EE 508
Lecture 44

Conventional Wisdom – Benefits and Consequences of Annealing Understanding of Engineering Principles

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Iowa State University

Conventional Wisdom:

Conventional wisdom is the collective understanding of fundamental engineering concepts and principles that evolves over time through interactions of practicing engineers around the world

Conventional Wisdom:

- Guides engineers in daily practice of the Profession
- Widely use to enhance productivity
- Heavily emphasized in universities around the world when educating next-generation engineers
- Often <u>viewed</u> as a fundamental concept or principle
- Validity of conventional wisdom seldom questioned

Are Conventional Wisdom and Fundamental Concepts and Principles Always Aligned?

Much of Society till 1200AD to 1600AD and later

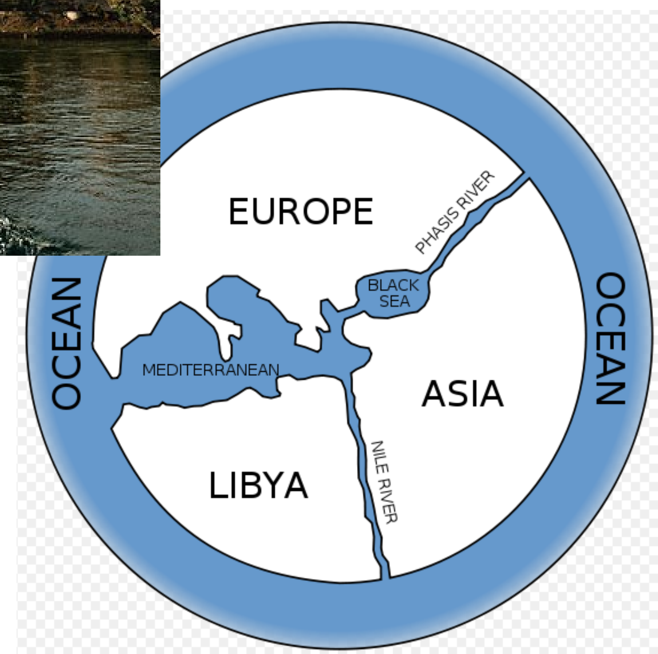
http://greenfunkdan.blogspot.com/2008/11/csiro-warns-of-climate-change-doomsday.html

Pythagoras 520BC
Aristotle 300BC

http://www.christiananswers.net/q-aig/aig-c034.html

Sometimes the differences can be rather significant !

Conventional wisdom, when not correctly representing fundamental principles, can provide conflicting perceptions or irresolvable paradoxes



Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

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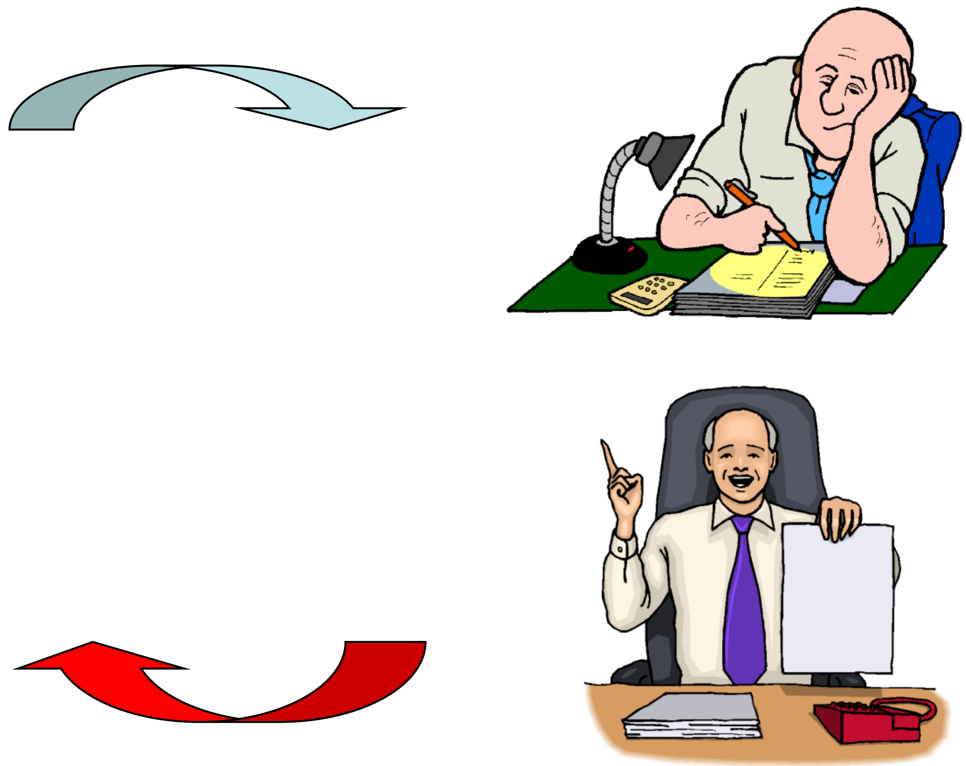


Records of

- **Conventional Wisdom**
- **Fundamental Concepts**
- **Occasional Oversight of Error**
- **Key information embedded in tremendous volume of materials (noise)**

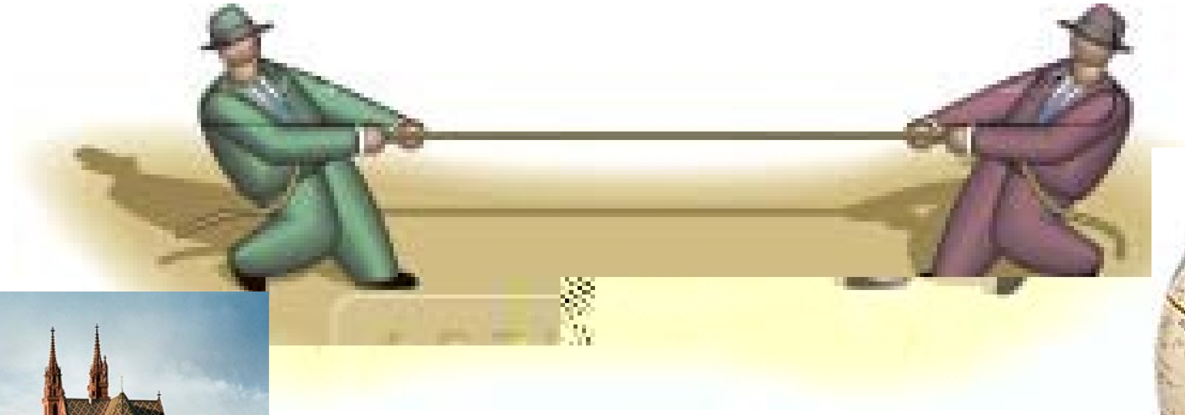
Conventional Wisdom

Do Conventional Wisdom and Fundamental Concepts Differ In the Microelectronics Field ?

Reliability ?

The process is good but not perfect !

What Happens When Fundamental Concepts and Conventional Wisdom Differ?



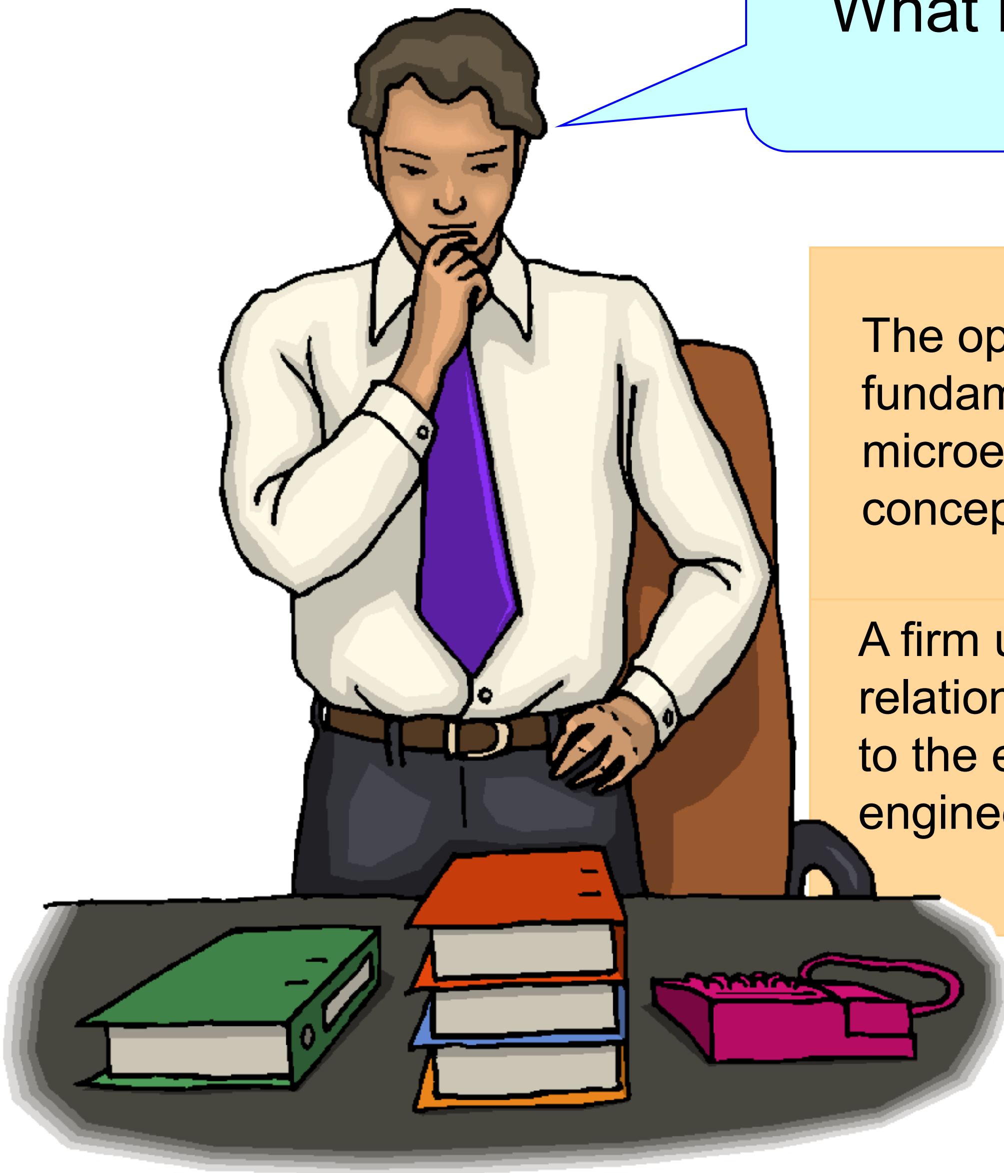
- Confusion Arises
- Progress is Slowed
- Principles are not correctly understood
- Errors Occur
- Time is Wasted

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Will consider 5 basic examples in this discussion

- Op Amp
- Positive Feedback Compensation
- Current Mode Filters
- Current Dividers
- Barkhausen Criterion

What is an operational amplifier ?



The operational amplifier is one of the most fundamental and useful components in the microelectronics field and is integral to the concept of feedback !

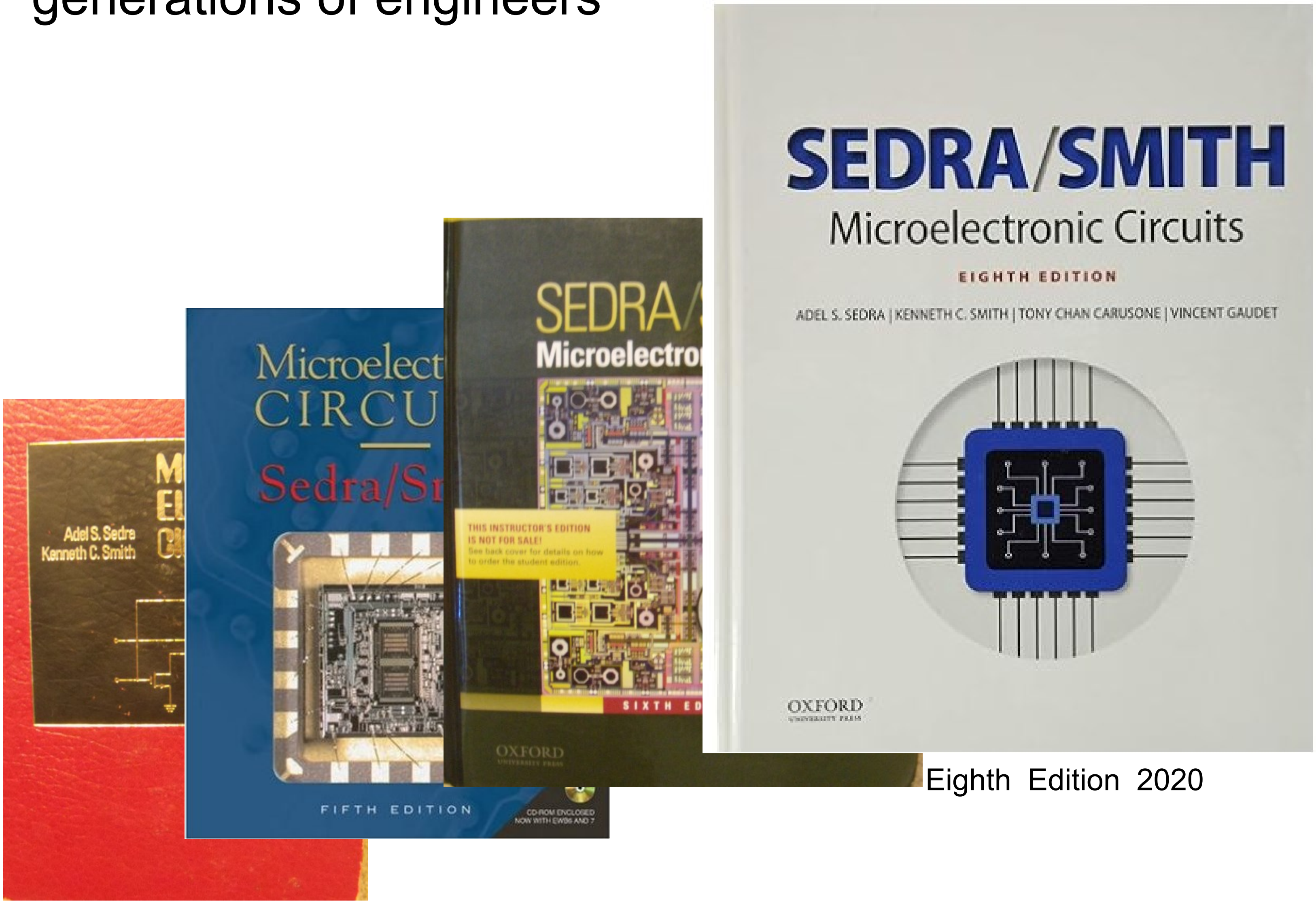
A firm understanding of feedback and its relation to the operational amplifier is central to the education of essentially all electrical engineers around the world today

What is an Operational Amplifier?

Lets see what the experts say !

Consider one of the most popular textbooks on the subject used in the world today

A classic textbook that has helped educate two generations of engineers



Eighth Edition 2020

First Edition 1982

In all editions, concept of the op amp has remained unchanged

2.1.2 Function and Characteristics of the Ideal Op Amp

We now consider the circuit function of the op amp. The op amp is designed to sense the difference between the voltage signals applied at its two input terminals (i.e., the quantity $v_2 - v_1$), multiply this by a number A, and cause the resulting voltage $A(v_2 - v_1)$ to appear at output terminal 3. Here it should be emphasized that when we talk about the voltage at a terminal we mean the voltage between that terminal and ground; thus v_1 means the voltage applied between terminal 1 and ground.

The ideal op amp is not supposed to draw any input current; that is, the signal current into terminal 1 and the signal current into terminal 2 are both zero. In other words, *the input impedance of an ideal op amp is supposed to be infinite.*

How about the output terminal 3? This terminal is supposed to act as the output terminal of an ideal voltage source. That is, the voltage between terminal 3 and ground will always be equal to $A(v_2 - v_1)$, independent of the current that may be drawn from terminal 3 into a load impedance. In other words, *the output impedance of an ideal op amp is supposed to be zero.*

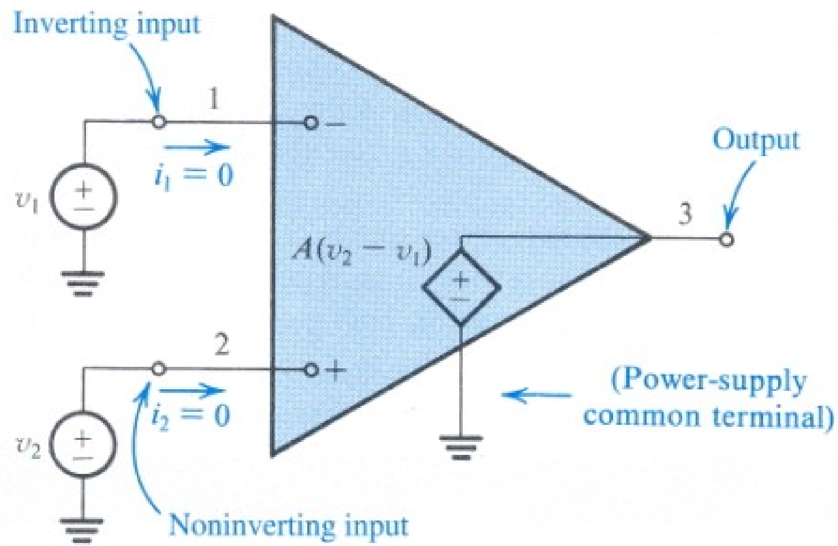
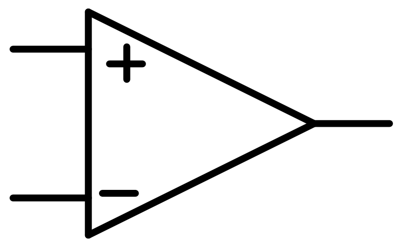


FIGURE 2.3 Equivalent circuit of the ideal op amp.

TABLE 2.1 Characteristics of the Ideal Op Amp

1. Infinite input impedance
2. Zero output impedance
3. Zero common-mode gain or, equivalently, infinite common-mode rejection
4. Infinite open-loop gain A
5. Infinite bandwidth

What is an Operational Amplifier?



Textbook Definition:

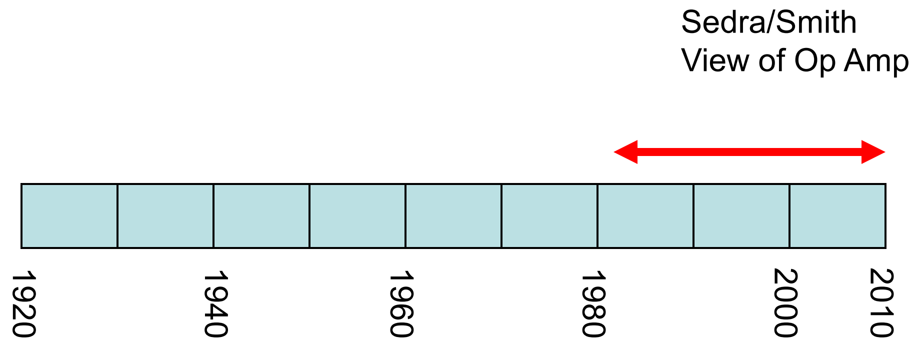
- Voltage Amplifier with Very Large Gain
  - Very High Input Impedance
  - Very Low Output Impedance

- Differential Input and Single-Ended Output

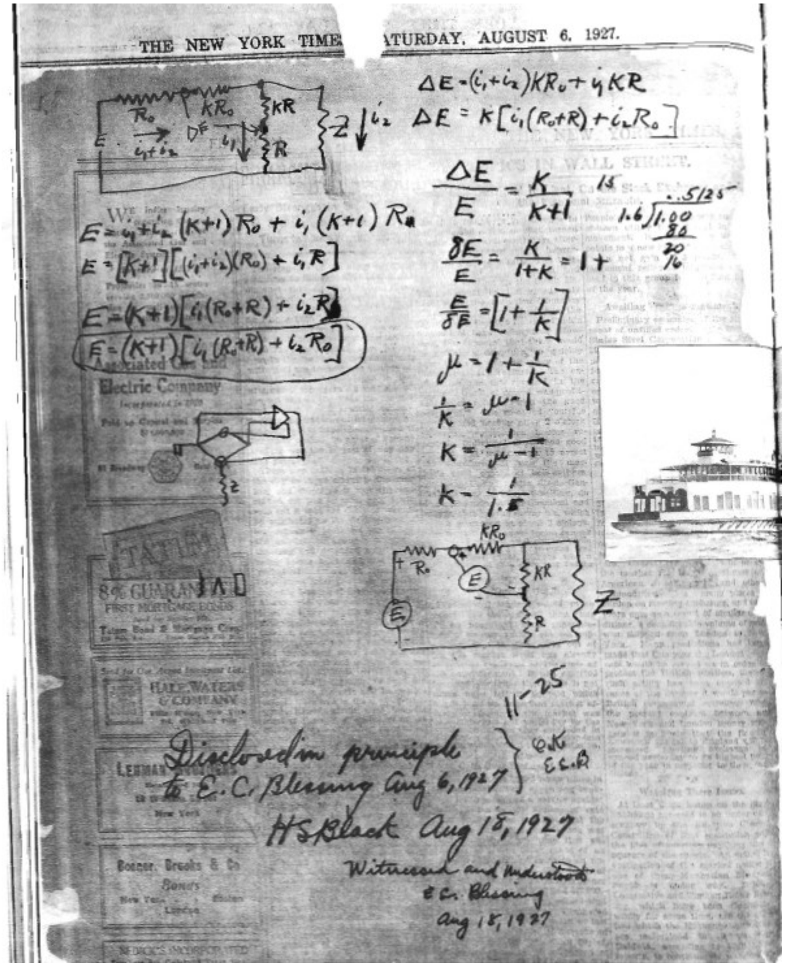
This represents the Conventional Wisdom !

Does this correctly reflect what an operational amplifier really is?

Operational Amplifier Evolution in Time Perspective



Consider some history leading up to the present concept of the operational amplifier

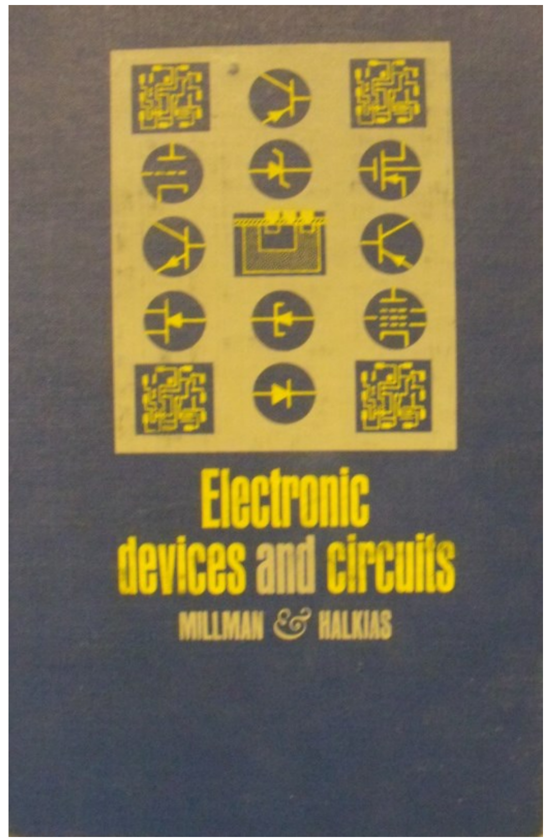


H.S. Black sketch of basic concept of feedback on Aug 6, 1927

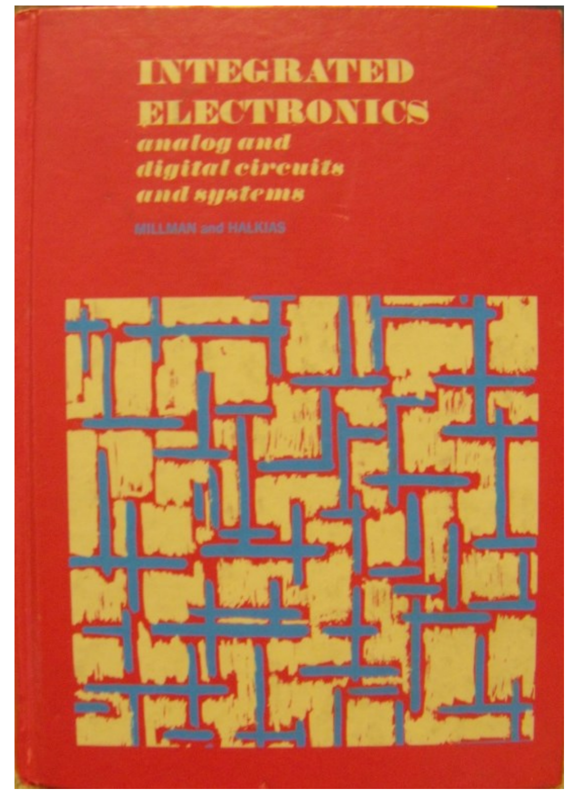
Black did not use the term operational amplifier but rather focused on basic concepts of feedback involving the use of high-gain amplifiers

A classic textbook sequence that has helped educate the previous two generations of engineers

First Edition 1958

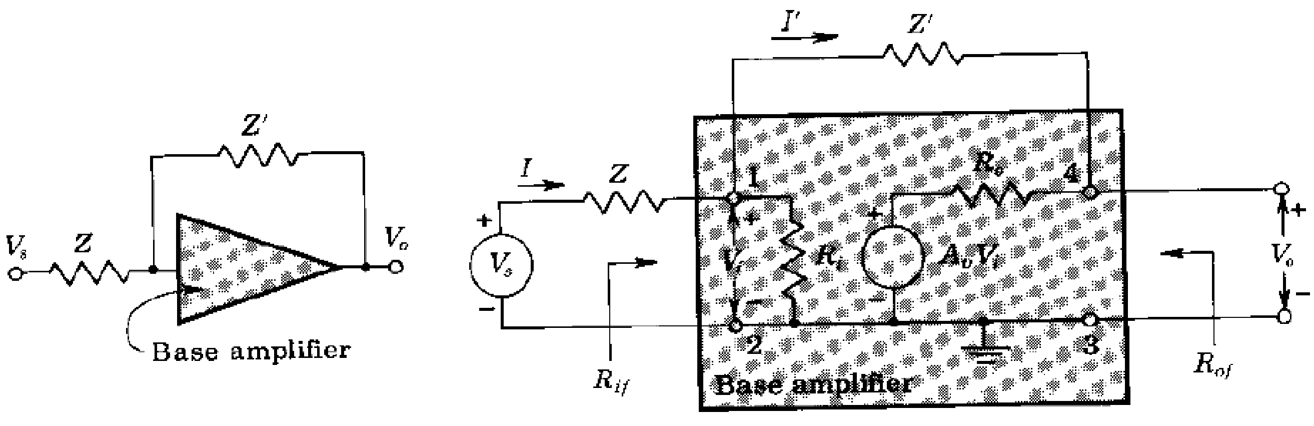


First Edition 1967



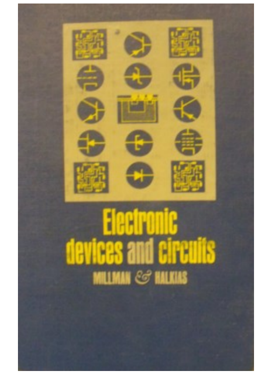
First Edition 1972

Millman view of an operational amplifier in 1967



(a) (b)

Fig. 17-26 (a) Schematic diagram and (b) equivalent circuit of an operational amplifier. The open-circuit voltage gain A_v is negative.

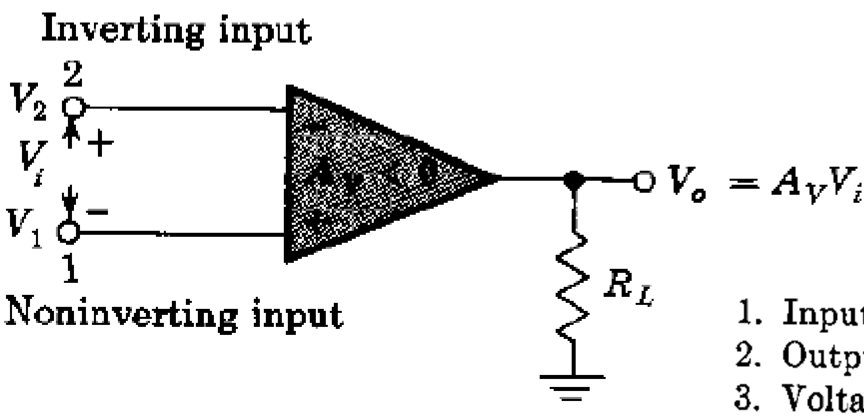


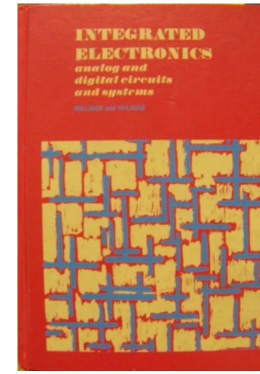
Operational Amplifier refers to the entire feedback circuit

Concept of a “Base Amplifier” as the high-gain amplifier block

Note Base Amplifier is modeled as a voltage amplifier with single-ended input and output

Millman view of an operational amplifier in 1972





1. Input resistance $R_i = \infty$
2. Output resistance $R_o = 0$
3. Voltage gain $A_v = -\infty$
4. Bandwidth $= \infty$
5. $V_o = 0$ when $V_1 = V_2$ independent of the magnitude of V_1
6. Characteristics do not drift with temperature.

This book was published several years after the first integrated op amps were introduced by industry

This fundamentally agrees with that in use today by most authors

Major change in the concept from his own earlier works

Seminal source for “Operational Amplifier” notation:

444 PROCEEDINGS OF THE I.R.E. May 1947

Analysis of Problems in Dynamics by Electronic Circuits*

JOHN R. RAGAZZINI†, MEMBER, I.R.E., ROBERT H. RANDALL‡, AND FREDERICK A. RUSSELL§, MEMBER, I.R.E.

The term “operational amplifier” is a generic term applied to amplifiers whose gain functions are such as to enable them to perform certain useful operations such as summation, integration, differentiation, or a combination of such operations.

Seminal source introduced a fundamentally different definition than what is used today

Consistent with the earlier use of the term by Millman

Seminal Publication of Feedback Concepts:

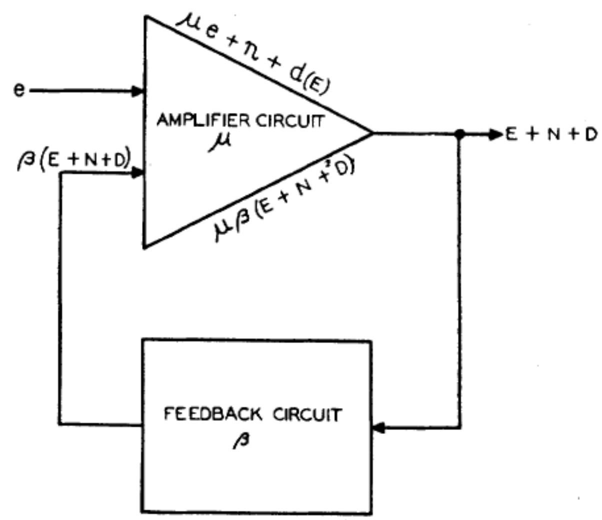
Stabilized Feed-Back Amplifiers

By
H. S. BLACK
MEMBER A.I.E.E.

Bell Telephone Laboratories, Inc.,
New York, N. Y.

Transactions of the American Institute of Electrical Engineers, Jan. 1934

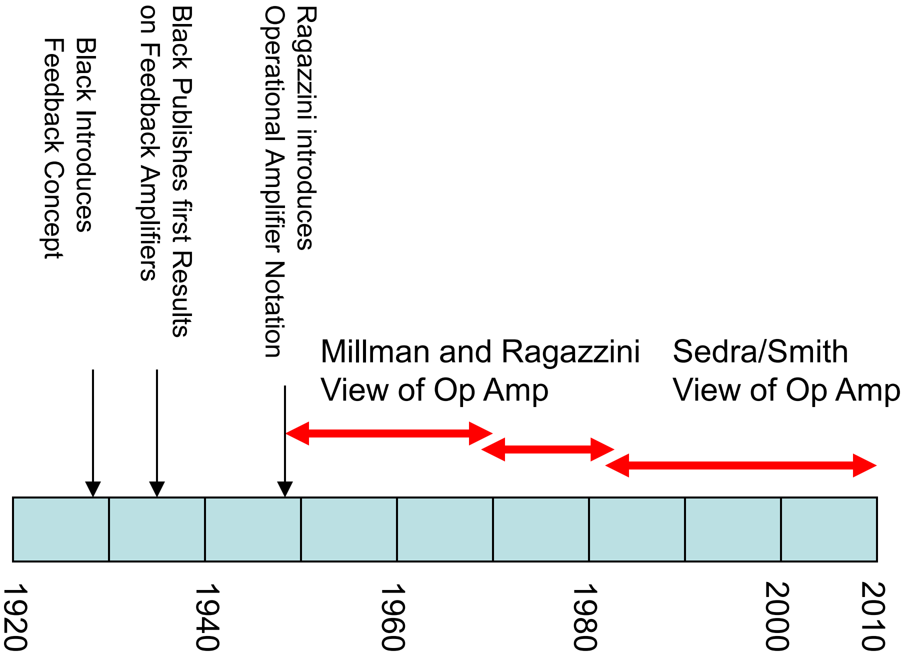
Fig. 1. Amplifier system with feed-back



Uses a differential input high-gain voltage amplifier (voltage series feedback)

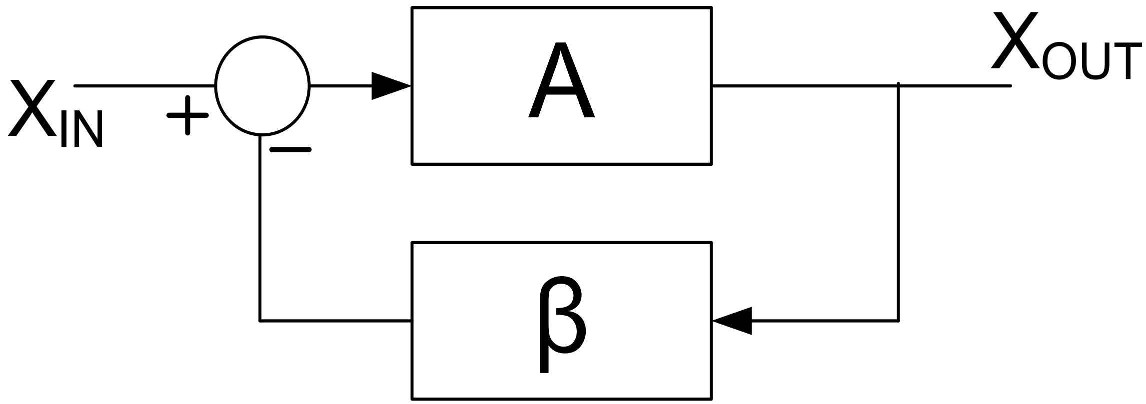
Subsequent examples of feedback by Black relaxed the differential input requirement

Operational Amplifier Evolution in Time Perspective



Do we have it right now?

Why are Operational Amplifiers Used?

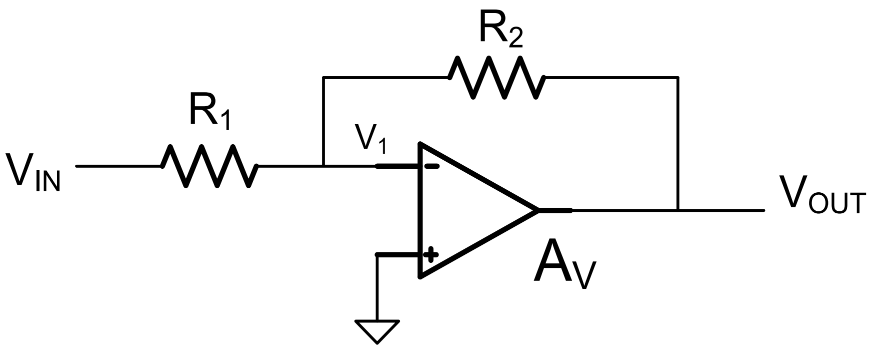


Input and Output Variables intentionally designated as "X" instead of "V"

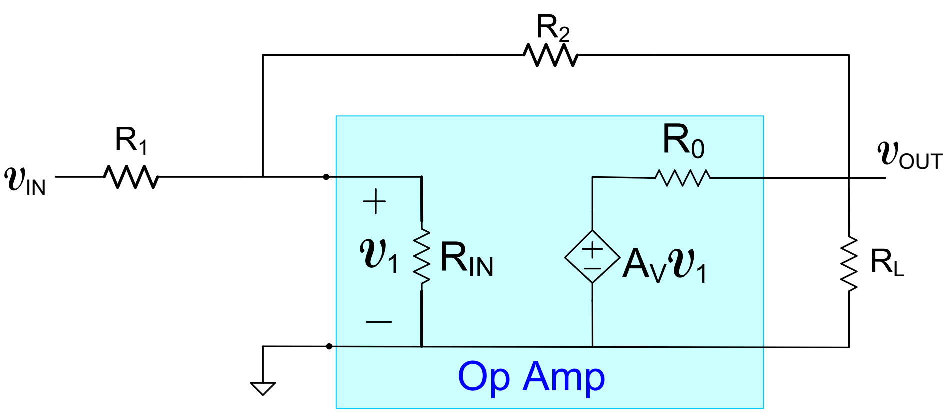
$$\frac{Xout}{Xin} = A_F = \frac{A}{1+A\beta} = \overset{A\to\infty}{\approx} \frac{1}{\beta}$$

Op Amp is Enabling Element Used to Build Feedback Networks !

