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Why 'Current Mode' Does Not Guarantee Good Performance

HANSPETER SCHMID

Bernafon AG, Morgenstrasse 131, 3018 Bern, Switzerland Tel.: +41 31 998 16 24, Fax: +41 31 998 15 90
E-mail: h.p.schmid@ieee.org

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Abstract. It is often said that there is a fundamental difference between current-mode and voltage-mode circuits. This conjecture is discussed in technical and philosophical terms, and it is shown that there is no such performance difference to be found, and that it is not possible to make a clear divide between 'voltage mode' and 'current mode.'

And yet performance differences appear in the literature. It is shown that they come from the different design practices of the current-mode and the voltage-mode research groups. The conclusion of this paper is that the practical knowledge of the current-mode research groups should be re-integrated into main-stream IC design, and that all propaganda of the type 'current-mode is better than voltage-mode' should be stopped immediately.

Key Words: current mode, voltage mode, circuit performance, research trends, philosophy of science

1. About the Unusual Form of This Paper

This is an unusual paper, and it attracted the widest possible range of reviewer comments. One of four reviewers wrote "very interesting, publication recommended," another one wrote "full of logical contradictions, not proper science." Both is true, and in order to prevent too much confusion, I write this pre-introduction to clarify what I intended to do when I wrote this paper.

In this paper, I want to give the reader some in-sight into current mode. In my opinion, this is not possible by ex-plaining, by taking current mode out (ex) into plain view, because the taking out of its context alters the object that is ex-plained. So I attempt to in-vite the reader to see current mode more clearly.

Doing this is *not* possible with logic analysis alone, as analysis always cuts apart what is a whole. So I attempt to use an integral method of writing, which is very seldom used in scientific discourse, although integral expression and working methods are becoming more common in *all* aspects of human life (c.f. Gebser [1] and Wilber [2,3]). I found that many engineers already think integrally. But they do not *write* integrally.

The problem with integral writing and expression is that three ingredients which are often deemed to be ultimately important in science are not dominant in integral thinking: logical analysis, perspective and temporality.

In this paper, I do not place current-mode into any perspective. I do indeed use several perspectives where they are appropriate, but I do not synthesise a new one. If I did, I would just produce one more perspective to be added to the others. Because I use perspectives, also distinctly non-technical ones, but do not let any perspective dominate the whole, the result is *free of* perspective, not *without* perspective, it is a-perspectivic, not un-perspectivic.

A classical scientific perspective that uses logical analysis is used in Sections 3 and 4, but it does not encompass all of the paper. So I use logical analysis, but there is no all-encompassing logical-analytical perspective. The result is a-logical, but not un-logical.

In classical scientific papers, time is treated as a space dimension, as a line on which the present is the point dividing between the past and the future, and I use this aspect of time in parts of this paper. But I also use another aspect of time, in which the past and the future are both ever present and not merely linear history and potential decisions. In a very literal way, I am *present*ing the past and future of current mode. With this integral view of time, there is a lot less individual freedom of decision in research than most researchers like to imagine. On the other hand, research like this is free of linear time (but again not without linear time). It is a-temporal, but not un-temporal.

Is this still empirical science? According to Wilber [2], 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?). I designed current-mode filters for six years, I had many experiences and apprehensions, and I talked a lot with other current-mode researchers and even published a paper in a peer-reviewed philosophical journal [4]. Now I submit my ideas to a wider engineering audience, and although these ideas are a-logical, a-perspectivic and a-temporal, they are clearly disputable, confirmable and refutable. So I think yes, this is in fact empirical science.

Readers who feel uncomfortable with the a-logical side of this paper should ask themselves some questions: is science one aspect of logical thinking, or is logical thinking one aspect of science? Similarly, is science a child of perspective thinking, or is perspective thinking one possible tool of science? Finally, can science only look at the future as a mathematical extrapolation of a linear past full of data, or is there more to it?

This long pre-introduction was intended to clarify beyond doubt that I knew what I meant to do when I wrote and submitted this unusual paper. It is of course an entirely different question how well I did it. Did I write intensively, as I also intended when I wrote [5], or did I just write extensively when I extended [5]?

I hope that this paper will trigger discussions and that you will make me part of them by sending me feedback, be it positive or negative, to h.p.schmid@ieee.org.

2. Introduction

The current-mode approach is comparatively young. The term “current-mode processing” was coined by Barrie Gilbert when he worked on strict trans-linear loops (c.f. [6]), in which the node voltages are incidental. Through Gilbert’s interesting circuits, the current-mode idea soon became a strong force driving several research groups. Nowadays, many people are convinced that current-mode integrators, filters, and oscillators have some special merits.

