The Current-Mode Story

How current-mode was created, how it changed, and how it is disappearing again.

Hanspeter Schmid

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IEEE CAS Distinguished Lecturer Program — Talk 1
Columbia University, New York, November 18, 2011.

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An altered state of mind . . .

Comment on Hanspeter’s 2003 Current-Mode paper [Schmid 03]:

Aghhh. . . I’ve read it. Are some herbs already legalized in Switzerland?

[Adam Jankiewicz, July 2009, diyaudio.com]

?

Found through the log file of my web server

– You may think the same after this talk

– In the future, you'll say "is this real or just a bad case of Swiss herbs?"

$\longrightarrow$ Inside jokes

– How long does it takes to explain this to someone else?

– Ludwik Fleck: Thinking Style $=$ altered state of mind!

$\longrightarrow$ Doing science works exactly like this.

$\longrightarrow$ Scientific facts are almost precisely the same as inside jokes.

$\longrightarrow$ Some of these jokes have got lame with time. [3/3]

Why current-mode *must* be good

Taken from the first six papers on **IEEE**Xplore on "current-mode filters" (December 2010):

- higher bandwidth
- simpler architecture
- better dynamic range
- operates at lower voltage
- better linearity
- lower power consumption

References:

- *Analog IC design: The current-mode approach* (eds. Toumazou/Lidgey/Haigh, 1990)
- "All current-mode frequency selective circuits" (Electronics Letters, Roberts/Sedra, 1989)

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Quick paper search:

– Two papers give *no reference at all.* Three give the "Analog IC design: The current-mode approach"

– One gives an Electronics Letter by Roberts and Sedra

– None gives proofs!

– During PhD: Tree search done, 70 papers, no proofs found.

$\longrightarrow$ What I found are "conclusions upgrades" like the following: [2/5]

Kumngern10 At present, the design and implementation of current-mode active filters using second-generation current conveyors (CCIIs) have received considerable attention owing to the fact that their bandwidth, linearity, simple circuitry, low power consumption and dynamic range performances are better than those of their operational amplifier (op-amp) based counterparts.

Roberts89 In this letter a new method for performing analogue signal filtering has been proposed. By exploiting the interreciprocal property of linear networks, voltage-amplifier filter circuits can be converted to equivalent current-amplifier filter circuits with identical sensitivity properties. However, higher bandwidths, greater linearity and wider dynamic range are expected from these current-mode filtering circuits.

Citing Roberts

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Kumngern takes Roberts's Expectation as a proof!

– I Ging: "Persistence brings good fortune"

– Tenacity is necessary for some time, otherwise you give up too soon

$\longrightarrow$ don't stick to it too long, or you only see what you want to see.

$\longrightarrow$ Today: current-mode as an example. [1/6]

Overview

So I go with you through a thinking style:

– how it comes into existence

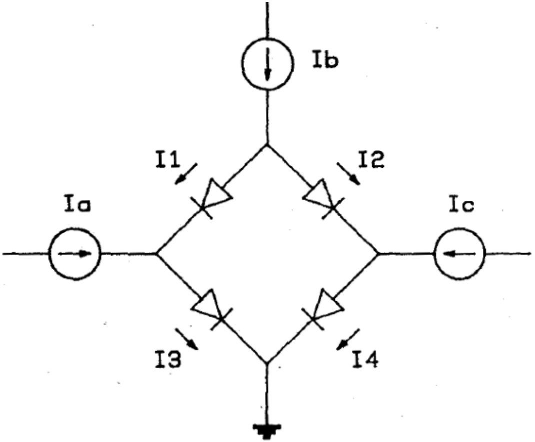
– how it gets stronger

– how it gets rigid to the point of becoming dangerous

– and what happens then . . .

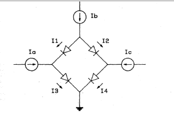
$\longrightarrow$ First we start with researchers in the mist. [1/7]

Gilbert's translinear loop



From "Current-mode Circuits From A Translinear Viewpoint: A Tutorial" Barrie Gilbert in [Toumazou 90]

Gilbert's translinear loop



From "Current-mode Circuits From A Translinear Viewpoint: A Tutorial" Barrie Gilbert in [Toumazou 90]

(Slide timing!)

