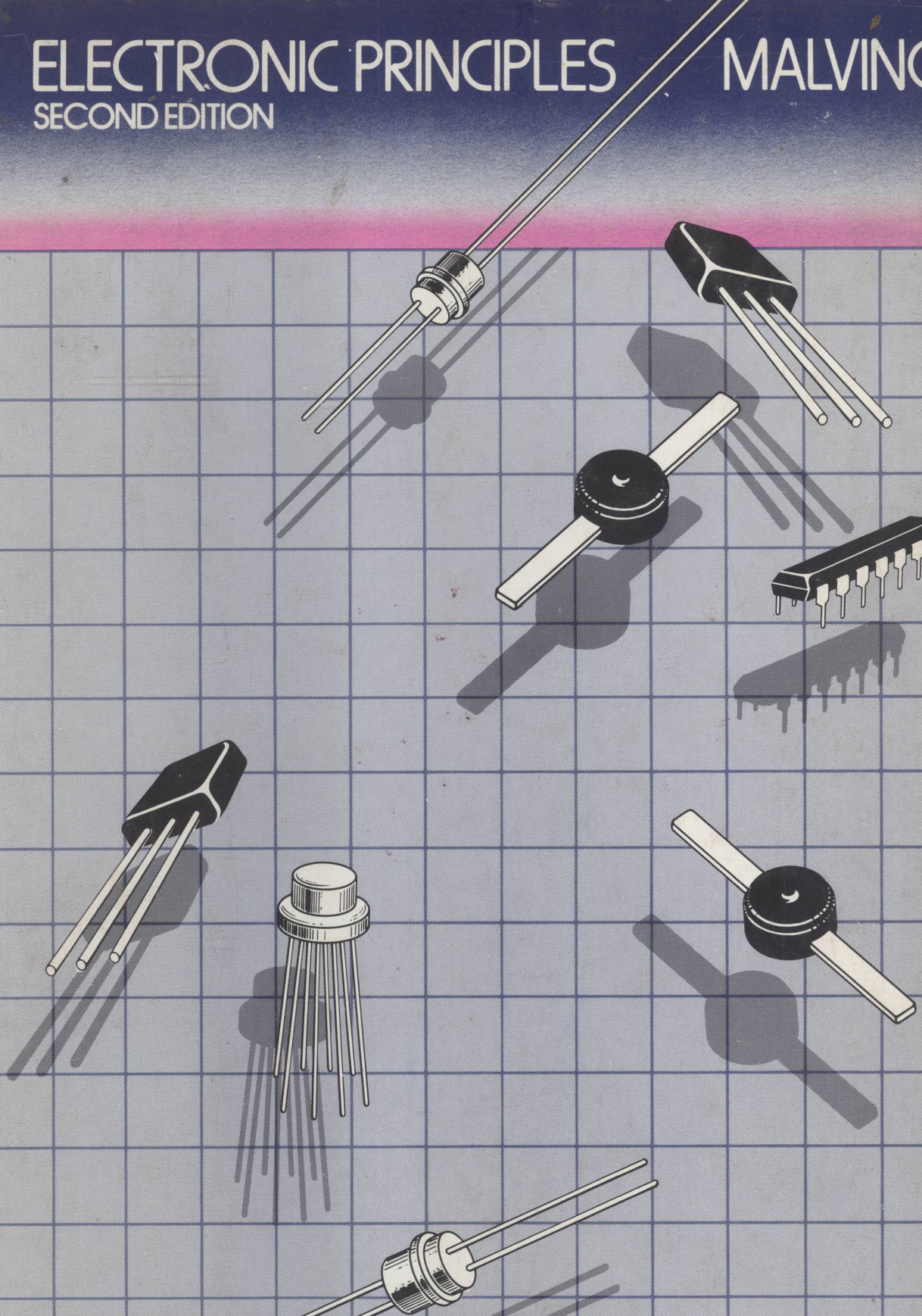
ELECTRONIC PRINCIPLES

SECOND EDITION

MALVINO



Electronic Principles

Second Edition

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TO JOANNA,

My brilliant and beautiful wife
without whom I would be nothing.
She always comforts and consoles,
never complains or interferes,
asks nothing and endures all,
and writes my dedications.

