Class 1: DC Circuits

Topics:

- What this course treats: Art? of Electronics
  DC circuits
  Today we will look 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.

Preliminary: What is "the art of electronics?"

Not an art, perhaps, but a craft. Here's the Text's formulation of what it claims to teach:

> ...the laws, rules of thumb, and tricks that constitute the art of electronics as we see it. (P. 1)

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 "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!

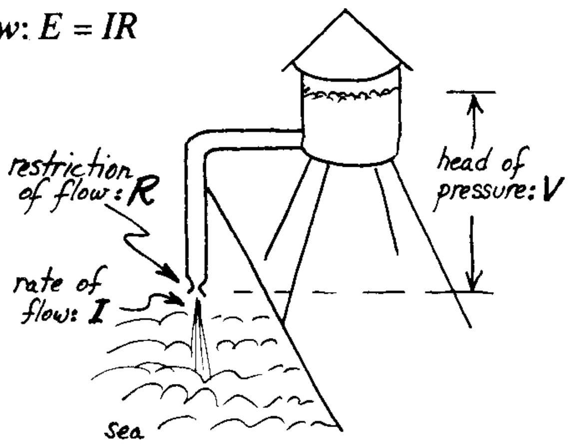
Two Laws

Text sec. 1.01

First, a glance at two *laws*: Ohm's Law, and Kirchhoff's Laws (V,I).

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

Ohm's Law: $E = IR$



E (old-fashioned term for voltage) is analog of water pressure or 'head' of water

R describes the restriction of flow

I is the rate of flow (volume/unit time)

Figure N1.1: Hydraulic analogy: voltage as head of water, etc. Use it if it helps your intuition

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.

Ohm's is a very useful rule; but it applies only to things that behave like *resistors*. What are these? They are things that obey Ohm's Law! (Sorry folks: that's as deeply as we'll look at this question, in this course[1].)

We begin almost at once to meet devices that do *not* obey Ohm's Law (see Lab 1: a lamp; a diode). Ohm's Law describes *one* possible relation between V and I in a component; but there are others.

As the text says,

> Crudely speaking, the name of the game is to make and use gadgets that have interesting and useful I vs V characteristics. (P. 4)

Kirchhoff's Laws (V,I)

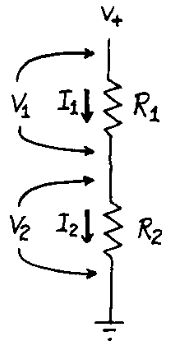
These two 'laws' probably only codify what you think you know through common sense:

Sum of voltages around loop (circuit) is zero.

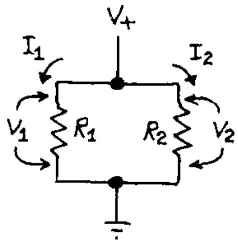
Sum of currents in & out of node is zero (algebraic sum, of course).

Figure N1.2: Kirchhoff's two laws

Applications of these laws: <u>series</u> <u>and</u> <u>parallel</u> <u>circuits</u>



Series: $I_{total} = I_1 = I_2$
$V_{total} = V_1 + V_2$
(current same everywhere; voltage divides)



Parallel: $I_{total} = I_1 + I_2$
$V_{total} = V_1 = V_2$
(voltage same across all parts; current divides)

Figure N1.3: 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?

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

1. If this remark frustrates you, see an ordinary E & M book; for example, see the good discussion of the topic in E. M. Purcell, <u>Electricity & Magnetism</u>, cited in the Text (2d ed., 1985), or in S. Burns & P. Bond, <u>Principles of Electronic Circuits</u> (1987).

Parallel Resistances: calculating equivalent R

The *conductances* add:
conductance$_{total}$ = conductance$_1$ + conductance$_2$ = $1/R_1 + 1/R_2$

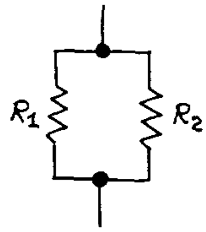


Figure N1.4: Parallel resistors: the *conductances* add; unfortunately, the *resistances* don't