In this paper, I show that this conviction is not justified at all, but I also show that the current-mode approach must not be neglected either. This cannot be shown with purely technical arguments, so I will use a combination of technical and philosophical reasoning.

2.1. Does ‘The Current Mode’ Exist?—No

This must sound absurd in the light of hundreds of current-mode publications that appeared in recent years. Nevertheless, it is not possible to define precisely what a current-mode circuit is as opposed to a non-current-mode circuit.

The most common approach is to define a black box with a current input signal and a current output signal as a current-mode circuit. There are two problems with this definition. The first problem is where to draw the border of the black box. For example, if a broad-band signal is picked up with a coil, this can be done by sensing the voltage over the coil or the current through the coil, i.e., with a voltage-mode or a current-mode circuit (see Section 8). But why should the border of the black box be drawn between the coil and the circuit? If it is drawn between free space and the coil, we end up with two magnet-field-mode circuits. The second problem is discussed in Section 3: if one constructs a class of circuits with clearly drawn borders, then the outcome is that there is no performance difference between them.

There have been other ideas to isolate current-mode circuits. Some authors write that ‘current mode’ means to have circuits in which signals are represented by currents. But even a simple current-mirror also has a signal-dependent input voltage. There were attempts to restrict ‘current mode’ to circuits in which the currents depend *linearly* on the signal, but unfortunately there are such signals in every voltage-signal operational amplifier. Externally linear current-signal filters (e.g., log-domain filters) will also escape this definition because they contain current signals that depend non-linearly on the processed signal.

This refinement of definitions can be continued almost infinitely, but it will only make clearer that there is no such thing as ‘the current mode.’ Paradoxically, it will also explain what ‘current mode’ is.

2.2. Does ‘Current Mode’ Then Not Exist?—No

Such explaining discussions, of which [6] is a good example, have clearly had a great impact on IC design. Several new circuits and amplifiers (e.g., the operational floating conveyor [7] or the current-feedback OTA [8]) emerged from this way of thinking. But this was not because ‘current mode’ exists as an independent concept, it was because the discussions *created* a current-mode *approach* to circuit design; not a super-theory, but a practical way of developing theories, concepts and circuits and of communicating them.

It would in fact be absurd to postulate the non-existence of 'current mode.' But it would be equally absurd to postulate its existence. The situation seems completely paradoxical. But the paradox is not caused by incorrect reasoning, it is caused by basing that reasoning on an incorrect assumption. This incorrect assumption is the attempt to isolate 'current mode' and look at it as an independently existing thing with independent qualities. Such an attempt is fundamentally incorrect: 'current mode' receives all its qualities through interdependence with other things, people and groups of people, as I will show below.

In the following technical and philosophical sections, I will treat some important dependencies and come to the conclusion that all propaganda of the type 'current-mode is better than voltage mode' should be stopped immediately, but the work on the current-mode approach should be intensified by re-integrating it into main-stream analog IC design.

3. Other Things Being Equal...

During my doctoral studies, I read lots of papers on current-mode circuits, and found lots of assertions like "current-mode circuits are faster, less noisy, more linear than voltage-mode circuits." I traced references back as far as possible, until I had a tree containing close to 100 papers—but no evidence at all. I only found assertions like "this current-mode circuit *can be expected* to have *these* performance advantages over *this* class of voltage-mode circuits." Which is quite different from "current mode is better than voltage mode."

To find out whether it makes a difference to represent signals by currents instead of voltages, a *ceteris paribus* (other things being equal) comparison must be made. In order to do this, one must use a clear definition, and the only examples known to me use the current-in current-out black-box definition applied to isolated G_m-C filter sections. One example for such a comparison is [9]. There the authors thoroughly compared the two filters shown in Fig. 1, which are not dual in the sense of circuit transposition, but have the same loop structure and the same low-pass transfer function.[1] The study takes into account the noise of the OTAs and the harmonic distortion induced by their non-linear transconductances, but not clipping effects caused by OTA output stage saturation. It is shown that both circuits have similar

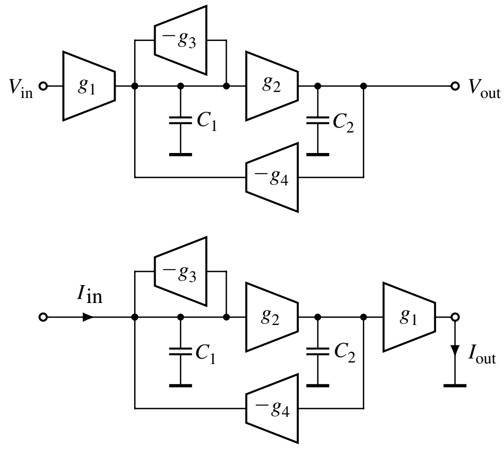

Fig. 1. Voltage-mode and current-mode G_m-C filter [9].

amounts of harmonic distortion. The circuits are then compared using a figure of merit,

$$F = \frac{\mathrm{DR} \cdot f_p^2}{P^2} \tag{1}$$

where DR is the dynamic range, f_p is the pole frequency, and P is the power consumption. The result shows that the dynamic range of the voltage-mode filter is better by at most 6 dB in the relevant range of pole Qs and DC gains.

