EE 508
Lecture 42

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

Part 1

by Randy Geiger
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

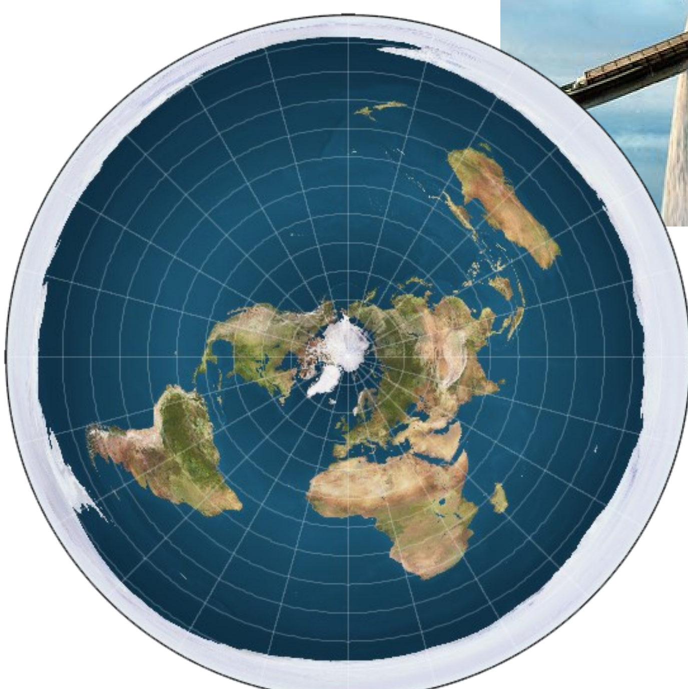
http://greenfunkdan.blogspot.com/2008/11/csiro-warns-of-climate-change-doomsday.html

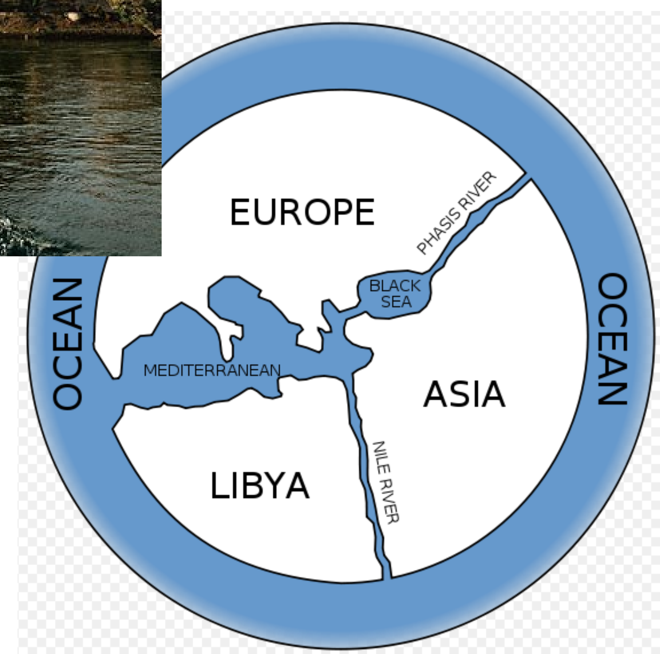
Pythagoras 520BC
Aristotle 300BC

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 ?

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

Records of

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

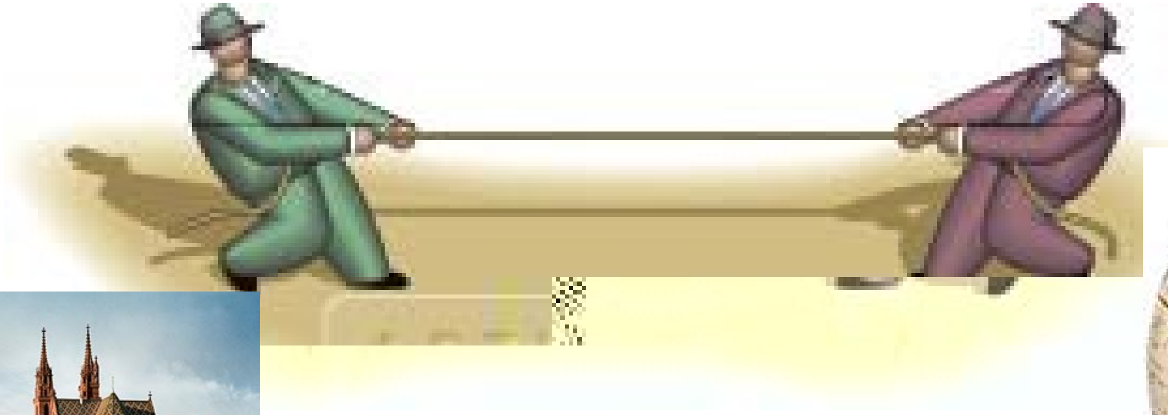
Conventional Wisdom

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?



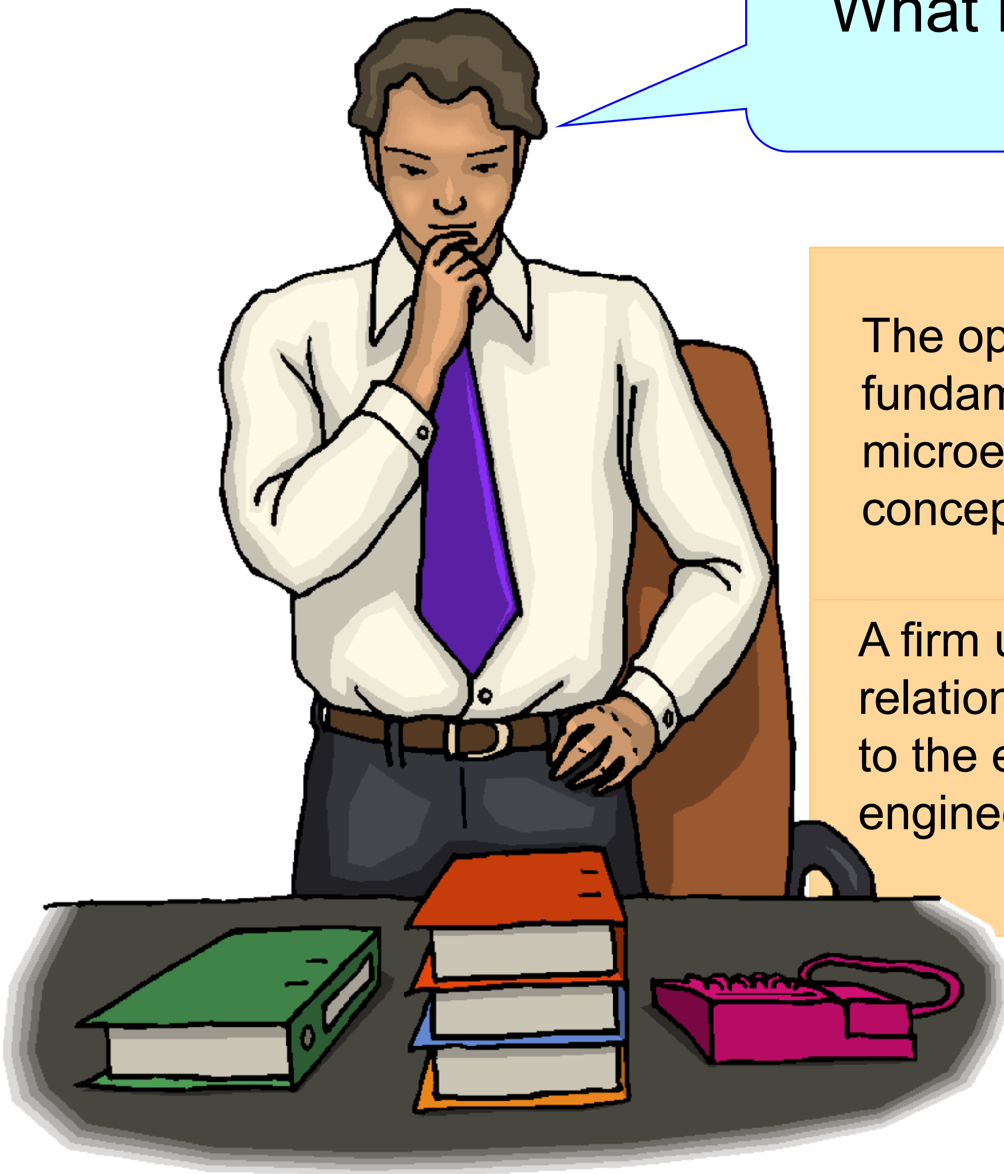
- Confusion Arises
- Progress is Slowed
- Principles are not correctly understood
- Errors Occur
- Time is Wasted

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 !

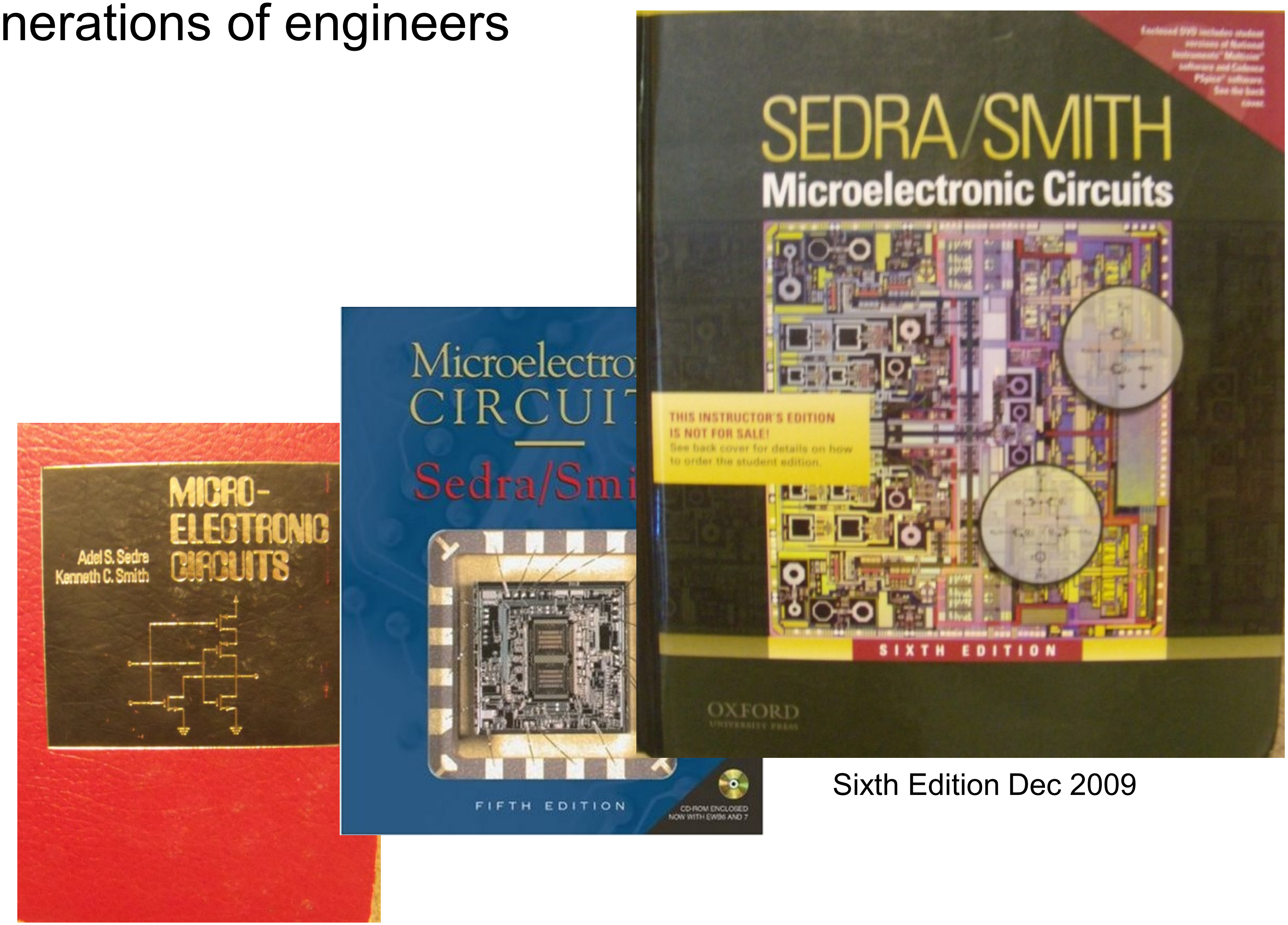
A firm understanding of feedback and its relation to the operational amplifier is central to the education of essentially all electrical engineers around the world today