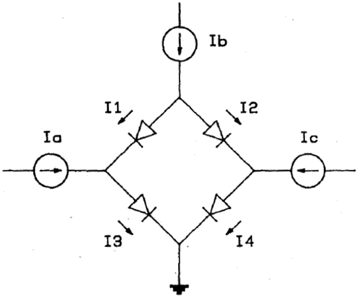
Tackling a difficult problem is like walking in the mist

– Suddenly, you see a path

$\longrightarrow$ Go far enough down the path to see where it leads.

– Gilbert's example: how can you calculate the diode currents? [1/8]

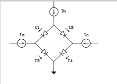
Gilbert's translinear loop



Emitter Current Density: $J_i = \dfrac{I_i}{A_i}$

$$\longrightarrow \quad J_1 J_4 = J_2 J_3 \; .$$

Gilbert's translinear loop



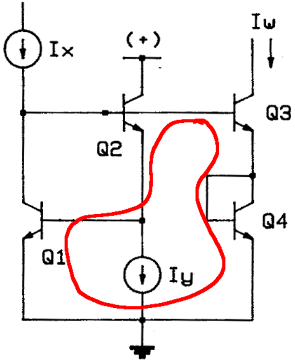
Emitter Current Density: $J_i = \frac{I_i}{A_i}$

$\longrightarrow \quad J_1 J_4 = J_2 J_3 \, .$

Barrie Gilbert's words: In a closed loop containing an even number of forward biased junctions, arranged so that there are an equal number of clockwise-facing and counterclockwise-facing polarities, the product of the current densities in the clockwise direction is equal to the product of the current densities in the counter clockwise direction.

$\longrightarrow$ Example: [1/9]

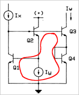
Example: Square-Root Circuit



$$J_1 J_2 = J_3 J_4 \xrightarrow{\text{same size}} I_1 I_2 = I_3 I_4$$

$$\longrightarrow \quad I_x I_y = I_w^2 \quad \longrightarrow \quad I_w = \sqrt{I_x I_y}\ .$$

Example: Square-Root Circuit



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The diode voltages are not necessary to be discussed if you want to understand this structure

$\longrightarrow$ "Current Mode"!

– Lots of circuits can be understood like this

– Now we see a path through the fog

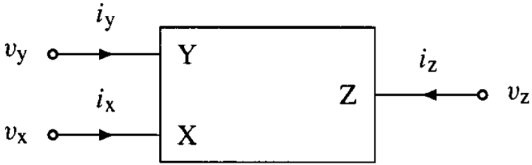
$\longrightarrow$ Let's see how far it will get us, and what we find along the way!

$\longrightarrow$ Persistence; Tenacity.

– The first thing we meet along the way are current conveyors. [2/11]

A family of current conveyors

A general block that is useful to process currents xCCyz:



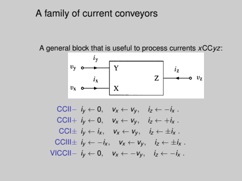
$$\text{CCII}- \quad i_y \leftarrow 0, \quad v_x \leftarrow v_y, \quad i_z \leftarrow -i_x \ .$$

$$\text{CCII}+ \quad i_y \leftarrow 0, \quad v_x \leftarrow v_y, \quad i_z \leftarrow +i_x \ .$$

$$\text{CCI}\pm \quad i_y \leftarrow i_x, \quad v_x \leftarrow v_y, \quad i_z \leftarrow \pm i_x \ .$$

$$\text{CCIII}\pm \quad i_y \leftarrow -i_x, \quad v_x \leftarrow v_y, \quad i_z \leftarrow \pm i_x \ .$$

$$\text{VICCII}- \quad i_y \leftarrow 0, \quad v_x \leftarrow -v_y, \quad i_z \leftarrow -i_x \ .$$

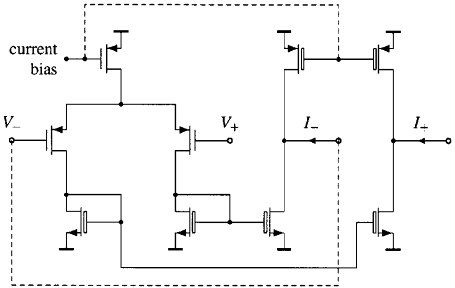


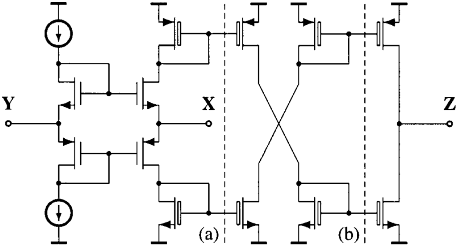
(Slide timing!)