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Electronic Principles

OTHER BOOKS BY ALBERT PAUL MALVINO

Digital Computer Electronics
Resistive and Reactive Circuits
Transistor Circuit Approximations
Electronic Instrumentation Fundamentals
Digital Principles and Applications (with D. Leach)
Experiments for Electronic Principles (with G. Johnson)

The entire truth about anything is almost impossible to tell within practical limits. No desert is absolutely dry, no liquid absolutely wet. No plain completely flat; no ball-bearing truly round.

Shidle

preface

This second edition reflects suggestions from several reviews, dozens of interviews, and hundreds of questionnaires. Everybody wanted more linear ICs and less discrete material. Also asked for were chapter summaries, more FET applications, thyristors, optoelectronics, etc. To strengthen and modernize the book, therefore, I have added:

1. A chapter on op-amp applications covering comparators, amplifiers, active diode circuits, integrators, VCOs, and active filters.

2. A chapter on voltage regulators, emphasizing the new breed of three-terminal IC regulators.

3. Self-testing reviews at the end of each chapter, designed to get reader participation.

4. More linear IC material throughout the book, emphasizing circuit designs extensively used in linear ICs.

5. Earlier coverage of zener diodes and simple regulators.

6. Material on thyristors and optoelectronic devices.

To make room for all this new material, I shortened almost every chapter in the original edition, rewriting some chapters completely and revising others heavily. Where possible, I simplified the mathematics and emphasized the logical approach. The result is a faster moving book that gets you through discretes and into ICs as soon as possible.

Here are some specific changes. Chapters 4 and 5 now include a discussion of zener diodes and regulators. I simplified the mathematical derivations in Chap. 7 (biasing) and introduced the dc load line as a visual aid. Chapter 9 now has new sections on RC coupling, direct coupling, and other types of interstage coupling. In Chap. 10, I added material on thermal resistances, transistor derating, and heat sinking. Chapter 11 discusses the current mirror, a potent circuit used extensively in linear ICs. Also important, Chaps. 7 through 11 now contain multistage amplifiers showing how the CE, CC, and CB connections are used. Chapter 14 now has all kinds of FET applications. In Chap. 15, I expanded the discussion of h parameters, showing how to convert h values on data sheets into r parameters. Chapter 17 analyzes the internal circuitry of typical op amps and audio ICs; this not only reinforces earlier learning, it allows me to explain fully slew rate and power bandwidth, the two most important large-signal concepts in linear ICs. Chapter 19 now includes direct-coupled positive-feedback circuits like four-layer diodes, SCRs, and UJTs. I made Chaps. 20 and 21 completely new because of the demand for op-amp applications and IC regulators. Finally, Chap. 23 now contains a section on the phase-locked

loop. Besides the foregoing, I made many other minor additions and deletions throughout the book.

As before, this is a book for a student taking a first course in linear electronics. The ideal prerequisites are a dc-ac course, algebra, and trigonometry. In some schools, it may be possible to take the ac and trigonometry courses concurrently. As in the first edition, the important equations have a triple asterisk *** attached to them. Other study aids include self-testing reviews and problems. Also note, a correlated laboratory manual *Experiments for Electronic Principles* is available.

If you liked the first edition of this book, I'm sure you will like this new edition even better. It accurately reflects the industrial use of discretes and ICs, retaining enough discrete discussion to lay a solid foundation and introducing enough IC material to get in step with industry. Best of all, this new edition is easier to teach from and easier to read.

I want to acknowledge those who helped me most with this second edition. Thanks to my reviewers, Hank Dinter of Hennepin County Area Vocational-Technical Center, Douglas V. Hall of Hall Electronics Consultants, and Thomas P. Herbert of the University of Akron. And thanks to my colleagues, Raymond P. Dong, F. Hilsenrath, A. Jensen, and William E. Long of Foothill College; Albert Camps and Lorne MacDonald of the College of San Mateo; Kenneth Muchow and Charles Wojslaw of San Jose City College; Joseph T. Livingstone of West Valley College; and Francis S. Horton of Southeastern Community College.

Albert Paul Malvino

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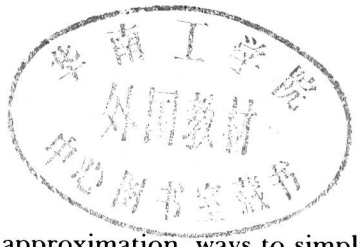
1 *introduction*



This chapter is about idealization and approximation, ways to simplify analysis. Included are common approximations for resistors, capacitors, and inductors.