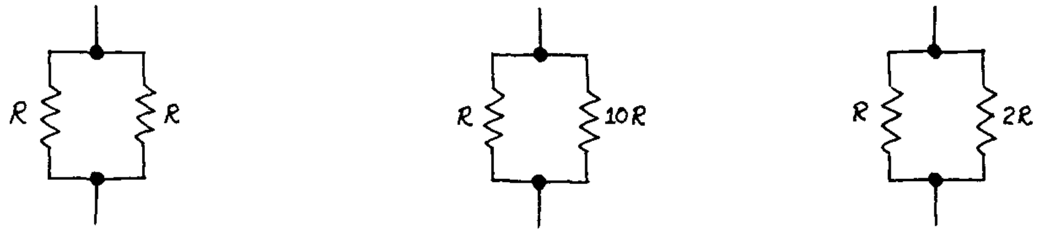
This is the easy notion to remember, but not usually convenient to apply, for one rarely speaks of conductances. The notion "resistance" is so generally used that you will sometimes want to use the formula for the effective resistance of two parallel resistors:

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

Believe it or not, even this formula is messier than what we like to ask you to work with in this course. So we proceed immediately to some tricks that let you do most work in your head.

Text sec. 1.02

Consider some easy cases:



two equal R's two very unequal R's R, 2R

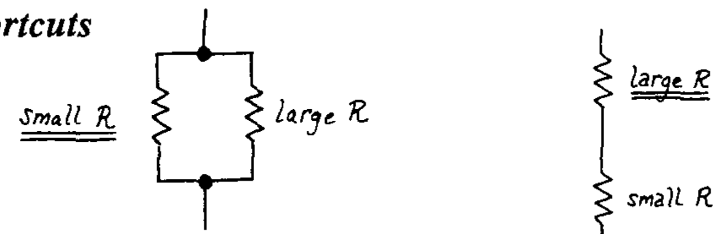
Figure N1.5: Parallel R's: Some easy cases

The first two cases are especially important, because they help one to *estimate* the effect of a circuit one can liken to either case. Labor-saving tricks that give you an estimate are not to be scorned: if you see an easy way to an estimate, you're likely to make the estimate. If you have to work to hard to get the answer, you may find yourself simply *not* making the estimate.

In this course we usually are content with answers good to 10%. So, if two parallel resistors differ by a factor of ten, then we can ignore the larger of the two.

Let's elevate this observation to a rule of thumb (our first). While we're at it, we can state the equivalent rule for resistors in series.

Parallel resistances: shortcuts



In a parallel circuit, a resistor much *smaller* than others dominates.
In a series circuit, the *large* resistor dominates.

Figure N1.6: Resistor calculation shortcut: parallel, series

Voltage Divider

Text sec. 1.03

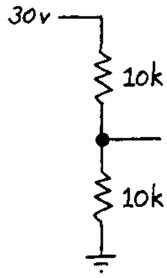


Figure N1.7: Voltage divider

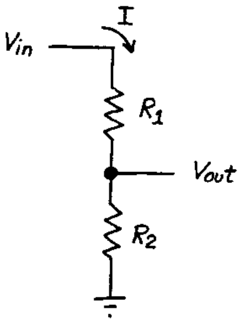
At last we have reached a circuit that does something useful.

First, a *note on labeling*: we label the resistors "10k"; we omit "Ω." It goes without saying. The "k" means kilo- or 10^3, as you probably know.

One can calculate V_{out} in several ways. We will try to push you toward the way that makes it easy to get an answer in your head.

Three ways:

1. Calculate the current through the series resistance; use that to calculate the voltage in the lower leg of the divider.



$I = V_{in} / (R_1 + R_2)$

Here, that's 30v / 20kΩ = 1.5 mA

$V_{out} = I \cdot R_2$

Here, that's 1.5 mA · 10k = 15 v

Figure N1.8: Voltage divider: first method (too hard!): calculate current explicitly

That takes too long.

