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Excerpt
More Information

Part I

Analog: Passive Devices

1N DC Circuits

Contents

1N.1 Overview

We will start by looking at circuits made up entirely of

- DC voltage sources (things whose output voltage is constant over time; things like a battery, or a lab power supply); and . . .
- resistors.

Sounds simple, and it is. We will try to point out quick ways to handle these familiar circuit elements. We will concentrate on one circuit fragment, the voltage divider.

1N.1.1 Why?

In each day’s class notes we will sketch the sort of task that the day’s material might let us accomplish. We do this to try to head off a challenge likely to occur to any skeptical reader: OK, this is a something-or-other circuit, but what’s it for? Why do I need a something-or-other? This is an integrator – but why do I want an integrator? Here is our first try at providing such a sample application:

Problem Given a constant (“DC”) voltage source, design a lower voltage source, strong enough to “drive” a particular “load” resistance.

Shorthand version of the problem: Make a voltage divider to deliver a specified voltage. Arrange things so that increasing load current to a maximum causes V_{out} to vary by no more than a specified percentage.

1N.1.2 What is "the art of electronics?"

Not art that you're likely to find in a museum,[1] but *art* in an older sense: a craft.[2] No doubt the title of *The Art of Electronics* (hereafter referred to as "AoE") was chosen with an awareness of the suggestion that there's something borderline-magical available here: perhaps a hint of "black art"?

AoE §1.1

Here is AoE's formulation of the subject of this course:

> *the laws, rules of thumb, and tricks that constitute the art of electronics as we see it.*

As you may have gathered, if you have looked at the text, this course differs from an engineering electronics course in concentrating on the "rules of thumb" and the bag of "tricks." You will learn to use rules of thumb and reliable "tricks" without apology. With their help you will be able to leave the calculator-bound novice engineer in the dust!

1N.1.3 What the course is *not* about

Wire my basement? Fix my TV?

Alumni of this course sometimes are asked for help that is beyond their capacities, and sometimes below – or beside – what they know. "So, now you can wire some outlets in my basement?" No. This course won't help much with that task, which is easy in a sense but difficult in another, in that it requires a detailed knowledge of electrical codes (required wire gauges; types of jacketing; where ground-fault-interrupters are required). And when your friend's TV quits, you're probably not going to want to fix it: much of the set's circuitry will be embodied in mysterious proprietary integrated circuits; an effective repair – if it were economically worthwhile – would likely amount to ordering a replacement for a substantial module, rather than replacing a burned-out resistor or transistor, as in the good old days of big and fixable devices.

Delivering power

A subtler point is worth making as well: only now and then, in this course, do we undertake to deliver *power* to something (the "something" is conventionally called a "load"). Occasionally, we are interested in doing that: when we want to make a loud sound from a speaker, or want to spin a motor. But much more often, we would like to minimize the flow of power; we are concerned, instead, with the flow of *information*.

On the wall of the lobby of MIT's Electrical Engineering building is a huge blowup of a photo of some MIT engineers standing among what look like large generators or motors, each about the size of a small cow. The photo in Fig. 1N.1 seems to date from the 1930s.

The "Electricals," back then, were concerned mostly with those big machines: with delivering power. It was the power companies that were hiring, when one of our uncles finished at MIT, around 1936. Hoover Dam, finished in 1935, was the engineering wonder of the day. Big was beautiful. (Even now, Hoover Dam's website boasts of the dam's *weight*! – 6.6 million tons, in case you were wondering.)

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[1] But see, if you find yourself in Munich, a spectacular exception: the world's greatest museum of science and technology, the Deutsches Museum. There you will find wonderful machines demonstrating such arcana as the history of the manufacture of threaded fasteners.

[2] "An industrial pursuit. . . of a skilled nature; a craft, business, profession." Oxford English Dictionary (1989).

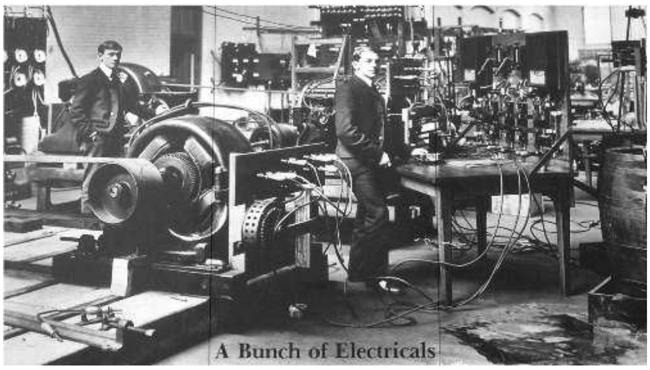

Figure 1N.1 Electronics ca. 1935 [used with permission of MIT.]