One of the Most Basic Op Amp Applications



Model of Op Amp/Amplifier including A_V, R_{IN}, R_O and R_L

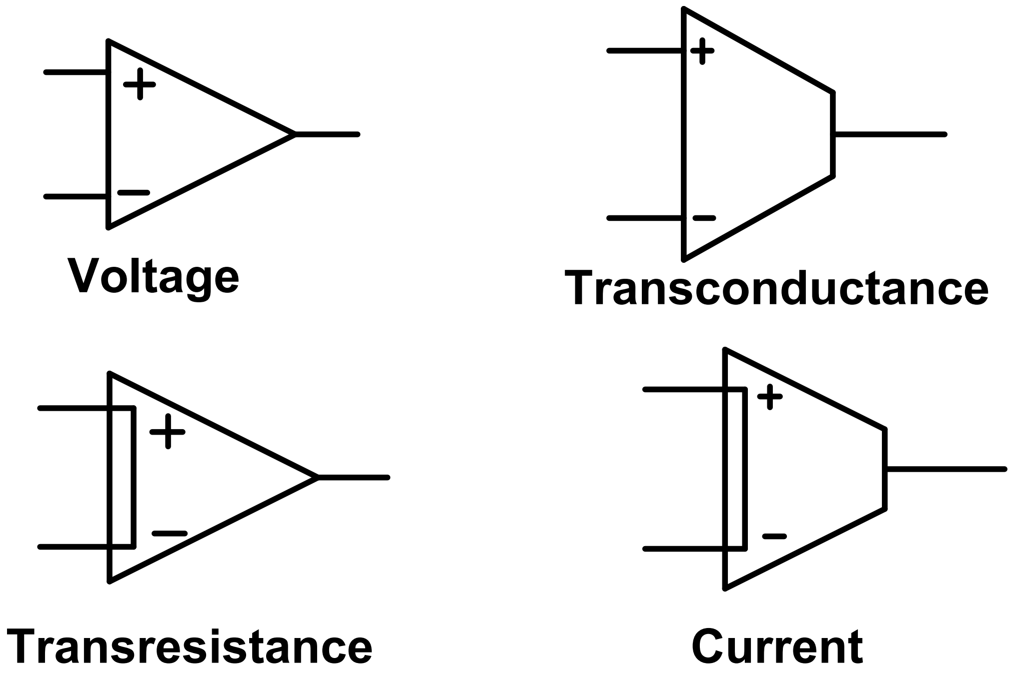


If it is assumed that A_V is large,

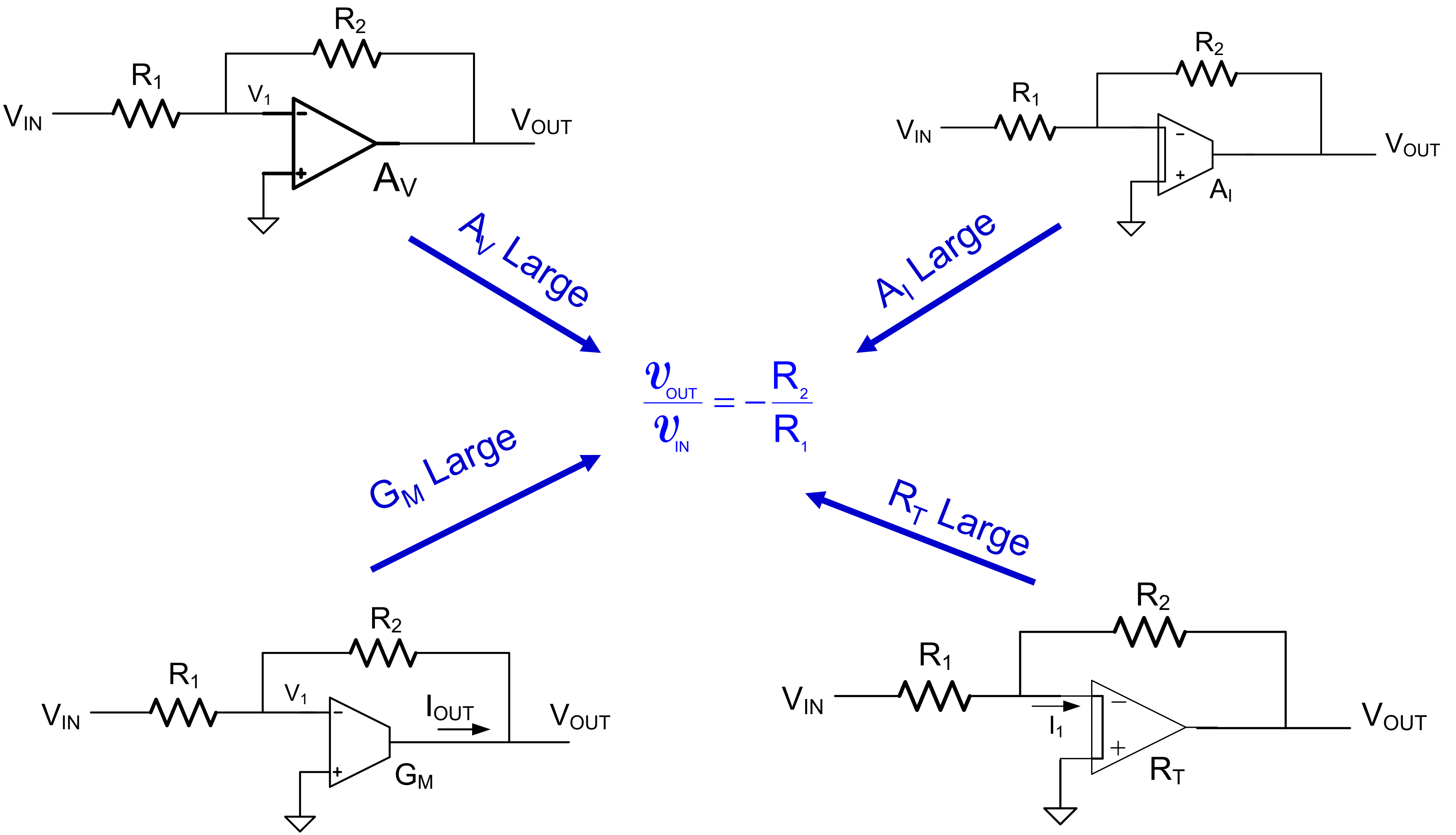
$$A_{VF} = \frac{v_{OUT}}{v_{IN}} \simeq -\frac{R_2}{R_1}$$

This result is not dependent upon R_{IN}, R_0 or R_L

The Four Basic Types of Amplifiers:



Four Feedback Circuits with Same β Network



$$\frac{v_{OUT}}{v_{IN}} = -\frac{R_2}{R_1}$$

All have same closed-loop gain and all are independent of R_{IN}, R_{OUT} and R_L if gain is large

Concept well known

AN-88 CMOS LINEAR APPLICATIONS

Gene Taatjes

JULY 1973

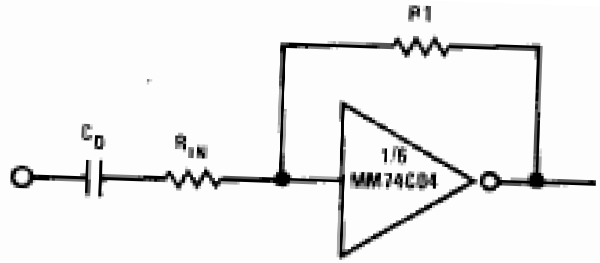
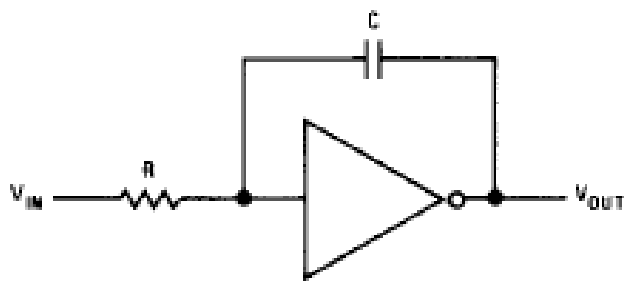


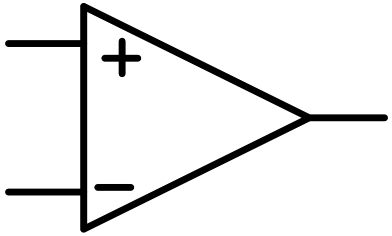
FIGURE 2. A 74CMOS Invertor Biased for Linear Mode Operation.



Integrator Using
Any Inverting CMOS Gate

Hex Inverters in 74C04 much less costly than 6 op amps at the time!

What is an Operational Amplifier?



Textbook Definition:

- Voltage Amplifier with Very Large Gain
  - Very High Input Impedance
  - Very Low Output Impedance

This represents the Conventional Wisdom !

Do we have it right now?

~~Voltage Amplifier?~~ ~~Low Output Impedance?~~ ~~Single-Ended Output?~~

~~High Input Impedance?~~ ~~Differential Input?~~ Large Gain !!!

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Will consider 5 basic examples in this discussion

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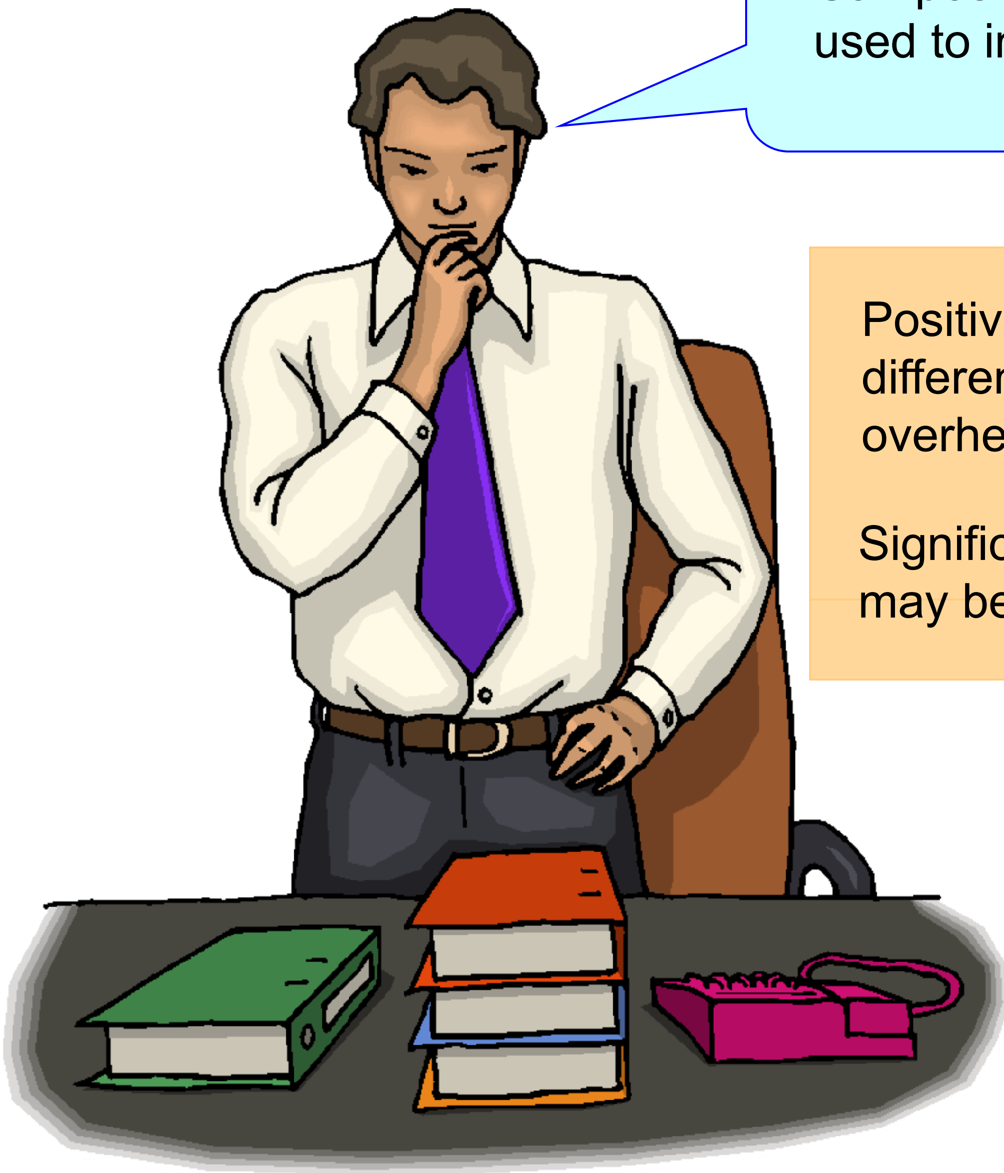
- Positive Feedback Compensation
- Current Mode Filters
- Current Dividers
- Barkhausen Criteriion



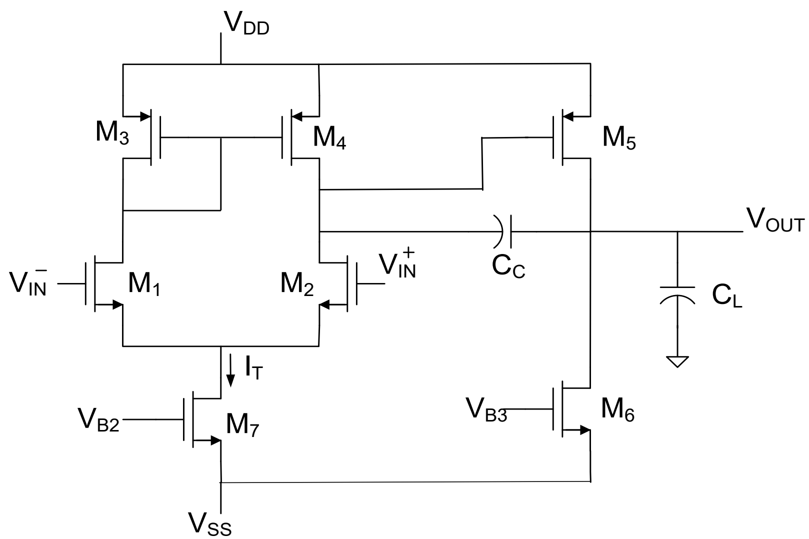
Can positive feedback compensation be used to improve amplifier performance

Positive feedback can be easily applied in differential structures with little circuit overhead

Significant gain enhancement in the op amp may be possible if positive feedback is used

Compensation of two-stage amplifiers

To illustrate concept consider basic two-stage op amp with internal compensation



$$A_V = \left(A_0 \frac{p_1 p_2}{z}\right) \frac{-s+z}{(s+p_1)(s+p_2)}$$

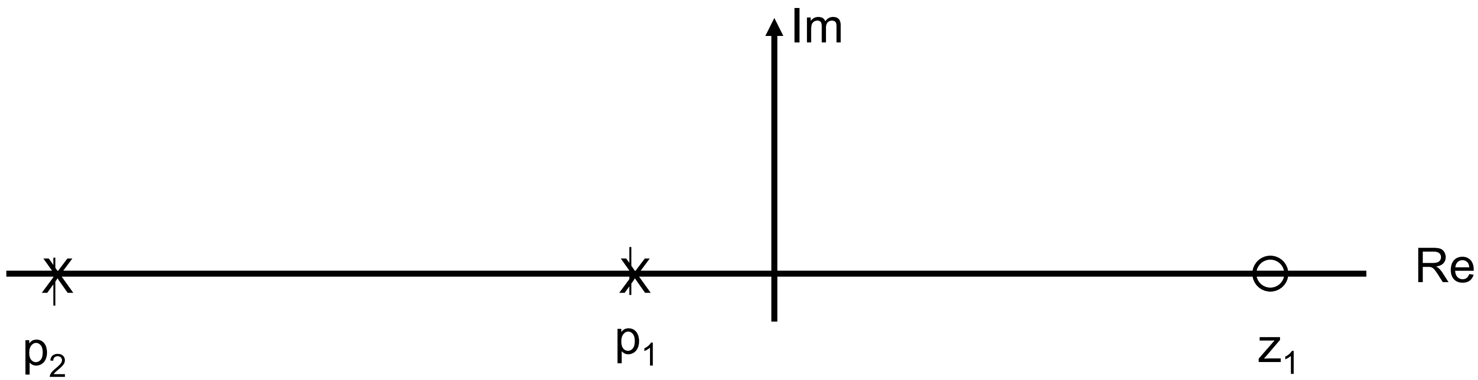
Miller Effect on C_C provides dominant pole on first stage

Compensation requires a large ratio of p_2/p_1 be established

Two-stage amplifier with LHP Zero Compensation

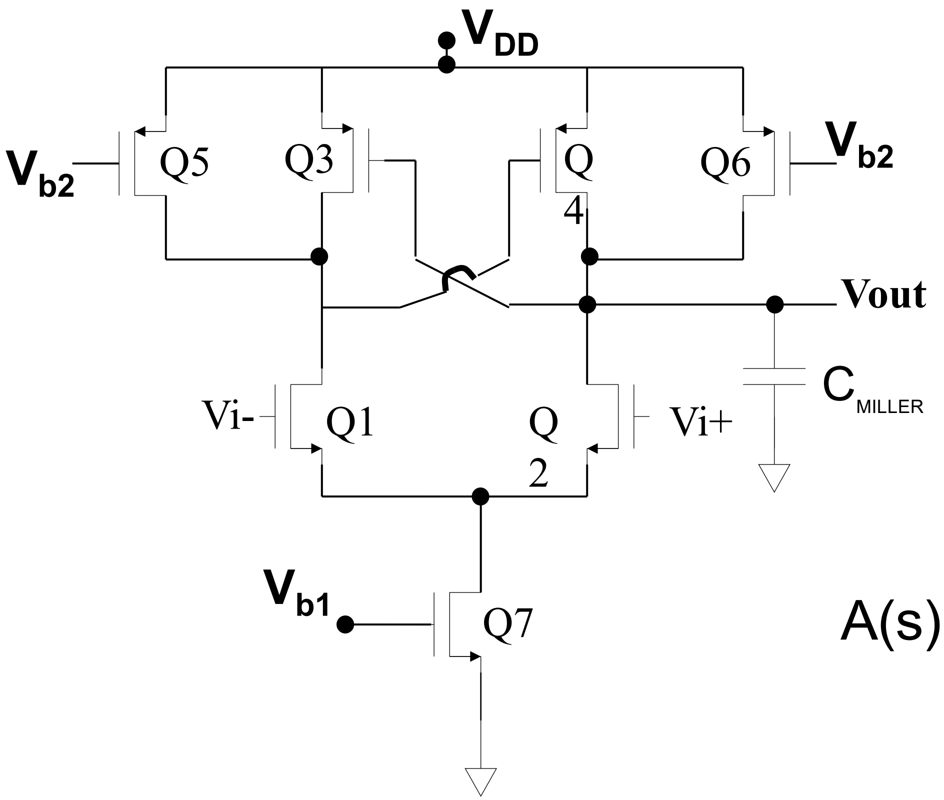
$$p_1 = -\frac{g_{o1} + g_{o5}}{C_C\left(\frac{g_{m5}}{g_{05} + g_{o6}}\right)}$$

$$p_2 = -\frac{g_{m5}}{C_L}$$



To make p_1 sufficiently dominant requires a large value for C_C

Positive Feedback on First-Stage for gain enhancement and pole control



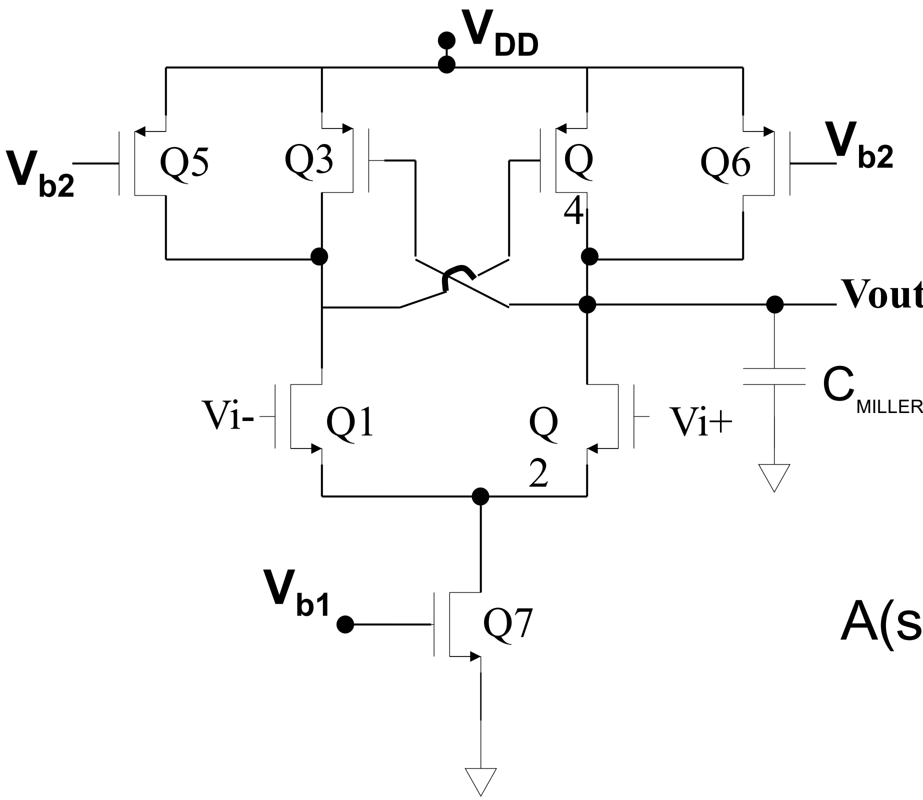
$$A(s) = \frac{(1/2)g_{m1}}{sC_{MILLER} + [g_{o2} + g_{o4} + g_{o6} - g_{m4}]}$$

$$p_1 \simeq -\frac{g_{o1}+g_{o5}+g_{o6}-g_{m4}}{C_{MILLER}}$$

Can reduce size of C_{MILLER} and enhance dc gain by appropriate choice of g_{m4}

Can actually move p_1 into RHP if g_{m4} is too big

Positive Feedback on First-Stage for gain enhancement and pole control



$$A(s) = \frac{(1/2)g_{m1}}{sC_{MILLER} + [g_{o2} + g_{o4} + g_{o6} - g_{m4}]}$$

$$A_{DC} \simeq -\frac{(1/2)g_{m1}}{g_{o1}+g_{o5}+g_{o6}-g_{m4}}$$

Dc gain actually goes to ∞ when $g_{m1} = g_{02} + g_{04} + g_{06}$!

This technique is not practical since Op Amp pole can move into RHP making it unstable!

$$p_1 \simeq -\frac{g_{o1}+g_{o5}+g_{o6}-g_{m4}}{C_{MILLER}}$$

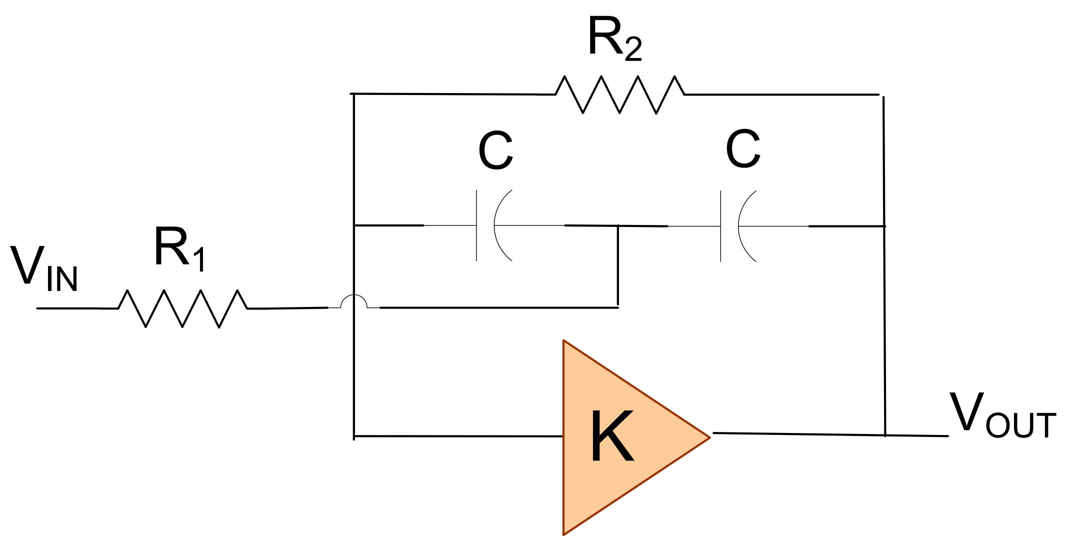
Several authors have discussed this approach in the literature but place a major emphasis on limiting the amount of positive feedback used so that under PVT variations, op amp remains stable

Is an unstable op amp really bad?

Will a circuit that embeds an op amp be unstable if the op amp is unstable?

Example: Filter Structure with Feedback Amplifier

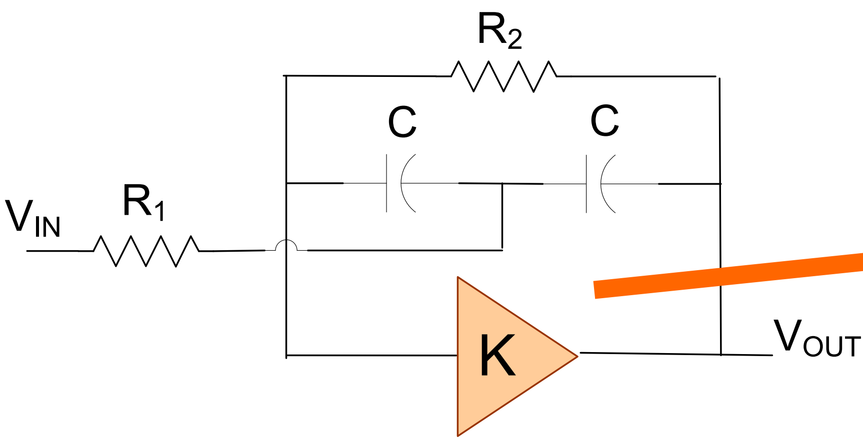
Bridged-T Feedback
(Termed SAB, STAR, Friend/Delyannis Biquad)

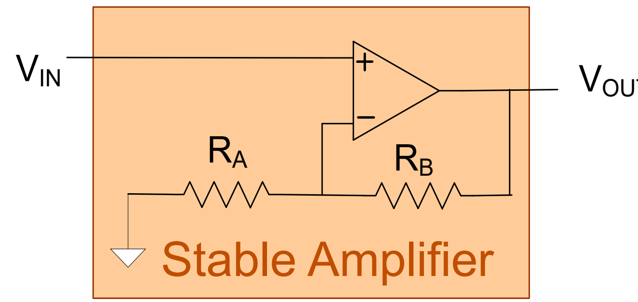


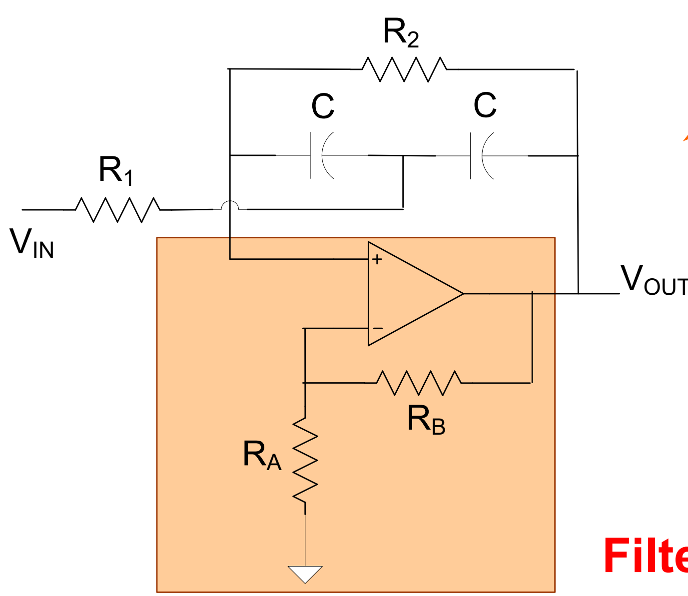
K is a small positive gain
want high input impedance on "K" amplifier

- Very popular filter structure
- One of the best 2nd-order BP filters
- Widely used by Bell System in 70's

Example: Filter Structure with Feedback Amplifier

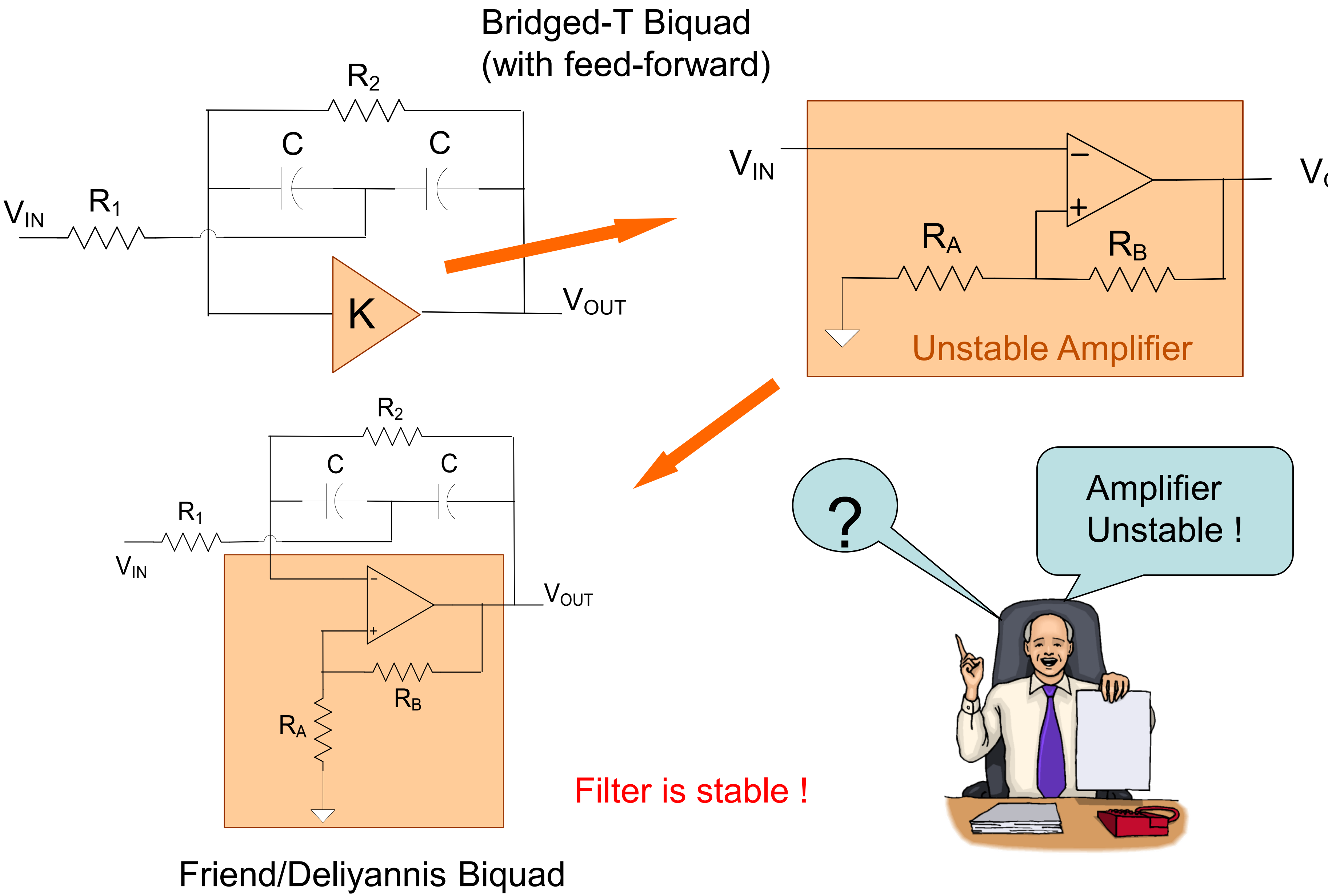






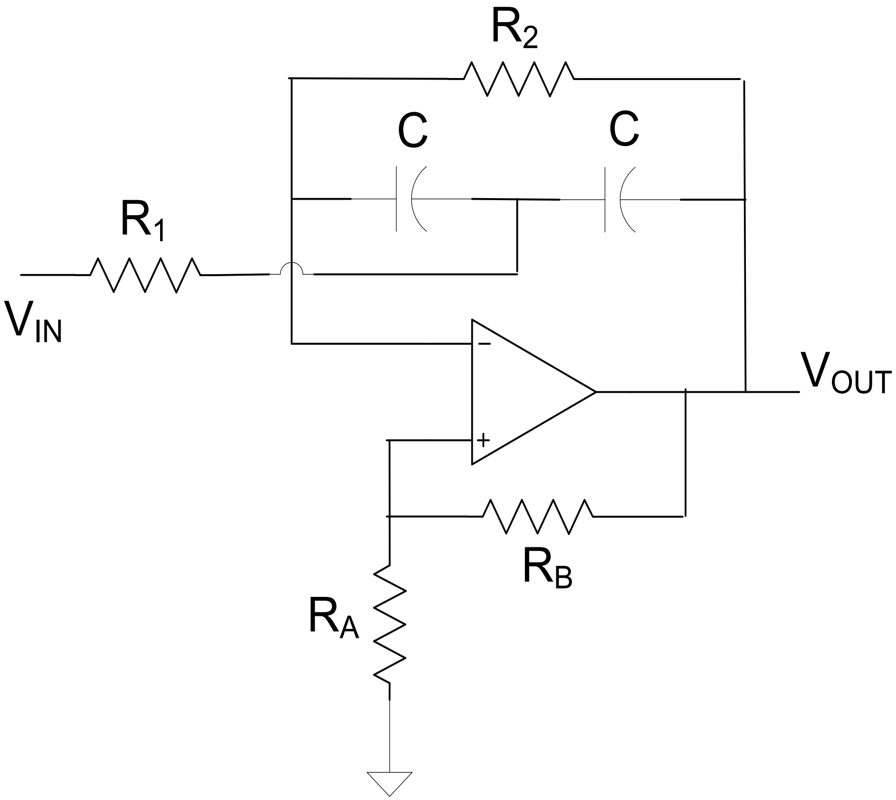
Filter is unstable !

Example: Filter Structure with Feedback Amplifier



Very Popular Bandpass Filter

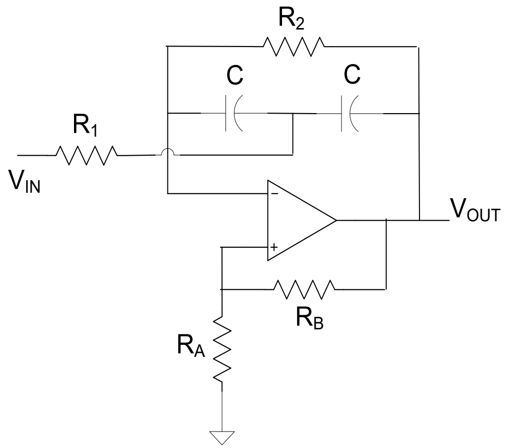
Friend-Deliyannis Biquad



One of the best bandpass filters !!

Embedded finite gain amplifier is unstable!!

Stability of embedded amplifier is not necessary (or even desired)

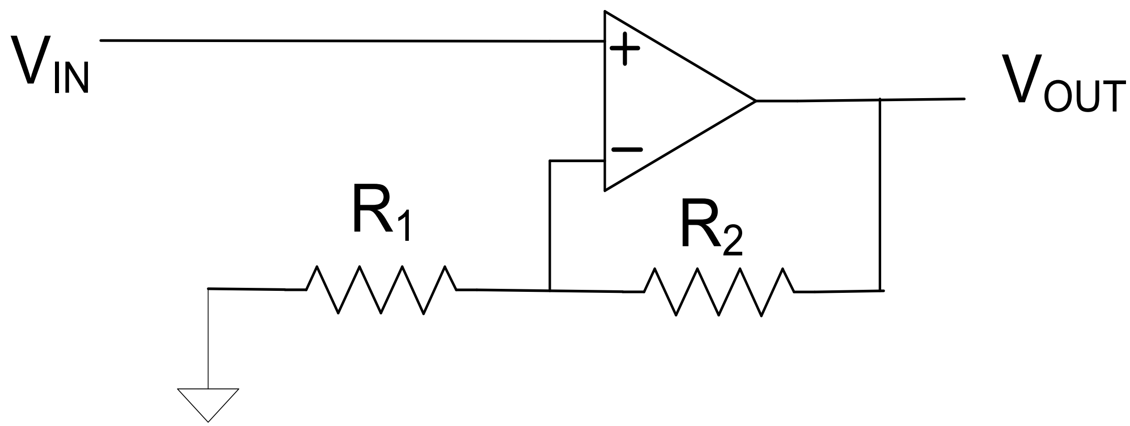


- Filter structure unstable with stable finite gain amplifier
- Filter structure stable with unstable finite gain amplifier
- Stability of feedback network not determined by stability of amplifier!

Is an unstable op amp really bad?

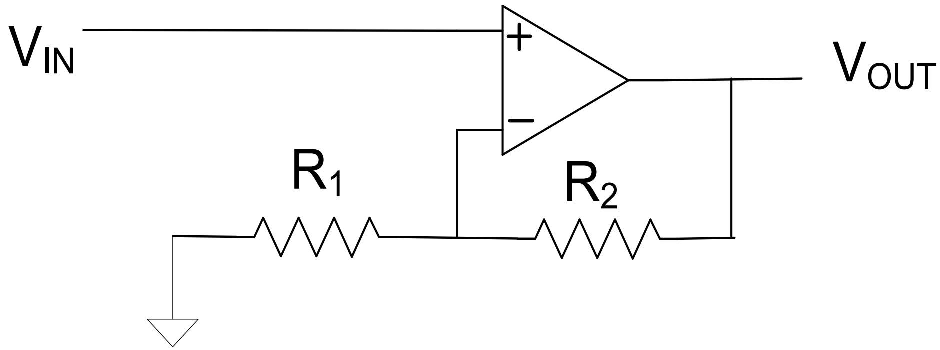
Will a circuit that embeds an op amp be unstable if the op amp is unstable? Not necessarily !

Example: Voltage Amplifier with Unstable Op Amp



$$A(s) = \frac{-A_o}{\frac{s}{-p} + 1} \qquad p > 0$$

Example: Voltage Amplifier with Unstable Op Amp



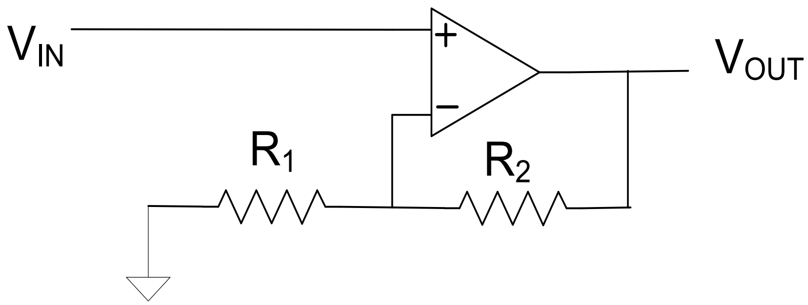
$$\beta = \frac{R_1}{R_2 + R_1}$$

$$A(s) = \frac{-A_o}{\frac{s}{-p} + 1}$$

$p > 0$

$$A_{FB}(s) = \frac{A(s)}{1 + \beta A(s)}$$

Example: Voltage Amplifier with Unstable Op Amp



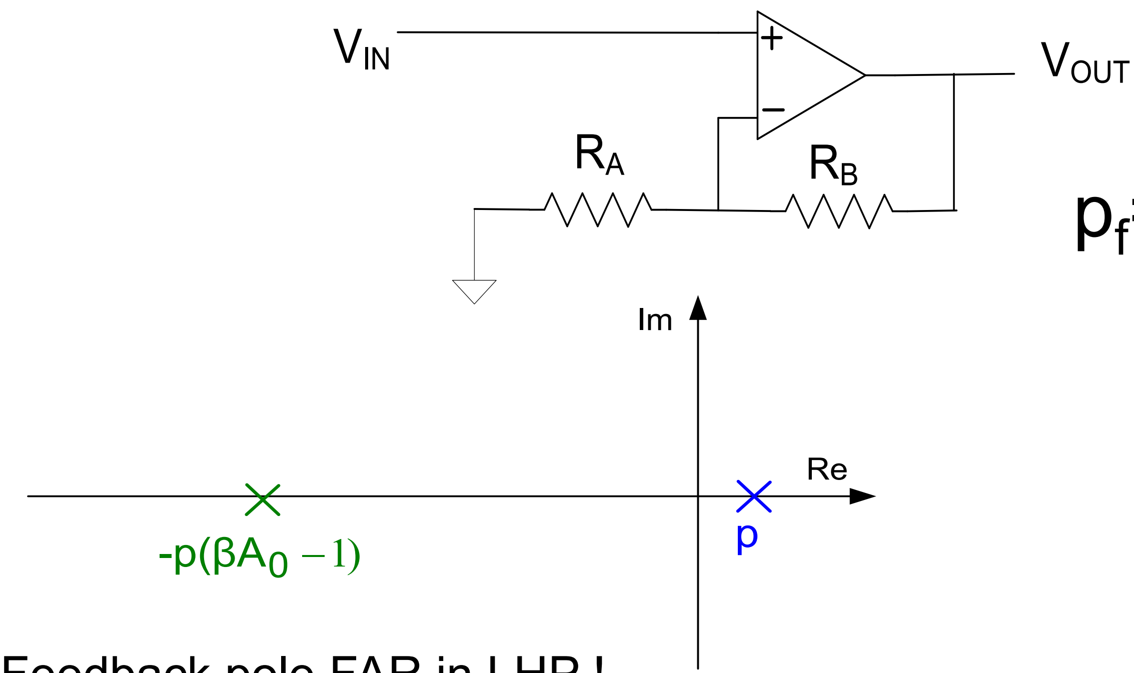
$$A_{FB}(s) = \frac{A(s)}{1+\beta A(s)} = \frac{A_o p}{s+p\left(\beta A_o - 1\right)}$$

$p > 0$

$$p_f = p(1-\beta A_0)$$

For $\beta A_o > 1$, Feedback Amplifier is Stable !!!

Example: Voltage Amplifier with Unstable Op Amp

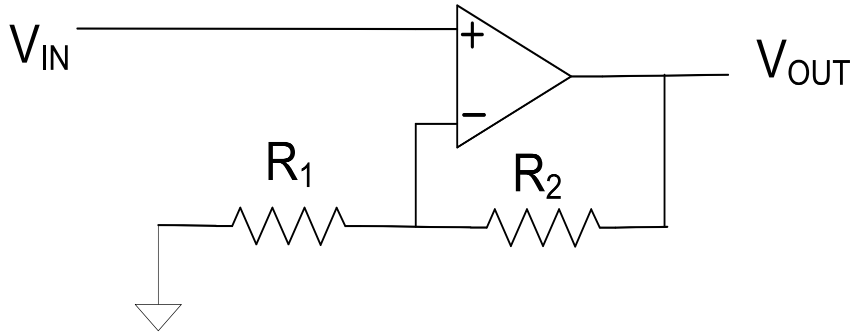


$$p_f = p(1-\beta A_0)$$

Feedback pole FAR in LHP !

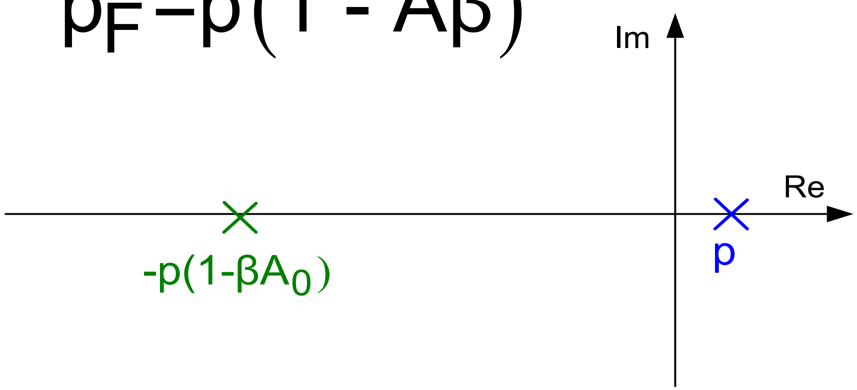
How does this compare to the feedback pole of a stable op amp with a pole
In the LHP at –p?

Example: Voltage Amplifier with Unstable Op Amp



$p > 0$

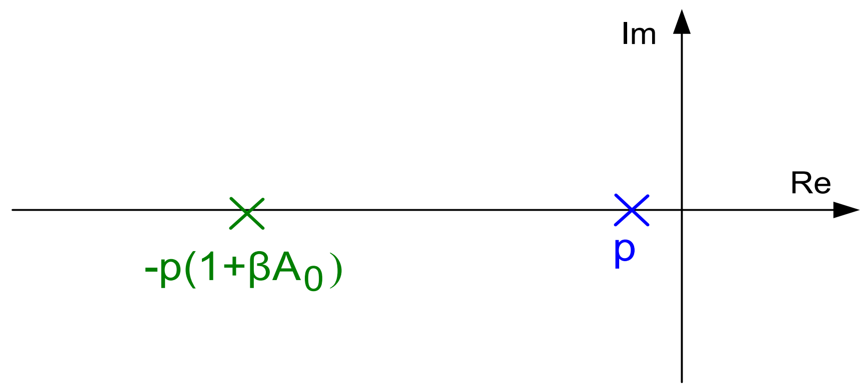
$$p_F = p(1 - A\beta)$$



Feedback pole FAR in LHP !

