EE 508
Lecture 43

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

Part 2

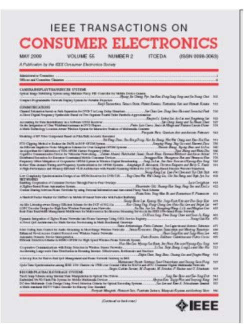
by Randy Geiger
Iowa State University

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

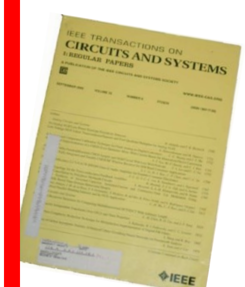
It is well known that current-mode circuits have been receiving significant attention owing to its advantage over the voltage-mode counterpart, particularly for higher frequency of operation and simpler filtering structure [1].

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:

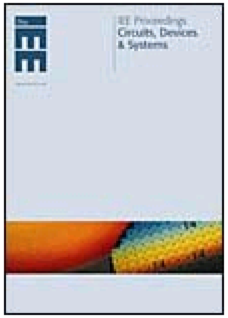
All current-mode frequency selective circuits **GW Roberts**, AS **Sedra** - Electronics Letters, June 1989 - pp. 759-761 Cited by 228

"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** - Circuits, Devices and Systems, IEE Proceedings G, pp. 63-77, Apr. 1990 Cited by 288

“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

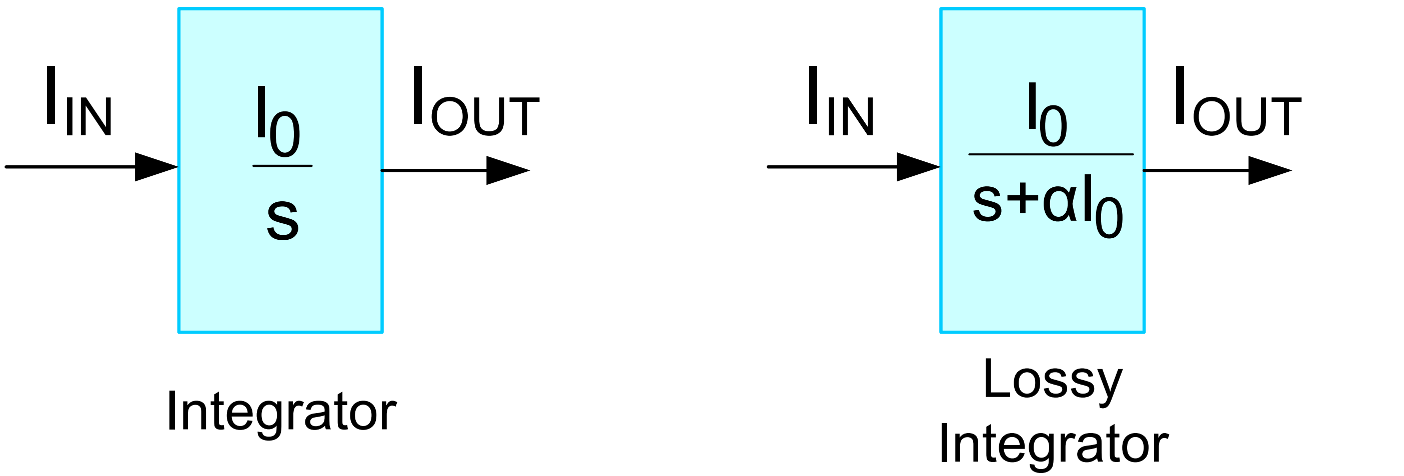
The Conventional Wisdom:

- 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!

Review from Earlier Lecture

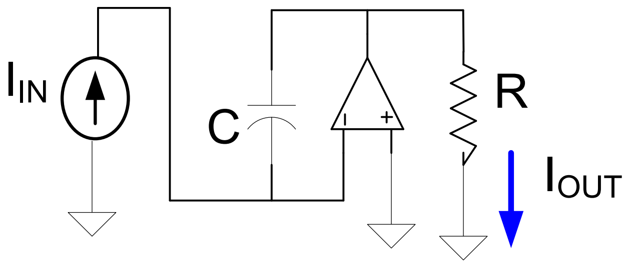
Current-Mode Filters



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

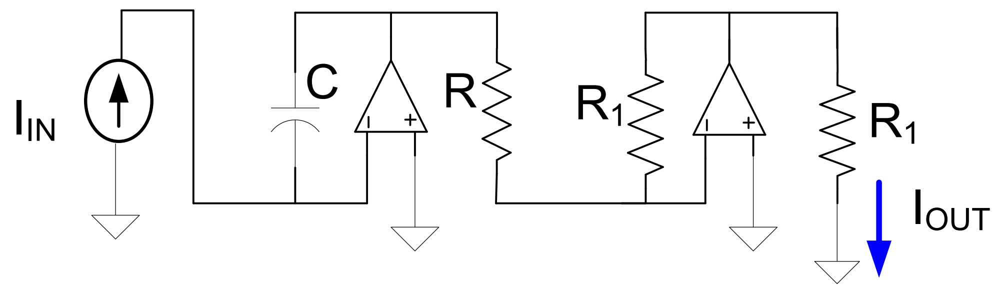
Some Current-Mode Integrators

Active RC



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

Inverting



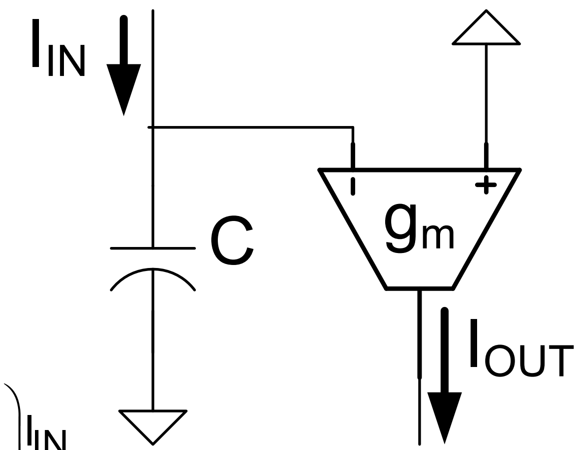
$$I_{OUT} = \left(\frac{1}{RCs}\right) I_{IN}$$

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

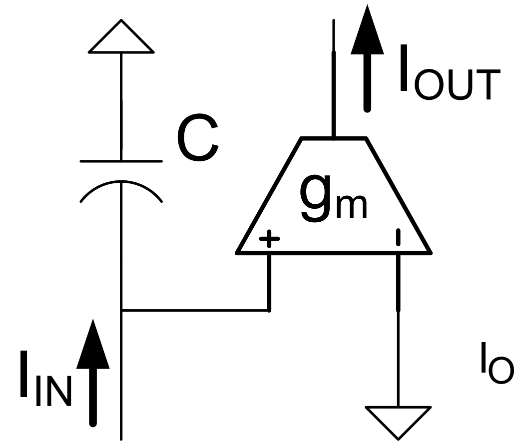
Some Current-Mode Integrators

OTA-C



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

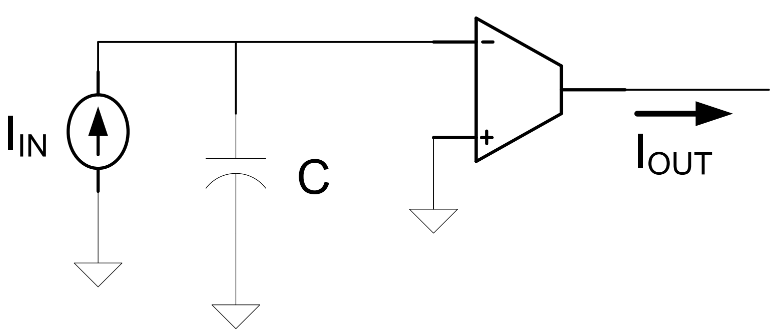
Inverting

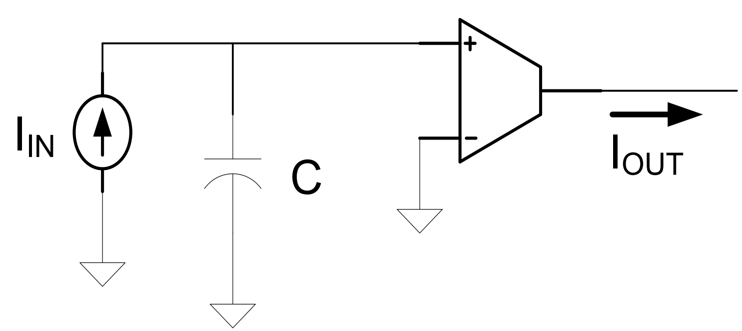


$$I_{OUT} = \left(\frac{g_m}{Cs}\right) I_{IN}$$

Noninverting

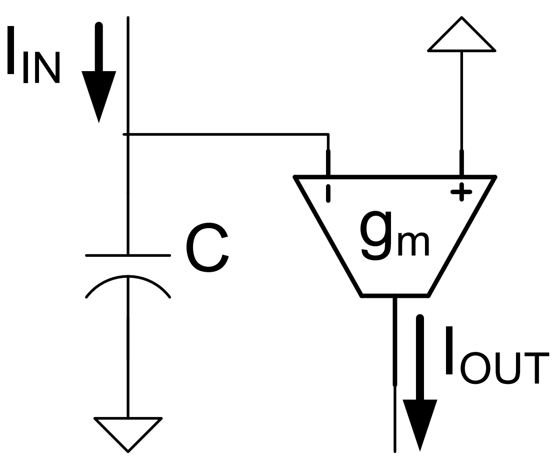
Alternate representation



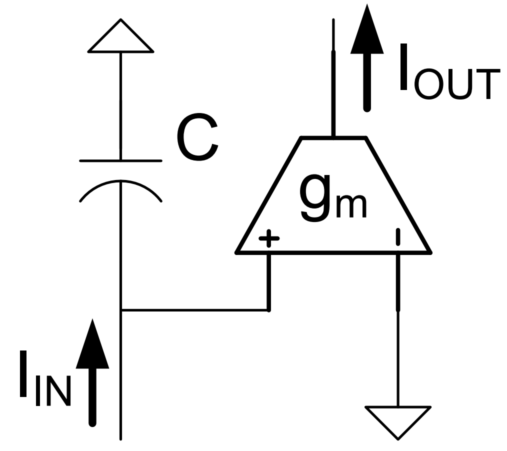


Some Current-Mode Integrators

OTA-C



Inverting

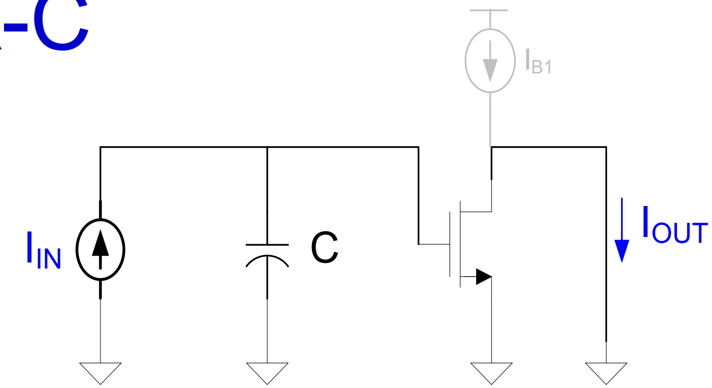


Noninverting

- 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

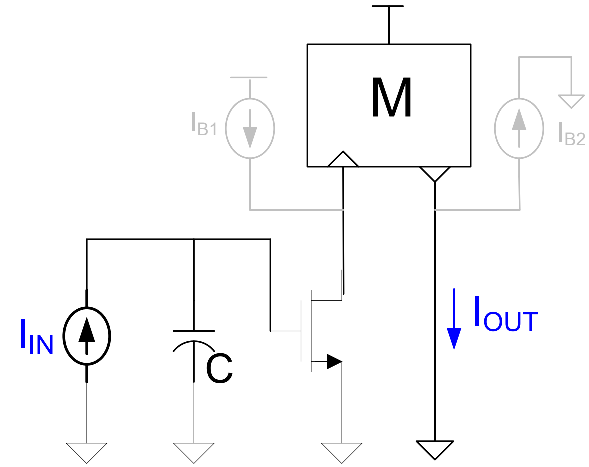
Some Current-Mode Integrators

TA-C



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

Inverting



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

Noninverting

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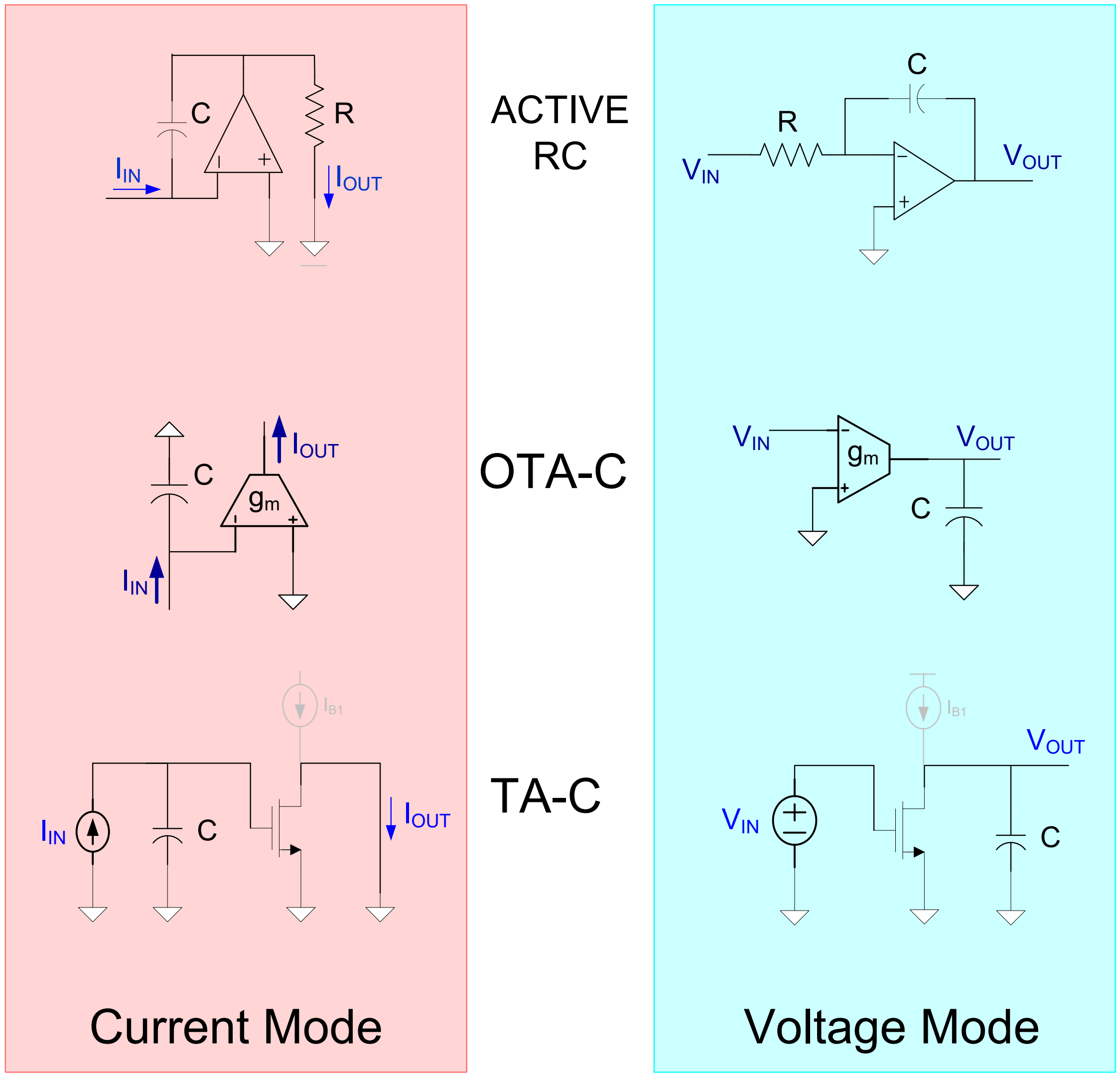
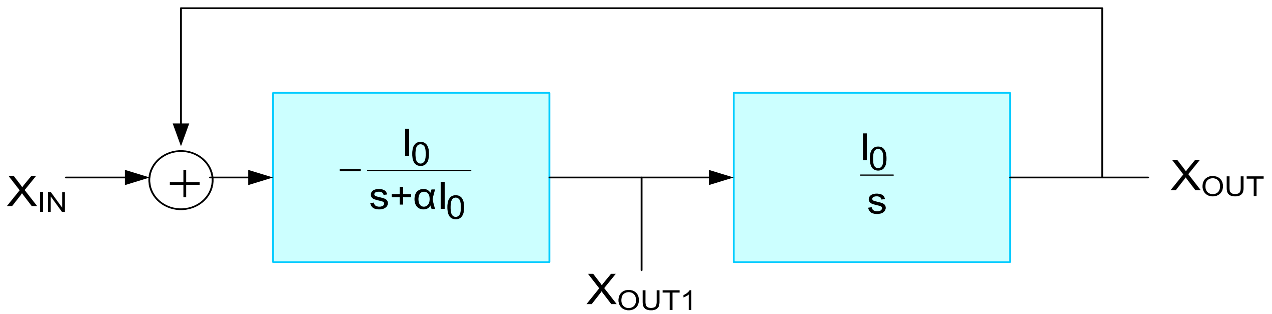
Comparison of Current Mode and Voltage Mode Integrators



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

Review from Earlier Lecture

Two-Integrator-Loop Biquad

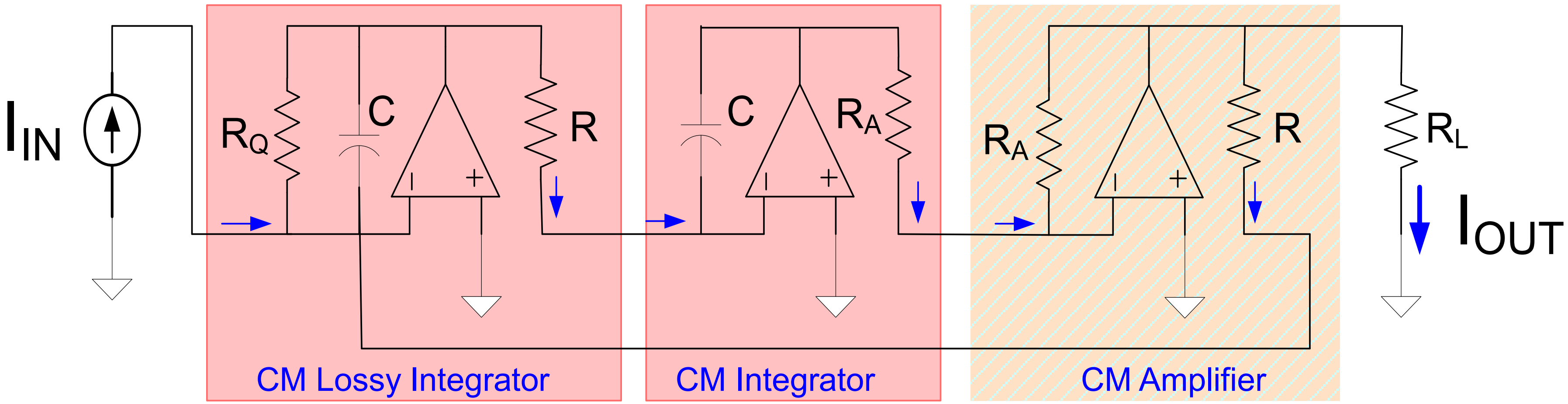


One of the most widely used architectures for implementing integrated filters

Review from Earlier Lecture

Current-Mode Two Integrator Loop

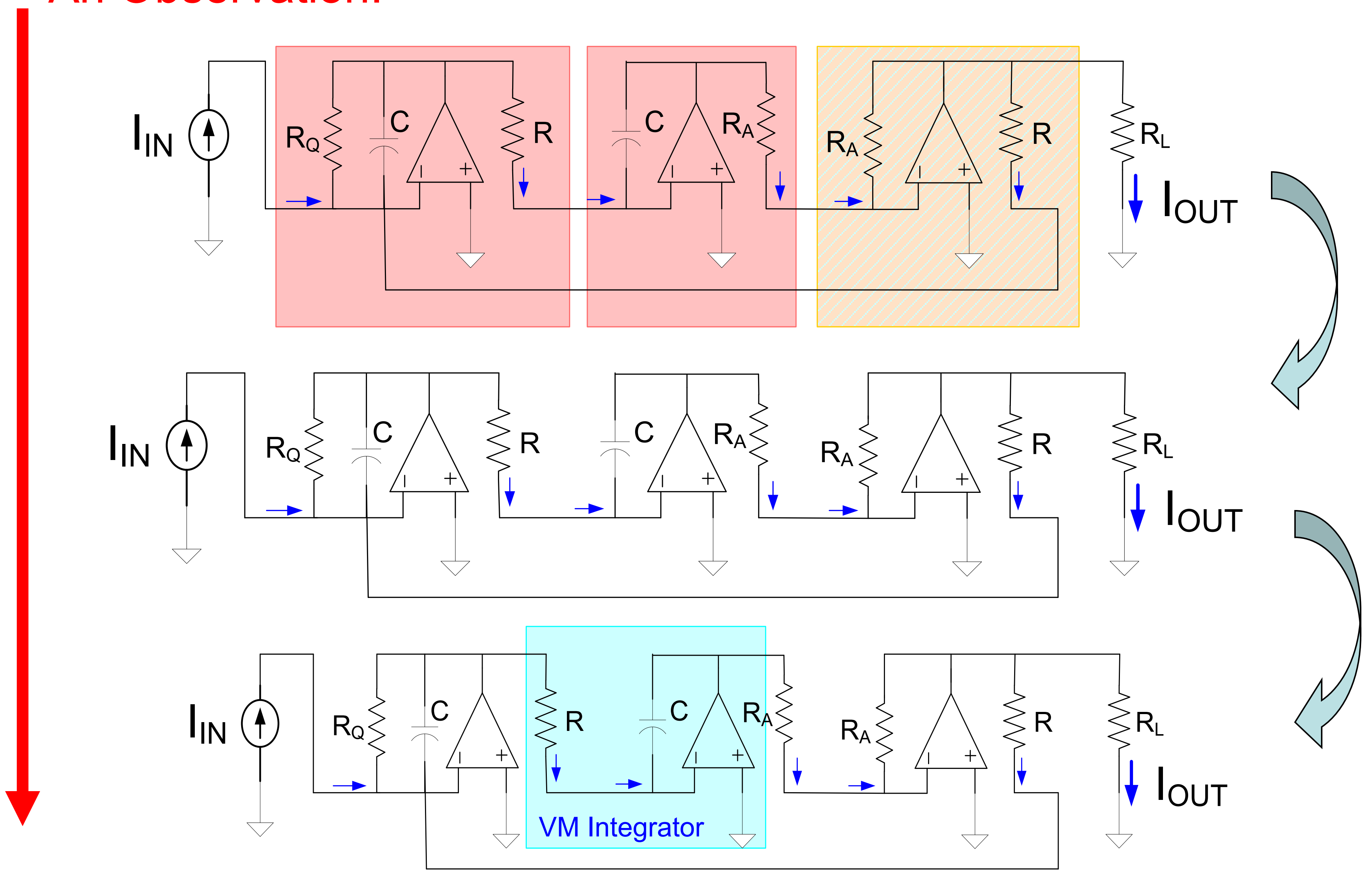
Active RC Current-Mode implementation



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

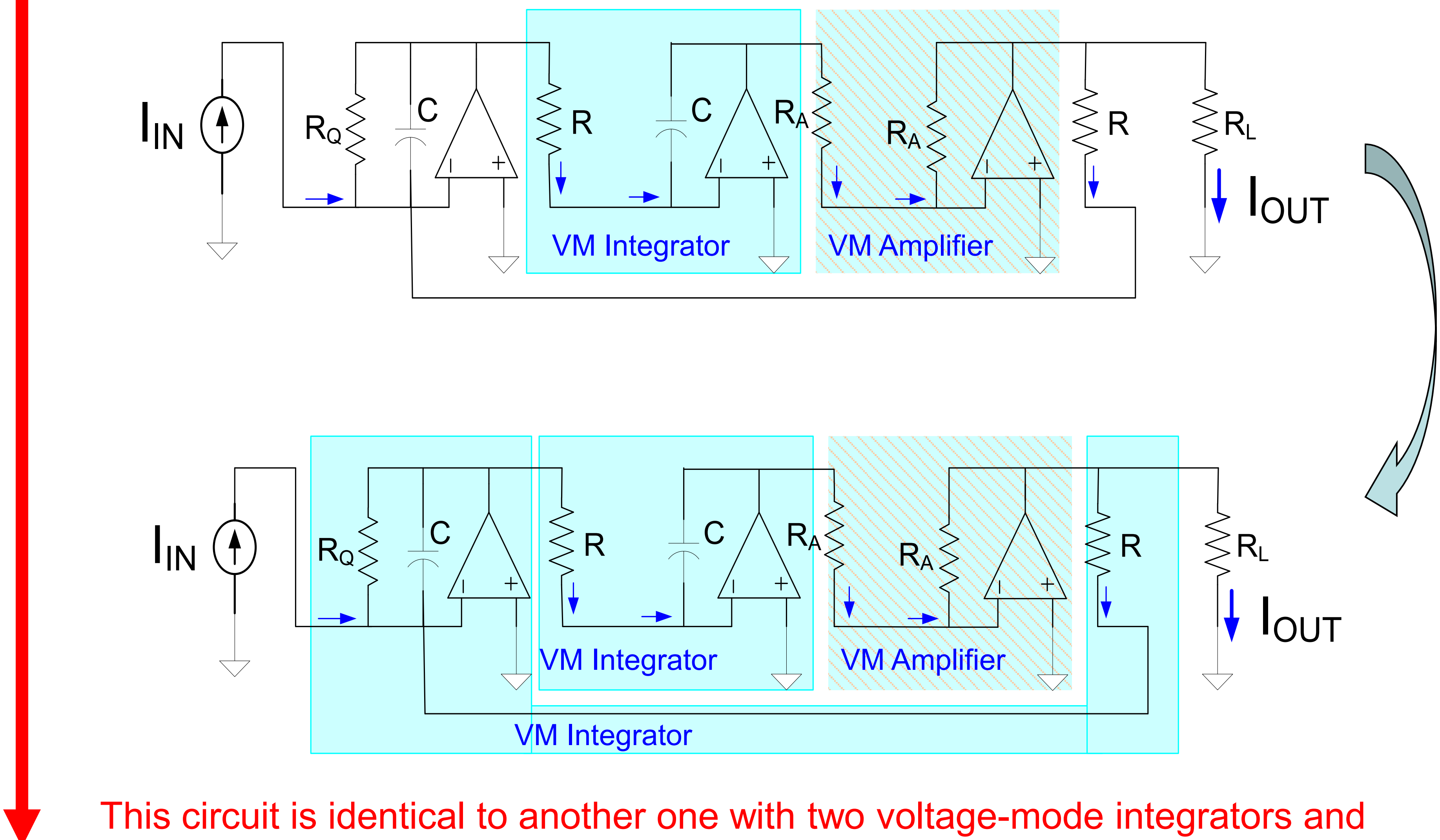
Current-Mode Two Integrator Loop

An Observation:



Current-Mode Two Integrator Loop

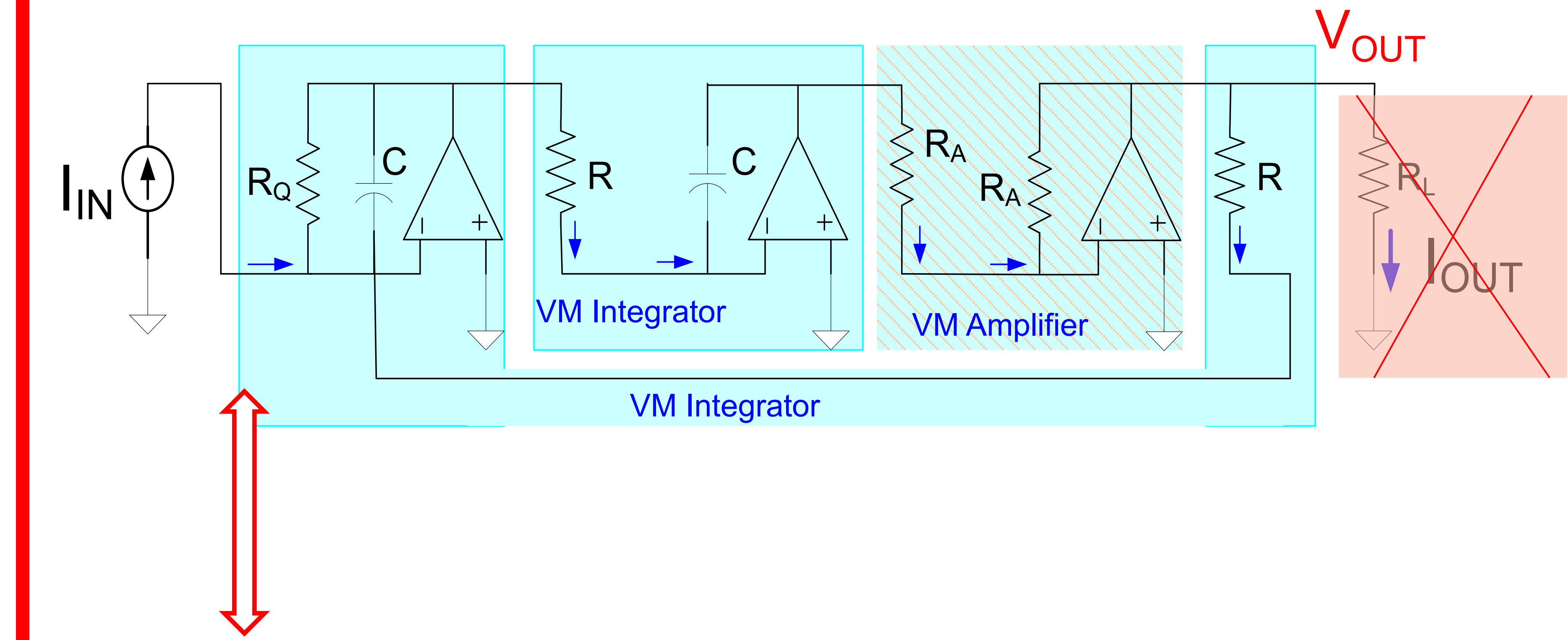
An Observation:

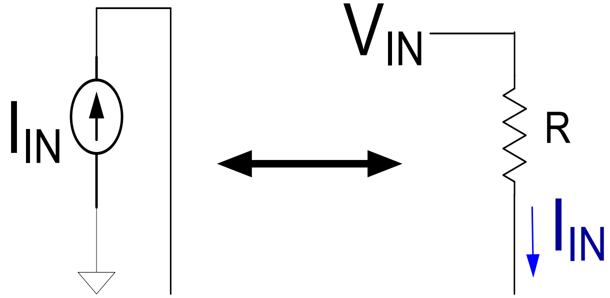


This circuit is identical to another one with two voltage-mode integrators and a voltage-mode amplifier !