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



Sixth Edition Dec 2009

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.*

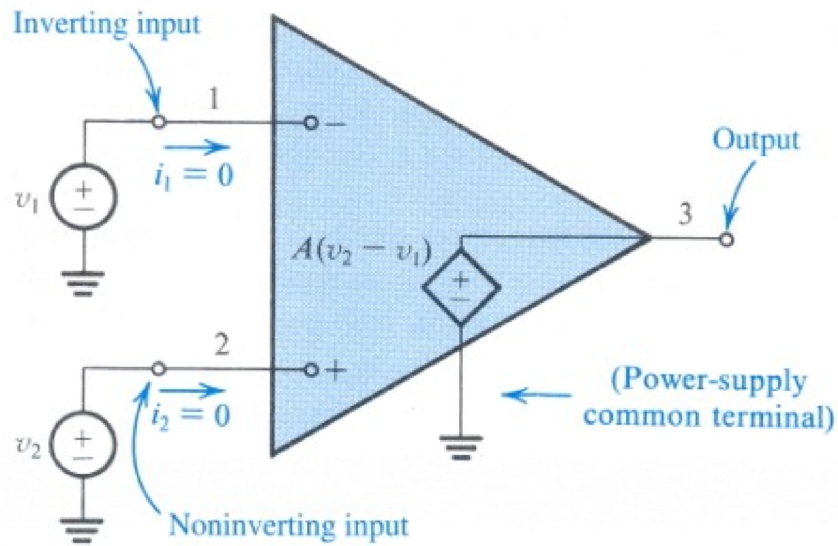
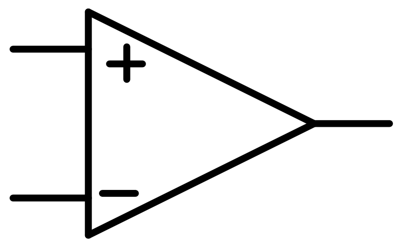


FIGURE 2.3 Equivalent circuit of the ideal op amp.

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:

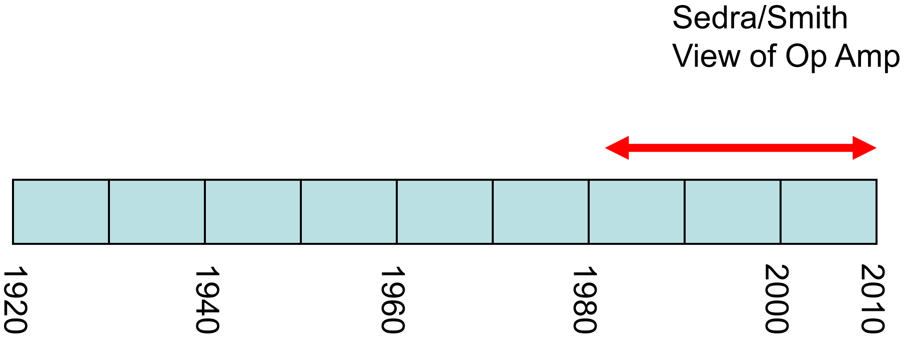
- Voltage Amplifier with Very Large Gain
  - Very High Input Impedance
  - Very Low Output Impedance

- Differential Input and Single-Ended Output

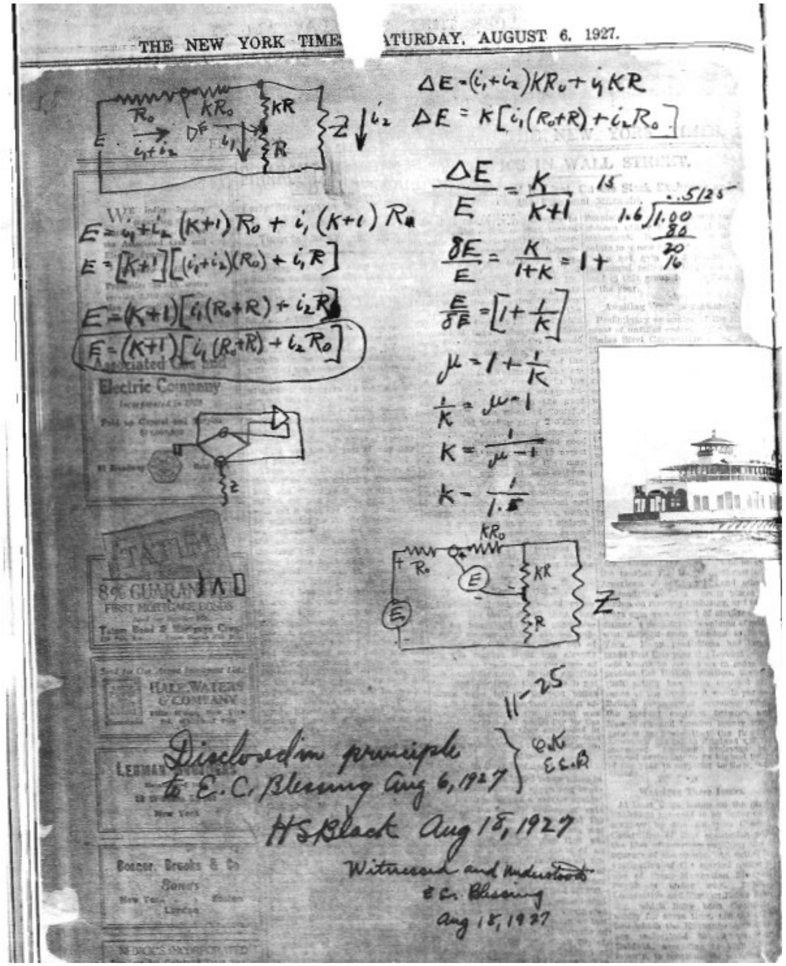
This represents the Conventional Wisdom !

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

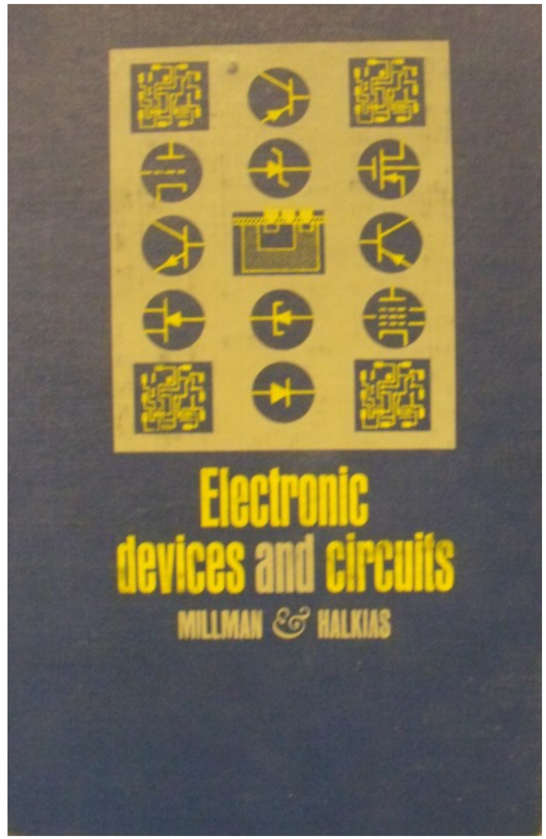


H.S. Black sketch of basic concept of feedback on Aug 6, 1927

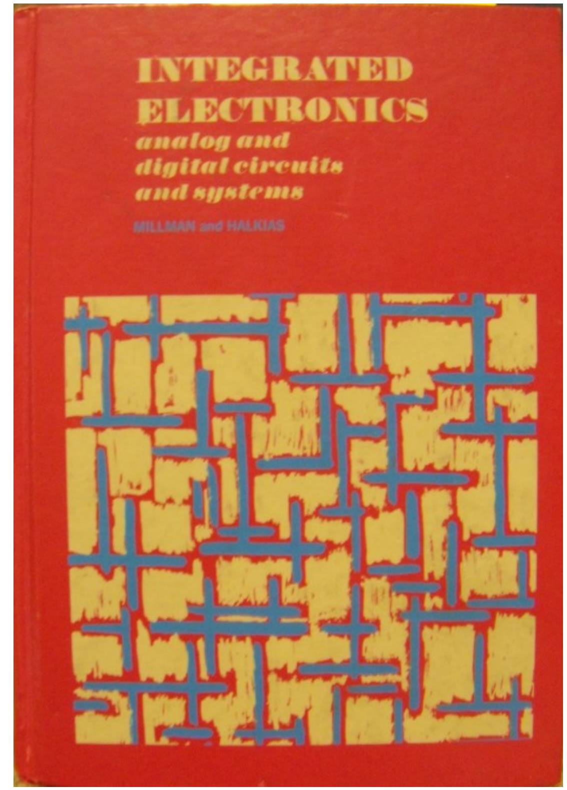
Black did not use the term operational amplifier but rather focused on basic concepts of feedback involving the use of high-gain amplifiers

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

First Edition 1958

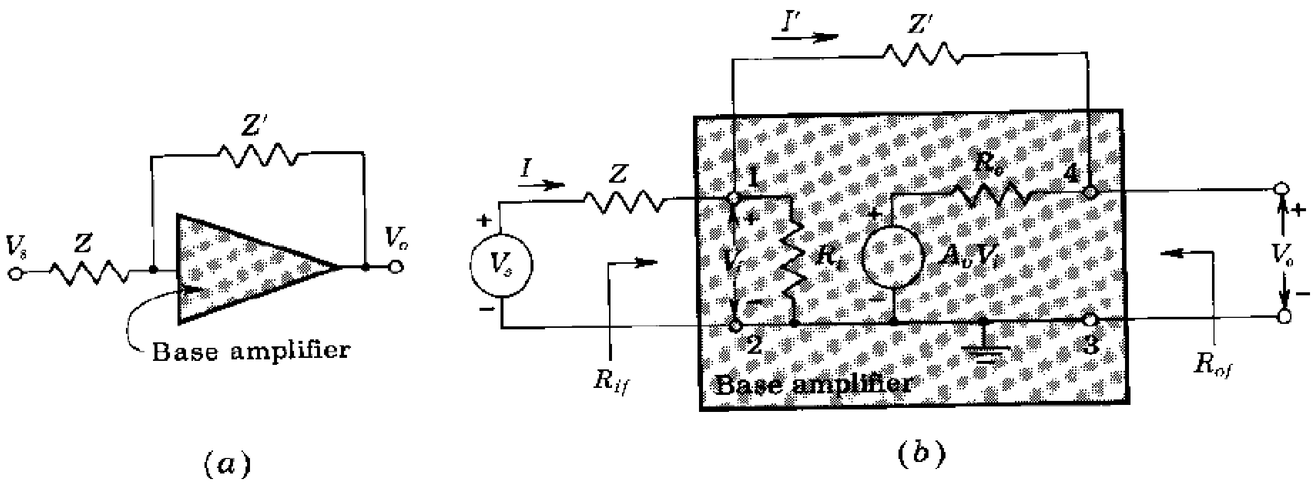


First Edition 1967



First Edition 1972

Millman view of an operational amplifier in 1967



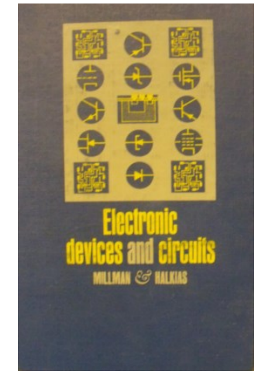


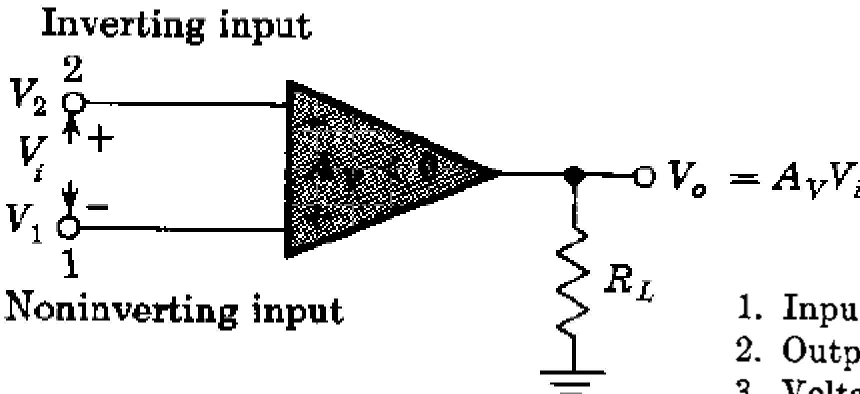
Fig. 17-26 (a) Schematic diagram and (b) equivalent circuit of an operational amplifier. The open-circuit voltage gain A_v is negative.