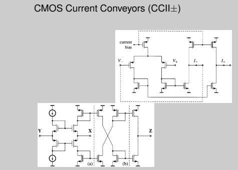
Current conveyors are a kind of bidirectional current mirrors

– different polarities of currents [1/12]

CMOS Current Conveyors (CCII±)



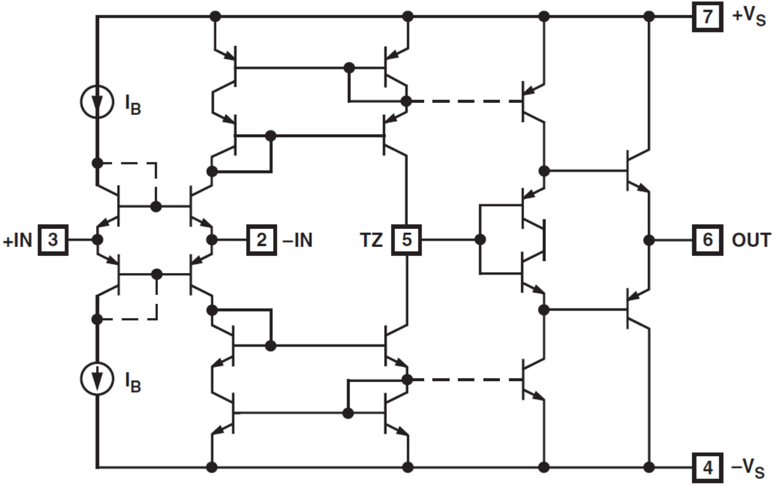




First structure: OTA with feedback

– Second structure more typical (no feedback) [1/13]

Current-Feedback Opamps: The AD844



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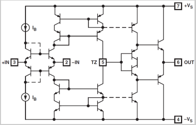


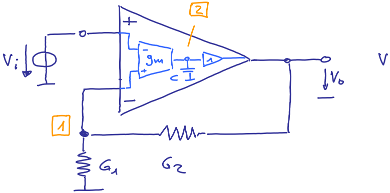
Function: IN+ to IN−: voltage buffer

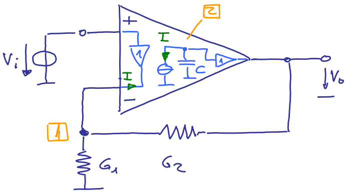
– Current into IN− copied to Z

– Z tou OUT: voltage buffer

– CCII+ and voltage buffer in one IC. [1/14]

CFB Opamp and Gain-Bandwidth Product

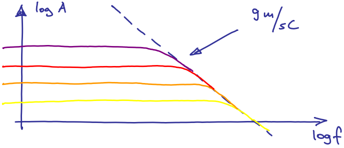




$$\frac{V_o}{V_i} = \frac{g_m/sC}{1 + \frac{g_m}{sC} \cdot \frac{G_2}{G_1+G_2}} = \frac{(G_1+G_2) \cdot g_m/sC}{(G_1+G_2) + G_2\, g_m/sC}$$

$$A_{DC} = \frac{G_1+G_2}{G_2} \qquad BW = \frac{G_2}{G_1+G_2} \cdot \frac{g_m}{C}$$

$$\Rightarrow A_{DC} \cdot BW = GBWP = \frac{g_m}{C}$$



$$\frac{V_o}{V_i} = \frac{(G_1+G_2)/sC}{1 + G_2/sC} = \frac{G_1+G_2}{sC + G_2}$$

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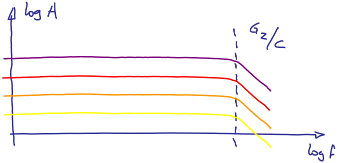
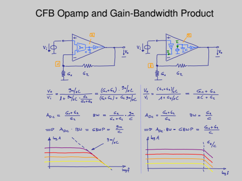




(Slide timing!)