The problem with [9] is that it is not really *ceteris paribus*. The difference mainly occurs because the noise of the input OTA in the voltage-mode filter is processed by the filter, which is not the case for the noise of the output OTA in the current-mode filter. Obviously, if both the input OTA of the voltage-mode filter and the output OTA of the current-mode filter were ideal and noiseless, both filters would perform identically.

The same can also be explained from a more practical point of view: the voltage-mode filter has a high-impedance output, which cannot be loaded without changing the filter transfer function. Similarly, the current-mode filter has a high-impedance input. Therefore, on a real IC, the voltage-mode circuit needs an additional output buffer, and the current-mode circuit needs an additional input buffer. This time the noise of the current buffer is filtered, but the noise of the voltage buffer is not filtered, and the performance difference between the two filters is reduced to the performance difference between the circuits used to insert signals into the feedback loop and extract signals from it. The resulting performance difference is certainly small, and it is not a question of signal mode, but of transistor-level design. Thus, [9] establishes that, other things being equal, there is no performance difference between the current-mode and the voltage-mode G_m-C filter discussed in the paper.

There is another study comparing G_m-C circuits [10], which uses reasoning with topological equivalence rather than mathematics, but comes to the same conclusion: that there is no performance difference between the studied current-mode and voltage-mode circuits. Reference [10] also shows that several of the popular current-mode structures are topologically equivalent to well-known voltage-mode structures, meaning that only the points where signals are fed in and out are different.

So there is not only no conclusive evidence to support any performance difference between voltage-mode and current-mode, there is even some good evidence that the performance does not depend on the mode.

4. Which Things Are Not Equal?

While it is by now clear that if current mode is defined as current in current out, then its performance is not advantageous, it should be equally clear that the widespread belief in the better performance of current-mode circuits is not just an unfounded myth. What has caused this belief is that many comparisons were not ceteris paribus at all. In most of the papers proposing very fast current-mode circuits, open-loop current amplifiers are compared to results obtained with closed-loop voltage amplifiers [11–14].

Many of the amplifiers derived with a current-mode approach base on current mirrors and provide a specific, low gain without feedback around the amplifier. In contrast, the typical low-gain voltage amplifier uses feedback around a high-gain amplifier. This feedback stabilises the gain and reduces harmonic distortion (see e.g., [15] for the latter), and it also improves the terminal impedances of the amplifier. But this is not for free.

Figure 2 shows the transfer functions and terminal impedances of a second-generation current conveyor (a CCII+ presented in [16]; c.f. Appendix for a brief description) and Analog Device's SSM 2135 audio opamp connected as a buffer and in an open-loop configuration. The frequency of the opamp has been multiplied by 50 to make the curves easily comparable. A look at the transfer functions shows that the closed-loop transfer function of the opamp and the open-loop current transfer function of the CCII+ look very similar. The reason is that both transfer functions are determined by non-dominant poles only, the dominant pole of the voltage opamp, whose effect is clearly visible in the open-loop transfer function, only plays a stabilising role once the feedback loop is closed, as I will explain below.

The impedance curves show that feedback decreases the output impedance of the opamp but increases the input impedance, which can be considered an improvement in both cases. However, close to the unity-gain frequency f_1 of the opamp, there is some peaking, which means that feedback actually makes the impedances worse above approximately $f_1/5$. Note that the output impedance of the opamp is far below the input impedance of the CCII+ because the former is built in a bipolar technology, but the latter in CMOS, and because the former has a higher supply current than the latter. Although Fig. 2 only shows two specific devices, the effects discussed are the same for other amplifiers.

Coming back to gain stabilisation, the low-gain amplifiers that are used in many filter and regulator circuits are normally built using one voltage opamp and two resistors, as in Fig. 3. The transfer function of the circuit in Fig. 3 is:

$$T(s) = \frac{V_{out}}{V_{in}} = \frac{A(s)}{1 + \frac{R_1}{R_1+R_2}A(s)} \tag{2}$$