$p < 0$

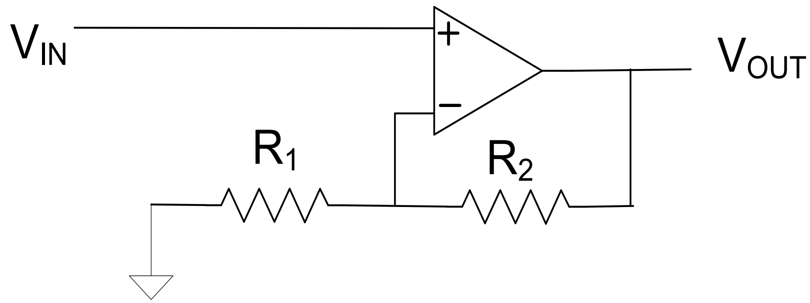
$$p_F = p(1 + A\beta)$$

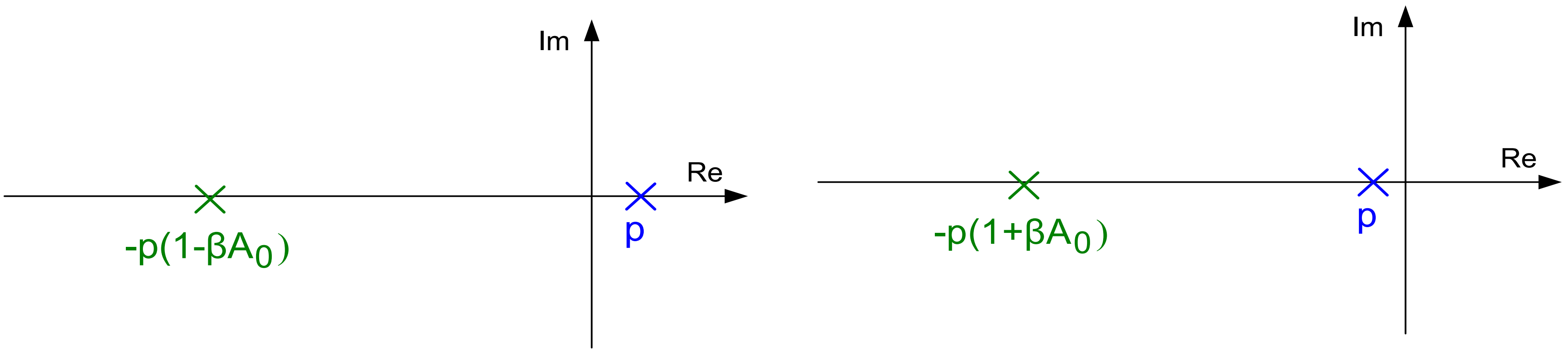


Feedback pole FAR in LHP !

Can show that some improvements in feedback performance can be realized if the open-loop pole is at the orgin or modestly in the RHP!

Example: Voltage Amplifier with Unstable Op Amp





Stability of open-loop amplifier is not a factor in determining the stability of the feedback structure in practical structures when |p| is small!

It can actually be shown that the performance of the feedback amplifier can be improved if the open-loop pole is moved modestly into the RHP

This is contrary to the Conventional Wisdom !

Is an unstable op amp really bad?

No, and it can actually improve performance of FB circuit!

Will a circuit that embeds an op amp be unstable if the op amp is unstable? Not necessarily !

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Will consider 5 basic examples in this discussion

- Op Amp
- Positive Feedback Compensation
- Current Mode Filters
- Current Dividers
- Barkhausen Criterion

What are the advantages of current-mode signal processing ?

EVERYBODY knows that Current-Mode circuits operate at lower supply voltages, are faster, are smaller, consume less power, and take less area than their voltage-mode counterparts !

And I've heard there are even some more benefits but with all of these, who really cares?

Have considered Current Mode Filters in earlier lectures

Showed by example that an Active RC Current-Mode Filter was identical to a Voltage-Mode Counterpart

Will now look at more general Current-Mode Architectures

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?
- Or have they?

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

- 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?

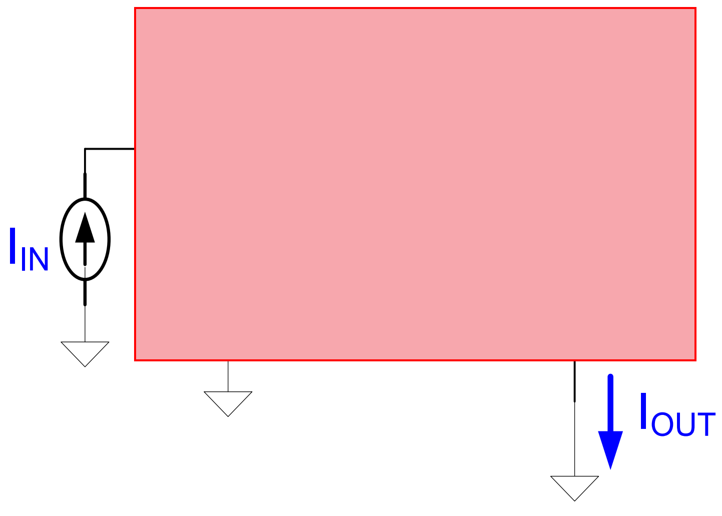
Questions about the Conventional Wisdom

Conventional Wisdom Definition:

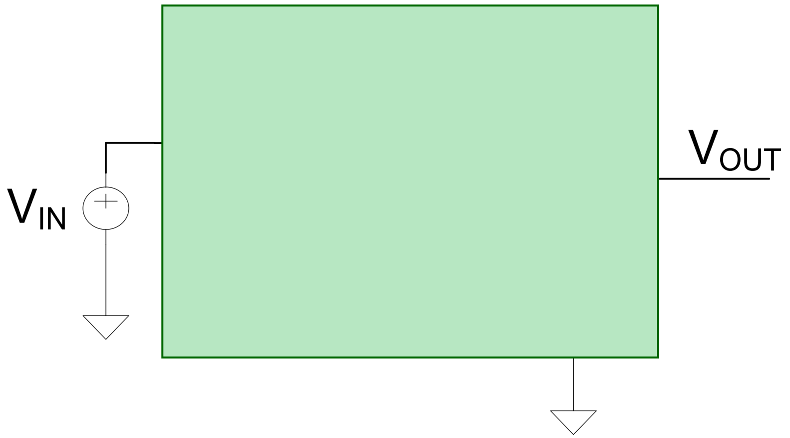
- A current-mode circuit is a circuit that processes current signals
- A current-mode circuit is one in which the defined state variables are currents

Example:

Is this a current-mode circuit?



Is this a voltage-mode circuit?

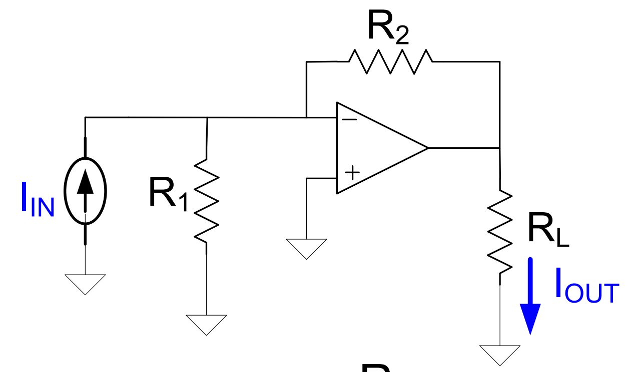


Conventional Wisdom Definition:

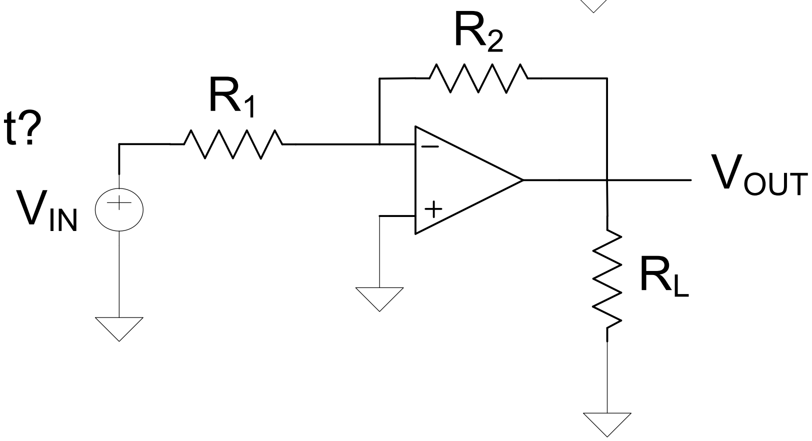
A current-mode circuit is a circuit that processes current signals

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 !**

Current-Mode Filters

Concept of Current-Mode Filters is Somewhat Recent:

Key paper that generated interest in current-mode filters (ISCAS 1989):

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

JB Hughes, NC Bird, IC Macbeth - … International Symposium on …, 1989 - ieeexplore.ieee.org

… **switched currents**, requiring only a baseline digital process and avoiding many of lhe anticipated low voltage prohlems by operating in the **current** … illustrate the **switched current** concept …

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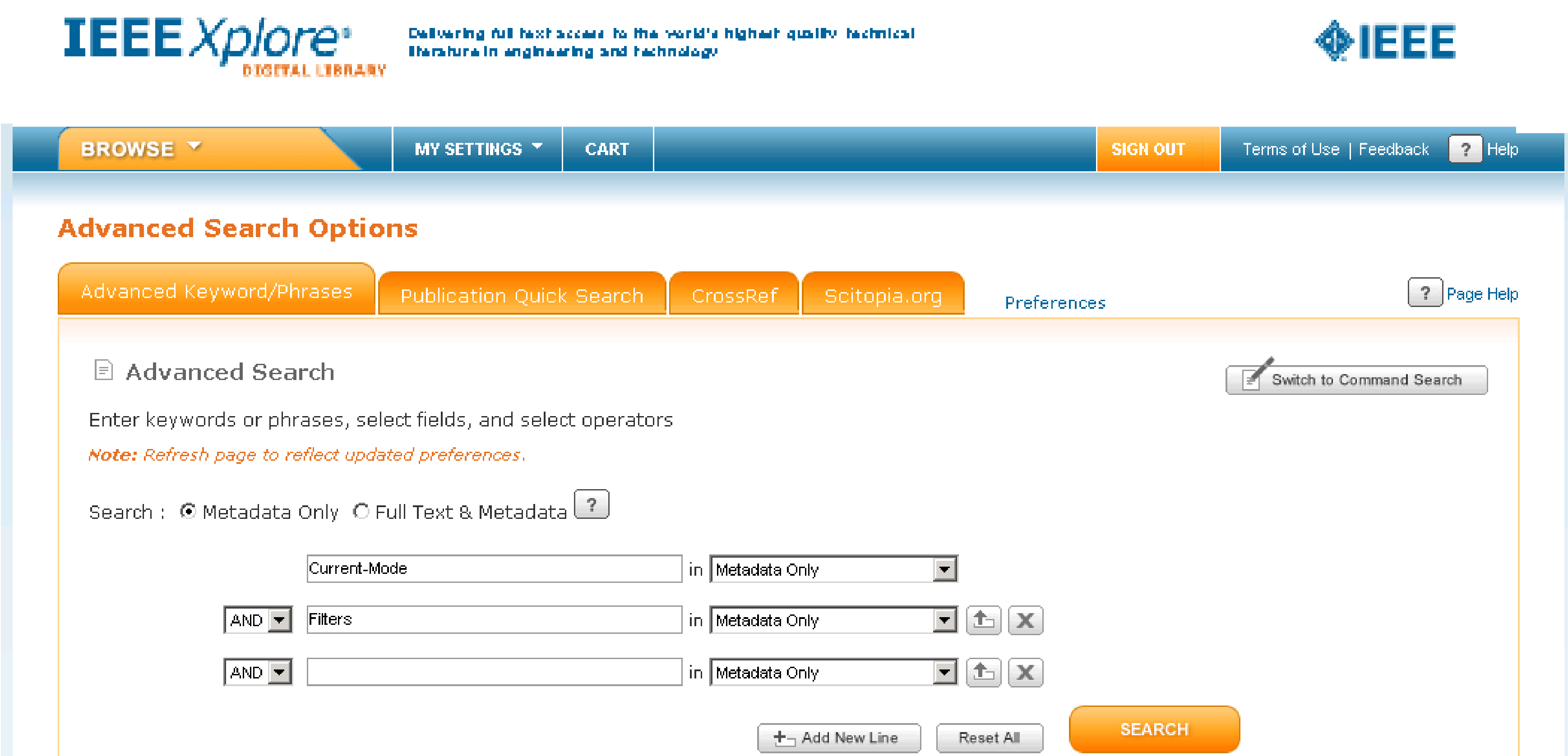
Scholar: Dec 13, 2024

This paper is one of the most significant contributions that has ever come from ISCAS

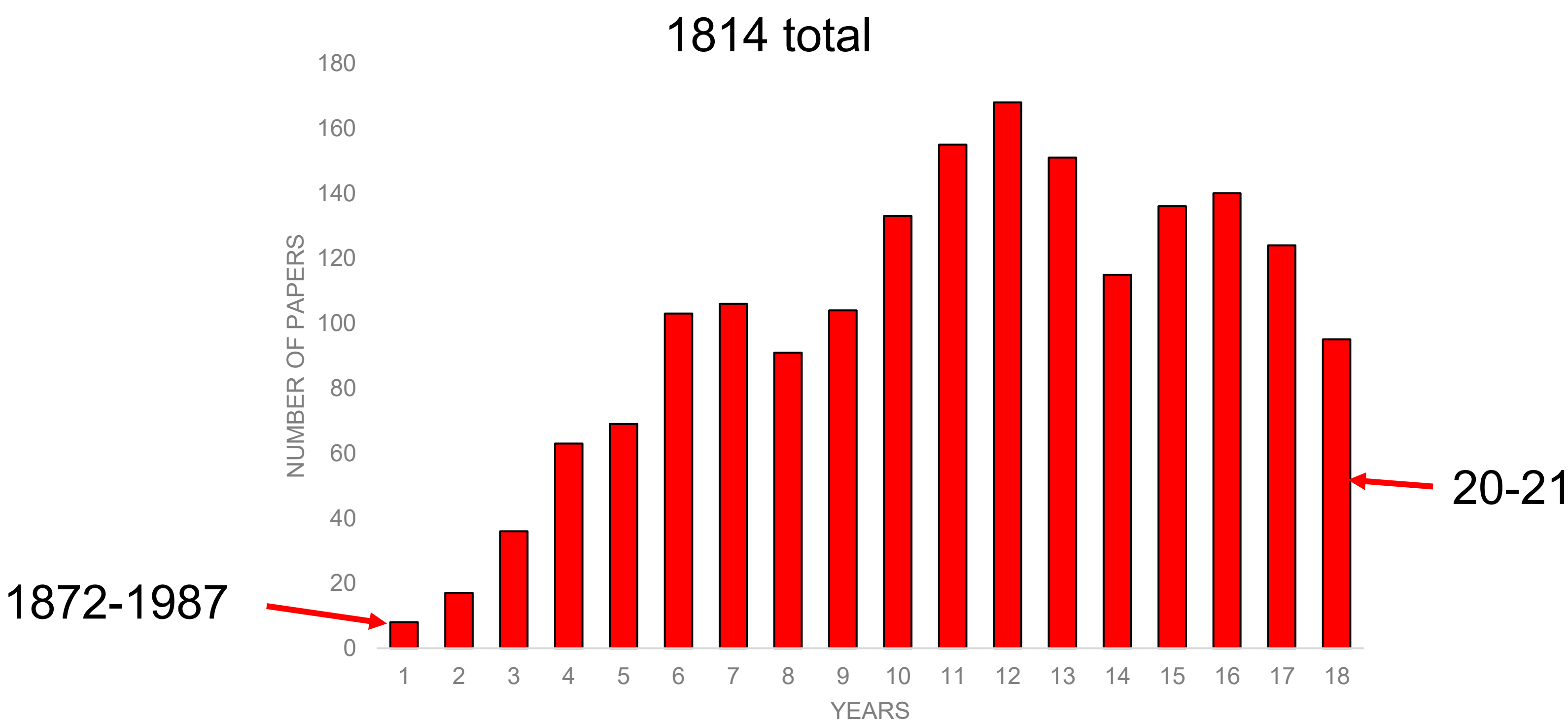
Highly under-cited for the impact it had on the analog circuits field

Current-Mode Filters



Current-Mode Filters

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



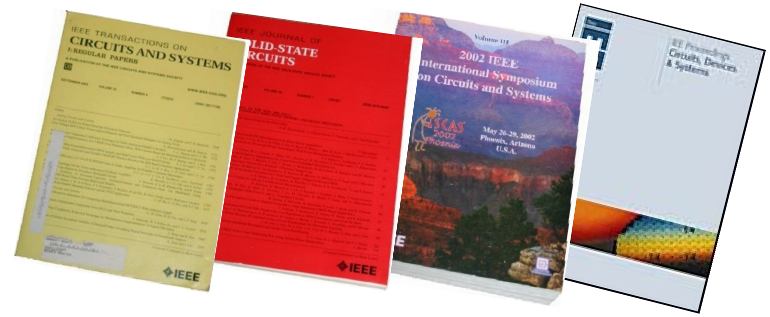
Histogram for 2-year intervals
Most recent is 2020-2021

1872-1987 – total of 8 references

Search done on Oct 28, 2022

Review from Earlier Lecture

Current-Mode Filters



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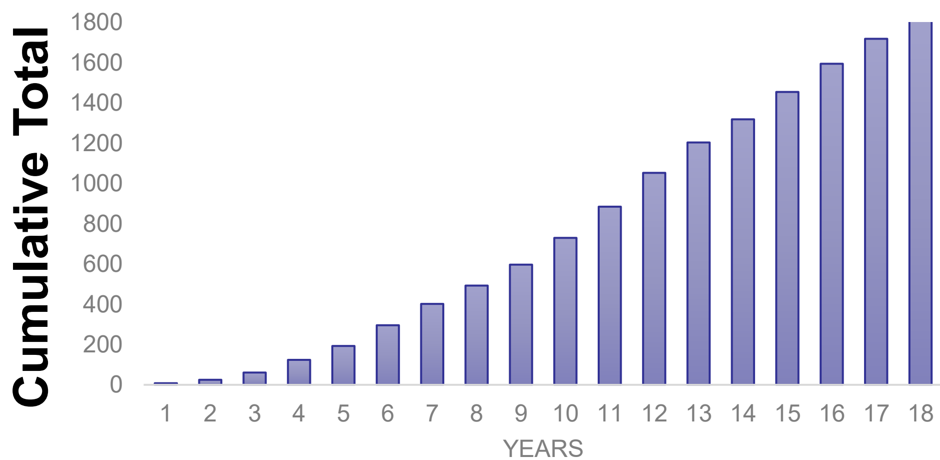


Histogram for 2-year intervals
Most recent is 2020-2021

Search done on Nov 28, 2022

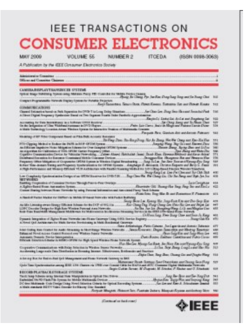
- Steady growth in research in the area since 1990 and publication rate is growing with time !!
- And growth is MUCH bigger outside of IEEE (e.g. Scholar)

Current-Mode Filters

The Conventional Wisdom:

Proc. ICASP May 2010:

It is well known that current-mode circuits can offer many advantages, such as simplicity of circuit structure, high-frequency operation, wide dynamic range, and so on, compared with their voltage-mode counterparts.



IEEE Trans. On Consumer Electronics, Feb 2009

Current mode signal processing is a better solution than conventional voltage mode processing for high speed, low power and low voltage analog circuit design.

Current-Mode Filters

The Conventional Wisdom:

Proc. IEE Dec 2006:

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

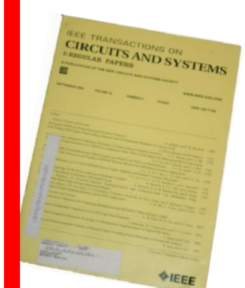
It is well known that current-mode circuits have been receiving significant attention owing to its advantage over the voltage-mode counterpart, particularly for higher frequency of operation and simpler filtering structure [1].

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, 1989 - IET

… amplifiers to operate at **frequencies** 100-500 times less than … further restricted to operate at **frequencies** approximately 10-50 … In contrast, **current-mode** circuits can be designed to derive …

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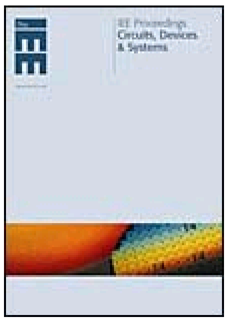
Scholar: Dec 13, 2024

"To make greatest use of the available transistor bandwidth 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 - IEE Proceedings G (Circuits, Devices and Systems), 1990 - IET

… The use of **current** rather than voltage as the active … A **current**-mode approach is not just restricted to **current** … This paper sets out to survey **developments** in **conveyors** and currentmode ..

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Scholar: Dec 13, 2024

"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."

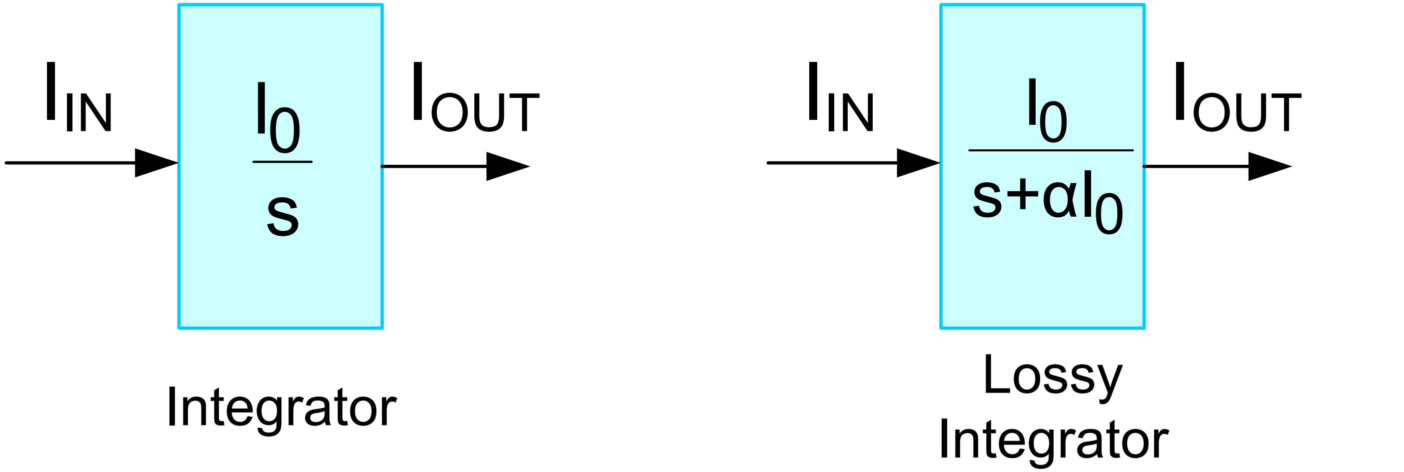
Current-Mode Filters

The 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

This represents four really significant benefits of current-mode circuits!

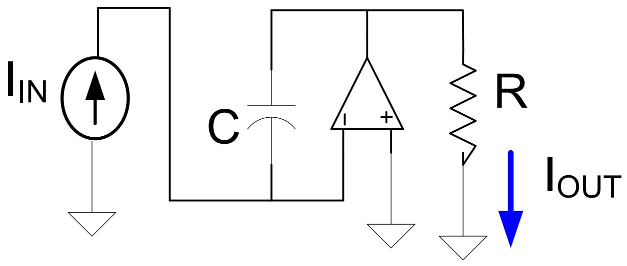
Current-Mode Filters



As with voltage-mode filters, most integrated current-mode filters are built with integrators and lossy integrators

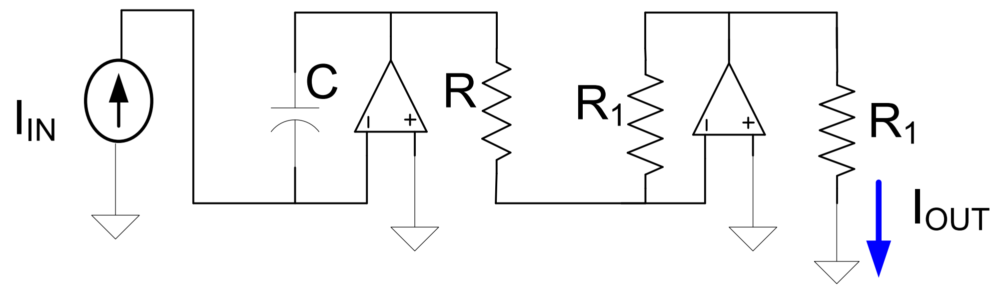
Some Current-Mode Integrators

Active RC



$$I_{OUT} = \left(\frac{-1}{RCs}\right) I_{IN}$$

Inverting



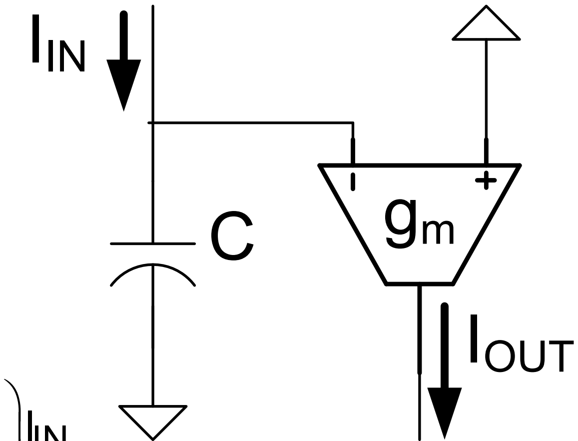
$$I_{OUT} = \left(\frac{1}{RCs}\right) I_{IN}$$

Noninverting

- Summing inputs really easy to obtain
- Loss is easy to add
- Some argue that since only interested in currents, can operate at lower voltages

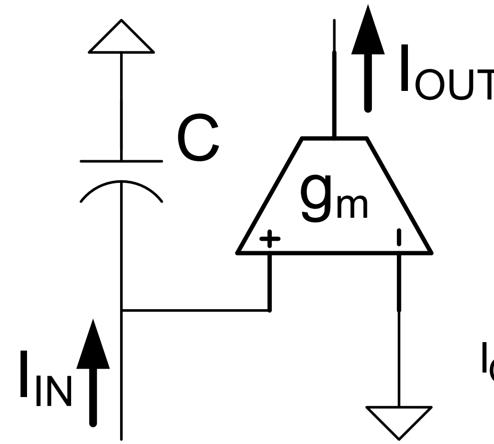
Some Current-Mode Integrators

OTA-C



$$I_{OUT} = \left(\frac{-g_m}{Cs}\right) I_{IN}$$

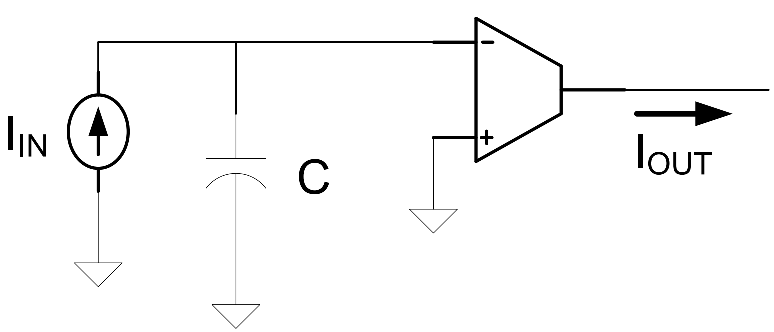
Inverting

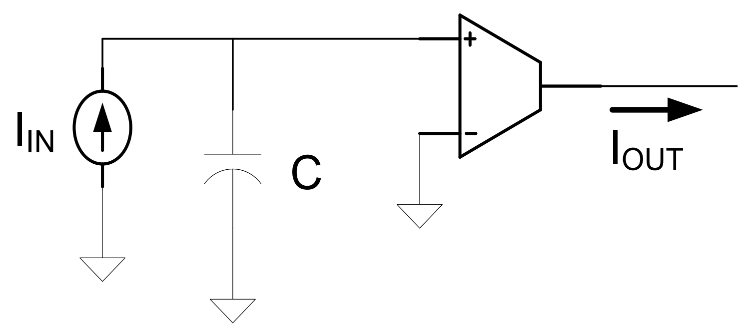


$$I_{OUT} = \left(\frac{g_m}{Cs}\right) I_{IN}$$

Noninverting

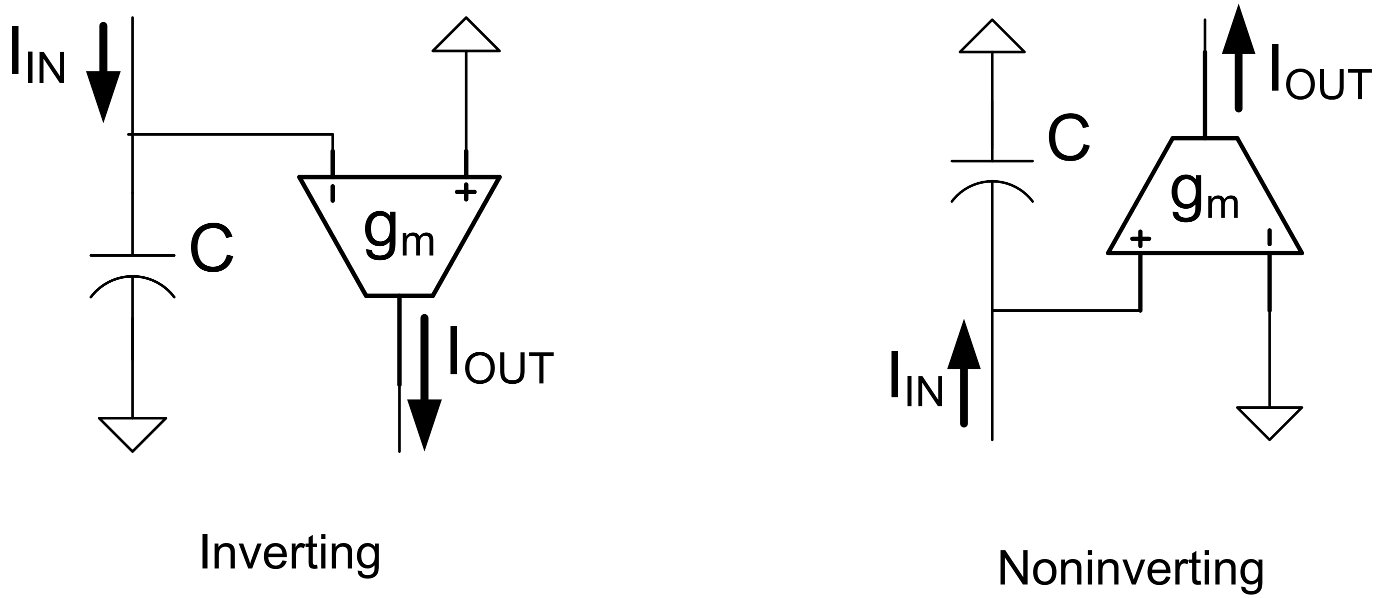
Alternate representation





Some Current-Mode Integrators

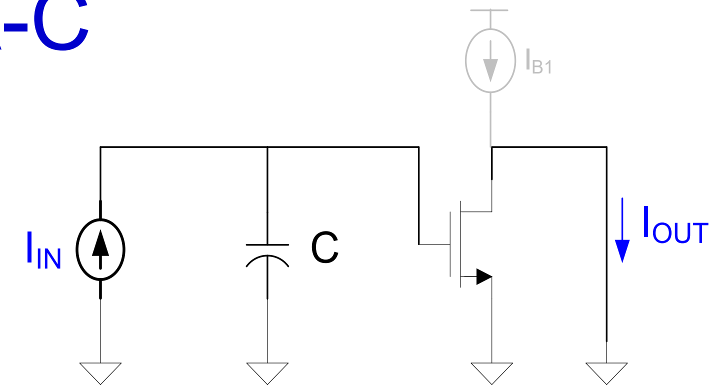
OTA-C



- Summing inputs really easy to obtain
- Loss is easy to add
- Many argue that since only interested in currents, can operate at lower voltages and higher frequencies

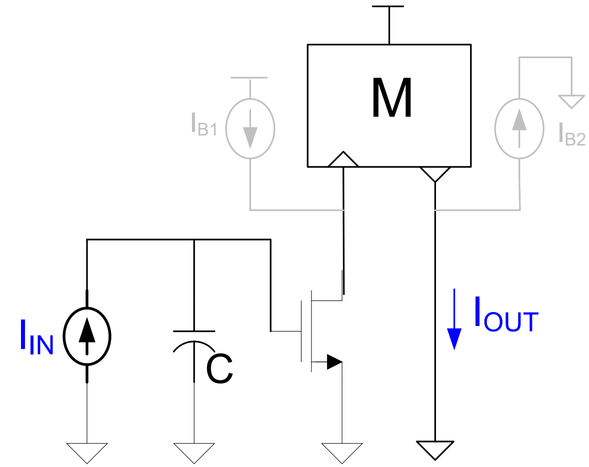
Some Current-Mode Integrators

TA-C



$$I_{OUT} = \left(\frac{-g_m}{Cs}\right) I_{IN}$$

Inverting

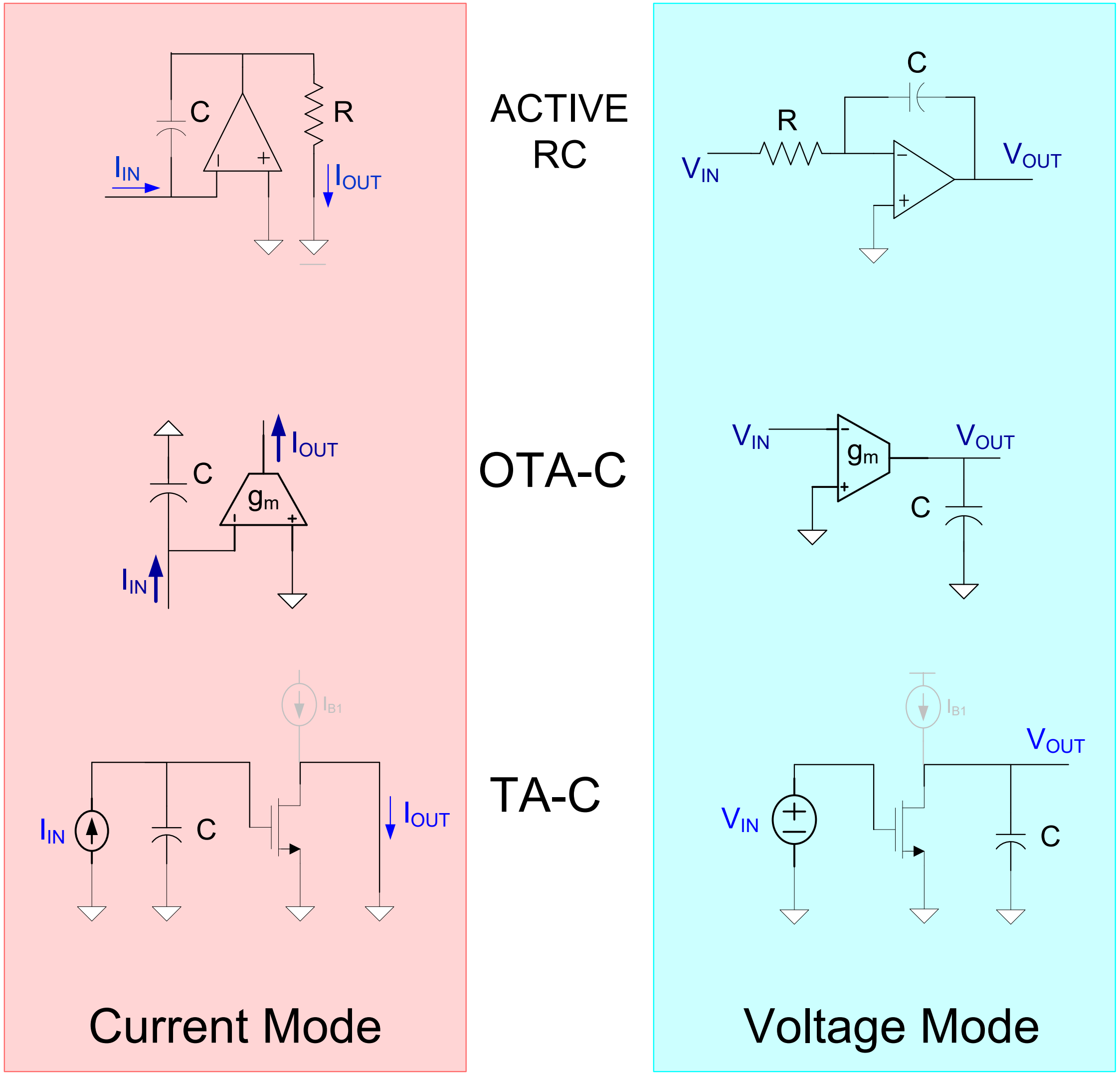


$$I_{OUT} = \left(\frac{g_m}{Cs}\right) I_{IN}$$

Noninverting

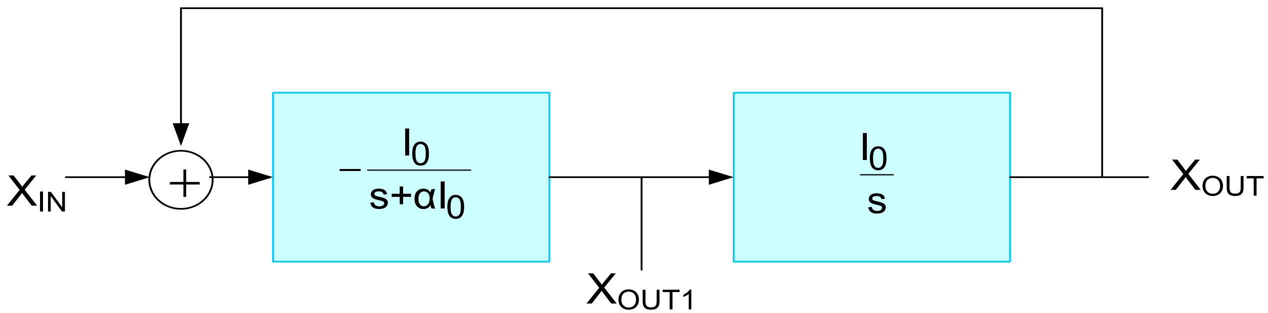
- Summing inputs really easy to obtain
- Loss is easy to add
- Many argue that since only interested in currents, can operate at lower voltages and higher frequencies

Comparison of Current Mode and Voltage Mode Integrators



- Current Mode and Voltage Mode Inverting integrators have same device counts
- Same is true of noninverting and lossy structures

