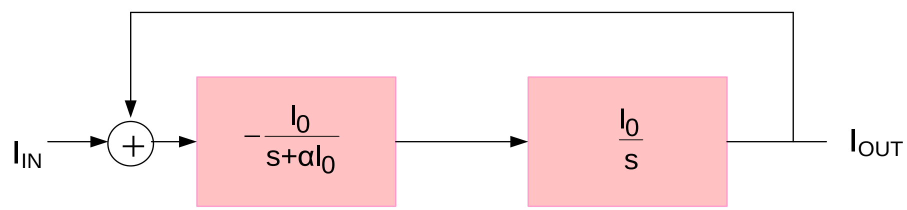


Notice considerable differences in the circuit-level implementations

Filter Background



$$T(s) = \frac{V_{OUT}}{V_{IN}} = \frac{-I_0^2}{s^2 + \alpha I_0 s + I_0^2}$$

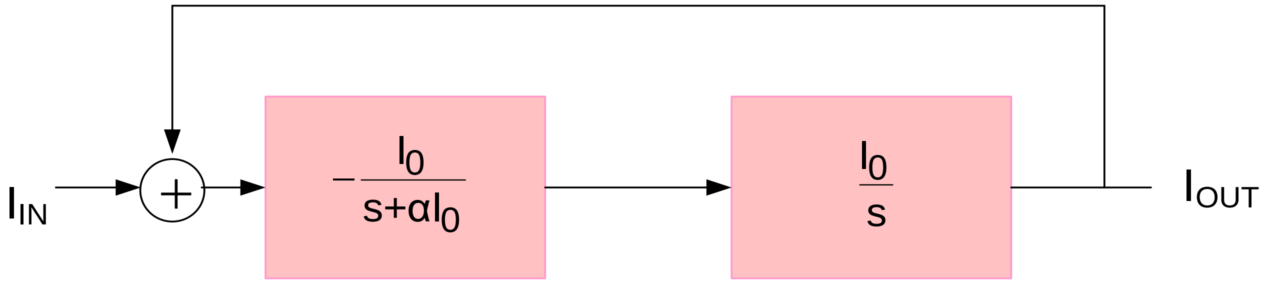


$$T(s) = \frac{I_{OUT}}{I_{IN}} = \frac{-I_0^2}{s^2 + \alpha I_0 s + I_0^2}$$

Observations:

- Structures for voltage mode and current mode Integrators are often the same
- Structures for voltage mode and current mode filters are often the same
- Circuit-level implementations appear to be quite different

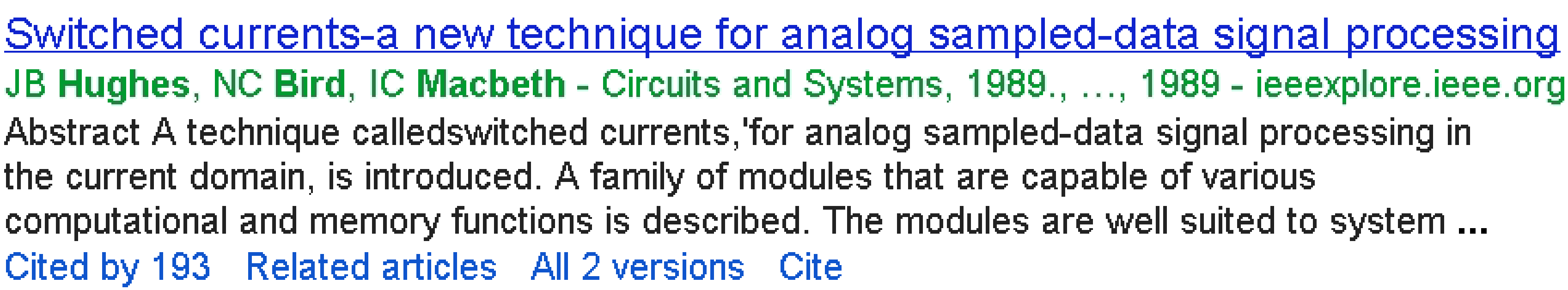
Current-Mode Filters



$$T(s)=\frac{I_{OUT}}{I_{IN}}=\frac{-I_0^2}{s^2+\alpha I_0 s+I_0^2}$$

Concept of Current-Mode Filters is Somewhat Recent:

Key paper that generated interest in current-mode filters:



Switched currents-a new technique for analog sampled-data signal processing

JB **Hughes**, NC **Bird**, IC **Macbeth** - Circuits and Systems, 1989., …, 1989 - ieeexplore.ieee.org

Abstract A technique calledswitched currents,'for analog sampled-data signal processing in the current domain, is introduced. A family of modules that are capable of various computational and memory functions is described. The modules are well suited to system **...**

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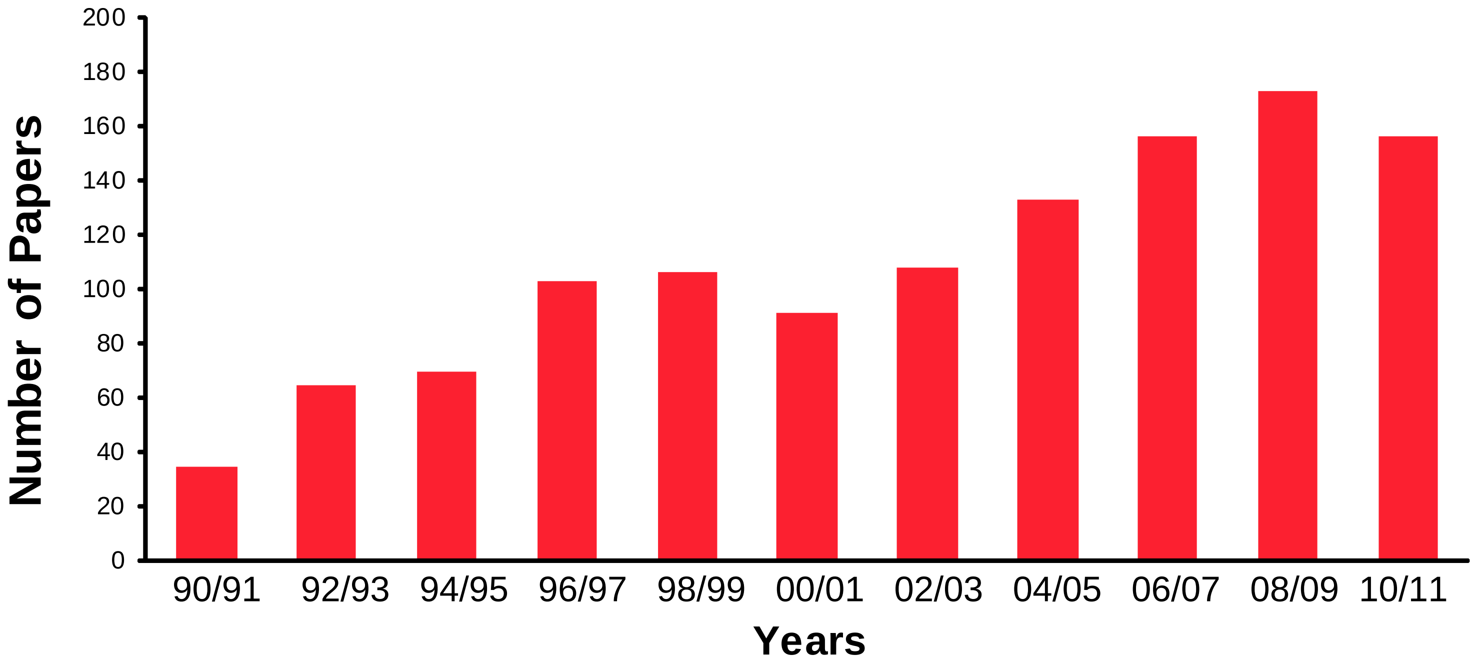
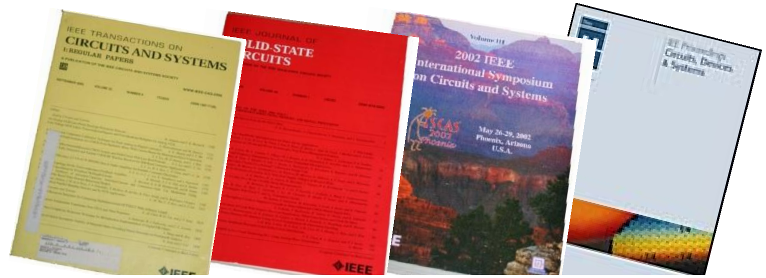
Current-Mode Filters

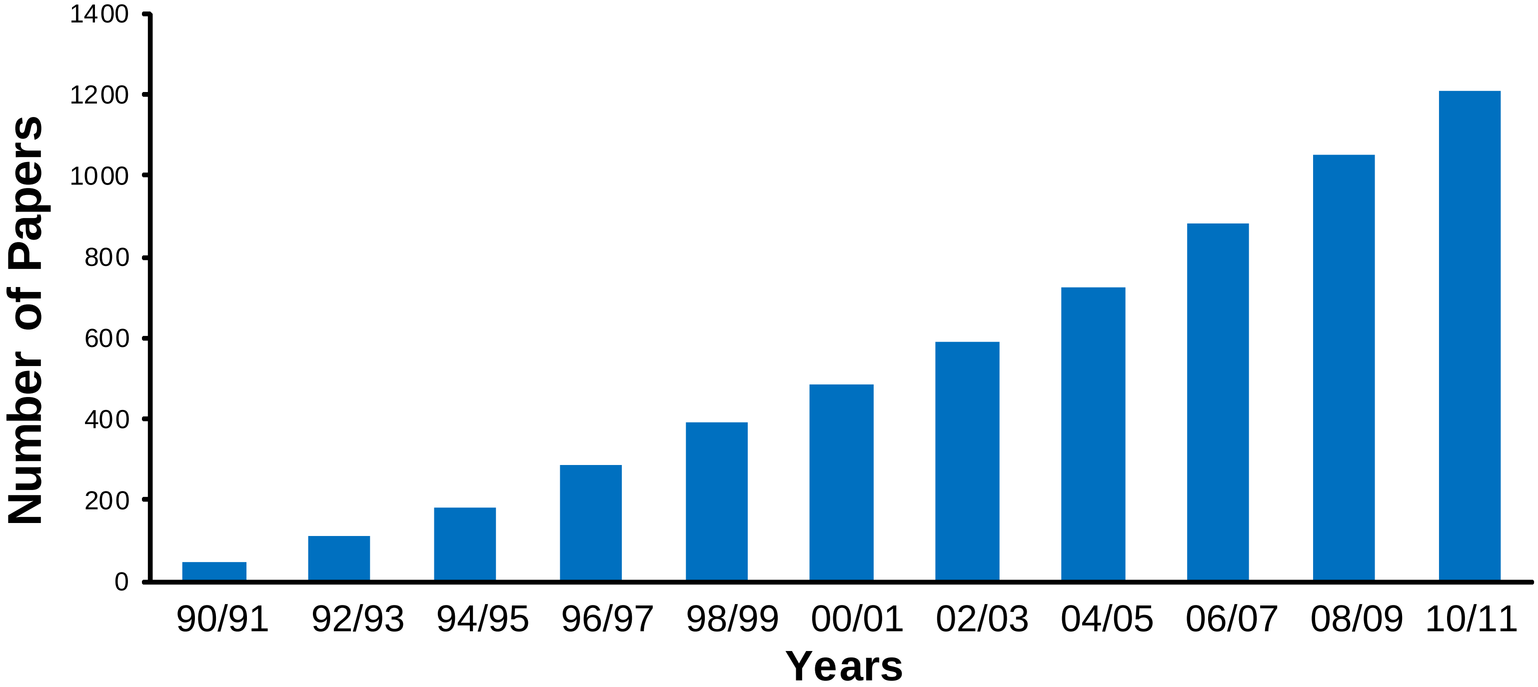
Advanced Search for “current-mode” and “filters” in Metadata



Updated Nov 22, 2012

Current-Mode Filters





Steady growth in research in the area since 1990 and publication rate is growing with time !!

Updated Nov 22, 2012

Current-Mode Filters

The Conventional Wisdom:

TSP 2012:

RECENTLY, current-mode circuits have been receiving considerable attention due to their potential advantages such as inherently wide bandwidth, higher slew-rate, greater linearity, wider dynamic range, simpler circuitry and lower power consumption [1].

CECNet 2012

In analog circuit design, many researches have been performed on current-mode active filters using different active elements [1–22]. The use of current-mode active devices has many other advantages such as larger dynamic, higher bandwidth, greater linearity, simple circuitry and low power consumption compared to that of voltage-mode counterparts for example operational amplifiers [1–2].

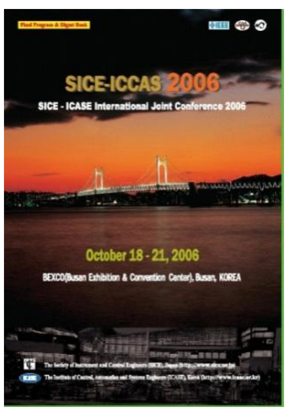
Current-Mode Filters

The Conventional Wisdom:

Proc. IEE Dec 2006:

1 Introduction

Current-mode circuits have been proven to offer advantages over their voltage-mode counterparts [1, 2]. They possess wider bandwidth, greater linearity and wider dynamic range. Since the dynamic range of the analogue circuits using low-voltage power supplies will be low, this problem can be solved by employing current-mode operation.



Proc. SICE-ICASE, Oct. 2006

1. INTRODUCTION

It is well known that current-mode circuits have been receiving significant attention owing to its advantage over the voltage-mode counterpart, particularly for higher frequency of operation and simpler filtering structure [1].

Current-Mode Filters

The Conventional Wisdom:

JSC April 1998:

"… current-mode functions exhibit higher frequency potential, simpler architectures, and lower supply voltage capabilities than their voltage-mode counterparts."

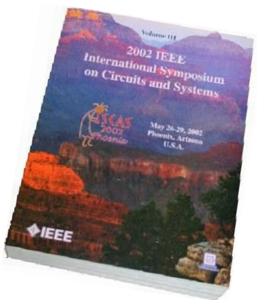
CAS June 1992

"Current-mode signal processing is a very attractive approach due to the simplicity in implementing operations such as … and the potential to operate at higher signal bandwidths than their voltage mode analogues" … "Some voltage-mode filter architectures using transconductance amplifiers and capacitors (TAC) have the drawback that …"

Current-Mode Filters

The Conventional Wisdom:

ISCAS 1993:

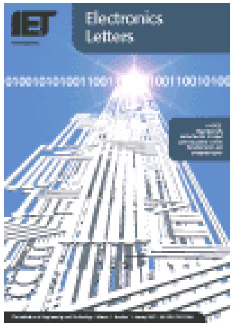


"In this paper we propose a fully balanced high frequency current-mode integrator for low voltage high frequency filters. Our use of the term current mode comes from the use of current amplifiers as the basic building block for signal processing circuits. This fully differential integrator offers significant improvement even over recently introduced circuit with respect to accuracy, high frequency response, linearity and power supply requirements. Furthermore, it is well suited to standard digital based CMOS processes."

Current-Mode Filters

The Conventional Wisdom:

Two key publications where benefits of the current-mode circuits are often referenced:



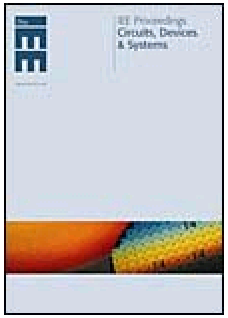
All current-mode frequency selective circuits **GW Roberts**, AS **Sedra** - Electronics Letters, June 1989 - pp. 759-761 Cited by 161

"To make greatest use of the available transistor bandwidth $\boldsymbol{f_T}$ **,** and operate at low voltage supply levels, it has become apparent that analogue signal processing can greatly benefit from processing current signals rather than voltage signals. Besides this, it is well known by electronic circuit designers that the mathematical operations of adding, subtracting or multiplying signals represented by currents are simpler to perform than when they are represented by voltages. This also means that the resulting circuits are simpler and require less silicon area."

Current-Mode Filters

The Conventional Wisdom:

Two key publications where benefits of the current-mode circuits are often referenced:



Recent developments in **current** conveyors and **current**-mode circuits **B Wilson** - Circuits, Devices and Systems, IEE Proceedings G, pp. 63-77, Apr. 1990 Cited by 203

"The **use** of current rather than voltage as the active parameter can result in higher usable gain, accuracy and bandwidth due to reduced voltage excursion at sensitive nodes. A current-mode approach is not just restricted to current processing, but also offers certain important advantages when interfaced to voltage-mode circuits."