For very high gains,

$$\lim_{A(s)\to\infty} T(s) = 1 + \frac{R_2}{R_1} = \alpha_V \tag{3}$$

and if the gain of the amplifier is expressed by the gain-bandwidth product, $A(s) \approx \omega_{gbw}/s$, then

$$T(s) = \frac{\alpha_V \omega_{gbw}}{\alpha_V s + \omega_{gbw}} \tag{4}$$

Calculating the relative sensitivity of the transfer function to variations in the gain-bandwidth product gives:

$$S^{T(s)}_{\omega_{gbw}} = \frac{dT(s)}{d\omega_{gbw}} \cdot \frac{\omega_{gbw}}{T(s)} = \frac{\alpha_V s}{\alpha_V s + \omega_{gbw}} \tag{5}$$

Similarly,

$$S^{T(s)}_{\alpha_V} = \frac{\omega_{gbw}}{\alpha_V s + \omega_{gbw}} \tag{6}$$

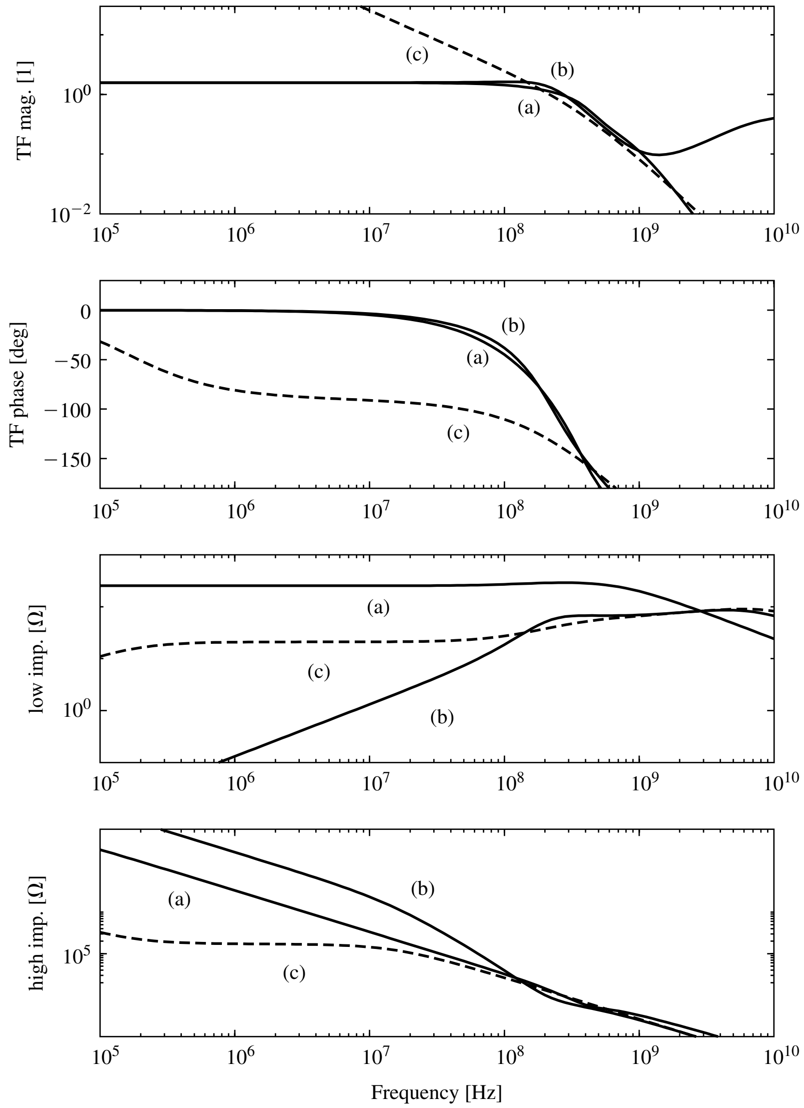

Fig. 2. Transfer functions and terminal impedances of (a) the CCII+ in [16], the AD SSM 2135 opamp (b) connected as a voltage buffer and (c) open-loop. The AD SSM 2135 is actually an audio opamp, its frequency has been multiplied by a factor of 50 to make the curves comparable. (‘high impedance’ is the input of the voltage amplifier and the output of the current amplifier.)

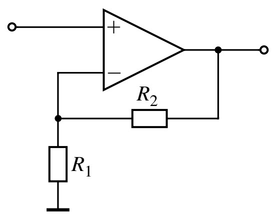

Fig. 3. Low-gain voltage amplifier.