1-1 *idealization*

Most electronic devices are complicated. To get to the main ideas, we often idealize; this means stripping away all unnecessary detail. The device that remains is then ideal or perfect.

need for idealization

You have used idealization many times already. A good example is a piece of wire. In most cases, you treat it as a perfect conductor; but this is far from the truth. Take a piece of copper wire 1 ft long as shown in Fig. 1-1*a*. If it is AWG 22, this piece of wire has a resistance of 0.016 Ω and an inductance of 0.24 μH. If the wire is 1 in above a metallic plane (see Fig. 1-1*b*), it has a capacitance of 3.3 pF. Therefore, the piece of wire acts like the circuit of Fig. 1-1*c*.

Even this is not exact. The truth is you cannot draw a circuit at all because the *R*, *L*, and *C* are *distributed* over the length of the wire rather than *lumped*

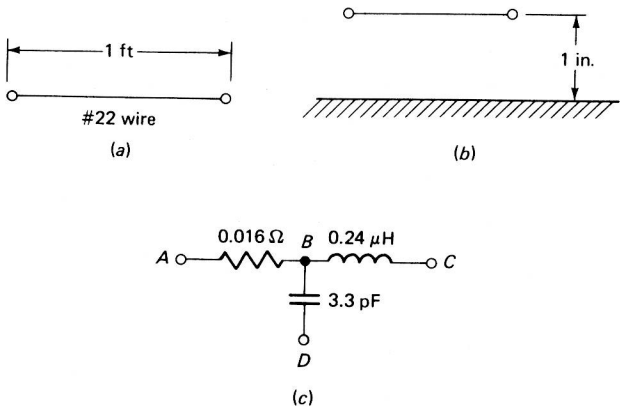


Figure 1-1. A piece of wire and its equivalent circuit.

between nodes *A, B, C,* and *D.* For exact analysis you need to use an approach based on advanced formulas called Maxwell's equations.

Fortunately, you don't need Maxwell's equations below 300 MHz, and you can use lumped-constant circuits like Fig. 1-1*c.* (Lumped constant means the resistance is between one pair of nodes, the inductance between another pair, and the capacitance between a third pair.) Better yet, for frequencies below 1 MHz the inductive and capacitive reactances are usually negligible, and the wire's resistance is so small compared with other circuit resistance that it too is negligible. In other words, most of the time we *idealize* a piece of wire by neglecting its *R, L,* and *C.*

approximations

Make no mistake about it. At high enough frequencies you do need an equivalent circuit like Fig. 1-1*c* for a piece of wire. This should give you a clue as to how complicated the exact circuits are for some electronic devices. For most everyday needs, we can approximate; otherwise, we'd be bogged down in unnecessary detail. Throughout this book, we use approximations as much as possible.

The *ideal,* or first approximation, strips away everything but the key ideas behind a device. In this way, we get to the bones of device operation. With ideal devices, circuit analysis is easier. When necessary, we can improve the analysis by using a second approximation, sometimes a third approximation, and once in a while, an exact equivalent circuit. In the chapters to come, look for these levels of approximation:

- Ideal or first approximation: the simplest equivalent circuit. It retains only one or two ideas of how the device works.
- Second approximation: includes extra features to improve analysis. Usually, this is as far as many engineers and technicians go in daily work.

- Third approximation: includes other effects of lesser importance. In some circuits, we will need this approximation.
- Exact circuit: this will be as complete as possible using lumped constants. We almost never use this circuit.

1-2 *resistor approximations*

Every resistor has a small amount of inductance and capacitance. At lower frequencies the unwanted L and C have negligible effect. But as the frequency increases, the resistor no longer acts like a pure resistance.

exact circuit

Figure 1-2*a* shows the exact equivalent circuit of a resistor. The inductance exists because current through the resistor produces a magnetic field. The capacitance exists because voltage across the resistor produces an electric field.

At lower frequencies, the inductive reactance approaches zero and the capacitive reactance approaches infinity. In other words, the inductor appears shorted and the capacitor appears open. In this case, the resistor acts like a pure resistance.