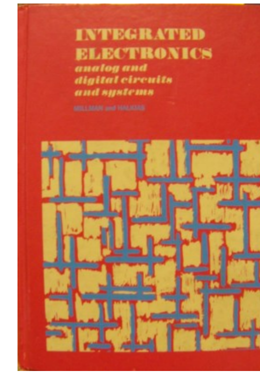
Operational Amplifier refers to the entire feedback circuit

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:

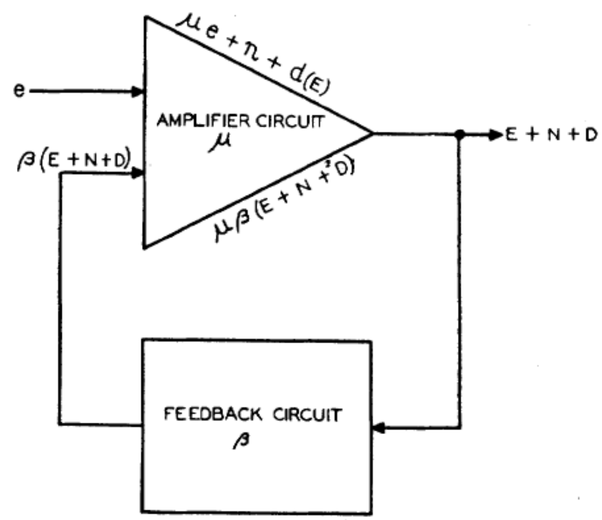
Stabilized Feed-Back Amplifiers

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

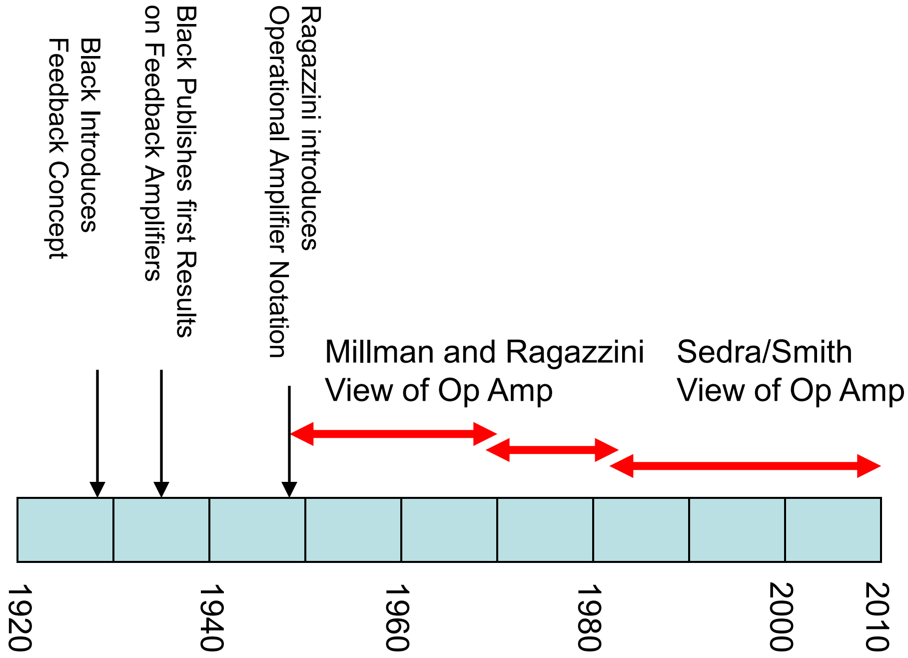
Fig. 1. Amplifier system with feed-back



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

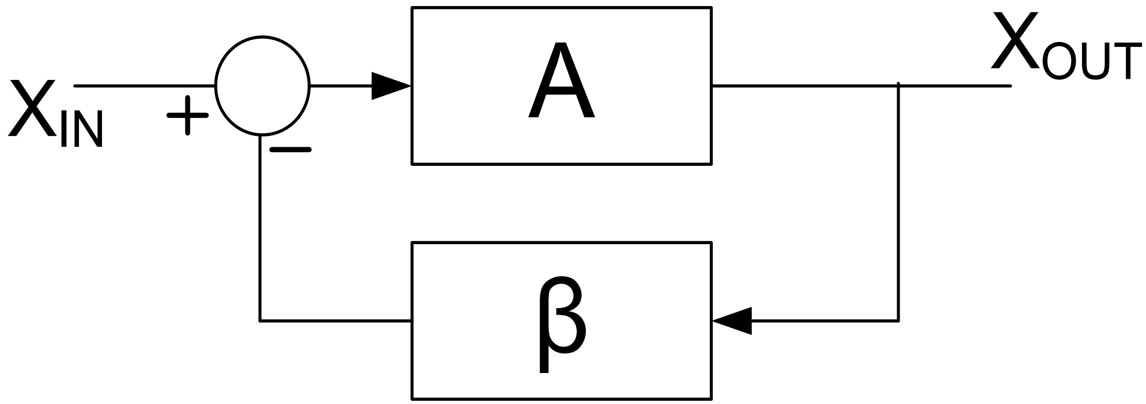
Subsequent examples of feedback by Black relaxed the differential input requirement

Operational Amplifier Evolution in Time Perspective



Do we have it right now?

Why are Operational Amplifiers Used?

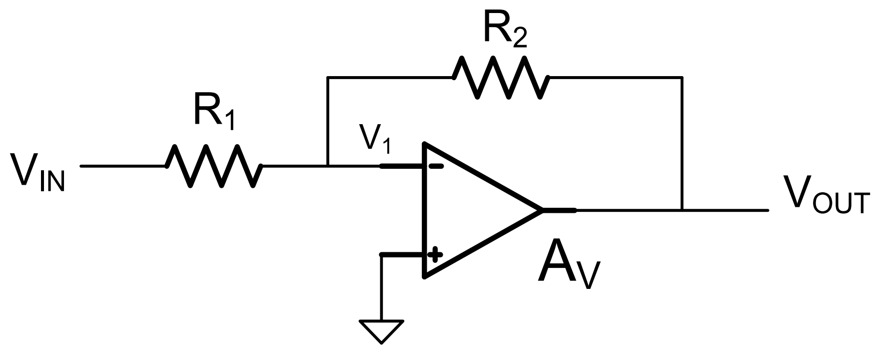


Input and Output Variables intentionally designated as "X" instead of "V"

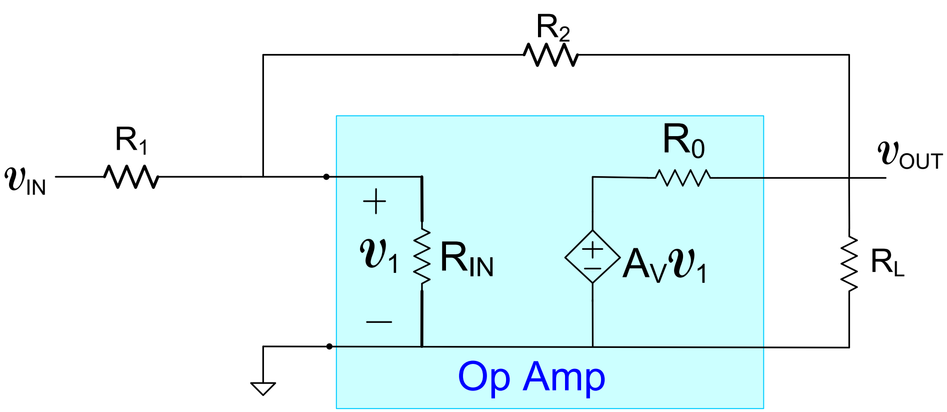
$$\frac{Xout}{Xin} = A_F = \frac{A}{1+A\beta} = \overset{A\to\infty}{\approx} \frac{1}{\beta}$$

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

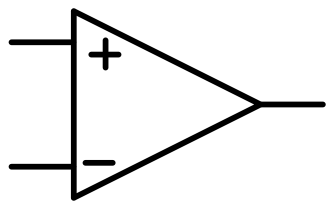


If it is assumed that A_V is large,

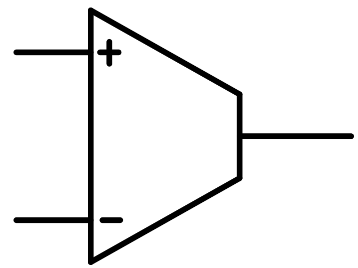
$$A_{VF} = \frac{v_{OUT}}{v_{IN}} \simeq -\frac{R_2}{R_1}$$

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

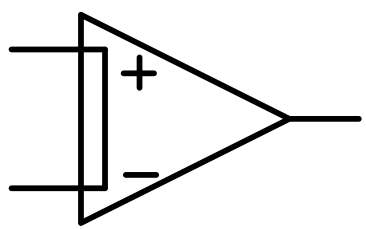
The Four Basic Types of Amplifiers:



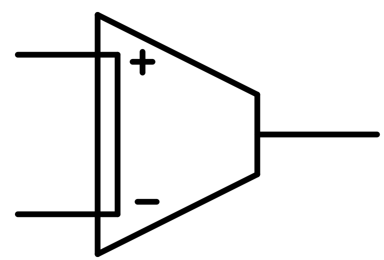
Voltage



Transconductance

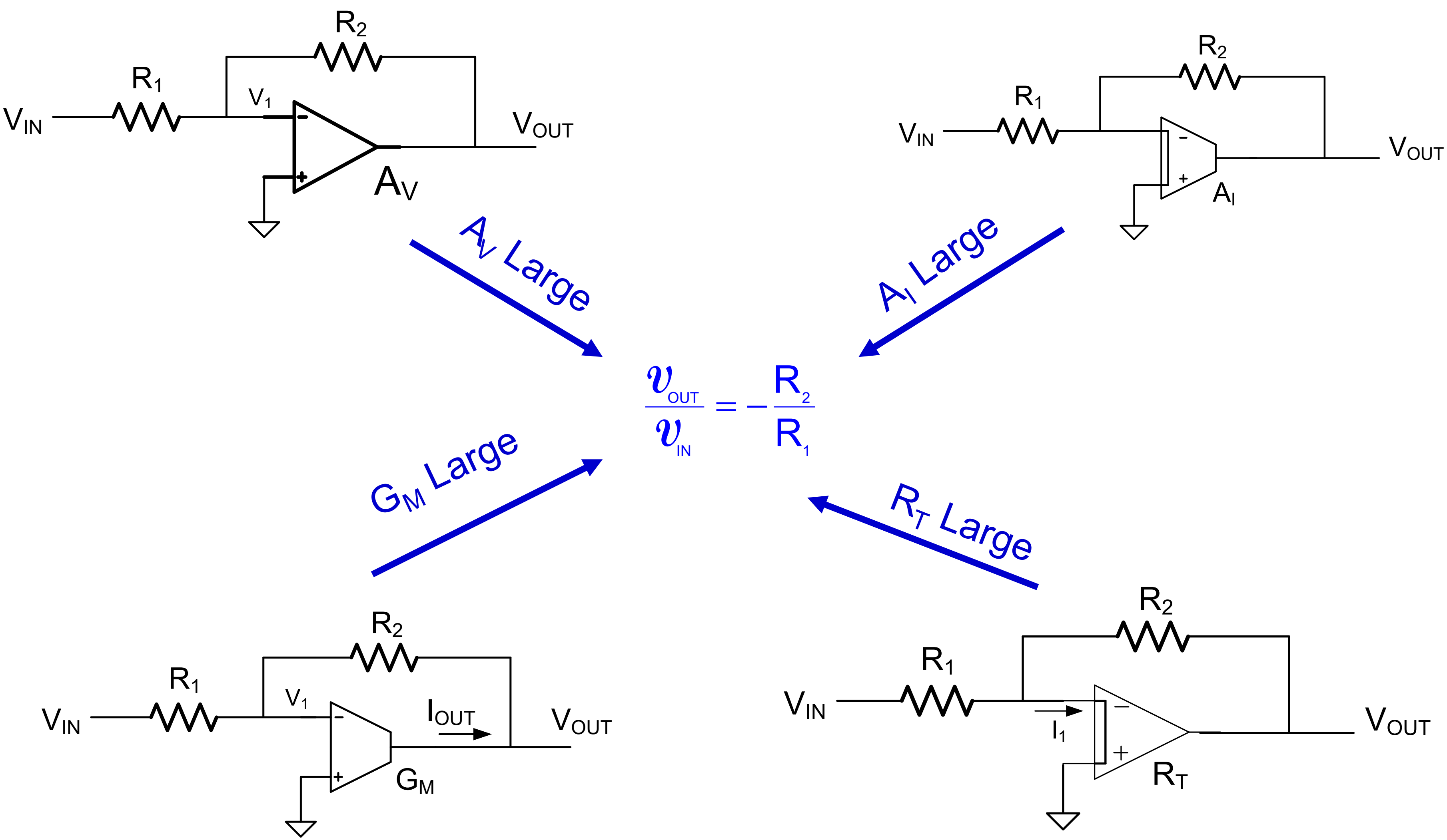


Transresistance



Current

Four Feedback Circuits with Same β Network



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

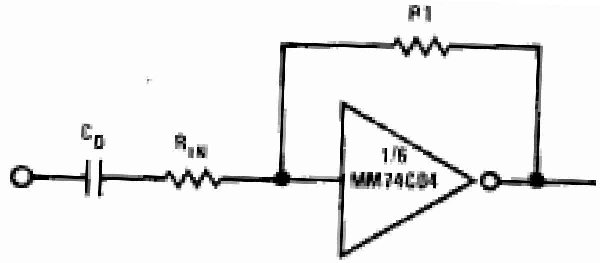
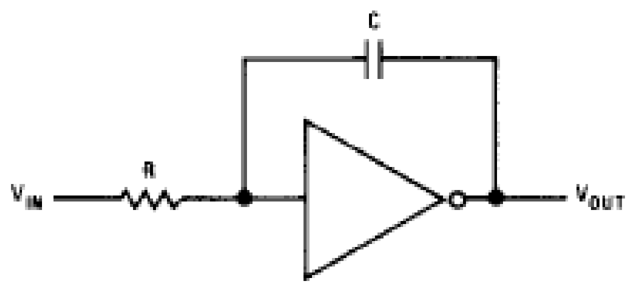


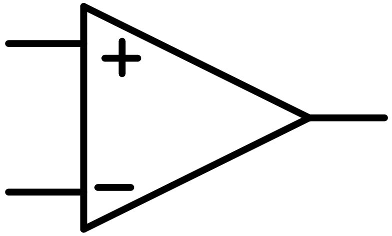
FIGURE 2. A 74CMOS Invertor Biased for Linear Mode Operation.



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?~~

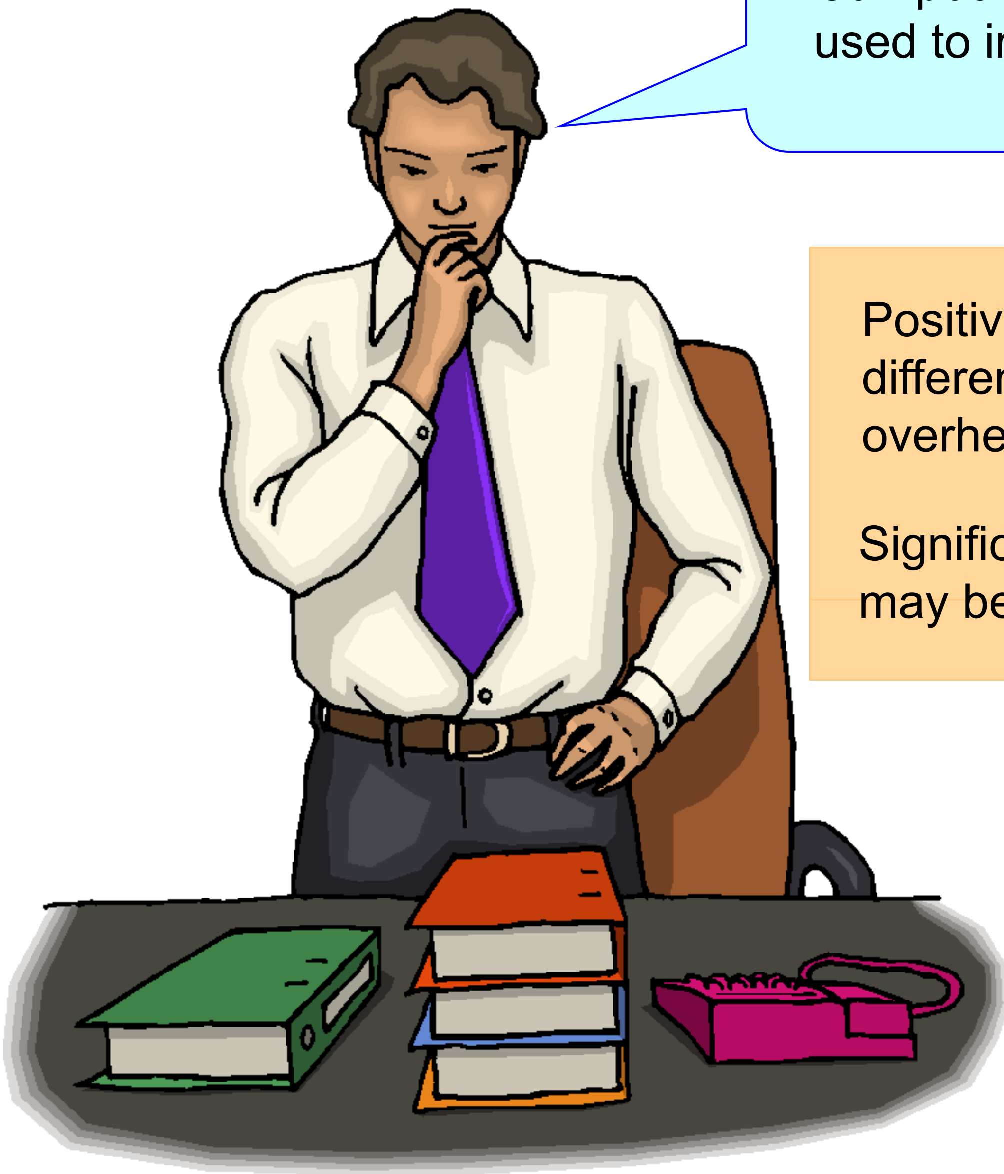
~~Differential Input?~~

Large Gain !!!

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

Will consider 5 basic examples in this discussion

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



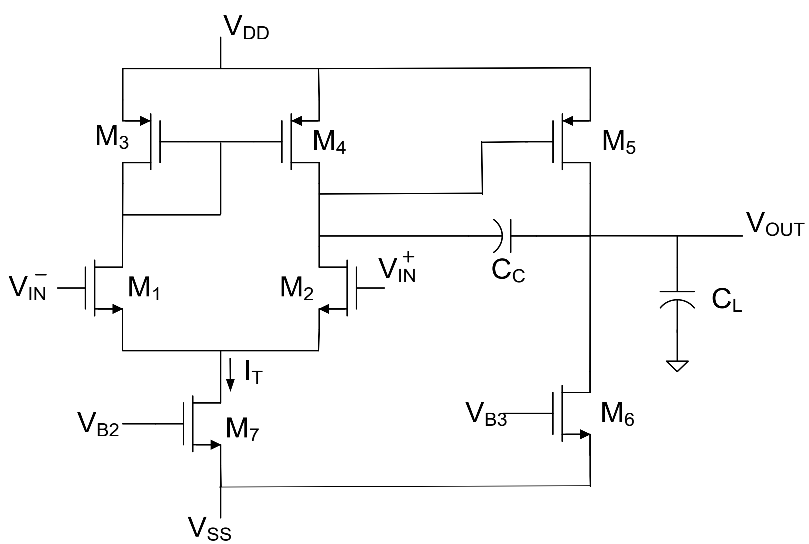
Can positive feedback compensation be used to improve amplifier performance

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



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

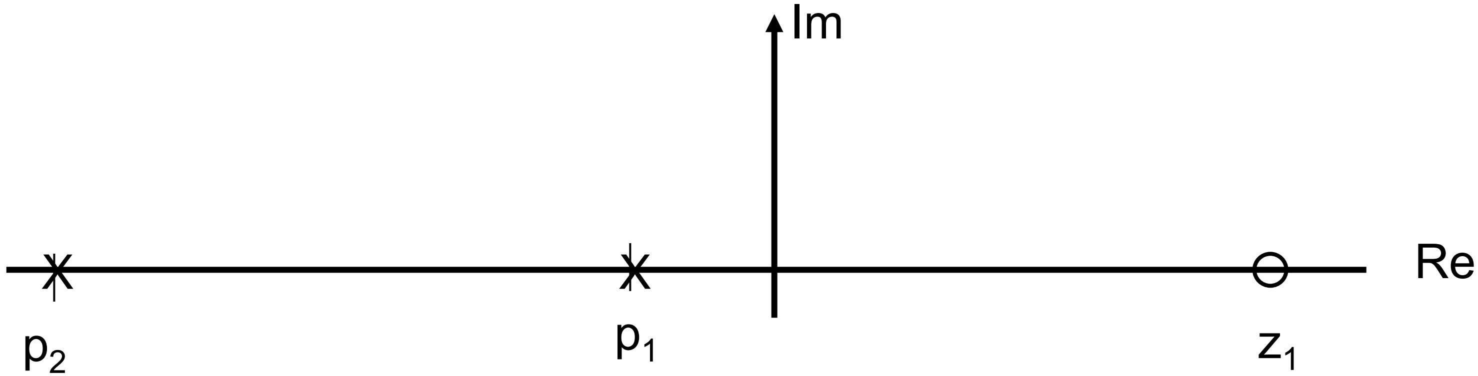
Miller Effect on C_C provides dominant pole on first stage