For low frequencies, $S^{T(s)}_{\omega_{gbw}} \approx \frac{\alpha_V s}{\omega_{gbw}}$ and is very small. This means that variations of ω_{gbw} have little influence on the overall gain. On the other hand, $S^{T(s)}_{\alpha_V} \approx 1$ for low frequencies, which means that any variations of the feedback gain directly translates into variations of the overall gain. Thus the overall gain is set by the precision of the ratio of the feedback resistors, which can be quite precise on chip. Note that the latter sensitivity can only get smaller for high frequencies, while the sensitivity to variations of the gain-bandwidth product goes towards one for high frequencies. This means that the stabilising effect of feedback around a high-gain amplifier decreases with increasing frequencies. We can now find out at which frequency the contributions to the standard deviation of $T(s)$ caused by the standard deviations of α_V and of ω_{gbw} become equal:

$$\bar{\sigma}_{\alpha_V} S_{\alpha_V}^{T(s)} = \bar{\sigma}_{\omega_{gbw}} S_{\omega_{gbw}}^{T(s)} \Longrightarrow s = \omega_{gbw} \frac{\bar{\sigma}_{\alpha_V}}{\alpha_V \bar{\sigma}_{\omega_{gbw}}} \quad (7)$$

On one CMOS IC, resistor ratios can be precise to within 0.1%, while two different ω_{gbw} can match to within 1%. Thus, setting e.g., $\alpha_V = 2$, the variance of the ω_{gbw} determines the variance of α_V for frequencies above $\omega_{gbw}/20$, i.e., it normally dominates close to the pole frequency of a filter built with a feedback amplifier, and the matching precision of the feedback resistors is lost. Ideally, the gain variation is then 1% around the unity-gain frequency of the opamp and decreases with 20 dB per decade towards lower frequencies, but as with the resistances, some over-peaking occurs in practical cases. The feedback opamp can now be compared to CCIIs, whose current gains can also be precise to within 1%. It then turns out that again, the feedback opamp is decidedly better than the CCII+ only for frequencies below $\omega_{gbw}/5$.

So there is in fact a real performance difference, but it is caused by the amount of feedback in the feedback loop, not by the signal mode.

5. Why the Performance Is Different

Thus I can now explain why current-mode circuits are considered to be faster than voltage-mode circuits: although both would be similarly good from an ideal point of view, over-peaking caused by second-order effects in the feedback loop makes problems close to the ω_{gbw} of the feedback opamps. It is important to see that the same over-peaking effects also occur in CCIIs that use local feedback to reduce the input resistance of the X terminal; in this case, the speed advantage of the CCII vanishes. It is also possible to build a current-mode circuit that is dual to the one in Fig. 3 using a current-mode opamp; its performance will then be similar. Furthermore, one can also build open-loop voltage amplifiers that show no over-peaking, e.g., amplifiers based on common-source stages. But it turns out that circuits without local stabilising feedback are just *more typical* for the current-mode approach.

Both the transfer function of the closed-loop opamp and the behaviour of the CCII are determined by the low-impedance nodes of the circuits only. These low-impedance nodes all look similar in both voltage-mode and current-mode circuits: a transistor g_m sets the node resistance, parasitic capacitances of transistors set the node capacitance, and the voltage swing is limited by transistors that would otherwise leave the region of saturation. Thus the non-dominant poles and zeros will be at similar frequencies, and the harmonic distortion and the noise properties will also be similar. What mainly determines the performance of a circuit is the number of low-impedance nodes and the way they are connected, i.e., the *complexity of a circuit* determines the performance of an amplifier or filter. This is independent of the signal mode: It has been shown in [8] that *all* nine types of operational amplifiers can be implemented with circuits of similar complexity. As with feedback, one finds that less complex circuits are just *more typical* for the current-mode approach.

There are of course also a few voltage-mode circuits with reduced complexity, like the very fast G_m-C filters presented in [17]. They were built with OTAs that only have input and output nodes, but no internal nodes at all. Of course, current-mode circuits can also be made more complex to improve their linearity and signal-to-noise ratio (e.g., [18,19]), but that slows them down again.

Thus the advantages of current-mode circuits that are often cited in the literature, like a potential for reaching higher frequencies, lower power consumption, and smaller chip area, are in fact real, but the reason is not technical, and has nothing to do with choosing voltages or currents to represent signals. The reasons for the difference are mainly the design preferences of the proponents of the current-mode approach (c.f. [4]).

Such design preferences are actually what was called a ‘paradigm’ by Kuhn [20]. A paradigm is not a kind of super-theory, as it is often interpreted, but a set of practices that require a long time to master; not things to think, but things to *do,* not ‘what,’ but ‘how.’ A paradigm cannot be acquired by reading papers, but only by practising the paradigm. ‘Current mode’ is not a set of facts and theories, but a different way of *doing* IC design. And since different current-mode research groups use substantially different practices, there *cannot* be a common opinion about what current mode is.

This is, unfortunately, not studied often in engineering sciences where the main focus is on theories and facts only. So I need to add a philosophical section to this paper such that I am able to show why ‘current mode’ is a very important contribution to circuit design although it cannot be defined generally and does not give better performance.

6. How 'Current Mode' Could Happen

In this philosophical section, I will talk about three aspects of engineering terms and research: first, that they are never only objective, second, that they are not unchanging once they are made, third that they are empty of inherent meaning and only have quality through relations.