This circuit has constant bandwidth instead of constant gain-bandwidth product! Useful for xDSL line drivers.

– explain normal OpAmp with resistive feedback

– explain CFB circuit

$\longrightarrow$ limit of the gain: input resistance at IN$-$

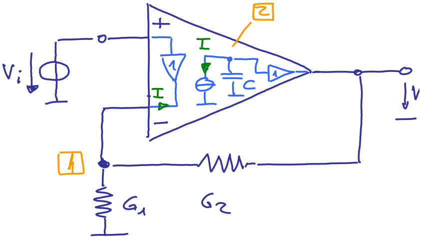
$\longrightarrow$ very good for xDSL line drivers (e.g., AD8016)

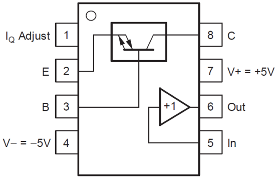
– OPA860 and AD844 can be used as CCII$+$

$\longrightarrow$ appear a lot in CM literature

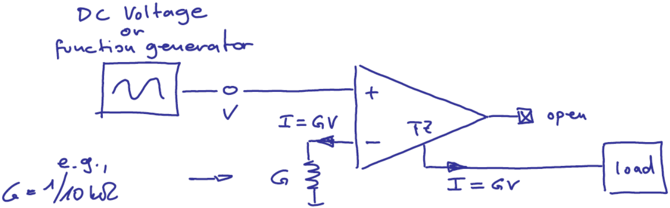
$\longrightarrow$ Example for your lab table: [3/17]

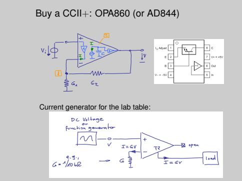
Buy a CCII+: OPA860 (or AD844)





Current generator for the lab table:





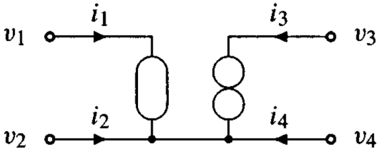
Very simple to build quickly

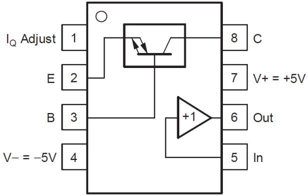
– Stable! (no feedback)

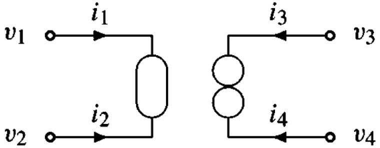
– In literature: a huge number of CCII circuits; CCII is *super!*

$\longrightarrow$ *Any* linear or nonlinear function can be implemented with CCIIs and passive elements. [2/19]

Universal Active Element







Amplificateur idéal (Tellegen)

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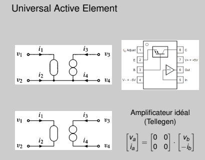


(Slide timing!)

Universal Active Element: “Set of Spice Elements”

– Explain Nullor; Golden opamp rules

– Carlin defined two nullors: 3T- and 4T-Nullor

– Tellegen had only one element.

$\longrightarrow$ Big difference: Tellegen described a 2-port, Carlin a 4-terminal

– CCII$+$ in OPA860, but CCII$-$ $=$ Three-Terminal Nullor.

$\longrightarrow$ Now we have connected many things into one thinking style:

– Gilbert’s translinear loops

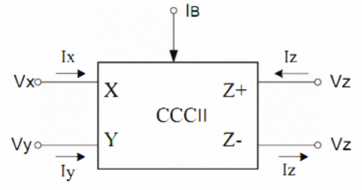
– CFB opamps and current conveyors

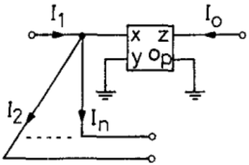
– universal active elements

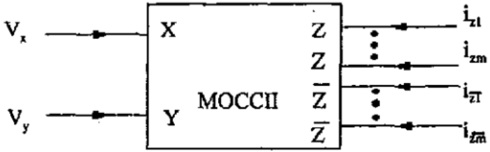
$\longrightarrow$ current-mode thinking style: “we do CM” $=$ “we use Swiss herbs”

– *Let’s anchor the herbs in your mind: [Distribute Ricola]*

Partial Blindness: Conveyor Galore . . .