2. Rely on the fact that I is constant in top and bottom, but do that implicitly. If you want an algebraic argument, you might say,

$$V_2/(V_1 + V_2) = IR_2 / (I[R_1 + R_2]) = R_2 / (R_1 + R_2)$$

or,

$$(1),\ V_{out} = V_{in}\ \{R_2 / (R_1 + R_2)\}$$

In this case, that means

$$V_{out} = V_{in}\ (10k/20k) = V_{in}/2$$

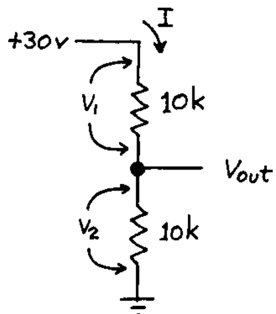


Figure N1.9: Voltage divider: second method: (a little better): current implicit

That's *much better*, and you will use formula (*1*) fairly often. But we would like to push you not to memorize that equation, but instead to—

3. Say to yourself in words how the divider works: something like,

> *Since the currents in top and bottom are equal, the voltage drops are proportional to the resistances* (later, *impedances*—a more general notion that covers devices other than resistors).

So, in this case, where the lower R makes up half the total resistance, it also will show half the total voltage.

For another example, if the lower leg is 10 times the upper leg, it will show about 90% of the input voltage (10/11, if you're fussy, but 90%, to our usual tolerances).

Loading, and "output impedance"

Text sec. 1.05,

Now—after you've calculated V_{out} for the divider—suppose someone comes along and puts in a third resistor:

Text exercise 1.9

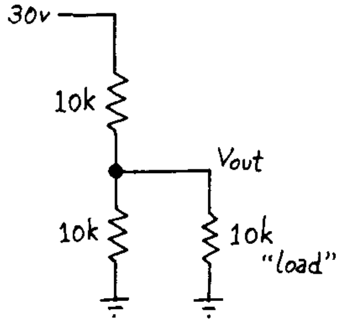


Figure N1.10: Voltage divider *loaded*

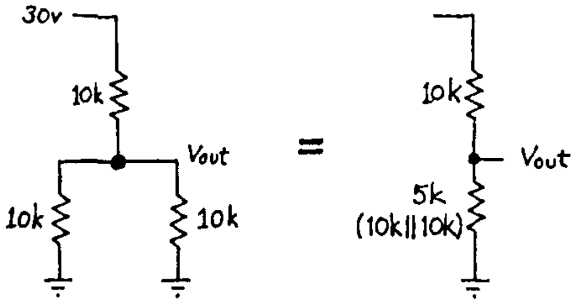
(*Query:* Are you entitled to be outraged? Is this no fair?) Again there is more than one way to make the new calculation—but one way is tidier than the other.

Two possible methods:

1. Tedious Method:

Text exercise 1.19

Model the two lower R's as one R; calculate V_{out} for this new voltage divider:



The new divider delivers 1/3 V_{in}

Figure N1.11: Voltage divider *loaded*: load and lower R combined in model

That's reasonable, but it requires you to draw a new model to describe each possible loading.

2. *Better method*: Thevenin's.

Text sec. 1.05

Thevenin Model

Thevenin's good idea:

Model the actual circuit (unloaded) with a simpler circuit—the *Thevenin model*—which is an idealized voltage source in series with a resistor. One can then see pretty readily how that simpler circuit will behave under various loads.

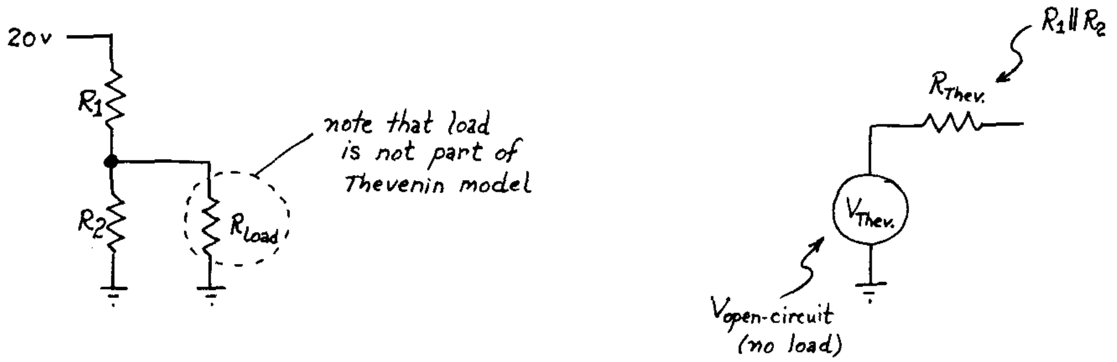


Figure N1.12: Thevenin Model: perfect voltage source in series with output resistance

Here's how to calculate the two elements of the Thevenin model:

V_{Thevenin}: Just $V_{\text{open circuit}}$: the voltage out when nothing is attached ("no load")

R_{Thevenin}: *Defined* as the quotient of $V_{\text{Thevenin}} / I_{\text{short-circuit}}$, which is the current that flows from the circuit output to ground if you simply *short* the output to ground.