6.1. True, Good and Beautiful

Most engineers are concerned with what is true or not true, but they seldom write about what is good or what is beautiful, because good and beautiful are not objective terms. And this is a pity. Most problems of our time, especially engineering and technology problems, have become problems because an excessive fixation on the True prevents people from looking at the Good and the Beautiful [2]. With this, I do not just mean that too much work prevents people from appreciating arts and engaging in ethics, I mean to say that science itself has non-negligible Good and Beautiful aspects and cannot be reduced just to the True.

Every reader will probably know something about the three aspects of the world. They have played a big role in the recent history of humanity, from Plato to Kant to Wilber; from western philosophy of science (Popper) to eastern existential philosophy (Nāgārjuna).[2] The concepts are similar, but the names are different:

Plato	Wilber	Kant	Popper	Nāgārjuna
True	It	Pure reason	World I	Dharma (the ultimate 'It')
Good	We	Practical reason	World II	Saṇgha (the ultimate 'We')
Beautiful	I	Judgement	World III	Buddha (the ultimate 'I')

This very brief summary should enable very reader to use personal experience and see what this implies for the current-mode debate: we have shed some light on the True, the 'it,' above, and have found that looking at the current mode as an objective thing by itself, one finds no performance advantage. This does not mean that current mode is bad. In fact, it has triggered lots of research and is still considered a valuable approach by many researchers and research teams. This research has produced a great number of fine circuits and design techniques. 'Current mode' has had a great impact on design strategies and values of research groups, meaning that it has proved to be a very good approach. Just disregarding that 'Good' side of the current mode may lead to the wrong conclusion that current-mode is useless.

Also, I have talked to many people who worked in some ways with the current-mode approach, and many of them like it very much. It broadens the horizon, they say, and gives intuitive access to lots of beautiful concepts. Current mode has had a great impact on many engineers' judgement about *all* circuits. Again, disregarding this 'Beautiful' side of the current mode may lead to the wrong conclusion that current-mode is useless.

And by being 'Good' and 'Beautiful,' the current-mode approach has also delivered many 'True' insights about circuits. Seen in this light, it is a minor problem for the current-mode approach that its main dogma, 'current-mode is better than voltage-mode,' is not true.

I emphasise this so strongly because the dynamic process that we call research is a delicate balance of *all three sides of reality,* not just objective, not just subjective, not just social. And looking at all three of them as interlinked gives an enlightening view on the genesis and development of scientific facts.

6.2. The Genesis and Development of Scientific Facts

So how does research work? One possible answer works as follows [4,22]: At the beginning of a new idea is chaos. The people involved in the genesis of the idea move around in that chaos by trying out many things and thinking many thoughts, without understanding what they are doing. The first non-chaotic thing they find when moving around in this chaos is resistance, they find it easier to move in some directions than in others. Then they make first assumptions about what they perceive as a chaos, they decide what they want to investigate first and what they want to neglect at first, or, in other words, they deliberately introduce thinking constraints. Sooner or later they will see patterns in the chaos, patterns which, once perceived, will from then on always be immediate appearances, "Gestalten,"[3] which are then called facts. One example of such facts are the current-mode circuits introduced by Barrie Gilbert.

Since the origin of these facts is not only the chaos, but also the thinking constraints that were introduced deliberately, facts are made rather than discovered. Already at this stage the 'Good' and the 'Beautiful' play a major role, because it is personal preferences and common strategies in research groups that decide what a researcher considers the direction of least resistance.

The normal development of a research idea is towards more and stronger thinking constraints and towards more intensive "Gestaltsehen." It is interesting that a person who first learns to use an approach or a scientist tackling a new, complex problem perceive a very similar process, starting with the feeling of facing a big chaos and suddenly arriving at seeing many immediate appearances. Thus acquiring knowledge goes hand in hand with reducing chaos, seeing a larger number of immediate appearances (in other words, knowing more facts) and *being more constrained* in ones thinking.

All this is very similar to the concepts of information theory, which says in mathematical terms that information is gained by reducing uncertainty (Shannon, e.g., [23]).

The reason why somebody introduces thinking constraints in the first place when he faces chaos is that he needs some continuity in thinking. This drive for continuity does not disappear. On the contrary: the further an idea develops, the more tenacious it gets. There is always a tendency to adjust everything to fit into an idea, but this can be done more passively or more actively.

The most passive kind of tenacity is that contradictions become unthinkable. The best examples here are the numerous authors who use 'current-mode is better than voltage-mode' statements in the introductions to their papers, not realising that they never saw a confirmation of these statements.