Current-Mode Two Integrator Loop

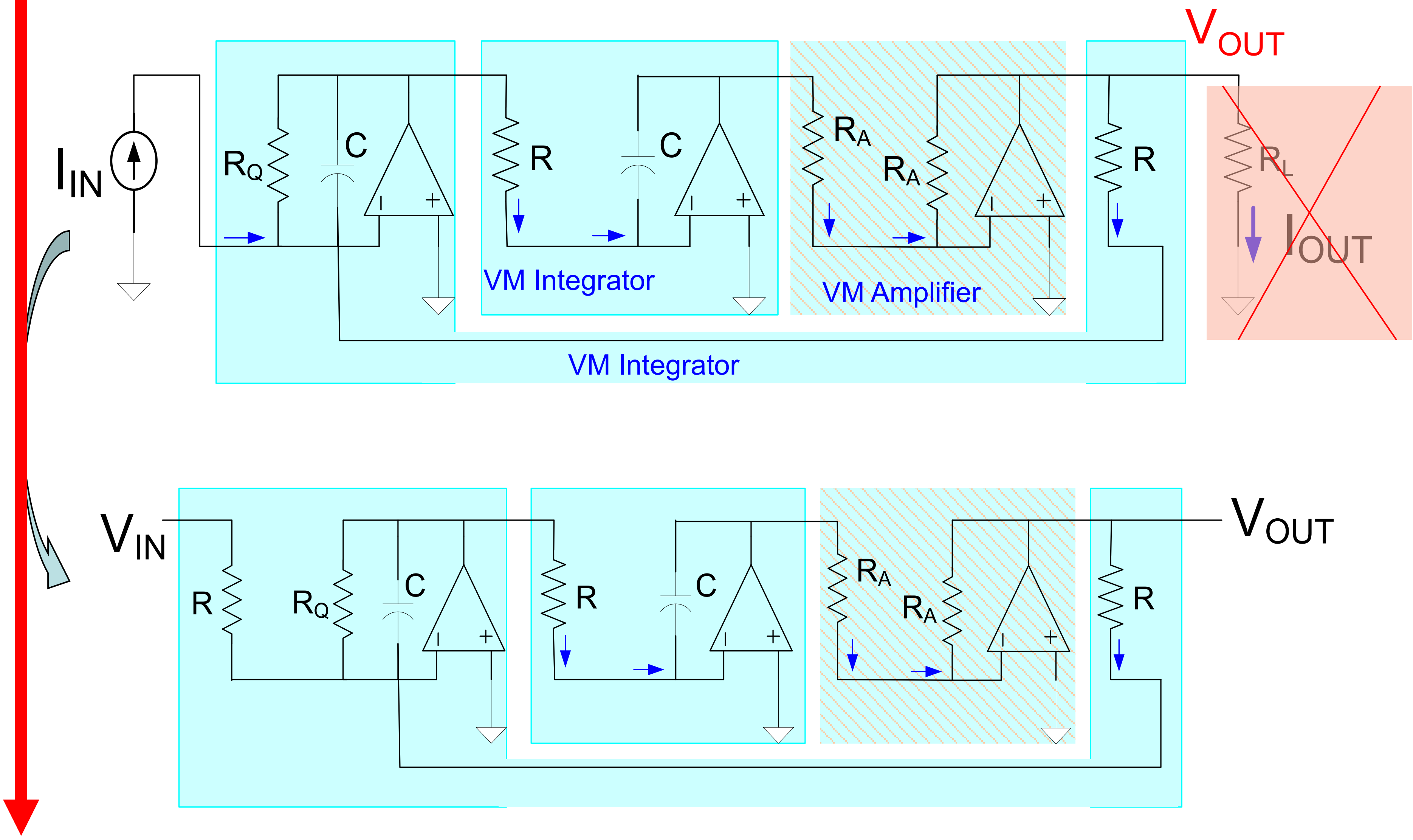
An Observation:





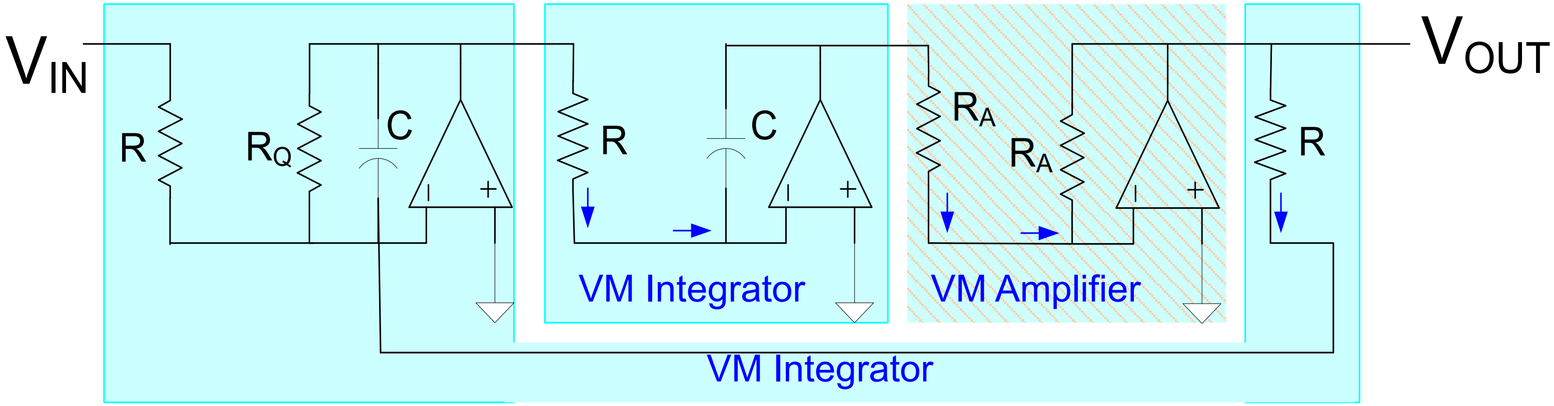
Current-Mode Two Integrator Loop

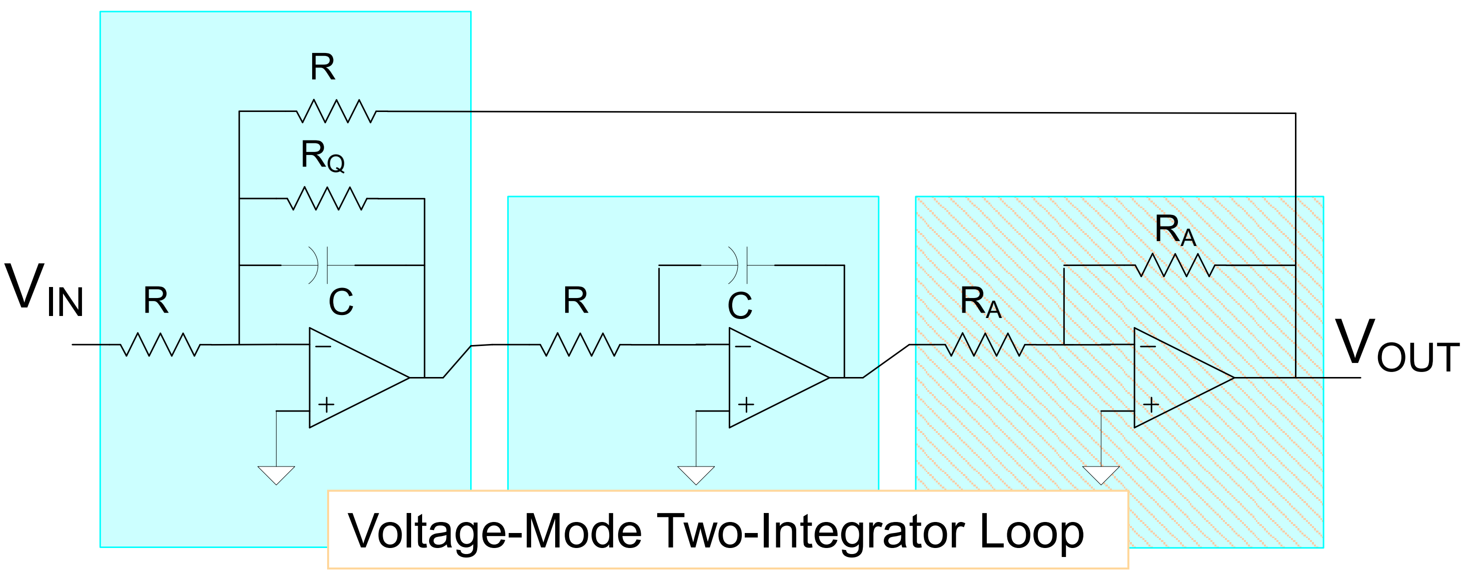
An Observation:



Current-Mode Two Integrator Loop

An Observation:



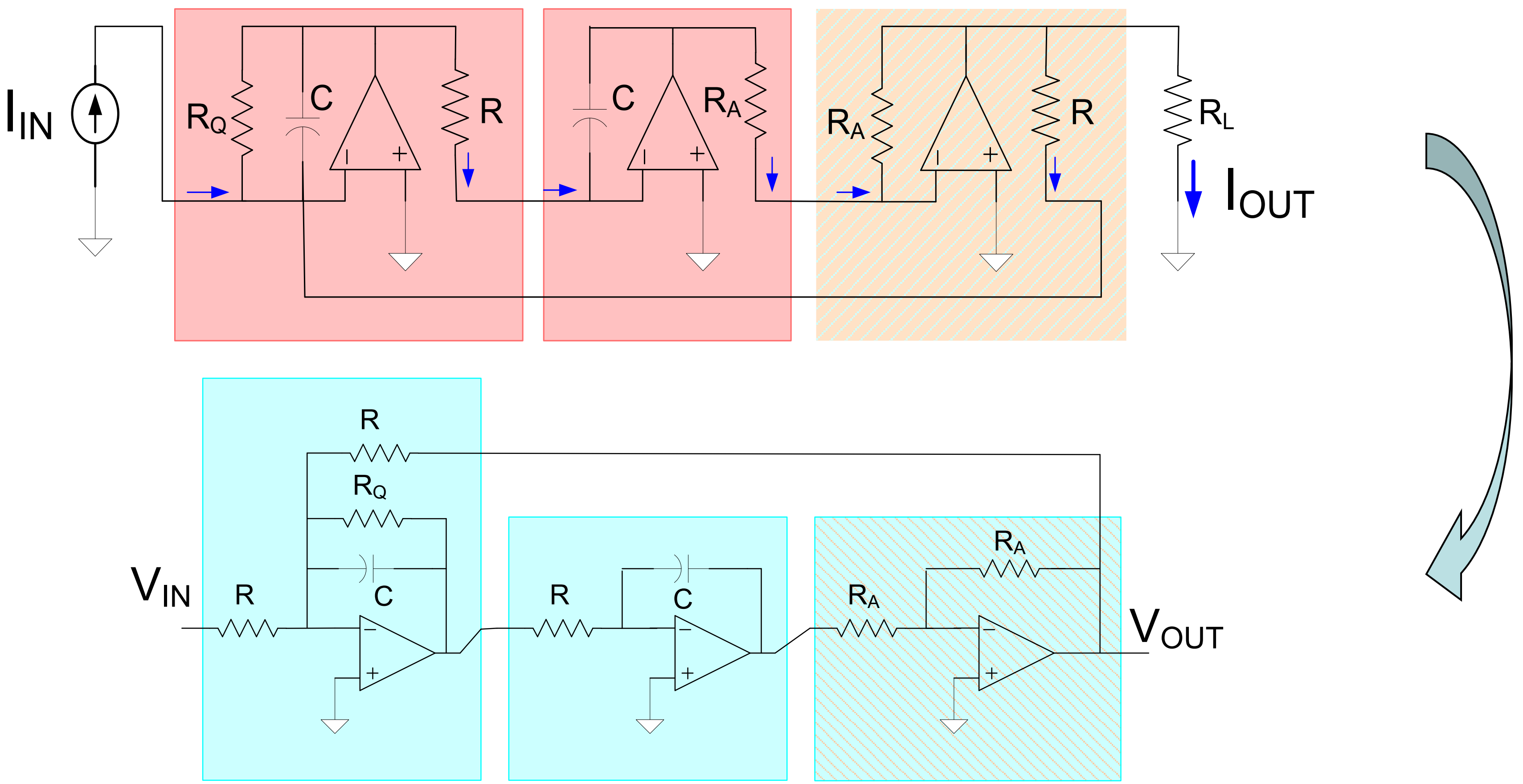


This circuit was well-known in the 60's

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

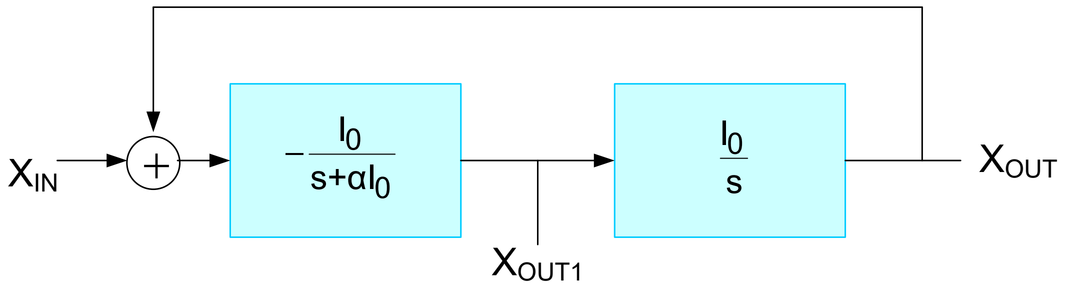
Observation

- 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

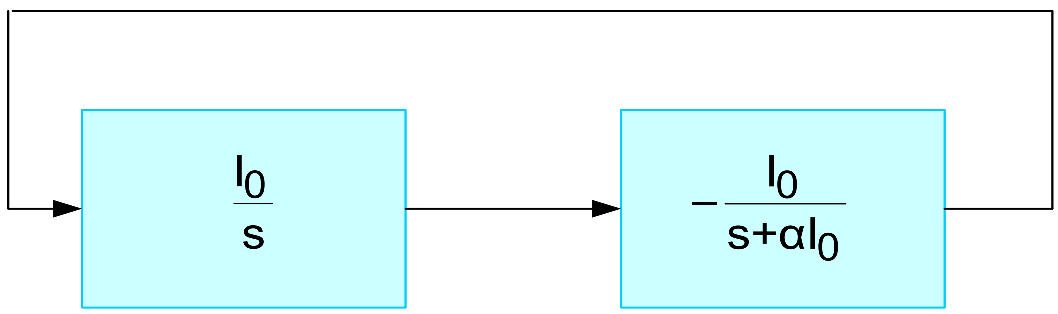
Observations (cont.)

- 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



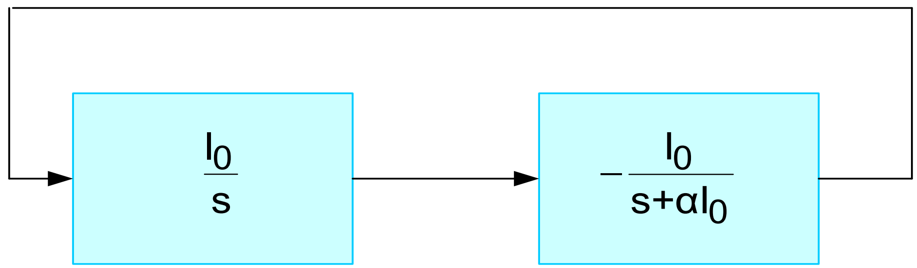
- For notational convenience, the input signal can be suppressed and output will not be designated
- This forms the "dead network"
- Poles for dead network are identical to original network as are key sensitivities



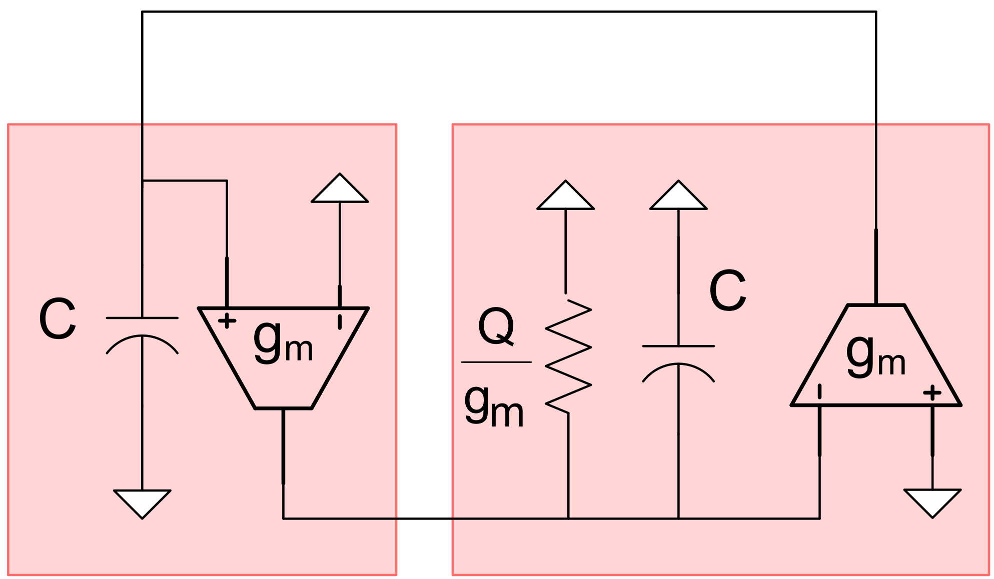
Two Integrator Loop Biquad

Two-Integrator-Loop Biquad

OTA-C implementation

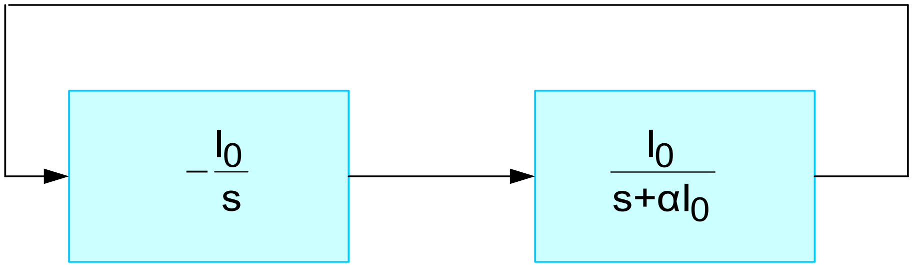


Consider a current-mode implementation:

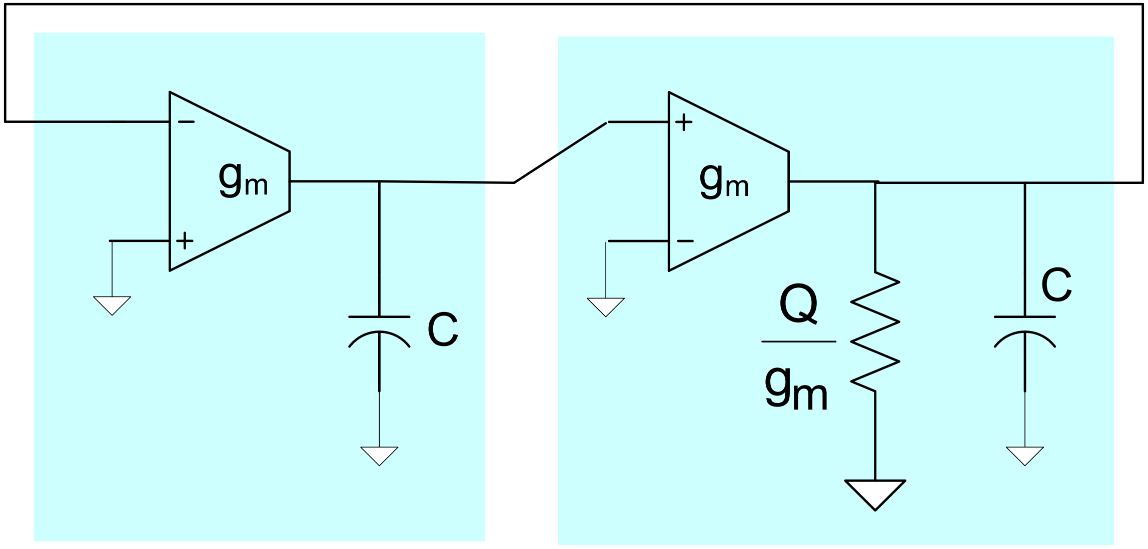


Numerous current-mode filter papers use this basic structure

Two-Integrator-Loop Biquad



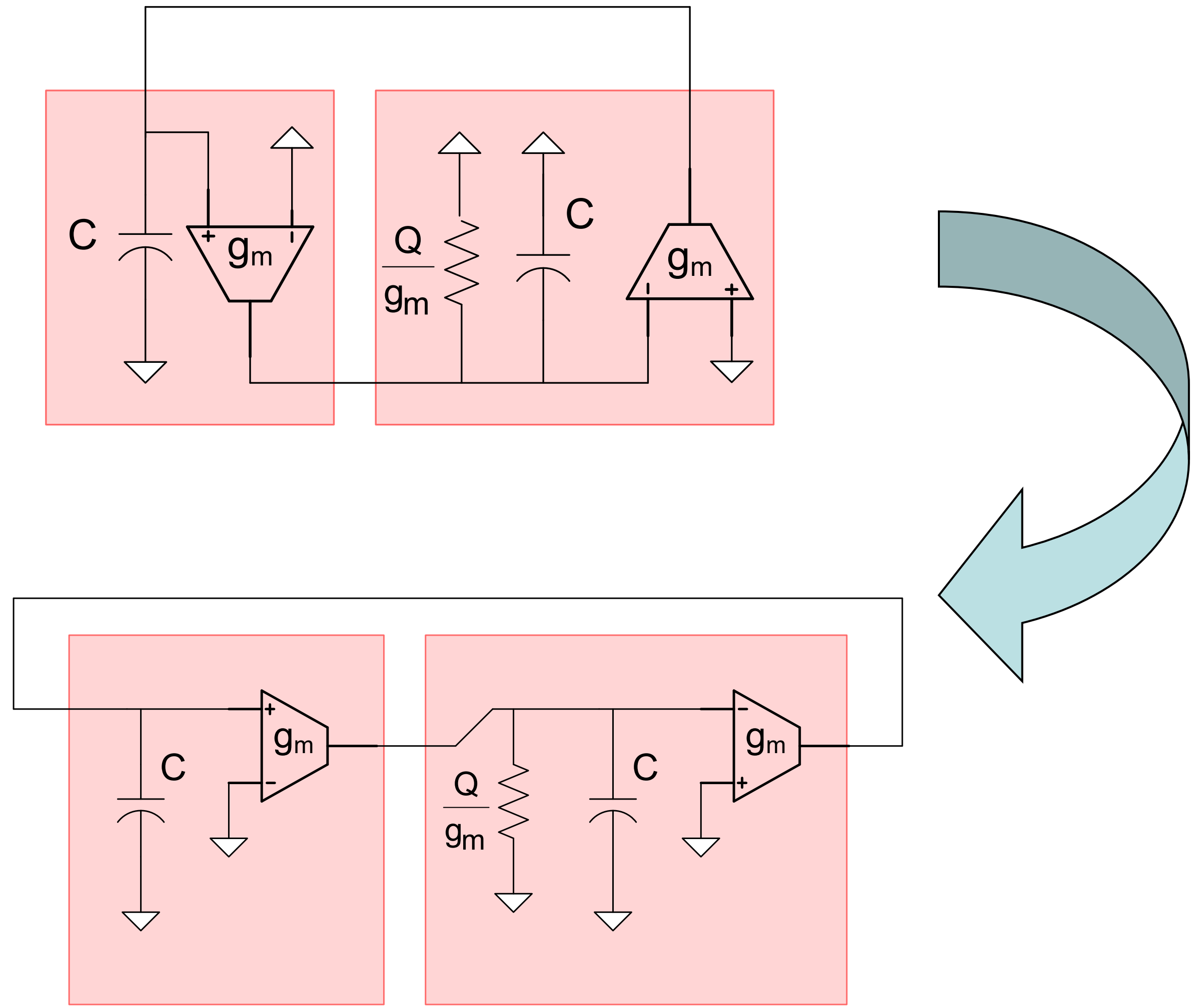
Consider the corresponding voltage-mode implementation:



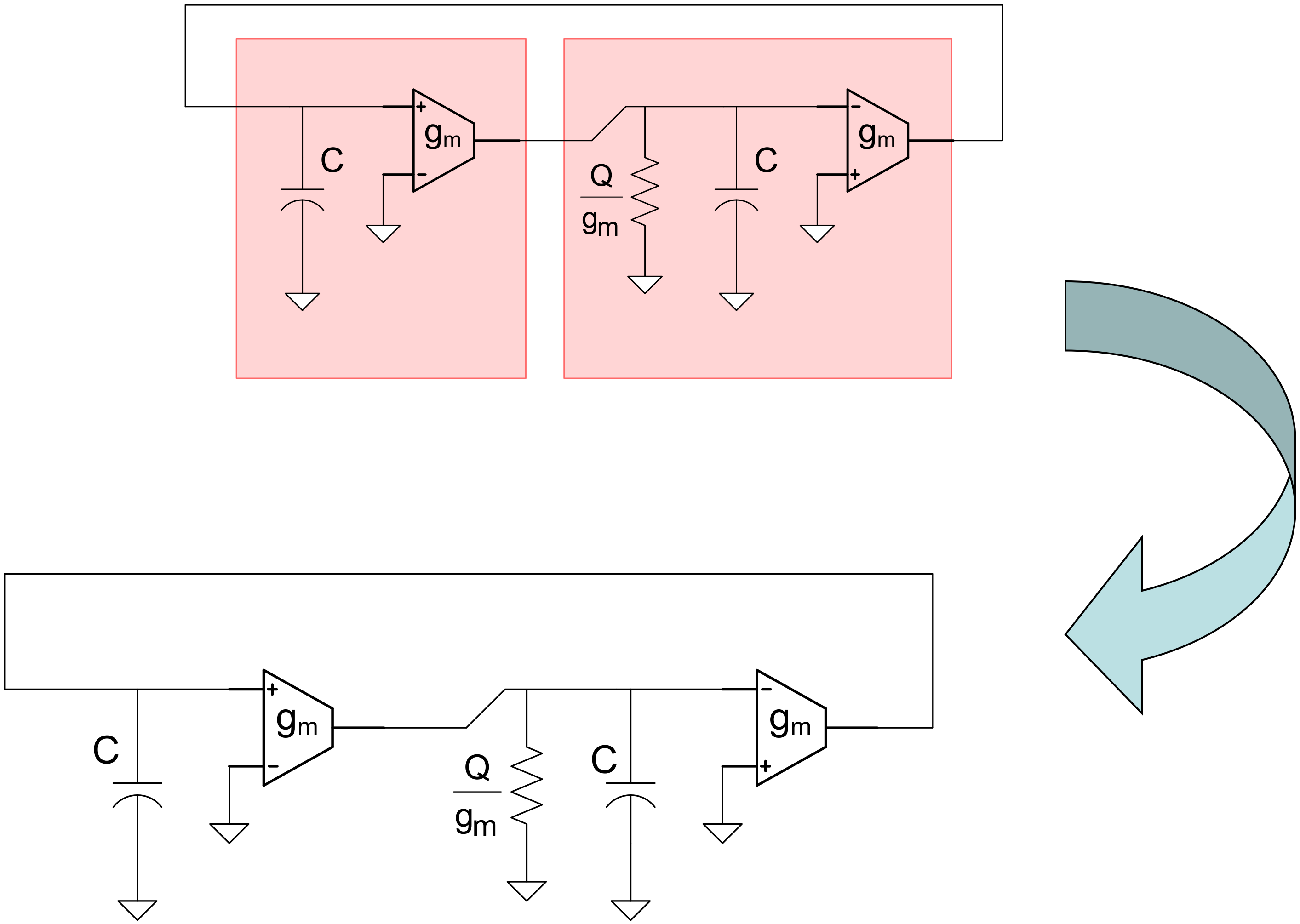
Two-Integrator-Loop Biquad

An Observation:

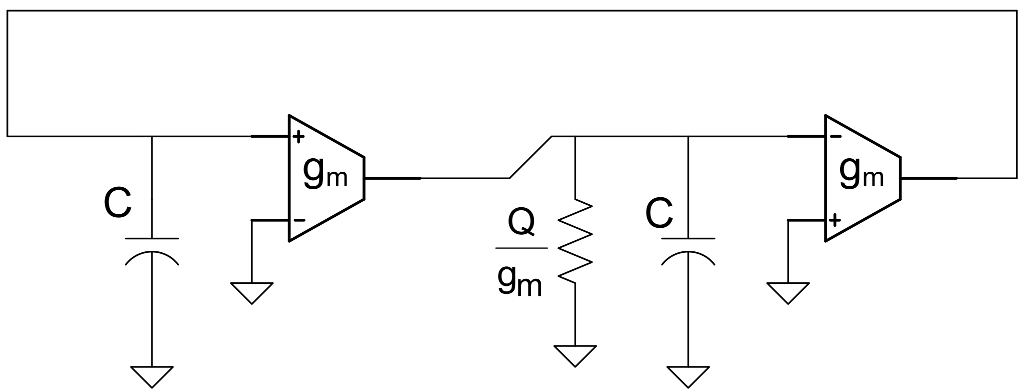
Current-mode

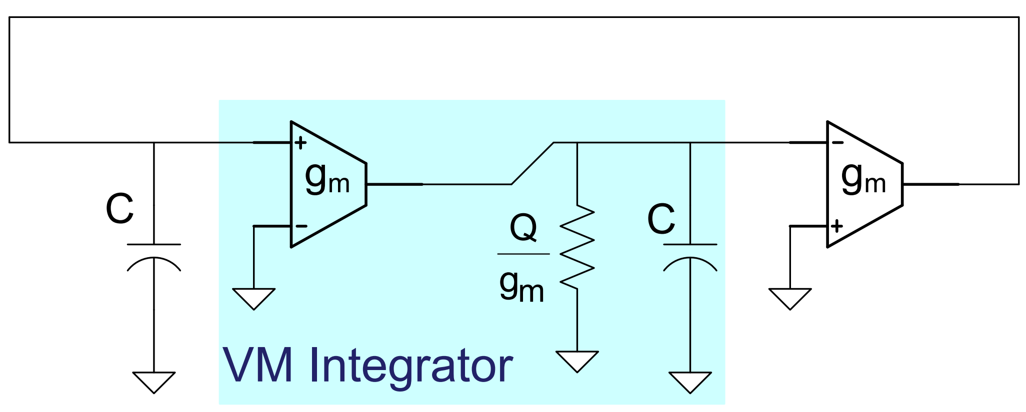


Two-Integrator-Loop Biquad



Two-Integrator-Loop Biquad





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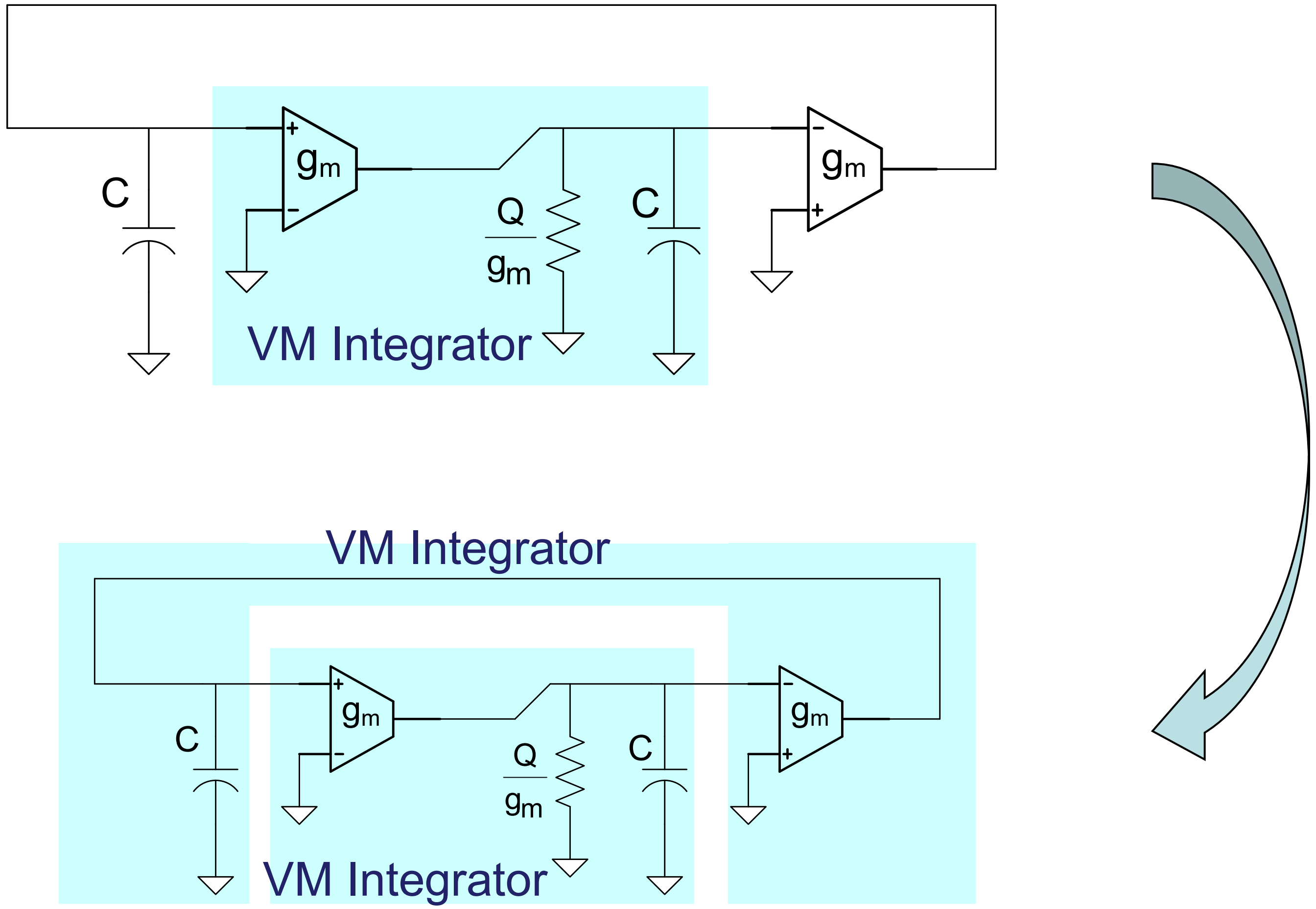

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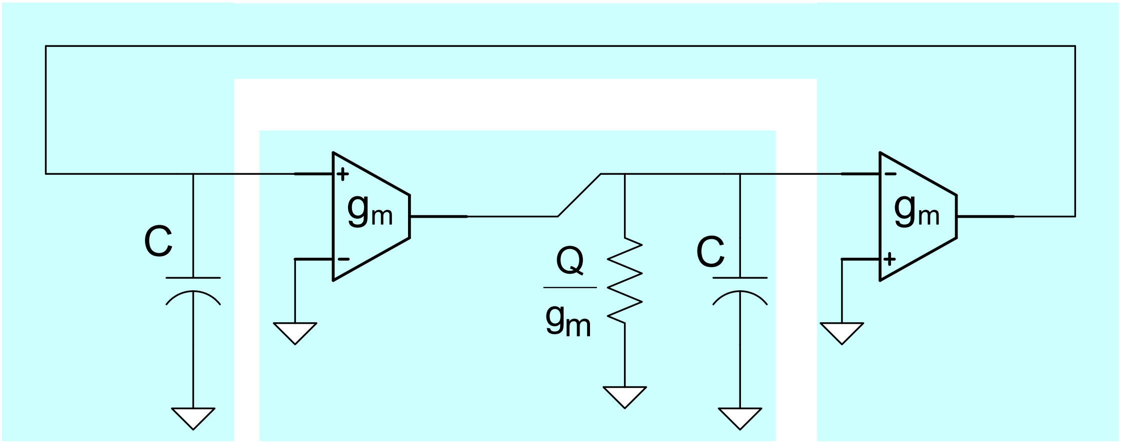
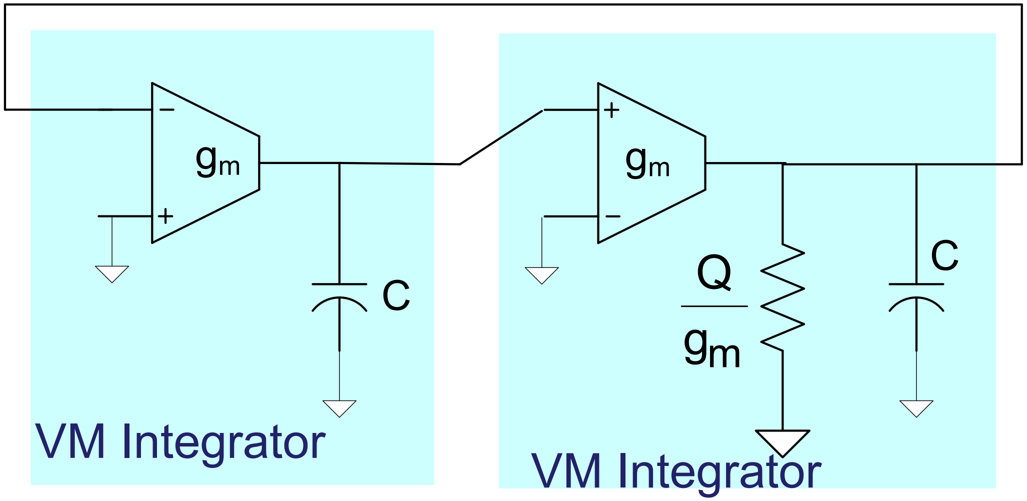
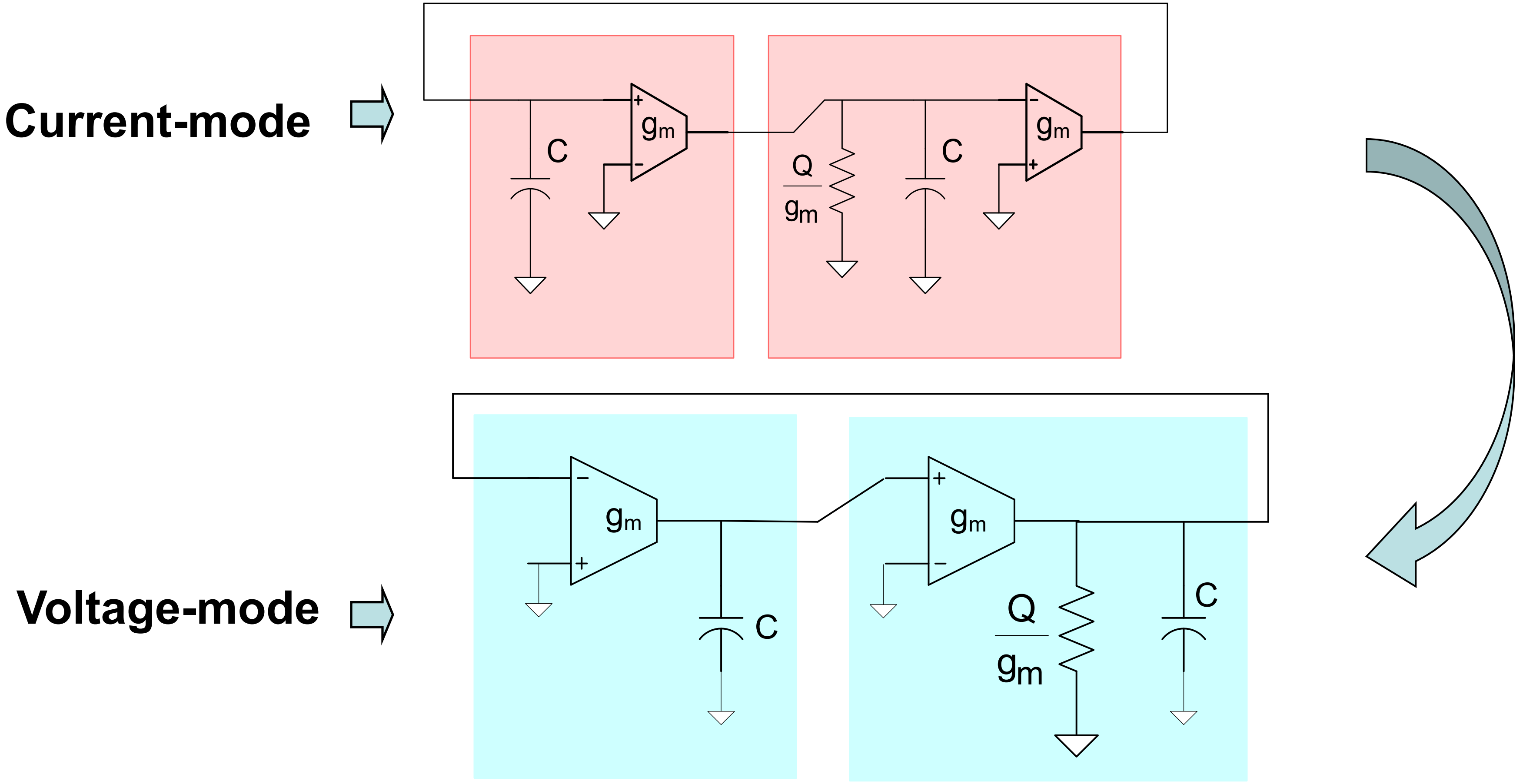




This circuit was well-known in the 80's

Two-Integrator-Loop Biquad

OTA-C implementation

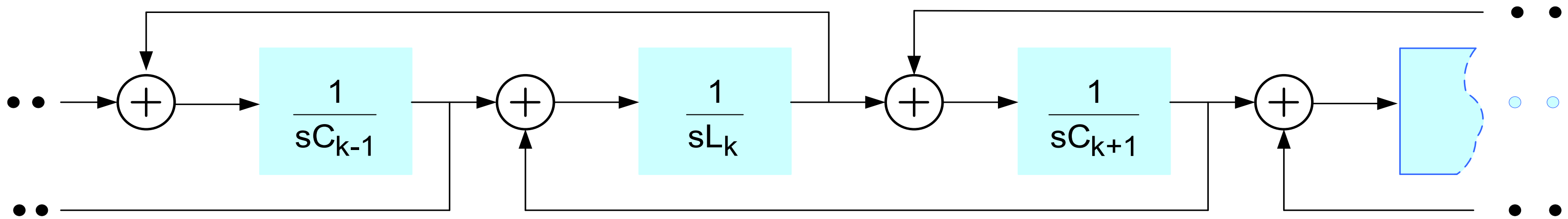


Current-mode and voltage-mode circuits have same component count
Current-mode and voltage-mode circuits are identical !
Current-mode and voltage-mode properties are identical !

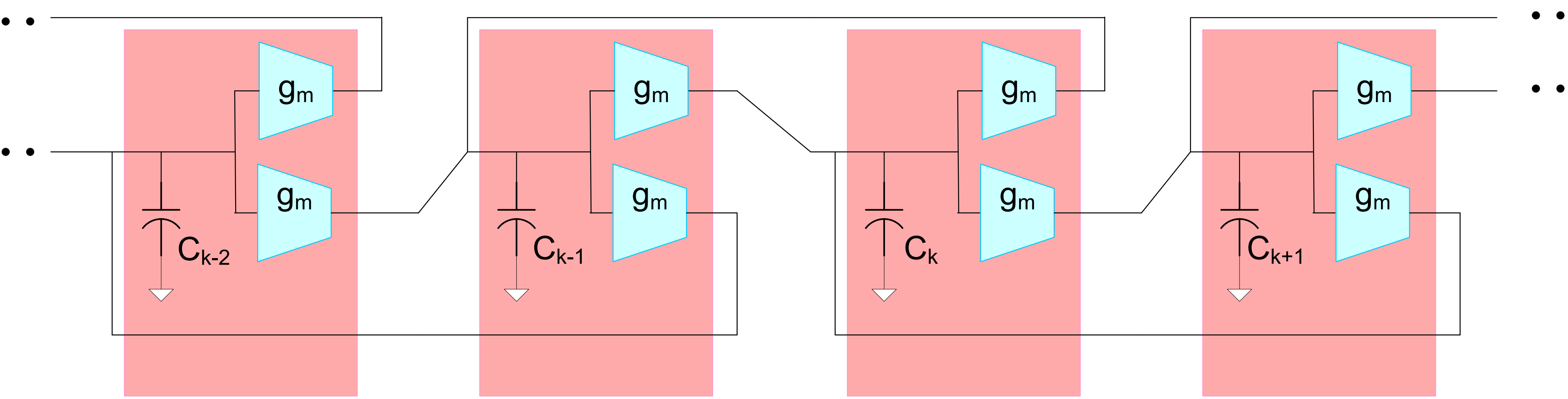
Current-mode circuit offers NO benefits over voltage-mode counterpart

Leap-Frog Filter

OTA-C implementation

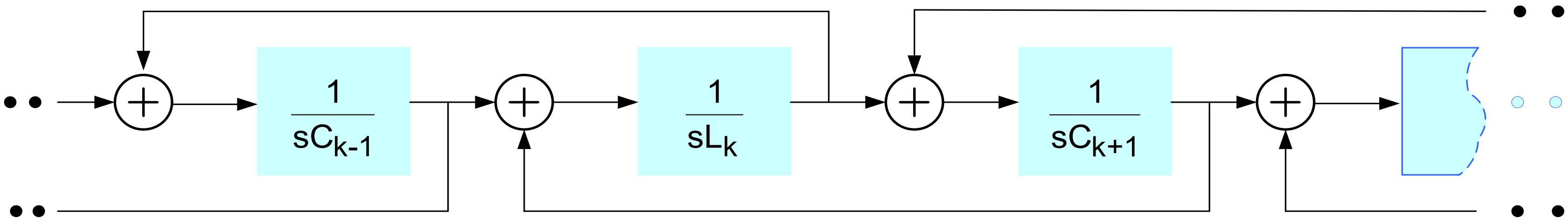


Consider a current-mode implementation:

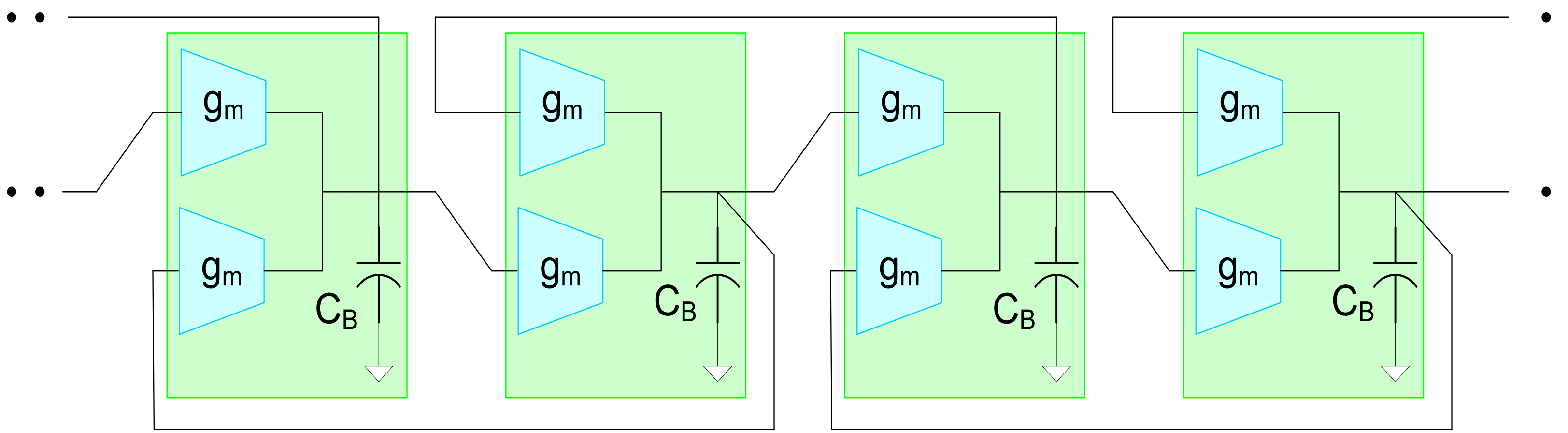


Numerous current-mode filter papers use this basic structure

Leap-Frog Filter

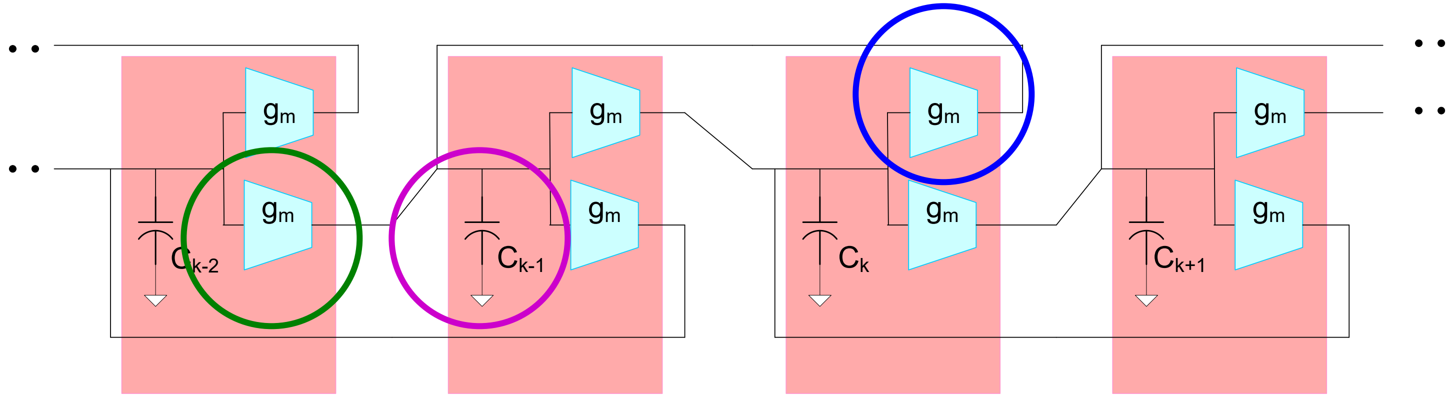


Consider a voltage-mode implementation:

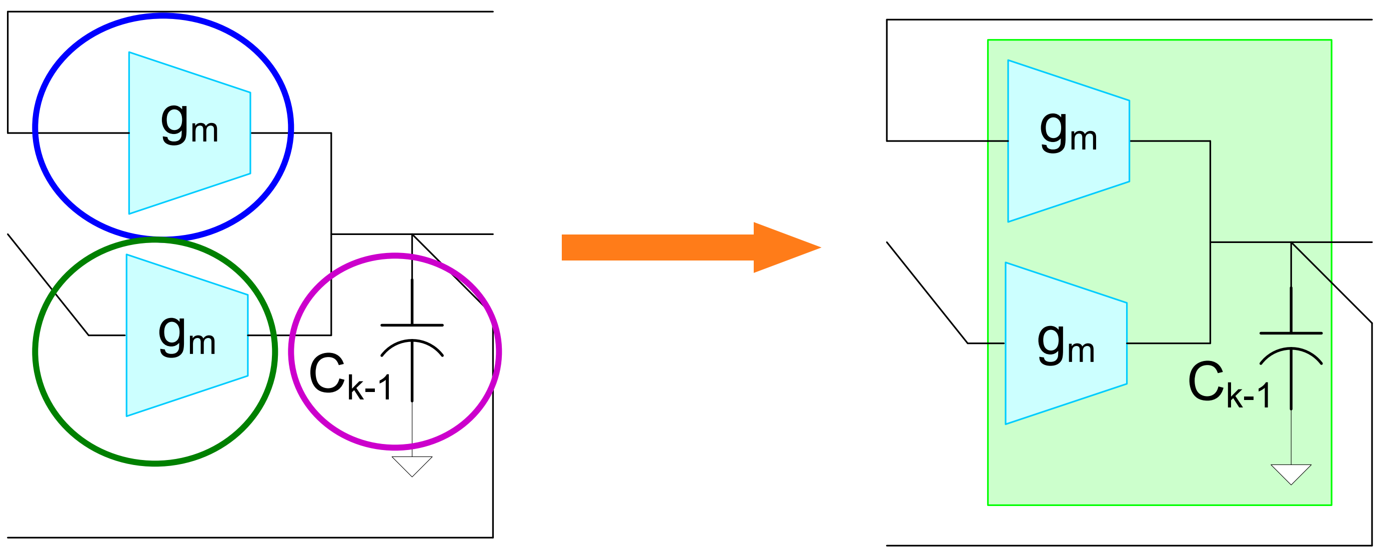


Leap-Frog Filter

An Observation:

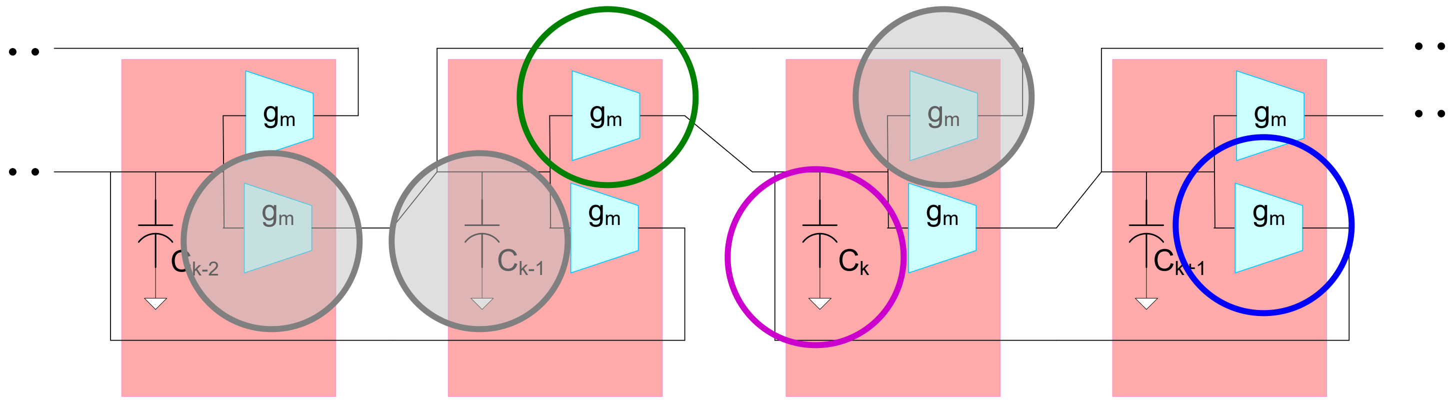


Consider lower OTA in stage k-2, capacitor in stage k-1 and upper OTA in stage k

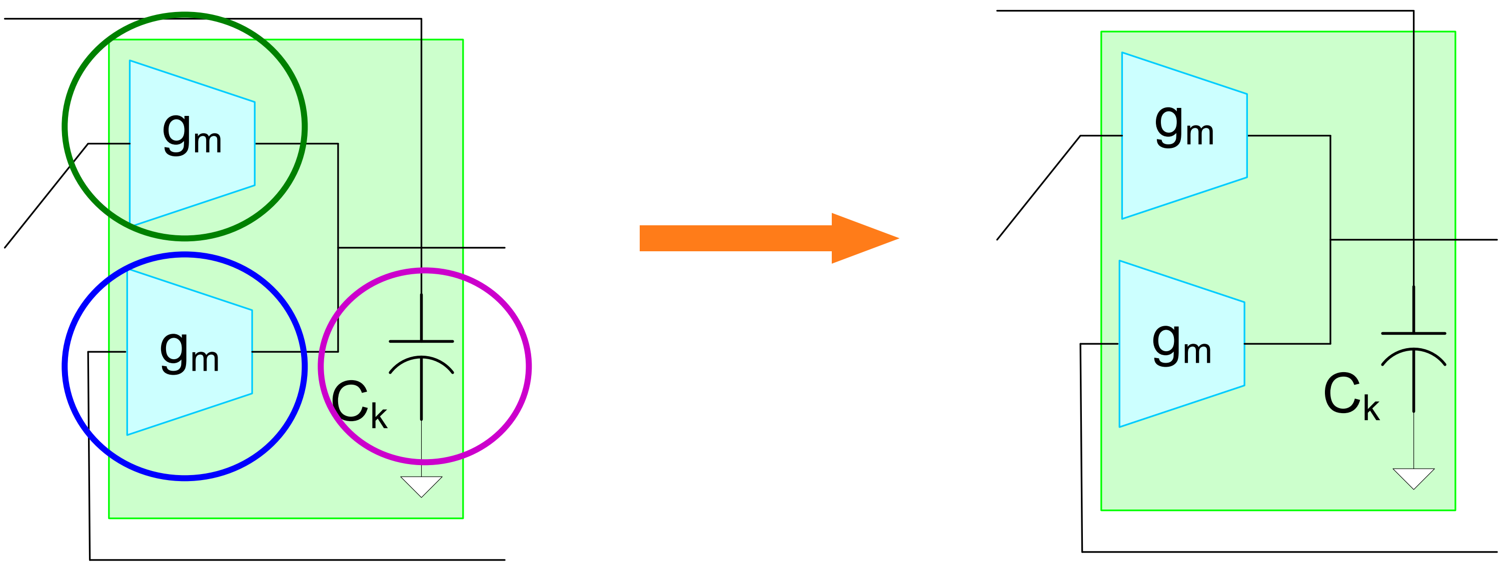


Leap-Frog Filter

Current-mode

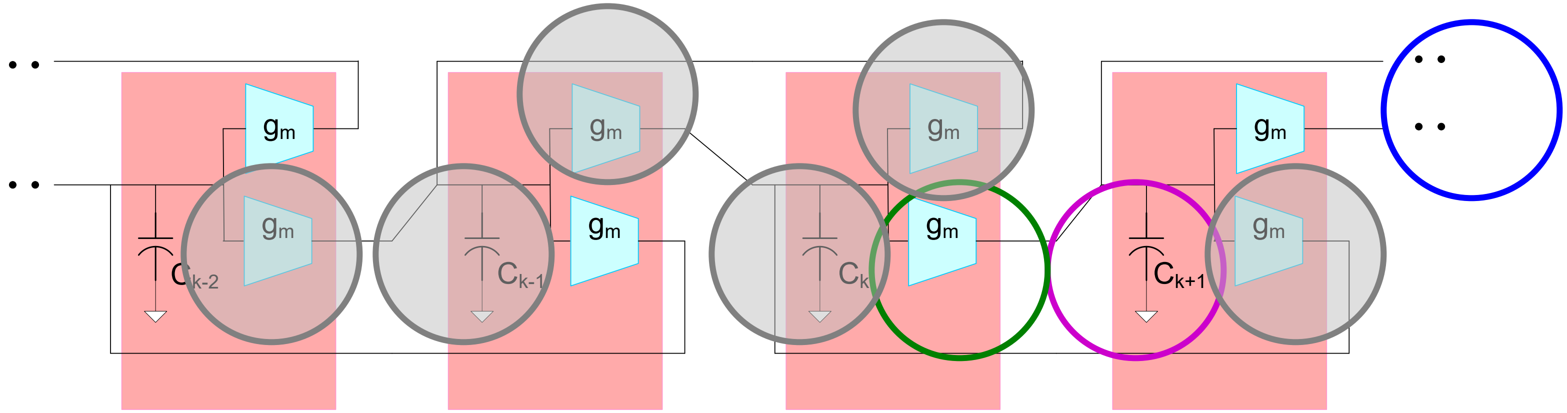


Consider upper OTA in stage k-1, capacitor in stage k and lower OTA in stage k+1

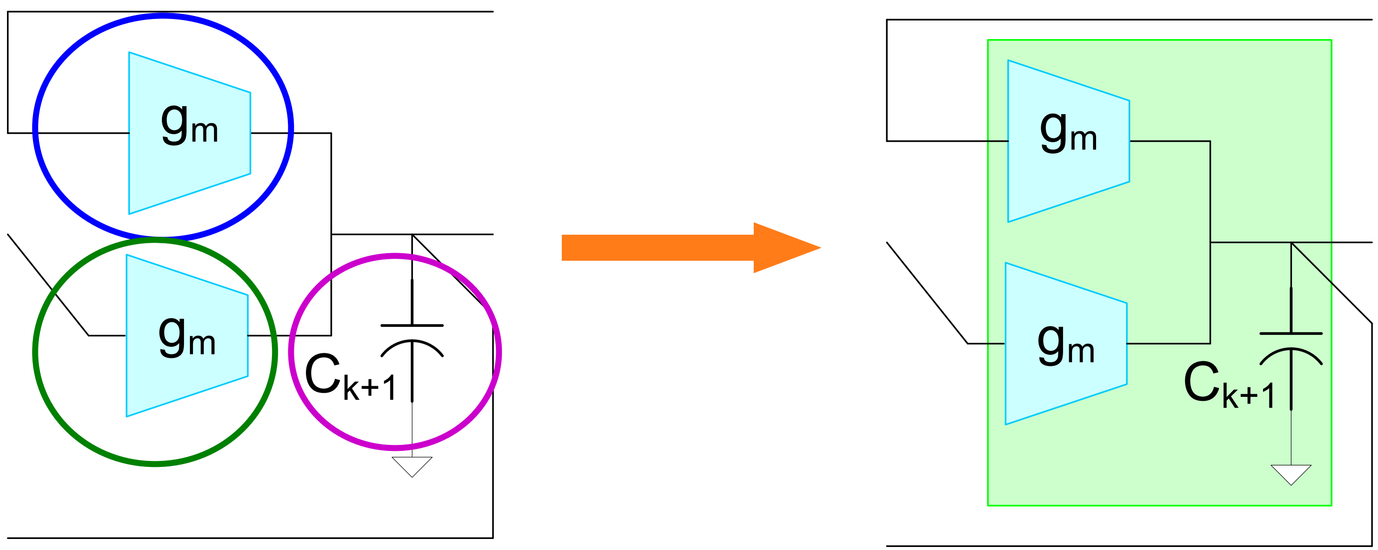


Leap-Frog Filter

Current-mode

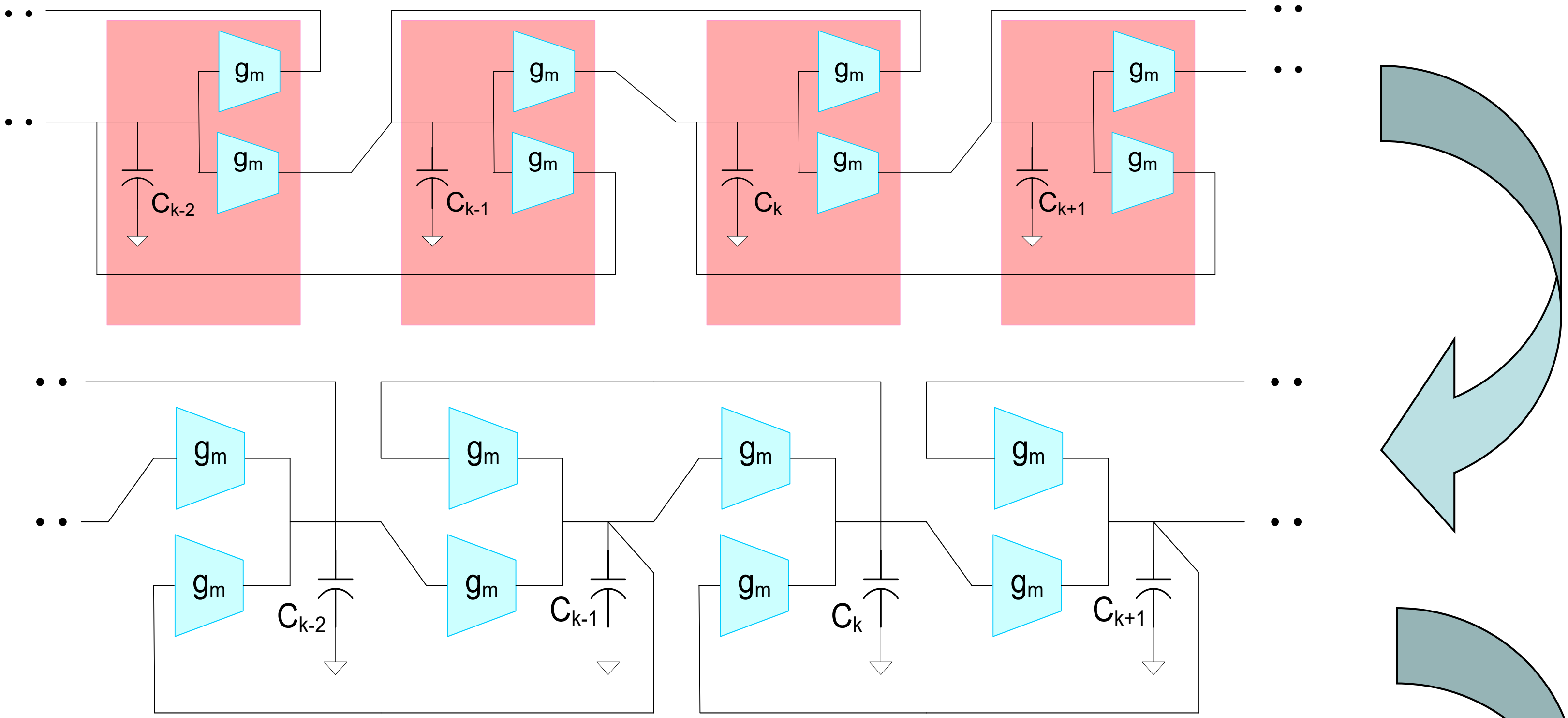


Consider lower OTA in stage k, capacitor in stage k+1 and upper OTA in stage k+2

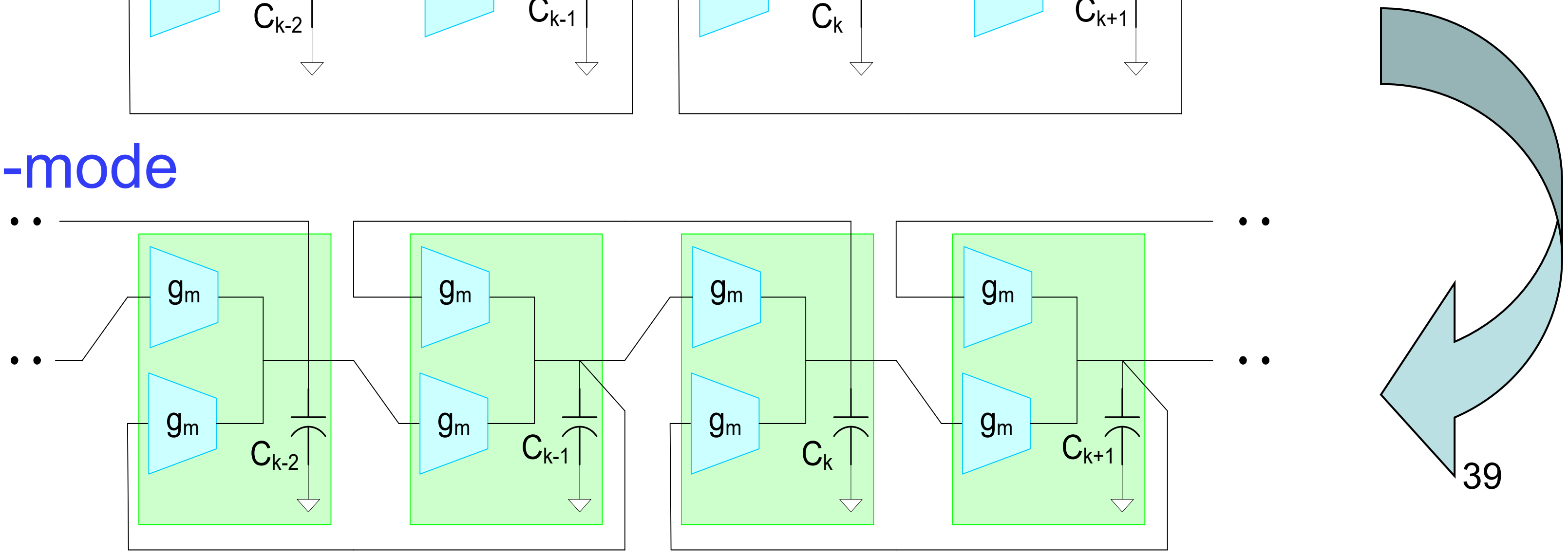


Leap-Frog Filter

Current-mode

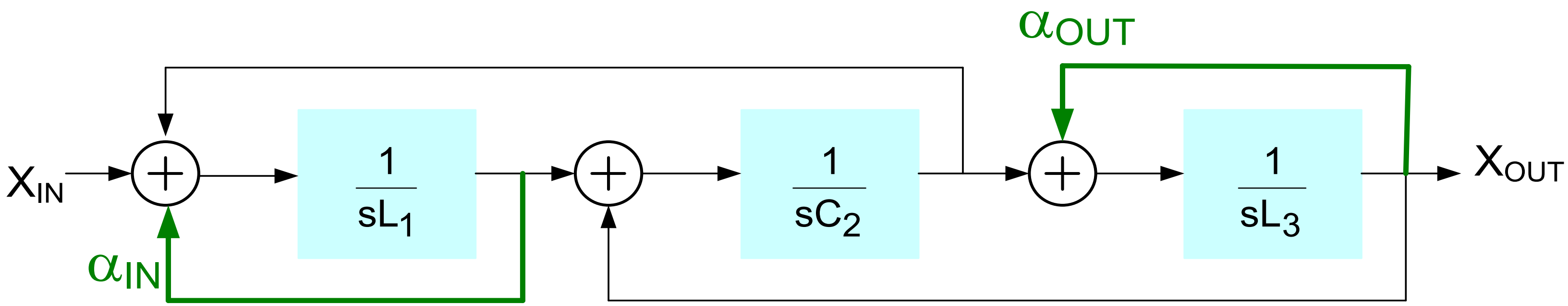


Voltage-mode

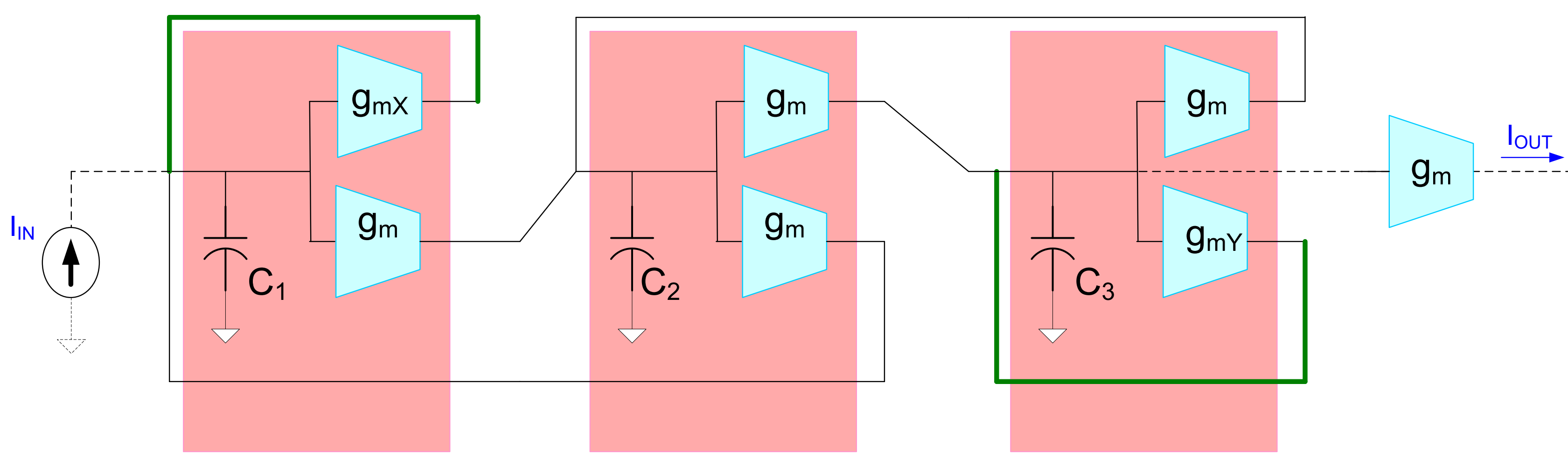


Leap-Frog Filter

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

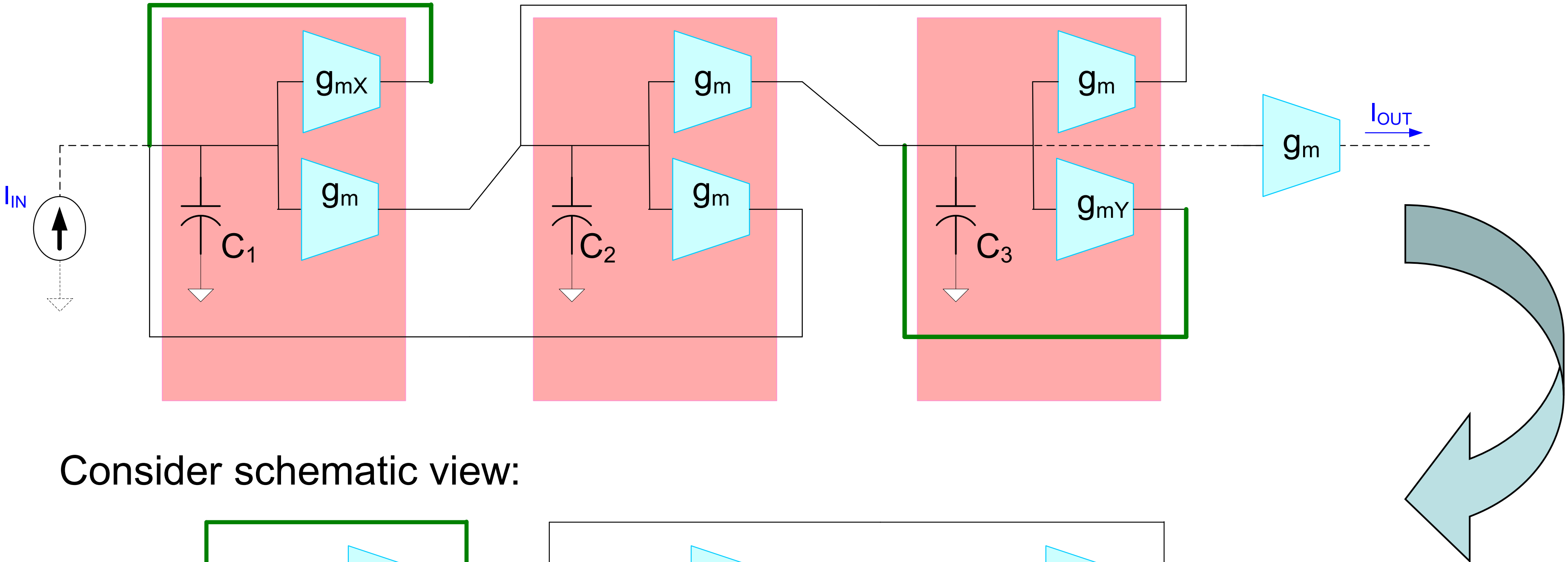


Current-mode implementation

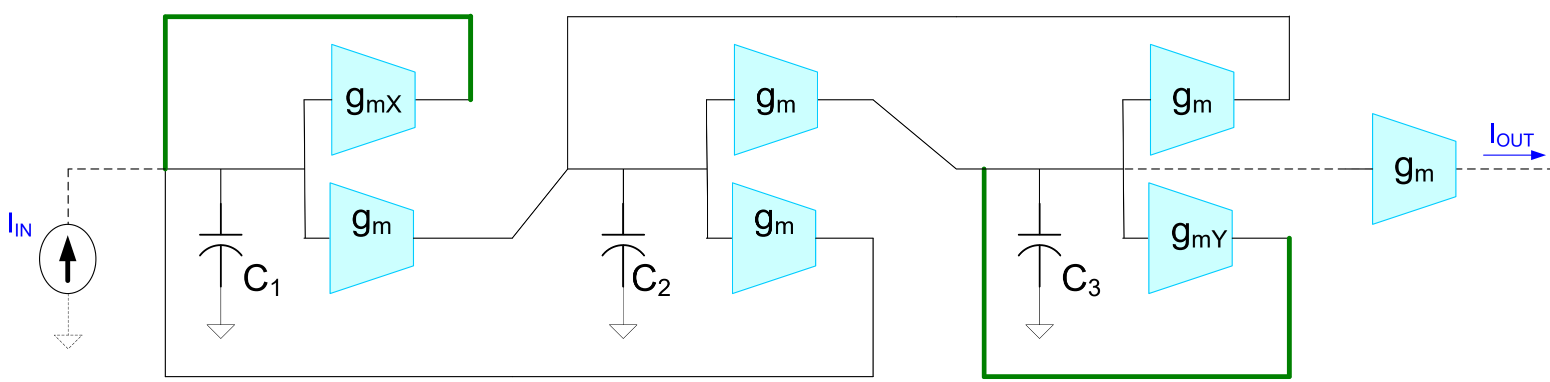


Leap-Frog Filter

Current-mode implementation

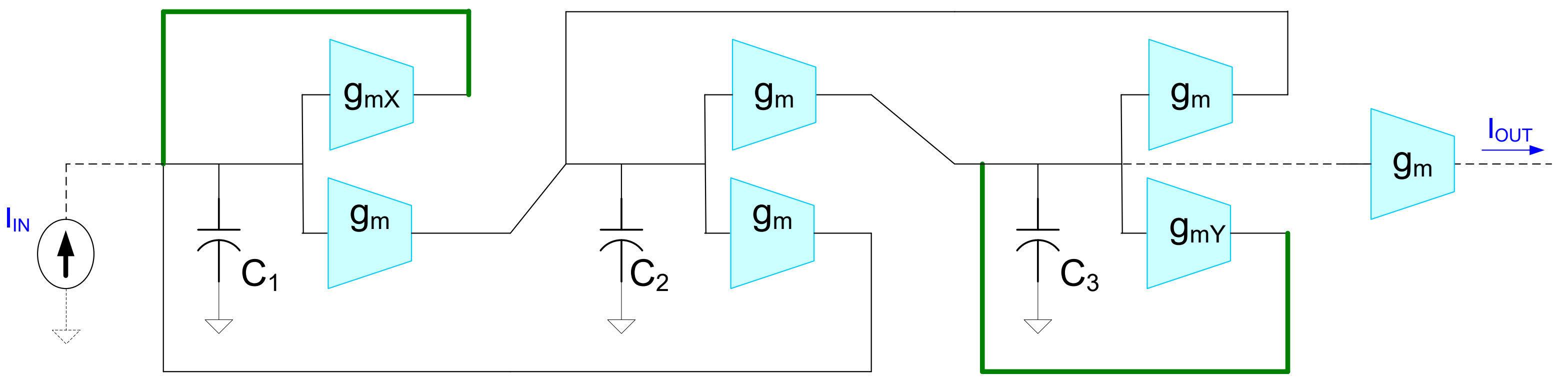


Consider schematic view:

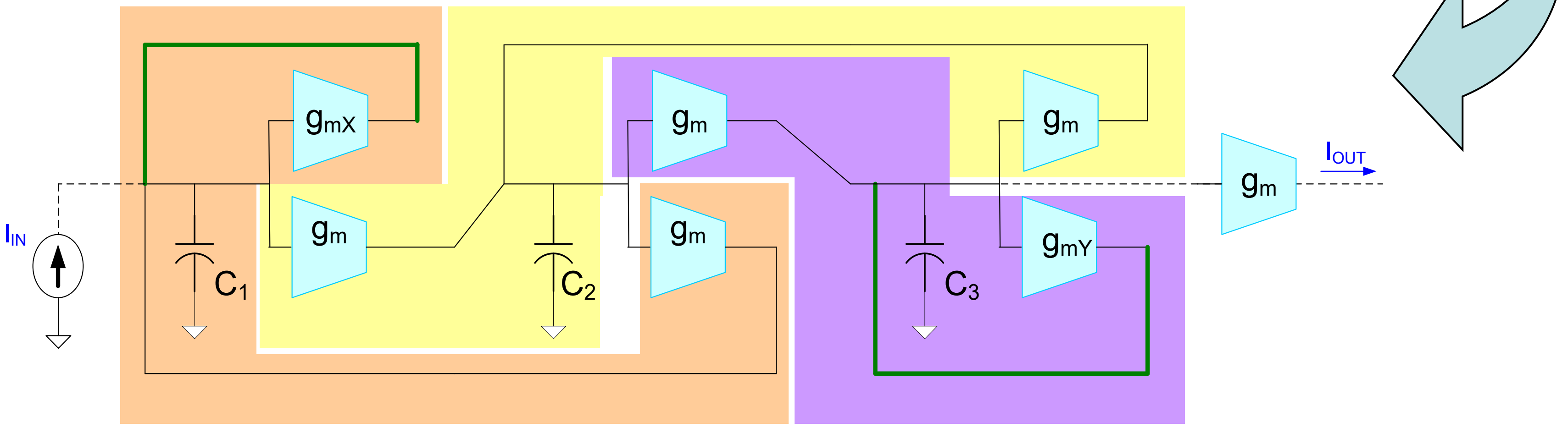


Leap-Frog Filter

Current-mode implementation

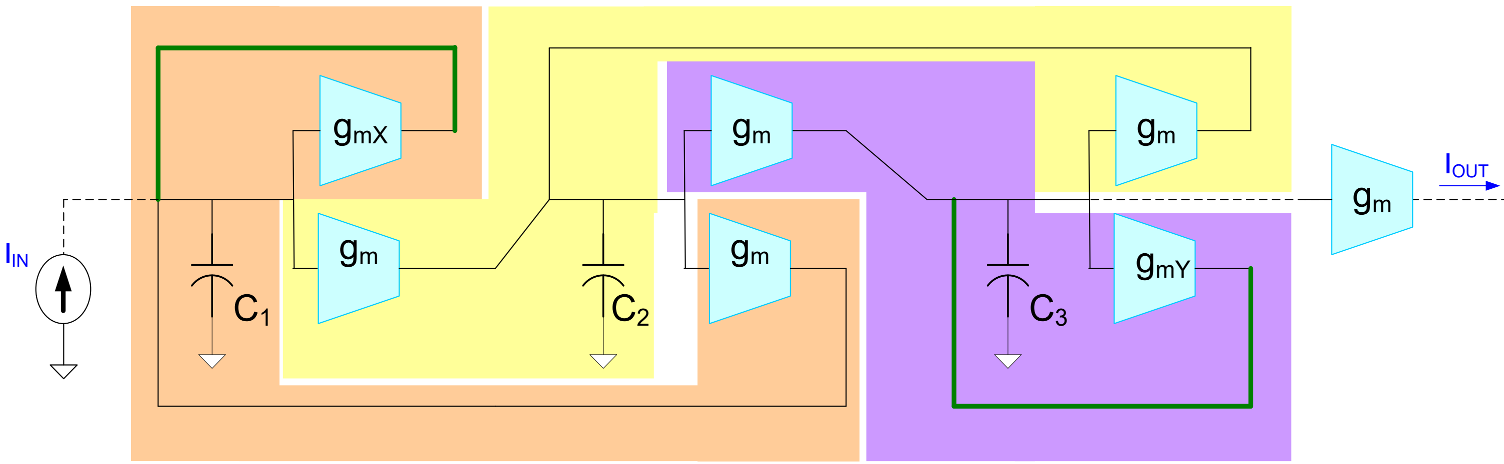


Re-group elements:

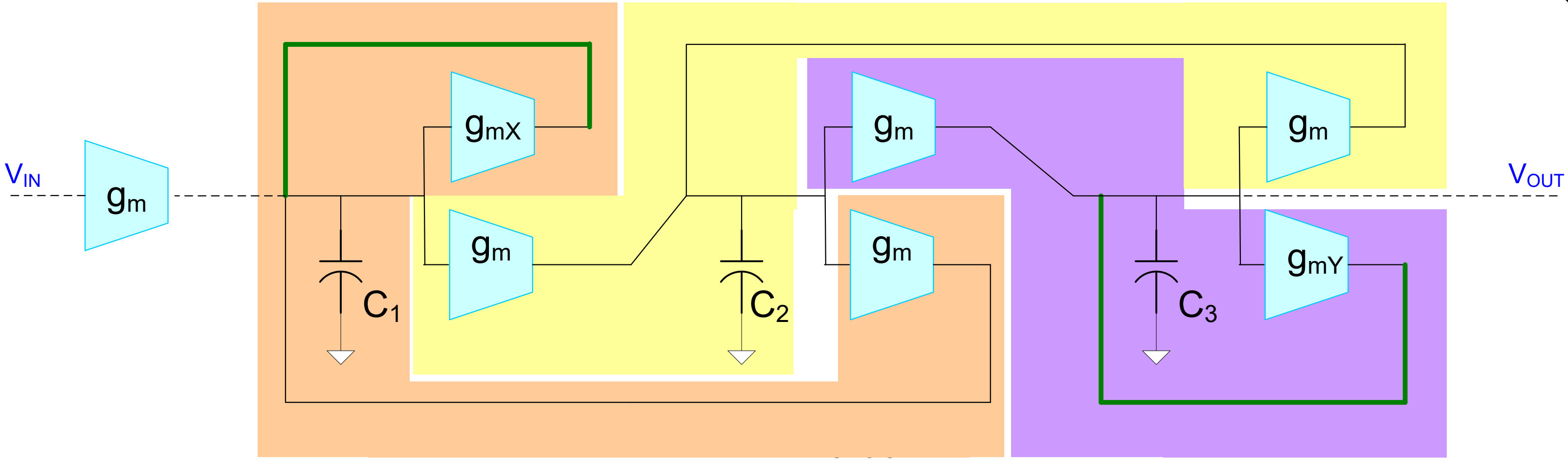


Leap-Frog Filter

Current-mode implementation

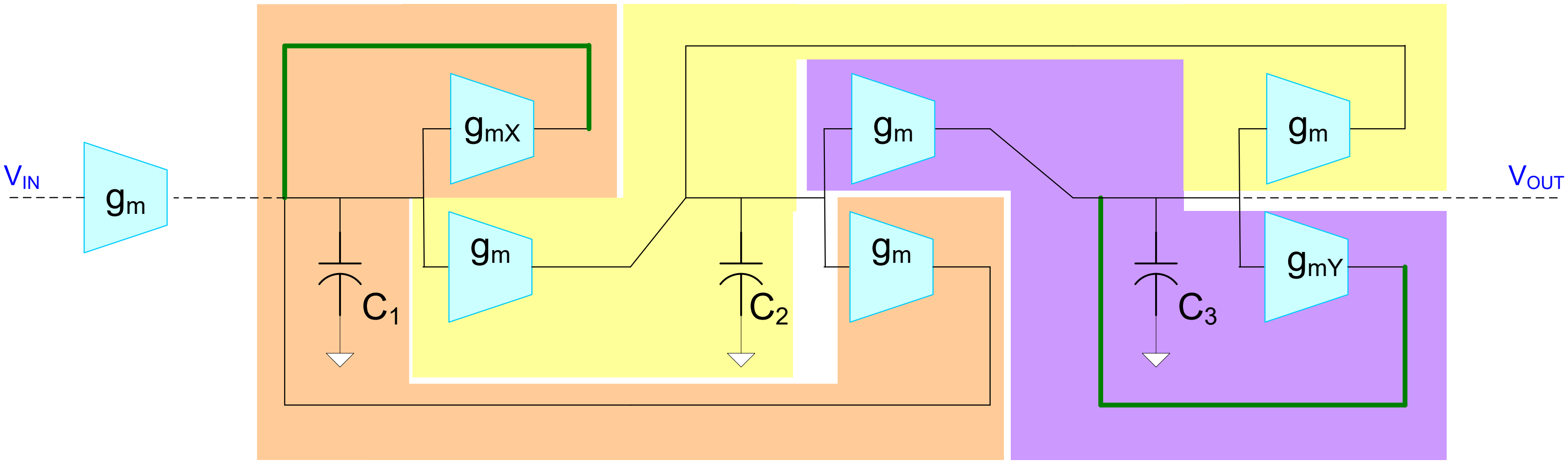


I/O Source Transformation

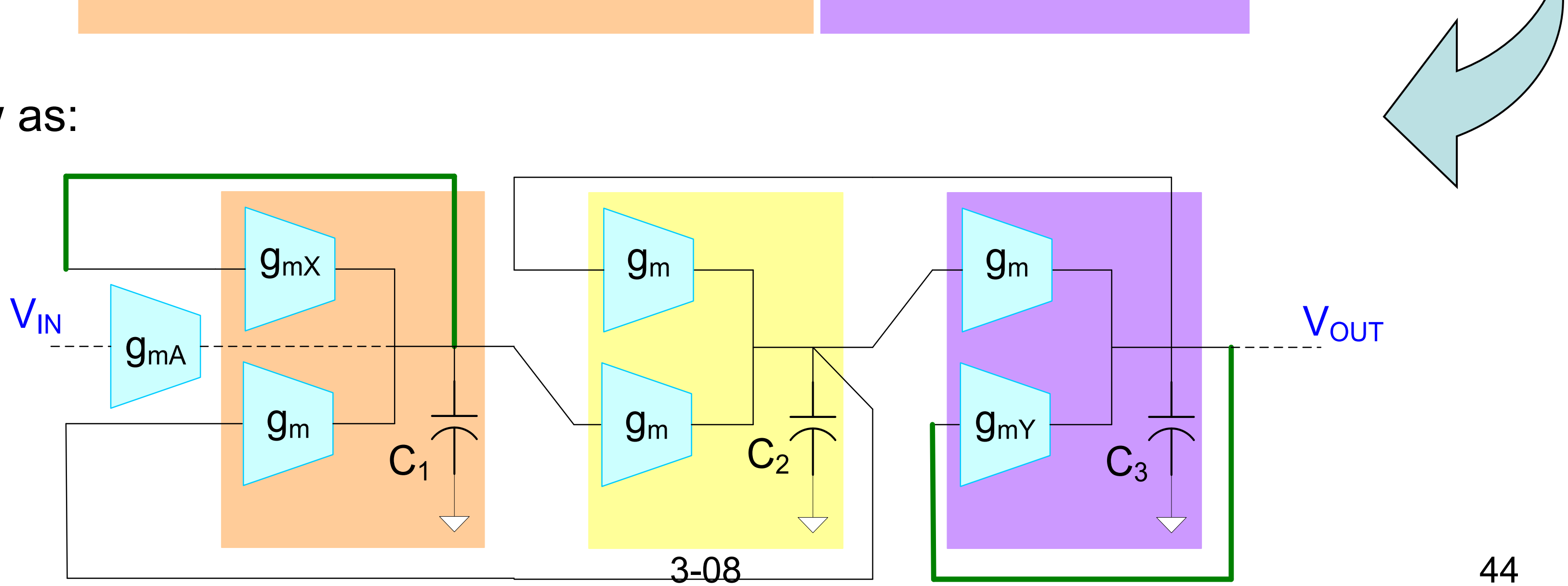


Leap-Frog Filter

Current-mode implementation

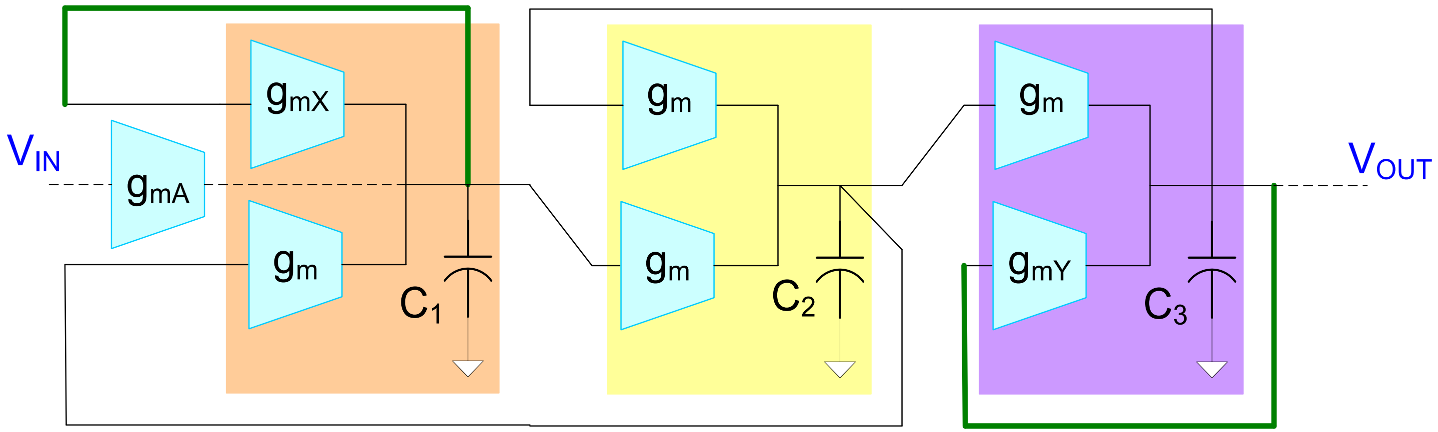


Redraw as:

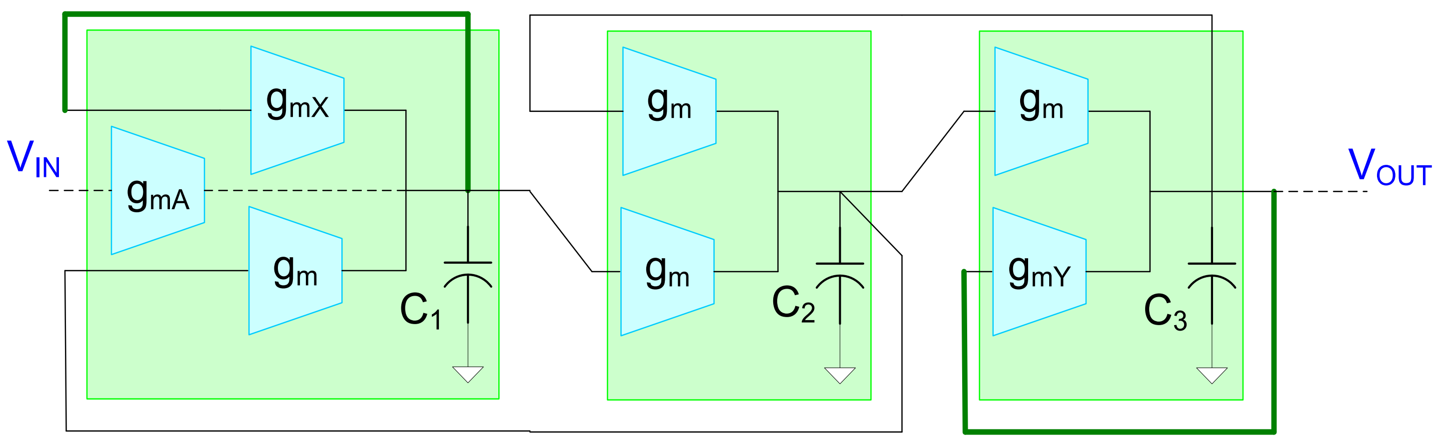


Leap-Frog Filter

Current-mode implementation

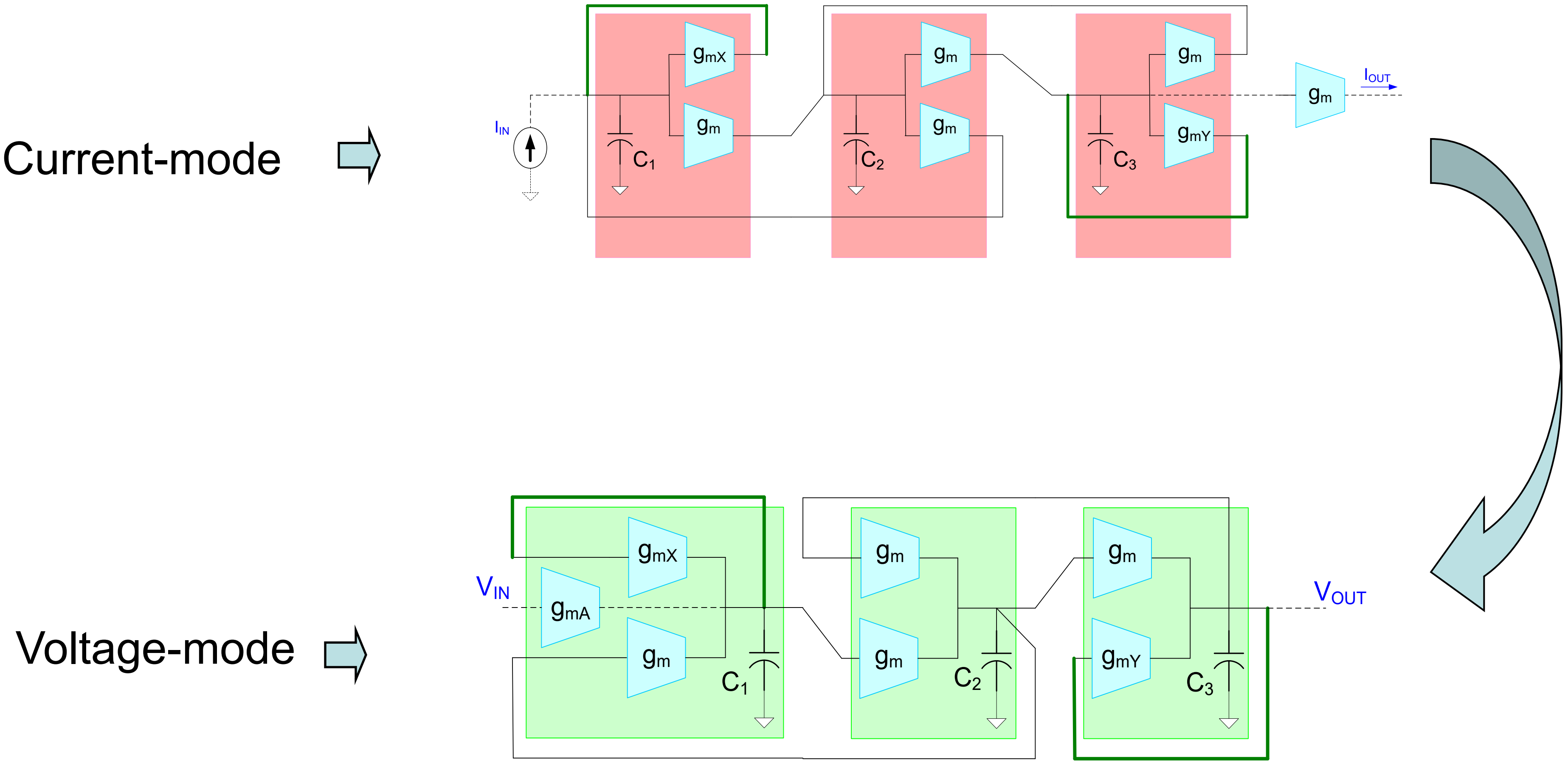


Change notation:



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

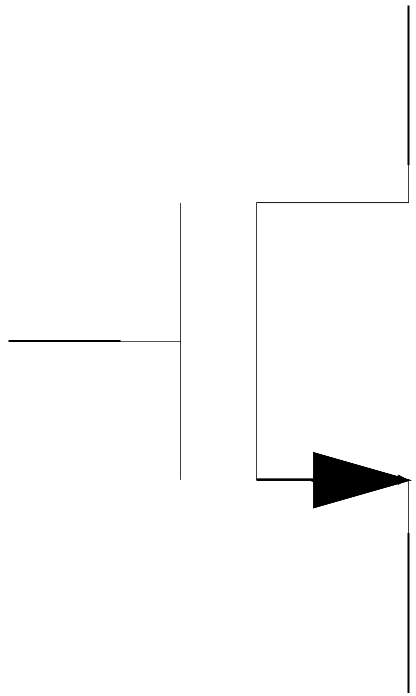
Questions about the Conventional Wisdom

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?

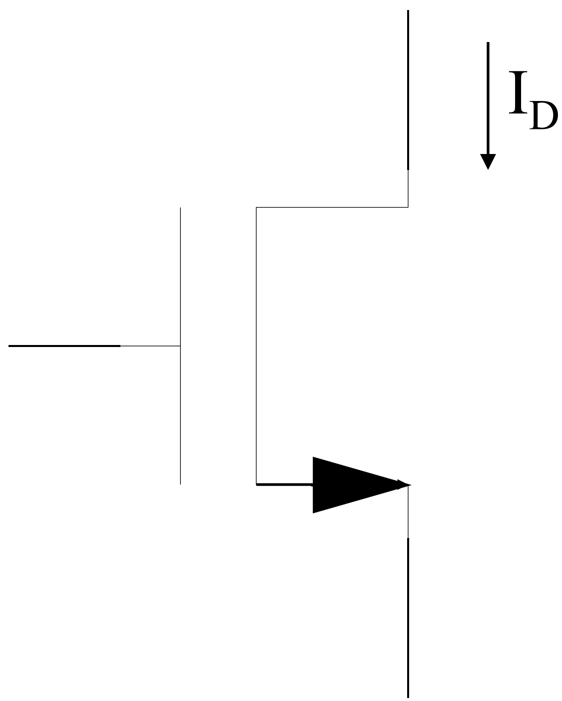
Question?

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



Question?

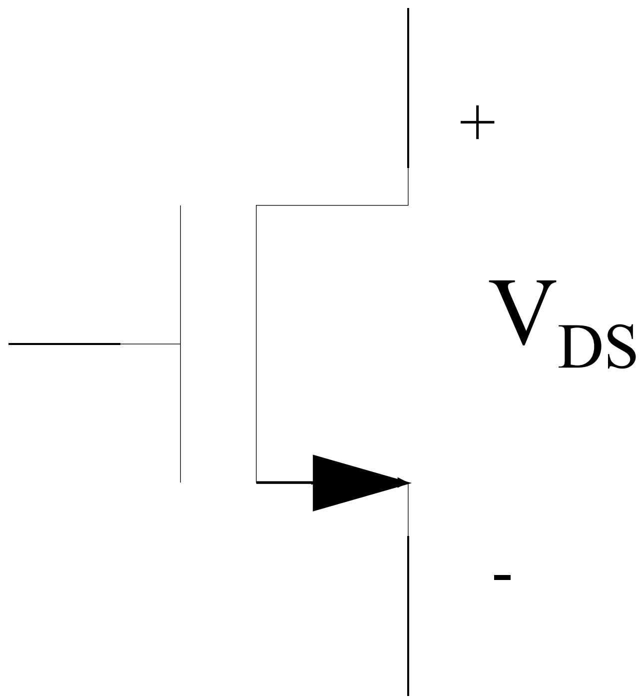
Is the following circuit a voltage mode-circuit or a current-mode circuit?



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

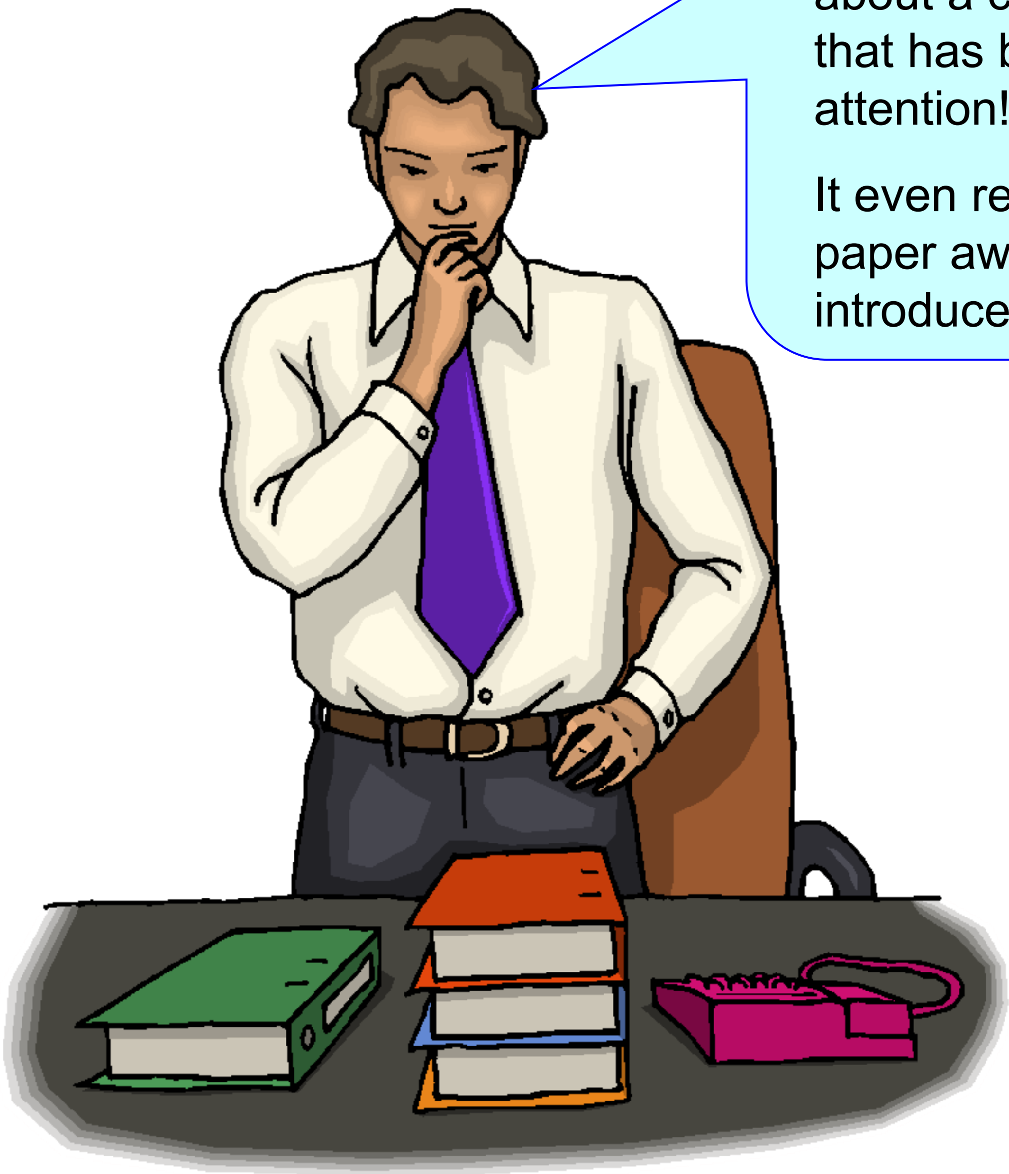
Observations (cont.)