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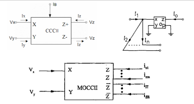


(Slide timing!)

Rigidity: Thinking constraints become self-sufficient thinking necessities:

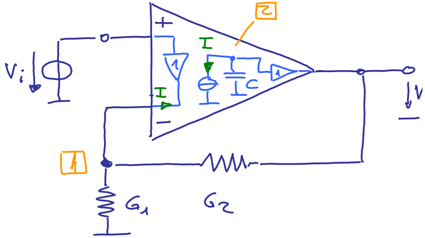
$\longrightarrow$ "Current Conveyor Versatility": more, more, more!!!

– lots of papers stopping at the block level, no real circuits

– if real circuit: often trivially slow, with almost ideal curves.

– at least it may work. There are examples for complete blindness, though: [1/25]

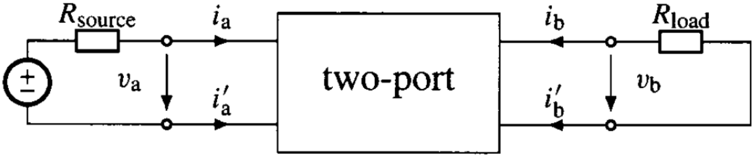
CFB Opamp: Universal active element?



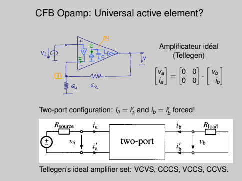
Amplificateur idéal (Tellegen)

$$\begin{bmatrix} v_a \\ i_a \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_b \\ -i_b \end{bmatrix}$$

Two-port configuration: $i_a = i'_a$ and $i_b = i'_b$ forced!



Tellegen's ideal amplifier set: VCVS, CCCS, VCCS, CCVS.



One way of dealing with contradictions is to declare them not to be contradicting, sometimes with great effort. — CFB does not fit.The all-zero chain matrix just describes the "what" (Golden opamp rules)

– Using anything as a two-port forces current constraints on the circuit!

– four ideal amplifiers: 4 controlled sources, with infinite gain

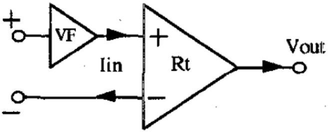
– unfortunately, the CFB opamp does not work in that configuration

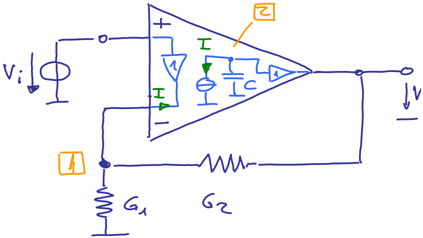
$\longrightarrow$ It obviously is a universal active element; so what do we do?

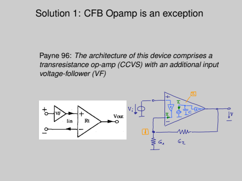
[3/28]

Solution 1: CFB Opamp is an exception

Payne 96: *The architecture of this device comprises a transresistance op-amp (CCVS) with an additional input voltage-follower (VF)*







Hitchhiker's guide to the galaxy: “Do you have a solution?”—“No, but I have a different name for the problem.”

– Turn the contradiction into an exception

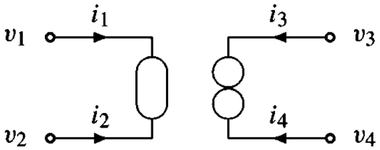
$\longrightarrow$ Cascade of two controlled sources: VCVS, CCVS

– Mathematically OK; unrealistic signal flow (real: CCII and VCVS).

– The author dealt with the contradiction. Another one ignored it. [2/30]

Solution 2: CFB Opamp is no exception

Cabeza 97:
starting from Tellegen
$\longrightarrow$ controlled sources
$\longrightarrow$ CCII circuits.



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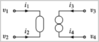

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Nullor again

– Plan: to express the four CS with Nullors

⟶ implement with CCIIs.

– Nullor circuits: look at the impedances

⟶ (c) is the CCVS

– CCII: impedances again: something fundamental changed!

⟶ (c) is now the CFB opamp.