Current-Mode Filters

Conventional Wisdom:

- Current-Mode filters operate at higher-frequencies than voltage-mode counterparts
- Current-Mode filters operate at lower supply voltages and lower power levels than voltage-mode counterparts
- Current-Mode filters are simpler than voltage-mode counterparts
- Current-Mode filters offer better linearity than voltage-mode counterparts
- Integrated Current-Mode filters require less area

Observation

- Many papers have appeared that tout the performance advantages of current-mode circuits
- In all of the current-mode papers that this author has seen, no attempt is made to provide a quantitative comparison of the key performance features of current-mode circuits with voltage-mode counterparts
- All justifications of the advantages of the current-mode circuits this author has seen are based upon qualitative statements

Observations (cont.)

- In selected comparisons this author has made, performance characteristics of current-mode filters do not appear to be substantially better than those reported for “other” approaches
- It appears easy to get papers published that have the term “current-mode” in the title
- Over 1200 papers have been published in IEEE forums alone !

Research Opportunity (for academia)

- Provide a formal justification of the high frequency, low voltage and low power benefits of current-mode circuits
- Gain insight into how these benefits can be further exploited
- Sounds like a simple problem

Questions about the Conventional Wisdom

- Why does a current-mode circuit work better at high frequencies?
- Why is a current-mode circuit better suited for low frequencies?
- Why do some “voltage”-mode circuits have specs that are as good as the current-mode circuits?

Questions about the Conventional Wisdom

- Why are most of the papers on current-mode circuits coming from academia?
- Why haven’t current-mode circuits replaced “voltage”-mode circuits in industrial applications?

Questions about the Conventional Wisdom

- Are current-mode circuits really better than their “voltage-mode” counterparts?

- What is a current-mode circuit?
  – Must have a simple answer since so many authors use the term

- Do all agree on the definition of a current-mode circuit?

Questions about the Conventional Wisdom

What is a current-mode circuit?

- Everybody seems to know what it is

- Few have tried to define it

- Is a current-mode circuit not a voltage-mode circuit?

Questions about the Conventional Wisdom

What is a current-mode circuit?

"Several analog CMOS continuous-time filters for high frequency applications have been reported in the literature… Most of these filters were designed to process voltage signals. It results in high voltage power supply and large power dissipation. To overcome these drawbacks of the voltage-mode filters, the current-mode filters circuits , which process current signals have been developed"

A **3V-50MHz Analog CMOS Current-Mode High Frequency Filter with a Negative Resistance Load**, pp. 260…,,IEEE Great Lakes Symposium March 1996.

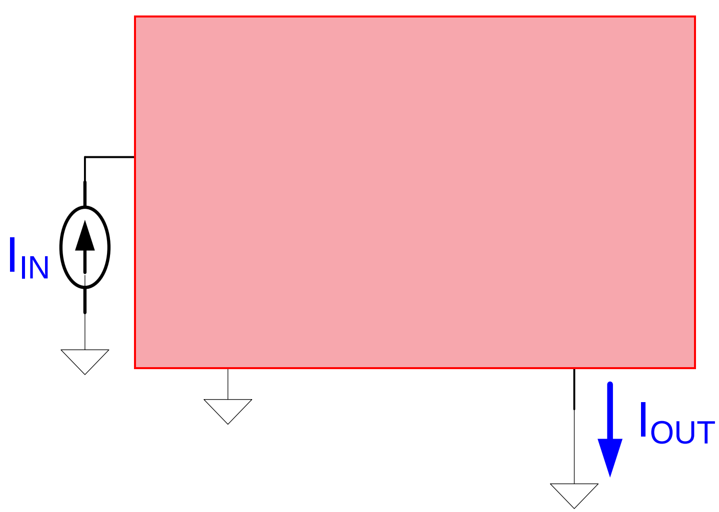
Questions about the Conventional Wisdom

Conventional Wisdom Definition:

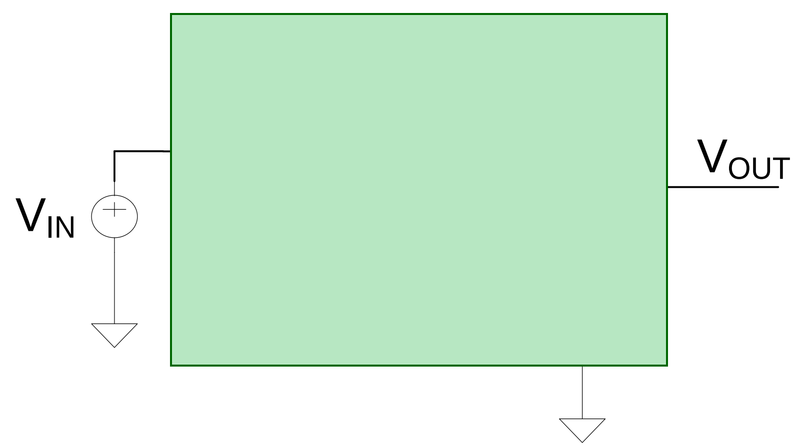
- A current-mode circuit is a circuit that processes current signals
- A current-mode circuit is one in which the defined state variables are currents

Example:

Is this a current-mode circuit?



Is this a voltage-mode circuit?

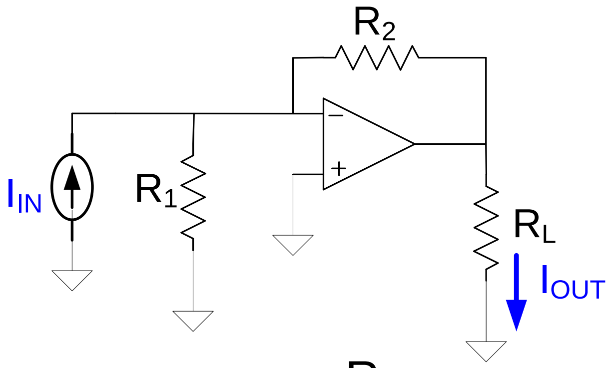


Conventional Wisdom Definition:

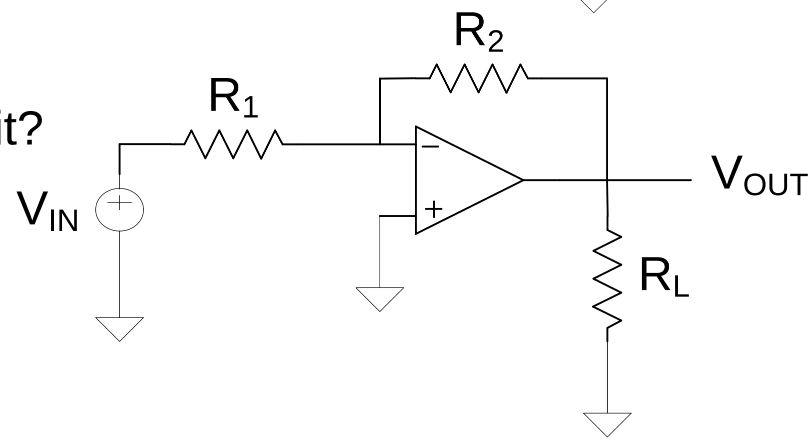
A current-mode circuit is a circuit that processes current signals

Example:

Is this a current-mode circuit?



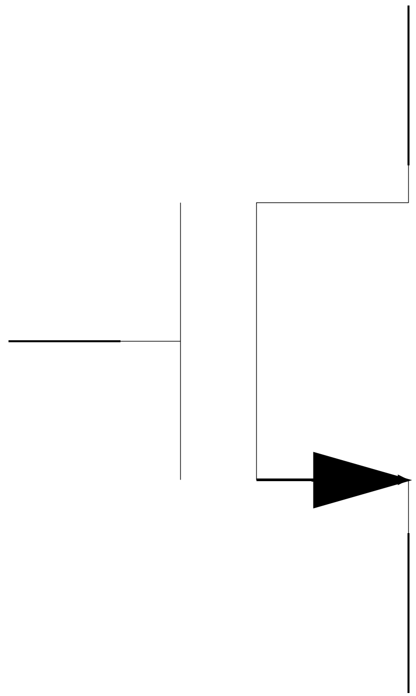
Is this a voltage-mode circuit?



- One is obtained from the other by a Norton to Thevenin Transformation
- **The poles and the BW of the two circuits are identical !**

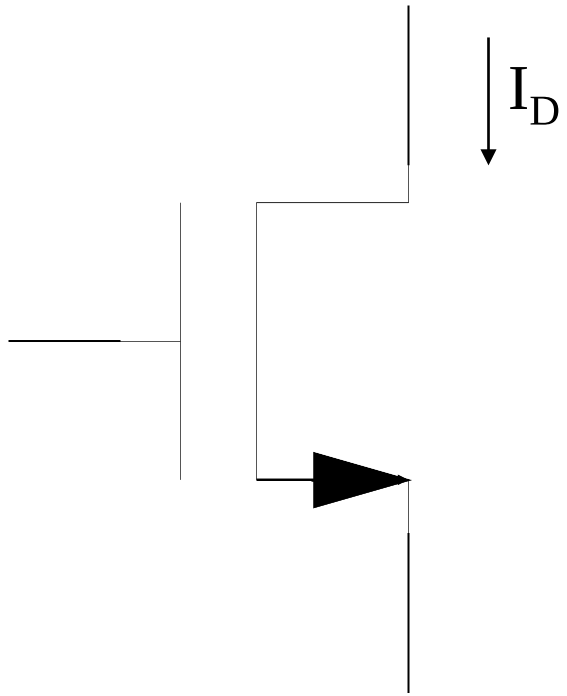
Question?

Is the following circuit a voltage mode-circuit or a current-mode circuit?



Question?

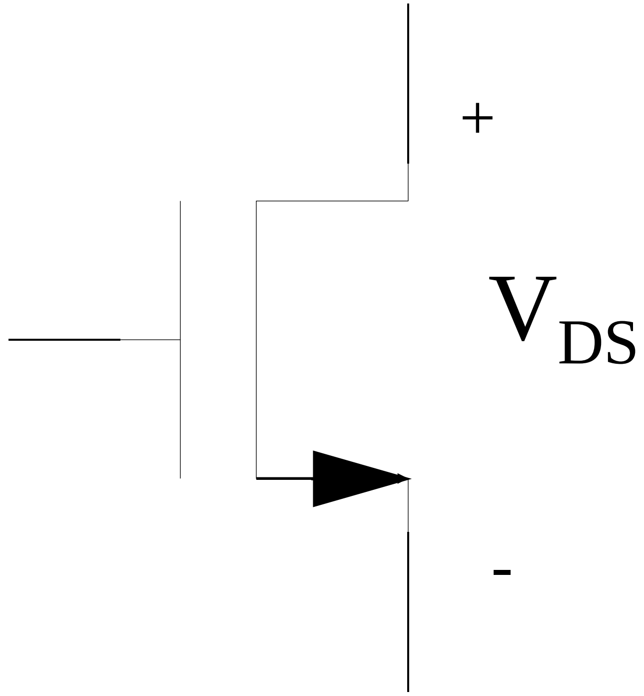
Is the following circuit a voltage mode-circuit or a current-mode circuit?



Current Mode !

Question?

Is the following circuit a voltage mode-circuit or a current-mode circuit?



Voltage Mode !

Observations:

- Voltage-Mode or Current-Mode Operation of a Given Circuit is not Obvious
- All electronic devices have a voltage-current relationship between the port variables that characterizes the device
- The “solution” of all circuits is identical independent of whether voltages or currents are used as the state variables
- The poles of any circuit are independent of whether the variables identified for analysis are currents or voltages or a mixture of the two

Questions about the Conventional Wisdom

Is it possible that there are really no benefits from frequency response, supply voltage and power dissipation viewpoints for "current-mode" circuits?

JSC April 1998:

"… current-mode functions exhibit higher frequency potential, simpler architectures, and lower supply voltage capabilities than their voltage-mode counterparts."

Questions about the Conventional Wisdom

Is it possible that there are really no benefits from a frequency response, supply voltage and power dissipation viewpoints for "current-mode" circuits?

Observation: If any so-called current-mode circuit is analyzed using voltages as the port variables, the poles, sensitivities, frequency response, power dissipation, supply voltage requirements and the power dissipation will all be the same!

Questions about the Conventional Wisdom

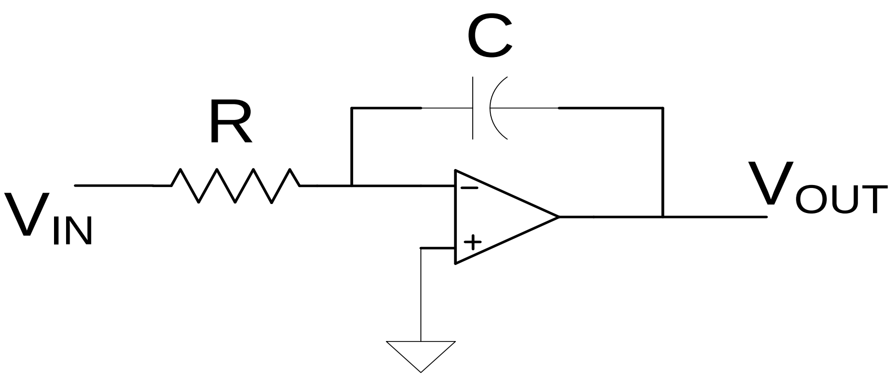
Since a given structure can be implemented with either current-mode or voltage-mode circuits, is there a fundamental relationship between the performance of so-called current-mode circuits and their “voltage-mode” counterparts?

Comparison of Continuous-Time Current-Mode and Voltage-Mode Filters

- Current-Mode and Voltage-Mode Integrators
  - Op-amp based current-mode and voltage-mode integrators
  - $g_m C$ current-mode and voltage-mode integrators
  - High frequency current-mode and voltage-mode integrators
- Structure Comparisons
  - Two integrator loop filters
  - Leapfrog filters

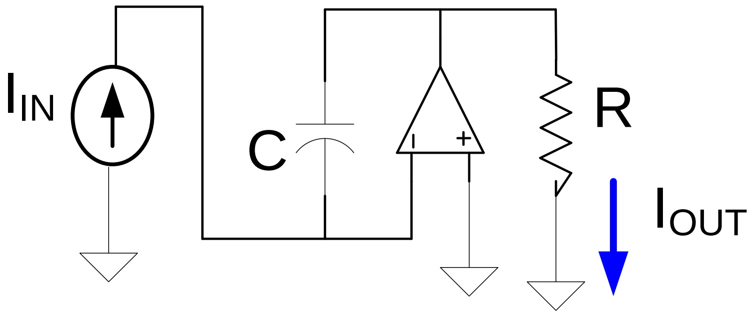
Basic Feedback Inverting Integrators

Voltage-Mode



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

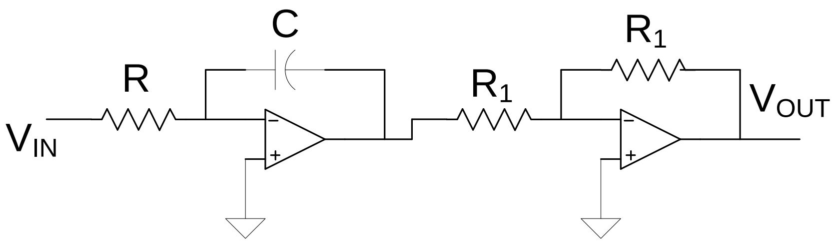
Current-Mode



$$\frac{I_{OUT}}{I_{IN}} = -\frac{1}{sRC}$$

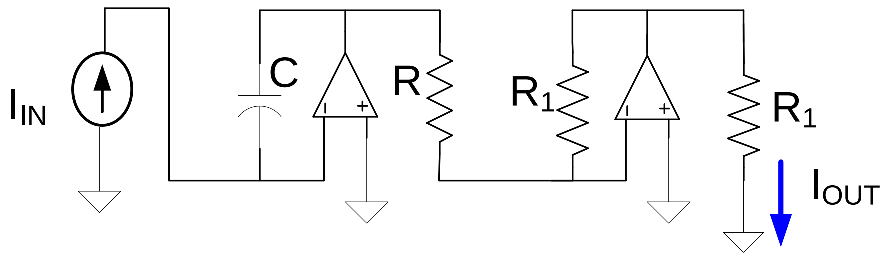
Basic Feedback Non-Inverting Integrators