Compensation requires a large ratio of p_2/p_1 be established

Two-stage amplifier with LHP Zero Compensation

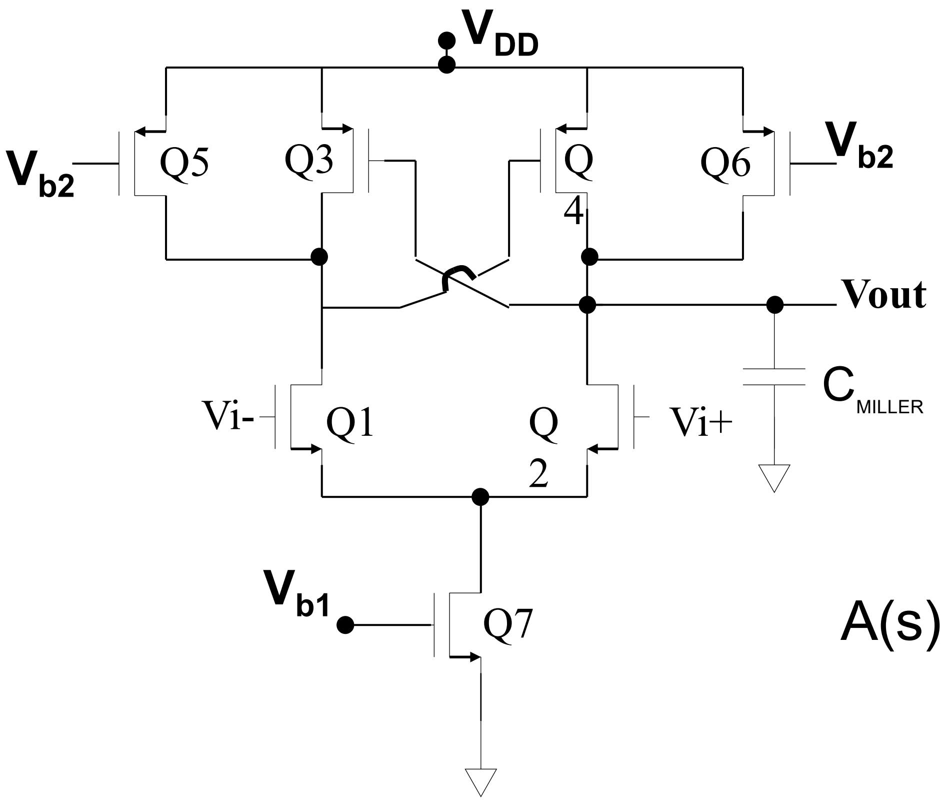
$$p_1 = -\frac{g_{o1} + g_{o5}}{C_C\left(\dfrac{g_{m5}}{g_{05} + g_{o6}}\right)}$$

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



To make p_1 sufficiently dominant requires a large value for C_C

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



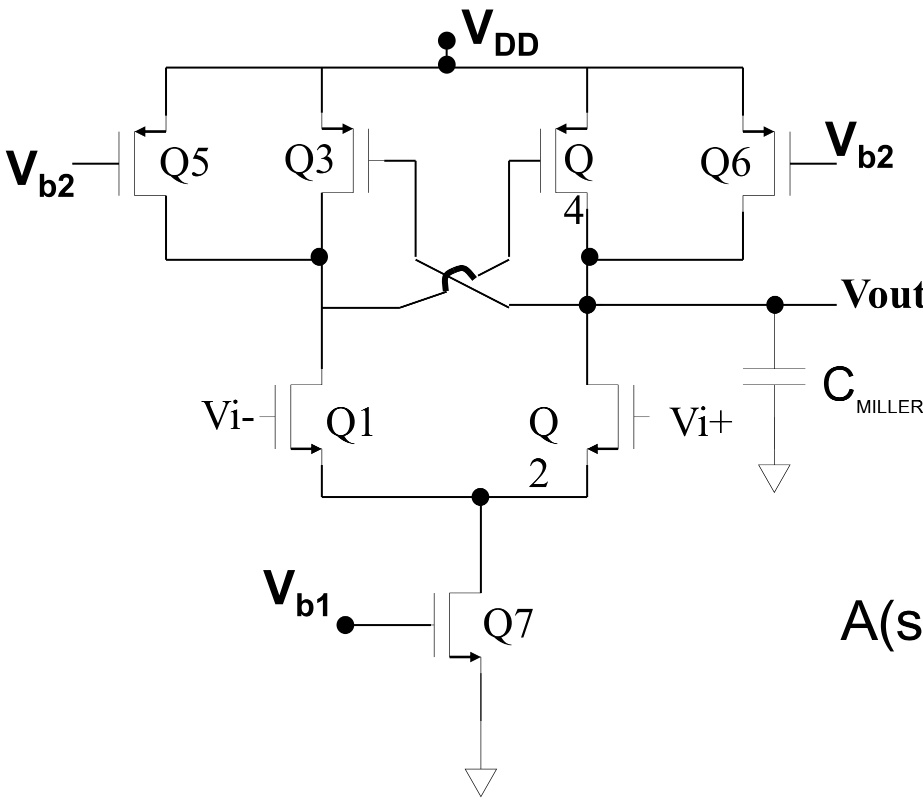
$$A(s)=\frac{(1/2)g_{m1}}{sC_{MILLER}+[g_{o2}+g_{o4}+g_{o6}-g_{m4}]}$$

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

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!

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

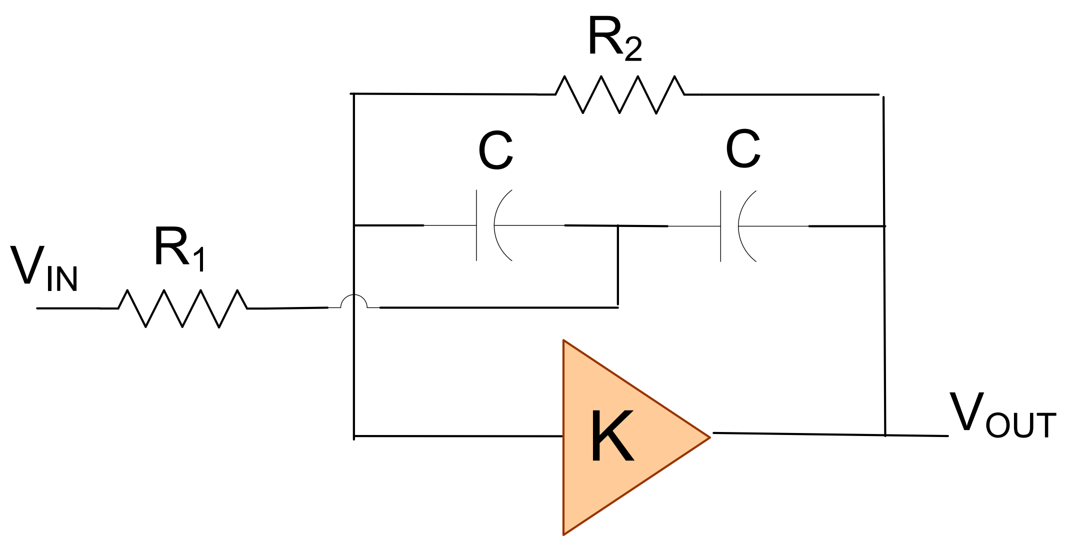
Several authors have discussed this approach in the literature but place a major emphasis on limiting the amount of positive feedback used so that under PVT variations, op amp remains stable

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

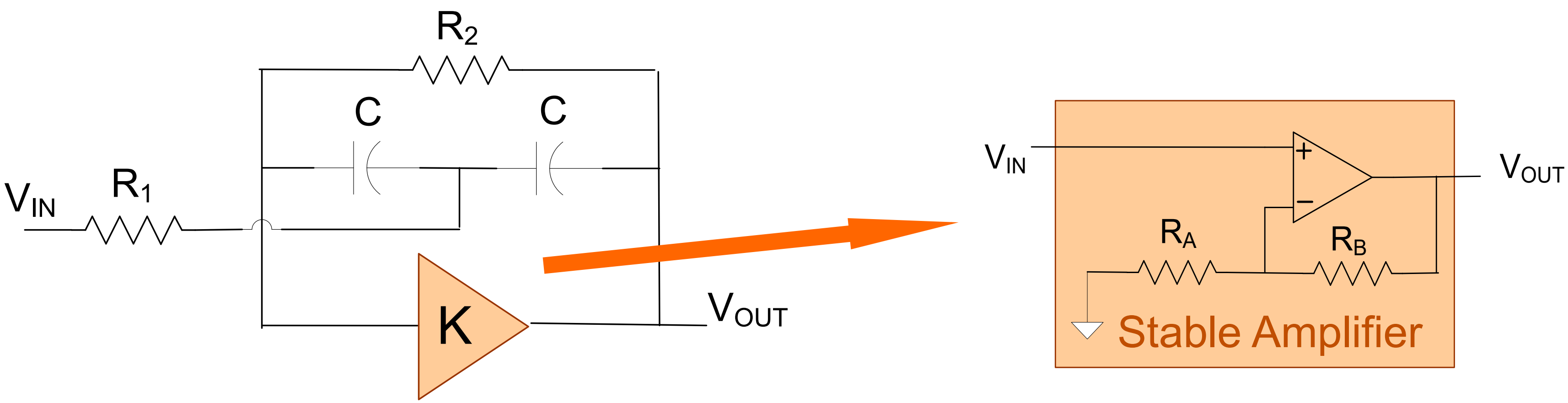
Bridged-T Feedback
(Termed SAB, STAR, Friend/Delyannis Biquad)