Two-Integrator-Loop Biquad

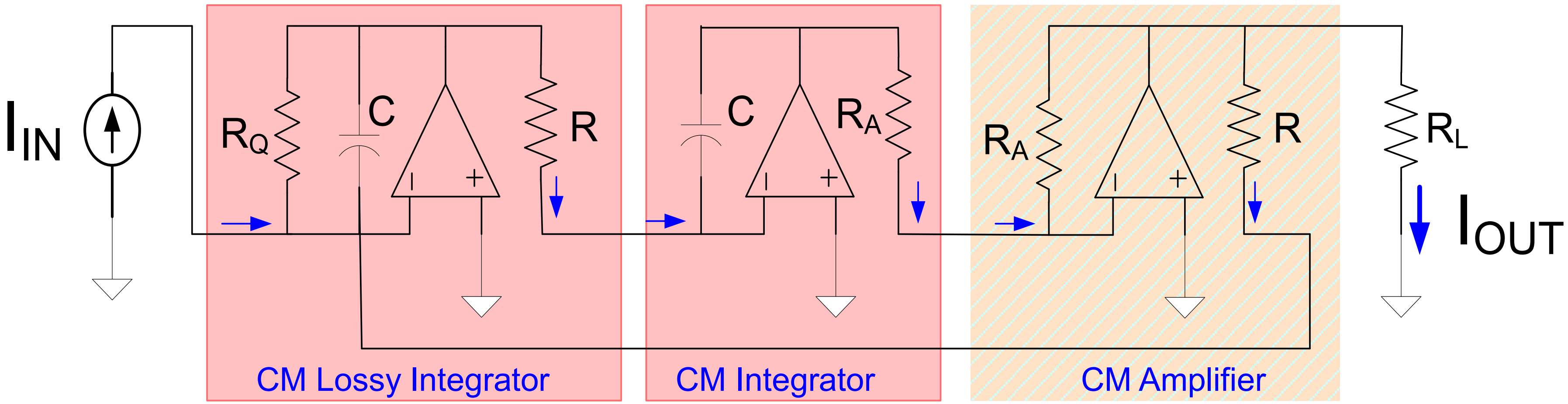


One of the most widely used architectures for implementing integrated filters

Review from Earlier Lecture

Current-Mode Two Integrator Loop

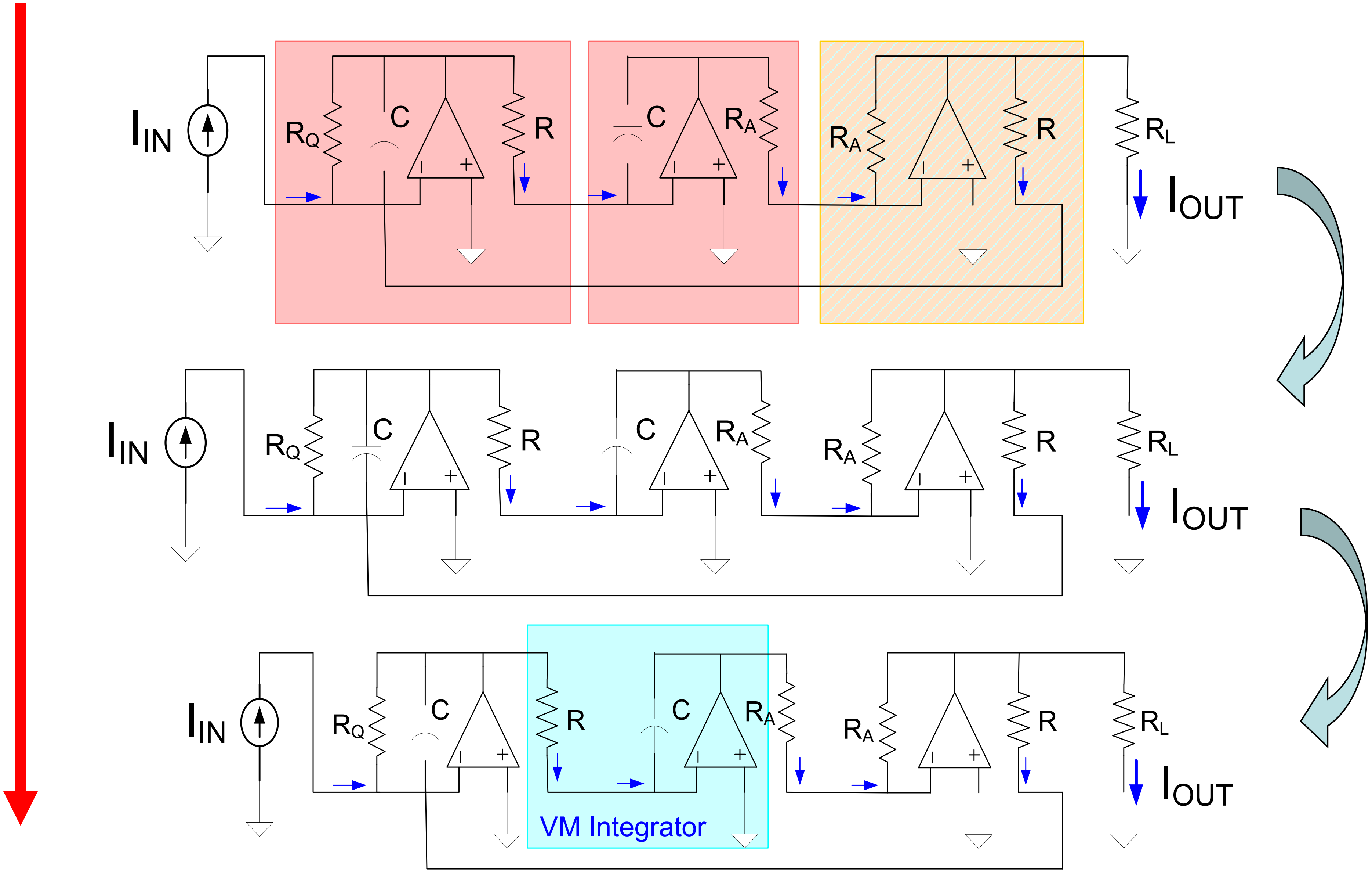
Active RC Current-Mode implementation



- Straightforward implementation of the two-integrator loop
- Simple structure

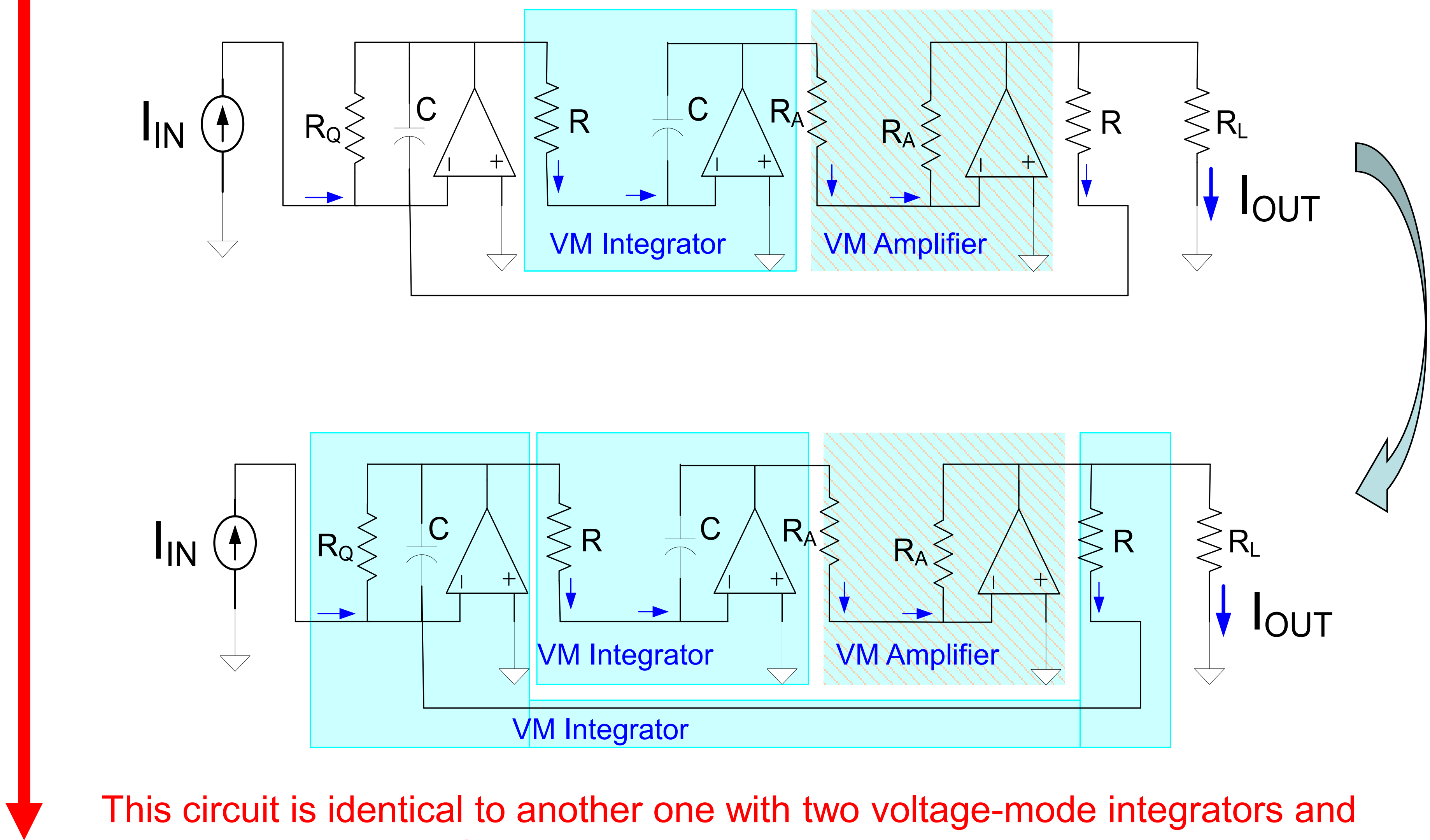
Current-Mode Two Integrator Loop

An Observation:



Current-Mode Two Integrator Loop

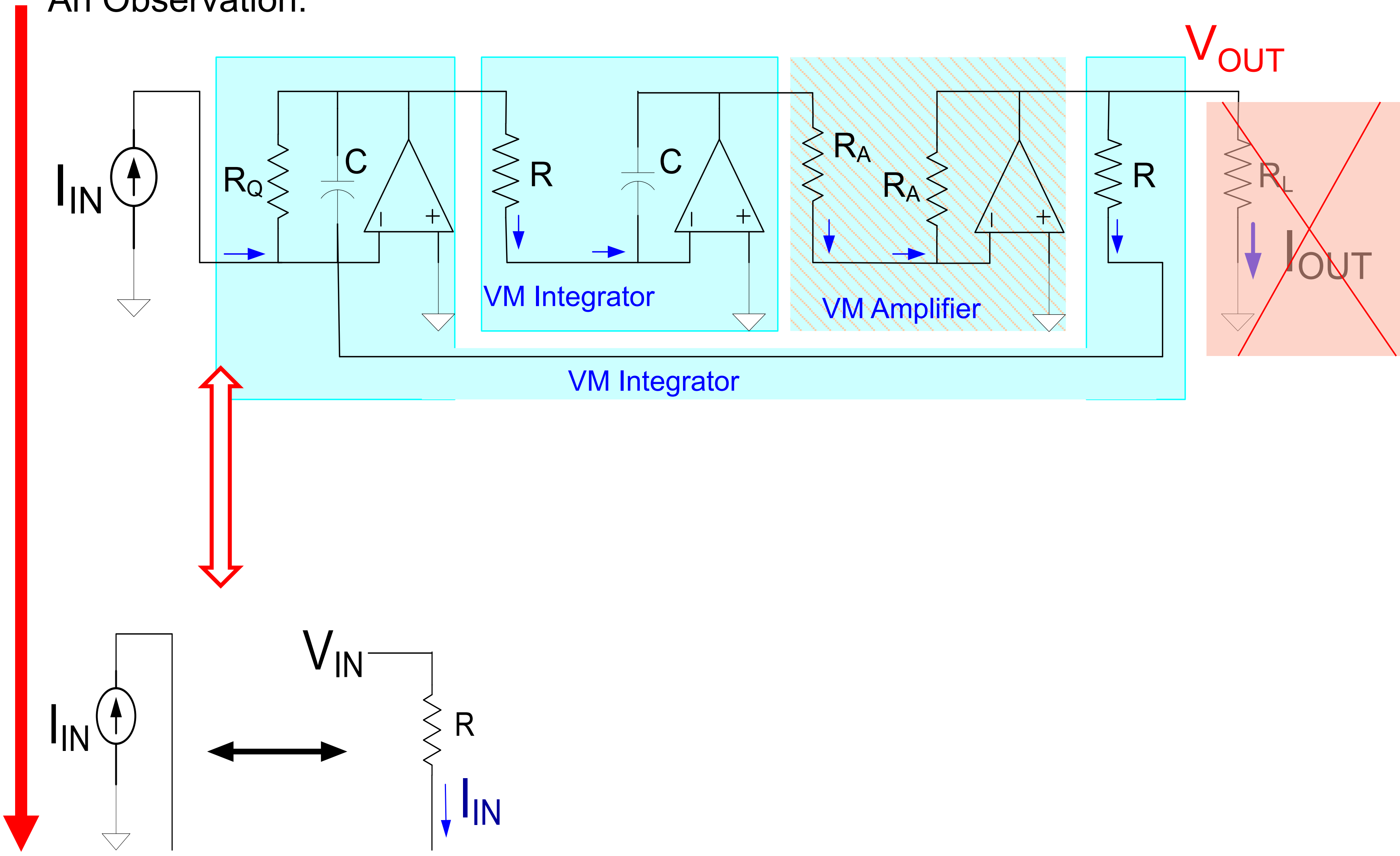
An Observation:



This circuit is identical to another one with two voltage-mode integrators and a voltage-mode amplifier !

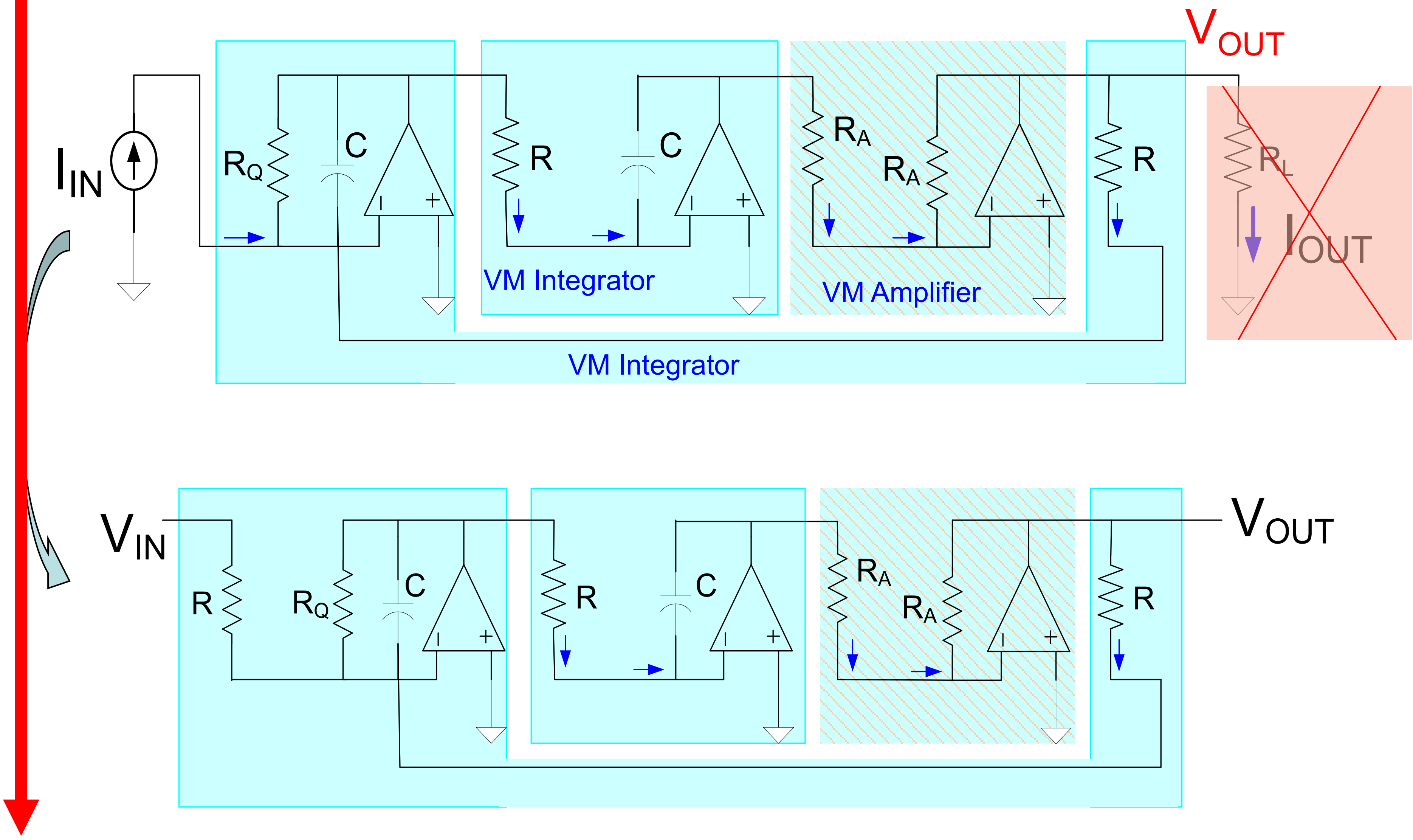
Current-Mode Two Integrator Loop

An Observation:



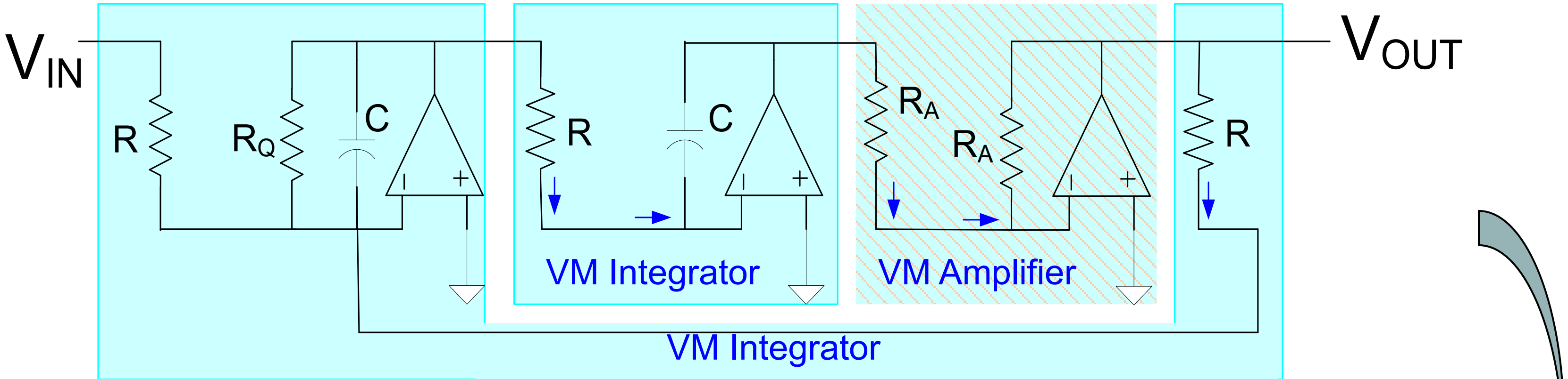
Current-Mode Two Integrator Loop

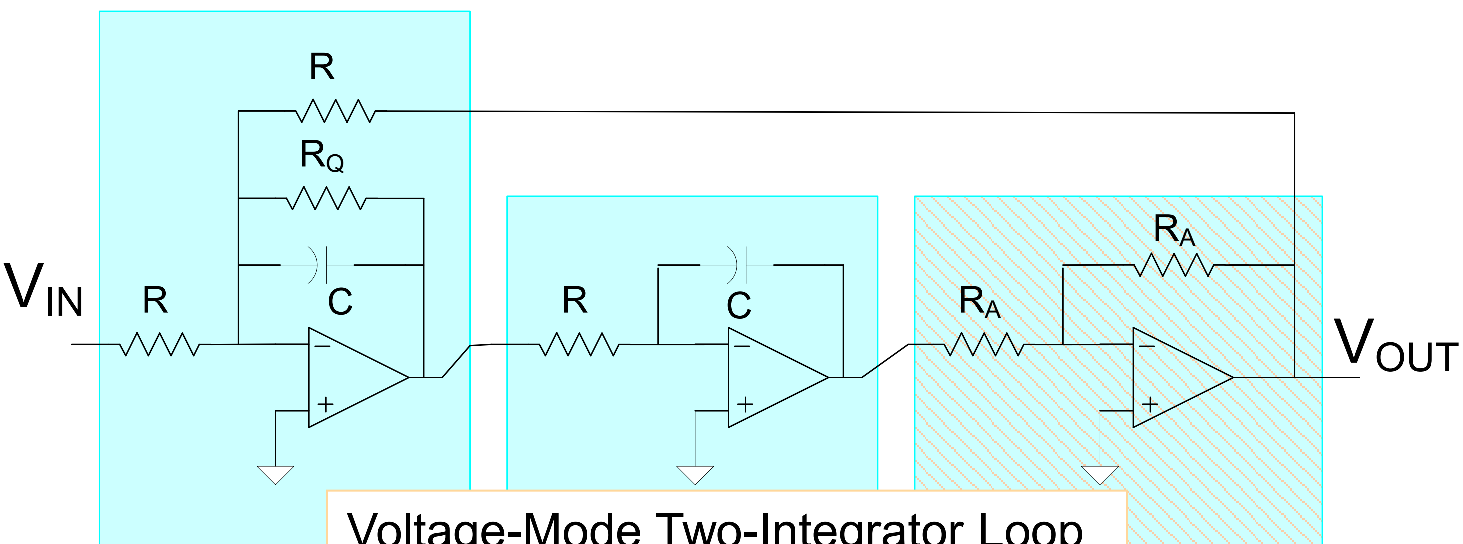
An Observation:



Current-Mode Two Integrator Loop

An Observation:





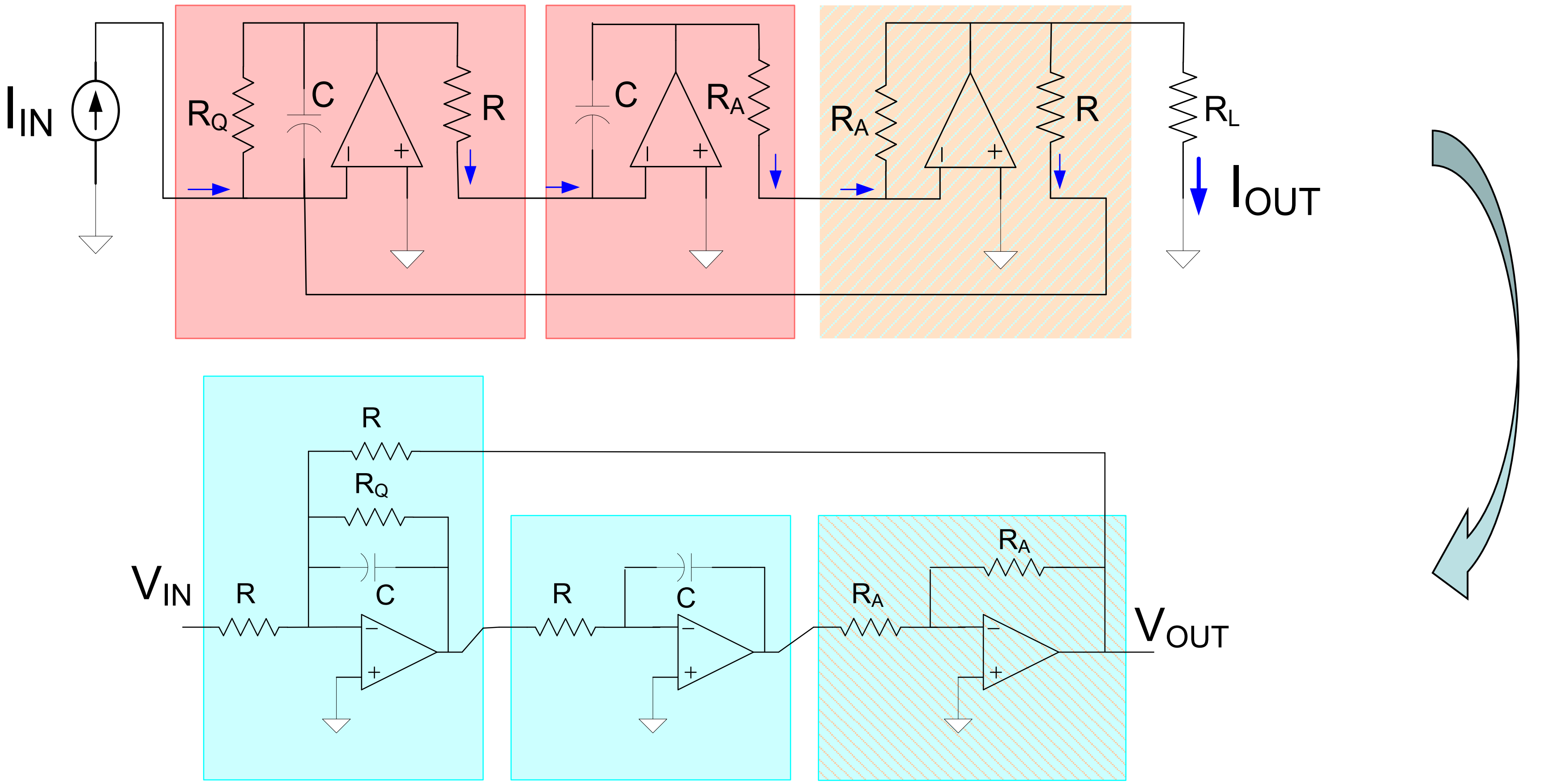
Voltage-Mode Two-Integrator Loop

This circuit was well-known in the 60's

Review from Earlier Lecture

Current-Mode Two Integrator Loop

Active RC Current-Mode implementation



Current-mode and voltage-mode circuits have same component count
Current-mode and voltage-mode circuits are identical !
Current-mode and voltage-mode properties are identical !

Current-mode circuit offers NO benefits over voltage-mode counterpart

Review from Earlier Lecture

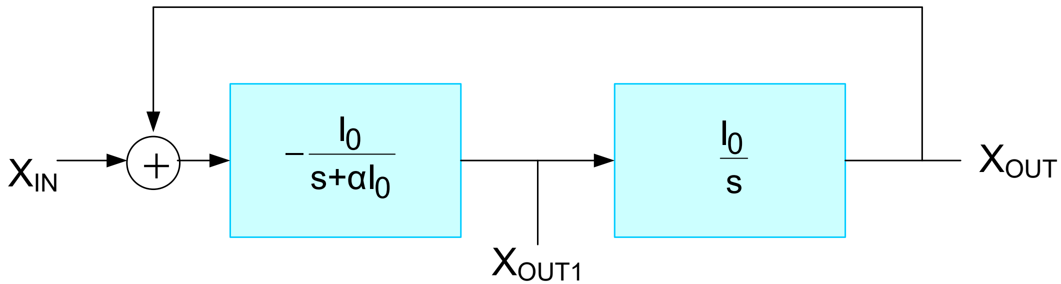
Observation

- Many papers have appeared that tout the performance advantages of current-mode circuits
- In all of the current-mode papers that this instructor 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 instructor has seen are based upon qualitative statements

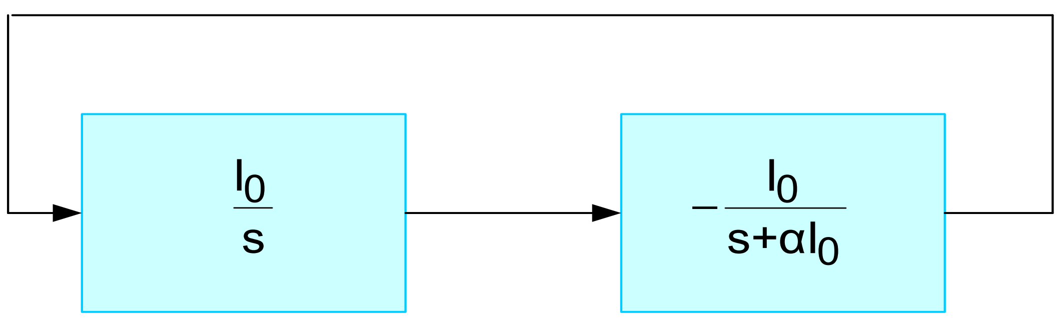
Observations (cont.)

- It appears easy to get papers published that have the term “current-mode” in the title
- Over 900 papers have been published in IEEE forums alone !
- Some of the “current-mode” filters published perform better than other “voltage-mode” filters that have been published
- We are still waiting for even one author to quantitatively show that current-mode filters offer even one of the claimed four advantages over their voltage-mode counterparts

Two-Integrator-Loop Biquad



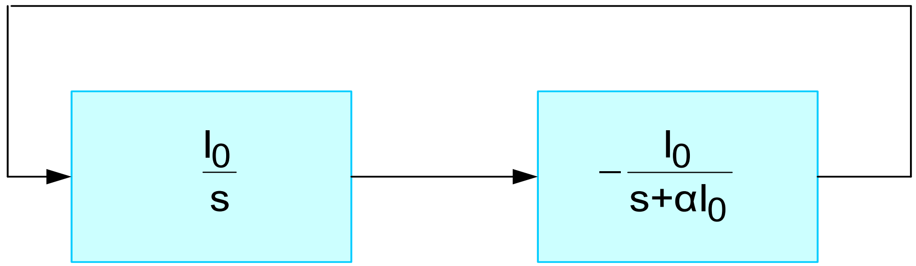
- For notational convenience, the input signal can be suppressed and output will not be designated
- This forms the “dead network”
- Poles for dead network are identical to original network as are key sensitivities



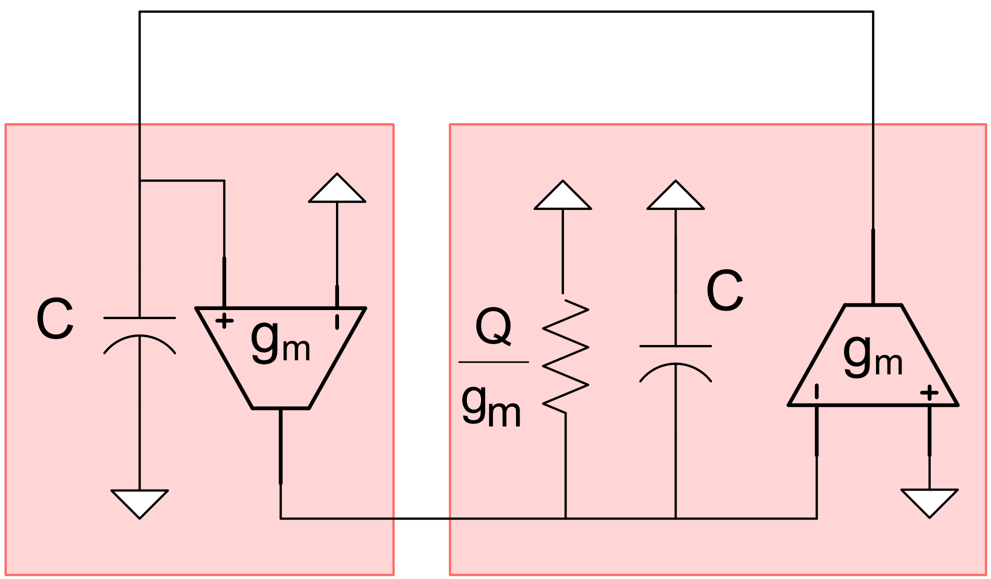
Two Integrator Loop Biquad

Two-Integrator-Loop Biquad

OTA-C implementation

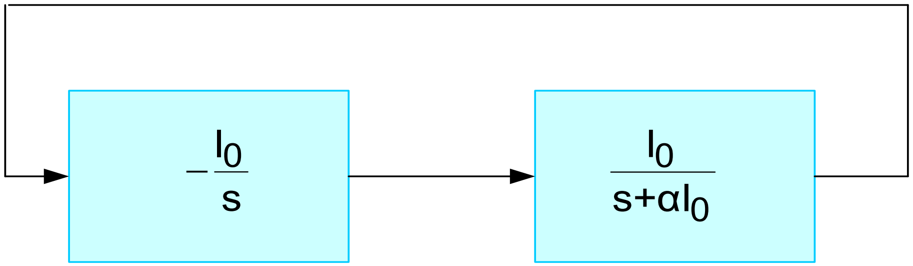


Consider a current-mode implementation:

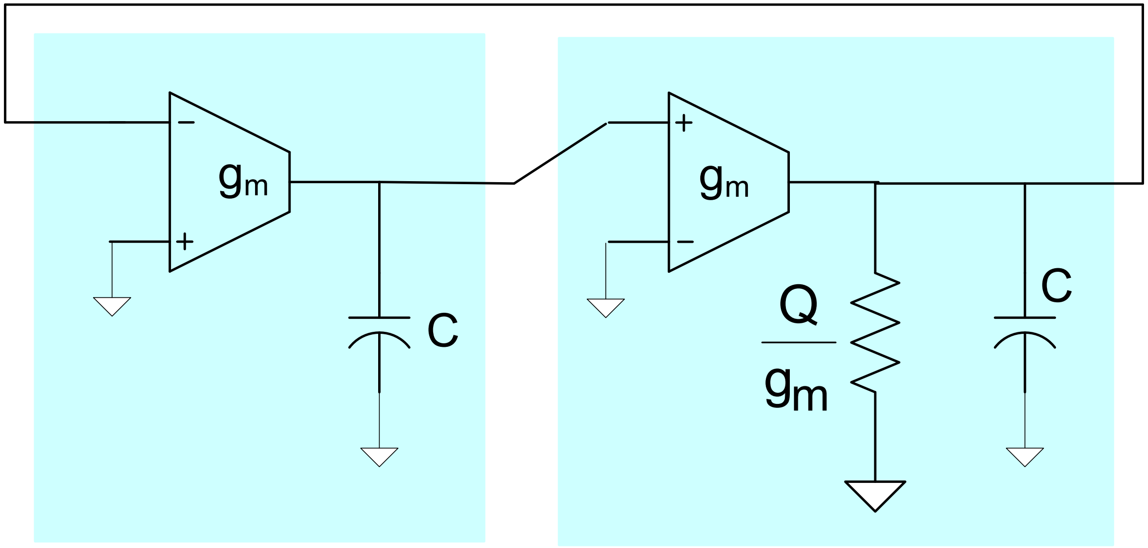


Numerous current-mode filter papers use this basic structure

Two-Integrator-Loop Biquad



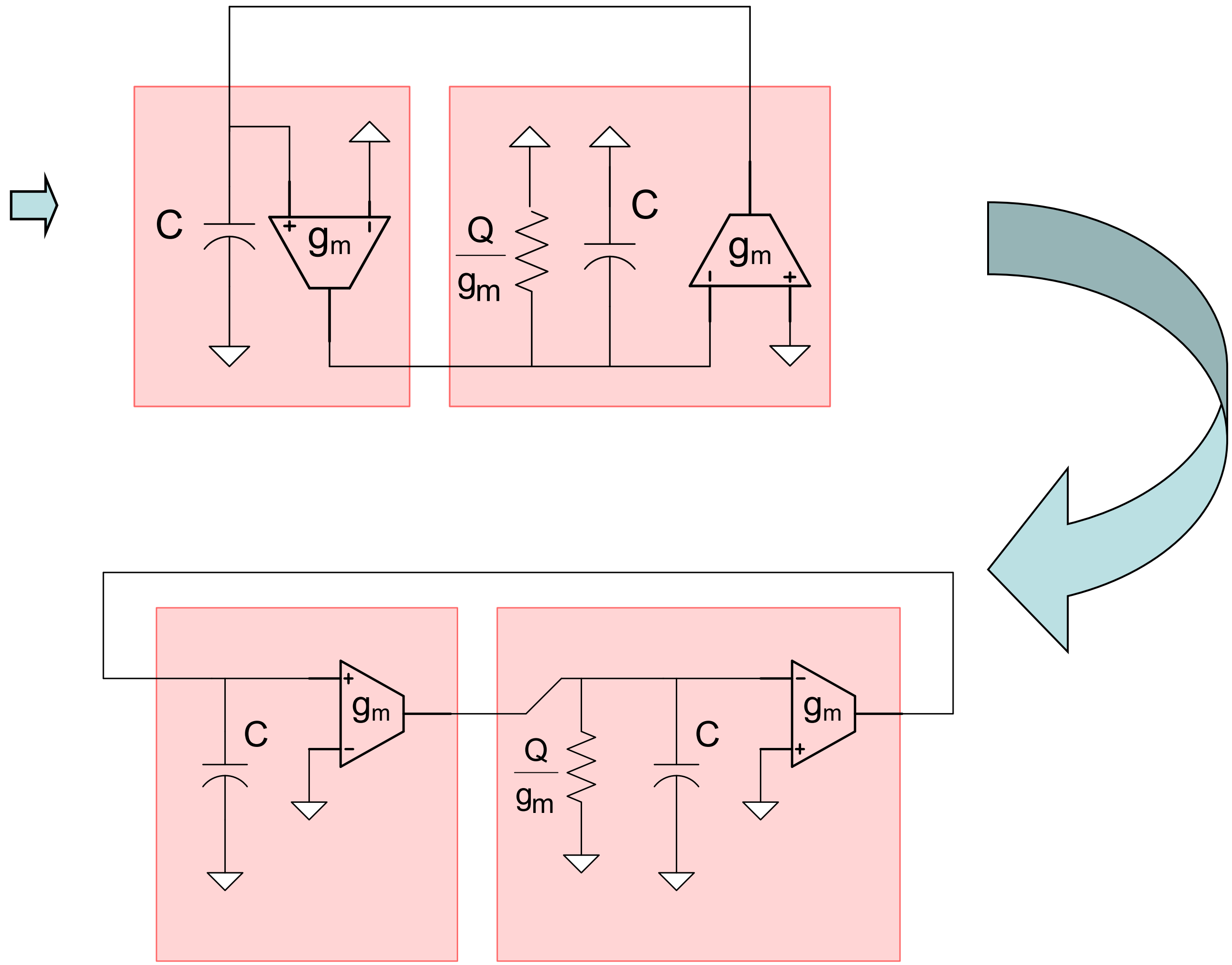
Consider the corresponding voltage-mode implementation:



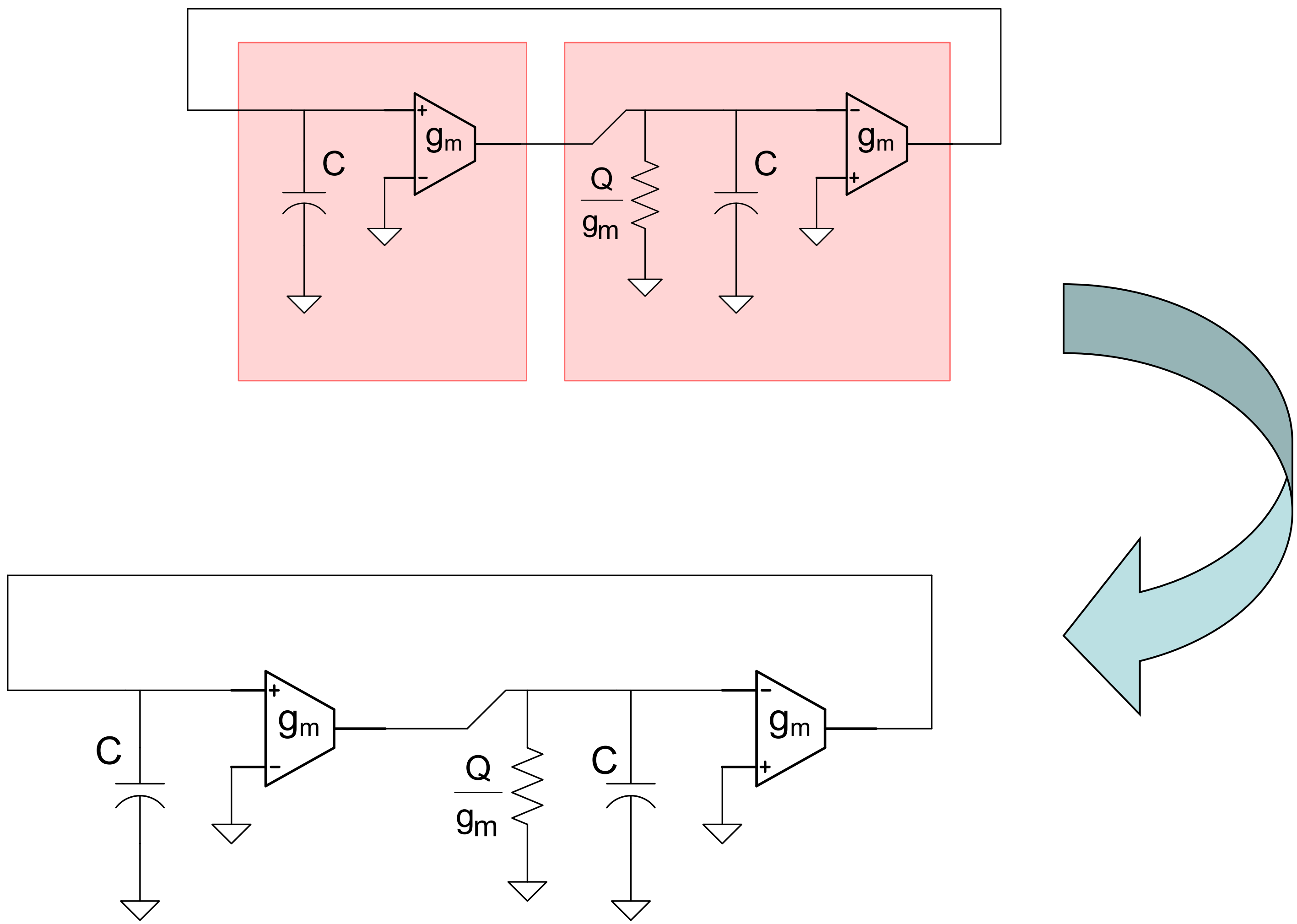
Two-Integrator-Loop Biquad

An Observation:

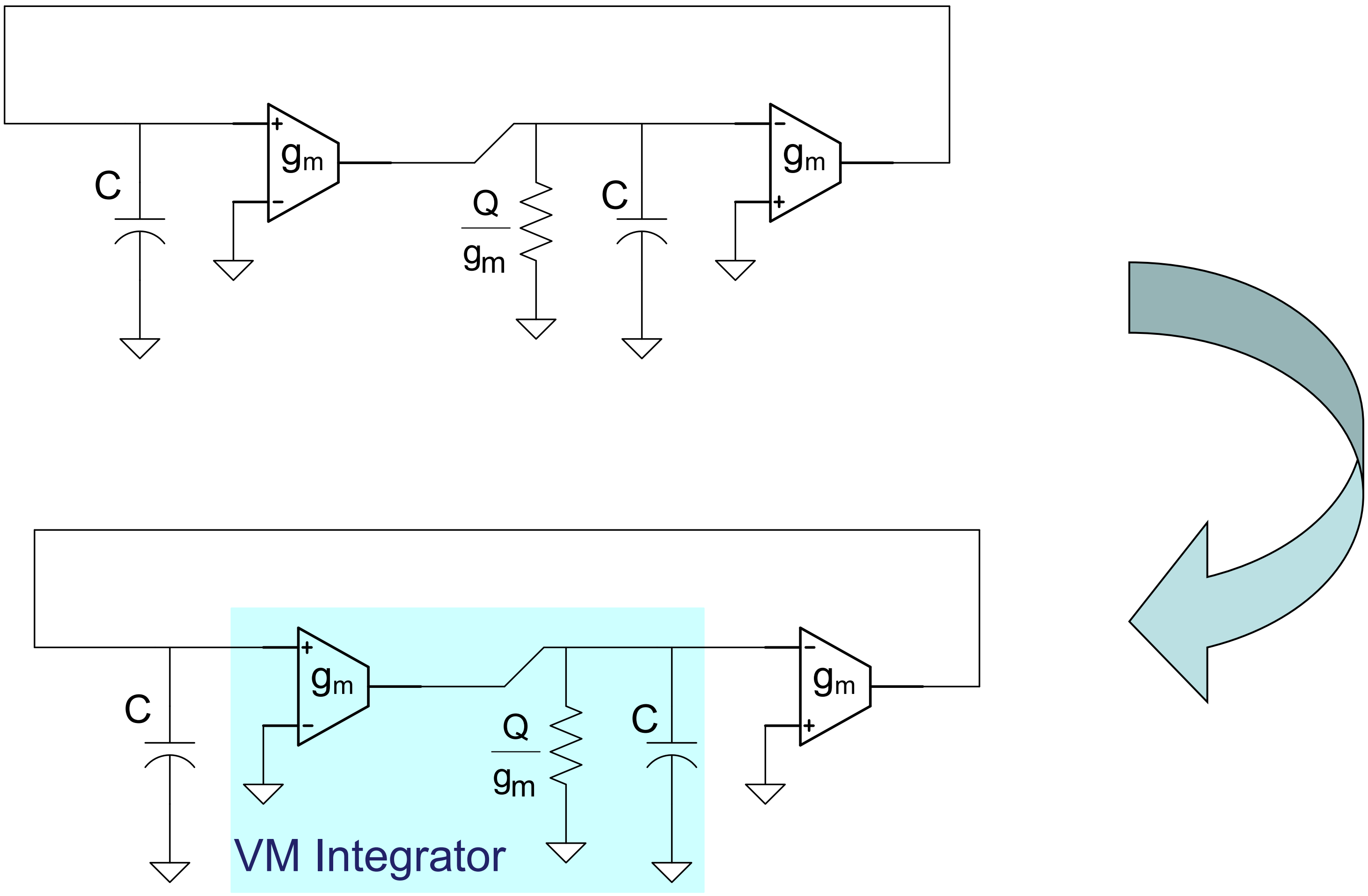
Current-mode



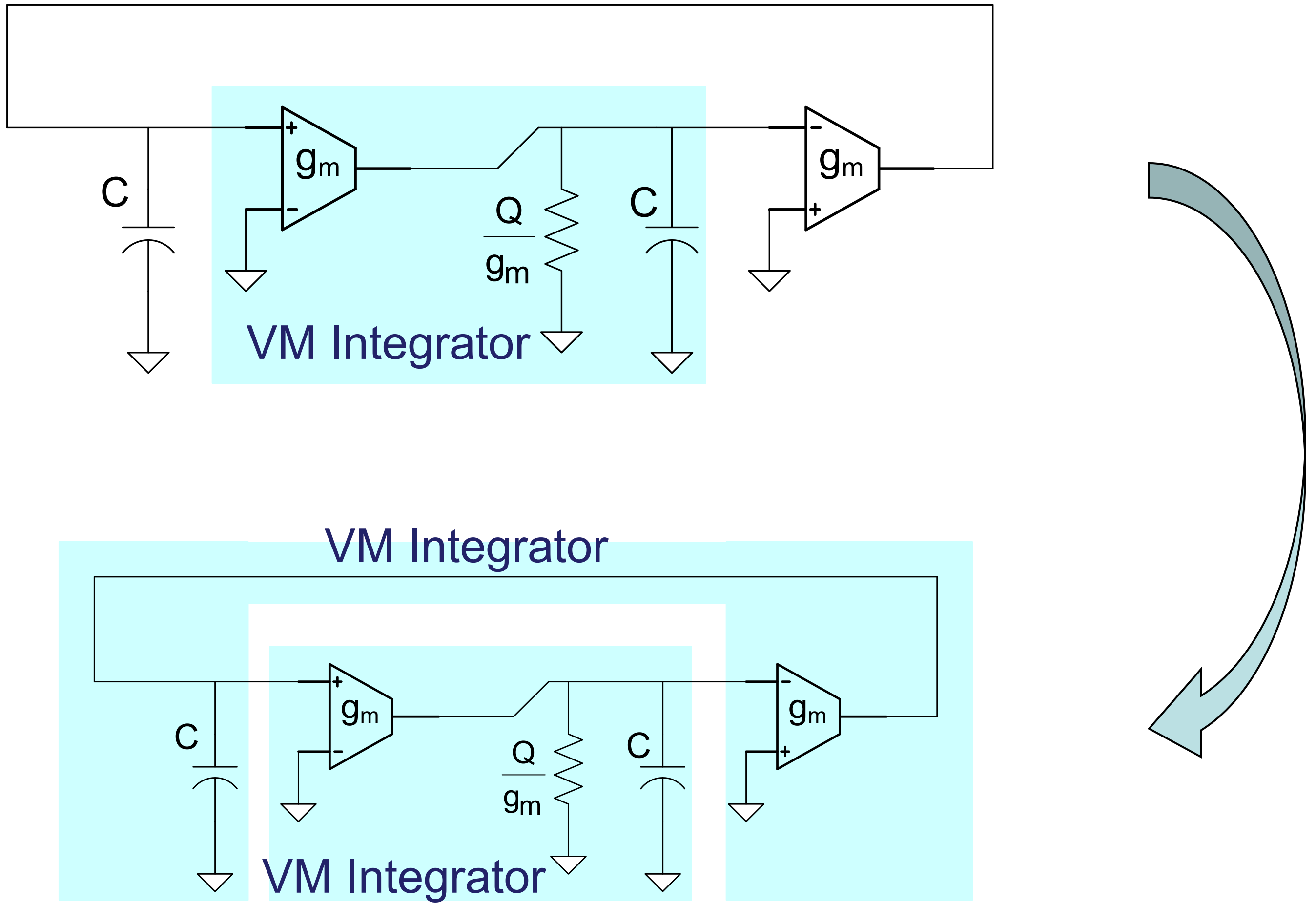
Two-Integrator-Loop Biquad



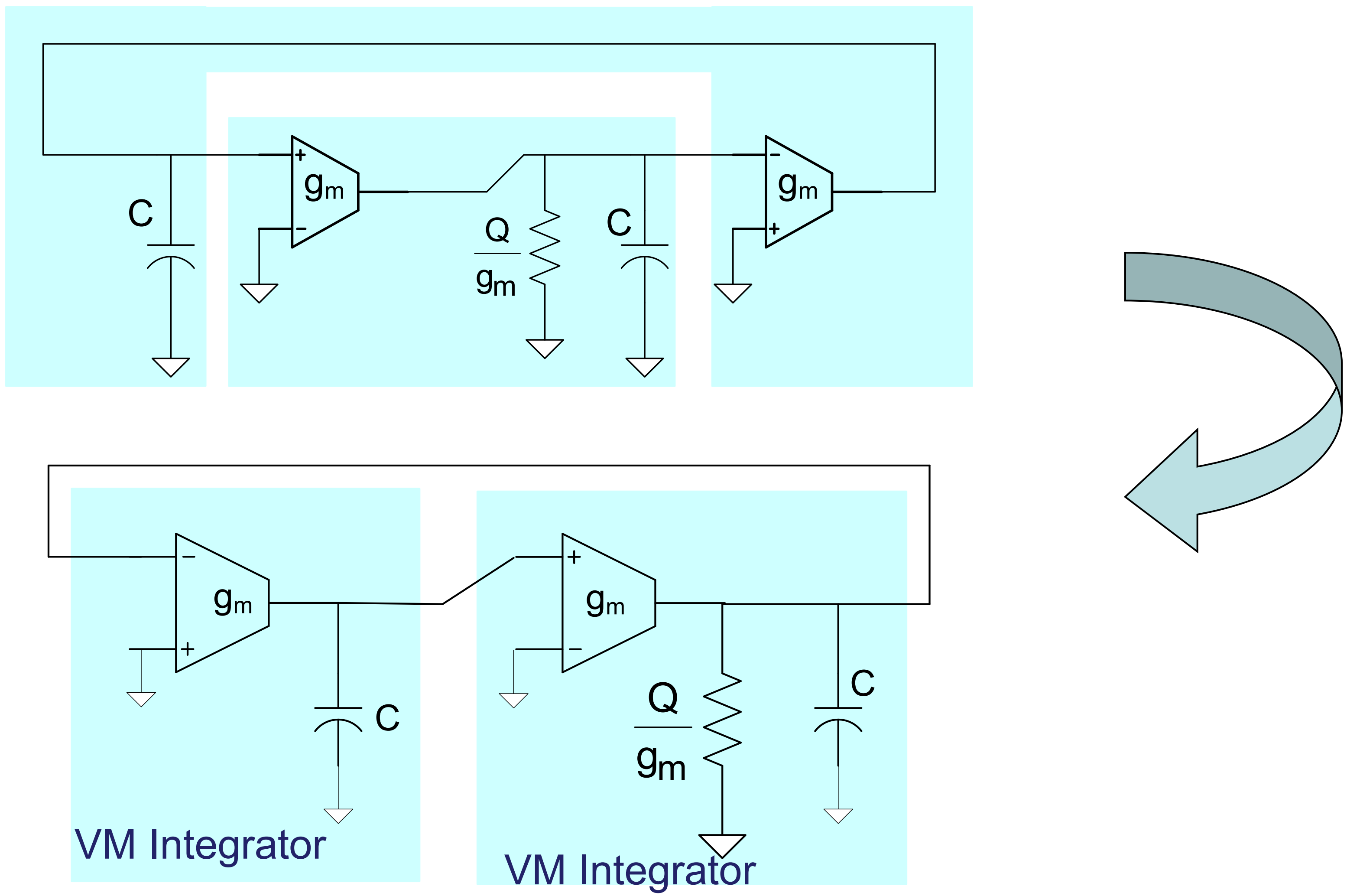
Two-Integrator-Loop Biquad



Two-Integrator-Loop Biquad



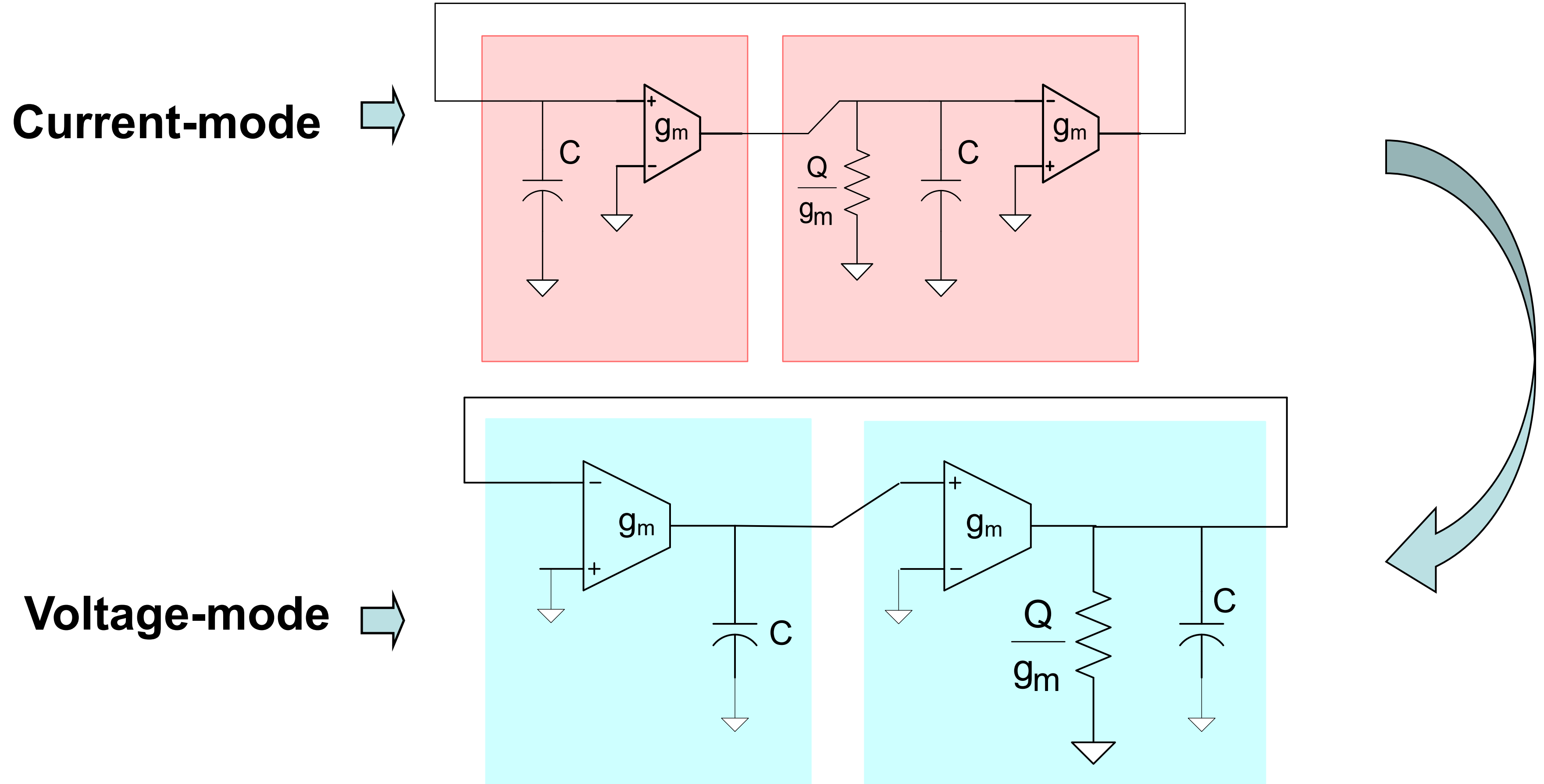
Two-Integrator-Loop Biquad



This circuit was well-known in the 80’s

Two-Integrator-Loop Biquad

OTA-C implementation

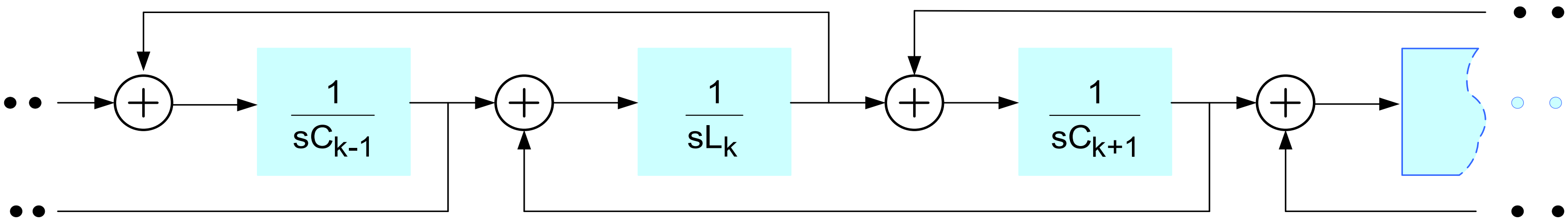


Current-mode and voltage-mode circuits have same component count
Current-mode and voltage-mode circuits are identical !
Current-mode and voltage-mode properties are identical !

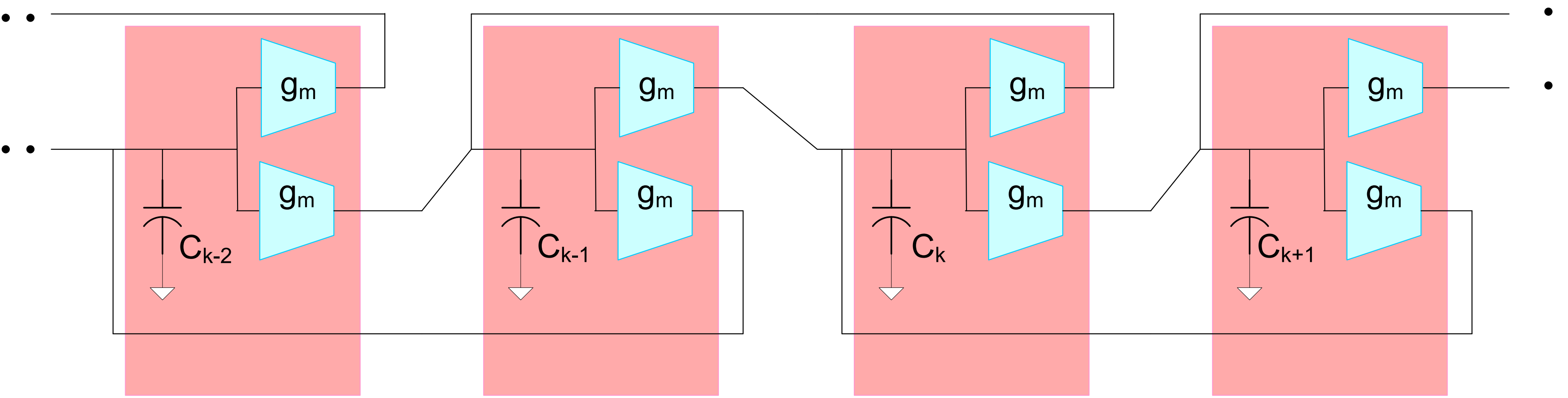
Current-mode circuit offers NO benefits over voltage-mode counterpart

Leap-Frog Filter

OTA-C implementation

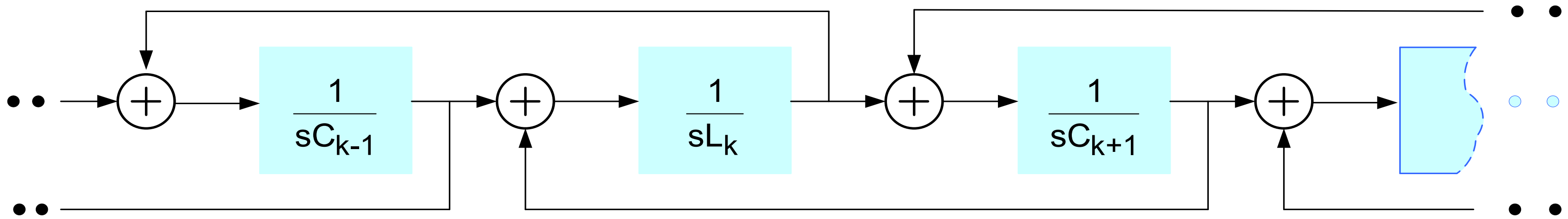


Consider a current-mode implementation:

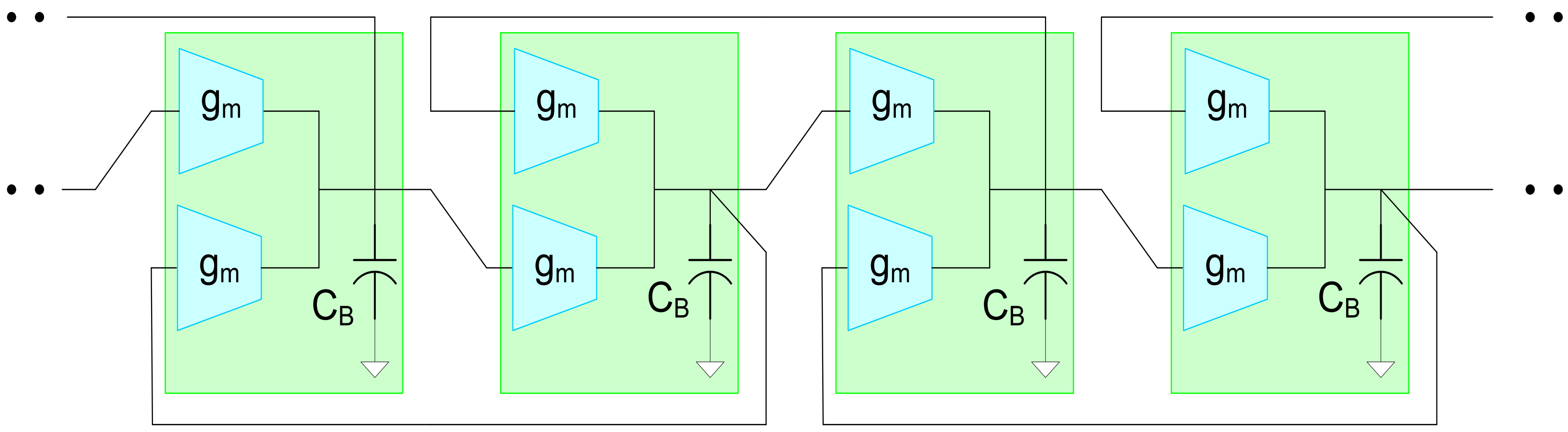


Numerous current-mode filter papers use this basic structure

Leap-Frog Filter

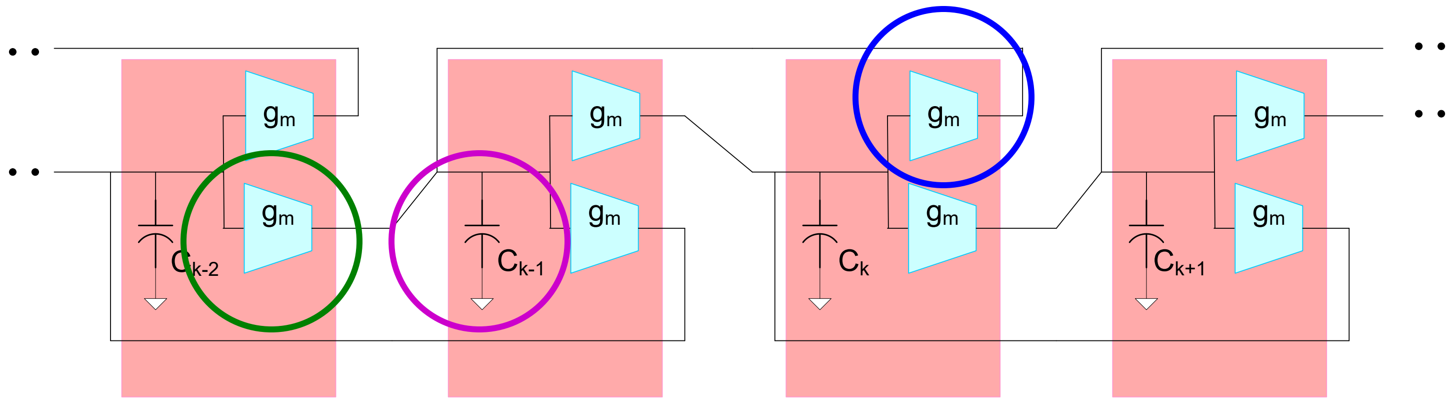


Consider a voltage-mode implementation:

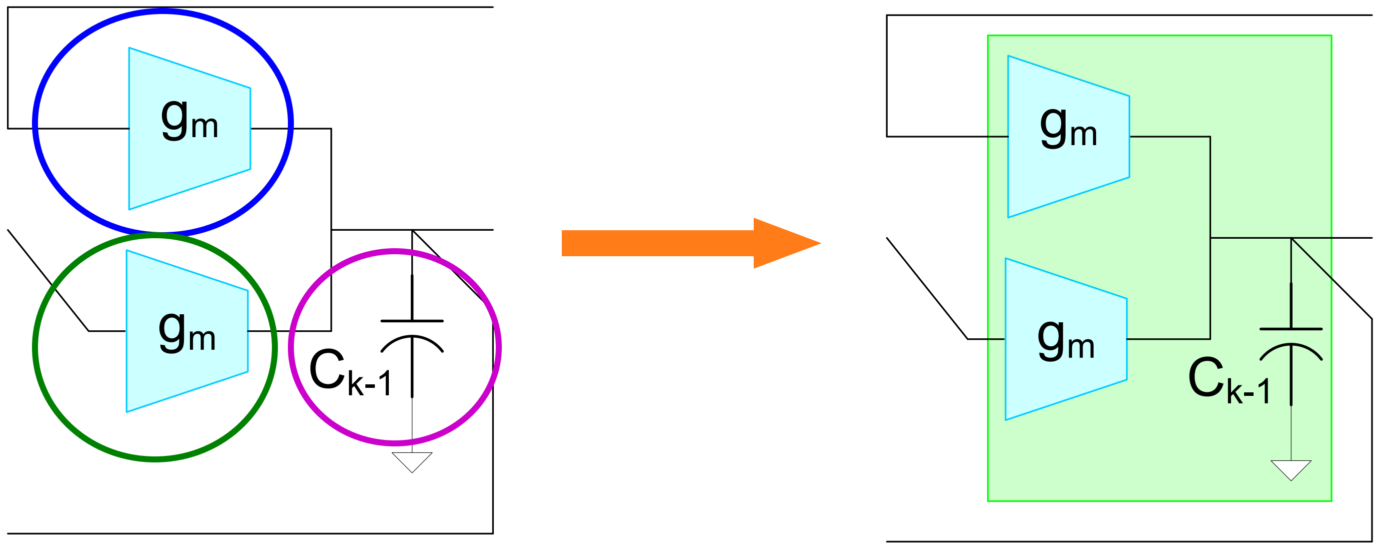


Leap-Frog Filter

An Observation:

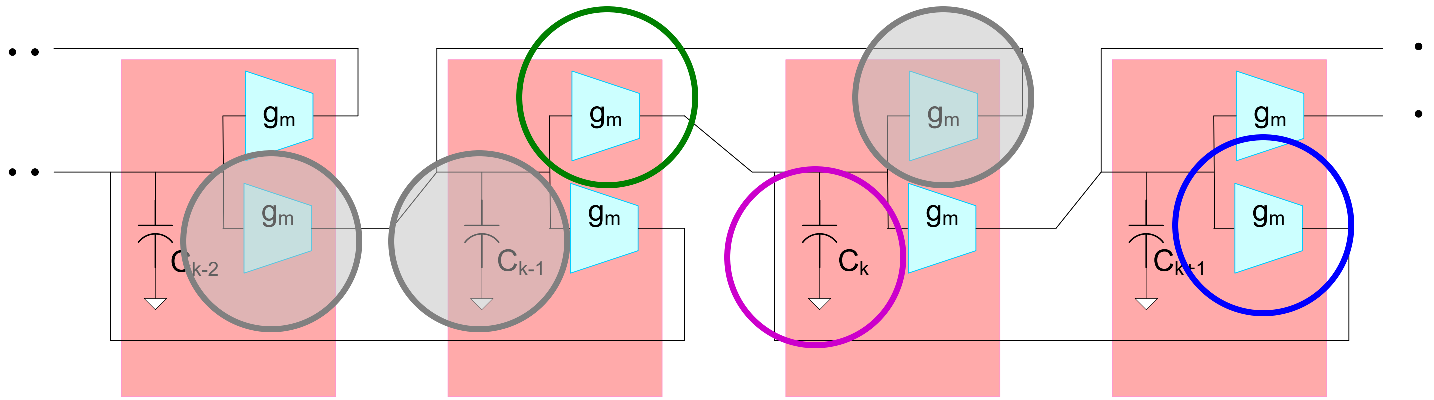


Consider lower OTA in stage k-2, capacitor in stage k-1 and upper OTA in stage k

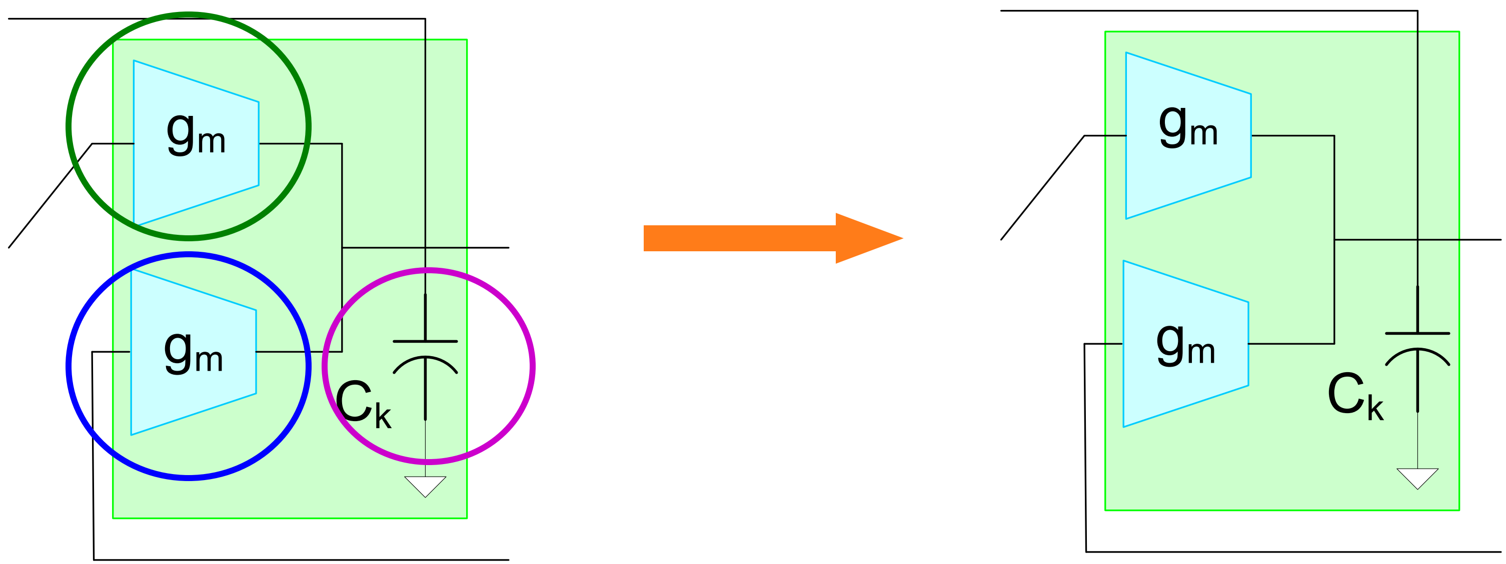


Leap-Frog Filter

Current-mode

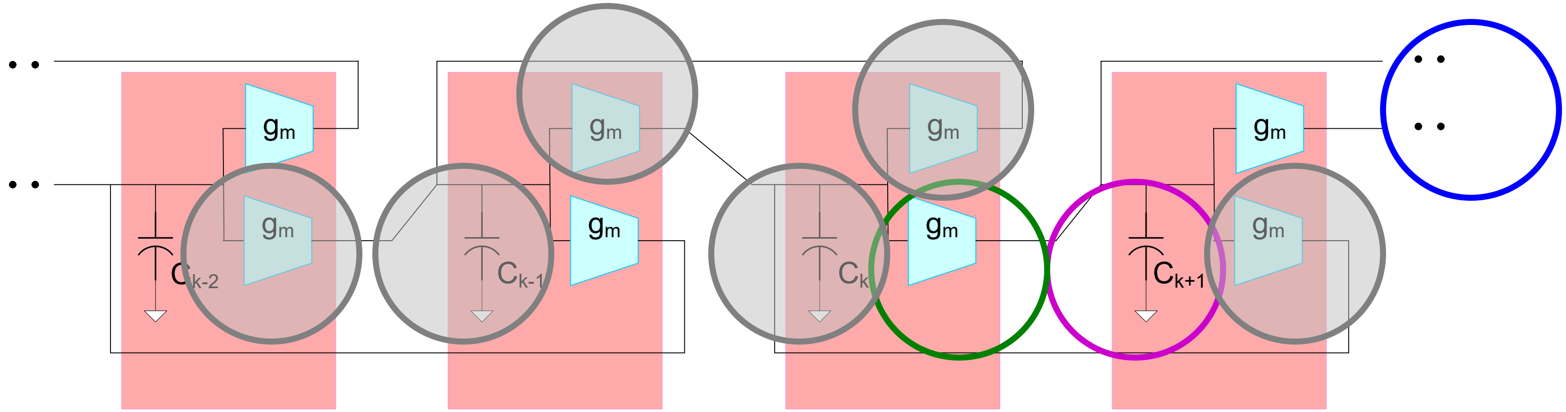


Consider upper OTA in stage k-1, capacitor in stage k and lower OTA in stage k+1

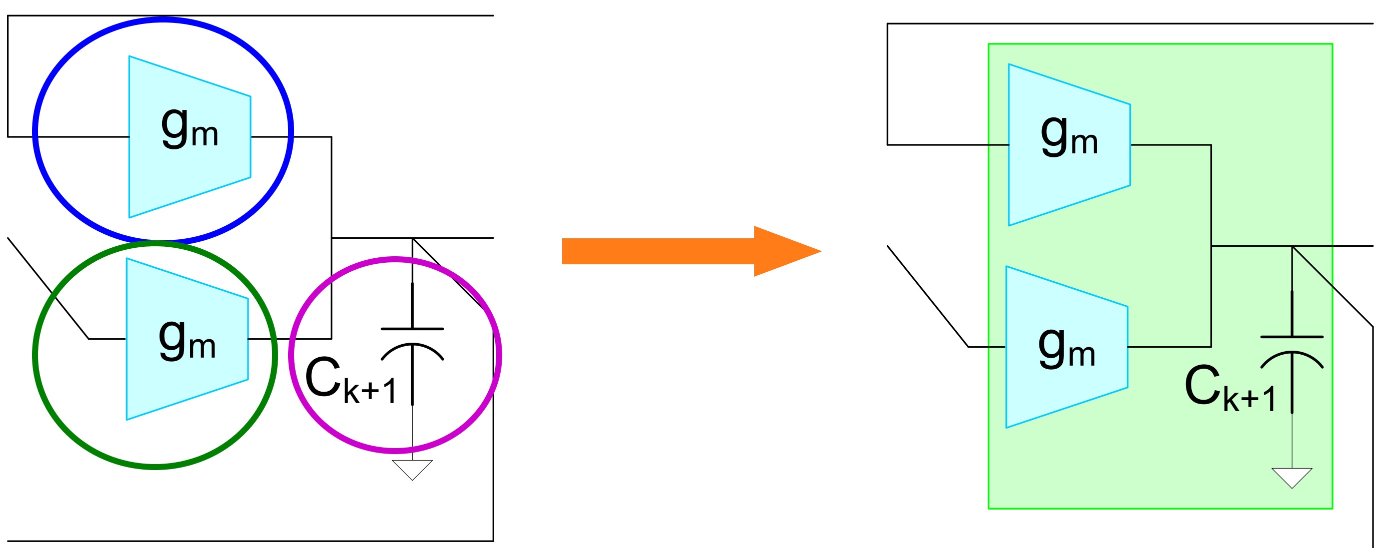


Leap-Frog Filter

Current-mode

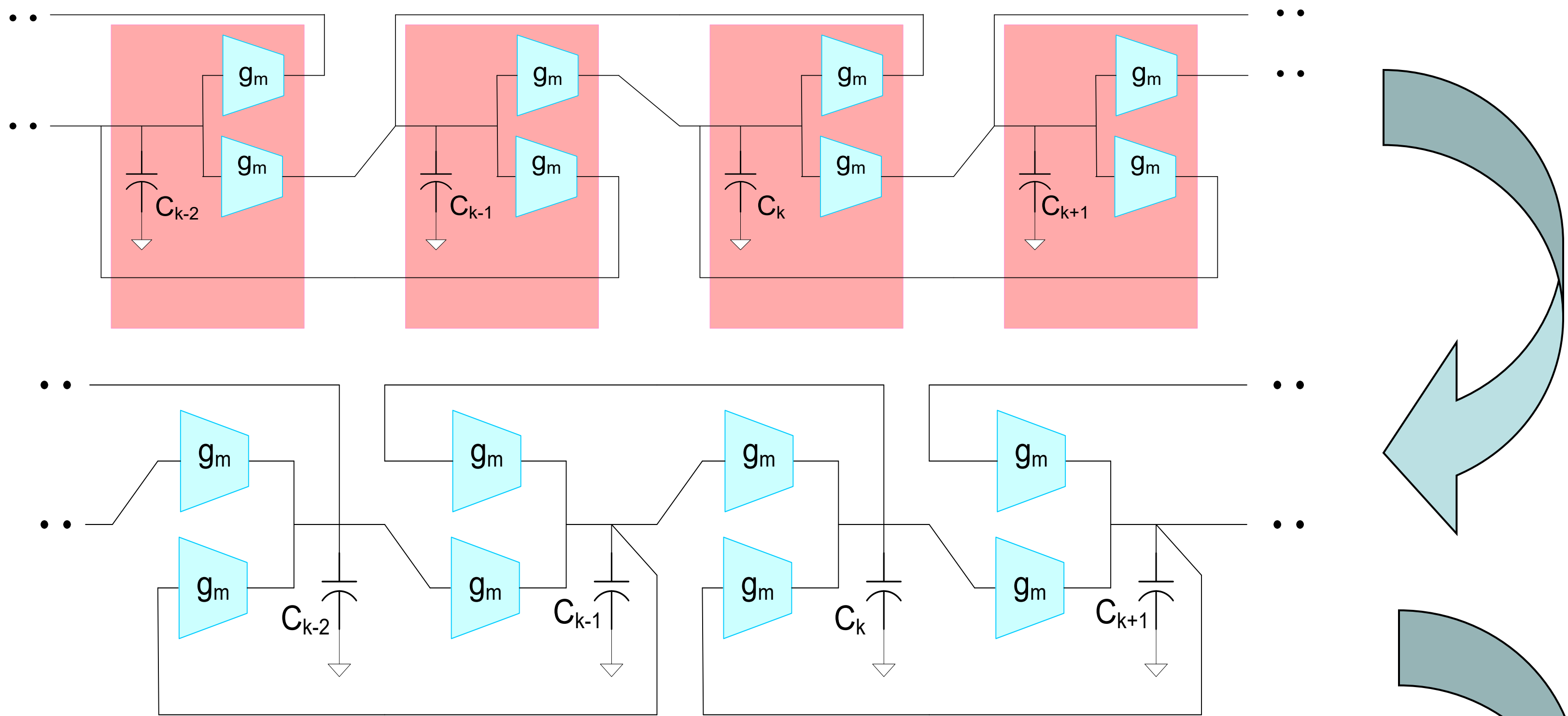


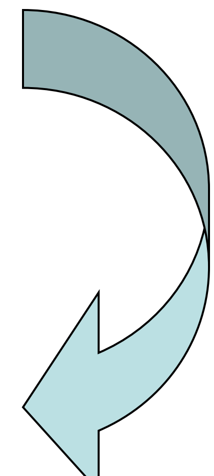
Consider lower OTA in stage k, capacitor in stage k+1 and upper OTA in stage k+2