1N.1.4 What the course *is* about: processing *information*

Times have changed, as you may have noticed. Small is beautiful; nano is extra beautiful – and electronics, these days, is concerned mostly with processing information.[3] So, we like circuits that pass and process signals while generating very little heat – using very little power. We like, for example, digital circuits made out of field-effect transistors that form switches; they offer low output impedance, gargantuan input impedance, and quiescent current of approximately zero. To a good approximation, they're not transferring power, not using it, not delivering it. They're dealing in information. That's almost always what we'll be doing in this course.

Obvious, perhaps? Perhaps.

We will postpone till next time – not to overload you, on the first day – discussion of a related topic: just what form the *information* is likely to take, in our circuits: *voltage* versus *current*. The answer may surprise you; or you may be inclined to reject the question as empty, since you know that long ago Ohm taught us that current and voltage in a device can be intimately related. Next time, we'll try to persuade you that you ought not to reject the question; that it's worth considering whether the signal is represented as a *voltage* or as a *current* (and see Note 1S on this topic).

Now on to less abstract topics, and our first useful circuit: a *voltage divider*.

1N.2 Three laws

AoE §1.2.1

A glance at three *laws*: Ohm's law, and Kirchhoff's laws (Voltage – "KVL," and current – "KCL").

We rely on these rules continually, in electronics. Nevertheless, we rarely will mention Kirchhoff again. We use his observations *implicitly*. By contrast, we will see and use Ohm's law a lot; no one has gotten around to doing what's demanded by the bumper sticker one sees around MIT: *Repeal Ohm's Law!*

1N.2.1 Ohm's law: $V = IR$

- V is the analog of water pressure or 'head' of water
- R describes the restriction of flow
- I is the rate of flow (volume/unit time)

The homely hydraulic analogy works pretty well, if you don't push it too far – and if you're not too proud to use such an aid to intuition.

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[3] We guess a potentially big exception is the continuing struggle to produce an efficient and economically-viable *electrically-powered* car. Some glory awaits the *electricals* who succeed at that task.

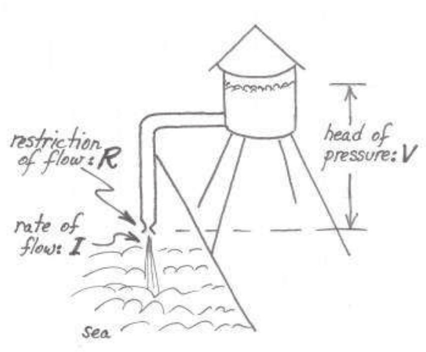

Figure 1N.2 Hydraulic analogy: voltage as head of water, etc. Use it if it helps your intuition.

What is "voltage," and other deeper questions

For the most part, we will evade such deep questions in this course. We're inclined to say, "Oh, a Volt is what pushes an Amp through an Ohm." But you don't have to be quite so glib (you don't have to sound so much like a Harvard student!). A less circular definition of *voltage* is the potential energy per unit charge. Or, equivalently, it can be defined as the work done to move a unit charge against an electric field (a word that we hope doesn't worry you; we suggest you try to get accustomed to use of the word, even if you have reservations about its usefulness[4]), from one electric potential (analogous to a position on a hillside) to a higher potential (higher on the hillside).

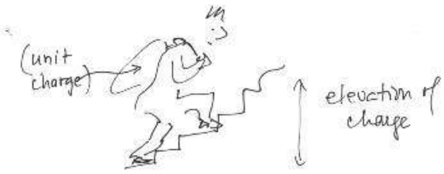

Figure 1N.3 Voltage is work to raise a unit charge from one level to a higher level (or "potential").

The voltage *difference* between two points on the hillside (or staircase, as in Fig. 1N.3) can be described as a difference in electric potential or voltage. The so-called "electric field" will tend to push that charge back down, just as gravity will tend to push the water down from the tank. You may or may not be interested to know that one volt is the work done as one adds one joule of potential energy to one coulomb of charge.[5] But we'll not again speak in these terms – which sound more like physics than like language for the "art of electronics."

"Ground"

Sometimes we speak of a voltage relative to some absolute reference – perhaps the planet earth (or, a bit more practically, the potential at the place where a copper spike has been driven into the ground, in the basement of the building where you are doing your electronics). In the hydraulic analogy, that absolute *zero*-reference might be sea-level. More often, as we will reiterate below, we are interested only in *relative* voltages: *differences* in potential, measured relative to an arbitrary reference point, not relative to planet earth.

