TRADE-OFFS IN ANALOG CIRCUIT DESIGN

The Designer's Companion

Trade-Offs in Analog Circuit Design

The Designer's Companion

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KLUWER ACADEMIC PUBLISHERS

NEW YORK, BOSTON, DORDRECHT, LONDON, MOSCOW

eBook ISBN: 0-306-47673-8
Print ISBN: 1-4020-7037-3

©2002 Kluwer Academic Publishers
New York, Boston, Dordrecht, London, Moscow

Print ©2002 Kluwer Academic Publishers
Dordrecht

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Foreword

With so many excellent texts about analog integrated circuit design now available, the need for yet another compilation of contributions may be questioned. Nevertheless, this book fills a notable void, in addressing a topic that, while a common aspect of a product designer's life, is only occasionally addressed in engineering texts. It is about Trade-Offs: What they are; the circumstances in which they arise; why they are needed; how they are managed, and the many ingenious ways in which their conflicting demands can be resolved. We call it a Designer's Companion, since it is more in the nature of a reference work, to dip into when and where some new perspectives on the topic are needed, rather than a text to be read in isolation and absorbed as a whole. However, it is an aspect of a trade-off that it is peculiar to each situation and there are no recipes for their instant resolution. That being true, their treatment here is frequently by example, suggestive rather than definitive. The personal insights, intuitions and inventiveness of the designer remain vital to the pursuit of a well-balanced solution, but which is even then only one of many, so its selection requires a relative-value judgment.

Understanding how to cope with trade-offs is an indispensable and inextricable part of all engineering. In electronics, and particularly in analog design, the dilemmas arise in the choice of basic cell topology, its biasing, the specific element values and in making performance compromises. For example, wireless communication systems are becoming increasingly sophisticated: they must operate at ever higher carrier frequencies, while using increasingly complex modulation modes, and posing extremely stringent performance demands. Meeting these requirements is only made more difficult as the dimensions of transistors and passive elements in modern IC processes continue to shrink, and as time-to-market and cost pressures mount. Similar trends are found throughout the field of electronics: in power management, fiber-optics, clock generation for CPUs, high-precision instrumentation for signal generation and metrology, and in analytical equipment of numerous kinds in science, industry, medicine and more recently in forensics and security.

Simply stated, the need for a trade-off is generated by the dilemma of being faced with a multiplicity of paths forward in the design process, each providing a different set of benefits or posing different risks, and which can only be resolved by giving up certain benefits in exchange for others of comparable value. The trade-off invariably generates a constellation of considerations which are specific to each situation, within a particular design context and set of circumstances that will often have never occurred before, and whose resolution will have little general applicability.

It is these latter features that make writing about trade-offs so difficult: they are not easy to anticipate in a systematic treatment, and they don't teach lessons of universal applicability. Furthermore, a trade-off calls for creativity: it requires us to provide what isn't there, in the data. Trade-offs cannot be made by tossing a coin; they are rarely of an either-or character to begin with. The longer one mulls over the unique particulars, the more likely it is that a panoply of solutions will present themselves, to be added to

one's bulging list of options. At some point, of course, ingenuity has to be curbed, and a decision has to be made.

Edward de Bono has noted that "In the end, all [human] decisions are emotional". In resolving a trade-off, our intervention as laterally thinking, resourceful individuals is not required if the facts unequivocally speak for themselves, that is, if the resolution of a transient dilemma can be achieved algorithmically. It involves selecting one from several similarly attractive choices. We invariably try to apply all sorts of wisdom and logic to our choice of which car or house to buy; but when logic fails to force the answer, as it so often does, we fall back on emotion. The essential role of emotion as an intrinsic part of rational intelligence and an ally to creative thought has recently been illuminated by a few pioneering psychologists. Intriguingly, in the index to Antonio Damasio's 1994 book *Descartes' Error*, one finds the entry "Decision making: see *Emotion*". Coping with trade-offs also requires the inquisitive anticipation of the circumstances in which they may arise, and a good deal of practice in playing out *What If?* scenarios. Joel Arthur Barker¹ makes this observation, in which we may want to substitute "the next IC development" in place of "the new worlds coming":