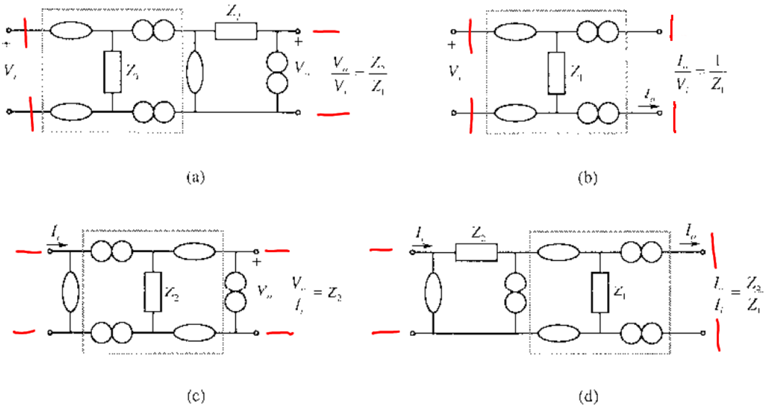
– All of them are fine researchers

⟶ locked in thinking style!

– How can we deal with this hurtful thinking constraint?

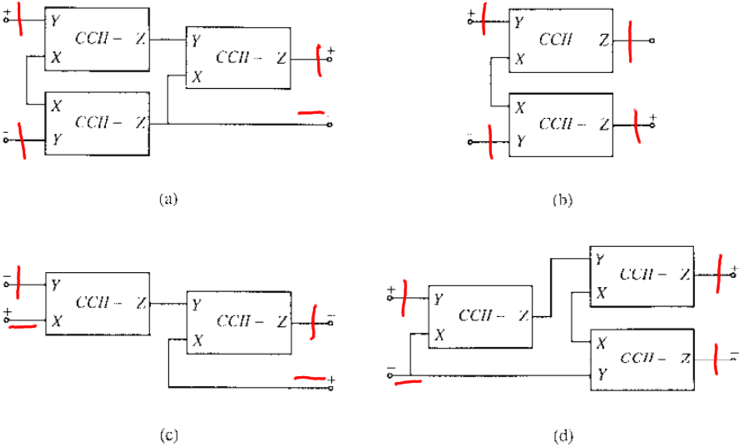
Solution 2: CFB Opamp is no exception

Nullor equivalent circuits of the four controlled sources:

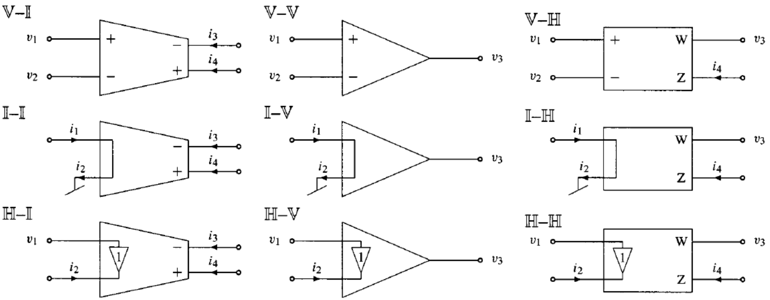


Solution 2: CFB Opamp is no exception

Second-Generation Current-Conveyor (CCII) circuits:



Solution 3: Get over thinking constraints



Class	Gain Equation	Operational for	Common Name
V–I	$i_3 = g_m(v_1 - v_2)$	$g_m R_{in} \to \infty$	operational transconductance amplifier (OTA)
V–V	$v_3 = A_v(v_1 - v_2)$	$A_v \to \infty$	operational amplifier (opamp)
V–H	$v_3 = A_v(v_1 - v_2)$	$A_v \to \infty$	floating opamp (operational floating amplifier, OFA)
I–I	$i_3 = A_i i_1$	$A_i \to \infty$	current-mode opamp
I–V	$v_3 = r_m i_1$	$r_m / R_{in} \to \infty$	operational transresistance amplifier (OTRA)
I–H	$v_3 = r_m i_1$	$r_m / R_{in} \to \infty$	floating OTRA
H–I	$i_3 = A_i i_2$	$A_i \to \infty$	current-feedback OTA (CFB OTA)†
H–V	$v_3 = r_m i_2$	$r_m / R_{in} \to \infty$	current-feedback opamp (CFB opamp)
H–H	$v_3 = r_m i_2$	$r_m / R_{in} \to \infty$	operational floating conveyor (OFC)

† This Name Is Proposed by Us

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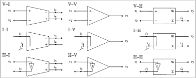

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Very simple: dump two-ports, use four-terminals

– input can have low, high, or mixed impedances

– output too

– so we now have *nine* amplifiers!