Ohm's is a very useful rule; but it applies only to things that behave like *resistors*. What are these?

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[4] You may be inclined to wonder, as Purcell suggests in his excellent book, "…what is a field? Is it something real, or is it merely a name for a factor in an equation which has to be multiplied by something else to give the numerical value of the force we measure in an experiment?" E.M. Purcell and D.J. Morin, *Electricity and Magnetism*, 3rd ed. (2013), §1.7. Purcell makes a persuasive argument that the concept of "field" is useful.

[5] See Purcell and Morin, §2.2.

They are things that obey Ohm's Law! (Sorry folks: that's as deeply as we'll look at this question, in this course.[6])

Why does Ohm's law hold?

The restriction of current flow that we call "resistance" – which we might contrast with the very-easy flow of current in a piece of wire[7] – occurs because the charge-carrying electrons, accelerated by an electric field, bump into obstacles (vibrations of the atomic lattice) after a short free flight, and then have to be re-accelerated in the direction of the field. Materials that are good conductors – metals – have a substantial population of electrons that are not tightly bound, and consequently are free to travel when pushed. The conductivity of a metal depends on the density of the population of charge carriers (usually, un-bound electrons), and it's kind of reassuring to find that conductivity degrades with rising temperature: the free flights become shorter, as electrons bump into the jumpier atoms of the hotter material. This effect you will see confirmed in Lab 1L if things come out right in your experiment (you'll have to do a little reasoning to see this effect confirmed; the notes to Lab 1L do not point out where this occurs). The stronger the field, the faster the drift of the electrons. Field strength goes with *voltage* difference between two points on the conductor; rate of drift of the electrons measures *current*. So, Ohm's Law is pretty plausible.

AoE §C.4

What determines the value of a resistor?

A "resistor" is also, of course, a "conductor"; it may seem a bit perverse to call this thing that is inserted in a circuit to permit current flow a "resistor." But the name comes from the assumption that the resistor is inserted where an excellent conductor – a piece of wire – might have stood, instead. To make a resistor, one can use either of two strategies: to make a "carbon composition" resistor (the sort that we'll use in lab because their values are relatively easy to read), one mixes up a batch of powdered insulator and powdered conductor (carbon), adjusting the proportions to give the material a particular resistivity. To make a "metal film" resistor (much the more common type, these days), one "deposits" a thin film of metal on a ceramic substrate, and then partially cuts away the thin conducting film.

How generally does Ohm's law apply? We begin almost at once to meet devices that do *not* obey Ohm's Law (see Lab 1L: a lamp; a diode). Ohm's Law describes *one* possible relation between V and I in a component; but there are others. As AoE says,

> Crudely speaking, the name of the game is to make and use gadgets that have interesting and useful I versus V characteristics.

In a resistor, current and voltage are proportional in a nice, linear way: double the voltage and you get double the current. Ohm's Law holds. Don't expect to use it where it doesn't fit. Even the lamp – whose filament is just a piece of metal that one might expect would behave like a resistor – doesn't follow Ohm's Law, as you'll see in Lab 1L. Why not?[8]

AoE §1.2.6

. . . But we can extend the reach of Ohm's law? Dynamic resistance: After today, we rarely will limit ourselves to devices that show simply *resistance* – and as we have said, even the resistor-like lamp that you meet in Lab 1L, along with the *diode*, defy Ohm's-Law treatment. But an extended version of Ohm's Law that we'll call *dynamic resistance* will allow us to apply the familiar rule in

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[6] If this remark frustrates you, see an ordinary E&M book; for example, see the good discussion of the topic in E.M. Purcell and D.J. Morin, *Electricity & Magnetism*, 3rd ed. (2013), or in S. Burns and P. Bond, *Principles of Electronic Circuits* (1987).

[7] You may prefer the contrast with a superconductor, whose resistance is not just small but is *zero*.

[8] Here's a powerful clue: it *would* follow Ohm's Law if you could hold the filament's temperature constant.

settings where otherwise it would not work. The idea is just to define a *local* resistance – the tangent to the slope of the device's V–I curve:

$$R_{\text{dynamic}} \equiv \Delta V/\Delta I.$$

This redefinition allows us to talk about the effective resistance of a diode, a transistor, or a current source (a circuit that holds current constant). Here is a sketch of a diode's V–I curve – oriented so that V is the vertical axis. This orientation puts the curves' slopes into the familiar units, *Ohms* (rather than into 1/Ohms,[9] as in the more standard I–V plot).