Some anticipation can be scientific, but the most important aspect of anticipation is *artistic*. And, just like the artist, *practice and persistence* will dramatically improve your abilities. Your improved ability will, in turn, increase your ability in dealing with the new worlds coming. [Emphases added]

Although often referred to as "an art" in casual conversation, circuit design is more correctly viewed as a craft. The central emphasis in formal treatments of integrated circuit design is generally on acquiring a thorough knowledge of the underlying electronic principles, and of semiconductor processes and devices, aided by a fluency in mathematics, familiarity with the particular domain of specialization under consideration, and a basic ability for applying various pre-packaged concepts, techniques and algorithms. But this hides the importance of developing the knack of making all the right judgments in practicing this craft, and the value of cultivating a personal flair in coping with the realities beyond the covers of the textbook.

Contrarily, from the layman's perspective, design is perceived as a linear intellectual process, which proceeds something like this: One is faced with a set of objectives, and then calls on experience to assemble all the pieces in a methodical, step-by-step fashion, making fact-driven decisions along the way. As each part of the product is considered, logic prevails at every juncture, and the whole gradually takes on a shape that is as optimal as it is inevitable, to become another testament to the power of the underlying rules and theories.

As a seasoned product designer, you will know that from the outset this will be far from the reality. Inspired guesses (more charitably labeled "engineering judgments")

¹ Joel Arthur Barker, *Paradigms: The Business of Discovering the Future*, 1994. This highly recommended work was previously published in 1992 under the title *Future Edge*. By that time anything with the word "Future" in its title was already becoming passé, so perhaps it enjoyed only lackluster sales. By contrast, "Paradigms" was a very marketable word in 1994.

are scattered all along the path, from start to finish. To begin with, those Objectives, that are supposed to inform every step of the proceedings and give the development a sure sense of direction, are either insufferably detailed and give one a feeling of being imprisoned in a straightjacket, or they are so comically sketchy and perhaps mutually inconsistent, that anything approaching a focused, optimal solution is out of the question. Regrettably, as your own experience may testify, both of these extremes are all-too common, as well as every flavour in between. Each in its own way is mischievously setting the stage for the first trade-off to be needed.

In the over-constrained scenario, one designer may be inclined to take a stab at satisfying the provider of the objectives with the desired results, no less, but no more, either: a just-right solution. This could be unwise, however, since the writer of these specifications might be viewing the development in a way that is strongly influenced by a prior discrete-element solution, and could be unaware of the special advantages that can be provided by a monolithic implementation. On the other, this tactic might be the right one if the product needs to meet only this one customer's need, and development time is severely limited, and die cost must be minimized. Another designer might adopt the opposite rationale: Sure, the product will meet all those fussy requirements, but it could be capable of doing a lot more, too. By skillful design, many additional applications and features can be anticipated, and the versatility extended to embrace these, for little extra design effort or manufacturing cost. Thus, each of these two designers is making a trade-off, right at the start, about how to interpret and react to the challenge implicit in the specifications.

Similarly, when faced with scant information about what is needed of this new product, one designer's approach might be to opt for caution, and painstakingly solicit more detailed information from the provider of the objectives. This only generates another trade-off, since the provider/user may in fact be no more informed than the designer; but, perhaps to hide his ignorance, he will nonetheless generate more numbers based on estimates and prior practice, in other words, more guesses. If these are received and acted on with unmerited respect, the outcome could be a disaster. Alternatively, if they are treated with disdain, and another set of guesses is substituted, the outcome could be equally undesirable.

Meanwhile, a second designer may lean on her specialized experience with similar products, and assume that the missing information can be adequately interpolated, without the need for any further consultation. That tactic could work out well, or it could be just the beginning of a monstrous headache for both the potential user and the designer. In all these scenarios, it is painfully evident that the tools needed for resolution of this particular dilemma will be found in no text book (including this one!) and they each in their own way call for a trade-off to be made. And this before the design has even begun.