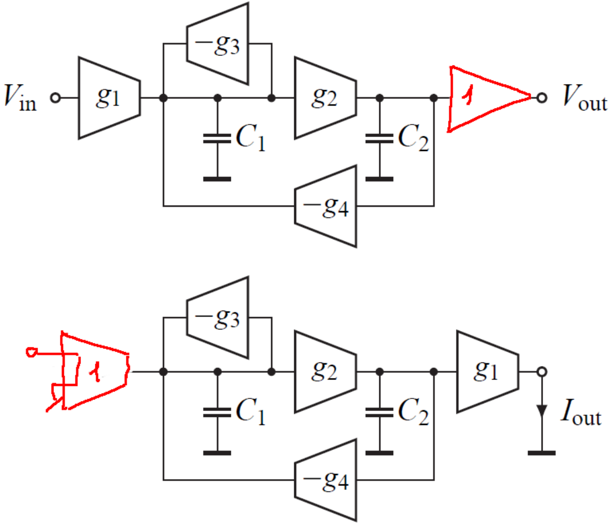
$\longrightarrow$ difficult to sell (out of style)

$\longrightarrow$ writing story ...

– The question “is it really better” arose ... [2/35]

Thorough comparison for one filter

[Mahattanakul 98]



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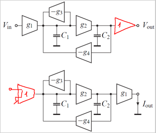
[Mahattanakul 98]



(Slide timing!)

I know of *only one* thorough comparison:

– Gm–C biquad: Noise, distortion, . . .

– VM slightly outperforms CM because all noise shaped

– However: on a real chip, pads could not be connected directly

– Now both would be the same.

$\longrightarrow$ The only existing thorough comparison shows no difference!

$\longrightarrow$ This being clear, attempts to extinguish CM were made. [2/37]

What is behind the vision?

Vision:

- higher bandwidth
- simpler architecture
- better dynamic range
- operates at lower voltage
- better linearity
- lower power consumption

Reality:

- less feedback
- simpler circuits
- wilder ideas
- lower focus on tradition
- different “second-order” problems

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- different “second-order” problems

Back to the start: the six most recent papers say …

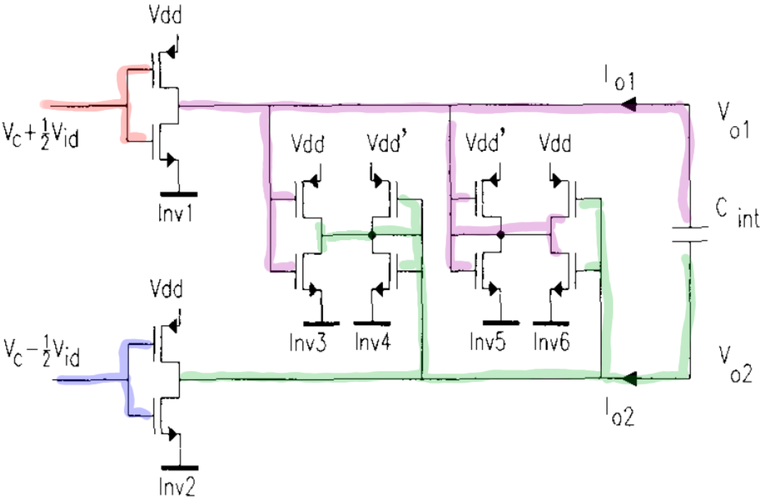
– Current-mode reality is…

$\longrightarrow$ Most decisive: different “second-order” problems

– There are also VM circuits doing this [1/38]

Very fast and simple circuits

...also exist in the traditional literature; e.g. Nauta 92:



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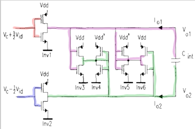

(Slide timing!)

100-MHz Gm–C filter in 3μ CMOS!

– Really funny: draw as inverters, show to a digital guy

$\longrightarrow$ enjoy the clash of thinking styles!

– This circuit has no internal nodes!