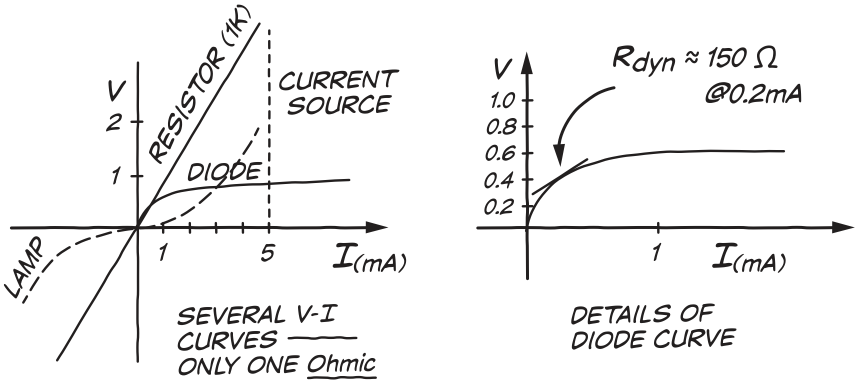

Figure 1N.4 Dynamic resistance illustrated: local slope can be defined for devices that are not Ohmic.

You may like the *resistor's* well-behaved straight line, because it is familiar. But the nice thing about the notion of R_{dynamic} is that is so broad-minded: it is happy to describe the V–I curve (or "I–V curve," as it is more often called) for any device. It will happily fit a transistor, an exotic current source – anything. The nearly-vertical plot of the *current source*, implying enormous R_{dynamic}, will become important to your understanding of transistors.

AoE §1.2.2C

Power in a resistor: Power is the rate of doing work, as you may recall from a course on mechanics. The concept comes up most often, in electronics, when one tries to specify a component that can safely handle the *power* that it is likely to have to dissipate. High power produces high heat, and calls for a component capable of unloading or dissipating that heat. The three resistors shown below illustrate the rough relation between power rating and size – because large size usually offers large area in contact with the surroundings or "ambient."

The indicated power ratings show the maximum that each can dissipate without damage. The tiny "surface-mount" on the left ("'0805 size," large by surface-mount standards) dissipates more than one might expect if one compares its size to that the of the 1/4W carbon-comp (the sort we use in the lab); it does better than one might expect because it is soldered directly to a circuit board, whose copper traces help to draw off and dissipate its heat.

In the coming labs you will sometimes run into the question whether your components can handle the power that is expected. Our usual resistors are rated at 1/4W. You can confirm that such a resistor can handle 15V (our usual maximum supply voltage) if the resistor's value is at least 1kΩ. Let's try that calculation: $P = I \times V$.

Thanks to Ohm's Law, the formula for power can be written in any of three ways:

- $P = I \times V$ (as we just said); but since $V = IR$,
- $P = I^2R$; and since $I = V/R$,

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[9] . . . or *Siemens*, the official name for inverse Ohms.

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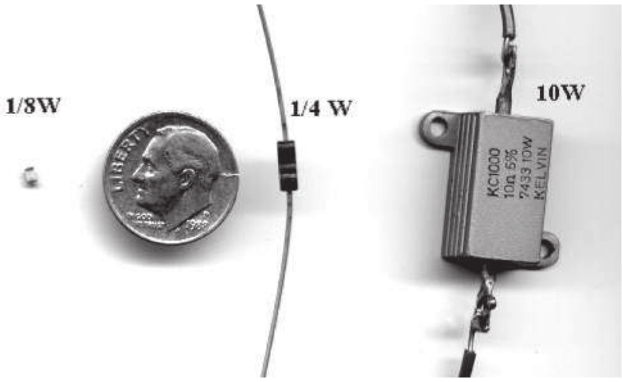

Figure 1N.5 Three resistors (plus a pretty good copper–nickel–alloy conductor).

- $P = V^2/R$

In the present case, it is the last form that is most useful. $1/4W = 15^2/R_{\text{min}}$. So $R_{\text{min}} = 225/(1/4) = 900$. So 1k is close to the minimum safe value, at 15V (910 would be safe, but let's not be so fussy; call it 1k).

So far, we have mentioned only power in a *resistor*. The notion is more general than that, and the formula,

$$P = V \times I$$

holds for any electronic component.

A closer look at what we mean by V and I makes this formula seem almost obvious:

- current measures charge/time
- voltage measures work/charge

So, the product, $V \times I$ = work/charge × charge/time = work/time, and this is *power*.