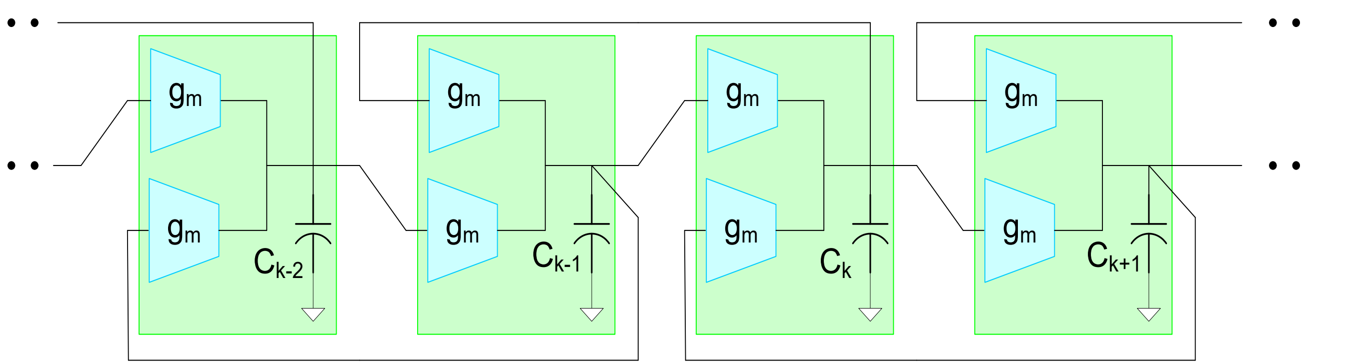
Leap-Frog Filter

Current-mode



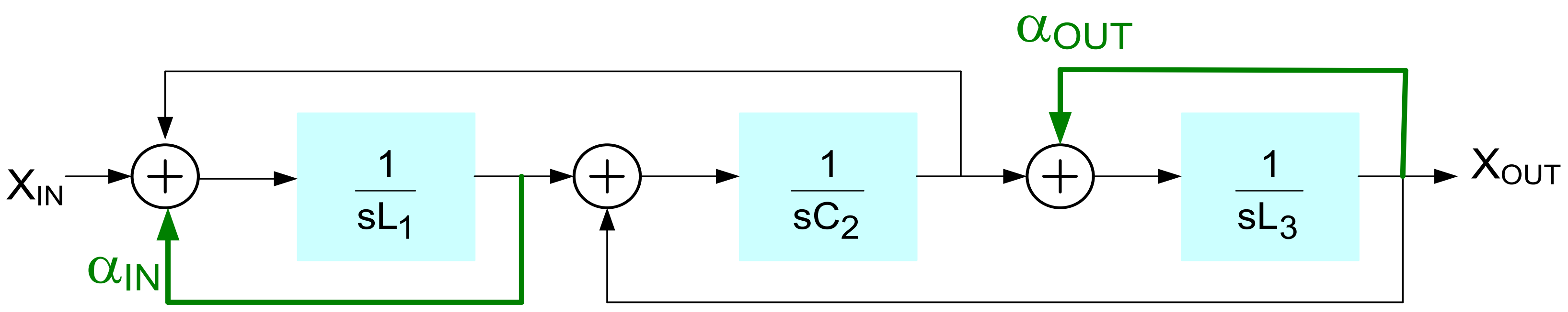


Voltage-mode

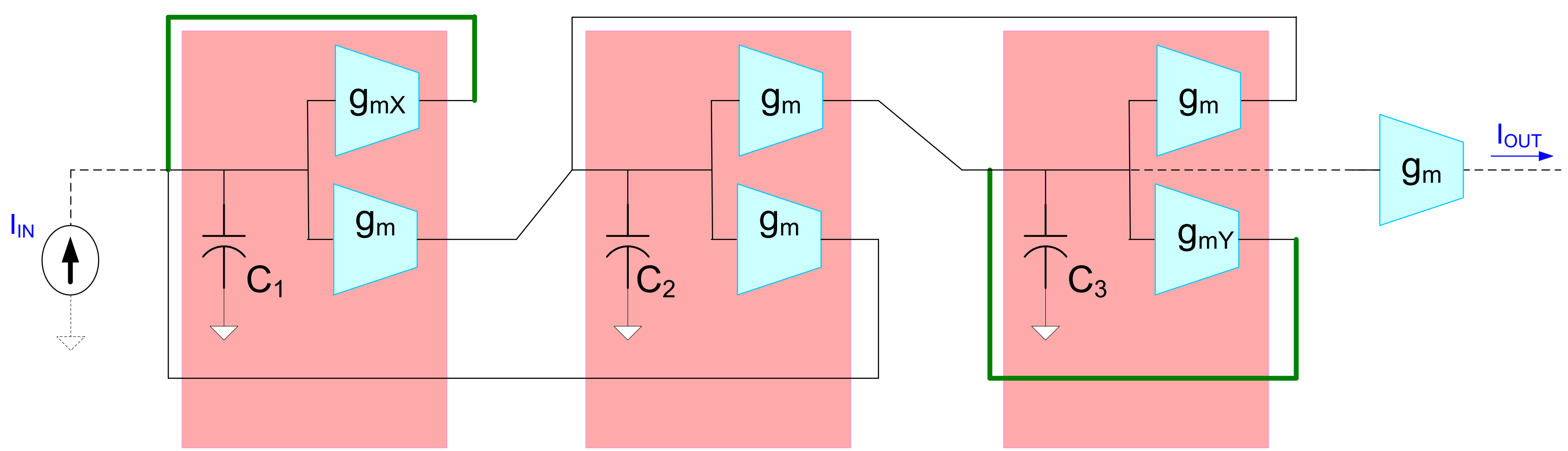


Leap-Frog Filter

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

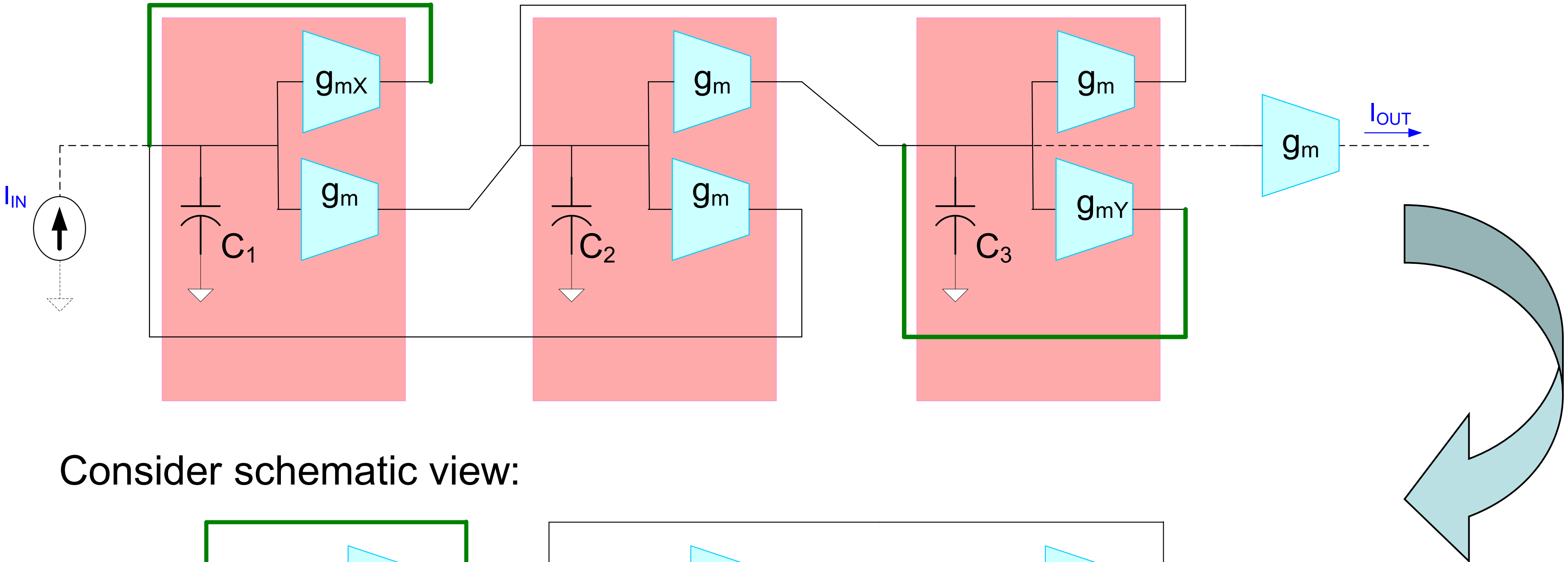


Current-mode implementation

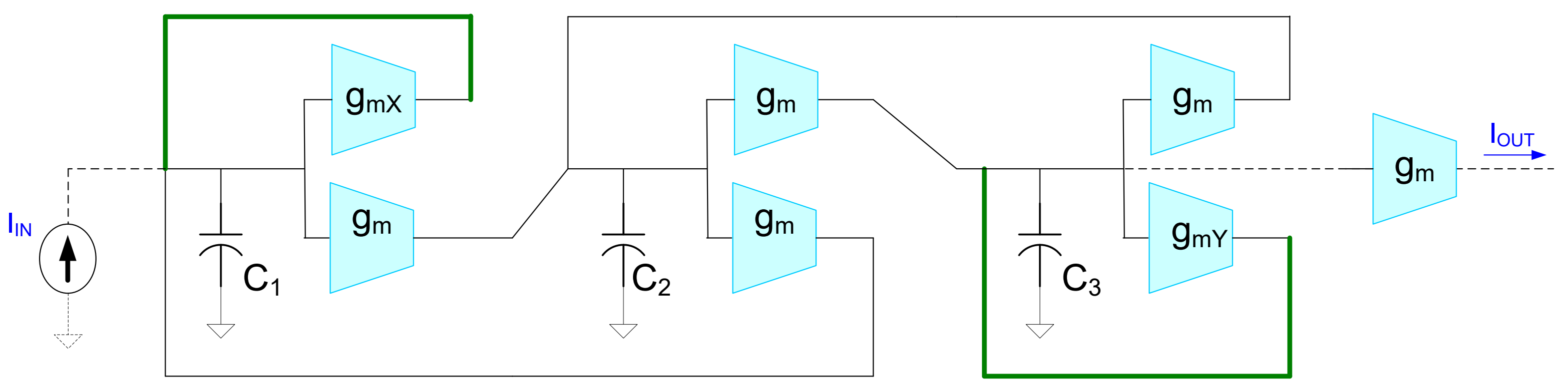


Leap-Frog Filter

Current-mode implementation

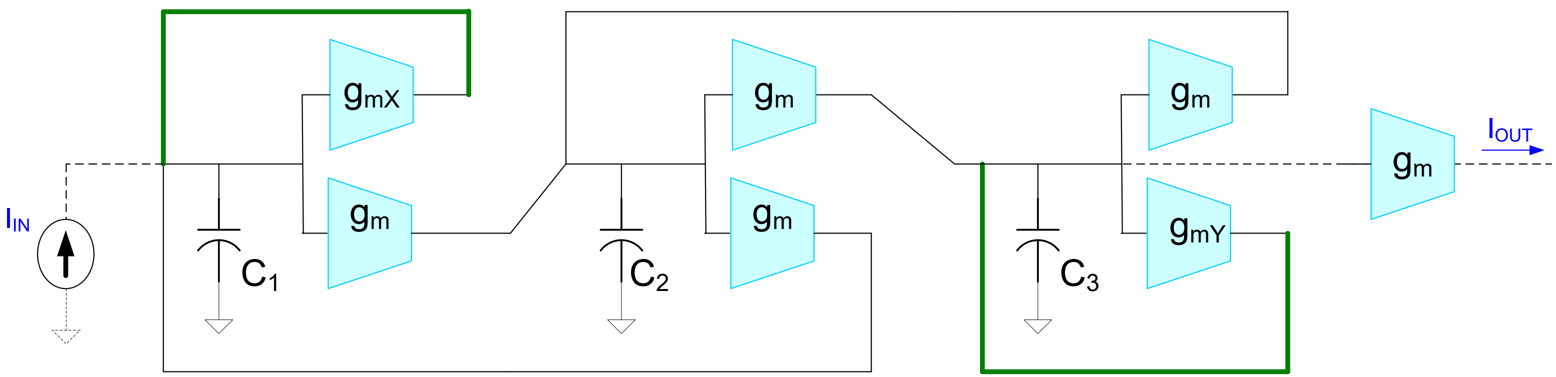


Consider schematic view:

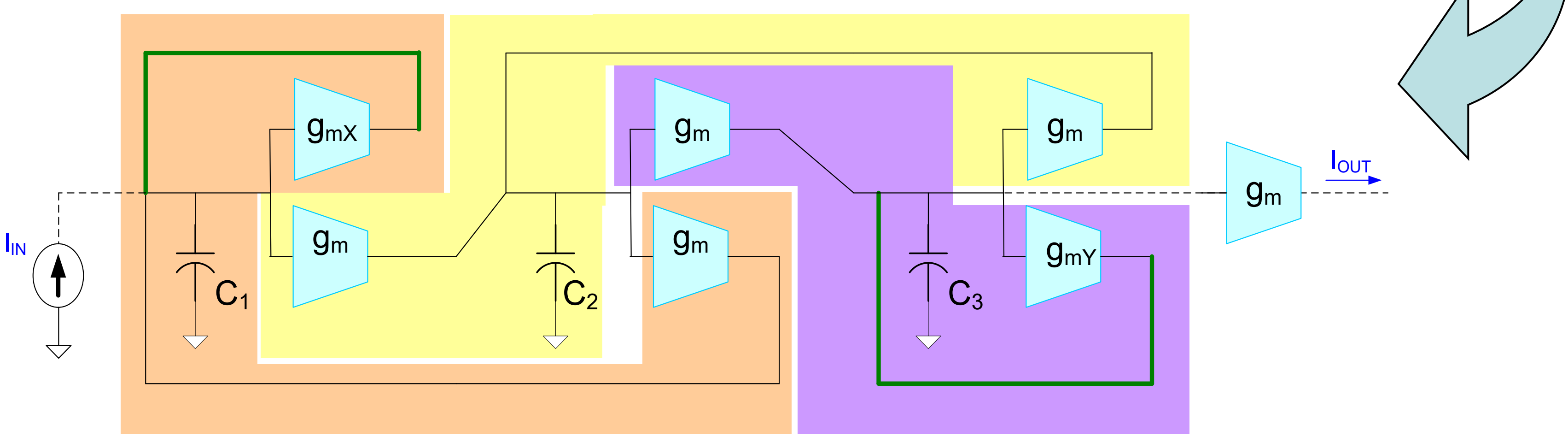


Leap-Frog Filter

Current-mode implementation

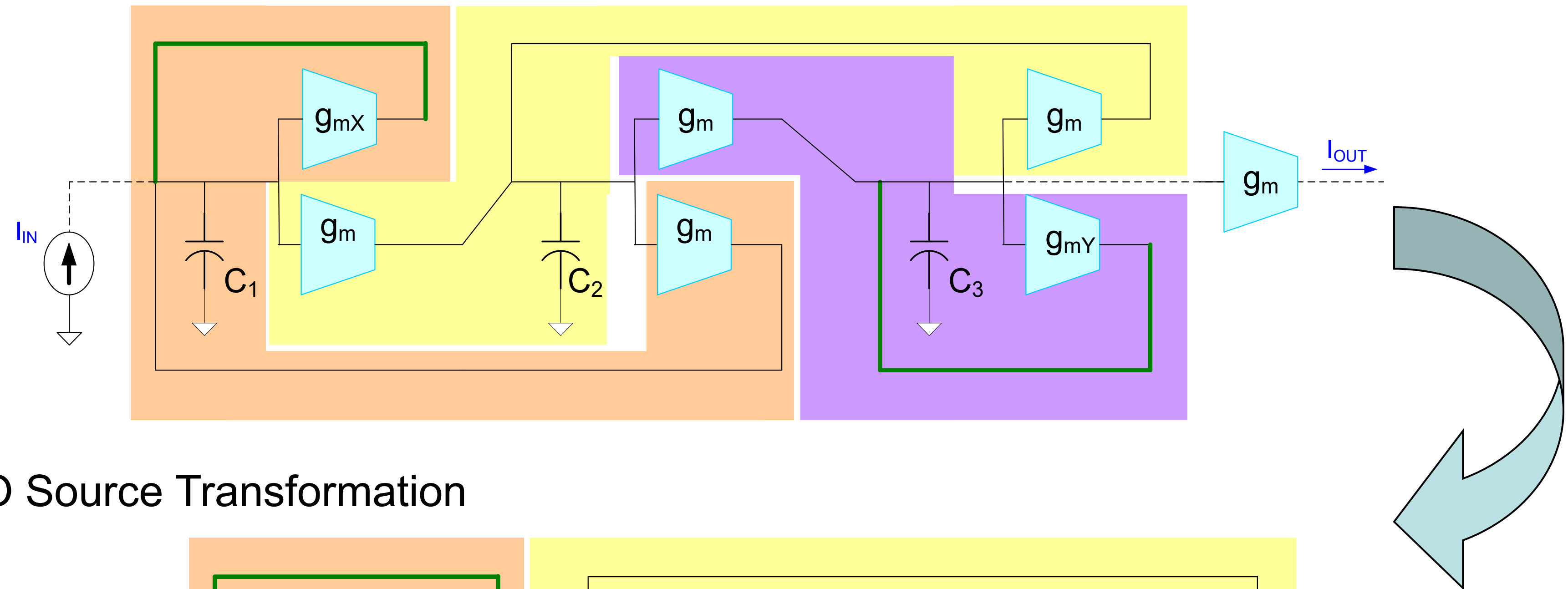


Re-group elements:

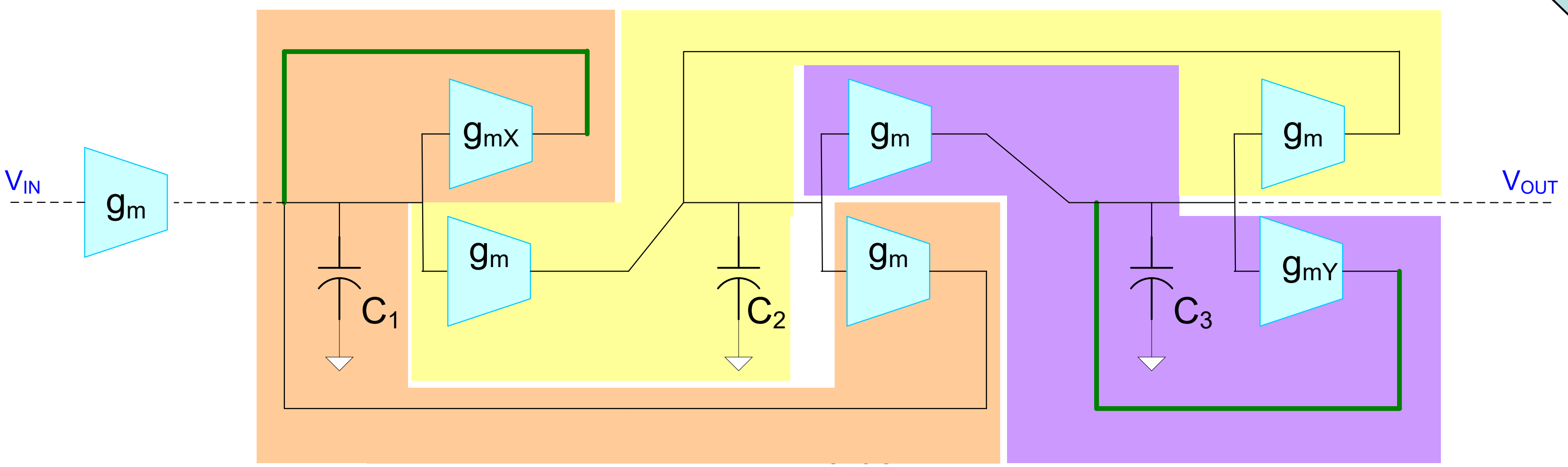


Leap-Frog Filter

Current-mode implementation

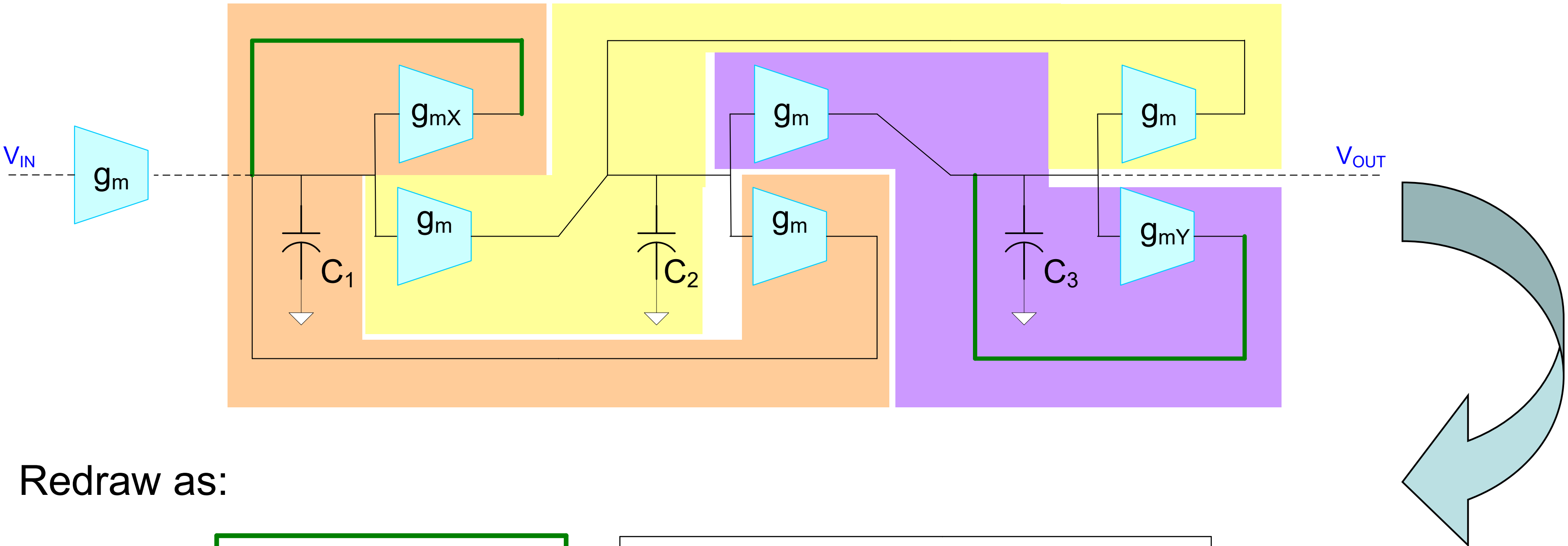


I/O Source Transformation

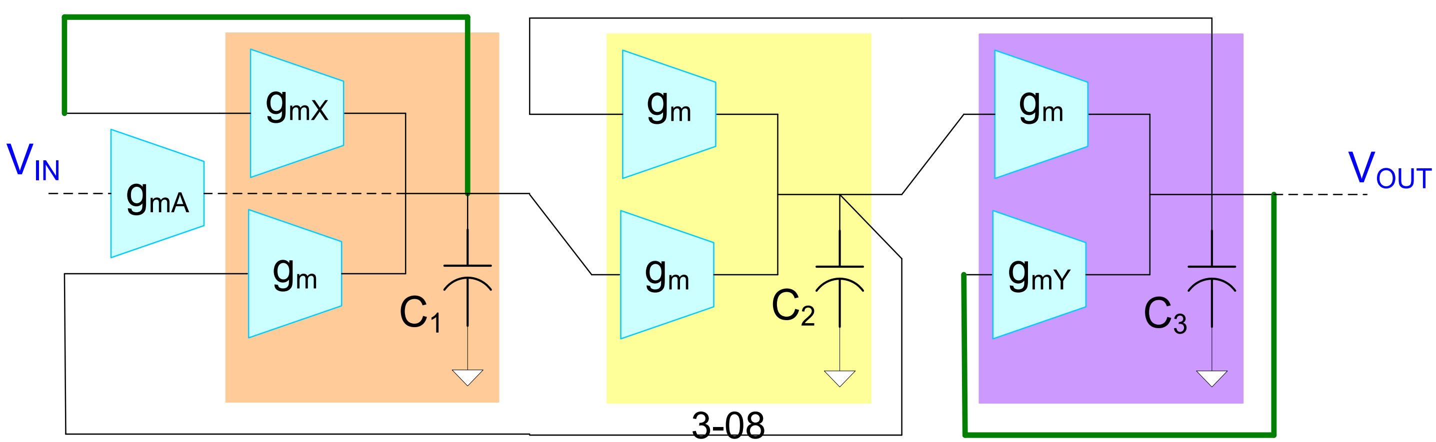


Leap-Frog Filter

Current-mode implementation

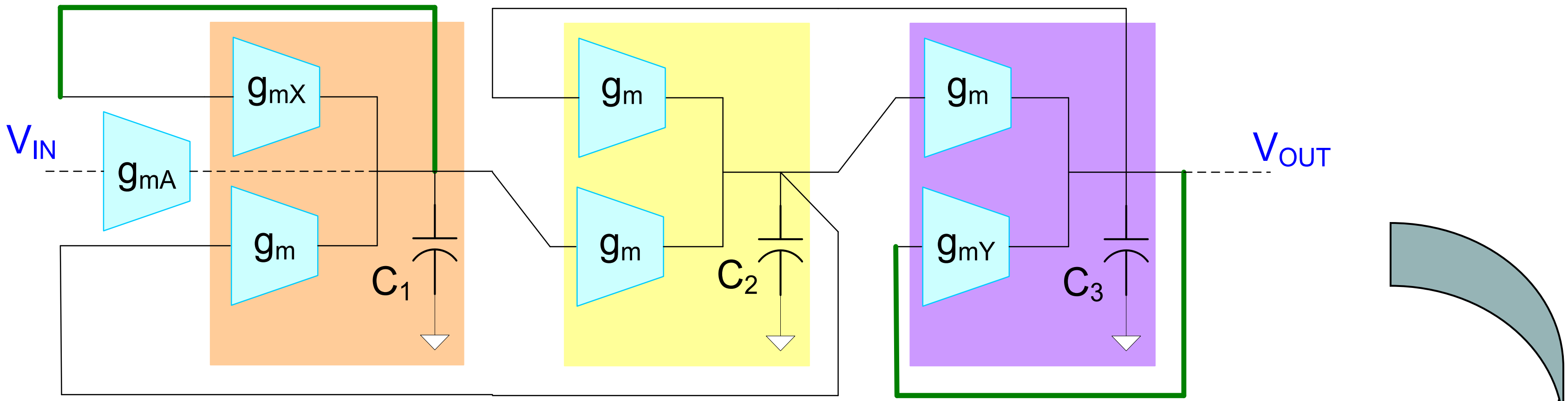


Redraw as:

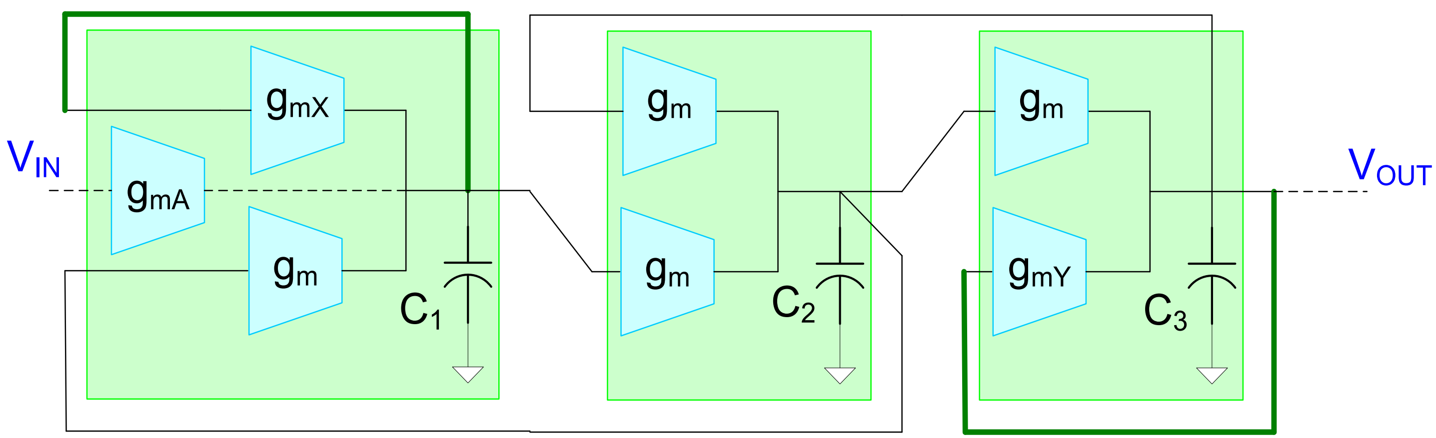


Leap-Frog Filter

Current-mode implementation

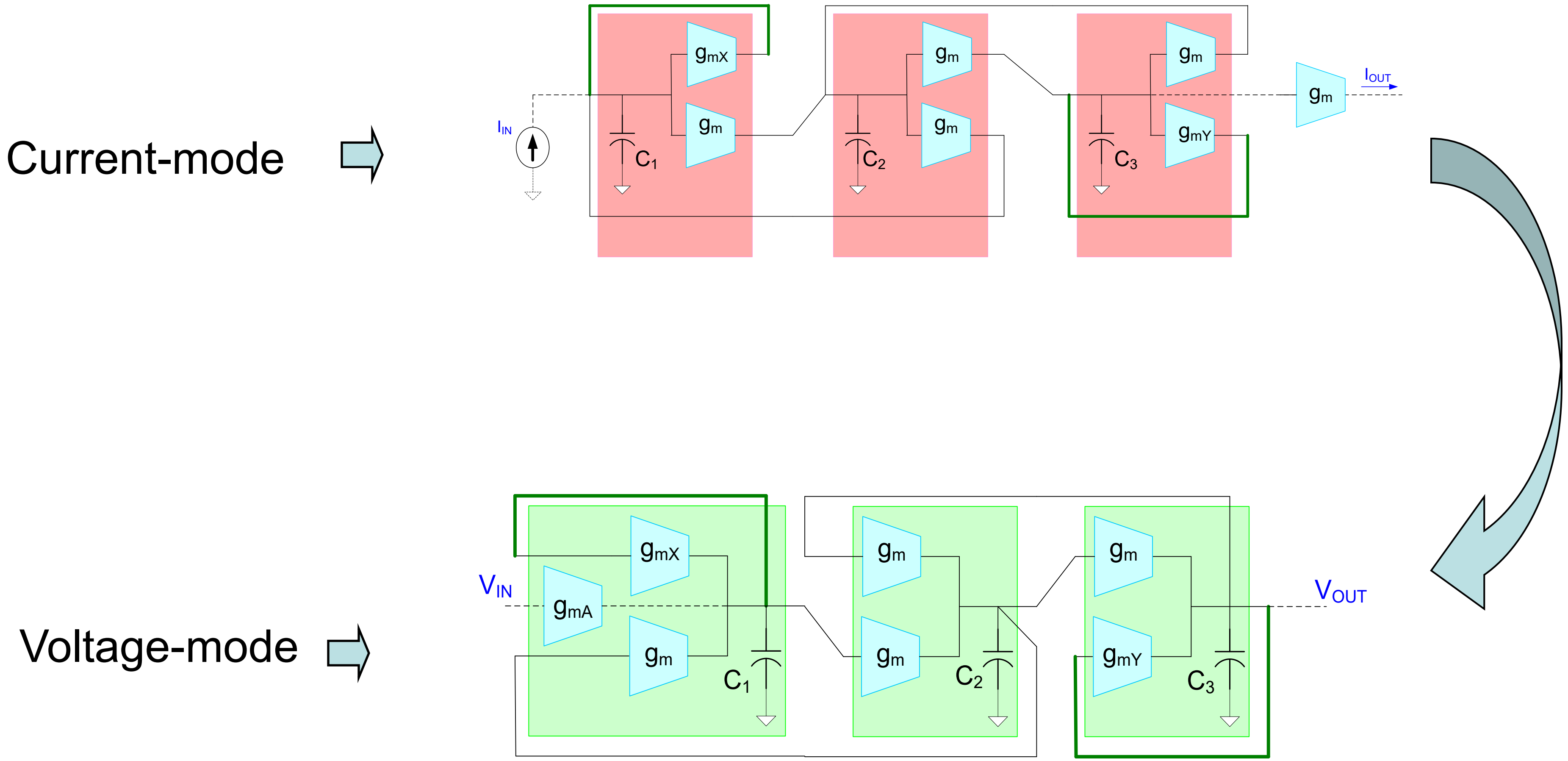


Change notation:



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

Leap-Frog Filter



Current-mode and voltage-mode circuits have same component count
Current-mode and voltage-mode circuits are identical !
Current-mode and voltage-mode properties are identical !

Current-mode circuit offers NO benefits over voltage-mode counterpart

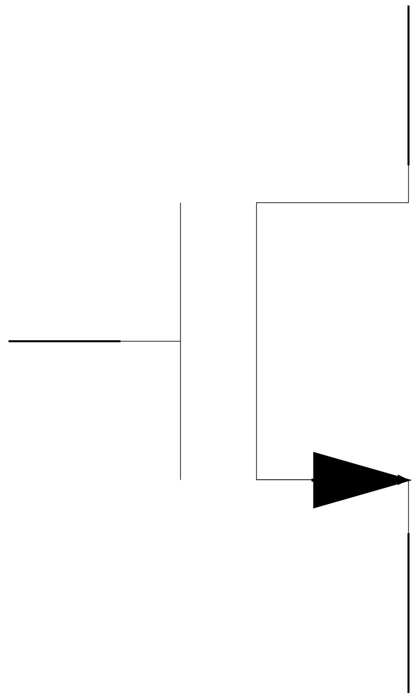
Questions about the Conventional Wisdom

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?

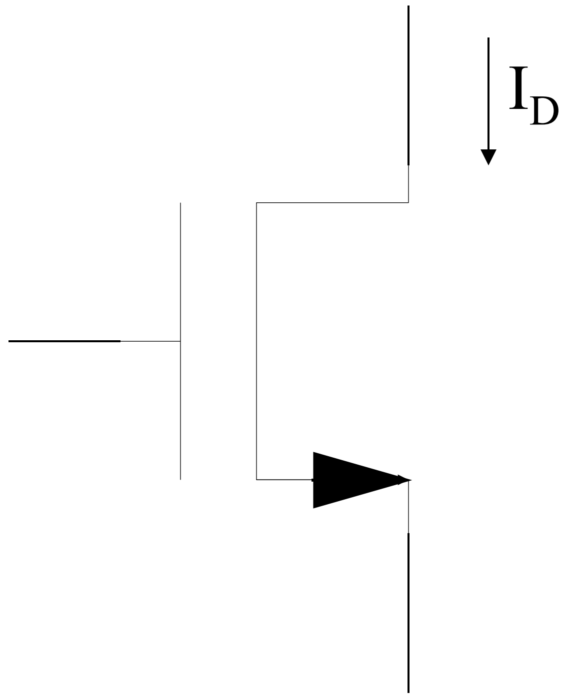
Question?

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



Question?

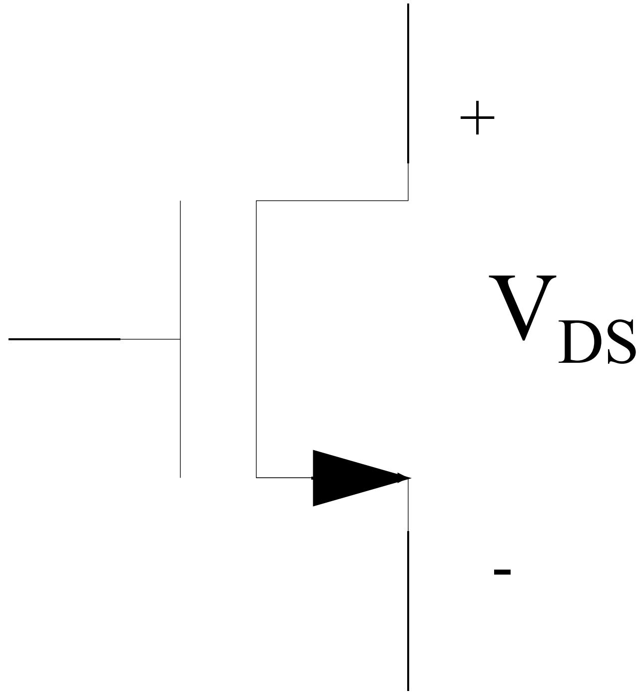
Is the following circuit a voltage mode-circuit or a current-mode circuit?



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

Observation

- Conventional wisdom suggests numerous performance advantages of current-mode circuits
- Some of the “current-mode” filters published perform better than other “voltage-mode” filters that have been published
- Few, if any, papers provide a quantitative comparison of the key performance features of current-mode circuits with voltage-mode counterparts
- It appears easy to get papers published that have the term “current-mode” in the title

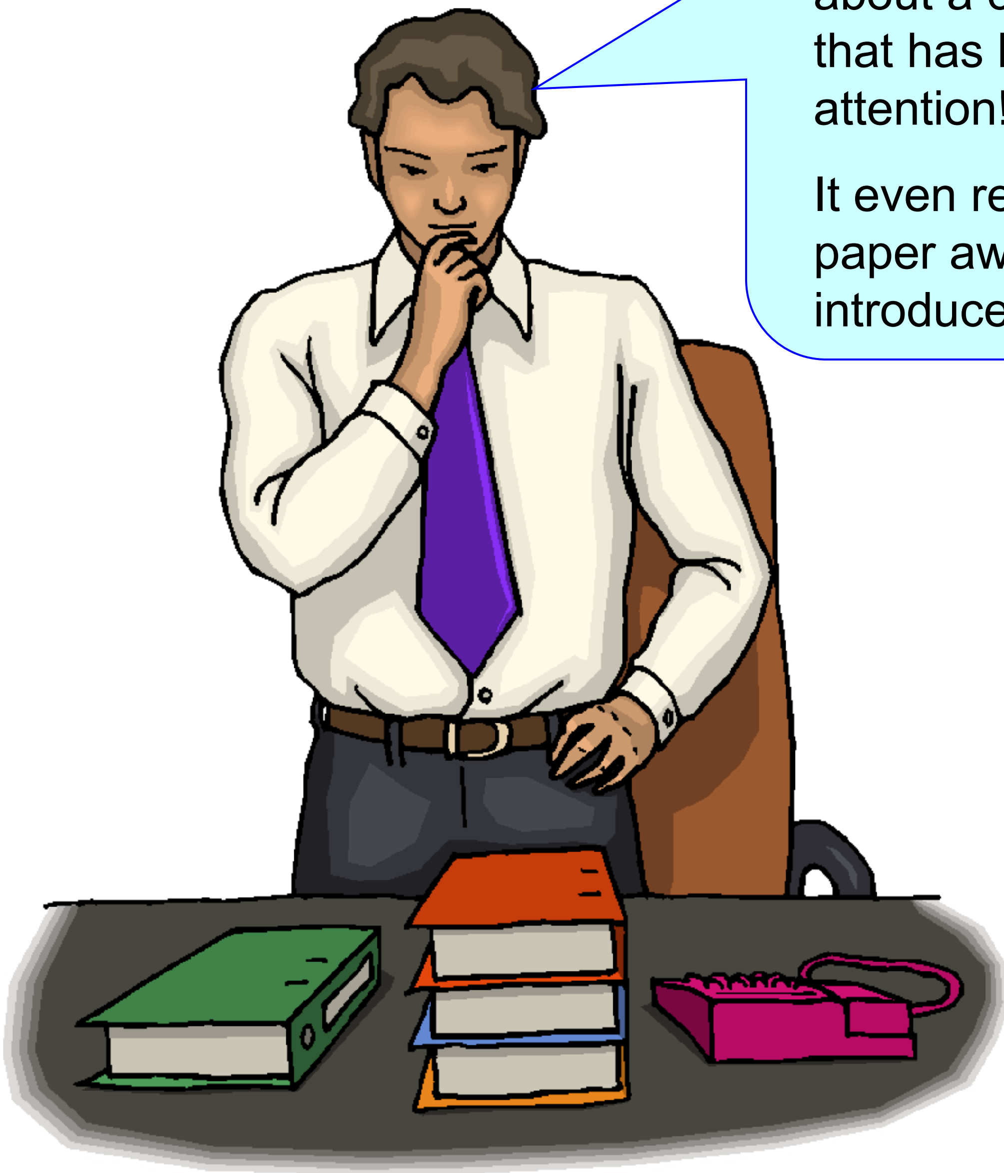
Observations (cont.)

- Over 900 current-mode papers have been published in IEEE forums alone !
- Most, if not all, current-mode circuits are IDENTICAL to a voltage-mode counterpart
- We are still waiting for even one author to quantitatively show that current-mode filters offer even one of the claimed four advantages over their voltage-mode counterparts

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Will consider 5 basic examples in this discussion

- Op Amp
- Positive Feedback Compensation
- Current Mode Filters
- Current Dividers
- Barkhausen Criterion



I’ve heard of some amazing claims about a clever current divider circuit that has been receiving lots of attention!

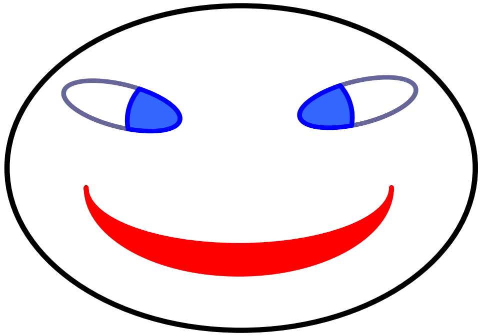
It even received the outstanding paper award at ISSCC when it was introduced!

Current Dividers

- Background
- Objective
- Concept of Current Divider
- Characterization of Inherently Linear Current Divider
- Inherent Current Division in Symmetric Circuits
- Conclusionhs

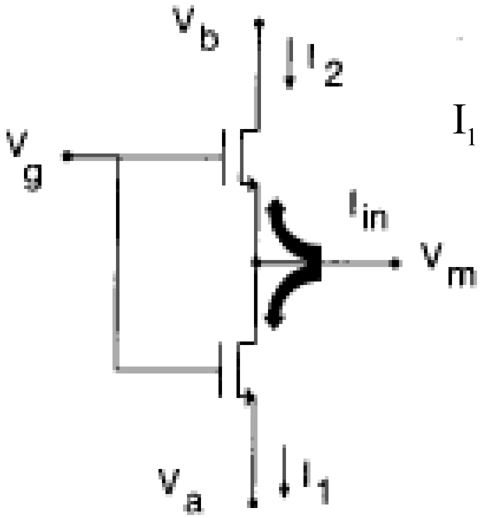
Current Dividers

Motivation: Circuits that do accurate current division in the presence of varying loading conditions could be among the most useful building blocks that are available



Background Introduction

Current divider with "Inherent Linearity"



. The basic principle of current division.

$$I_1 = \theta I_{IN}$$

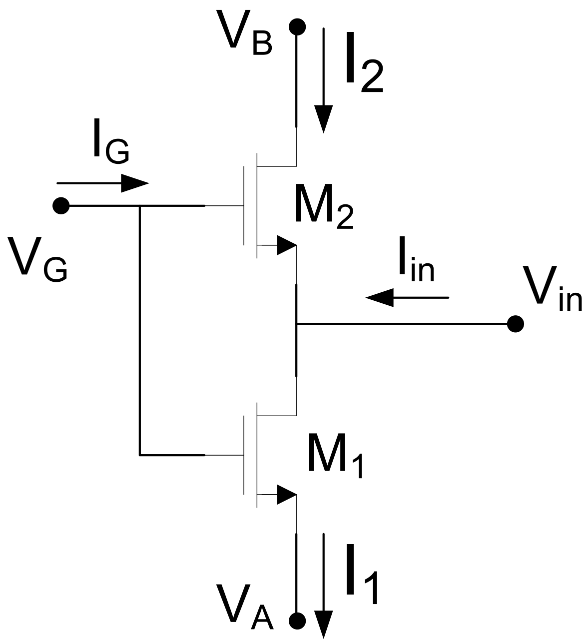
- constant and independent of I_{in} (implying low distortion),
- independent of the values of V_a and V_b,
- independent of whether one or both devices are saturated or nonsaturated,
- and also independent of whether one or both devices operate in strong or in weak inversion.

above we have assumed that V_a and V_b are ideal voltage sources, i.e., having zero output impedance.

- Examples that were given did not have zero impedance on V_A and V_B nodes
- Experimentally reported THD from -80dB to -85dB
- Experimentally measured Dynamic Range in excess of 100dB
- All digital standard CMOS process

Bult and Geelen, ISSCC Feb1992, JSC Dec 1992 "An Inherently Linear and Compact MOST-only Current Division Technique"

Background Introduction



$$I_1 = \theta I_{IN}$$

Current Division Factor

$$\theta = \frac{(W/L)_1}{(W/L)_2}$$

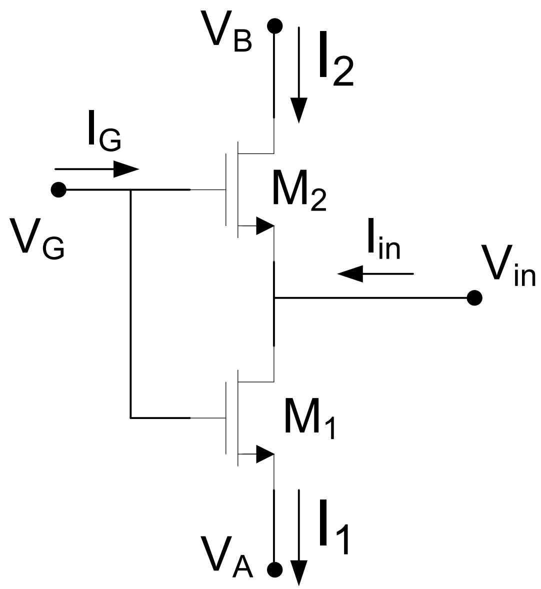
Very Simple and Compact

Elegant !