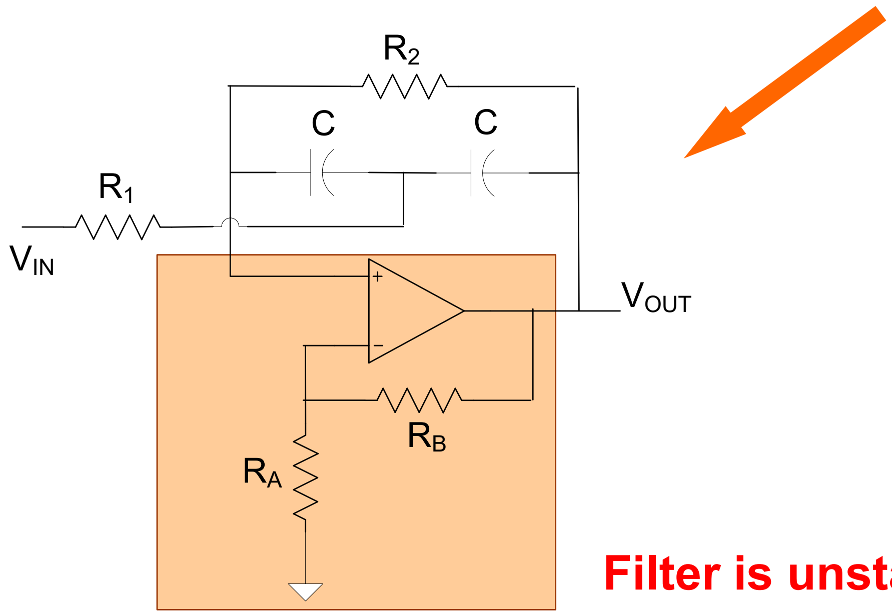


K is a small positive gain
want high input impedance on “K” amplifier

- 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

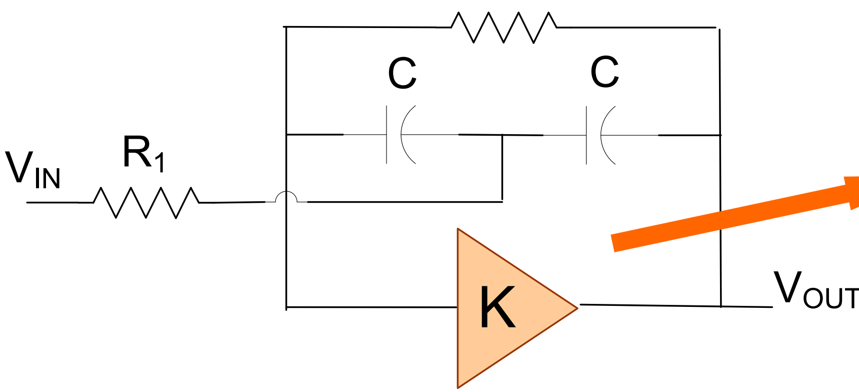


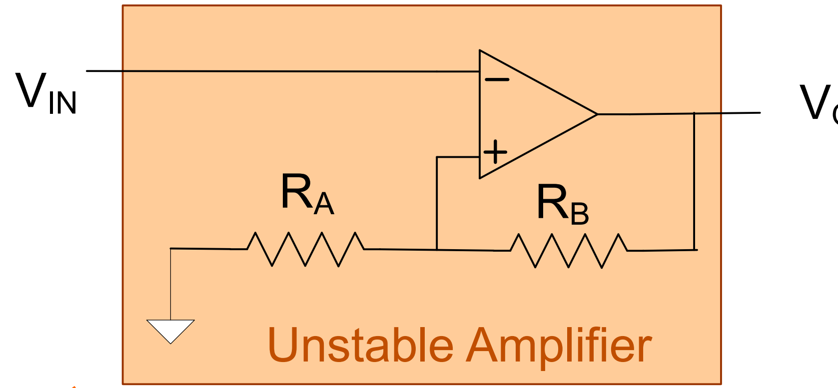


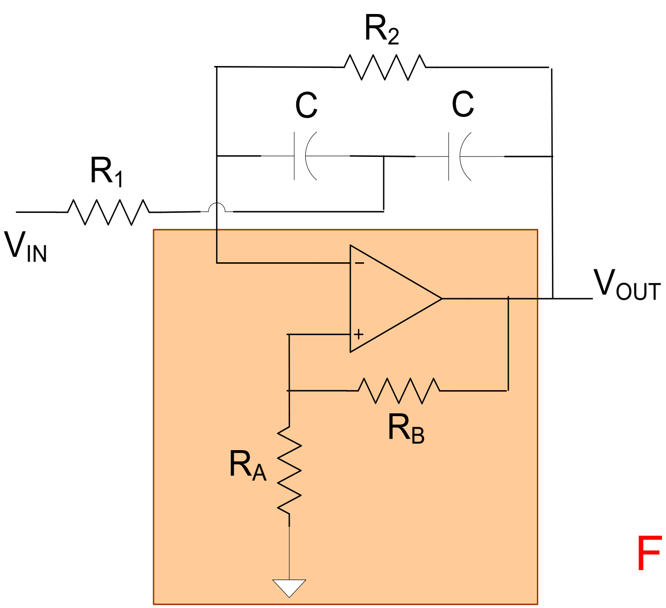
Filter is unstable !

Example: Filter Structure with Feedback Amplifier

Bridged-T Biquad
(with feed-forward)

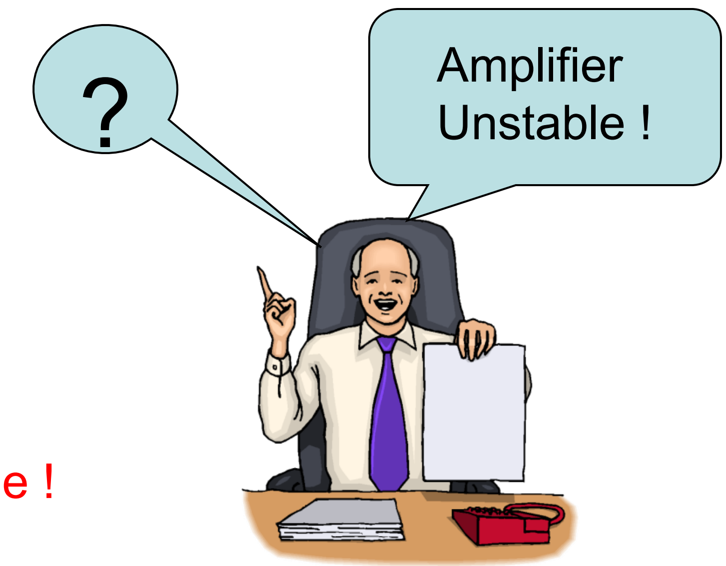






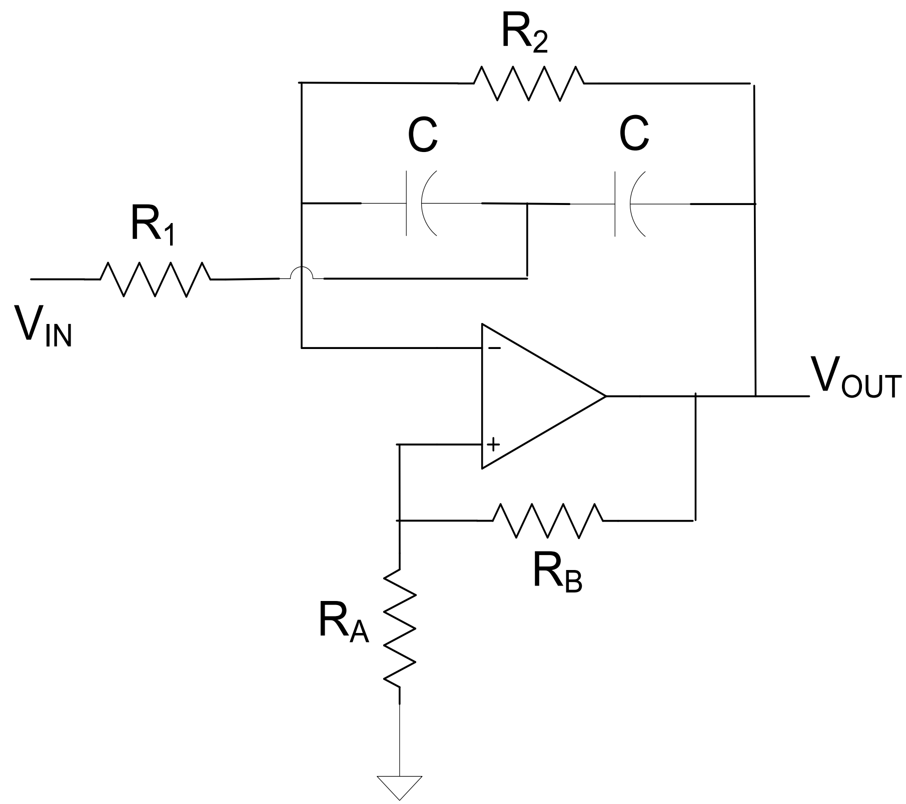
Friend/Deliyannis Biquad

Filter is stable !



Very Popular Bandpass Filter

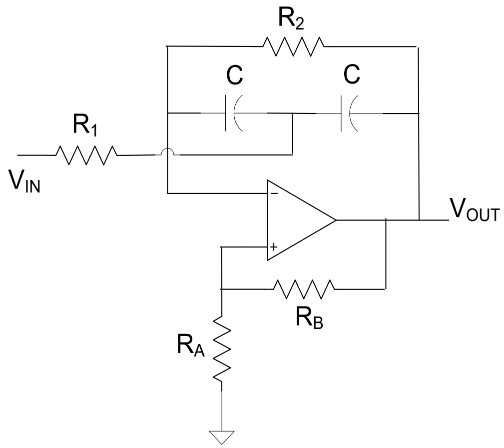
Friend-Deliyannis Biquad



One of the best bandpass filters !!

Embedded finite gain amplifier is unstable!!

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

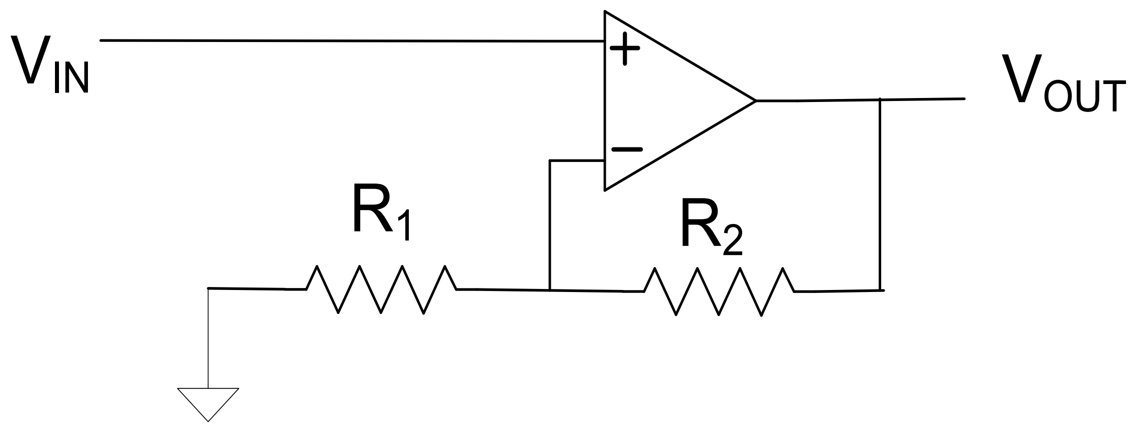


- Filter structure unstable with stable finite gain amplifier
- Filter structure stable with unstable finite gain amplifier
- Stability of feedback network not determined by stability of amplifier!

Is an unstable op amp really bad?

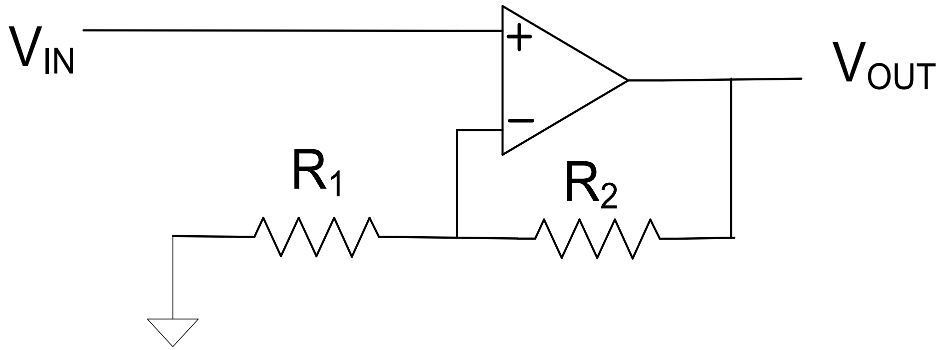
Will a circuit that embeds an op amp be unstable if the op amp is unstable? Not necessarily !