These sketches also make us aware of the arbitrariness of the trade-off. It's an idiosyncratic response to a dilemma. The more practiced the engineer, the more likely it is that the majority of the hundreds of trade-offs that eventually will have to be made, during the course of developing even a relatively straightforward analog circuit, will be based on good judgment, and a balanced consideration of all the alternatives that came

to mind. But we cannot say that these decisions will be entirely rational, or optimal. There are no algorithms for success.

This book covers ten subject areas: Design Methodology; Technology; General Performance; Filters; Switched Circuits; Oscillators; Data Converters; Transceivers; Neural Processing; and Analog CAD. It addresses a diversity of trade-offs ranging from such well-known couplets as frequency versus dynamic range, or gain-bandwidth vs power consumption, or settling-time vs phase-noise in PLLs, to some of the more subtle trade-offs that arise in design for robustness in manufacture and in the “polygon world” of IC layout. During its several years in development, it has transcended its original scope, becoming a designer’s desktop companion while also having value as a graduate textbook, inasmuch as numerous fundamental relationships leading to design conflicts are explained, in many cases with practical examples.

Its thirty-three chapters come from a variety of sources, including some of the world’s most eminent analog circuits and systems designers, to provide, for the first time, a timely and comprehensive text devoted to this important aspect of analog circuit design. Those authors who are professional designers are faced every day with difficult decisions on which the success of their products depend, and not always with all the analytic horsepower that may be demanded by some of the situations. Taken in aggregate, the trade-offs that they choose eventually shape the competitive stature and reputation of the companies for whom they work. Other authors allow themselves to take a more academic view of the nature of a trade-off, and as a group are more inclined to have greater optimism about the amenability of challenging circumstances to yield to formal approaches, and even a degree automation.

The first section on Design Methodology opens with a discussion by Toumazou about the nature and value of qualitative reasoning, in contrast to the usual emphasis in engineering on the towering importance of quantitative analysis. The underlying need for intuition, playful inventiveness and emotion in the pursuit of an engineering life is picked up by Gilbert, in Chapters 2 and 33, although the more serious focus here is nonetheless on making decisions within the context of commercial product development. In all these chapters, the sheer breadth of the field allows only an introduction to the subject matter.

The next three chapters, in the Technology section, range from the “Big Picture” of VLSI, and in particular, some of the trade-offs in CMOS circuit development, as explored by Mezhiba and Friedman, to the specific and detailed topic of bandgap voltage references, as perceived by Staveren, Kouwenhoven, Serdijn and Verhoeven (Chapter 5). Perched between these two chapters is a presentation of the less-familiar floating-gate devices and circuits that have a unique, although limited, scope of applications and might also comfortably fit into the later (and short) section on Neural Processing, in Chapter 30 of which Hanggi, Dogaru and Chua discuss specialized trade-offs in integrated neural networks.

In some cases, the emphasis is on the tension between two dominant aspects of performance. This approach is particularly evident in the five chapters about General Performance issues. A very basic trade-off is that which arises between amplifier bandwidth and gain; this is discussed by Toumazou and Payne in Chapter 7, and from a different perspective by Meyer in Chapter 8. Aspects of frequency compensation

in integrated amplifiers is explored in Chapter 9, by Staveren, Kouwenhoven, Serdijn and Verhoeven. In amplifier design, one cannot increase bandwidth without regard for noise, and this in turn is strongly influenced by the power consumption that one can afford to assign to the amplifier. Noise and bandwidth are likewise linked by device geometry. Attempts to push bandwidth may impact DC offsets or gain accuracy in certain cases, or distortion and intermodulation in others. Thus, trade-offs are usually multi-faceted, and in a very real way, nearly all the key specifications that will appear in a product data sheet will be linked to a considerable extent. Vittoz and Tsvividis face up to these harsh realities in Chapter 10.