We will refer to the inductance as the *lead inductance* because much of it is produced by the leads going into the resistor. And we will refer to the capacitance as the *stray capacitance* because it represents the lumped capacitance between the ends of the resistor.

second approximation

For most resistors the stray capacitance is more important than the lead inductance. This is why our second approximation is the parallel RC circuit of Fig. 1-2*b*. The stray capacitance of typical resistors (⅛ to 2 W) is in the vicinity of 1 pF, with the exact value determined by the length of the leads, the size of

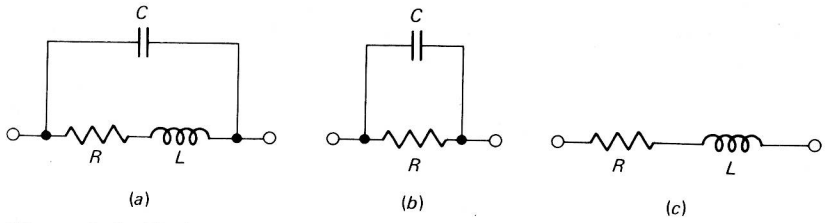


Figure 1-2. Resistor equivalent circuits. (a) *Exact.* (b) *Second approximation.* (c) *Third approximation.*

the resistor body, and other factors. When you need the exact capacitance value, you can measure it on an *RLC* bridge.

When is stray capacitance negligible? Many people use this guide: neglect stray capacitance when reactance is ten times greater than resistance. That is,

$$\frac{X_C}{R} > 10 \tag{1-1}$$

As an example, if a 10-kΩ resistor has 1 pF of stray capacitance, the X_C at 1 MHz equals

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(10^6)\ 10^{-12}}$$
$$= 159\ \text{k}\Omega$$

The ratio of reactance to resistance is

$$\frac{X_C}{R} = \frac{159\ \text{k}\Omega}{10\ \text{k}\Omega} = 15.9$$

This is greater than 10; therefore, we can neglect the stray capacitance of a 10-kΩ resistor operating at 1 MHz.

third approximation

When the resistance is very low, lead inductance is more important than stray capacitance. In this case, we use the third approximation of a resistor (Fig. 1-2*c*). This approximation includes lead inductance, approximately 0.02 μH/in for wire sizes commonly used in electronic circuits. (These sizes are from around AWG 18 to 26. AWG 18 has 0.018 μH/in; AWG 26 has 0.024 μH/in.)

When can you neglect lead inductance? The usual rule is this: neglect lead inductance when

$$\frac{R}{X_L} > 10 \tag{1-2}$$

For example, suppose the leads of a 1-kΩ resistor are cut to ½ in on each end. Then, the total lead length is 1 in. Estimating the inductance by 0.02 μH/in, we have a lead inductance of 0.02 μH. At 300 MHz, the reactance is

$$X_L = 2\pi fL = 2\pi(300)10^6(0.02)10^{-6}$$
$$= 37.7\ \Omega$$

and the ratio of resistance to reactance is

$$\frac{R}{X_L} = \frac{1000}{37.7} = 26.5$$

Therefore, even at 300 MHz we can neglect the lead inductance of a 1-kΩ resistor.

selecting an approximation

Which approximation of a resistor should you use? The ideal, the second, or the third? The answer depends on the frequency and the value of resistance.

By setting $X_C/R = 10$ and $R/X_L = 10$, we can plot frequency versus resistance as shown in Fig. 1-3. This graph gives the dividing lines between the ideal, second, and third approximations, assuming a stray capacitance of 1 pF and a lead inductance of 0.02 μH.

Here is how we use the graph. For any point below the two lines, we can idealize the resistor, that is, neglect its capacitance and inductance. On the other hand, if a point falls above either line, we may want to use the second or third approximation. For instance, a 10-kΩ resistor operating at 1 MHz can be idealized because it falls in the ideal region of Fig. 1-3. But if this 10-kΩ resistor operates at 5 MHz, we may include stray capacitance in precise calculations. Similarly, a 20-Ω resistor acts ideally up to 16 MHz, but beyond this frequency, the lead inductance becomes important.

Don't lean too heavily on Fig. 1-3; it is only a guide to help you estimate when to include stray capacitance or lead inductance in your calculations. If working at high frequencies where precise analysis is required, you may have to measure the stray capacitance and the lead inductance on a high-frequency *RLC* bridge.

1-3 *inductor and capacitor approximations*

Figure 1-4*a* shows the ideal, second, and third approximations of an inductor. For frequencies where only the X_L matters, we use the ideal approximation. But at lower frequencies where X_L is not large compared with R, we must use the second approximation. At higher frequencies, the distributed capacitance between the inductor windings becomes important. In this case, we need the third approximation shown in Fig. 1-4*a*. We will use these inductor approximations later.