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

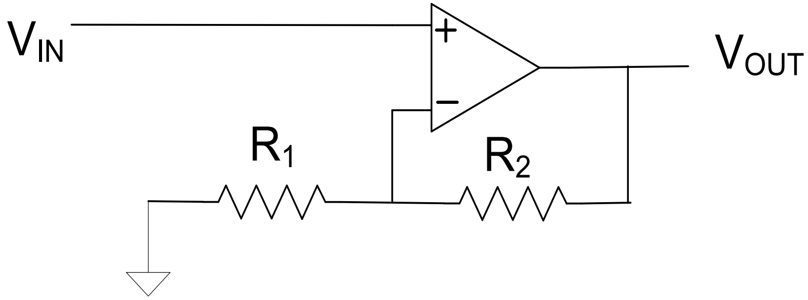


$$\beta = \frac{R_1}{R_2 + R_1}$$

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

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

Example: Voltage Amplifier with Unstable Op Amp

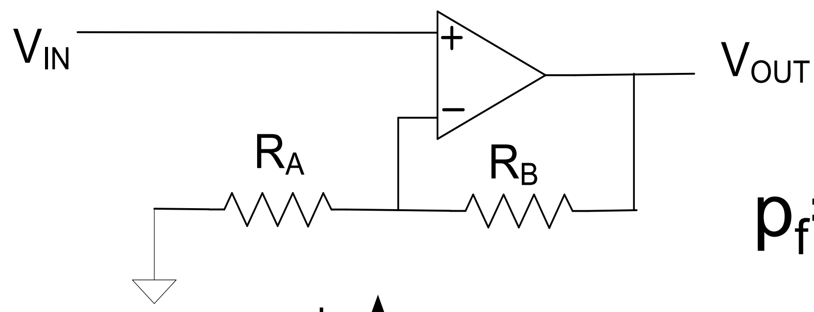


$$A_{FB}(s) = \frac{A(s)}{1+\beta A(s)} = \frac{A_o p}{s+p\left(\beta A_o - 1\right)} \qquad p > 0$$

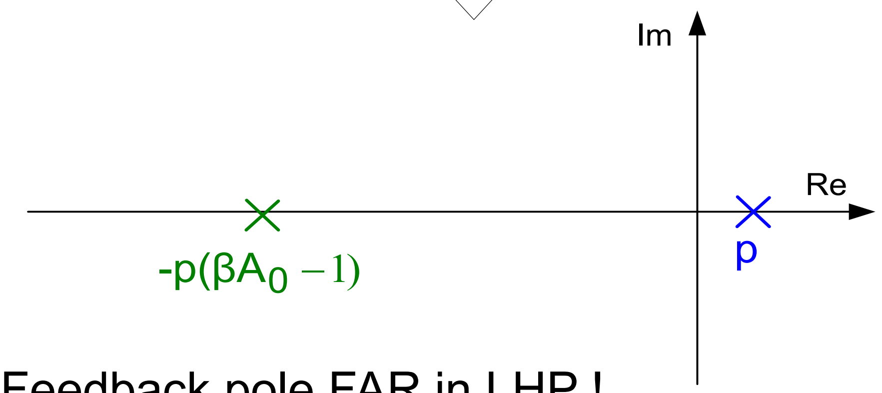
$$p_f = p(1-\beta A_0)$$

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

Example: Voltage Amplifier with Unstable Op Amp



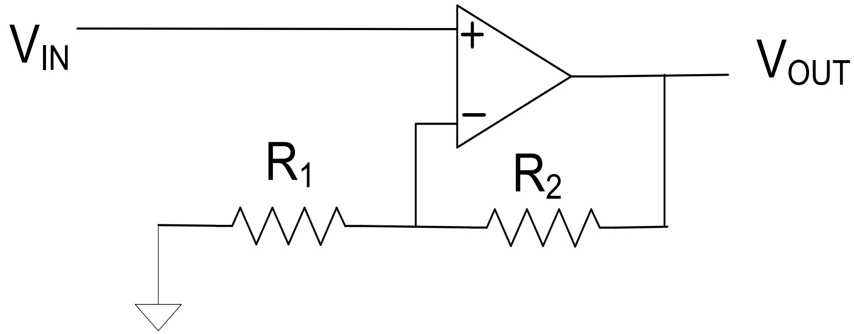
$$p_f=p(1-\beta A_0)$$



Feedback pole FAR in LHP !

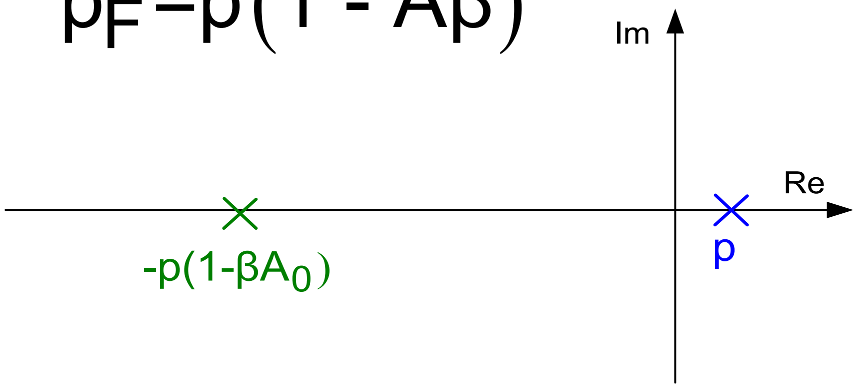
How does this compare to the feedback pole of a stable op amp with a pole
In the LHP at –p?

Example: Voltage Amplifier with Unstable Op Amp



$p > 0$

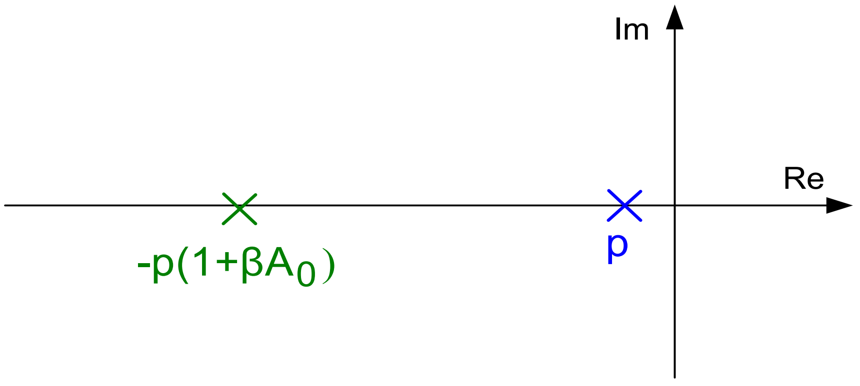
$$p_F = p(1 - A\beta)$$



Feedback pole FAR in LHP !

$p < 0$

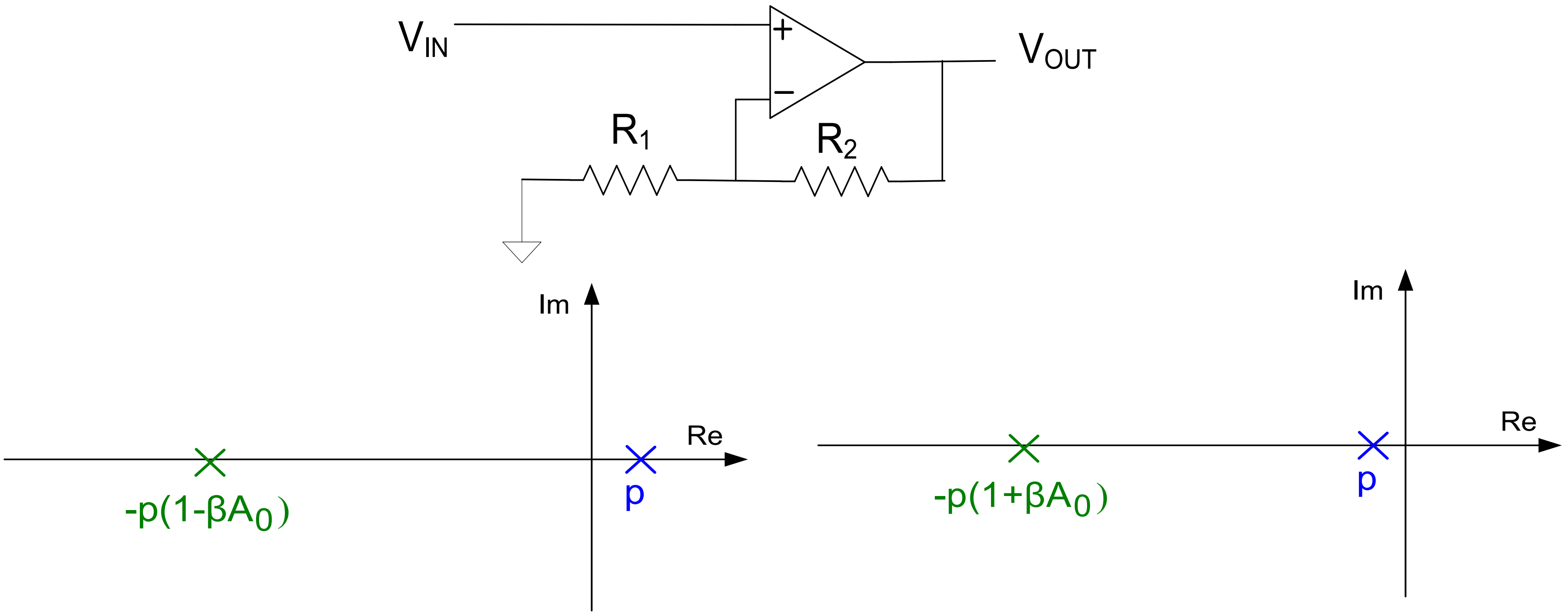
$$p_F = p(1 + A\beta)$$



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 Lecture 31 and 32

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?

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?

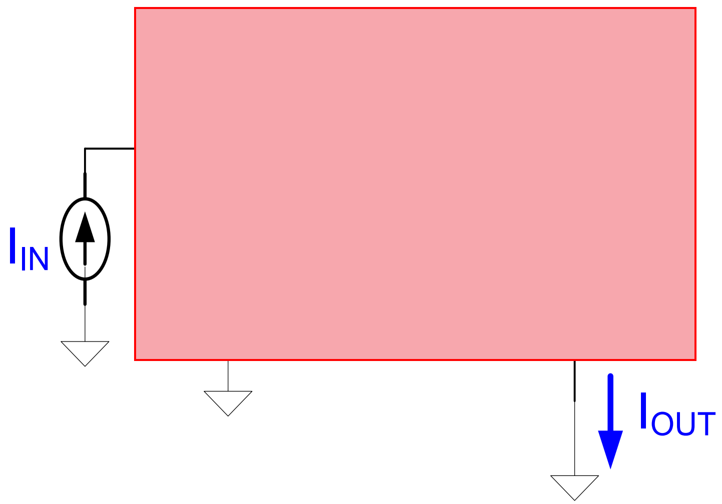
Questions about the Conventional Wisdom

Conventional Wisdom Definition:

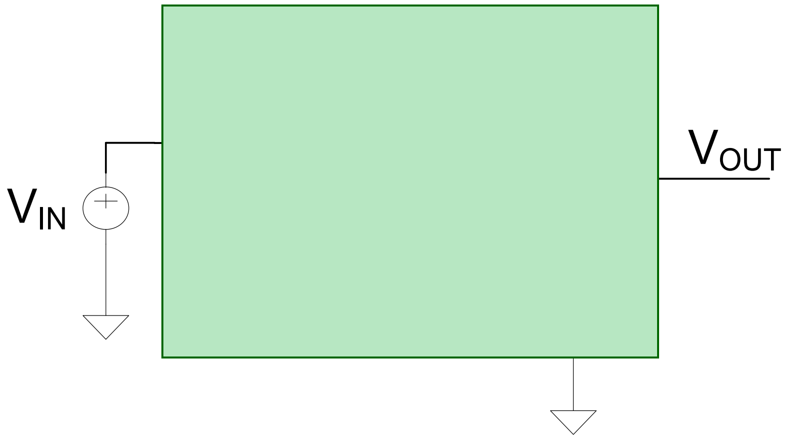
- A current-mode circuit is a circuit that processes current signals
- A current-mode circuit is one in which the defined state variables are currents

Example:

Is this a current-mode circuit?



Is this a voltage-mode circuit?