Tenacity becomes more active when something that does not fit into an idea remains unseen, or is even kept secret. Often, current-mode papers exclude critical performance parameters, although some of the authors must have made simulations showing that there are problems. In the majority of cases, this is not a conscious act of cheating, but rather a remainder of the starting times of the current mode where the chaos was still so dominant that one could impossibly have a look at all aspects simultaneously and had to postpone the investigation of less pressing problems.

Tenacity becomes more active when something that does not fit into an idea is presented as if it fitted. Examples are papers where circuits are presented as current-mode circuits although no definition given by the authors defines them as such.

The most active form of idea tenacity is when people see certain facts although they contradict other important ideas and concepts they use concurrently. Examples are a few papers published during the most active times of current-mode research, where a few current-mode filters were published that do not even work from a theoretical point of view, and not by a flaw that is difficult to see, but because the published transfer functions cannot have complex poles.

It is very important that one does not forget how essential this tenacity is. Without some tenacity and propaganda at the beginning, no idea can ripen because people could not be convinced to invest time and money. Propaganda of the kind 'current-mode is better than voltage-mode' is not a despisable side effect of research, but *an indispensable ingredient* of successful research.[4] But at some stage, an idea has become so tenacious that it is not flexible anymore, does not give new results anymore, cannot adapt to new insights anymore. Then propaganda is certainly not justified anymore and turns from a driving force into a reputation killer. It is then time to break up the idea and re-use its good aspects in another frame of ideas.

In our case, I think that the current-mode approach has reached its terminally inflexible state, and this paper contains a conscious attempt to break it up, not by asking the readers to forget about current-mode, but to stop all 'current-mode is better than voltage-mode' propaganda now and re-integrate the current-mode approach and its good ideas and techniques into main-stream IC design.

And this is the story of every single concept in engineering and science: it appears from chaos, it develops, changes, and finally disappears again when its emptiness is all that remains.

6.3. On the Emptiness of Engineering Terms

By 'emptiness of a term' I mean that a term has no significance or meaning whatsoever *by itself* [21]. If you isolate a term from its context, nail it down, ex-plain it, and see what you find, you find emptiness.[5] An easy way to get a feeling of this emptiness is to take an English dictionary, start from one word and look up words in the definitions of this starting word. It will become apparent quickly that there is not a single word in the whole English language which carries its meaning by itself, without relation to other words.

So in the ultimate analysis, everything is empty. But that does not mean that nothing exists. Of course 'current mode' exists, but only as a living term used in dynamic interrelations with other terms, people, and research groups. Once a term like 'current mode' comes into a state where there is no dynamics anymore and little interrelations, meaning when people start to take it as 'current mode as such' and just use it to fend themselves off from non-current-mode people, its emptiness becomes dominating.

It is then very important to abandon the wrong idea that the term itself has inherent meaning and qualities, but *not* abandon the dynamic interrelationships that gave it meaning before. This can be generalised: if *anything* seems to have qualities by itself, this is a good indicator that there is a rigid idea around and that the dynamic interrelations through which the qualities arise are not sufficiently well known.

7. Conclusion

While it is true that many current-mode circuits live up to the reputed advantages of the current mode, the reason is not that current has been used as a signal, but that circuit simplicity, lower power consumption and speed are often achieved at the cost of higher distortion, higher gain variation, and so on.

Therefore the work done in the many current-mode research groups also may give valuable insight to voltage-mode designers who need to build low-power, low-voltage, or high-speed circuits and are ready to trade in gain variation, distortion, or noise performance to achieve the goal. In the same way, the techniques used in classical voltage-mode design, like Miller feedback, offset compensation, and so on, can also be used in circuits that process current signals.

I believe that the current-mode–voltage-mode divide that is so thoroughly described in [6] has now served its purpose, which was to drive and protect research. The current-mode idea has become very rigid, and it has by now become apparent that the term 'current mode' by itself is empty of inherent meaning.

Conscious efforts should now be made to reintegrate the current-mode community's knowledge into the main stream of IC design. In order that this can happen, it is very important that any kind of 'current-mode is better' propaganda is immediately stopped. Many main-stream IC designers have already lost trust in the current-mode community and have to be convinced now by solid, propaganda-free work.

8. And Yet . . .

Someone from the audience at ISCAS 2002 [5] asked me which term we should use if we cannot use 'current mode' anymore. My conclusion does not mean to abandon 'current mode.' Quite the opposite. One should keep current mode, but instead of defining it, one should talk about its dynamic interrelations with other theories, ideas, people, groups.