- 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!

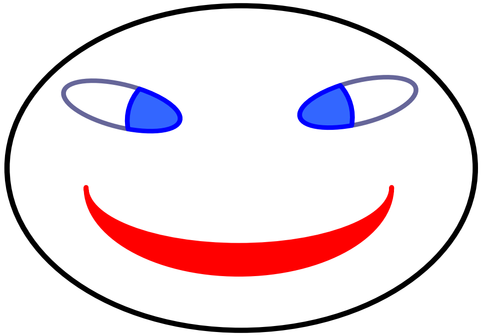
It even received the outstanding paper award at ISSCC when it was introduced!

Current Dividers

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

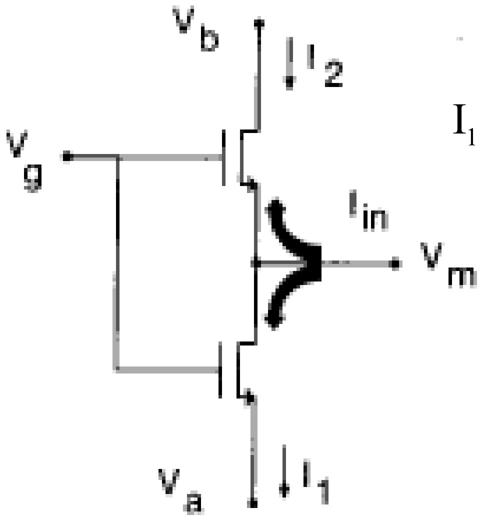
Current Dividers

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"



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

. The basic principle of current division.

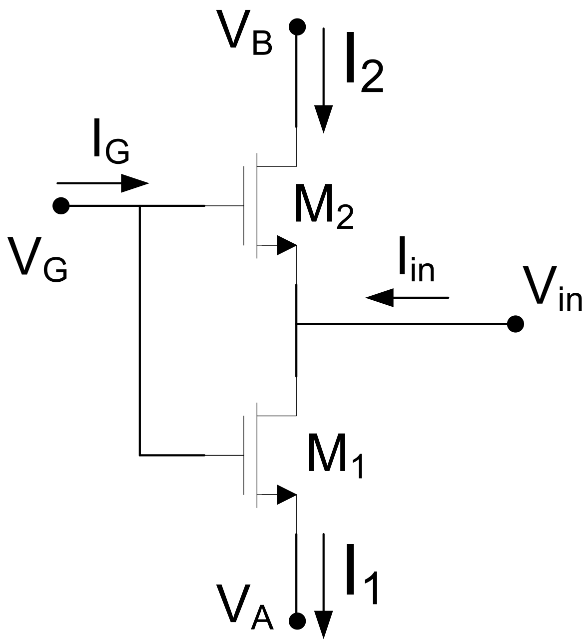
- constant and independent of I_{in} (implying low distortion),
- independent of the values of V_a and V_b,
- independent of whether one or both devices are saturated or nonsaturated,
- and also independent of whether one or both devices operate in strong or in weak inversion.

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



Current divider with “Inherent Linearity”

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

Current Division Factor

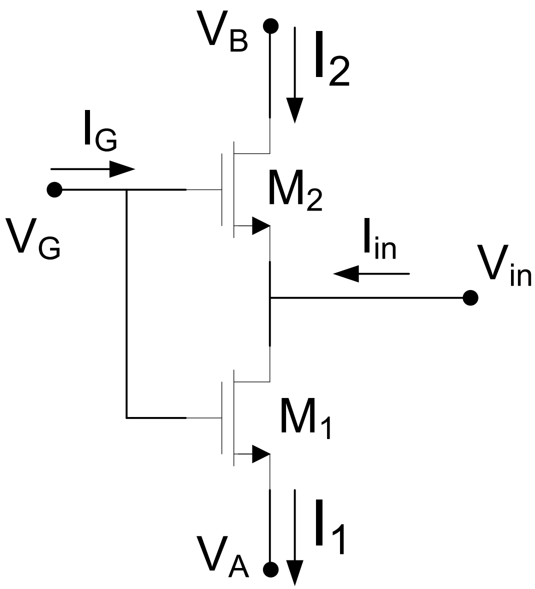
$$\theta = \frac{(W/L)_1}{(W/L)_2}$$

Very Simple and Compact

Elegant !

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

Background Introduction



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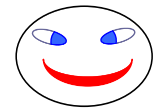

Current divider with “Inherent Linearity”

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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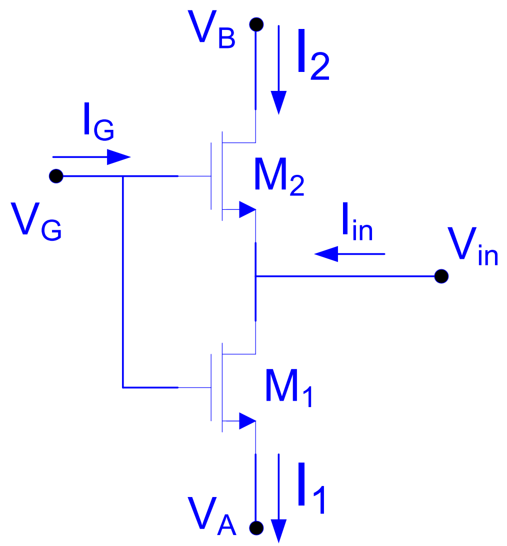
Dec 5 2022 (36 additional citations in past 4 years)

Background Introduction

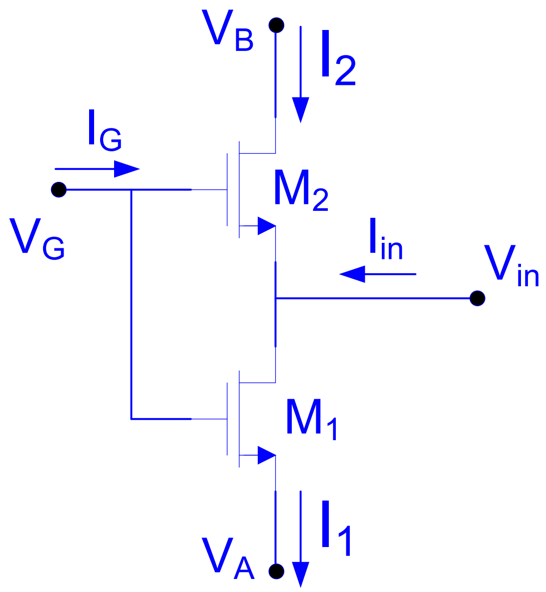


Inherently Linear Current Divider

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

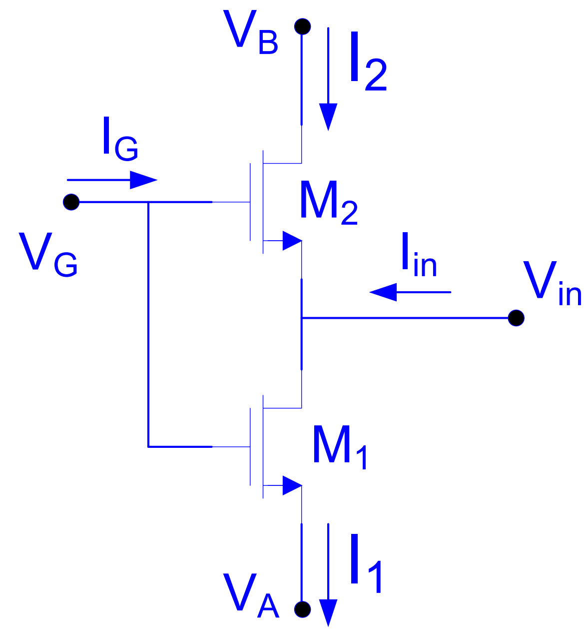
only weakly dependent upon second-order effects

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 280 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



Inherently Linear Current Divider

Dec 2016 search !

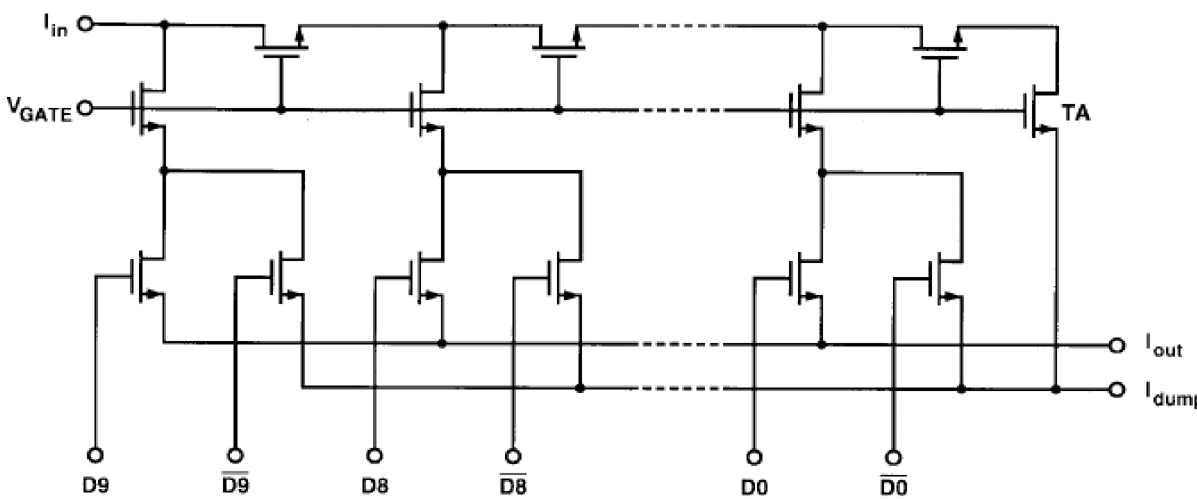
An example application of the concept and the circuit

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



40 Google Scholar Citations (Dec. 15, 2010)

96 Google Scholar Citations (Dec. 5, 2018)

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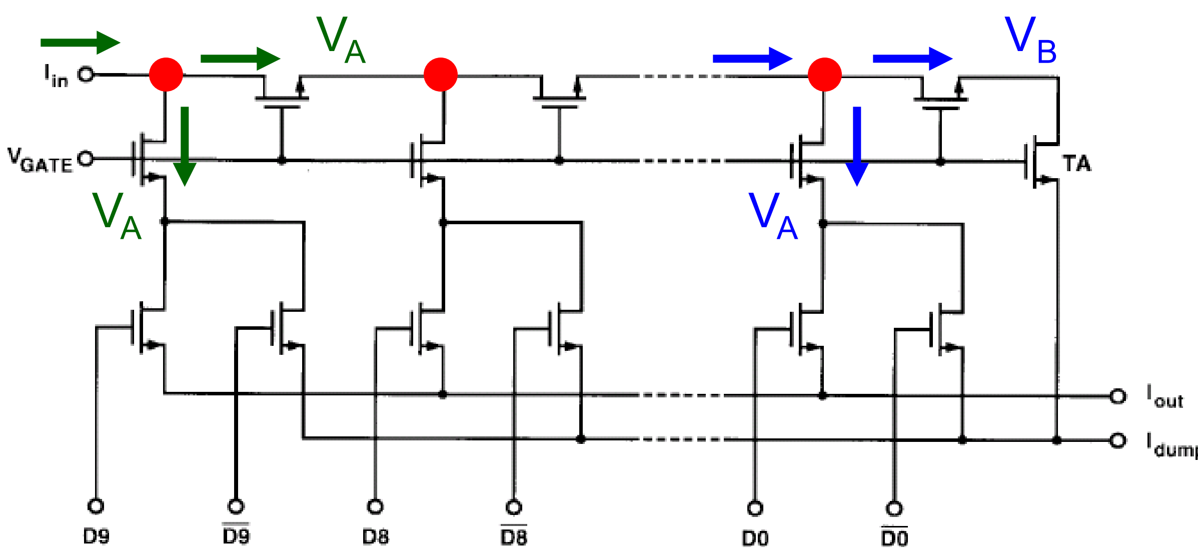

V_A and V_B not even at zero impedance nodes !

An example application of the concept and the circuit

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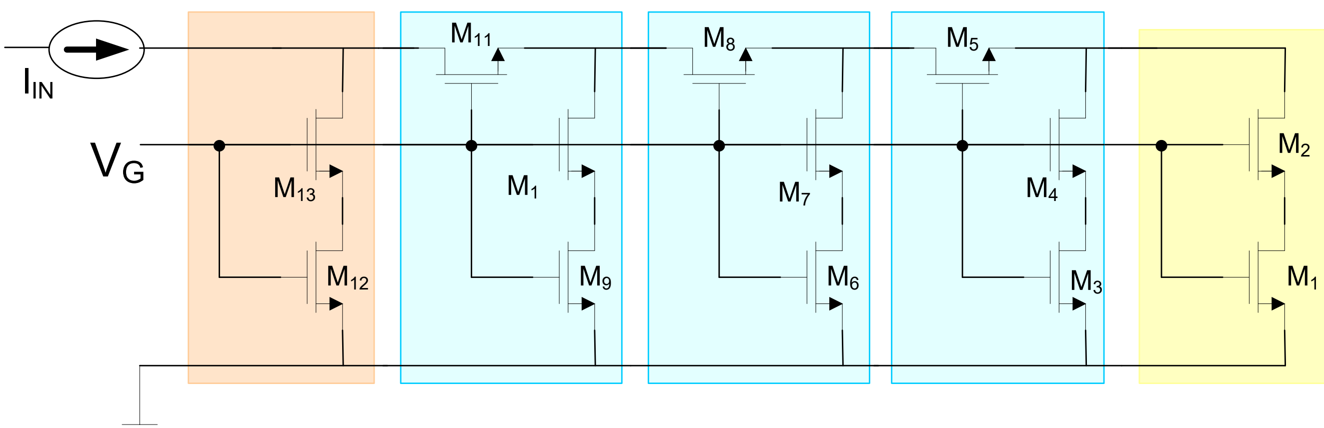
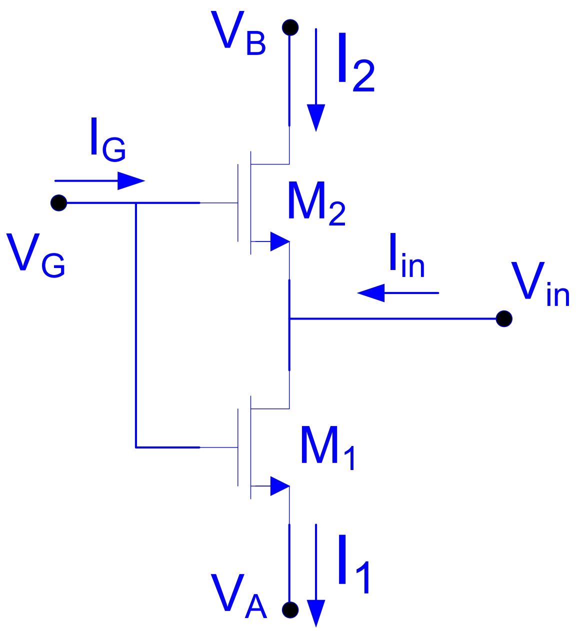


But



Inherently Linear Current Divider

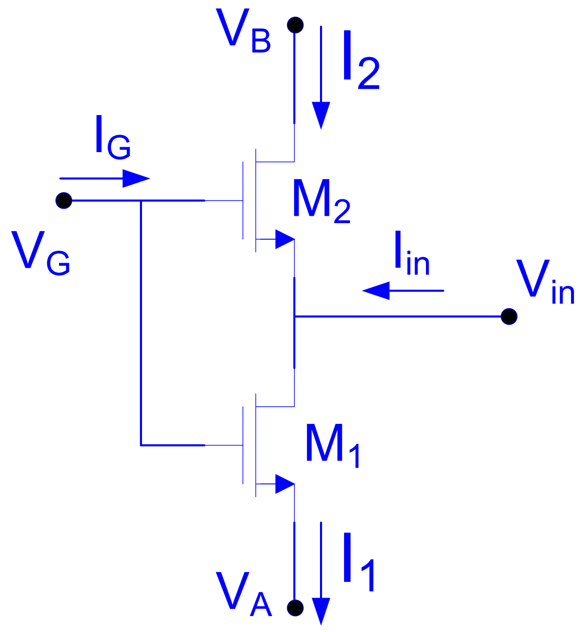
We have been unable to achieve linearity that is even close to that reported in different but closely related applications of this circuit

(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
- Conclusionhs

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

- Background
- Objective
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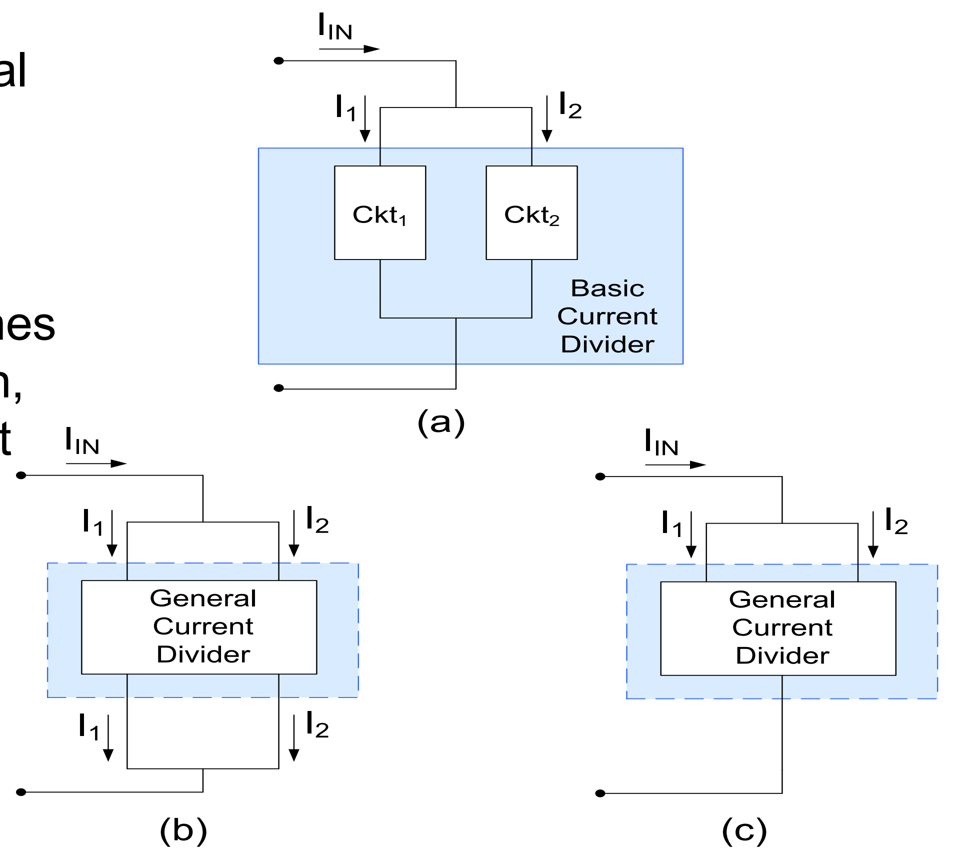
Concept of Current Divider

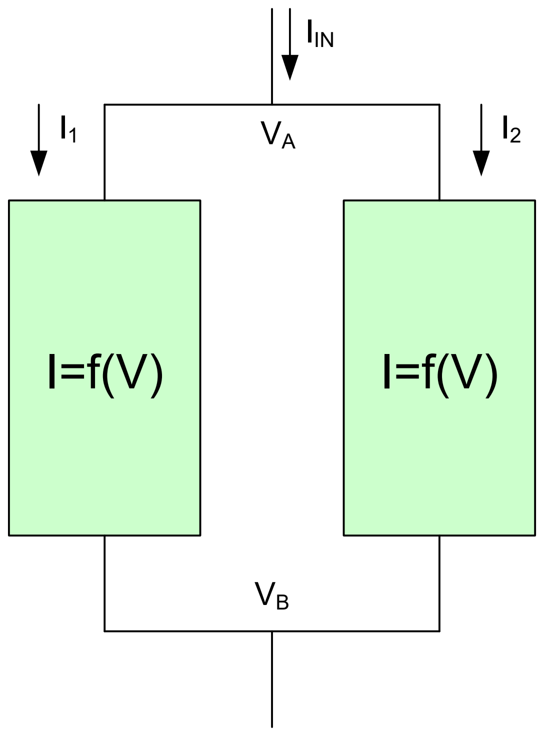
What is a current divider ?

- 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



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

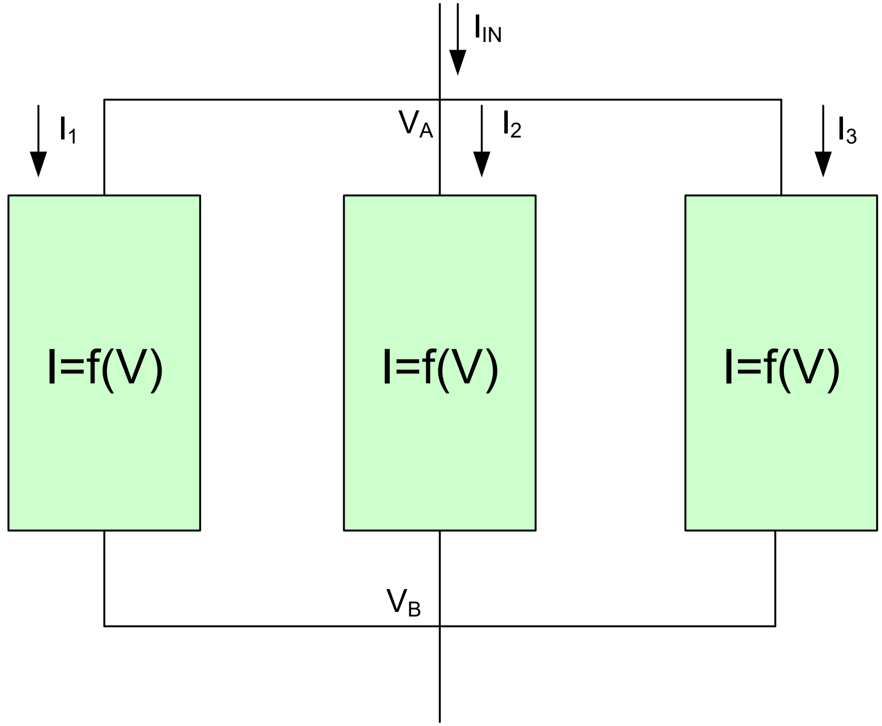
Independent of V_A, V_B, $I_{IN,}$, f

Inherent property of symmetric network

Current Divider !

Concept that has probably been known for well over 100 years

Observations that Will Become Relevant

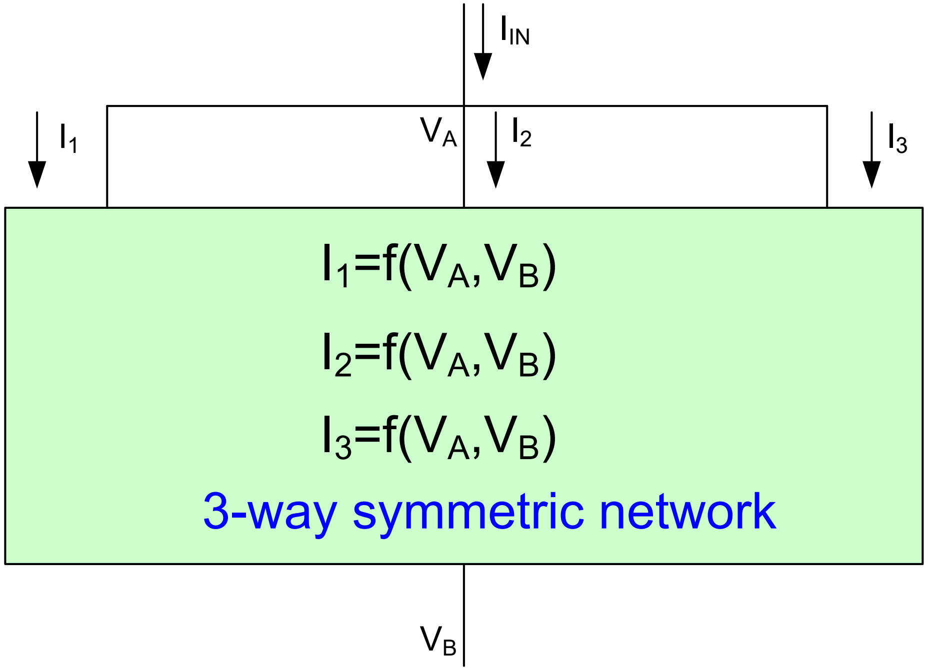


$$\mathbf{I_1 = \frac{1}{3} I_{IN}}$$

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

Inherent property of symmetric network

Observations that Will Become Relevant



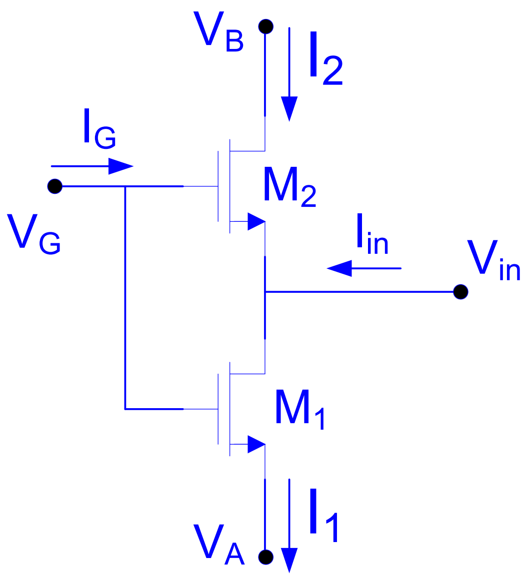
$$\mathbf{I_1 = \frac{1}{3} I_{IN}}$$

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



Conventional Wisdom: current division factor independent of

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

Current Dividers

- Background
- Objective
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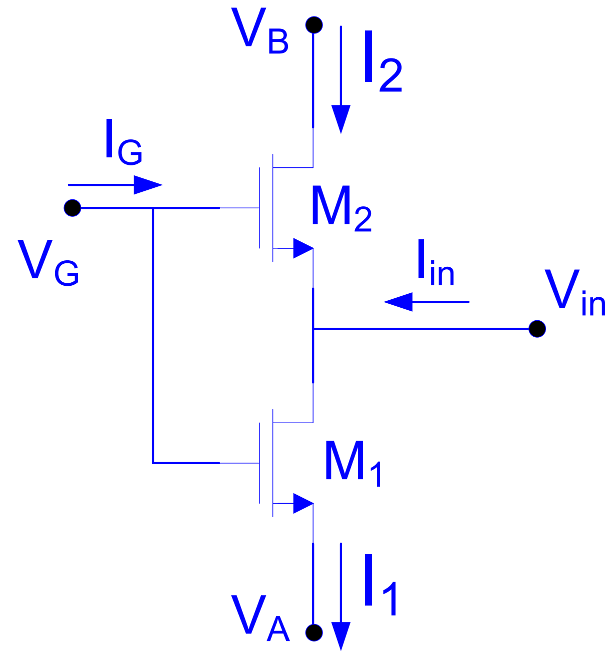
Assumptions