In the section on Filters, the many conflicts and compromises that surround continuous-time active-filter design are addressed by Moschytz in Chapter 11, and by Fox in Chapter 12. The particular way in which trade-offs arise in Log-Domain (Translinear) Filters is discussed by Drakakis and Burdett in Chapter 13. The next section is about Switched Circuits in general, and includes four differing perspectives. The optimization of comparators is the focus of Chapter 14, by Rodríguez-Vázquez, Delgado-Restituto, Domínguez-Castro and de la Rosa, while a general overview of switched-capacitor circuits is presented by Baschiroto in Chapter 15, followed by a review of the compatibility of such circuits with advanced digital technologies, provided by Leelavattananon. This section closes with Chapter 17, which offers some thoughts by Hughes and Worapishet about the differences and trade-offs that arise between the standard switched-capacitor circuits that are now well established and the less well-known switched-current forms that are sometimes viewed as equally useful, in certain situations.

Communications circuits are a minefield of trade-offs, and the very stringent performance required of Oscillators are examined in the Chapters 18 and 19 of this section. In the first, by Ham, some of the special problems of maintaining low phase-noise using the relatively poor on-chip components (principally low-Q inductors and lossy varactors of limited range) are put under scrutiny. A different perspective on the same subject is provided by Hajimiri. The next three chapters, in the section on Data Converters, provide insights from the foremost exponents of these extremely important gateways between the analog and digital domains. The first, which sets forth principles for the systematic design of high-performance data converters, is authored by an impressive team composed of Gielen, Vandenbussche, Van de Plas, Daems, den Bosch, Steyaert and Sansen. The following Chapter 21 is more specialized in its approach: Gielen and Lauwers discuss particular issues of power modeling for data converters and filters. Chapter 22, authored by Schreier, Steensgaard and Temes, provides a definitive account of the fundamental trade-off between speed and dynamic range in over-sampled converters.

The focus next shifts to Transceivers, in several very different arenas. In Chapter 23, Abidi shares his considerable experience in the design of wireless circuits, and the systems of which they are an integral part, where power conservation is a dominant concern. This is followed by a review by Forbes of the design trade-offs that arise in optical receivers. Finally, Chapter 25 closes this section with some considerations for analog front-ends in digital subscriber-line systems. In all these cases, the overarching challenge is the attainment of a very high dynamic range, entailing the simultaneous

provision of low distortion, of various disparate types, with a near-fundamental noise floor. The endless search for low noise is also featured in Chapter 26, as illuminated by Kouwenhoven, Staveren, Serdijn and Verhoeven, and again, noise and intermodulation are the central challenges in mixer design, the topic of the next chapter by Kathiresan and Toumazou. Phase detectors once bore a passing resemblance to mixers, and their close cousin, the analog multiplier; but in today's phase-locked loops, there is a more pressing need to capture both phase and frequency information. Some special techniques are presented by Li and Ismail. The closing chapter of this section, authored by Chan, Tu and Toumazou, looks at the trade-offs that arise in the design of various sorts of power amplifiers.

The final section is concerned with CAD for analog design. Chandra and Roberts present an overview of a design methodology for analog circuits using Matlab and Simulink, while in Chapter 32, Gielen adds a concluding word about the possibilities for using symbolic analysis tools for analog circuits.

Clearly, no book on the topic of trade-offs can ever be truly representative of the entire field of analog design, nor exhaustive in its treatment of those subjects which do get included. The primary function of any engineering text is to inform, and provide accurate and authoritative guidance of both a general and specific sort. However, as earlier suggested in this Foreword, and as these chapters testify, it is unlikely that very many general recommendations can be made regarding trade-offs, and the specialized case histories have a strictly limited scope of application. But another function of any good text is to enthuse, to inspire, to illuminate the less-explored corners of the domain, and to point the way to new perspectives on each topic. It is hoped that the material assembled here serves that objective.

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11 March 2002

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