Current divider with “Inherent Linearity”

Bult and Geelen, ISSCC Feb1992, JSC Dec 1992 “An Inherently Linear and Compact MOST-only Current Division Technique”

Background Introduction



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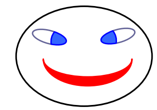

Current divider with “Inherent Linearity”

Bult and Geelen, ISSCC Feb1992, JSC Dec 1992 “An Inherently Linear and Compact MOST-only Current Division Technique”

An **inherently linear** and **compact** MOST-only current division technique

K Bult, GJGM Geelen - IEEE Journal of Solid-State Circuits, 1992 - ieeexplore.ieee.org

… A common technique is to use resistors or capacitors for the **linear** and accurate division of … in the **linear** region), it is shown here that the current division function is **inherently linear**. To …

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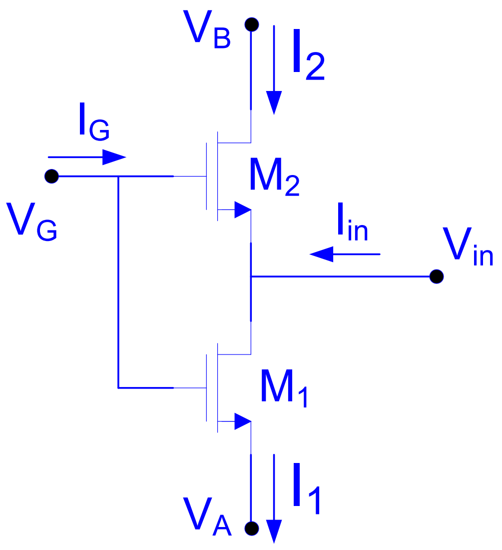
Dec 13 2024 (37 additional citations in past 6 years)

Background Introduction

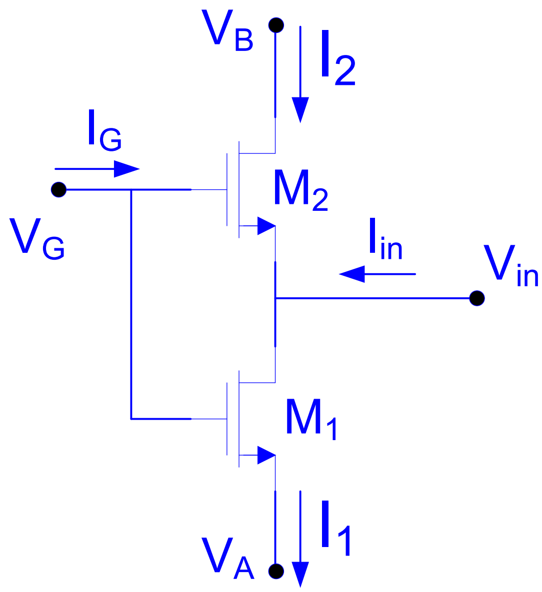


Inherently Linear Current Divider

Conventional Wisdom: current division factor independent of

- I_{IN}
- V_A and V_B
- Device operation region (weak, moderate, or strong inversion; triode or saturation region)
- body effect, mobility degradation

Background Introduction



Inherently Linear Current Divider

only weakly dependent upon second-order effects

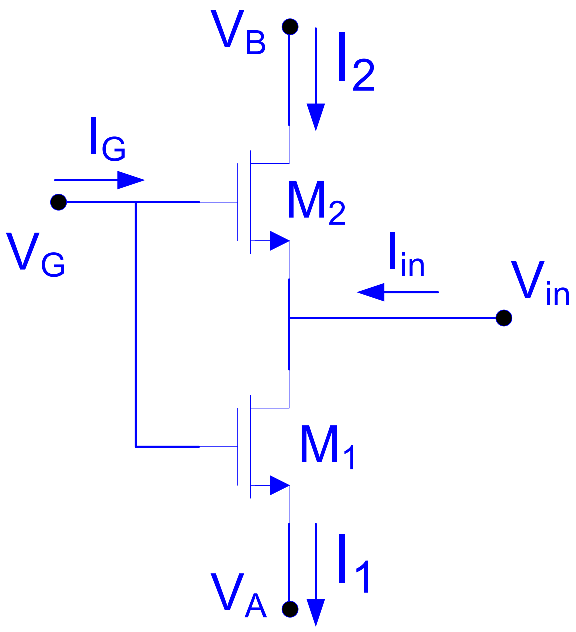
THD better than -85dB in audio range
Dynamic Range better than 100dB
Experimentally verified

Very impressive linearity properties !

Influential Concept

- Outstanding paper of ISSCC 1992
- Cited >370 times Google Scholar
- Reported applications include
  - Volume controller
  - Data converter
  - Tunable filters
  - Variable gain amplifier
  - Accurate current generator
  - Sensors
  - Other circuits
- Numerous reported works experimentally verify the high linearity

Dec 2016 search !



Inherently Linear Current Divider

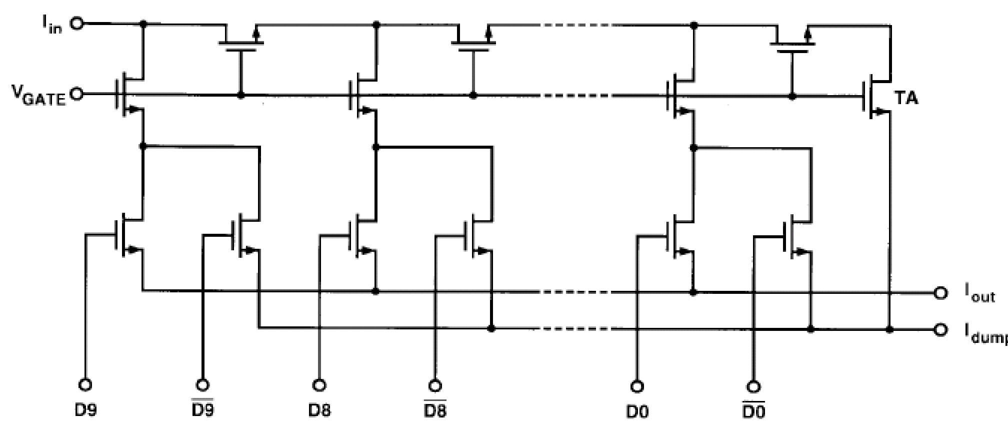
An example application of the concept and the circuit

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 33, NO. 8, AUGUST 1998

Design and Implementation of an Untrimmed MOSFET-Only 10-Bit A/D Converter with −79-dB THD

Clemens M. Hammerschmied, *Student Member, IEEE*, and Qiuting Huang, *Senior Member, IEEE*

The MOSFET ladder is based on a linear current division principle instead, the basic circuit of which is depicted in Fig. 4 [14]. An input current I_{in} is divided into two currents



Scholar Dec 13 2024

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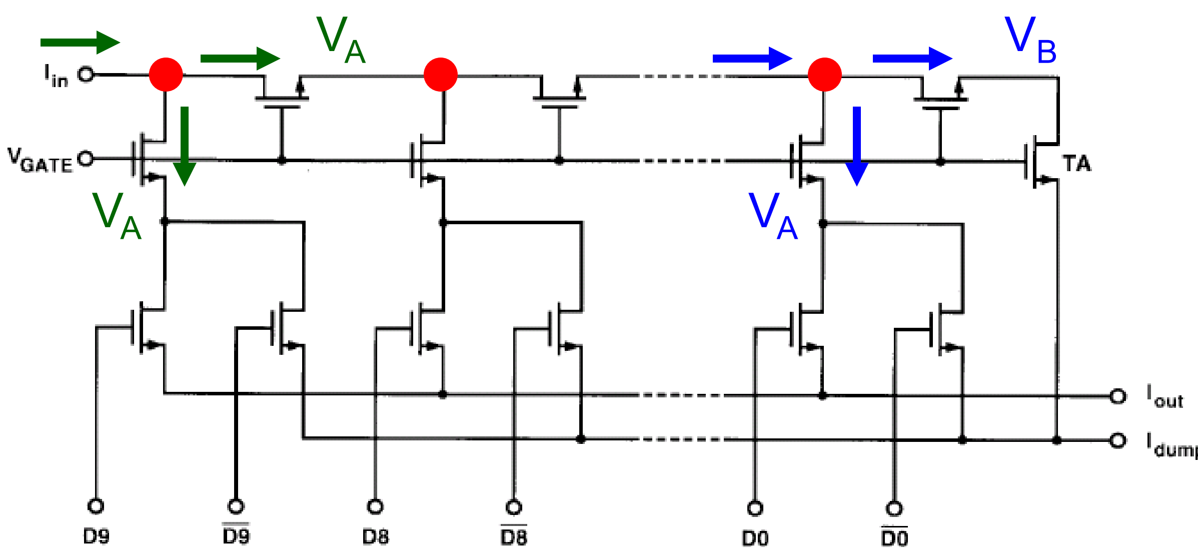

V_A and V_B not even at zero impedance nodes !

An example application of the concept and the circuit

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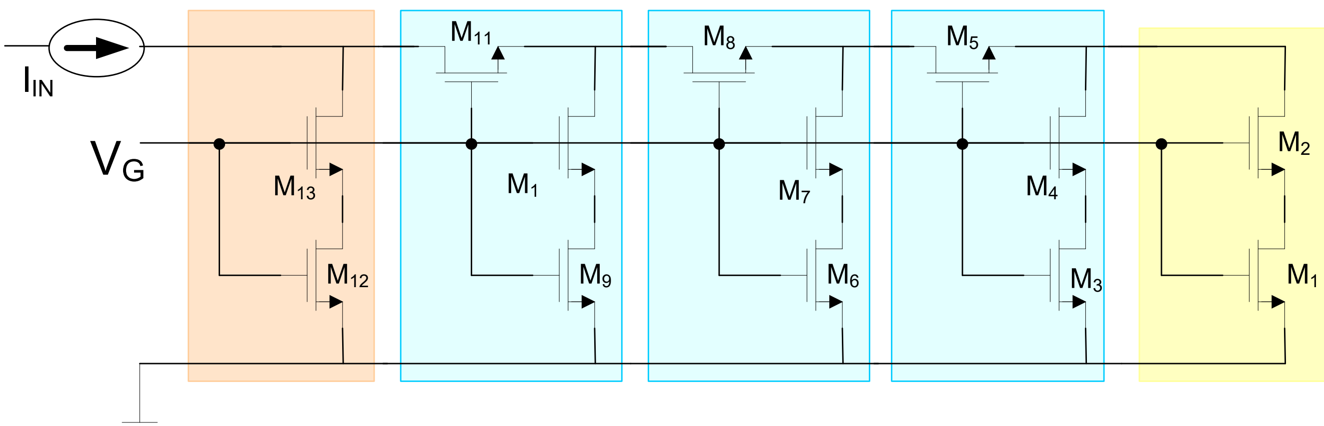
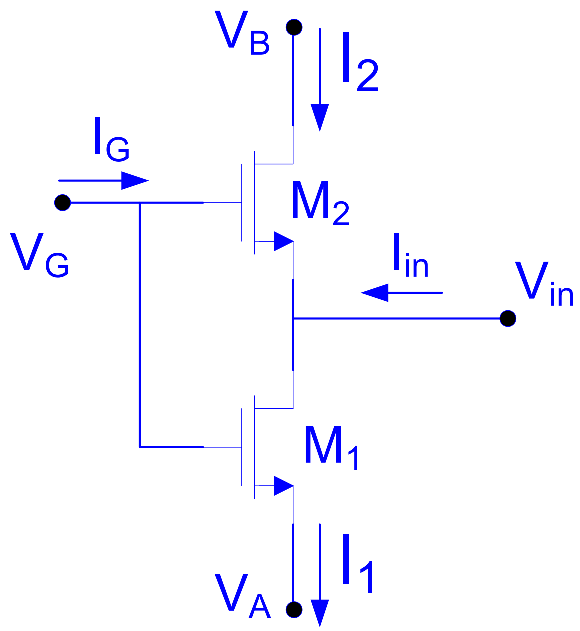


But



Inherently Linear Current Divider

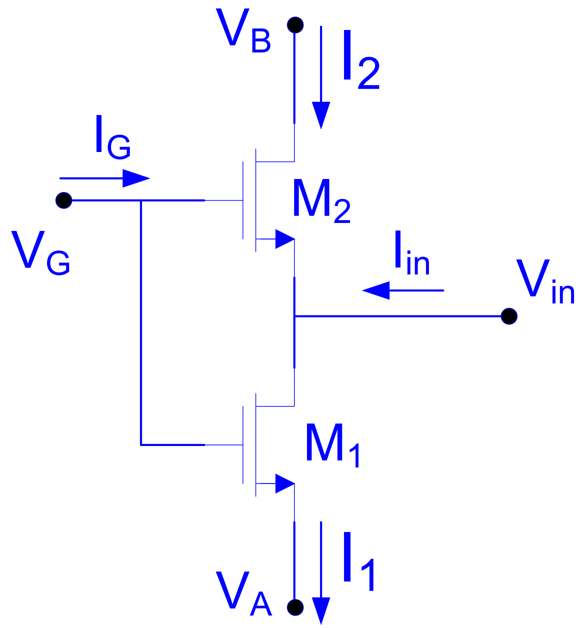
We have been unable to achieve linearity that is even close to that reported in different but closely related applications of this circuit

(e.g. -40dB or less linearity in contrast to -85dB or better performance)

Outline

- Background
- Objective
- Concept of Current Divider
- Characterization of Inherently Linear Current Divider
- Inherent Current Division in Symmetric Circuits
- Conclusions

Purpose of this work



Clarify and quantify the potential and limitations of the “inherently linear current divider”

(Do not question the reported experimental results attributed to this circuit)

Current Dividers

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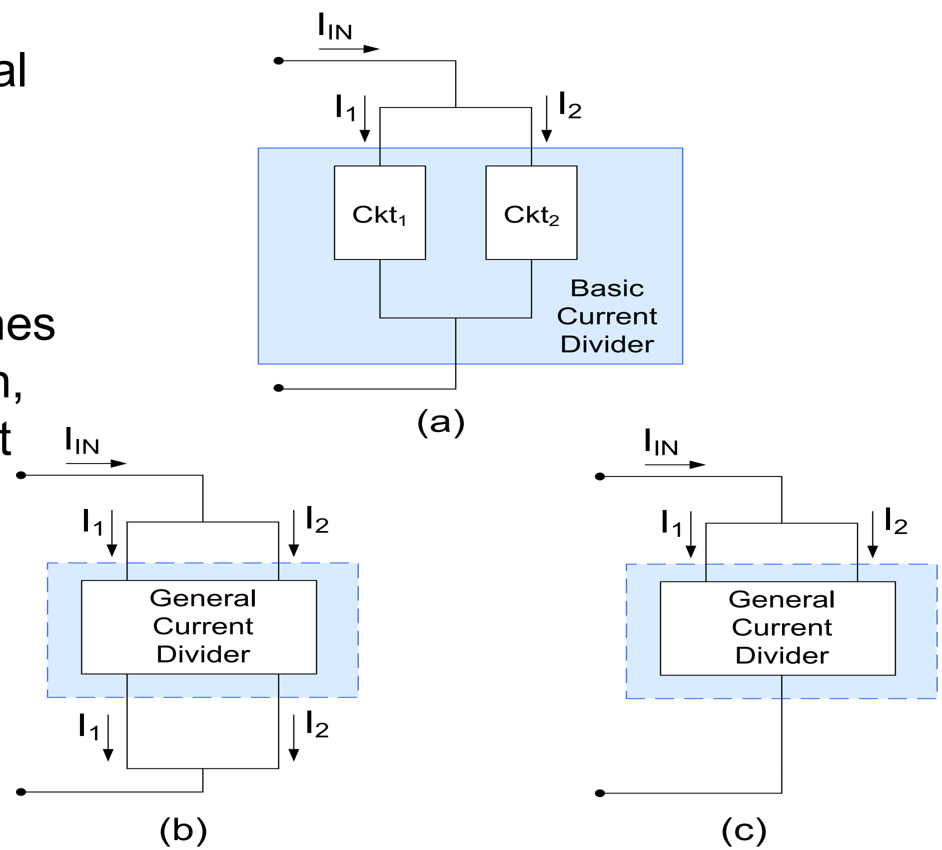
Concept of Current Divider

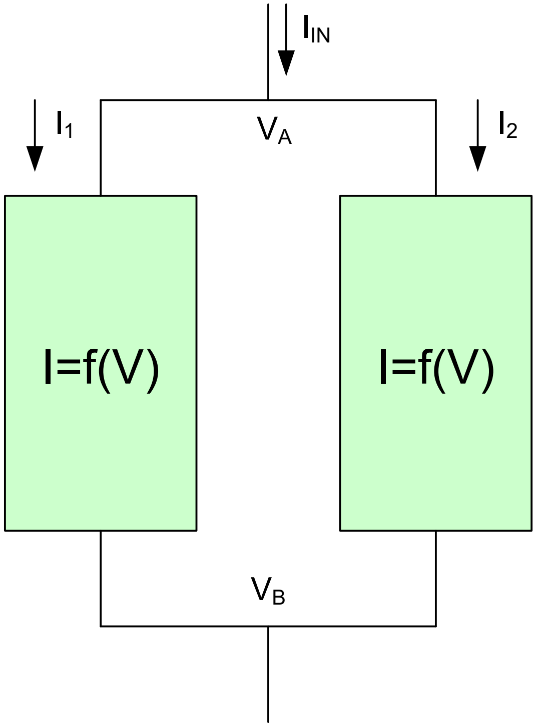
What is a current divider ?

- Although the term is widely used, formal definitions seldom if ever given
- Consider a node with three incident branches in a circuit
- If the current in one of the three branches is proportional to that in another branch, we will define this circuit to be a current divider

$$I_1 = \theta I_{IN}$$



Observations That Will Become Relevant



$$I_1 = \frac{1}{2} I_{IN}$$

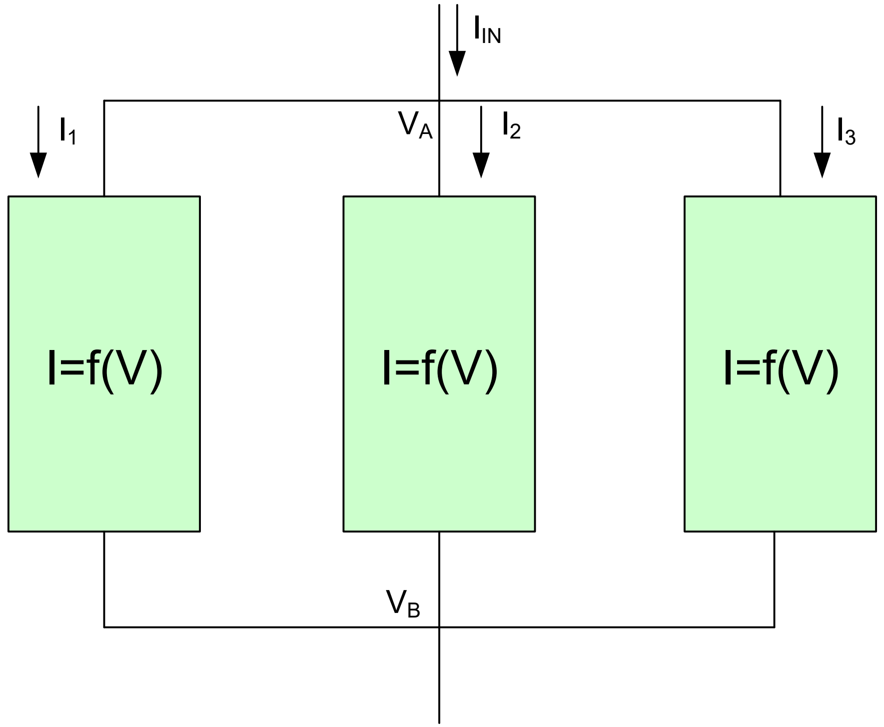
Independent of V_A, V_B, $I_{IN,}$, f

Inherent property of symmetric network

Current Divider !

Concept that has probably been known for well over 100 years

Observations that Will Become Relevant

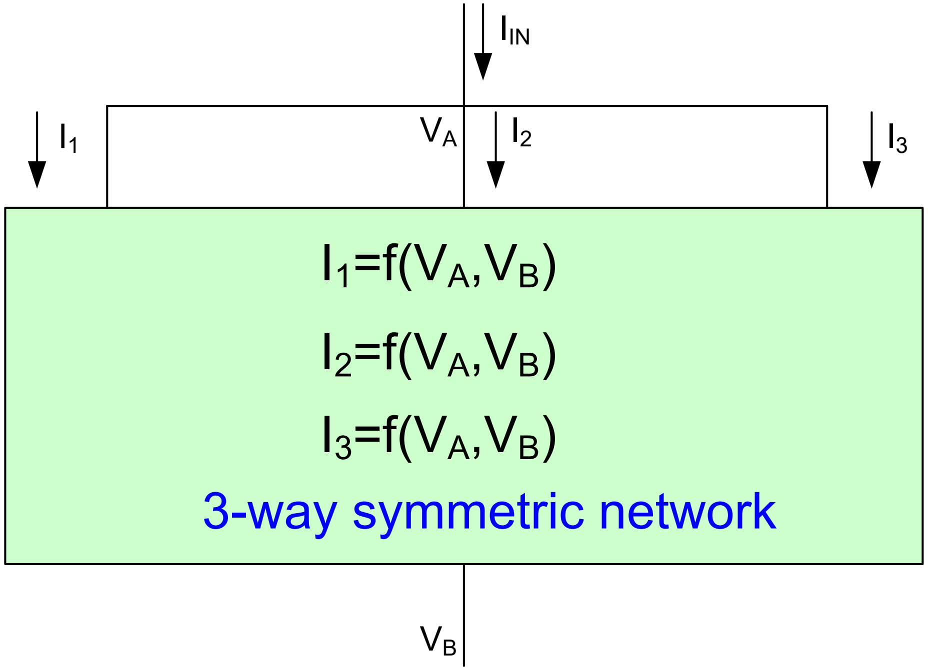


$$I_1 = \frac{1}{3} I_{IN}$$

Independent of V_A, V_B, $I_{IN,}$, f

Inherent property of symmetric network

Observations that Will Become Relevant



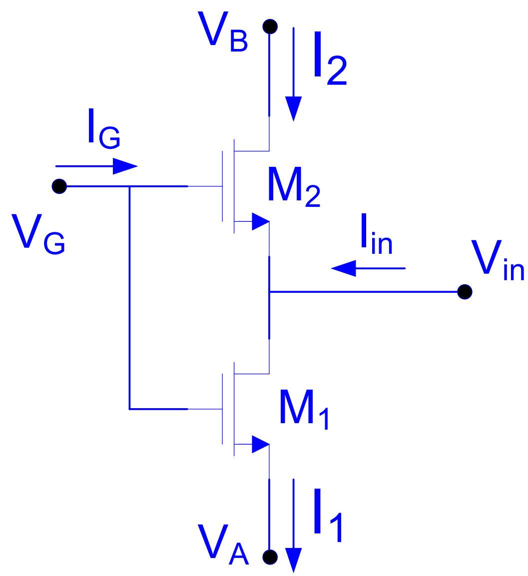
$$\mathbf{I_1 = \frac{1}{3} I_{IN}}$$

Independent of V_A, V_B, $I_{IN,}$, f

Inherent property of symmetric network

Concept that has probably been known for well over 100 years

Consider the Inherently Linear Current Divider with Linearity Challenges



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- Device operation region (weak, intermediate, or strong inversion; triode or saturation region of operation)
- body effect, mobility degradation

Current Dividers

- Background
- Objective
- Concept of Current Divider
- ➡ Characterization of Inherently Linear Current Divider
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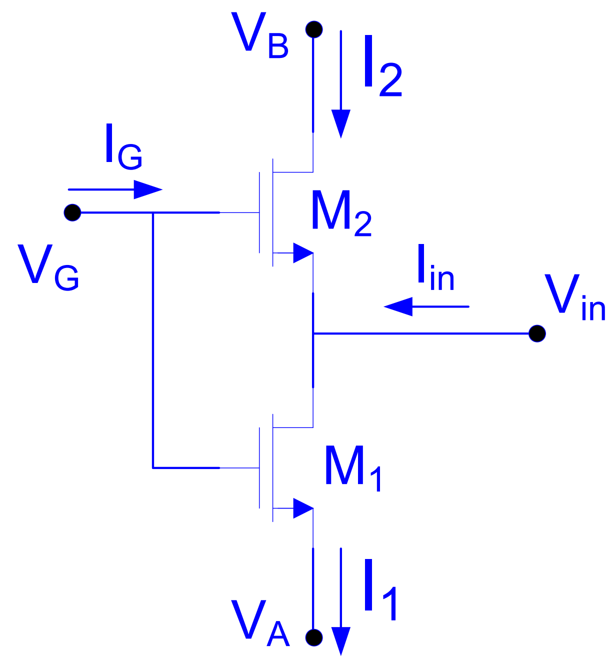
Assumptions

- Square-law model
- Identical V_{th}
- No Body or Output Conductance Effects

- $\{I_{in}, V_{GA}, V_{BA}\}$ independent variables

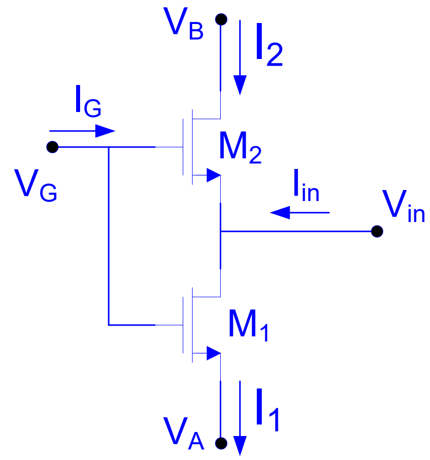


$\eta_1 = \mu C_{OX}(W_1/L_1)$
$\eta_2 = \mu C_{OX}(W_2/L_2)$

From a straightforward but tedious analysis

If M_1 in the triode region and M_2 in the triode region

$$I_1 = \left[\frac{\eta_1}{\eta_1+\eta_2}\right] I_{in} + \frac{\eta_1\eta_2}{\eta_1+\eta_2} V_{BA}\left(V_{GA} - V_T - \frac{V_{BA}}{2}\right)$$



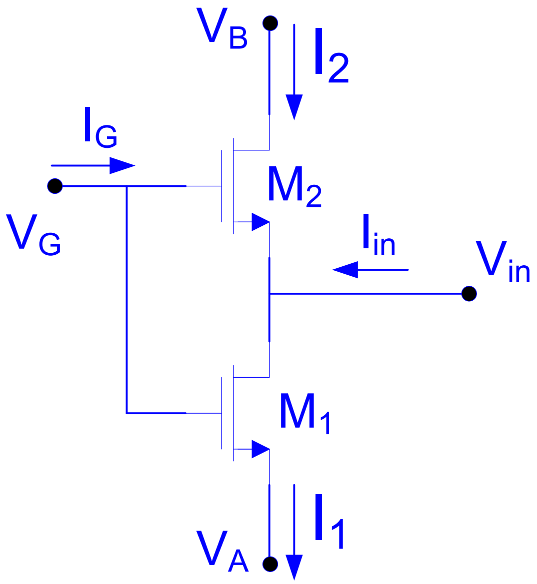
$$V_{inA} = V_{GA} - V_T - \sqrt{(V_{GA} - V_T)^2 - 2\left(\left[\frac{1}{\eta_1+\eta_2}\right] I_{in} + \frac{\eta_2}{\eta_1+\eta_2} V_{BA}\left(V_{GA} - V_T - \frac{V_{BA}}{2}\right)\right)}$$

Oddly, the driving point voltage is dependent upon the driving point current !

From a straightforward but tedious analysis

If M_1 in the triode region and M_2 in the saturation region

$$I_1 = \left[\frac{\eta_1}{\eta_1+\eta_2}\right] I_{in} + \frac{\eta_1\eta_2}{2(\eta_1+\eta_2)}(V_{GA}-V_T)^2$$

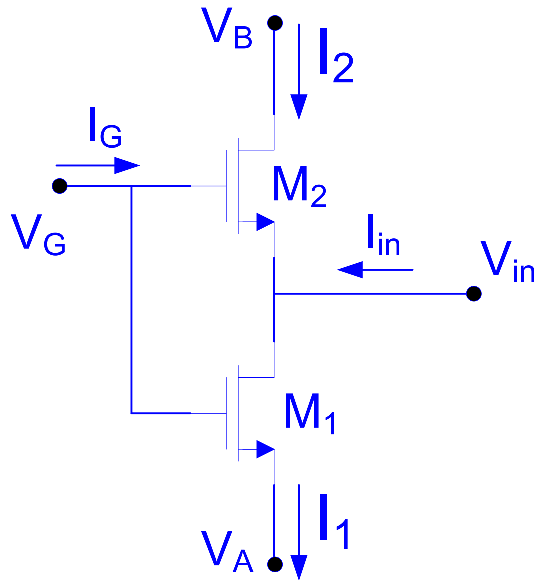


$$V_{inA} = (V_{GA}-V_T)\left(1-\sqrt{\frac{\eta_1-\frac{2I_{in}}{(V_{GA}-V_T)^2}}{\eta_1-\eta_2}}\right)$$

Oddly, the driving point voltage is dependent upon the driving point current !

From a straightforward but tedious analysis using the basic square-law model

If V_{GA} and V_{GB} do not depend upon I_{IN}, then
- the circuit performs as a linear current divider with an offset
- the current divider ratio does not change as M_1 and M_2 change from the triode region to the saturation region



But, if these conditions are not satisfied, will the circuit still perform as a linear current divider ?

Some things ignored in previous analysis

- Device model errors (not exactly square-law)
- Threshold voltages mismatches
- Finite output impedance of transistors
- Body effect
- Finite output impedance of the current source

More Accurate Analysis

- Analytical study is unwieldy with highly complicated model
- Computer simulation helpful for predicting linearity

Linearity Metrics

– Static linearity defined as deviation from fit line

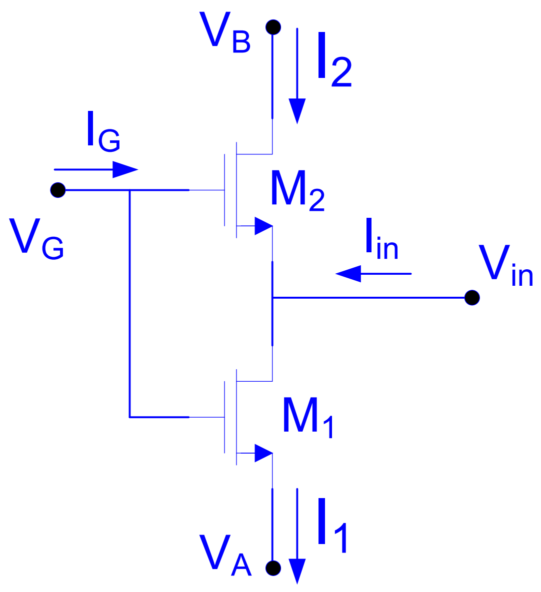
$$I_{1FIT}(I_{in}) = I_{1Q} + \left.\frac{\partial I_1}{\partial I_{in}}\right|_{\{I_{inQ}, V_{GAQ}, V_{inAQ}\}} \cdot (I_{in} - I_{inQ})$$

$$\Delta = \left[\frac{I_1(I_{in}) - I_{1FIT}(I_{in})}{I_{1FIT}(I_{in})}\right] \times 100\%$$

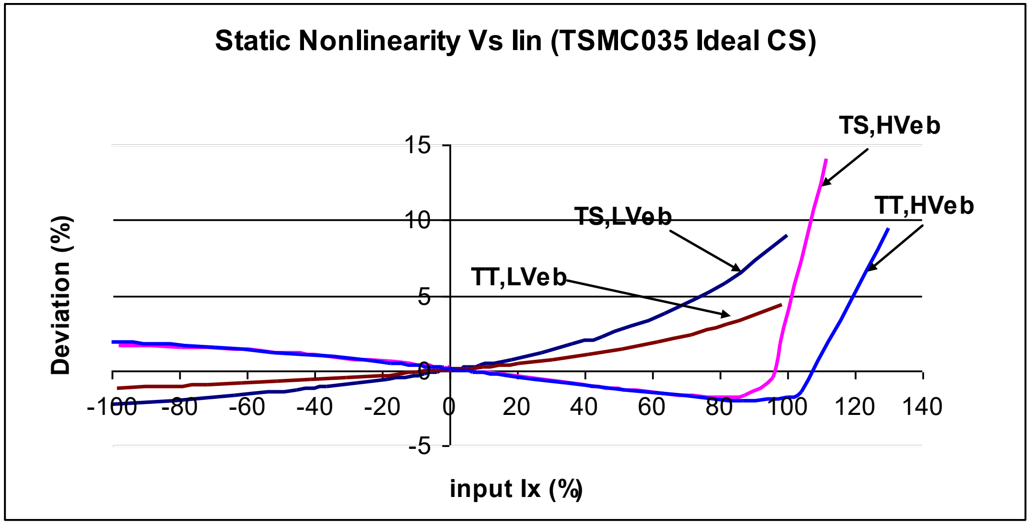
– Dynamic linearity defined as the THD performance with continuous sinusoid excitation

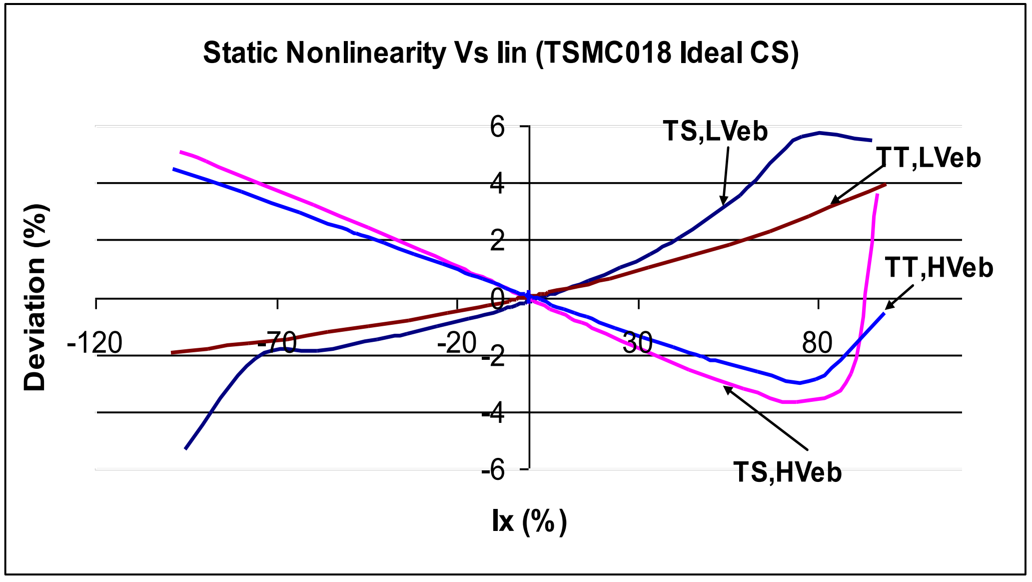
Simulation Environments

- Different operation regions (M_1, M_2)
  - Triode, Triode ("TT")
  - Triode, Saturation ("TS")
- Different bias level
  - Large V_{EB}
  - Small V_{EB}
- Different size devices (width, length)
- Different process
  - TSMC 0.18um
  - TSMC 0.35um
- V_{AS}, V_{BS}, V_{GS} fixed
- Ideal current source excitation

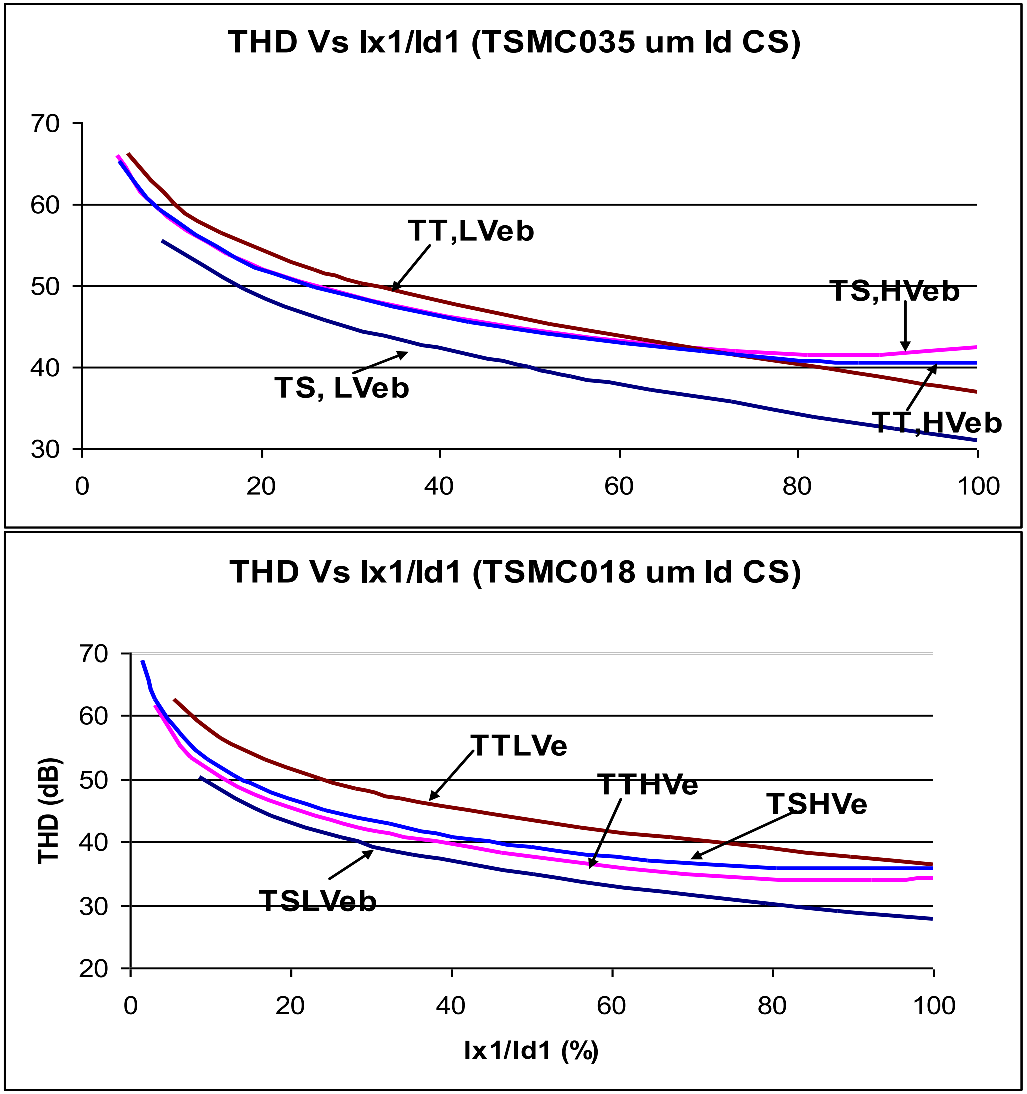


Static Linearity Simulation





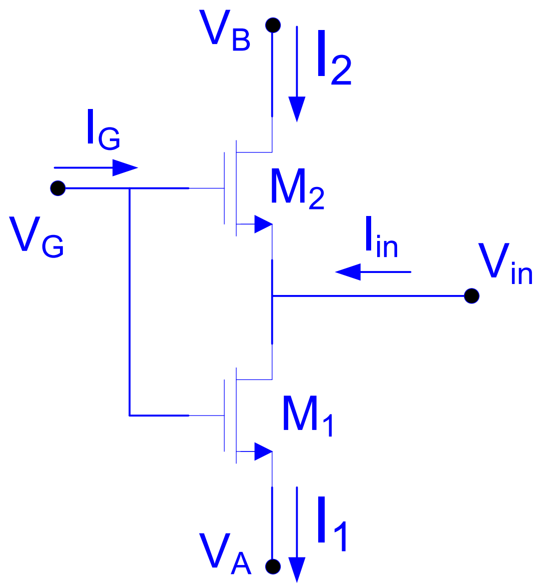
Dynamic Linearity Simulation



Observations about Linearity

- Static nonlinearity in the few percent range
- Dynamic linearity is quite limited with even moderate input current levels
  - limited to about 30~40 dB level if reasonable input current swings occur
- Including effects of output impedance of current source and circuit dependence of V_{AS} and V_{BS} will further degrade performance

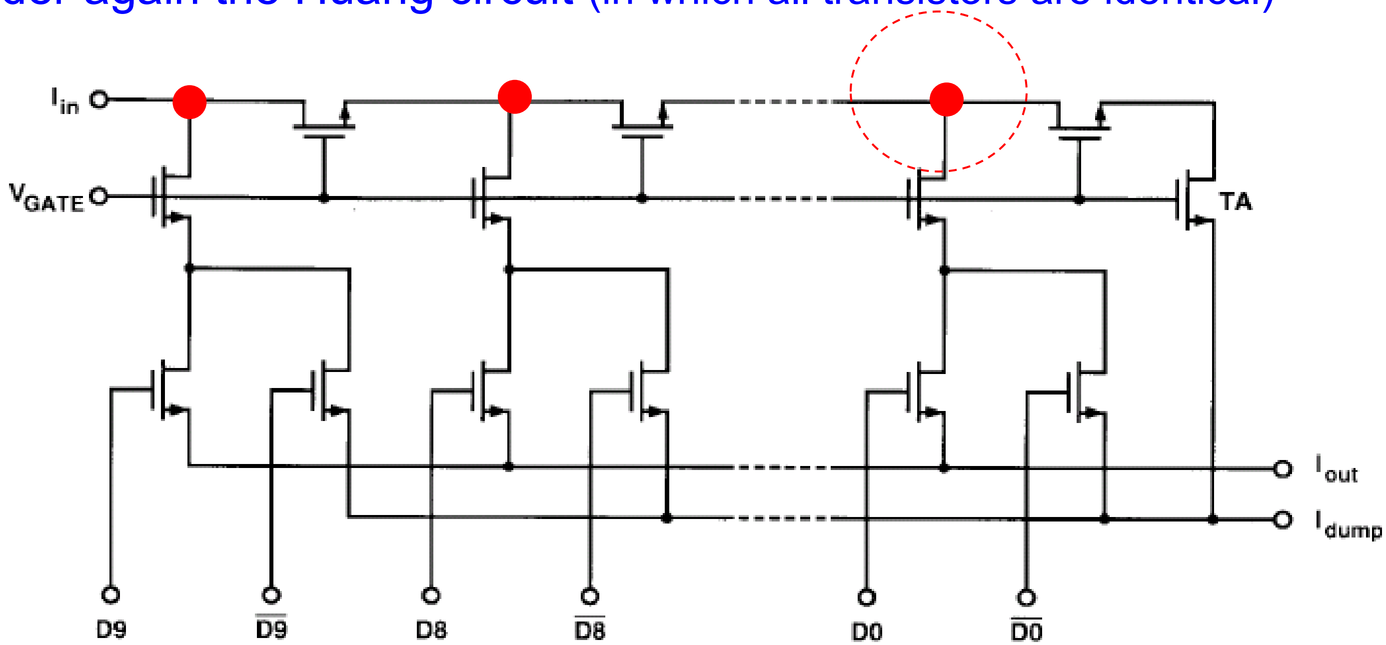
Observations about inherently linear current divider



- Performance as a current divider is somewhat questionable
- Not inherently linear (appears to be strongly dependent upon model)

Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

Consider again the Huang circuit (in which all transistors are identical)

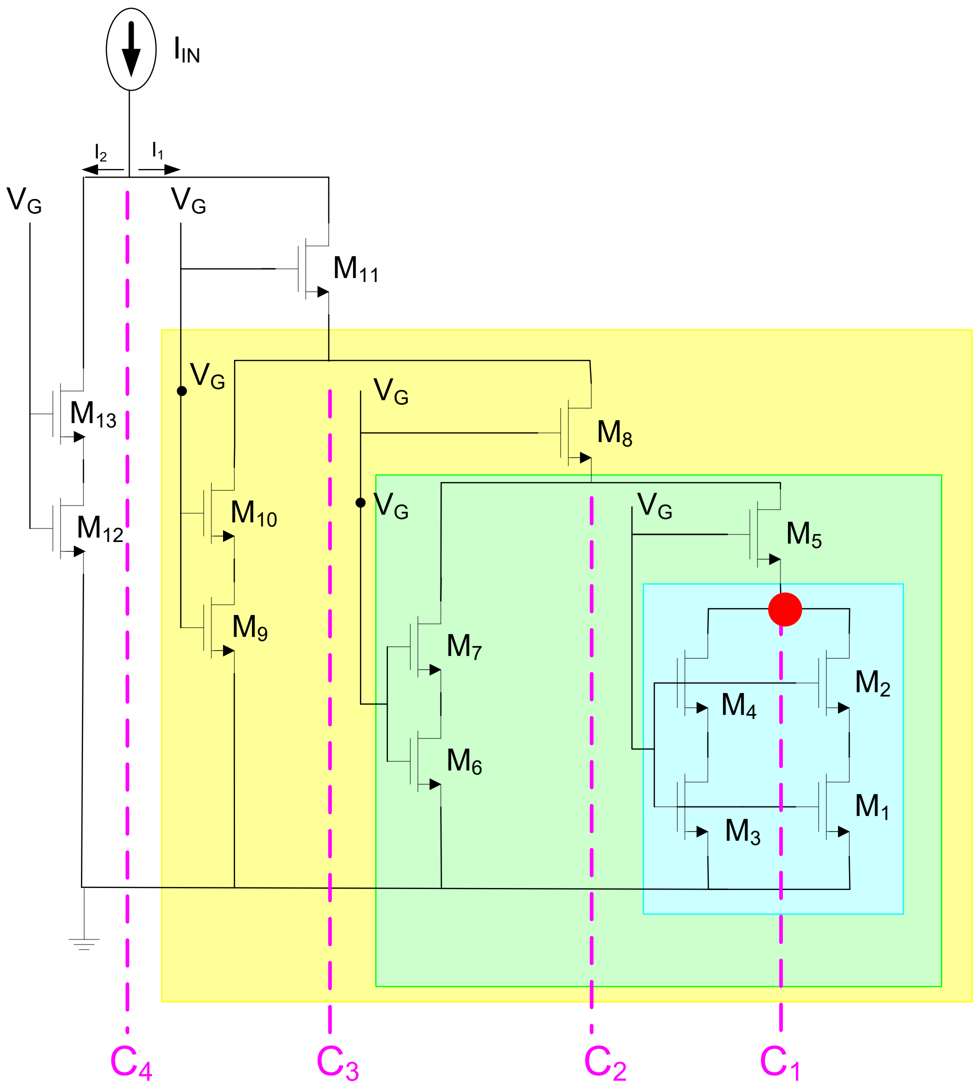


For proper operation, it is critical that currents divide equally at each of The current division nodes !