Voltage-Mode



$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{sRC}$$

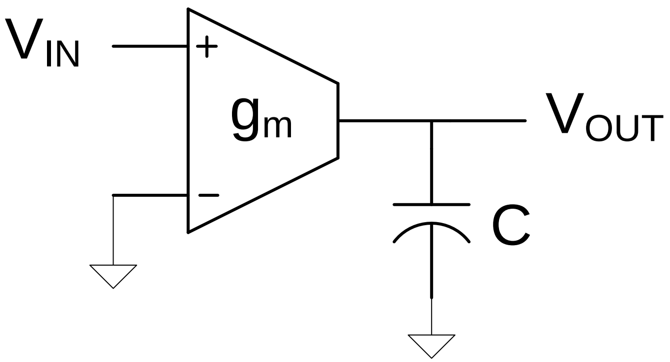
Current-Mode



$$\frac{I_{OUT}}{I_{IN}} = \frac{1}{sRC}$$

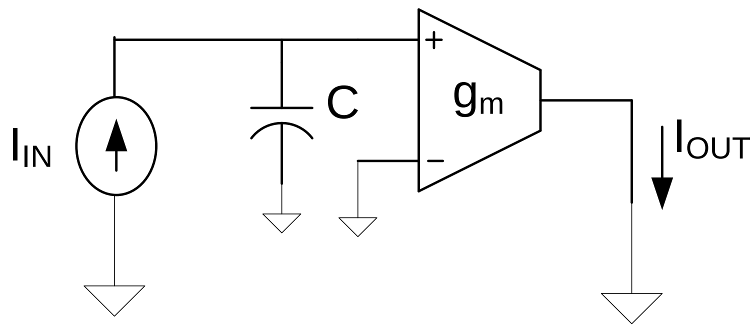
Basic OL Non-Inverting Integrators

Voltage-Mode



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

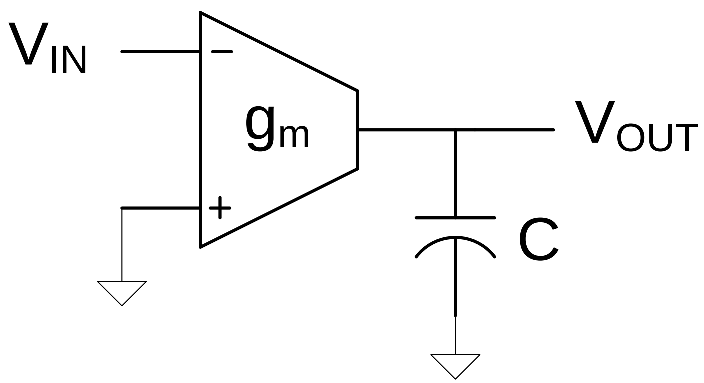
Current-Mode



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

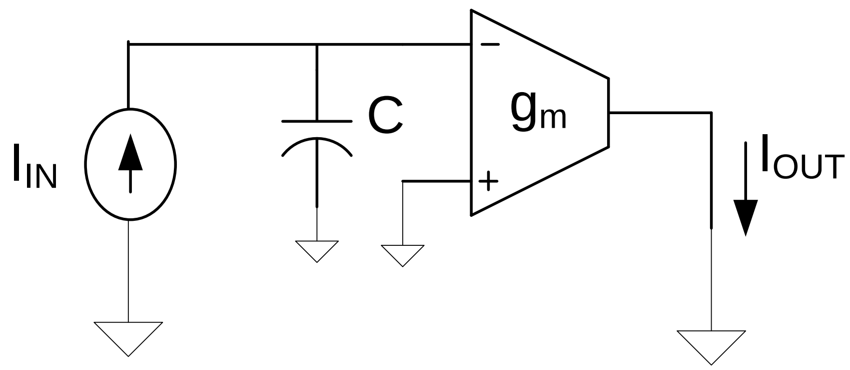
Basic OL Inverting Integrators

Voltage-Mode



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

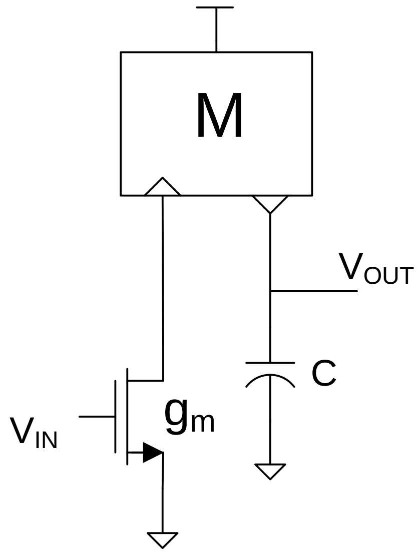
Current-Mode



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

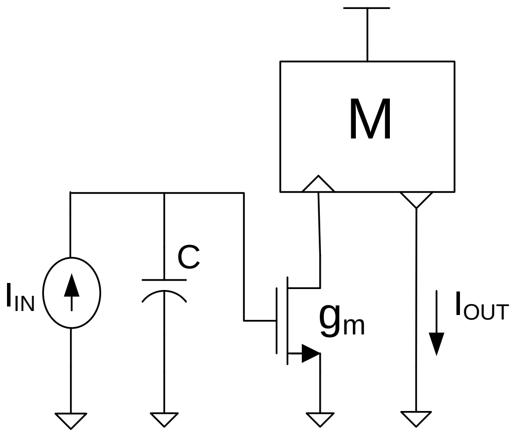
High-Frequency Non-Inverting Integrators

Voltage-Mode



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

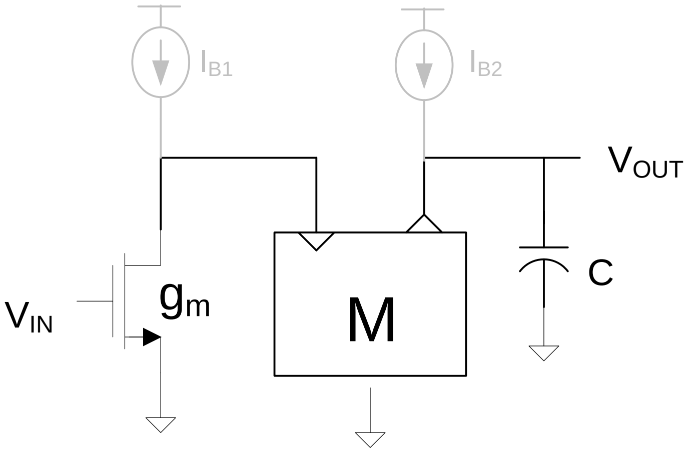
Current-Mode



$$\frac{I_{OUT}}{I_{IN}} = \frac{M \bullet g_m}{sC}$$

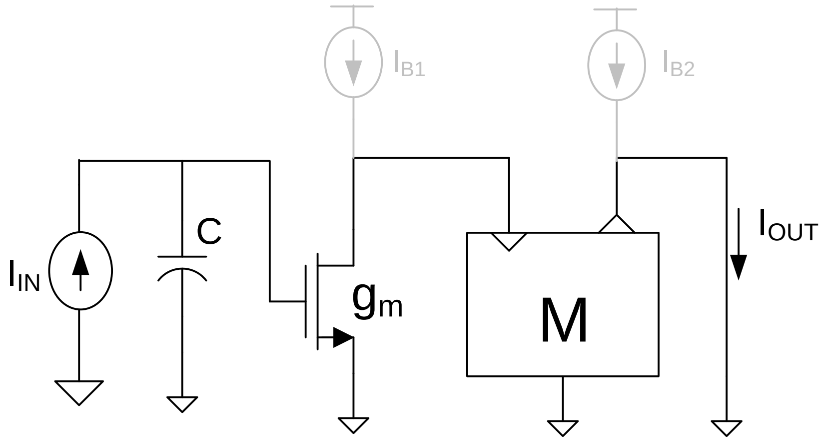
High-Frequency Non-Inverting Integrators

Voltage-Mode



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

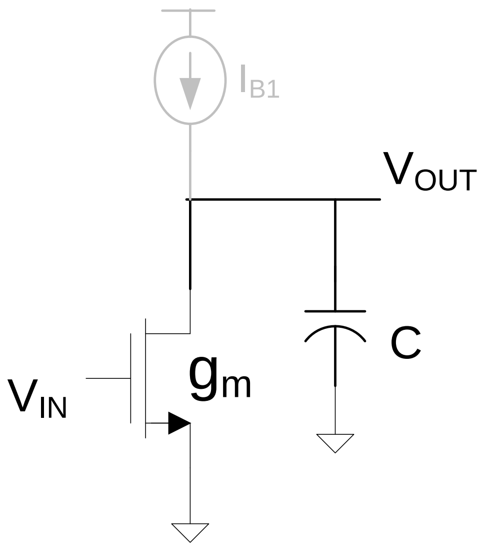
Current-Mode



$$\frac{I_{OUT}}{I_{IN}} = \frac{M \bullet g_m}{sC}$$

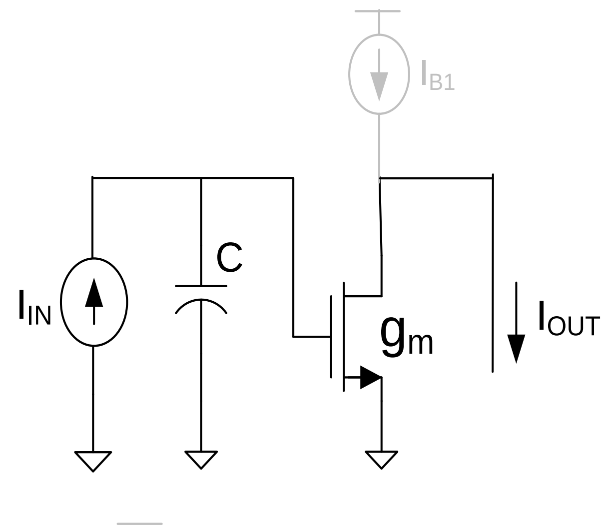
High-Frequency Inverting Integrators

Voltage-Mode



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

Current-Mode

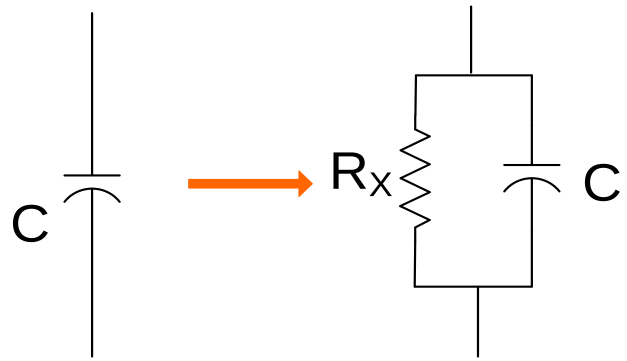


$$\frac{I_{OUT}}{I_{IN}} = \frac{-g_m}{sC}$$

Lossy Integrators

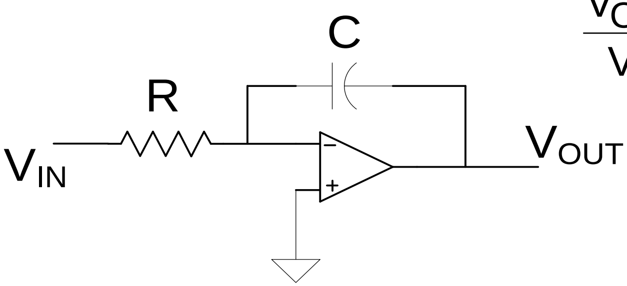
Well-known Property:

All voltage-mode and current-mode integrators can be made lossy by placing a resistor in shunt with the capacitor

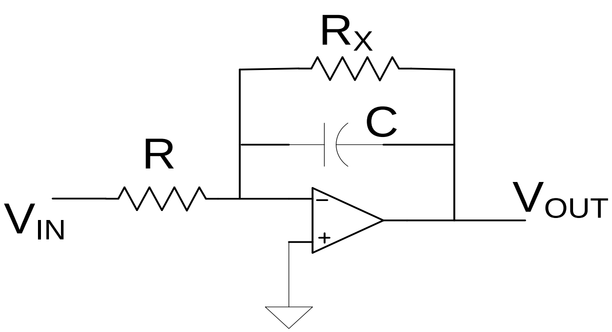


Basic Feedback Lossy Inverting Integrators

Voltage-Mode

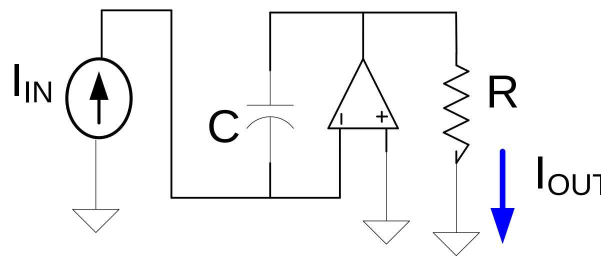


$$\frac{V_{OUT}}{V_{IN}} = -\frac{1}{sRC}$$

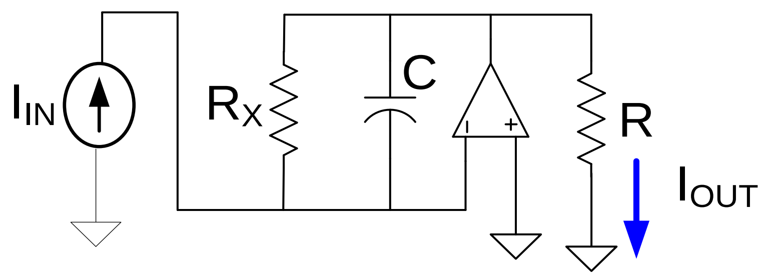


$$\frac{V_{OUT}}{V_{IN}} = -\frac{1}{sRC + R/R_X}$$

Current-Mode



$$\frac{I_{OUT}}{I_{IN}} = -\frac{1}{sRC}$$



$$\frac{I_{OUT}}{I_{IN}} = -\frac{1}{sRC + R/R_X}$$

Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?

A fair comparison should be within a common structure and with a common integrator type

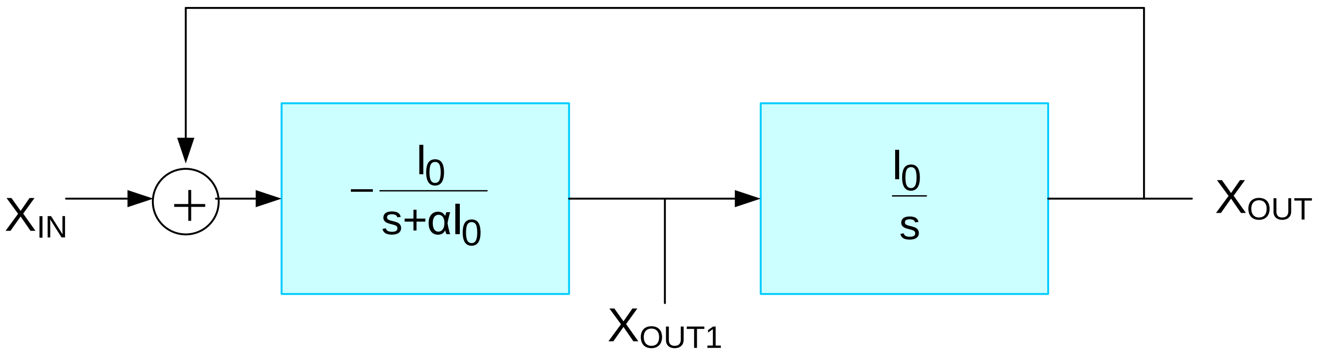
Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?