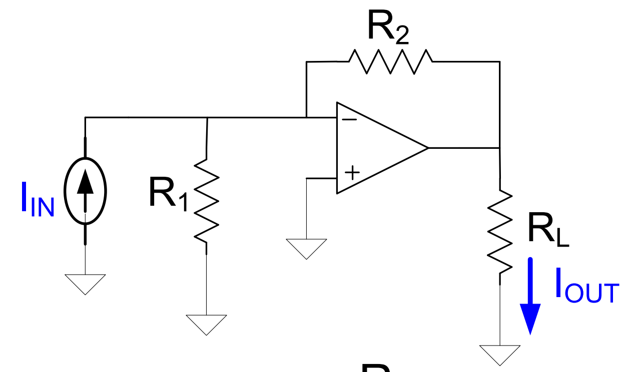


Conventional Wisdom Definition:

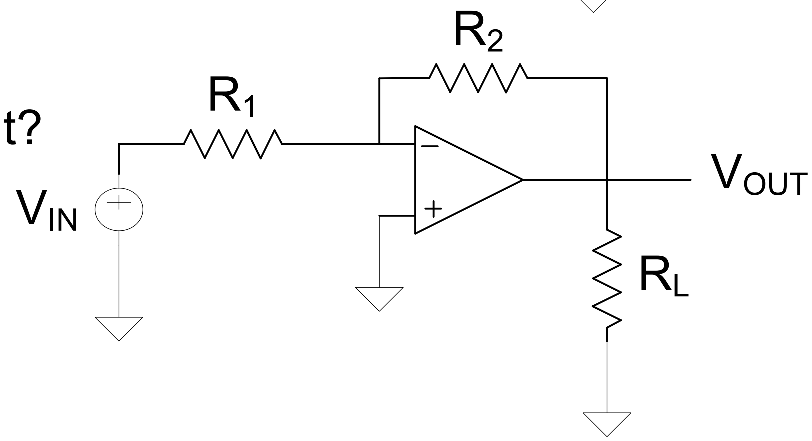
A current-mode circuit is a circuit that processes current signals

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

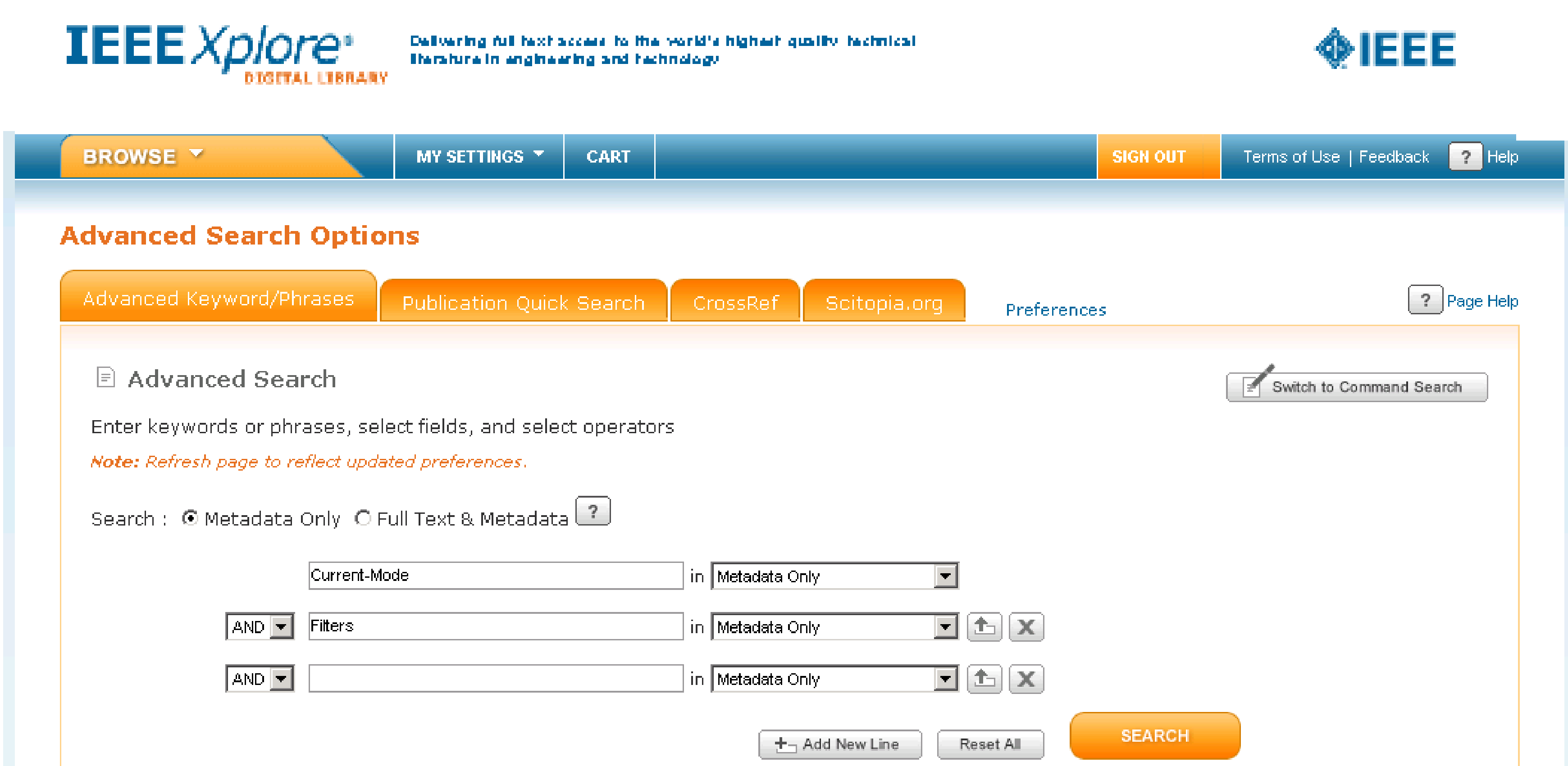
Concept of Current-Mode Filters is Somewhat Recent:

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... - Circuits and Systems, 1989 ..., 2002 - ieeexplore.ieee.org
NTRODUCTION The enormous complexity available in state-of-the-art CMOS processing has made possible the integration of complete systems, including both digital and analog signal processing functions, within the same chip Through the last decade, the **switched** capacitor technique **...**
Cited by 151 - Related articles

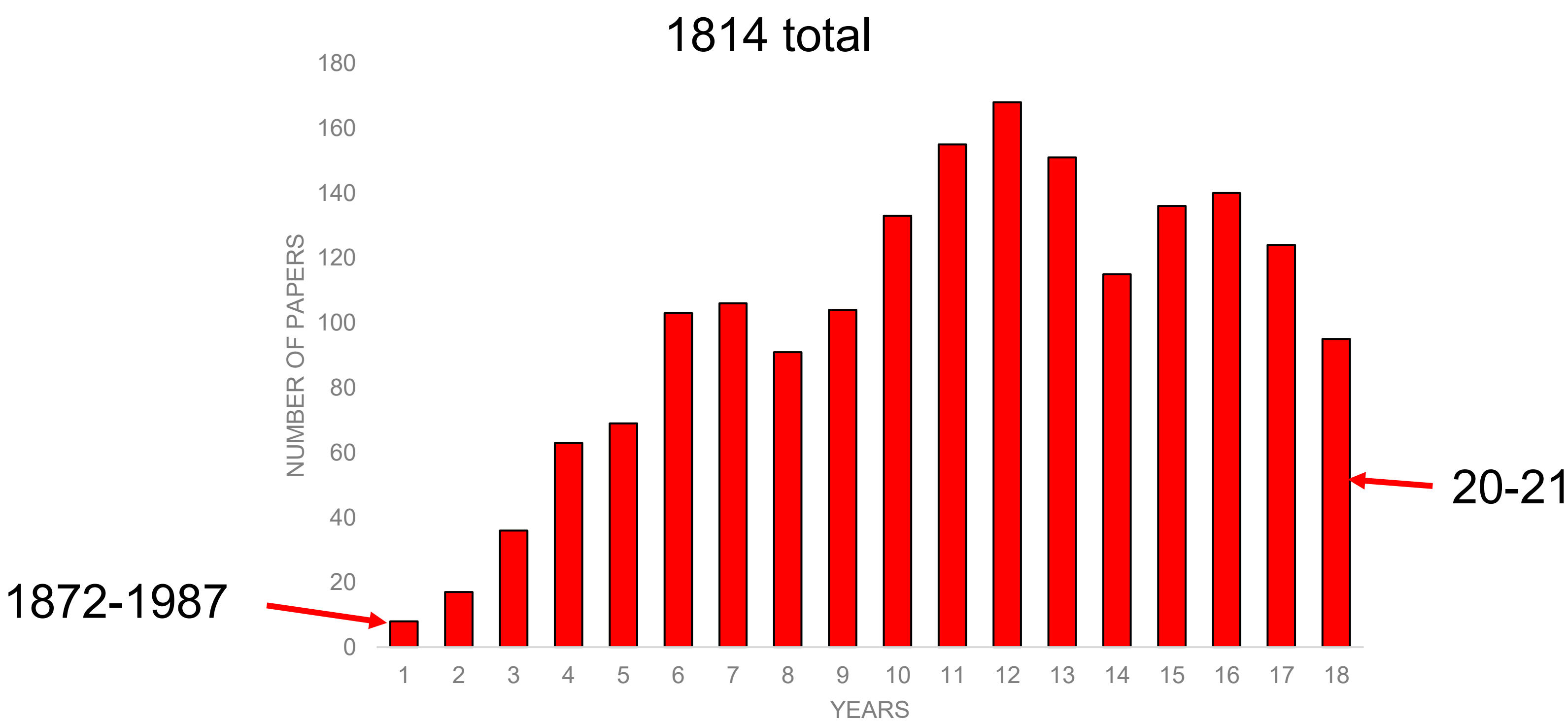
This paper is one of the most significant contributions that has ever come from ISCAS

Current-Mode Filters



Current-Mode Filters

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

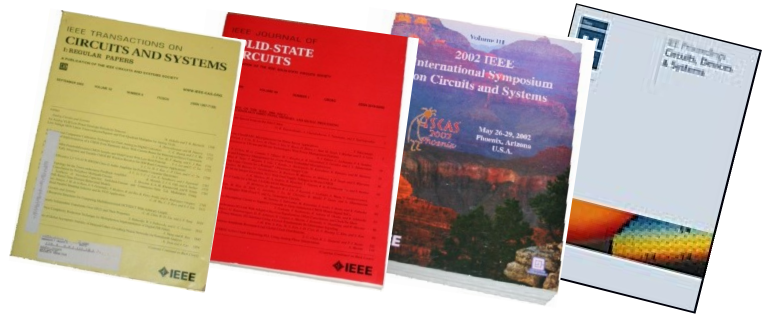


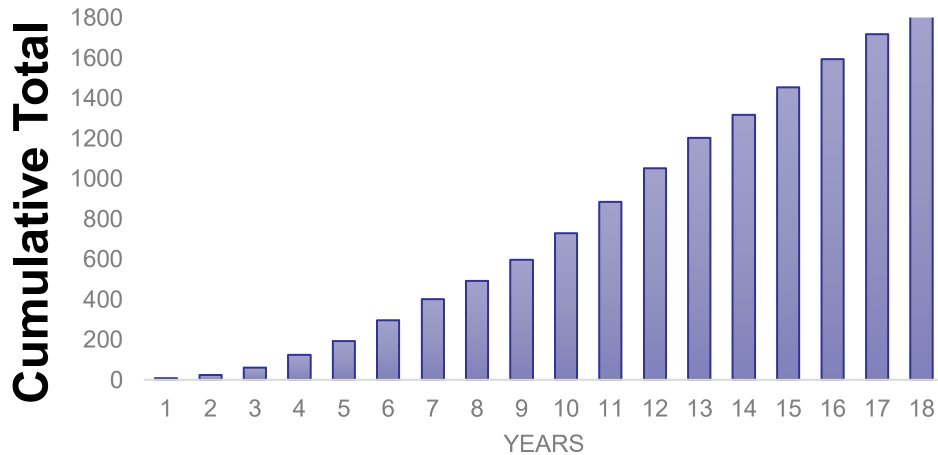
Histogram for 2-year intervals
Most recent is 2020-2021

Search done on Oct 28, 2022

1872-1987 – total of 8 references

Current-Mode Filters





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)

Thank you
for your attention !

End of Lecture 42