In this course, the exceptional cases where we do worry about power are those cases in which we either use large voltage swings (for example, the 30V output swing of the "comparator" in Lab 8L) or want to provide unusually large currents (for example, the speaker drive of Lab 6L, the light-emitting diode drive of the music-transmission lab, 13L, and the voltage regulators of Lab 11L).

1N.2.2 Kirchhoff's laws: V, I

These two 'laws' probably only codify what you think you know through common sense:

- Sum of voltages around the loop (or "circuit") is zero; see Fig. 1N.6, left.
- Sum of currents in and out of a node is zero (algebraic sum, of course); see Fig. 1N.6, right.

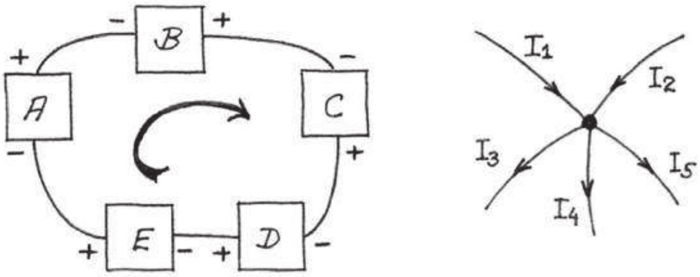

Figure 1N.6 Kirchhoff's two laws. Left: KVL – sum of voltages around a loop is zero; right: KCL – sum of currents in and out of a node is zero.

Applications of these laws: series *and* parallel circuits:

Series $I_{\text{total}} = I_1 = I_2$
Parallel $I_{\text{total}} = I_1 + I_2$
Series $V_{\text{total}} = V_1 + V_2$
Parallel $V_{\text{total}} = V_1 = V_2$

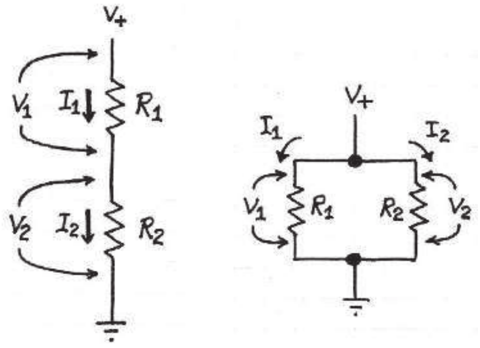

Figure 1N.7 Applications of Kirchhoff's laws: series and parallel circuits: a couple of truisms, probably familiar to you already

Query Incidentally, where is the "loop" that Kirchhoff's law refers to? *Answer:* the "loop" (or "circuit," a near-synonym) is apparent if one draws the voltage source as a circuit element, and ties its foot to the foot of the R: see Fig. 1N.8.

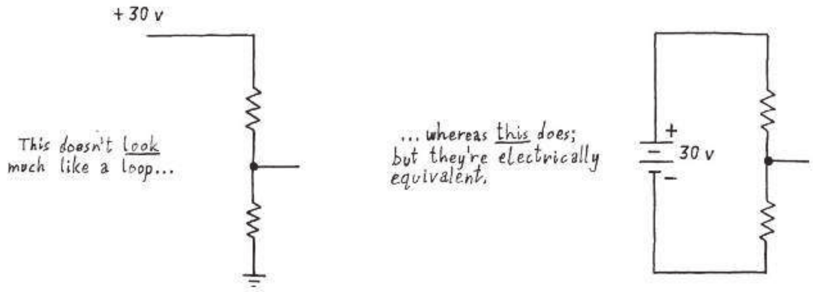

Figure 1N.8 Voltage divider redrawn to look more like a "loop" or "circuit".

Usually we don't bother to draw the voltage source that way; we label points with voltage values, and assume that you can picture the circuit path for yourself, if you choose to.

This is kind of *boring.* So, let's hurry on to less abstract circuits: to applications – and tricks. First, some labor-saving tricks.

Parallel resistances: calculating equivalent R

The *conductances* add:

$$\text{Conductance}_{\text{total}} = \text{Conductance}_1 + \text{Conductance}_2 = 1/R_1 + 1/R_2$$

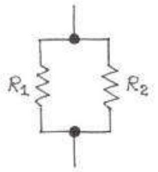

Figure 1N.9 Parallel resistors: the *conductances* add; unfortunately, the *resistances* don't.

This is the easy notion to remember, but not usually convenient to apply, for one rarely speaks of conductances. The notion "resistance" is so generally used that you will sometimes want to use the formula for the effective resistance of two parallel resistors:

$$R_{\text{tot}} = (R_1 \cdot R_2)/(R_1 + R_2)$$

Believe it or not, even this formula is messier than what we like to ask you to work with in this