Will compare the filter performance of

- a two-integrator loop biquad
- a leapfrog filter

Two-Integrator-Loop Biquad



"Integrator and Lossy Integrator in a Loop"

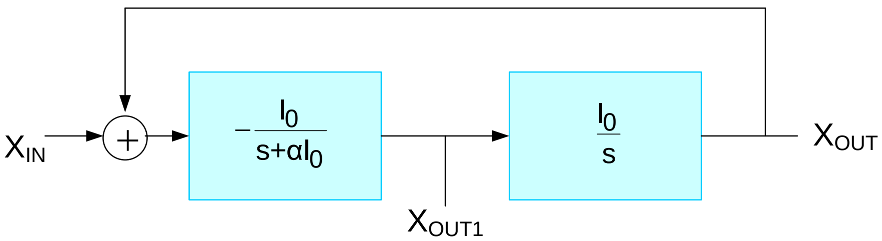
Lowpass output to X_{OUT}

$$T(s) = \frac{-I_0^2}{s^2 + \alpha I_0 s + I_0^2}$$

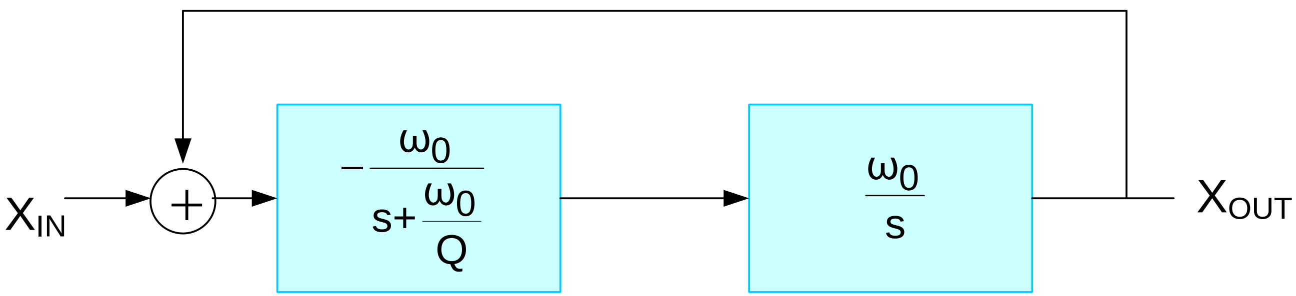
Bandass output to X_{OUT1}

$$T_1(s) = \frac{-sI_0}{s^2 + \alpha I_0 s + I_0^2}$$

Two-Integrator-Loop Biquad



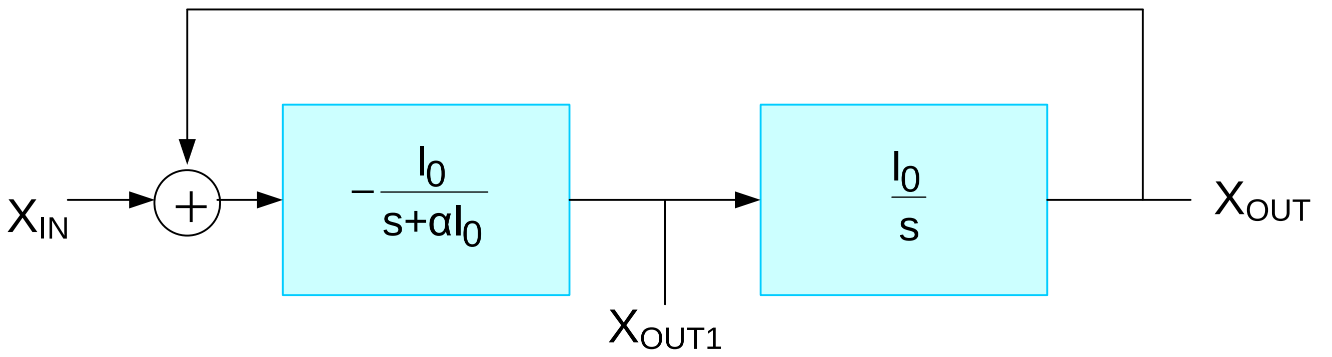
Alternate Equivalent Representation: $I_0 \leftrightarrow \omega_0$ $\alpha_0 \leftrightarrow \omega_0$



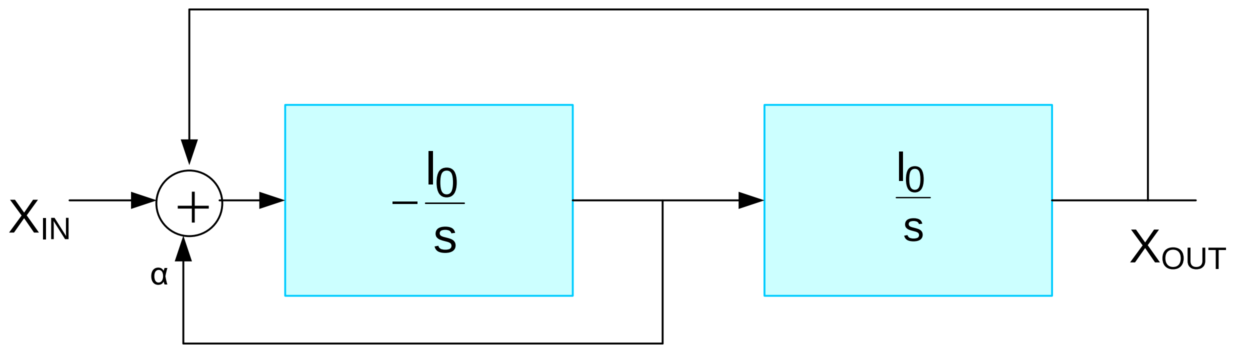
Lowpass output to X_{OUT} $$T(s)=\frac{-\omega_0^2}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}$$

Bandass output to X_{OUT1} $$T(s)=\frac{-s\omega_0}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}$$

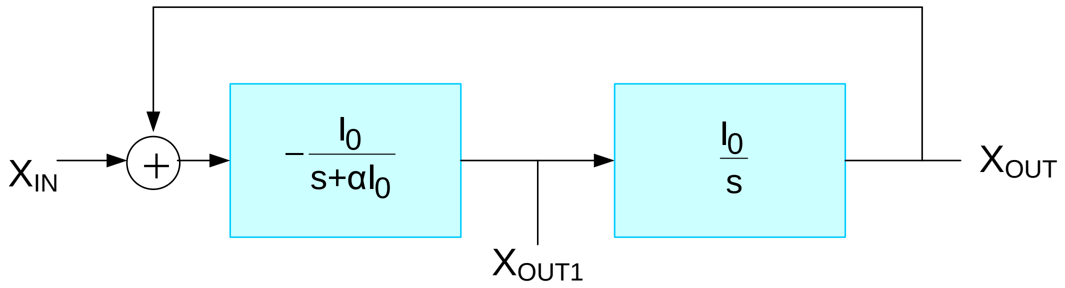
Two-Integrator-Loop Biquad



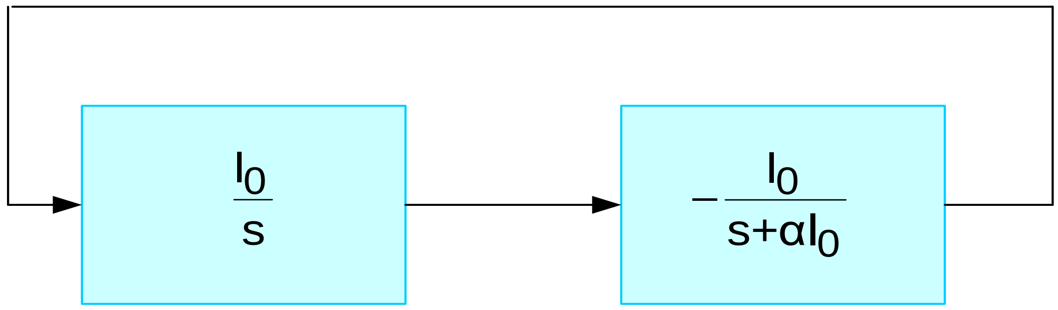
Alternate implementation of Lossy Integrator



Two-Integrator-Loop Biquad

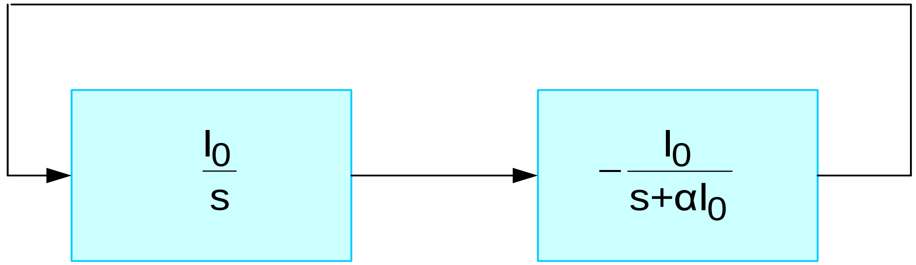


- For notational convenience, the input signal can be suppressed and output will not be designated
- This forms the “dead network”
- Poles for dead network are identical to original network as are key sensitivities

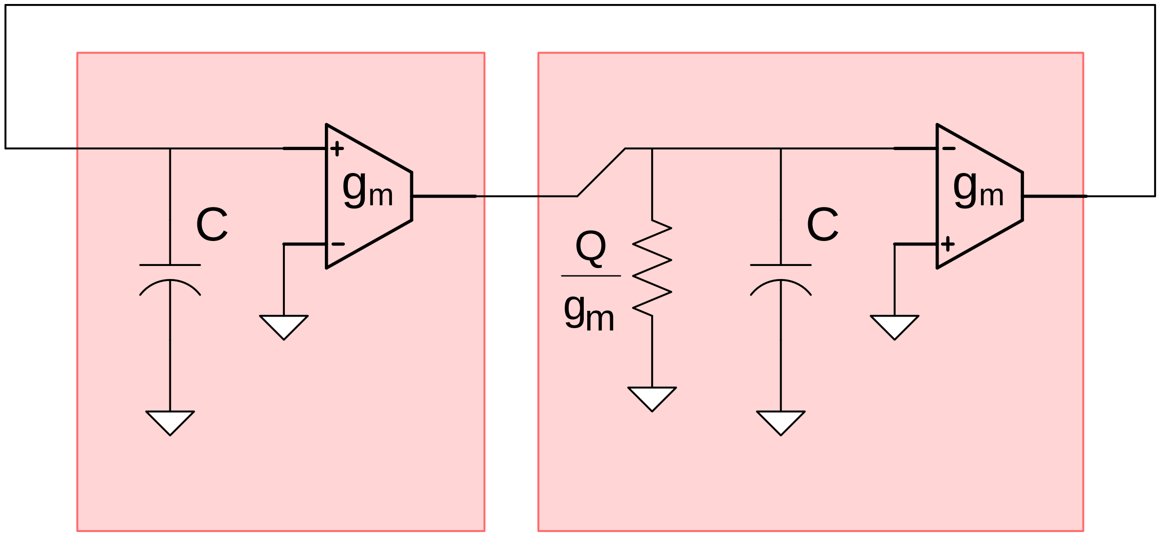


Two Integrator Loop Biquad

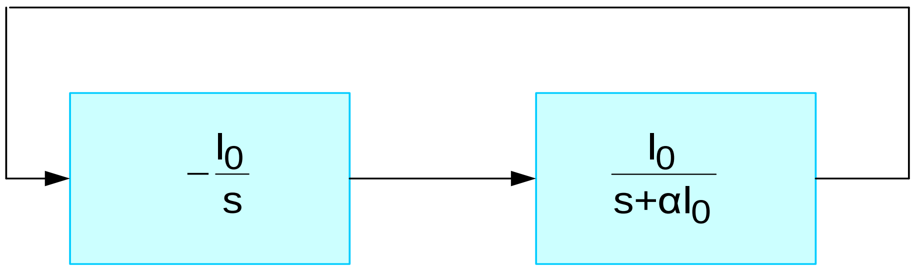
Two-Integrator-Loop Biquad



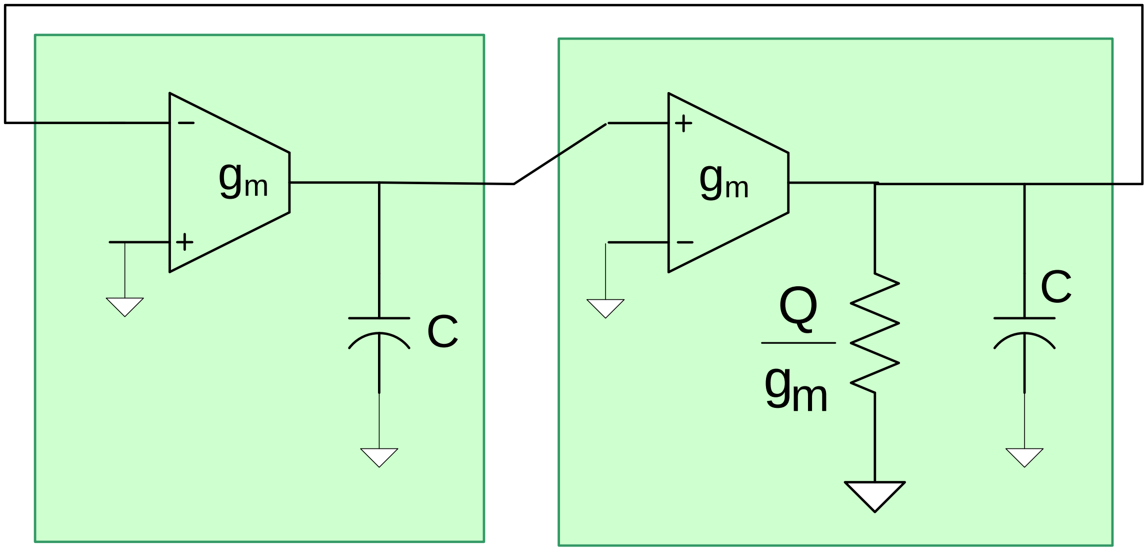
Consider a current-mode implementation:



Two-Integrator-Loop Biquad

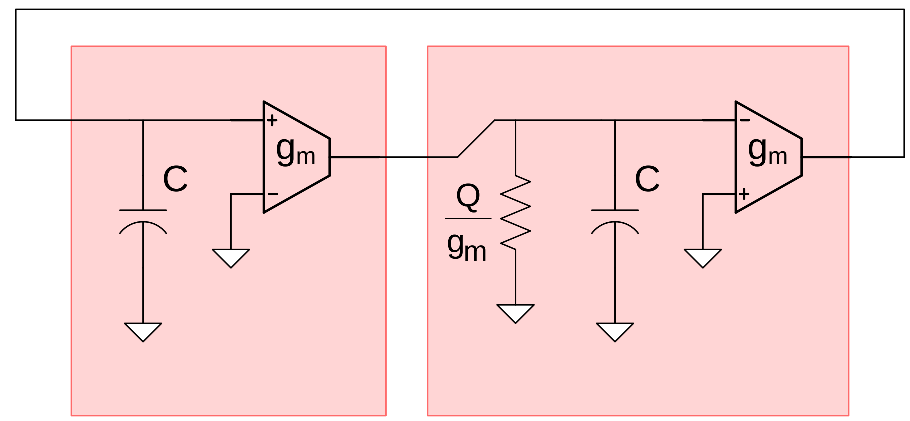


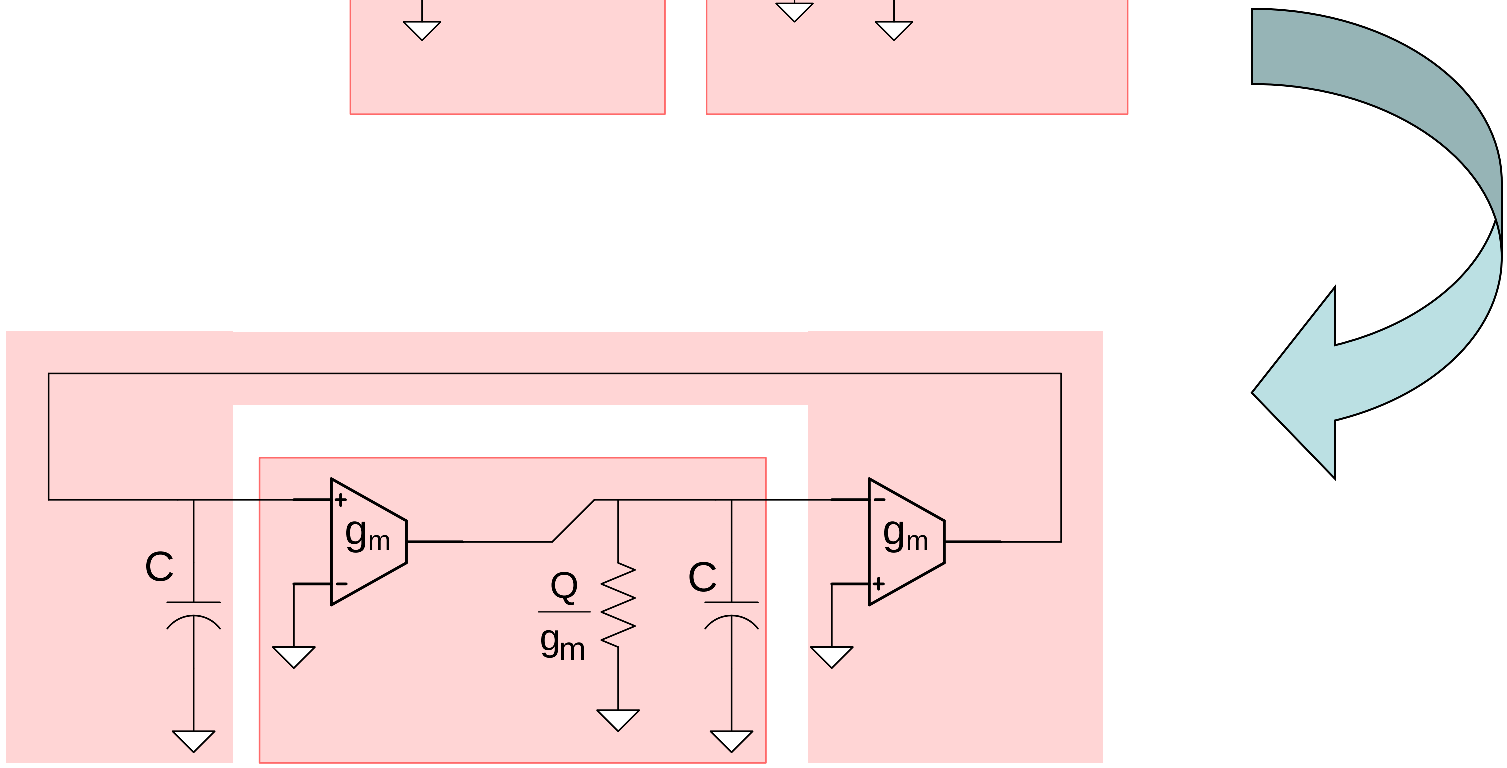
Consider the corresponding voltage-mode implementation:



Two-Integrator-Loop Biquad

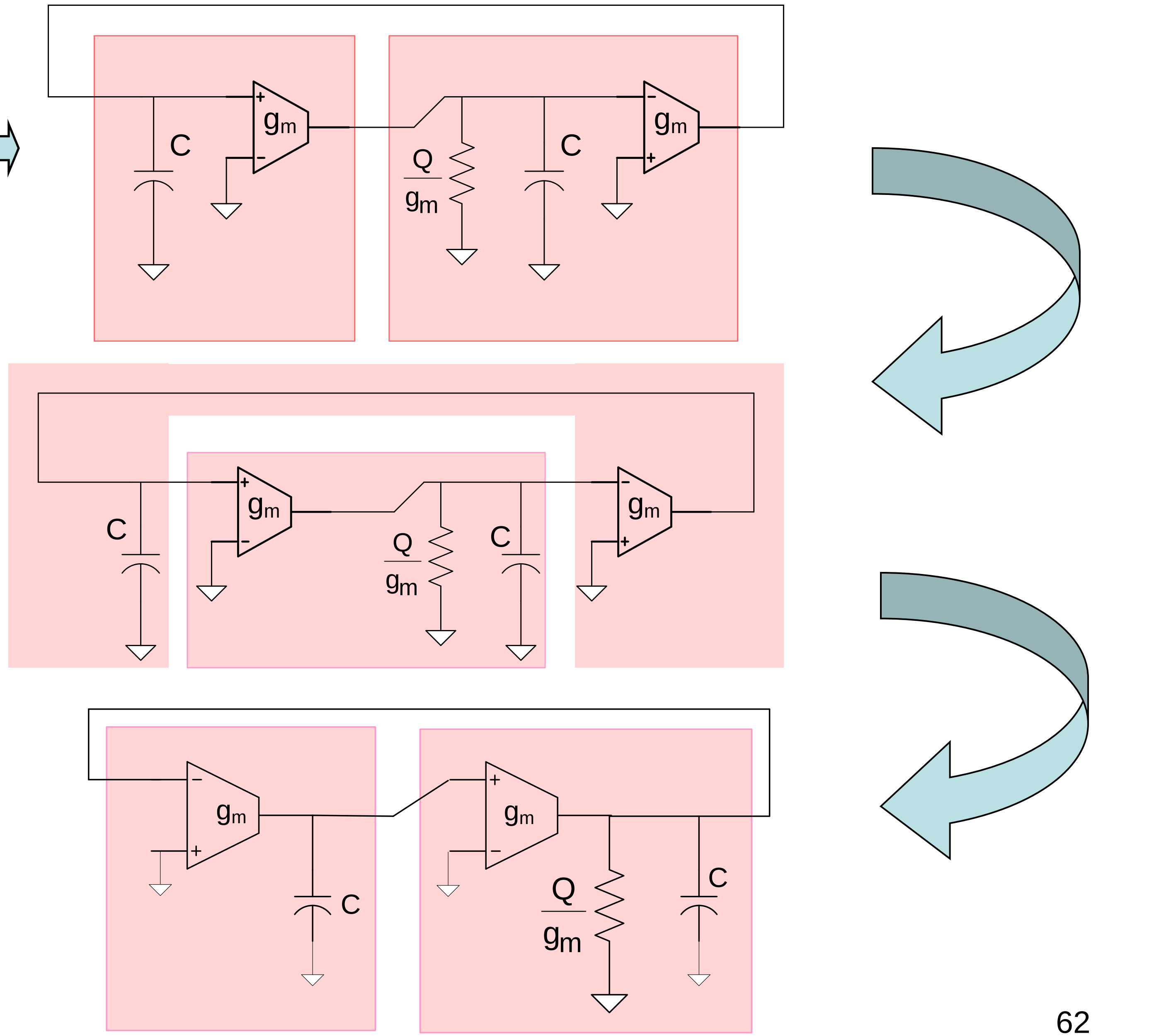
Current-mode





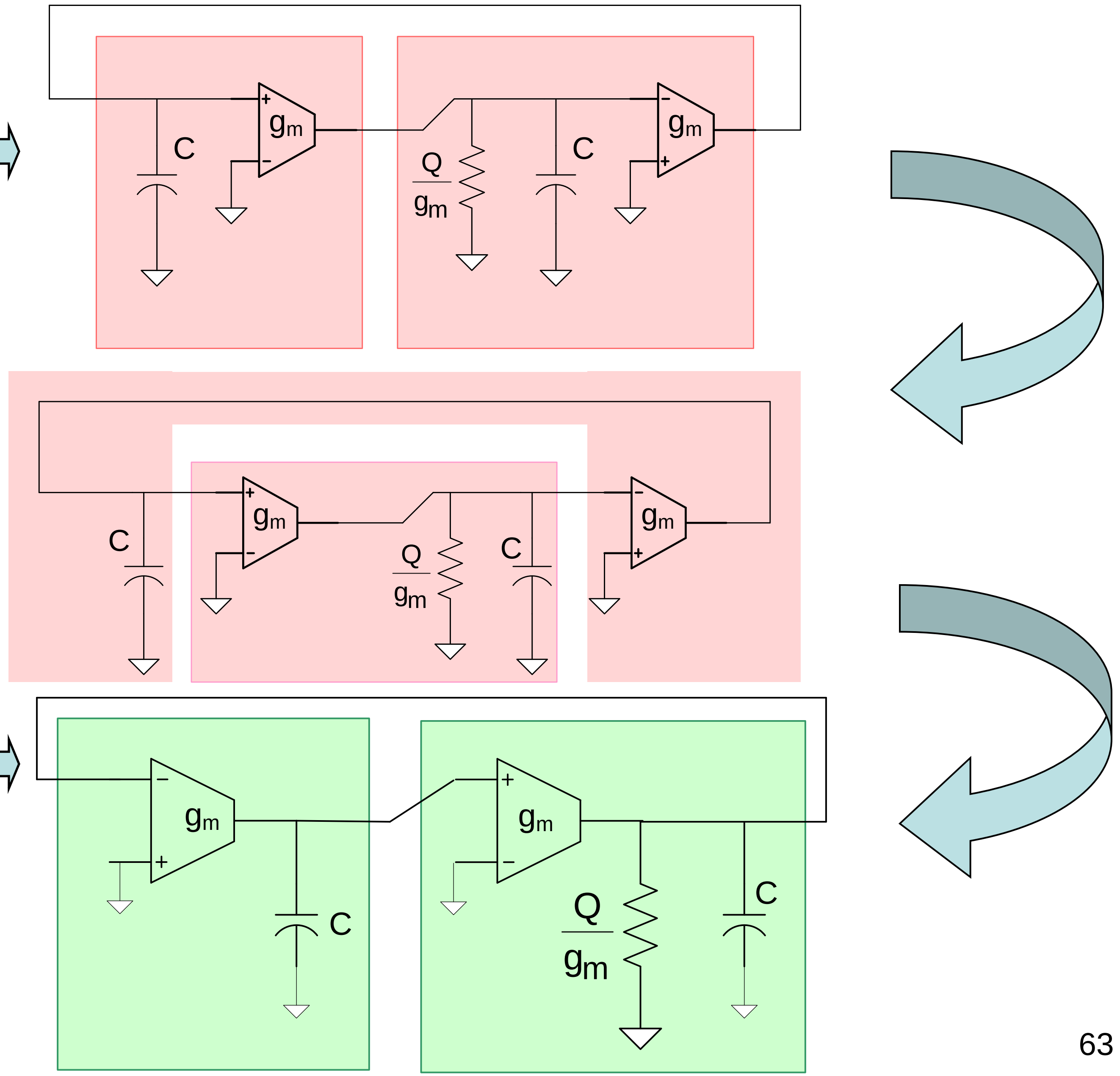
Two-Integrator-Loop Biquad

Current-mode



Two-Integrator-Loop Biquad

Current-mode



Voltage-mode

Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?

Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?

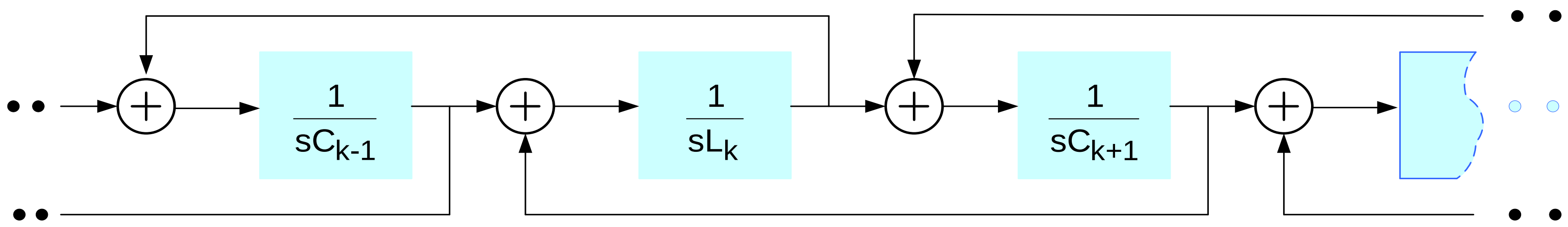
The corresponding current-mode and the voltage-mode two integrator loop biquad filters are identical!

Question:

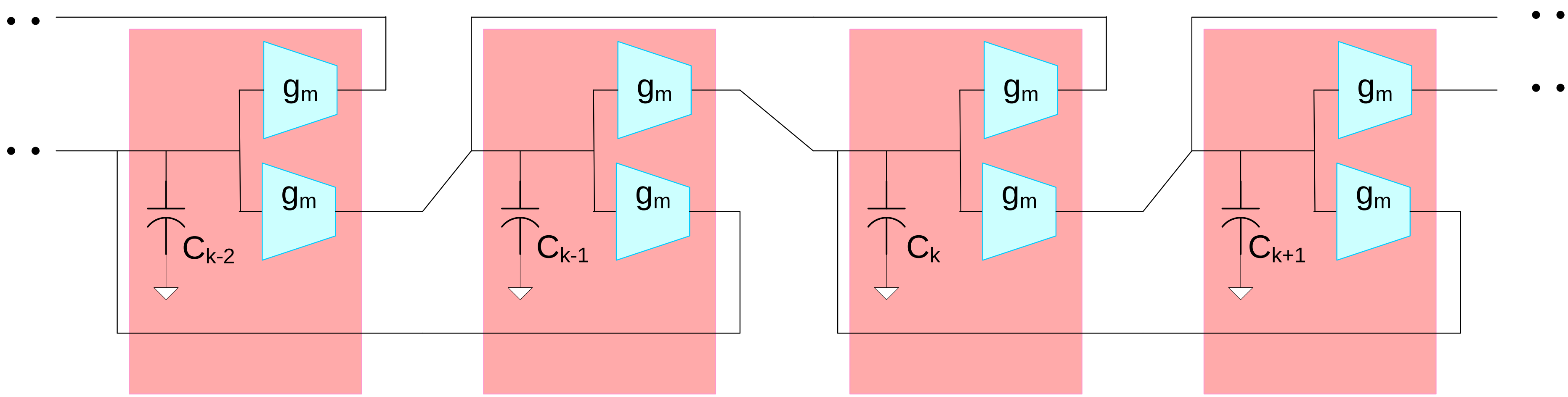
How does the performance of filters that use the current-mode and voltage-mode integrators compare?

The performance (speed, signal swing, sensitivity, linearity,power dissipation, etc.) of these circuits is identical !

Leap-Frog Filter

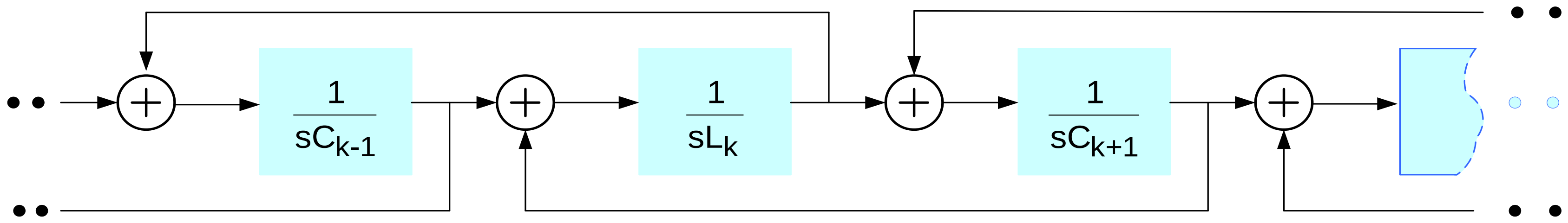


Current-mode:

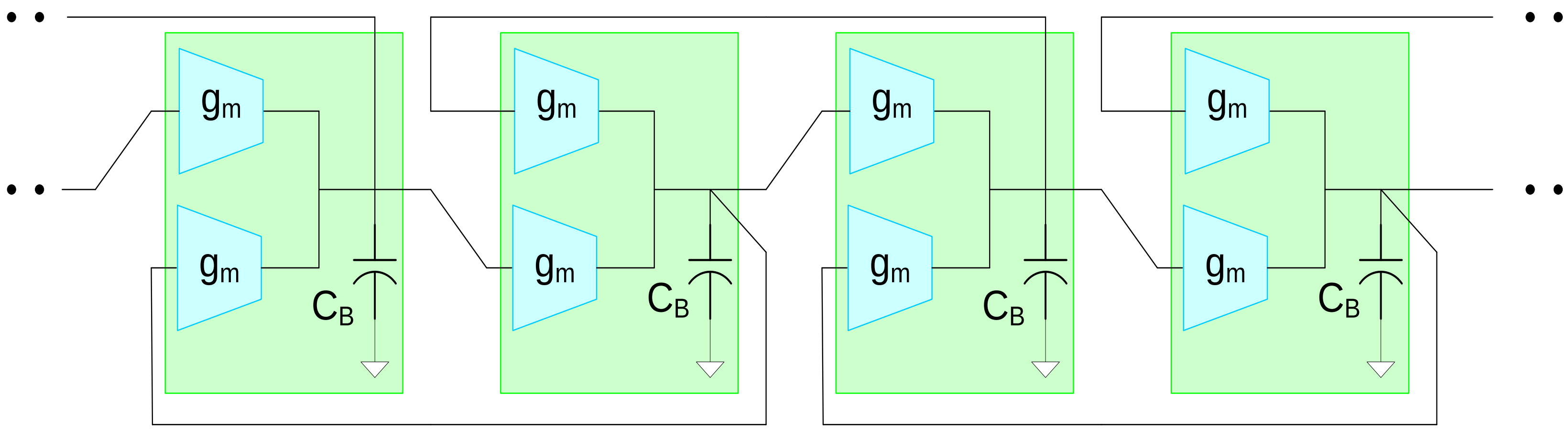


Standard OTA

Leap-Frog Filter



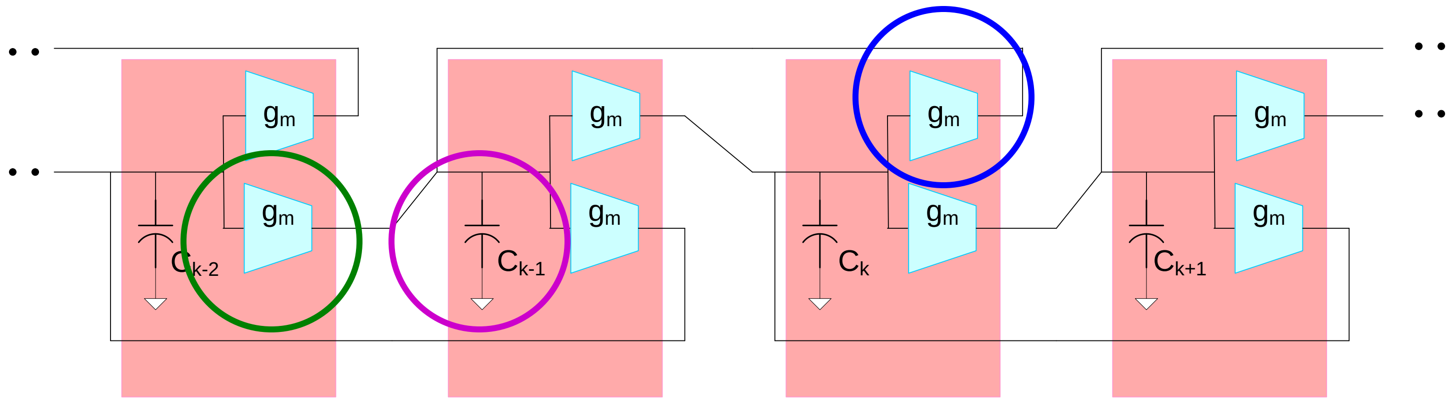
Voltage-mode:



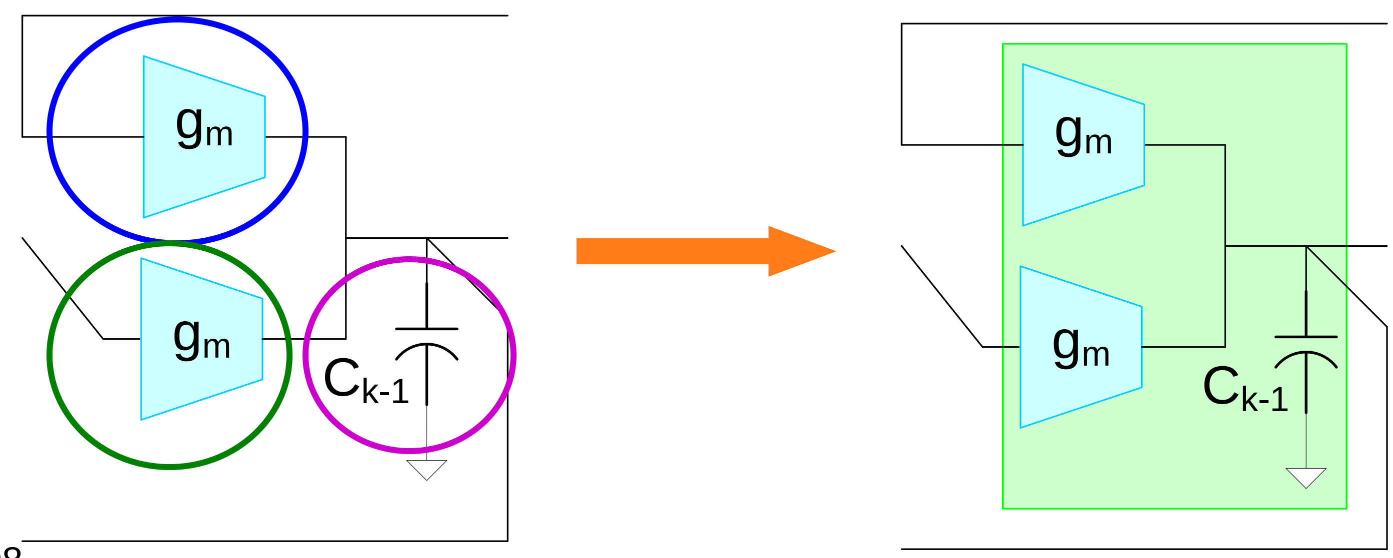
Standard OTA

Leap-Frog Filter

Current-mode

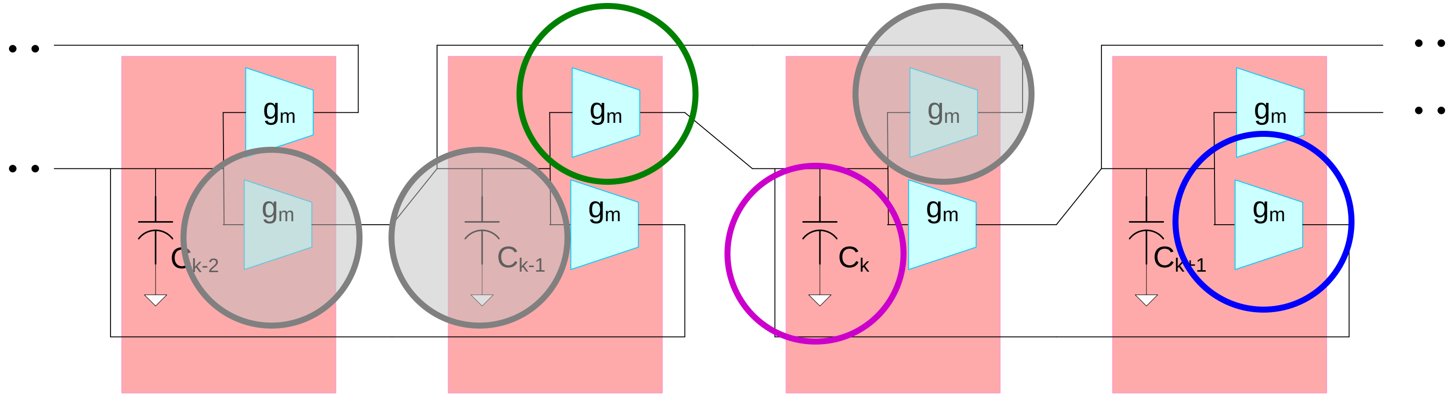


Consider lower OTA in stage k-2, capacitor in stage k-1 and upper OTA in stage k

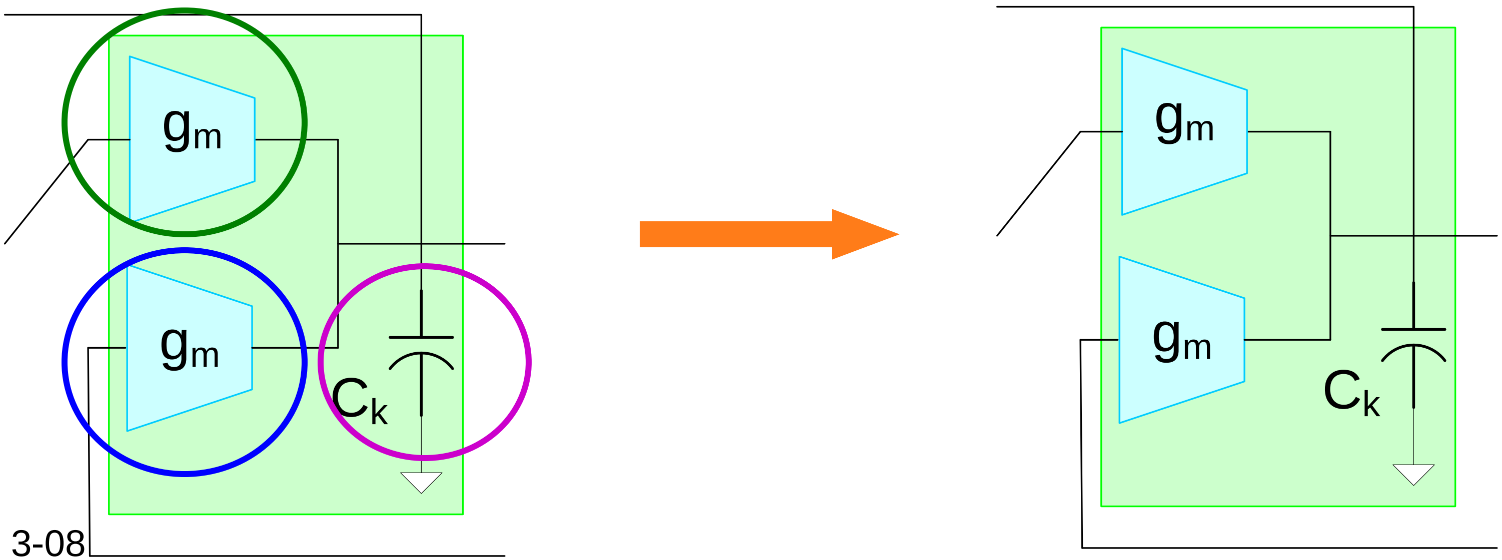


Leap-Frog Filter

Current-mode

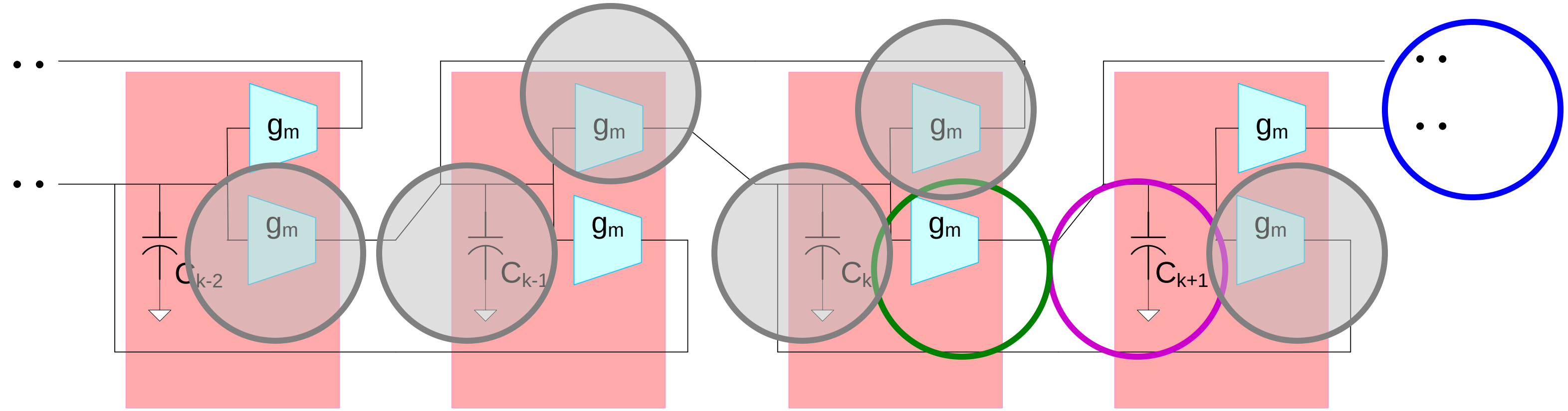


Consider upper OTA in stage k-1, capacitor in stage k and lower OTA in stage k+1

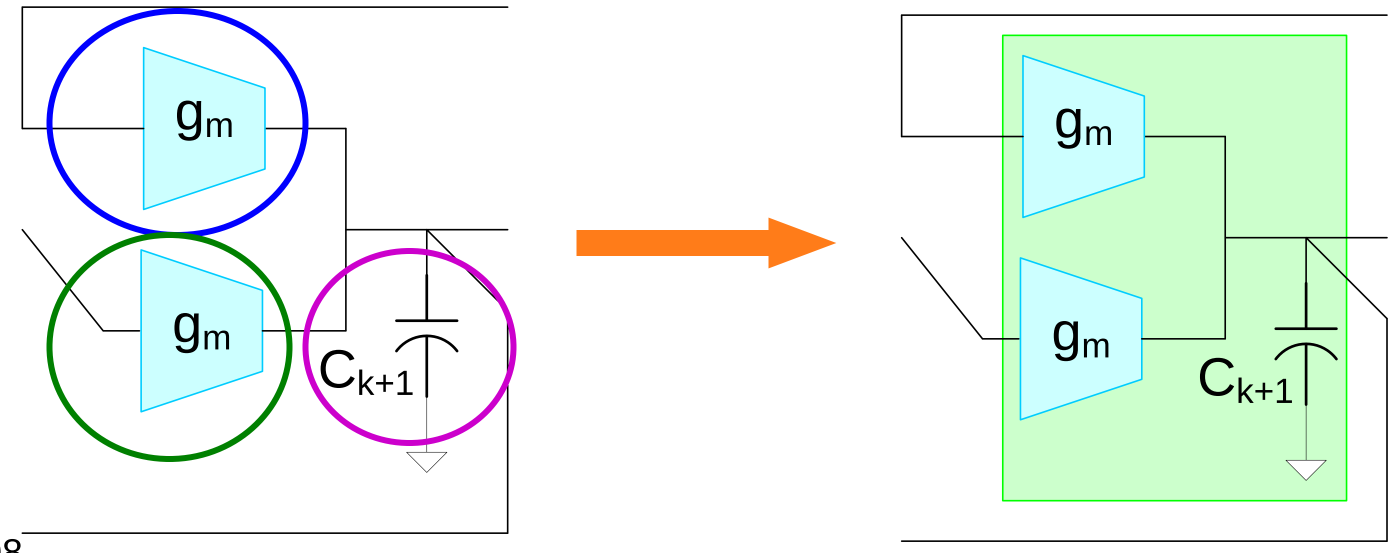


Leap-Frog Filter

Current-mode

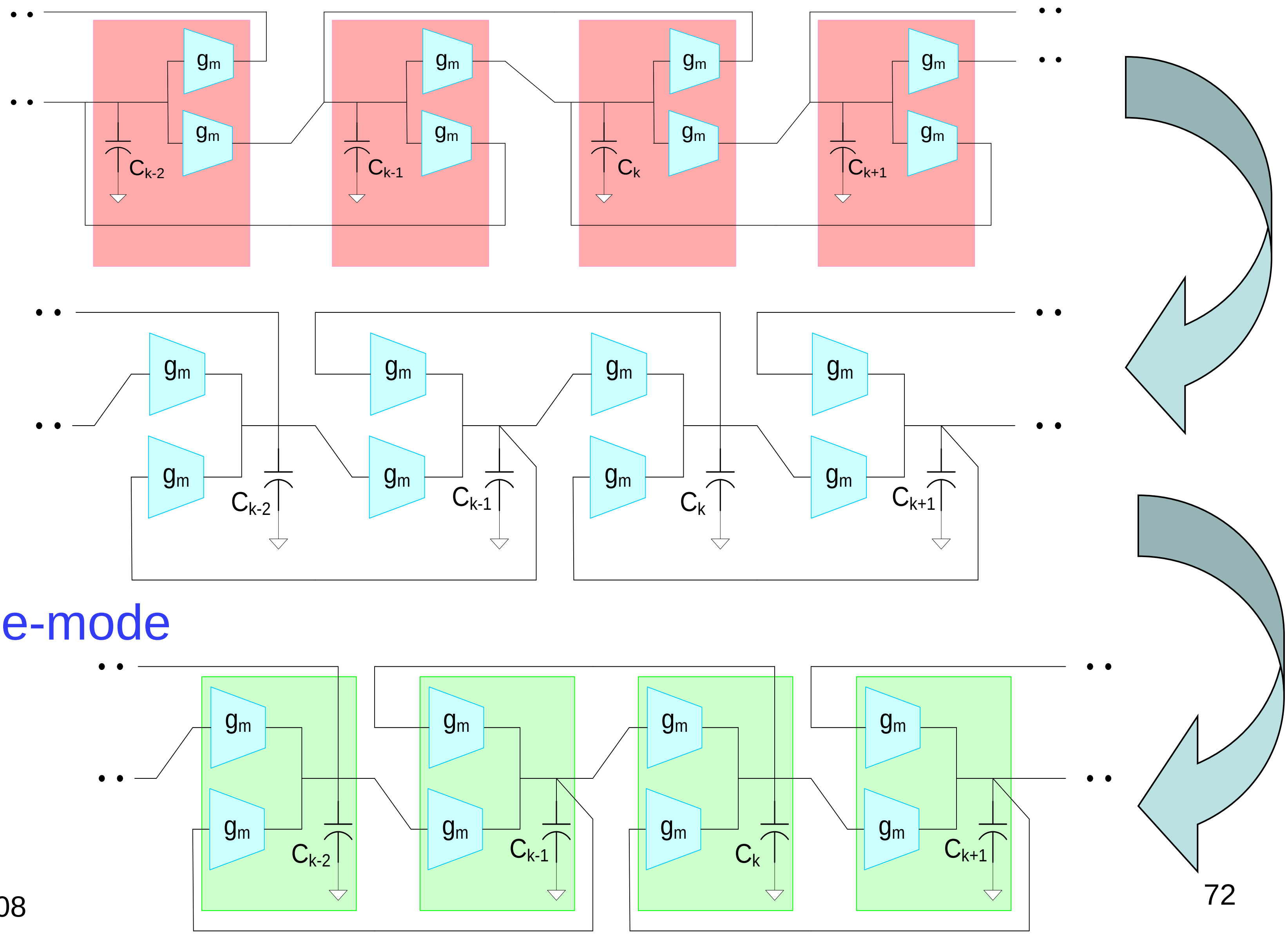


Consider lower OTA in stage k, capacitor in stage k+1 and upper OTA in stage k+2