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

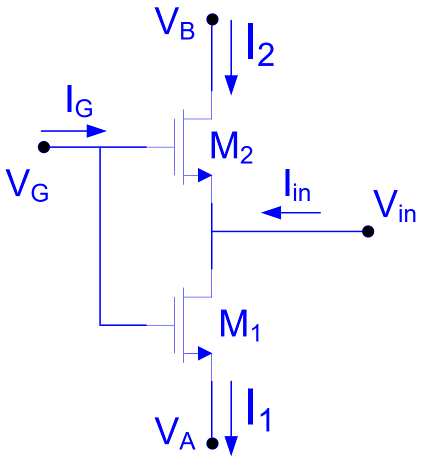
- $\{I_{in}, V_{GA}, V_{BA}\}$ independent variables



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

From a straightforward but tedious analysis

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



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

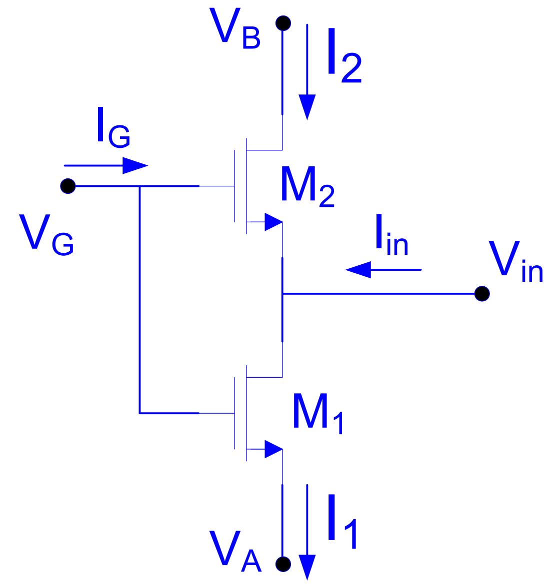
$$V_{inA} = V_{GA} - V_T - \sqrt{(V_{GA}-V_T)^2 - 2\left(\left[\frac{1}{\eta_1+\eta_2}\right] I_{in} + \frac{\eta_2}{\eta_1+\eta_2} V_{BA}\left(V_{GA} - V_T - \frac{V_{BA}}{2}\right)\right)}$$

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

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

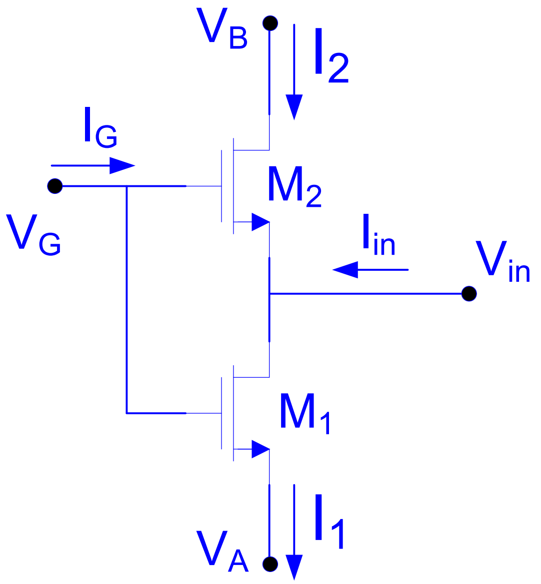


$$V_{inA} = \left(V_{GA}-V_T\right)\left(1-\sqrt{\frac{\eta_1-\frac{2I_{in}}{\left(V_{GA}-V_T\right)^2}}{\eta_1-\eta_2}}\right)$$

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

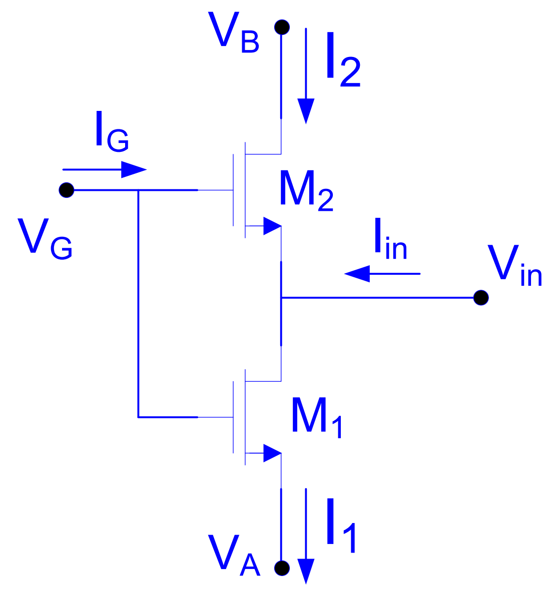
$$I_{1FIT}\left(I_{in}\right) = I_{1Q} + \left.\frac{\partial I_1}{\partial I_{in}}\right|_{\left\{I_{inQ}, V_{GAQ}, V_{inAQ}\right\}} \cdot \left(I_{in} - I_{inQ}\right)$$

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

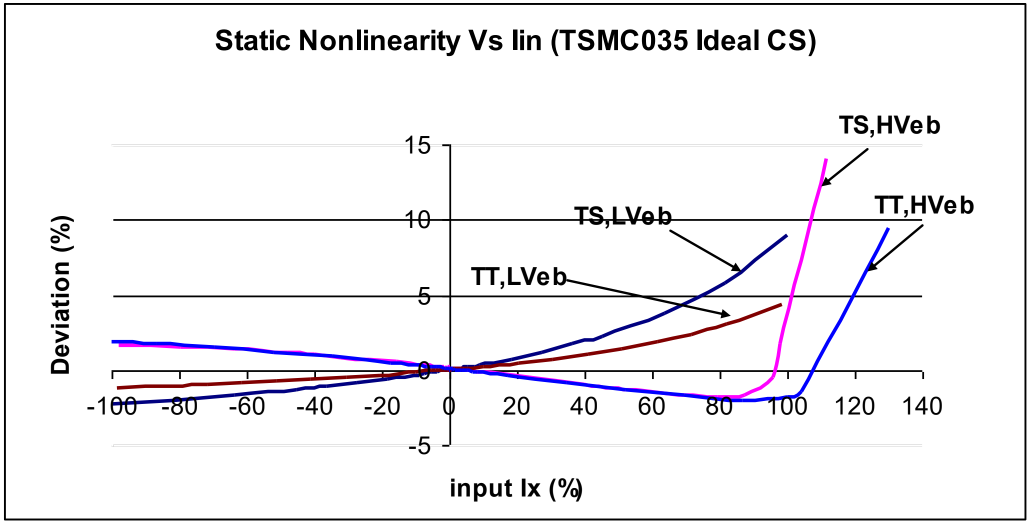
– Dynamic linearity defined as the THD performance with continuous sinusoid excitation

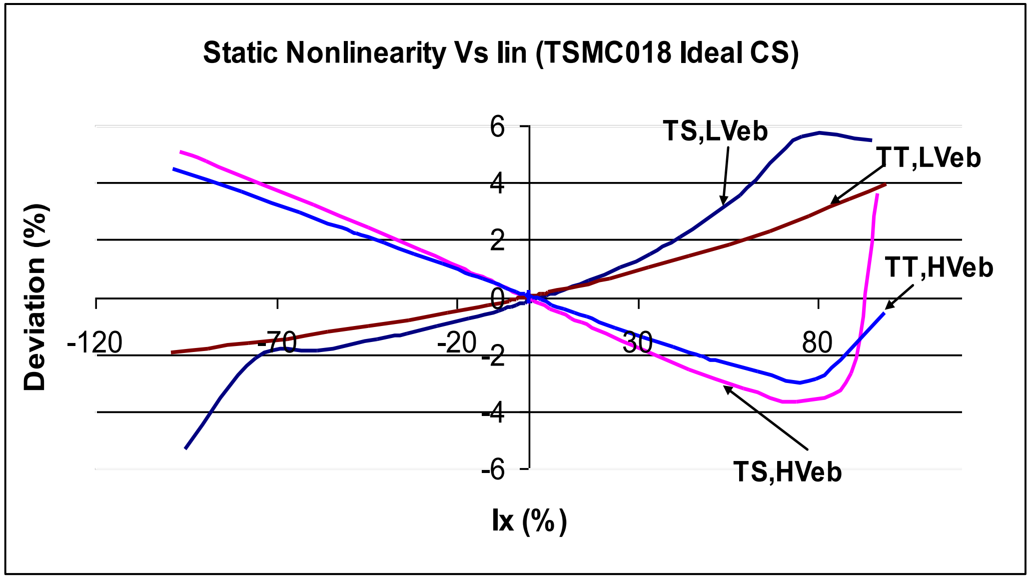
Simulation Environments

- 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

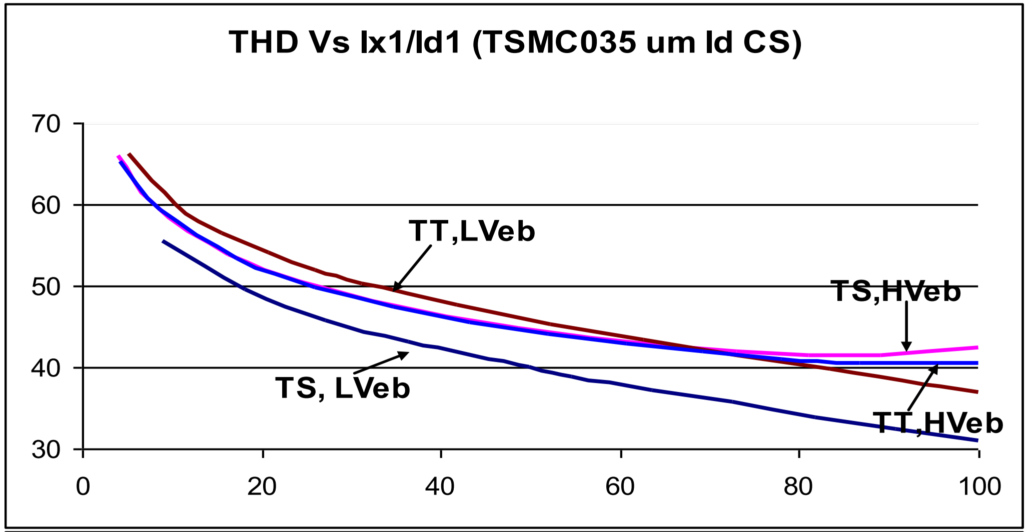


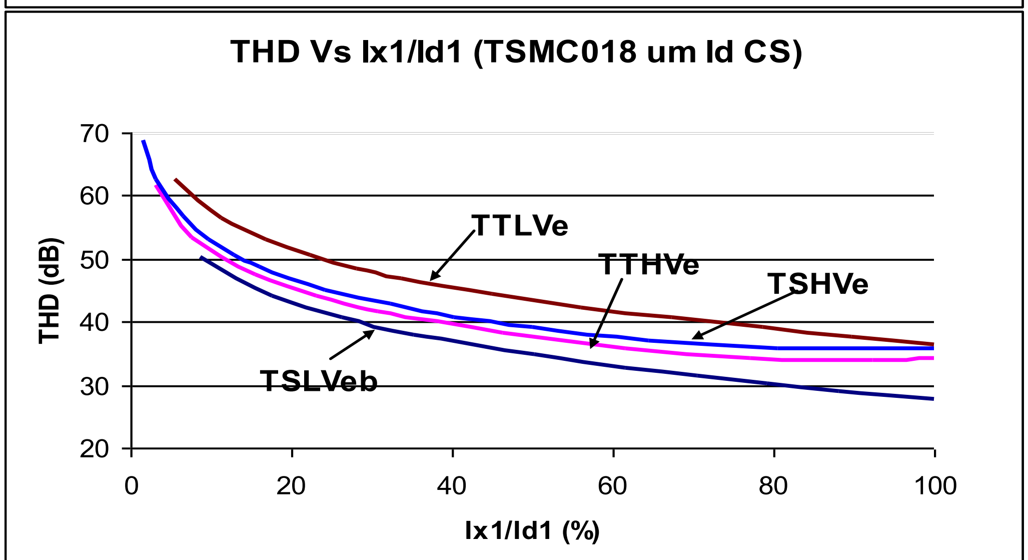
Static Linearity Simulation





Dynamic Linearity Simulation

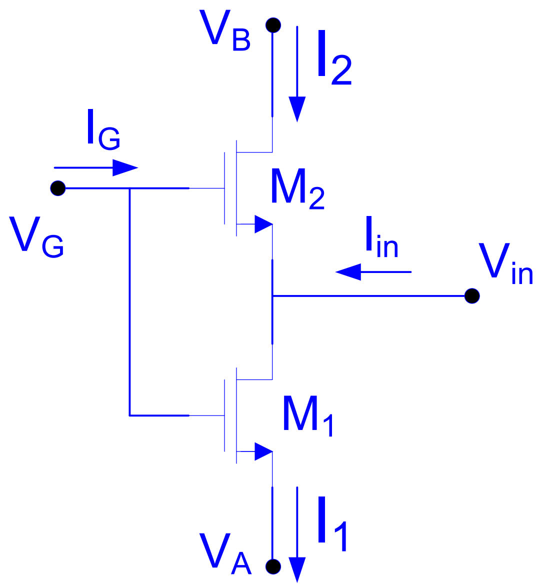




Observations about Linearity

- 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

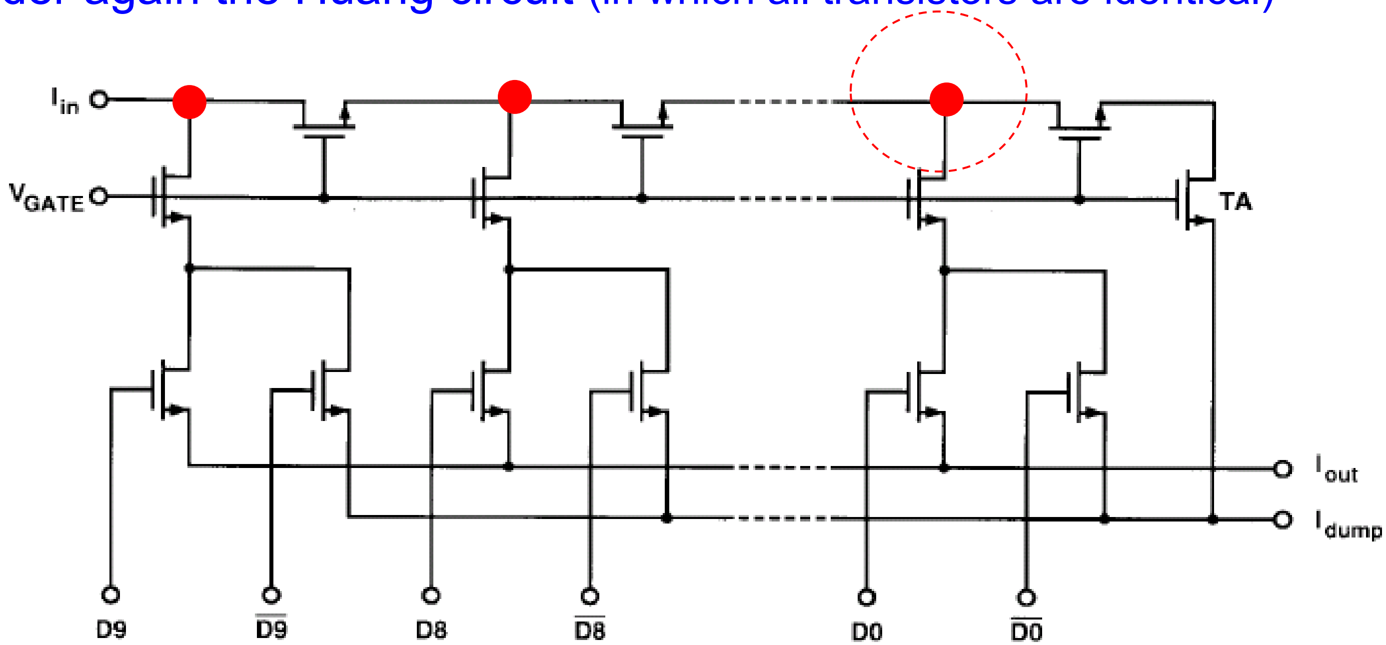
Observations about inherently linear current divider



- 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)

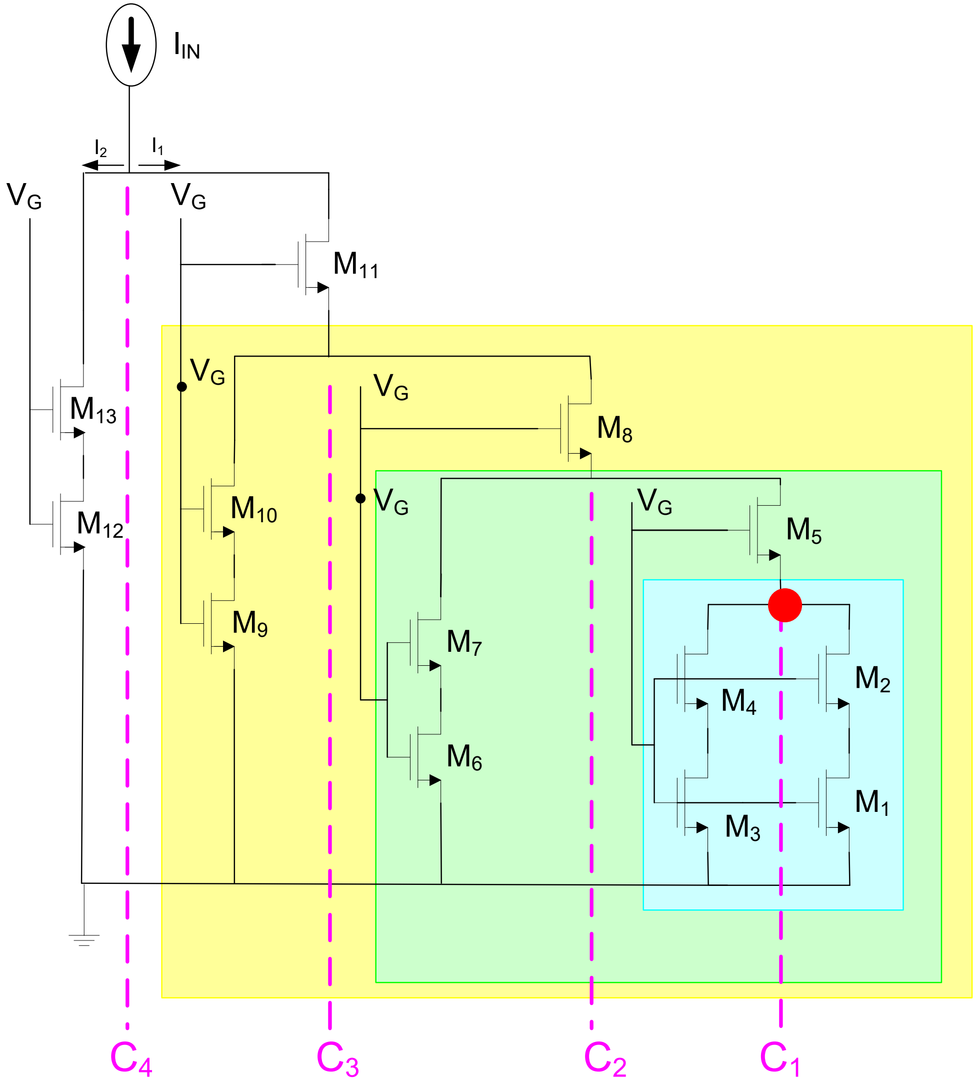


For proper operation, it is critical that currents divide equally at each of The current division nodes !

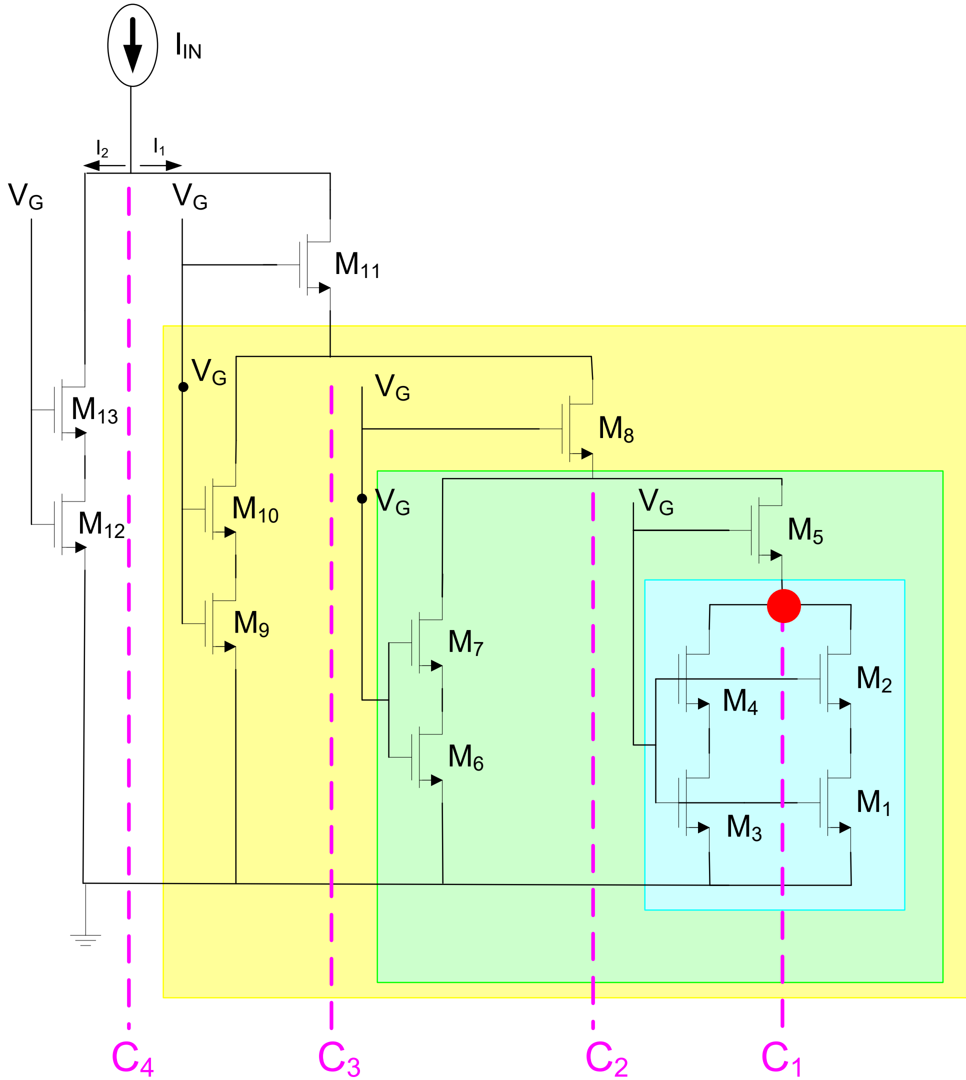
Even the assumption that the voltages V_A and V_B must be zero-impedance sources was not required to obtain the good performance (79 dB range) !

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?

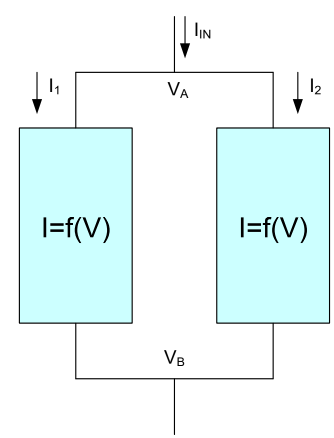
Redraw the Huang Circuit and Consider the right-most Current Divider node



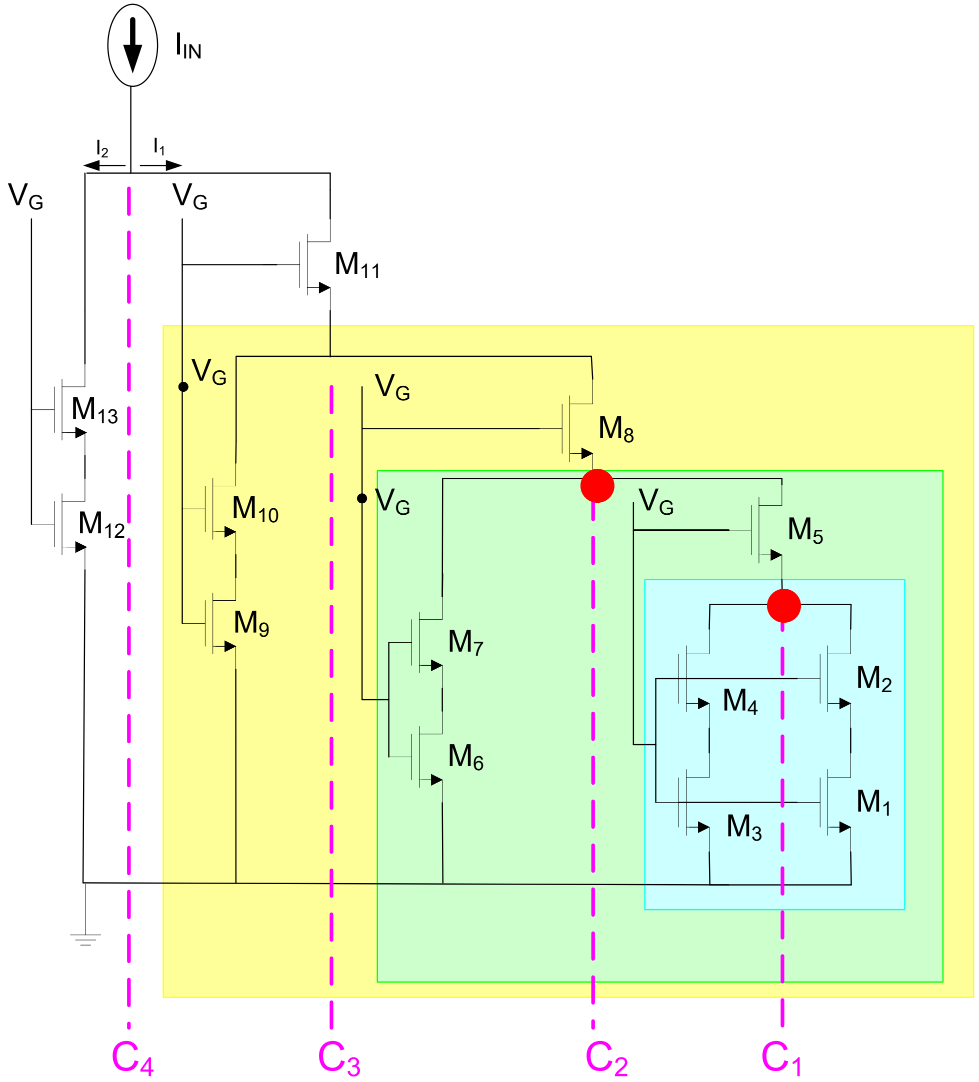
Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?



- 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 !