Figure 1-4*b* shows the approximations for a capacitor. Most of the time, we can idealize a capacitor. For large capacitors, especially the electrolytic type, we may include the leakage resistance (the second approximation). And at the highest frequencies, the lead inductance becomes important; therefore, occasionally, we need the third approximation shown in Fig. 1-4*b*.

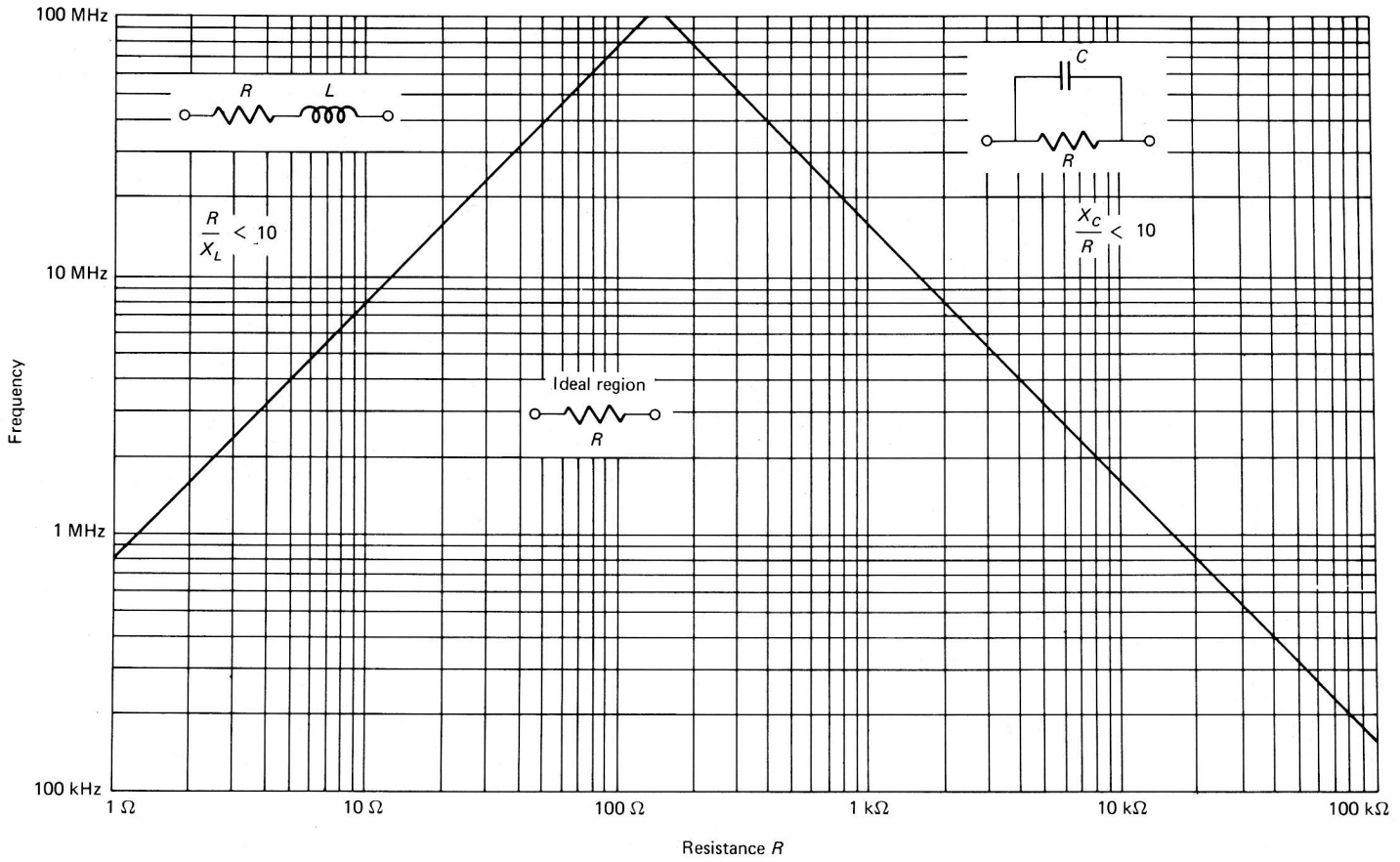


Figure 1-3. Approximation guide for resistors.