I conclude this paper with three brief examples to make that point clear:

Many hearing aids use a *very* basic wireless audio transmission system, where audio signals are transmitted in the baseband (meaning, essentially, that the loudspeaker in a HiFi system is replaced by a wire loop). This system is very primitive, but for a simple reason: a so-called 'telecoil receiver' can pick up any magnetic audio signal, i.e., the hearing-impaired person can listen to the magnetic field produced by loudspeakers in headphones or telephones. In an air plane, they can listen to the sound of the movie without hearing the engine noise![6]

A telecoil receiver is a coil that picks up the magnetic signal which is connected to a low-noise amplifier (LNA). The whole receiver, including coil, will have a passband, a lower cut-off frequency, and a higher cut-off frequency. One can either sense the current through the coil and amplify it (current-mode receiver), or sense the voltage over the coil and integrate it (voltage-mode receiver). In the current-mode receiver, the size of the coil determines the lower cut-off frequency, and the LNA the upper cut-off frequency. In the voltage-mode receiver, it is exactly the opposite. While one can still not tell that either is better *a priori,* production issues and trimming requirements can make one of the two modes clearly preferable *for a certain application*. For example, when the necessary lower cut-off frequency would require an unacceptably large coil, the voltage-mode receiver is the better choice, but when the same coil should also be used to receive, e.g., FM signals, then a current-mode receiver may be the better choice. This is what I meant by dynamic interrelations.

Another example is interconnects. In broadband applications, it does indeed make a difference whether the load that has to be driven is mainly capacitive or inductive. For example, if the main load is the capacitance of the pad and housing, as it was in the measurements described in [24,25], then it makes sense to use current signals. If the main load is inductive, voltage signals are often preferable. Both again depends on the application and on the context; the above is true if the context is to *measure* a video-frequency signal coming out of one chip. However, if these circuits are intended to inject video-frequency signals into a device under test, then a capacitive load has to be driven with a voltage and an inductive load with a current, in order to make them invisible to the device under test. If the broadband signal has to be transmitted between two chips of a multi-chip solution, then the situation is again different. Again, this is is an example of quality given by interrelations rather than isolated concepts.

Last, but not least, there is in fact a huge difference between switched-current (SI) and switched-capacitor (SC) circuits [26]. But this difference comes, again, not from the signal-mode, but from the very different circuits used to build discrete-time integrators in the two techniques. Even then, one cannot tell a priori whether SC or SI is better. It is shown in [26] that even if one specific SC circuit is compared to one specific SI circuit, the decision depends on the process technology and may very well change over the years. Which is a very good example for quality given by dynamic interrelations of terms (switched-current), people (Hughes and other designers who develop design techniques) and groups (foundries and their large customers who set technology road maps).

Appendix

The second-generation current conveyor with current gain +1, the CCII+ [27,28], is often drawn with the circuit symbol shown in Fig. 4. The CCII+ is described by three equations,

$$i_y = 0, \quad v_x = v_y, \quad i_z = i_x \tag{8}$$

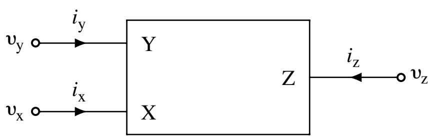

Fig. 4. Symbol used for all types of current conveyors.

Various ways to implement current conveyors in CMOS and bipolar technologies are described in [8,29].

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Notes

1. Actually the filter in Fig. 1 realizes two transfer functions. Choosing the node to which C_1 is connected as the output node (top) or input node (bottom) results in a bandpass transfer function, but all that is said in this section applies to the bandpass filters as well.
2. It is very important to note here that Nāgārjuna used the traditional religious terms Buddha, Dharma and Saṇgha in a distinctly philosophical way, not only to denote the historical or religious figure Buddha, his teachings, and his community [21]. In some ways, Nāgārjuna has similarities with Wittgenstein who de-constructed the purely True in the "Tractatus Logico-Philosophicus."
3. The English psychology literature uses the German terms, because there are no simple English words for that which immediately appears to a person.
4. Note that there is a huge difference between this kind propaganda and a conscious lie!
5. As was pointed out very nicely in [21], this is also true for the term 'emptiness' itself. Nothing is empty, period. Things are empty *of* inherent existence. Thus even emptiness only exists through relations.
6. The advent of piezo-electronic loudspeakers in modern telephones is a problem for the hearing impaired.

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Hanspeter Schmid received the diploma in electrical engineering in 1994, the post-graduate degree in information technologies in 1999, and the degree Doctor of Technical Sciences in 2000 from the Swiss Federal Institute of Technology (ETH Zürich), Switzerland. He is now an analog IC designer with Bernafon AG, Switzerland, where he develops analogue electronics for hearing aids. He is a lecturer at ETH Zürich (Analog Signal Processing and Filtering), a member (currently the Secretary) of the Analog Signal Processing Technical Committee of the IEEE Circuits and Systems (CAS) Society, a member of the IEEE CAS Board of Governors, and he serves several journals and conferences as a reviewer.