– Needs controlled V_{dd}

What remains today:

$\longrightarrow$ valuable ideas, already absorbed by the IC desiners

$\longrightarrow$ propaganda.

– Was it all a scam? Should it have been prevented? No!

– Don’t forget the researcher in the mist!

Thinking Styles (after Fleck 35)

- Facts[1] are made by deliberately introducing thinking constraints to make things simpler.
- Therefore facts appear, change, and disappear again.
- Facts: elements of style as well as models of reality.
- To publish, “in style” is more important than “true”.
- The only thing that keeps style and reality correlated is a social feedback process in a scientific community.
- Ken Wilber (cited in [Schmid 03]): All that is empirical science has three things in common: a practical injunction (*if you want to know this, you have to do this*); an apprehension, illumination, or experience (*if you do this, you see this*), and communal checking (*did others who did this also see the same?*).

[1] lat. *facere* = make/build/construct/create/cause/do

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Matrix Revolutions: "Everything that has a beginning has an end."

– We do not discover facts, we make them!

$\longrightarrow$ All facts will eventually be un-made.

– If this is true, then even scientists have a wrong idea about science.
How can this be? Because of what we read!

Publications and style development

1. Lab journals; written communication with colleagues
2. Conference papers
3. Journal papers
4. Handbooks (for experts)
5. Textbooks (for students)
6. Popular-science articles and books

Now ask yourself:

- What have you read in your particular field?
- What have you read about the stuff the other group is doing?
- What have you read about string theory, evolution biology, neuropsychology, geodesy, limnology?

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The further down, the simpler, more logical . . . and further away from reality, both with facts and descriptions how the facts were obtained.

$\longrightarrow$ So get more confident: “die andern kochen auch nur mit Wasser” [3/48]

Conclusions

- "Current-mode" is not a matter of having voltages and currents in a circuit: there are always both!
- "Current-mode" is not a matter of using some transistor circuits rather than others: circuits are just tools.
- "Current-mode" is not a matter of using less feedback, nor of simpler circuits: has been done everywhere.
- "Current-mode" is not even a matter of current-in current-out: currents and voltages are not even interesting! (e.g., FM radio is electromagnetic-wave-in sound-wave-out).

"Current mode" is simply a thinking style in which a group of people have made their own facts.

And so it is for every research topic.

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Questions?

Literature

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Arbitrarily chosen current-mode papers

Excerpts from the first six papers on **IEEE**Xplore on “current-mode filters” in a quick literarure search done in December 2010:

Laoudias (Melecon 2010): Current-mode signal processing is a very promising technique for achieving higher maximum frequency of operation and reduced circuitry compared with those offered by the conventional opamp configurations. Thus, a number of appropriate active blocks have been employed for realizing the corresponding topologies [Toumazou90]

Li 2010 (Wireless Communications, Networking and Information Security (WCNIS)): And the current-mode universal filter has been more popular than the voltage mode type due to requirements in low-voltage environments such as portable and battery-power equipments. The current-mode technique is more ideally suited to the environment than the voltage-mode variety. For the potential advantage of the current-mode circuits have, such as larger dynamic range, higher signal bandwidth, greater linearity, simpler circuitry, and lower power consumption [Toumazou90], it becoming more popular in recent years.

Kamat (IET Circuits, Devices and Systems, 2010): At present there is growing interest in current-mode signal processing [Toumazou90] because of its advantages like increased bandwidth, high dynamic range and reduced power supply requirements.

Imran (ARTcom 2010): In the last decade ,one has seen the grew of the prominence of the current mode circuits. Current mode circuits exhibit reliable high frequency response, have simpler architecture, provides better dynamic ranges and operate at lower voltages than their VM counterparts. Current Conveyor introduced in 1968 by Sedra and Smith is a versatile building block.. In the literature many modified versions of the current conveyor exist like for example DVCCII, ICCII, FDCCII, DOCCCII and many others. [no reference!]

Zhao (ICASSP 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 counterpart [no reference!]

Kumngern (ECTI-CON 2010): At present, the design and implementation of current-mode active filters using second-generation current conveyors (CCIIs) have received considerable attention owing to the fact that their bandwidth, linearity, simple circuitry, low power consumption and dynamic range performances are better than those of their operational amplifier (op-amp) based counterparts [Roberts89]