In practice, you are not likely to discover R_{Thev} by so brutal an experiment; and if you have a diagram of the circuit to look at, there is a much faster shortcut:

Shortcut calculation of $\underline{R}_{Thev}$

Given a circuit diagram, the fastest way to calculate R_{Thev} is to see it as *the parallel resistance of the several resistances viewed from the output*.

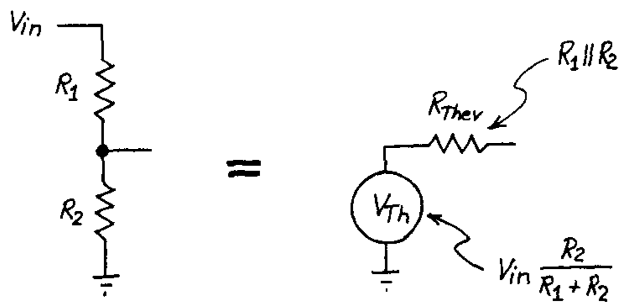


Figure N1.13: $R_{Thev} = R_1$ parallel R_2

(This formulation assumes that the voltage sources are ideal, incidentally; when they are not, we need to include their output resistance. For the moment, let's ignore this complication.)

You saw this result above, but this still may strike you as a little odd: why should R_1, going up to the positive supply, be treated as *parallel* to R_2? Well, suppose the positive supply were set at 0 volts. Then surely the two resistances would be in parallel, right?

Or suppose a different divider (chosen to make the numbers easy): twenty volts divided by two 10k resistors. To discover the *impedance* at the output, do the usual experiment (one that we will speak of again and again):

A general definition and procedure to determine <u>impedance</u> at a point:
To discover the *impedance* at a point:
apply a ΔV; find ΔI.
The quotient is the impedance

This you will recognize as just a "small-signal" or "dynamic" version of Ohm's Law.

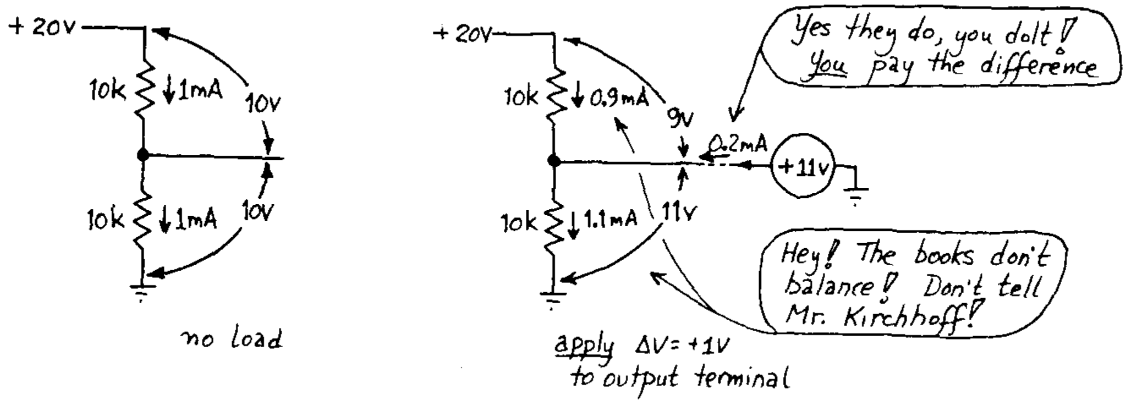


Figure N1.14: Hypothetical divider: current = 1 mA; apply a wiggle of voltage, ΔV; see what ΔI results

In this case 1 mA was flowing before the wiggle. After we force the output up by 1v, the currents in top and bottom resistors no longer match: upstairs: 0.9 mA; downstairs, 1.1 mA. The difference must come from you, the wiggler.