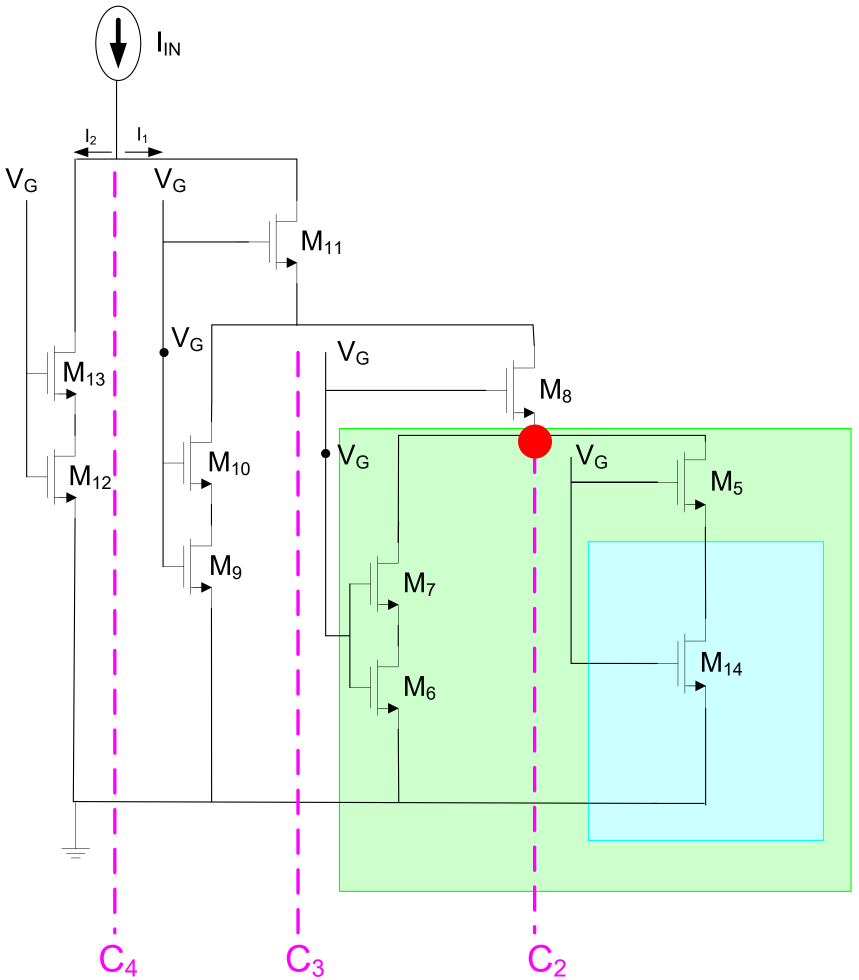


Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

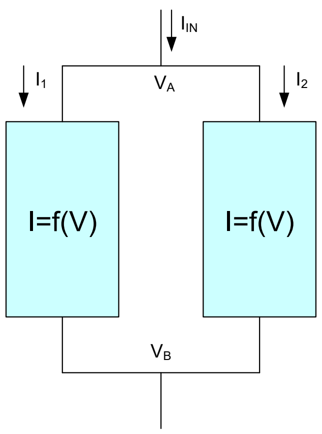


- Observe that M_1, M_2, M_3, M_4 can be modeled as a single transistor
  that is of the same size as M_1
- Call this M_{14}
- Consider now the next closest current-divider node

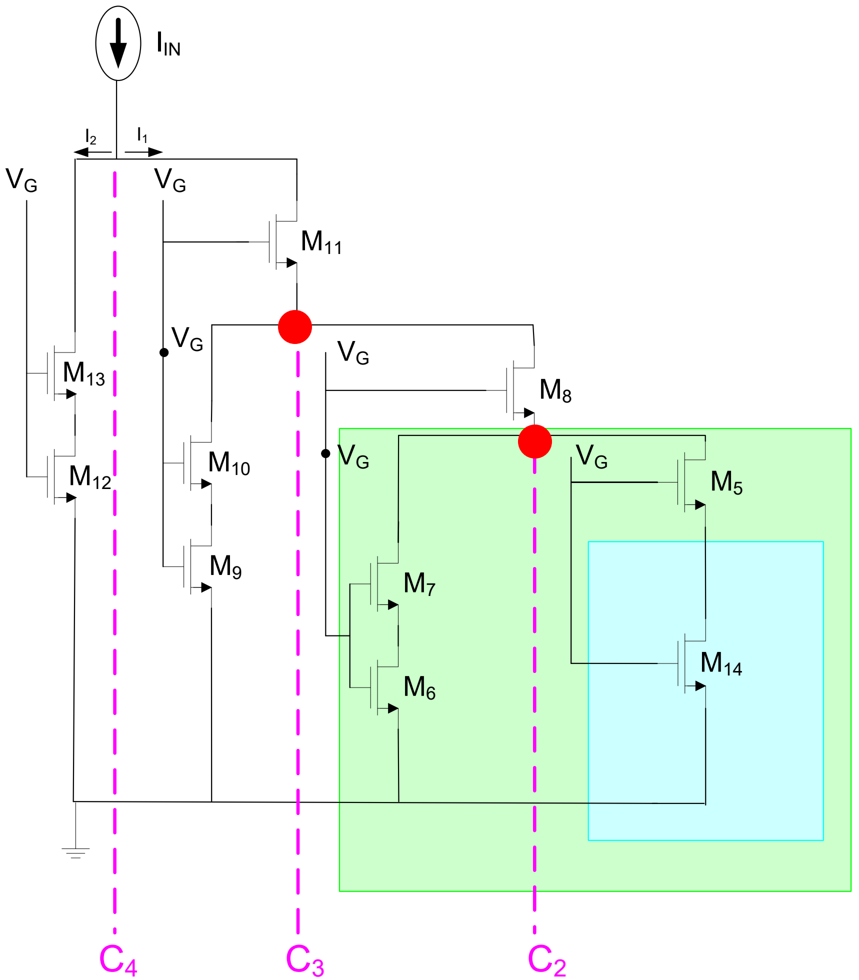
Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?



- 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 !

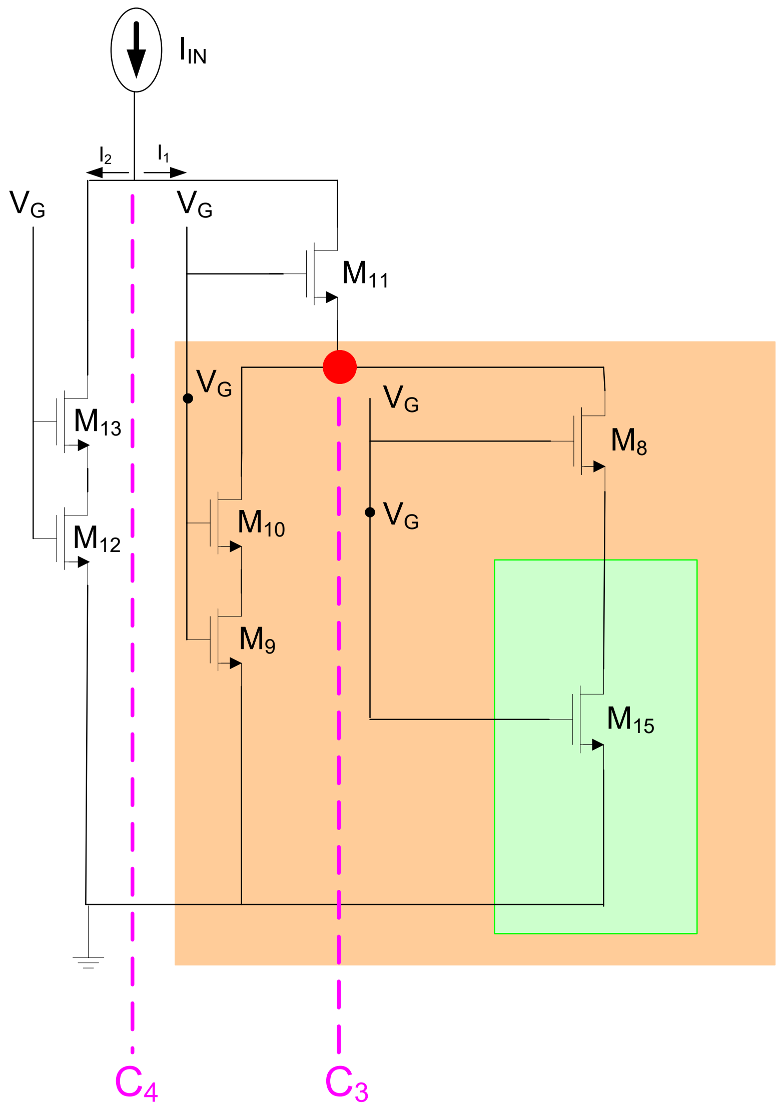


Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

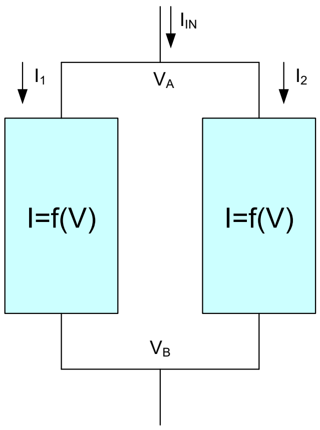


- Observe that M_6,M_7,M_5,M_{14} can be modeled as a single transistor that is of the same size as M_1
- Call this M_{15}
- Consider now the next closest current-divider node

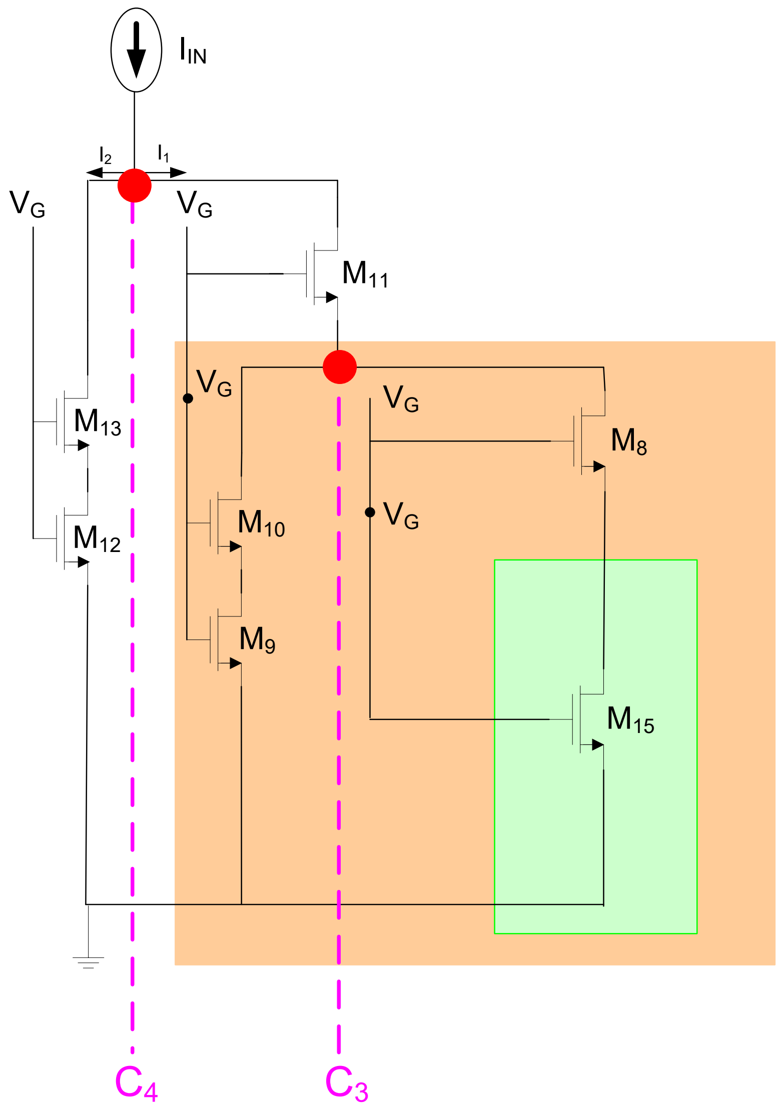
Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?



- 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 !

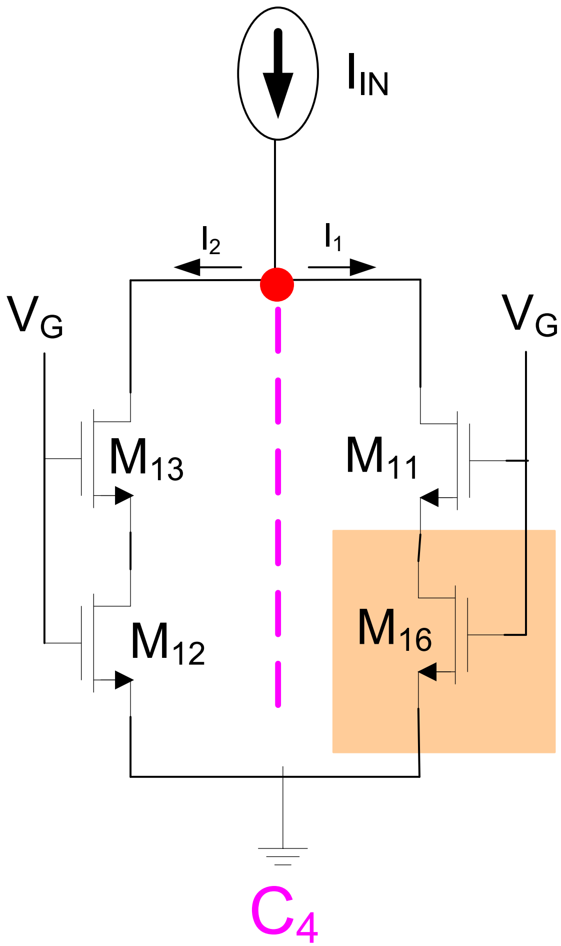


Question: How was the excellent linearity obtained in the author's own work and that reported in the literature if it is difficult to verify the linearity?

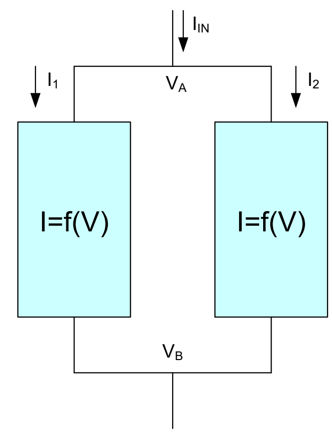


- Observe that M_9,M_{10},M_8,M_{15} can be modeled as a single transistor that is of the same size as M_1
- Call this M_{16}
- Consider now the next closest current-divider node

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?

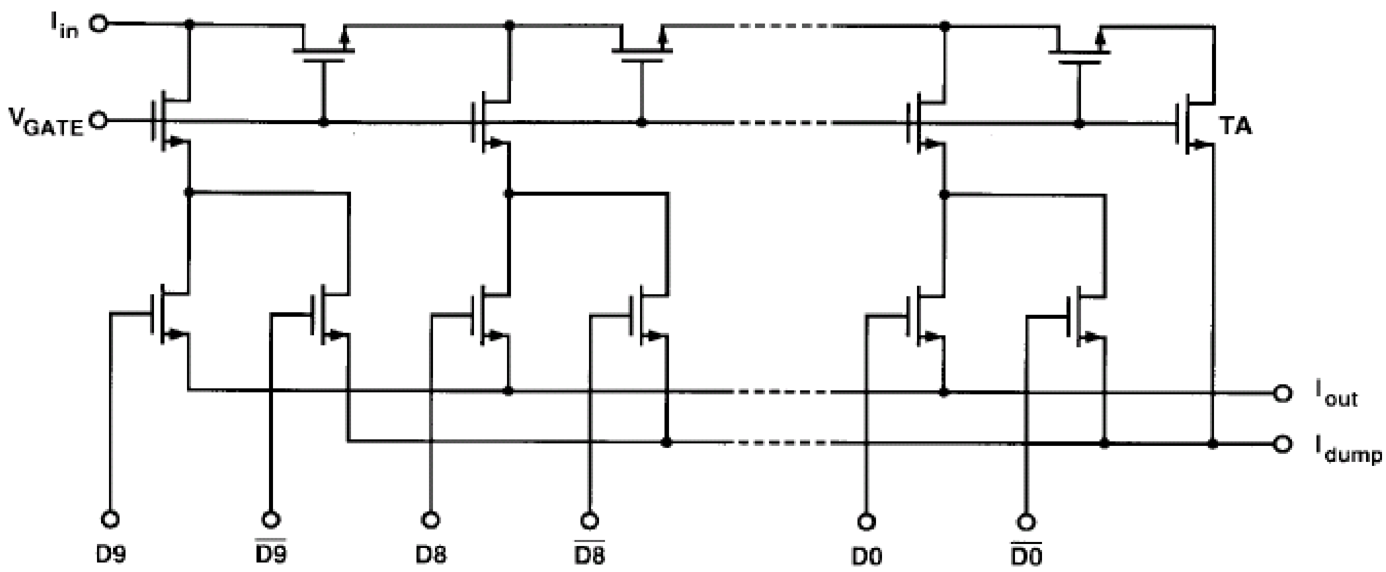


- Circuit shown is completely symmetric on C_3 and is the well-known current divider
- it is not dependent upon any specific properties of the transistors !



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?

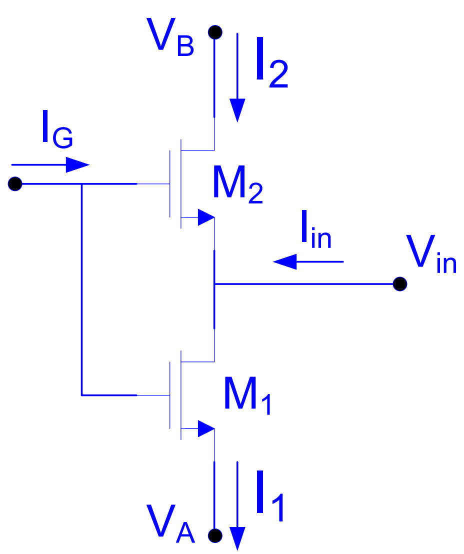
Current divider properties of the Huang DAC (ADC) were all dependent upon the general current division property of symmetric networks and had nothing to do with the current division in two transistors !

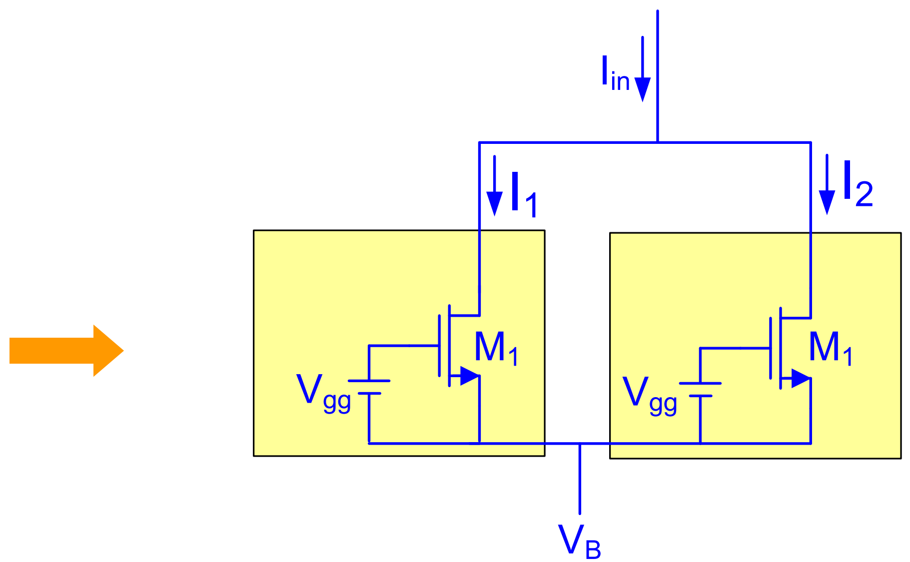


Current divider properties of the experimentally reported work of the original author were all dependent upon the general current division property of symmetric networks and had nothing to do with the current division in two transistors !

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





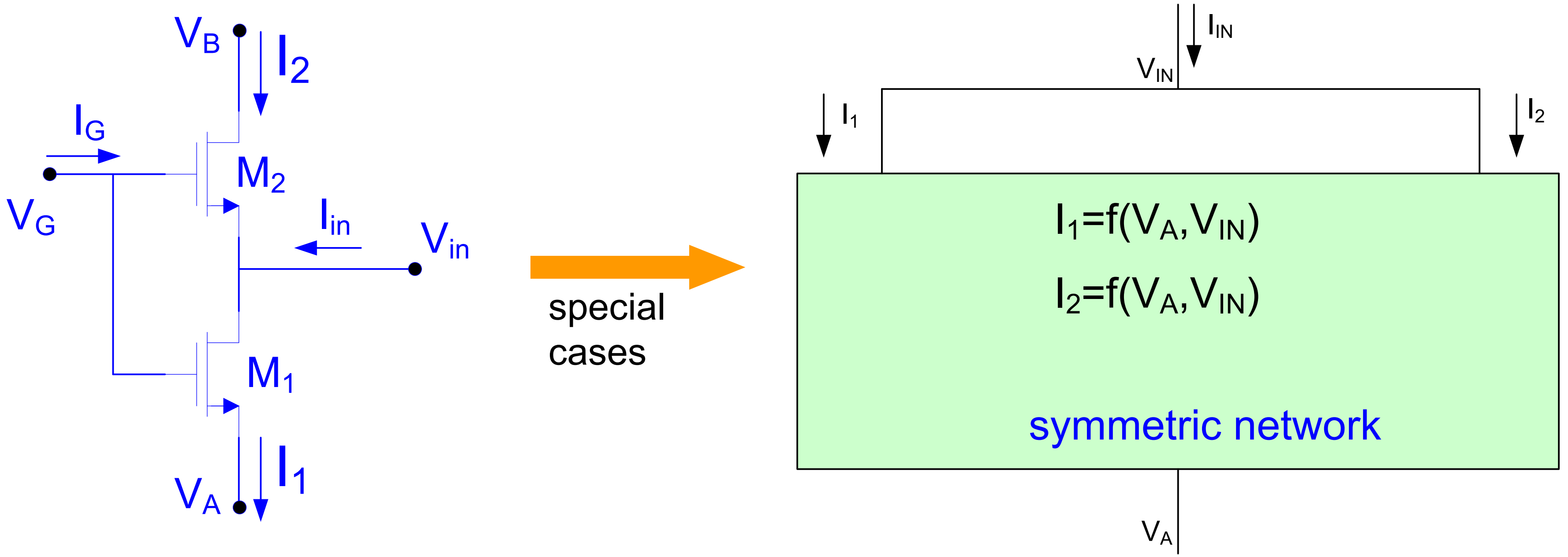
Symmetric Circuit

$I_1=I_2$

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

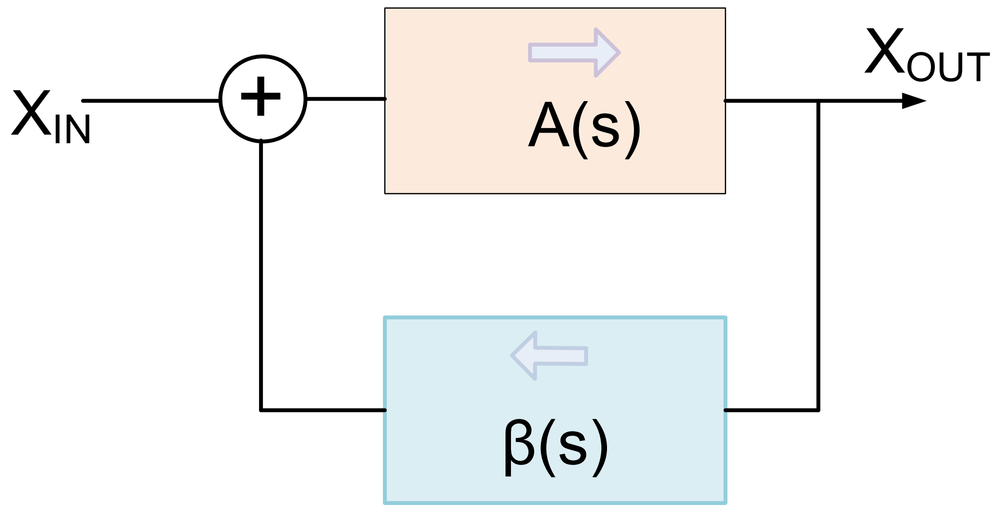
Barkhausen Stability Criterion - MIT

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

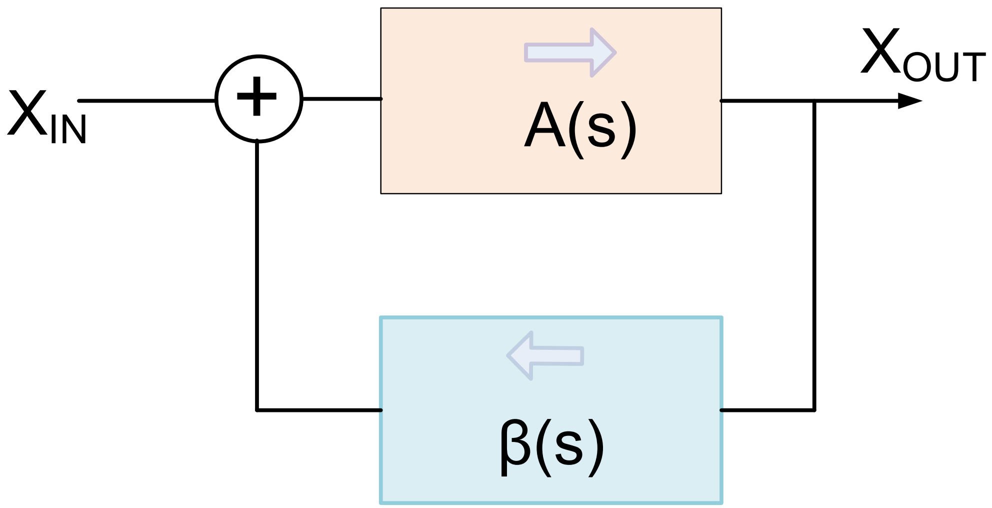
Barkhausen Criterion



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 the loop gain as 1 and the phase shift is 360º .

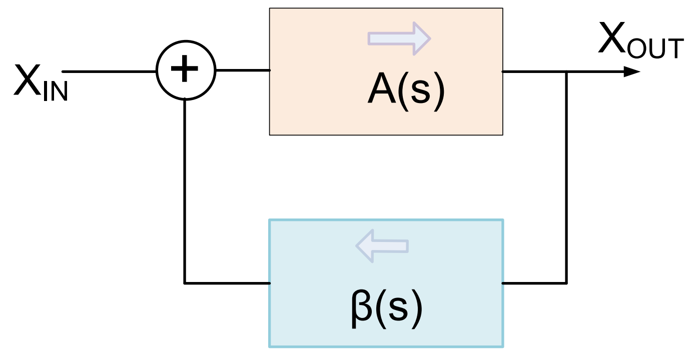
Barkhausen Criterion



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.

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.

Counter example refuting alternate conventional statement:

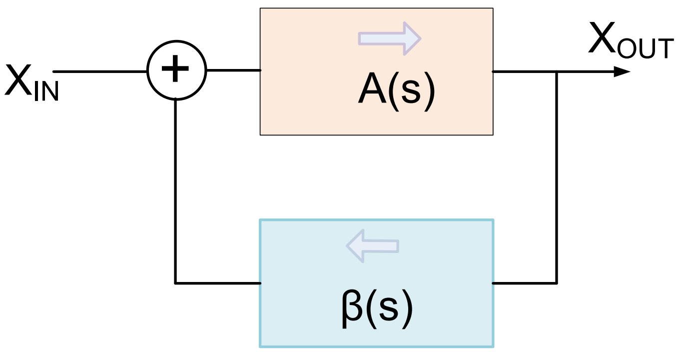
$$A(s) = \frac{10(s+1)^2}{s^3}$$

$$\beta(s) = -1$$

$$T(s) = \frac{10(s+1)^2}{s^3 + 10(s+1)^2} = \frac{10(s+1)^2}{s^3 + 10s^2 + 20s + 10}$$

Poles in LHP thus stable !

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.

Counter example refuting alternate conventional statement:

$$A\beta(j1) = -1 \bullet \frac{10(j+1)^2}{j^3} = \frac{20j}{j} = 20$$

Phase = 360°

$$\left|A\beta(j1)\right| = 20 > 1$$

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 !

End of Lecture 43