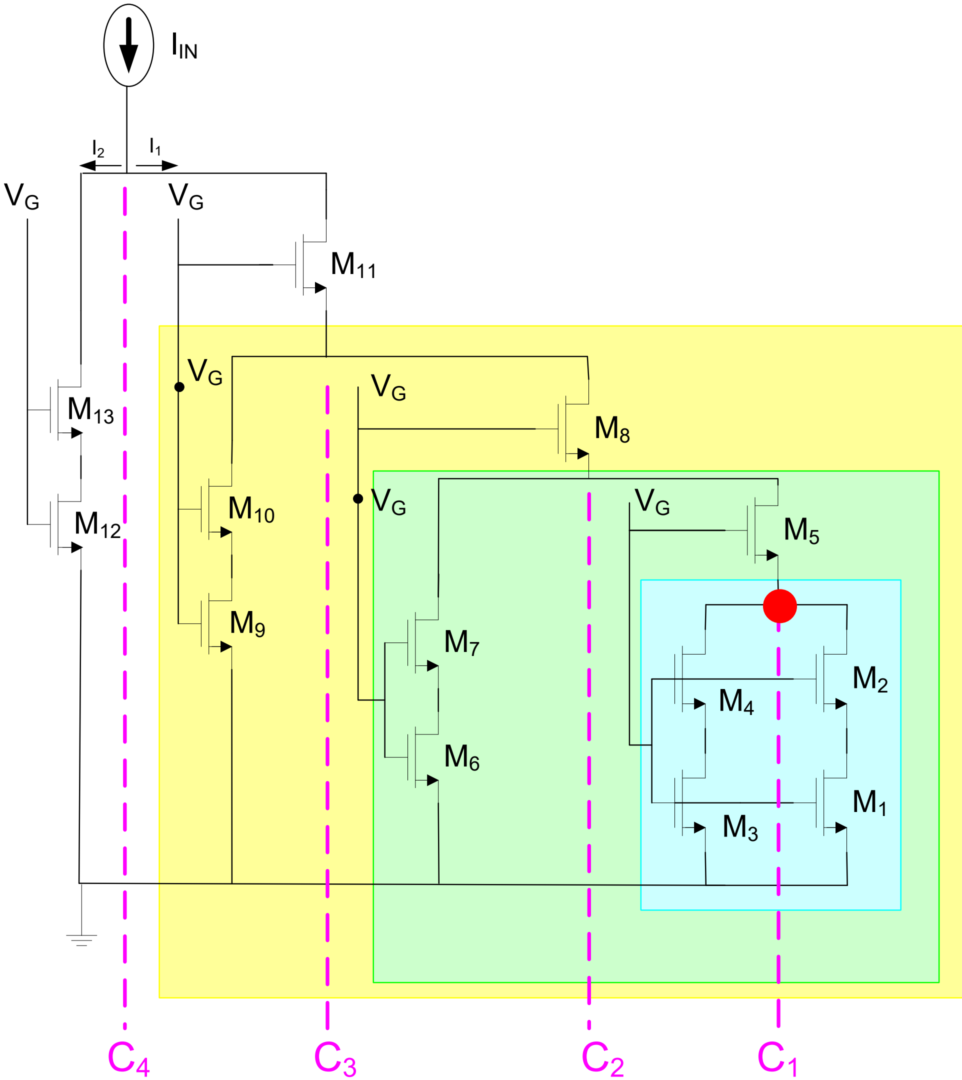
Even the assumption that the voltages V_A and V_B must be zero-impedance sources was not required to obtain the good performance (79 dB range) !

Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

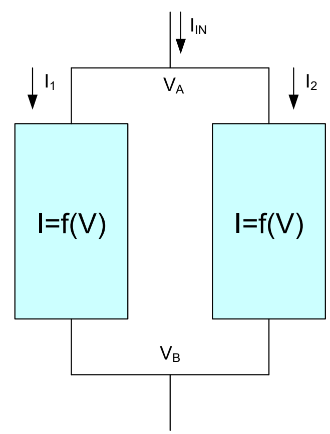
Redraw the Huang Circuit and Consider the right-most Current Divider node



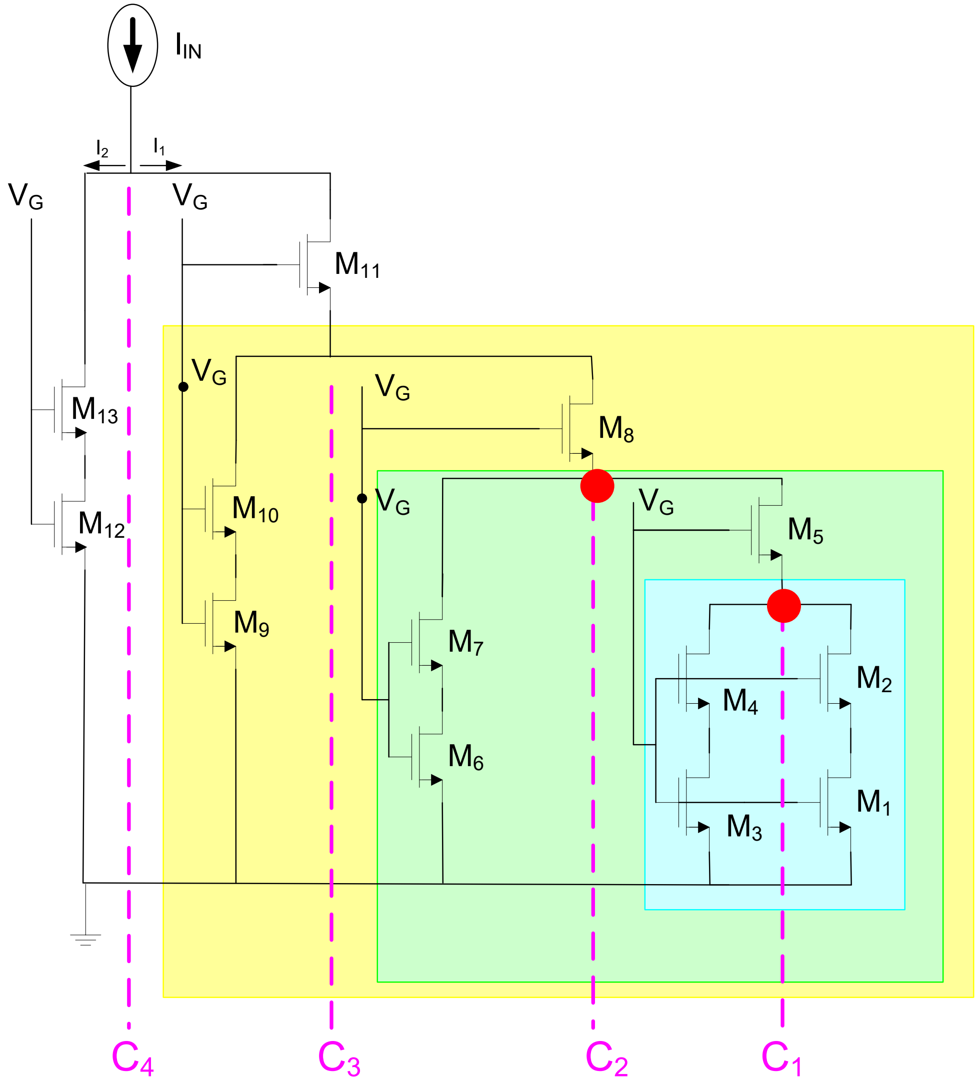
Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?



- Circuit in blue is completely symmetric on C_1 and is the well-known current divider
- it is not dependent upon any specific properties of the transistors !
- This was the right-most node where the "inherently linear" current divider was used !

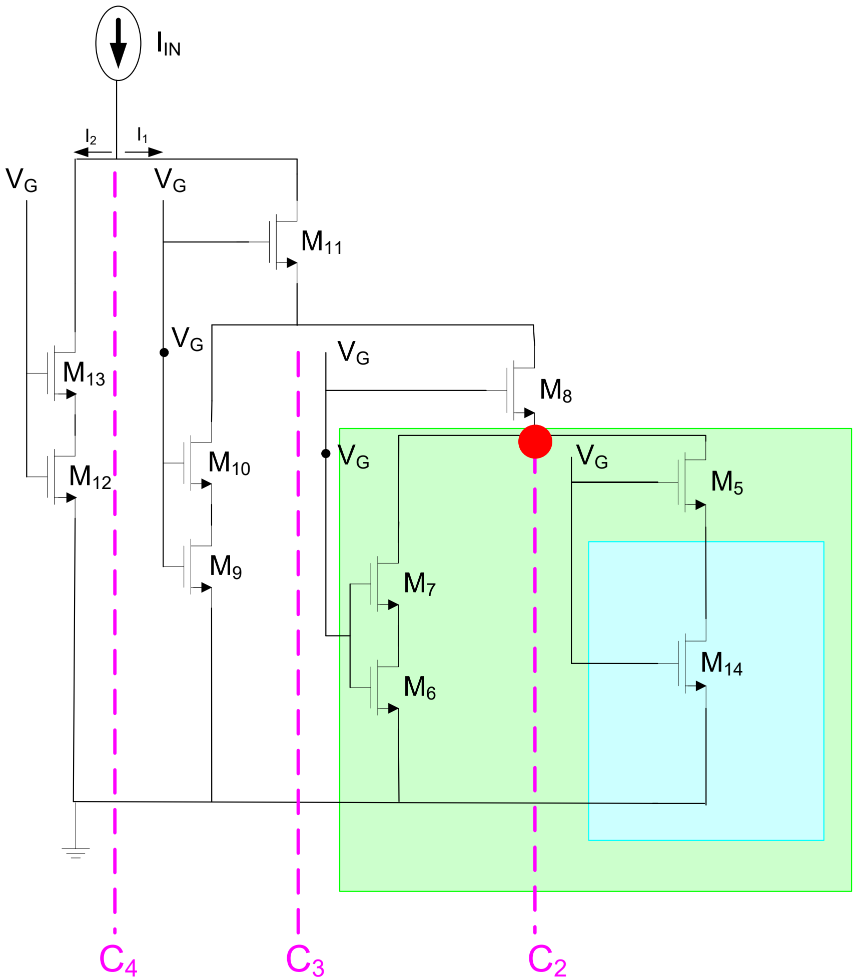


Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

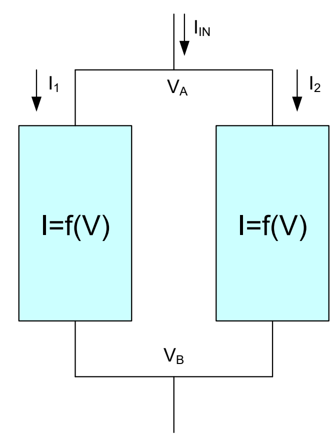


- Observe that M_1,M_2,M_3,M_4 can be modeled as a single transistor that is of the same size as M_1
- Call this M_{14}
- Consider now the next closest current-divider node

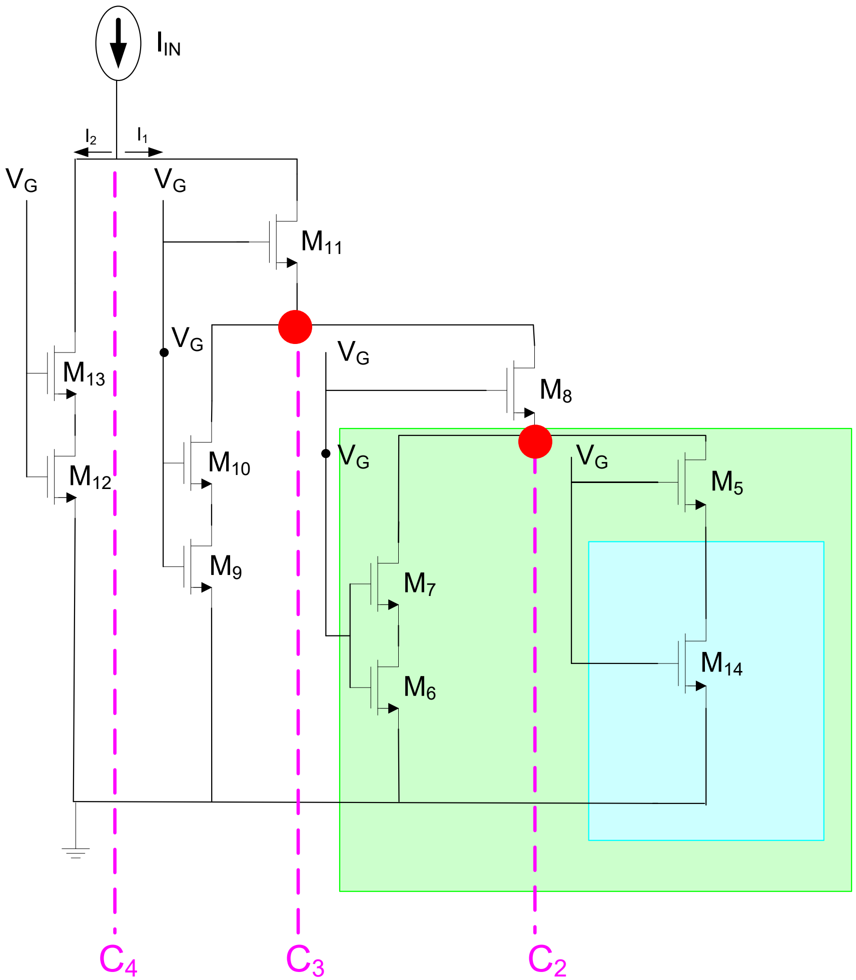
Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?



- Circuit in green is completely symmetric about C_2 and is the well-known current divider
- it is not dependent upon any specific properties of the transistors !

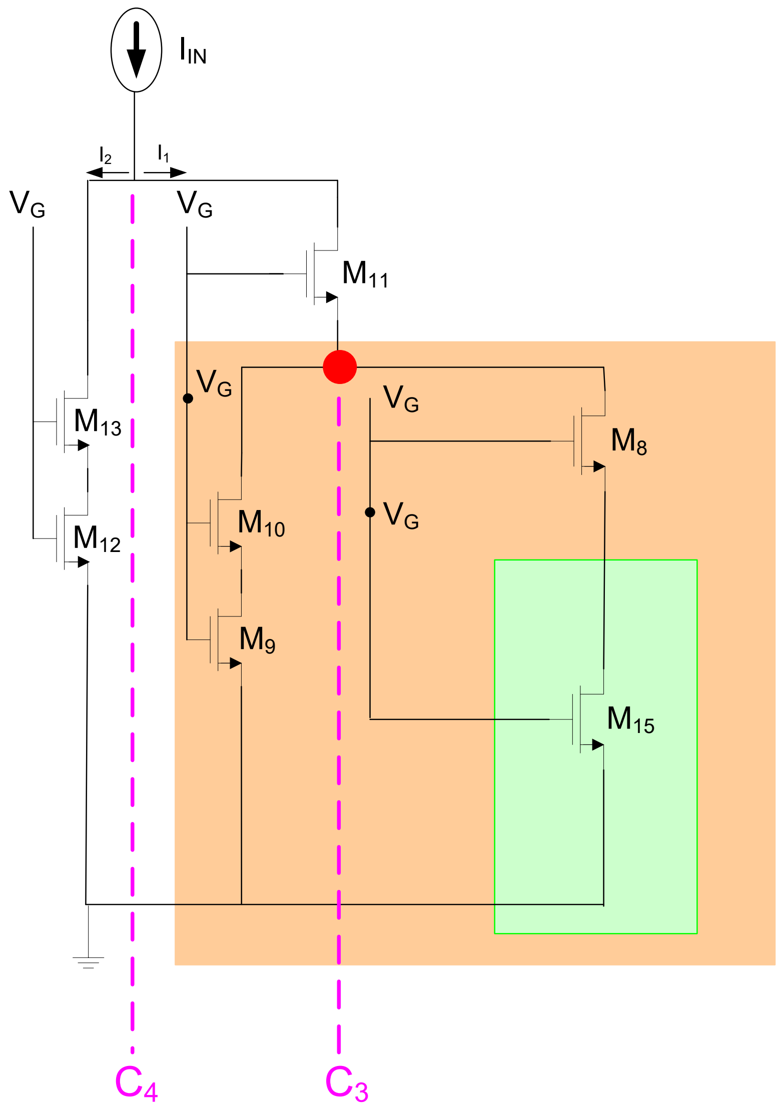


Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

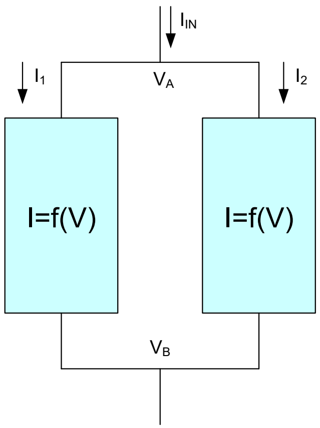


- Observe that M_6,M_7,M_5,M_{14} can be modeled as a single transistor that is of the same size as M_1
- Call this M_{15}
- Consider now the next closest current-divider node

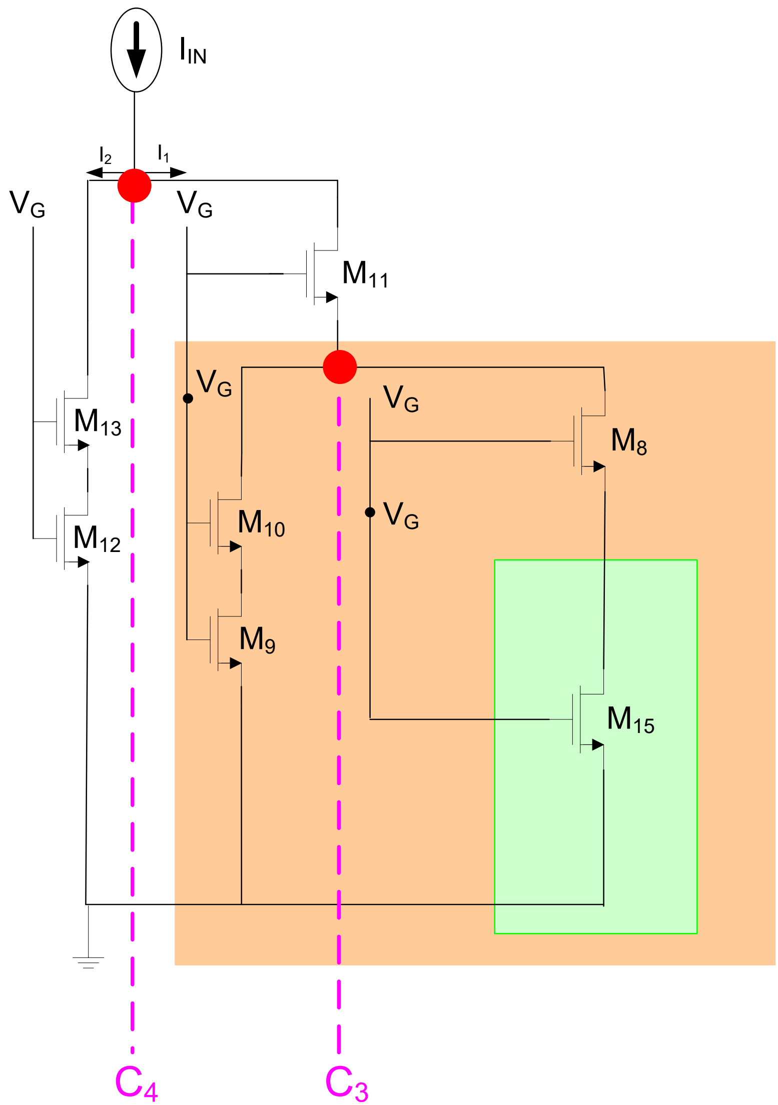
Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?



- Circuit in brown is completely symmetric on C_3 and is the well-known current divider
- it is not dependent upon any specific properties of the transistors !

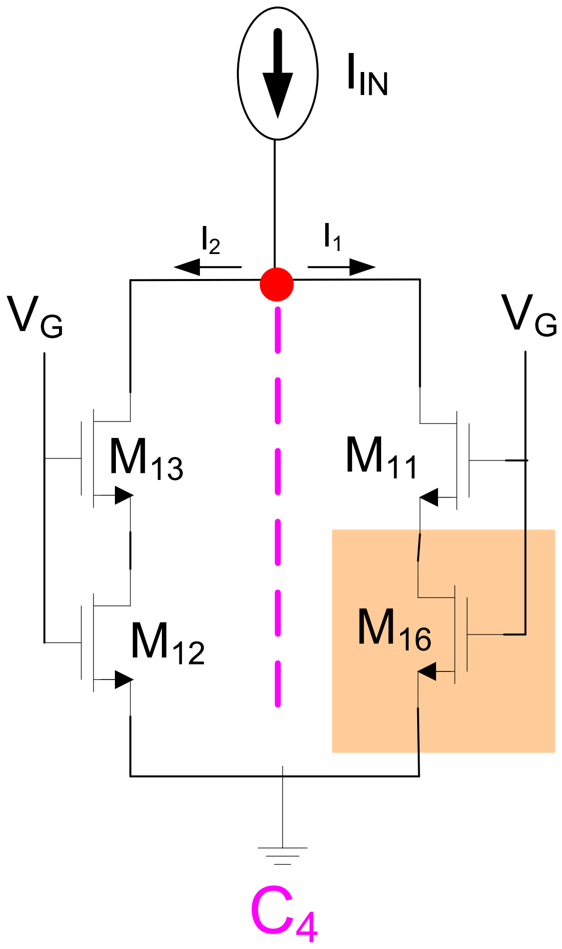


Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

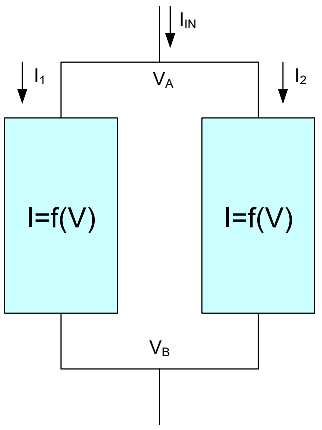


- Observe that M_9, M_{10}, M_8, M_{15} can be modeled as a single transistor that is of the same size as M_1
- Call this M_{16}
- Consider now the next closest current-divider node

Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

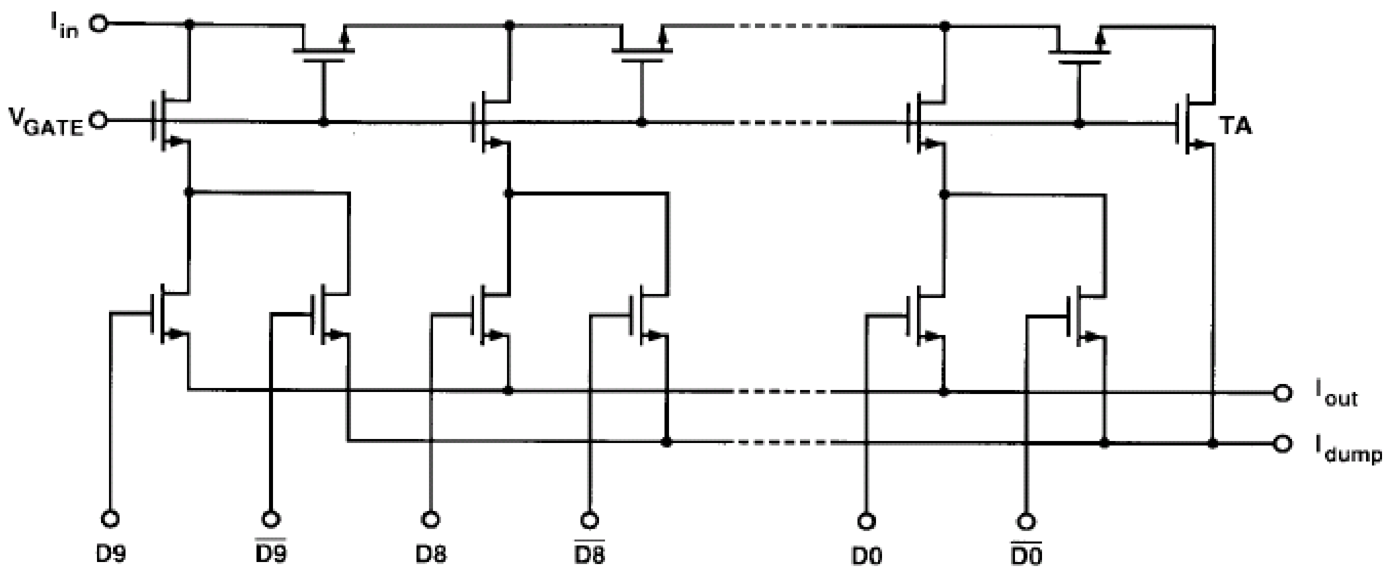


- Circuit shown is completely symmetric on C_3 and is the well-known current divider
- it is not dependent upon any specific properties of the transistors !



Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

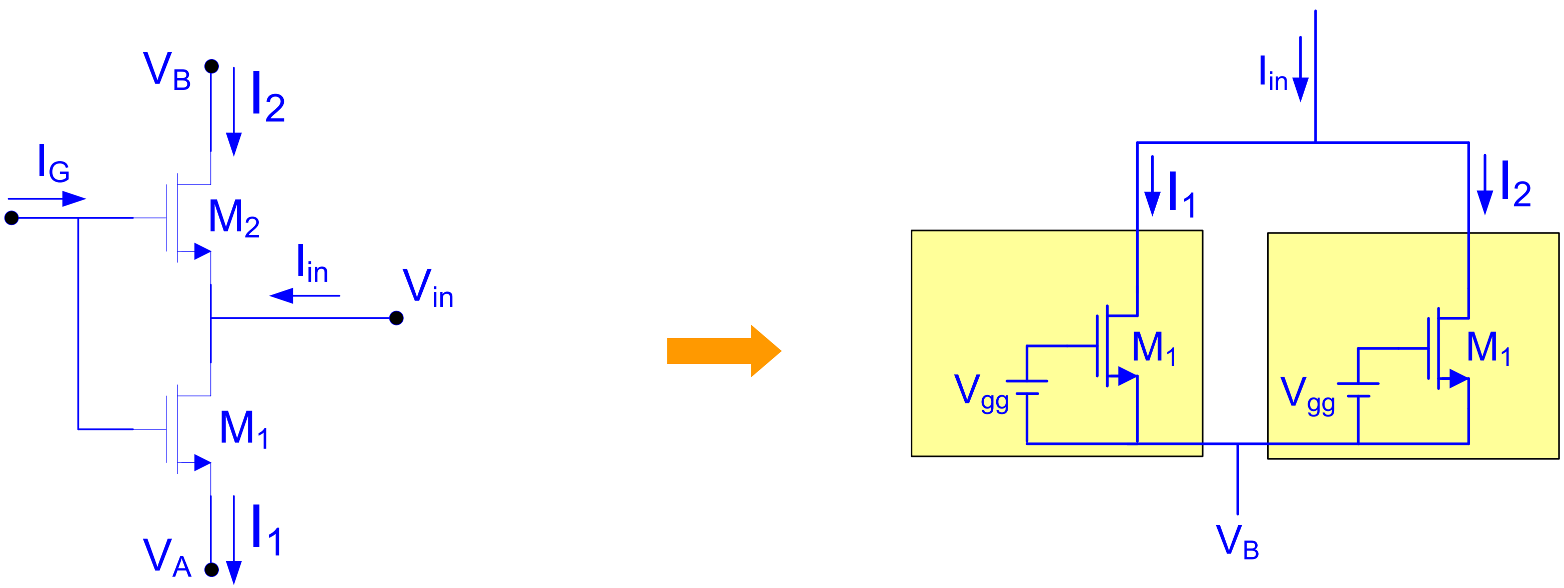
Current divider properties of the Huang DAC (ADC) were all dependent upon the general current division property of symmetric networks and had nothing to do with the current division in two transistors !



Current divider properties of the experimentally reported work of the original author were all dependent upon the general current division property of symmetric networks and had nothing to do with the current division in two transistors !

How was the very good performance of the "inherently linear" current divider obtained?

A few years ago one of our Ph.D. students looked at all SCI citations that referenced the "inherently linear" current divider and the performance in all cases was a special case of the general symmetric circuit



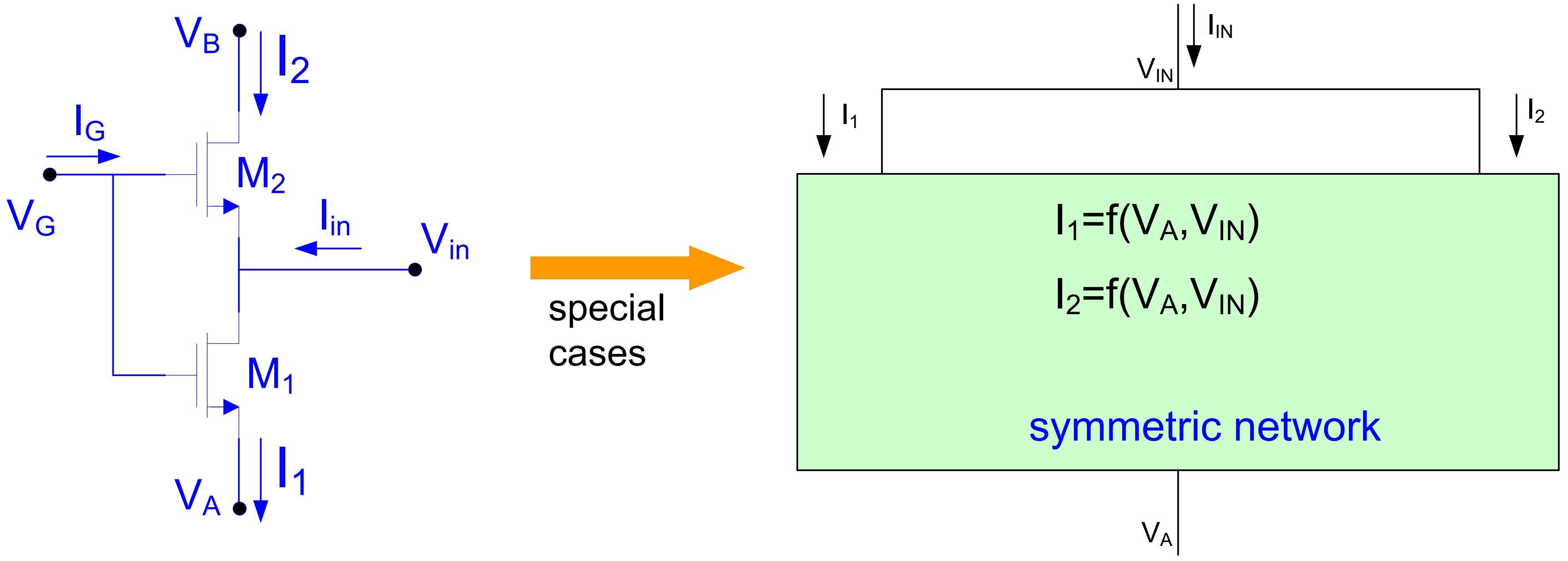
Symmetric Circuit

$I_1 = I_2$

Current Dividers

- Background
- Objective
- Concept of Current Divider
- Characterization of Inherently Linear Current Divider
- Inherent Current Division in Symmetric Circuits
- Conclusionhs

Good linearity properties of "inherently linear" current divider for those we found in the literature are due to well-known symmetry properties of circuits, not due to unique properties of the two-transistor current-divider structure



Conclusion

- The linearity properties are not apparent with existing device models
- Based upon existing models, operation as a current divider in question and linearity can be orders of magnitude worse than previously reported
- Good linearity properties of all applications found in literature survey for this circuit are due to well-known symmetry properties, not inherent characteristics of the two-transistor structure
- Experimental evidence appears to be lacking to support the inherently linearity properties of the current divider
- Is it possible that the circuit performs as an inherently linear current divider that has not yet been experimentally verified?
- Is it possible that there are major errors in existing device models used in circuit simulators that cause dramatic linearity errors in the simple 2-transistor current divider ?

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Will consider 5 basic examples in this discussion

- Op Amp
- Positive Feedback Compensation
- Current Mode Filters
- Current Dividers
- Barkhausen Criteriion

Barkhausen Criterion

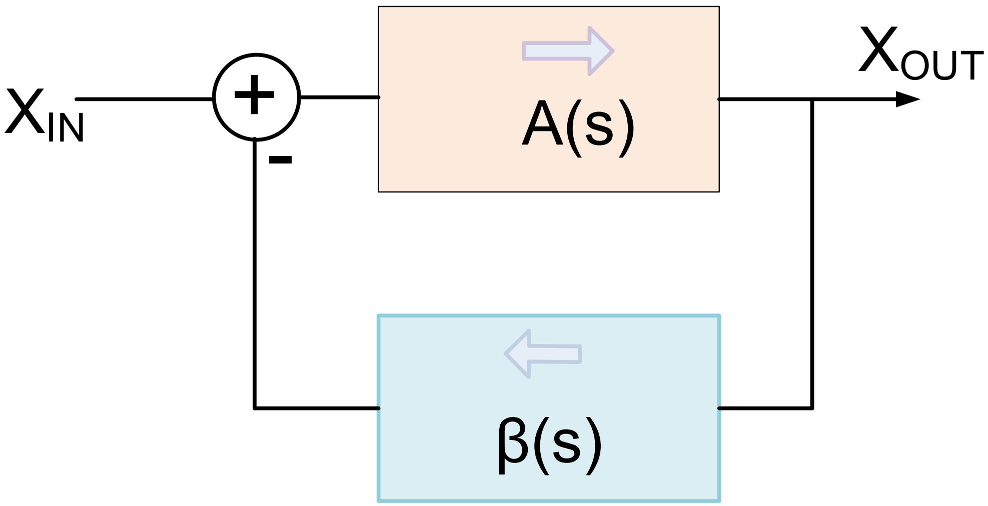
Barkhausen Stability Criterion - MIT

web.mit.edu/klund/.../node4.html ▾ Massachusetts Institute of Technology ▾

Nov 14, 2002 - The **Barkhausen** Stability **Criterion** is simple, intuitive, and **wrong**. During the study of the phase margin of linear systems, this **criterion** is often ...

Attributed to Kent H Lundberg, PhD from MIT and a lecturer at MIT

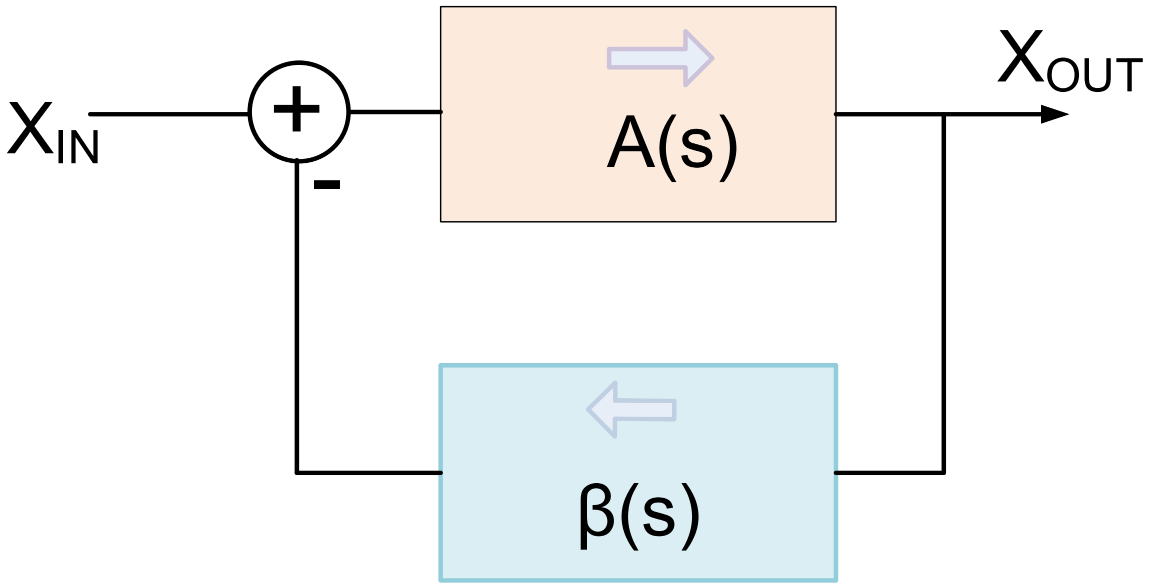
Barkhausen Criterion



Conventional Statement of Barkhausen Criterion:

A system is oscillatory if at some frequency the magnitude of the loop gain is 1 and the total phase shift around the loop is 360º. And, the frequency of oscillation will be the frequency at which the loop gain as 1 and the phase shift is 360º .

Barkhausen Criterion



Alternate Conventional Statement of Barkhausen Criterion:

A system will be unstable if at some frequency the magnitude of the loop gain is greater than 1 at a frequency where the phase shift is 360°. And the frequency of oscillation will be the frequency at which the phase shift is 360° when the magnitude of the loop gain is larger than 1.

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Just considered conventional wisdom in 5 basic examples

- Op Amp
- Positive Feedback Compensation
- Current Mode Filters
- Current Dividers
- Barkhausen Criterion

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Four examples involving some of the most basic concepts in the microelectronics field were identified where the alignment of conventional wisdom and fundamental concepts are weak

Many more examples exist where alignment is weak

Are Conventional Wisdom and Fundamental Concepts always aligned in the Microelectronics Field ?

Conventional Wisdom is VERY USEFUL for enhancing productivity and identifying practical approaches to engineering design and problem solving

Conventional Wisdom, however, should not be viewed as a basic principle or fundamental concept

Keep an OPEN MIND when using Conventional Wisdom to recognize both the benefits and limitations and recognize that even some of the most reputable sources and reputable engineers/scholars do not always distinguish between conventional wisdom and fundamental concepts

Thank you
for your attention !

Stay Safe and Stay Healthy !

End of Lecture 43