Leap-Frog Filter

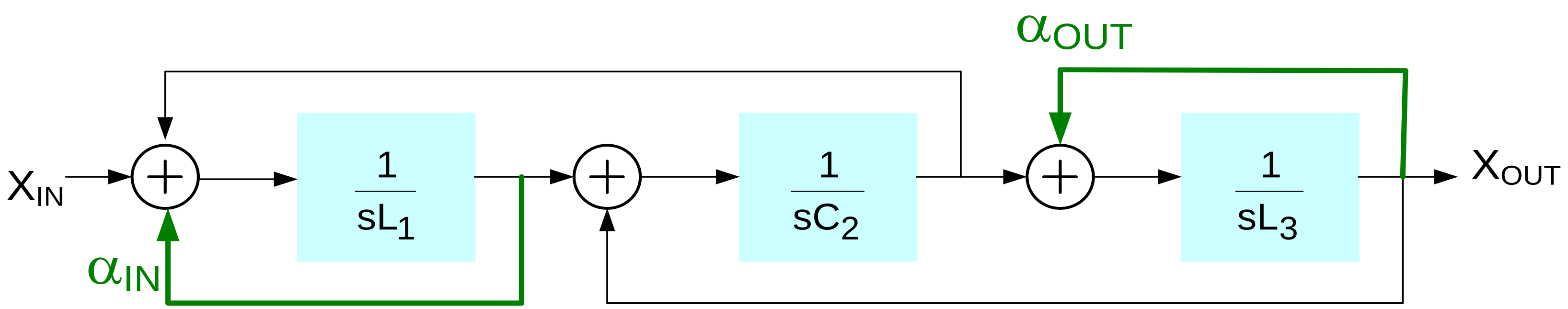
Current-mode



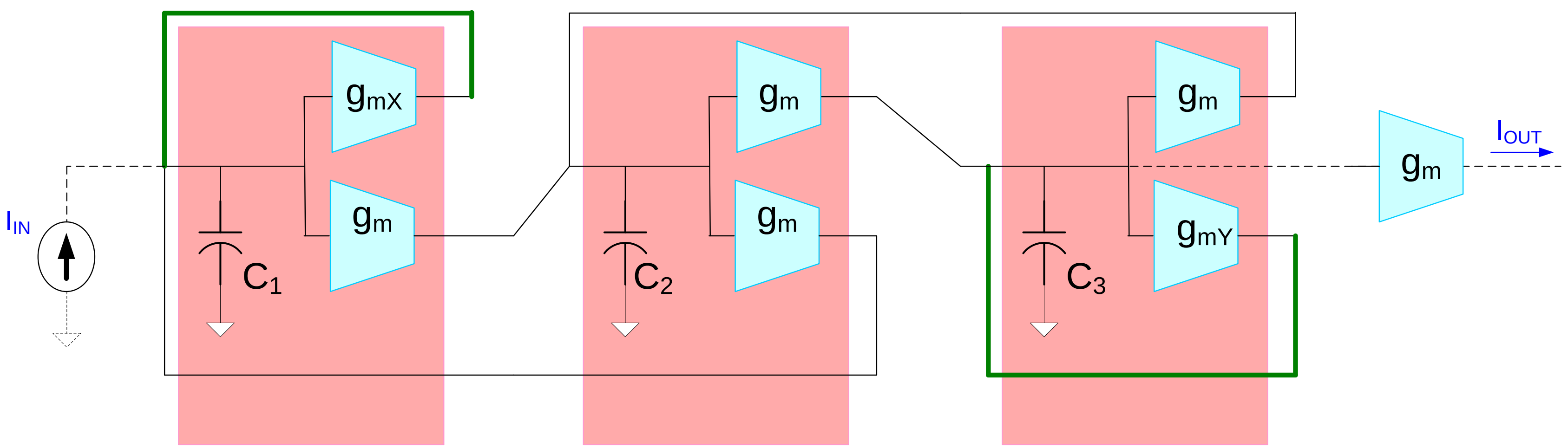
Voltage-mode

Leap-Frog Filter

Terminated Leap-Frog Filter (3-rd order lowpass)

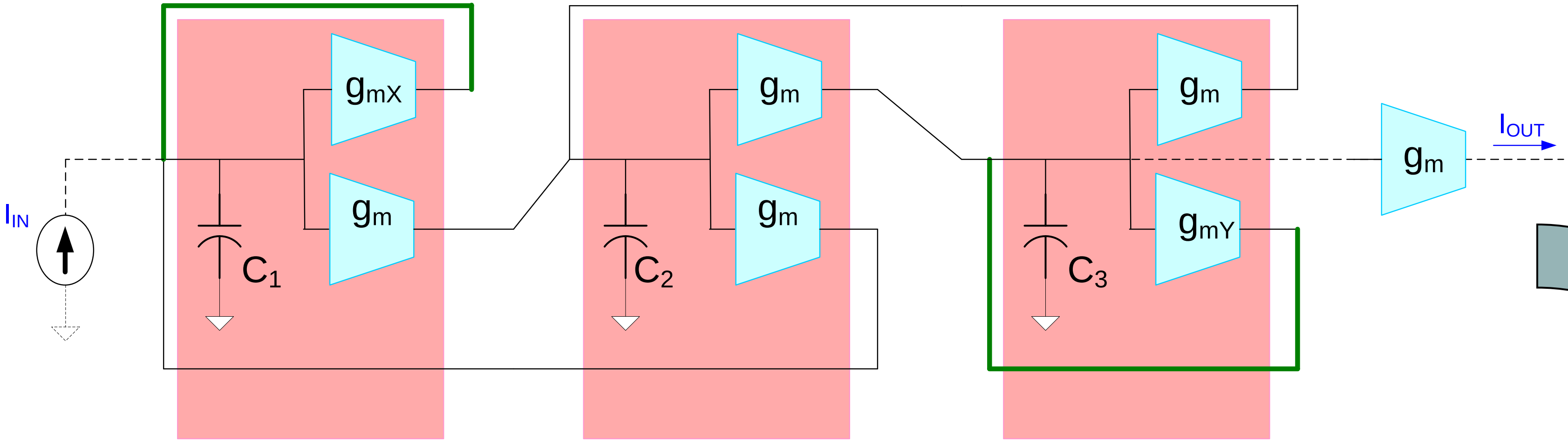


Current-mode implementation

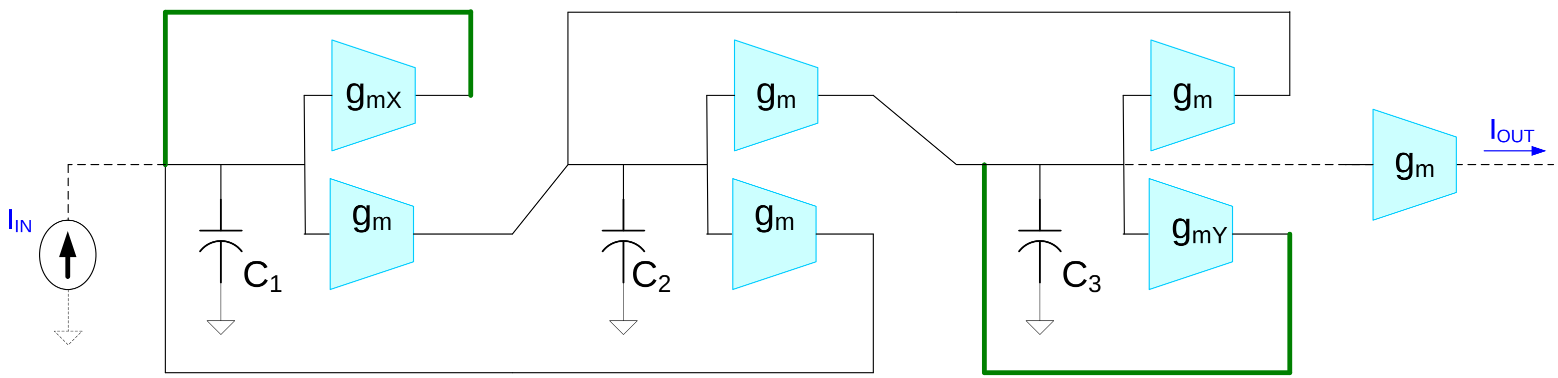


Leap-Frog Filter

Current-mode implementation

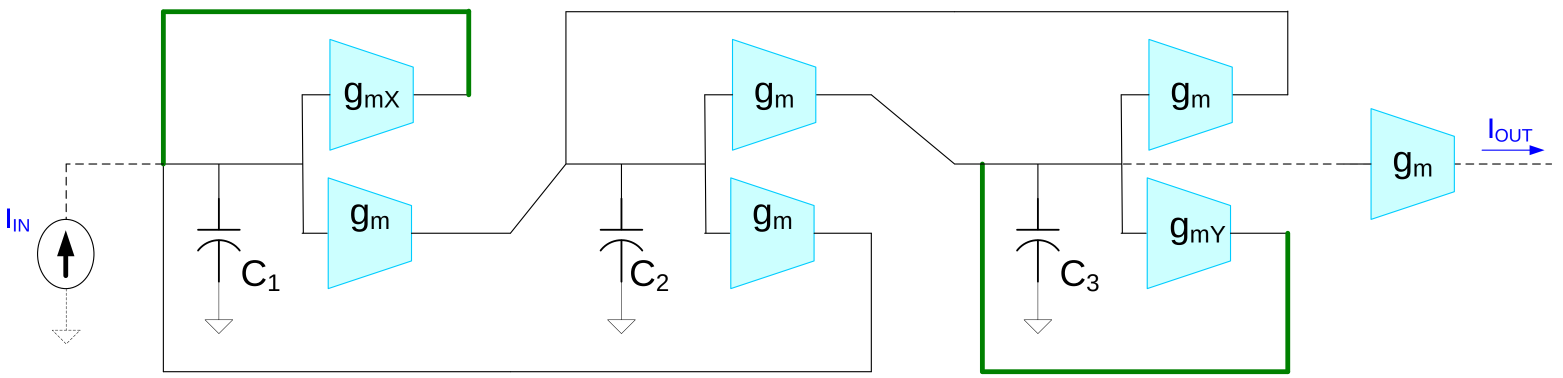


Consider schematic view:

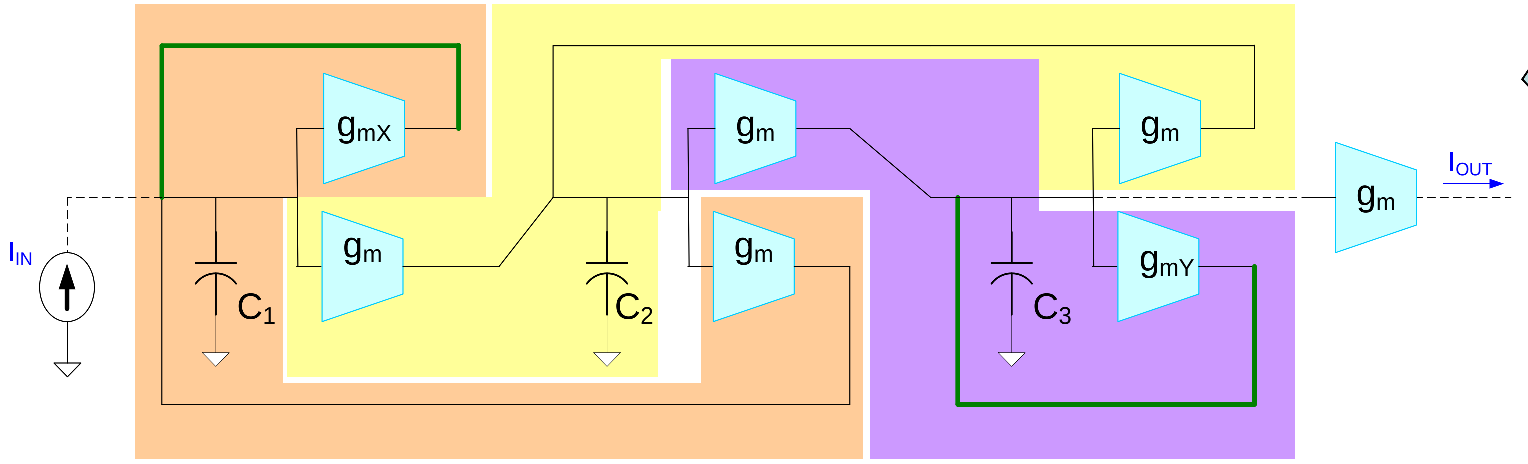


Leap-Frog Filter

Current-mode implementation

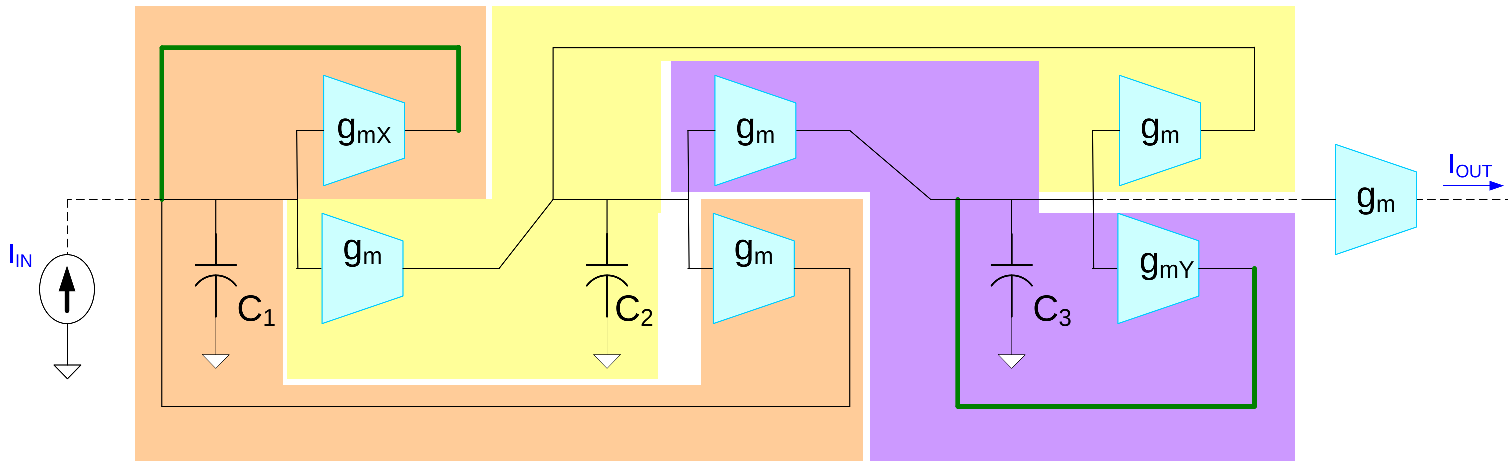


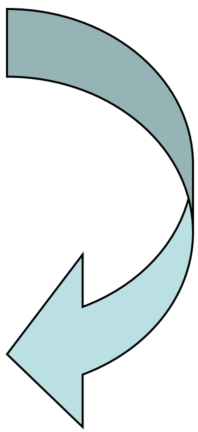
Re-group elements:



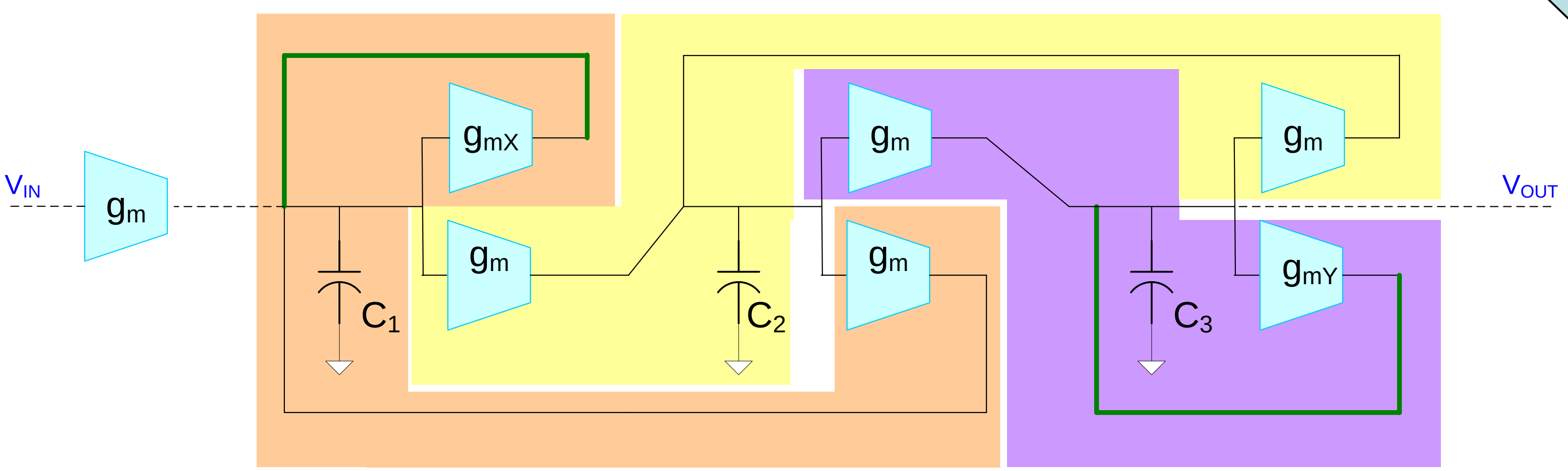
Leap-Frog Filter

Current-mode implementation



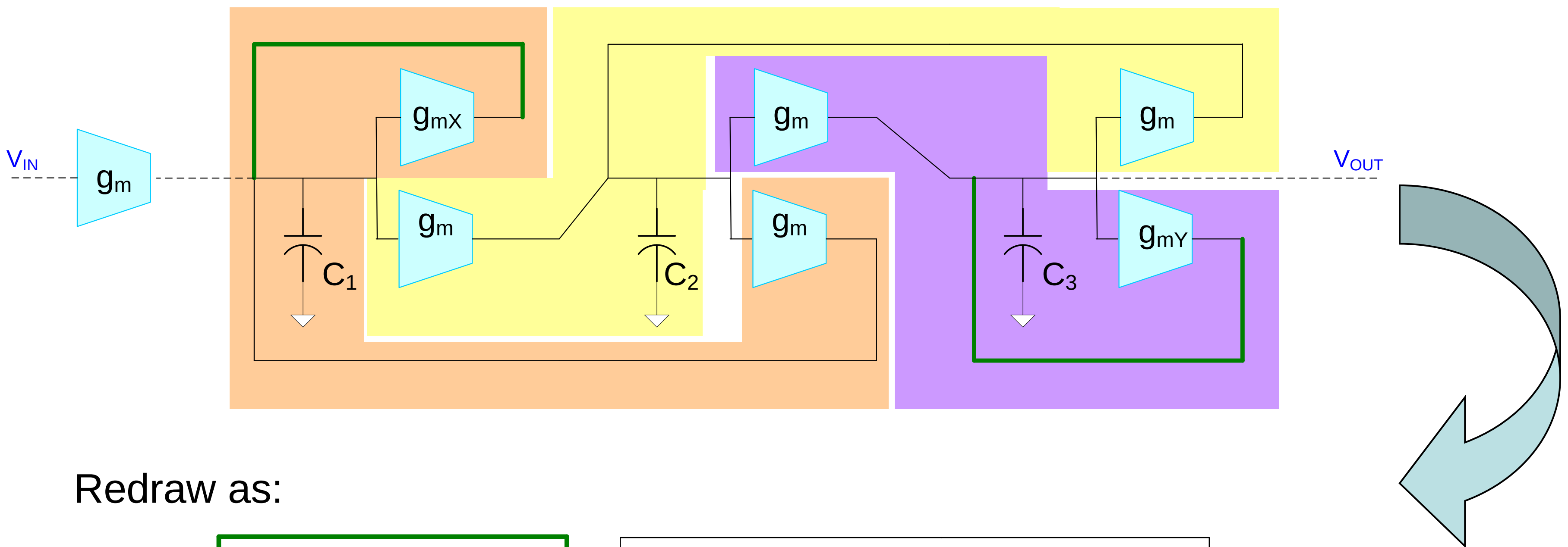


I/O Source Transformation

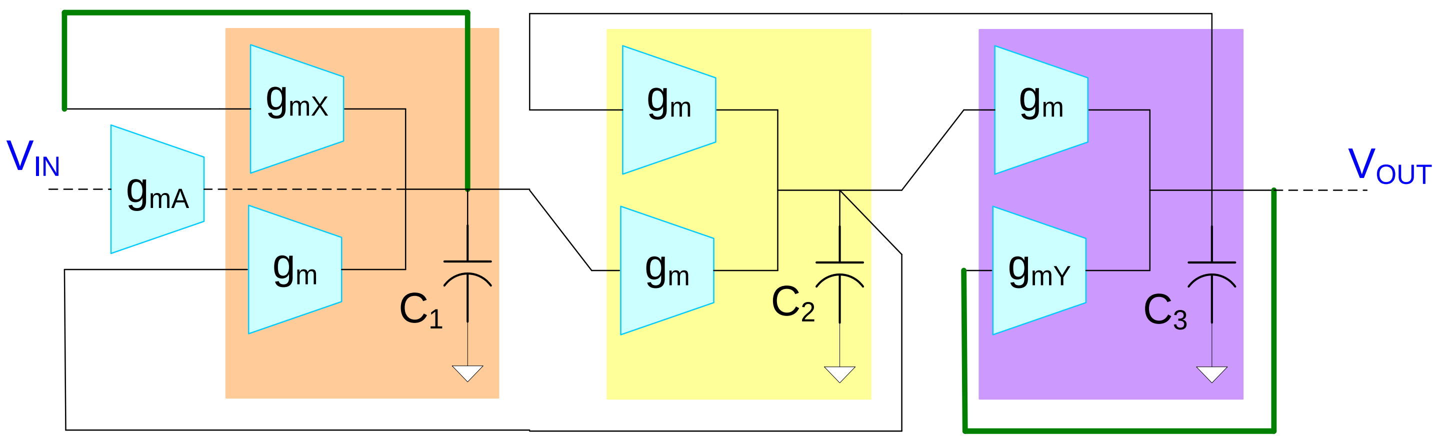


Leap-Frog Filter

Current-mode implementation

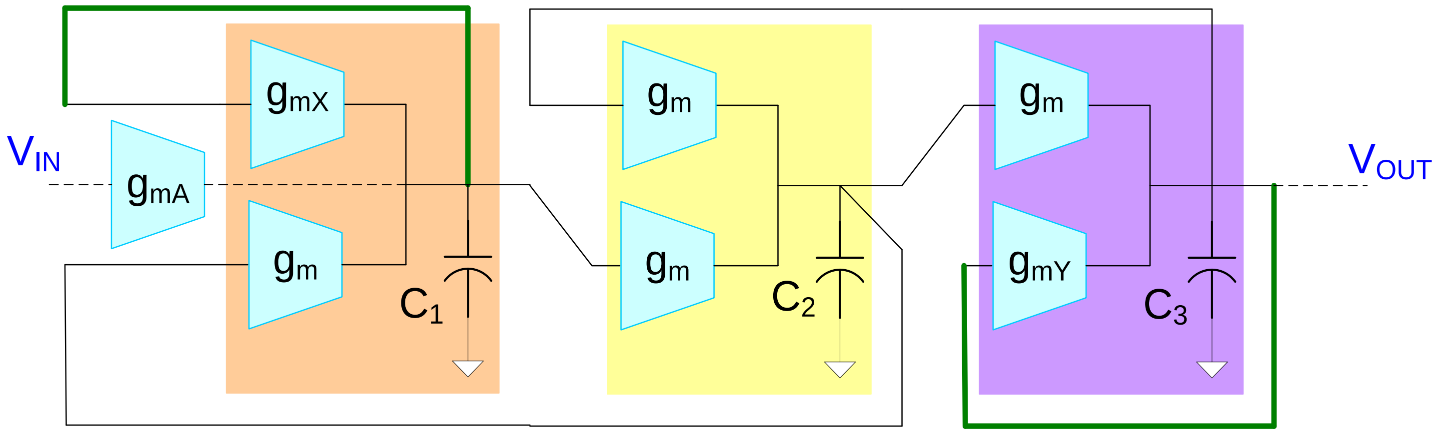


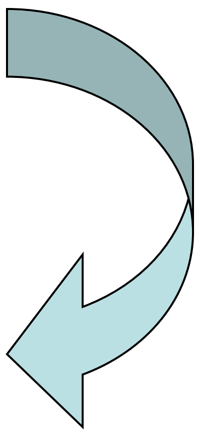
Redraw as:



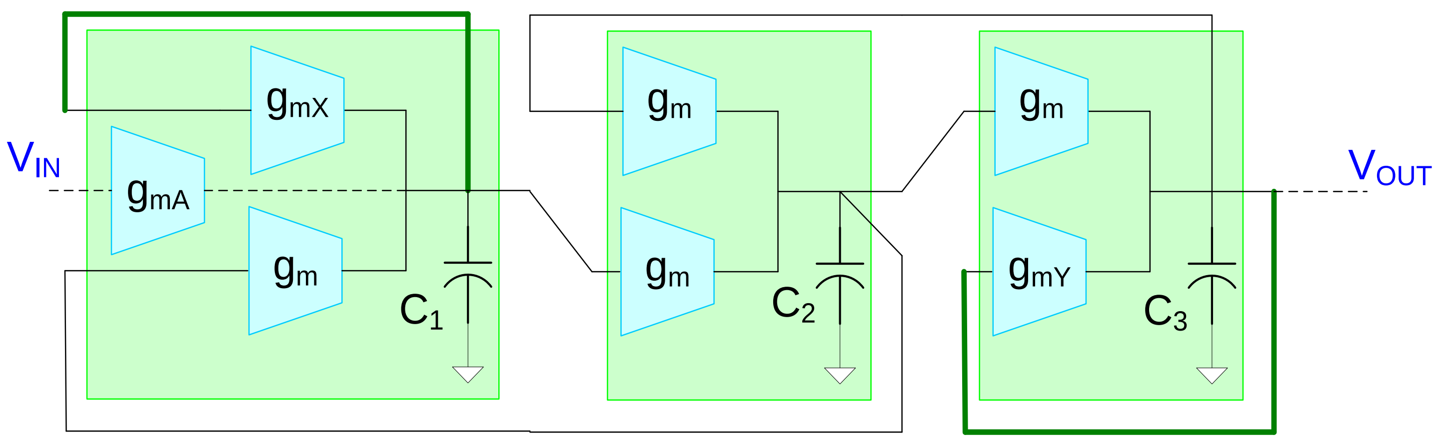
Leap-Frog Filter

Current-mode implementation





Change notation:

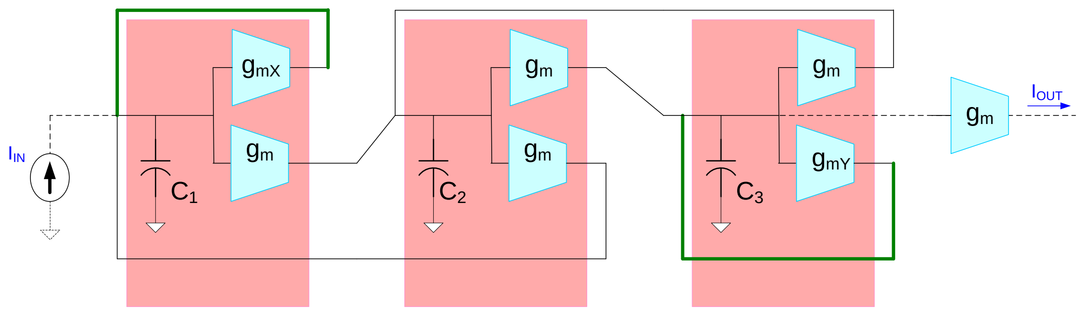


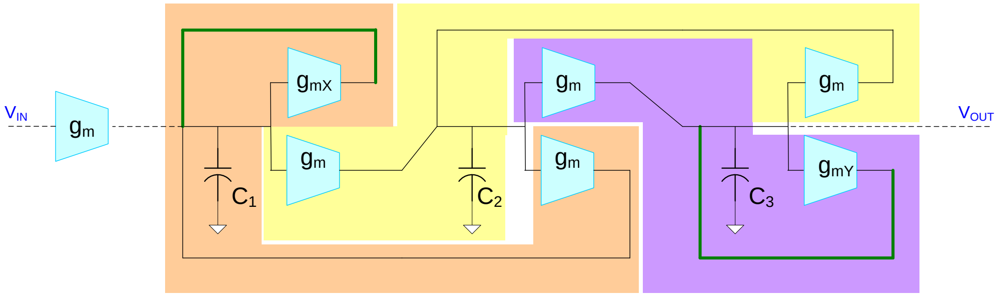
This is a voltage-mode implementation of the Leap-Frog Circuit !

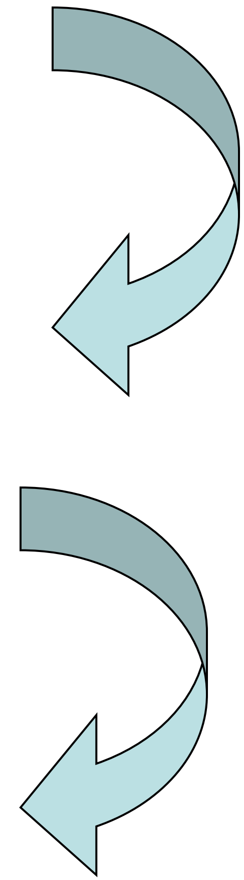
Leap-Frog Filter

SUMMARY

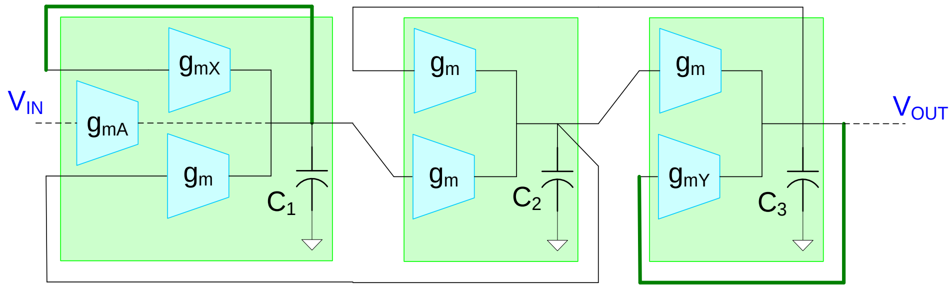
Current-mode implementation







Voltage-mode implementation

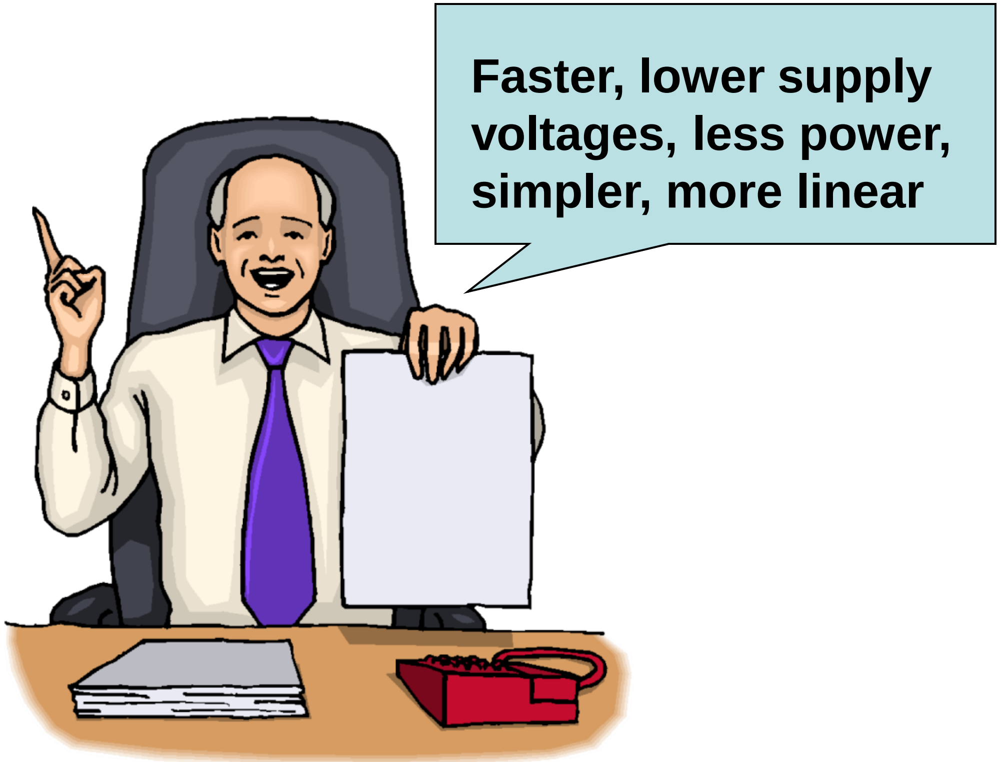


Comment

The current-mode and voltage-mode equivalence also exists for the high-frequency single transistor two-integrator loop filters and leapfrog filter structures

Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?



Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?

$\boxed{\text{The current-mode and the voltage-mode leapfrog filters are identical!}}$

Question:

How does the performance of filters that use the current-mode and voltage-mode integrators compare?

The performance (speed, signal swing, sensitivity, linearity, etc.) of these circuits is identical !

Current-Mode Filters

Conventional Wisdom

- Current-Mode circuits operate at higher-frequencies than voltage-mode counterparts
- Current-Mode circuits operate at lower supply voltages and lower power levels than voltage-mode counterparts
- Current-Mode circuits are simpler than voltage-mode counterparts
- Current-Mode circuits offer better linearity than voltage-mode counterparts

Reconciliation of Conventional Wisdom and Fundamental Concepts

- The choice of state (or stated) port variables plays no role on the fundamental performance characteristics of a filter
- Many current-mode and voltage-mode filters that have appeared in the literature are identical
- The issue of whether there are any performance advantages from the viewpoint of supply voltage, speed of operation and linearity of continuous-time current-mode filters over volt-mode counterparts is in question