Result: impedance = $\Delta V / \Delta I$ = 1v / 0.2 mA = 5 k

And—happily—that is the parallel resistance of the two R's. Does that argument make the result easier to accept?

You may be wondering why this model is useful. Here is one way to put the answer, though probably you will remain skeptical until you have seen the model at work in several examples: Any non-ideal voltage source "droops" when loaded. How much it droops depends on its "output impedance". The Thevenin equivalent model, with its $R_{Thevenin}$, describes this property neatly in a single number.

Applying the Thevenin model

First, let's make sure Thevenin had it right: let's make sure his model behaves the way the original circuit does. We found that the 10k, 10k divider from 30 volts, which put out 15v when not loaded, drooped to 10V under a 10k load. Does the model do the same?

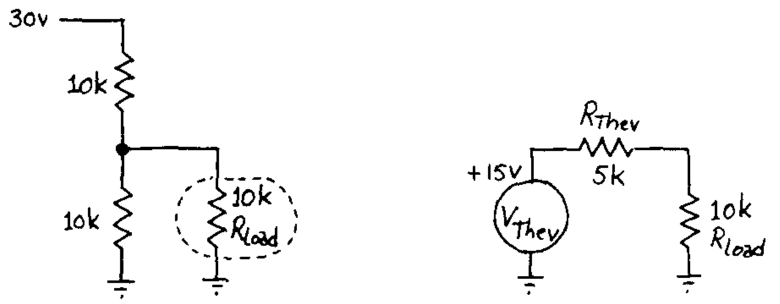


Figure N1.15: Thevenin model and load: droops as original circuit drooped

Yes, the model droops to the extent the original did: down to 10 v. What the model provides that the original circuit lacked is that single value, R_{Thev}, expressing how droopy/stiff the output is.

If someone changed the value of the load, the Thevenin model would help you to see what droop to expect; if, instead, you didn't use the model and had to put the two lower resistors in parallel again and recalculate their parallel resistance, you'd take longer to get each answer, and still you might not get a feel for the circuit's *output impedance*.

Let's try using the model on a set of voltage sources that differ *only* in R_{Thev}. At the same time we can see the effect of an instrument's *input impedance*.

Suppose we have a set of voltage dividers, dividing a 20v input by two. Let's assume that we use 1% resistors (value good to ±1%).

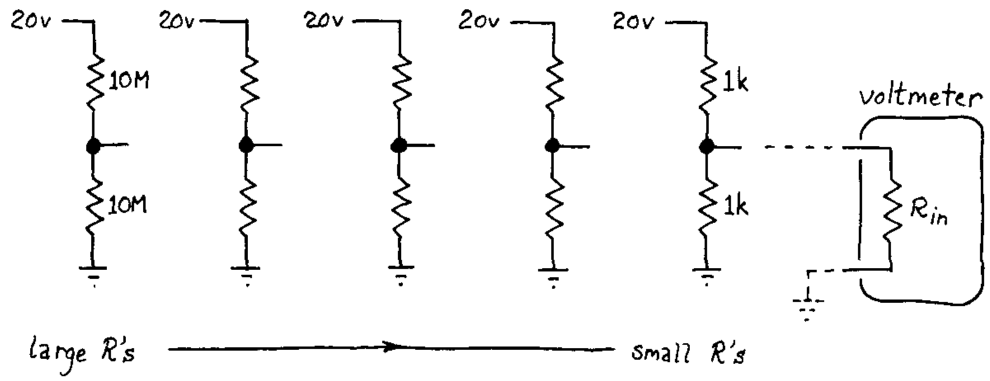


Figure N1.16: A set of similar voltage dividers: same V_{Th}, differing R_{Th}'s

V_{Thev} is obvious, and is the same in all cases. R_{Th} evidently varies from divider to divider.

Suppose now that we try to *measure* V_{out} at the output of each divider. If we measured with a *perfect* voltmeter, the answer in all cases would be 10v. (*Query*: is it 10.000v? 10.0v?)

But if we actually perform the measurement, we will encounter the R_{in} of our imperfect lab voltmeters. Let's try it with a VOM ("volt-ohm-meter," the conventional name for the old-fashioned "analog" meter, which gives its answers by deflecting its needle to a degree that forms an analog to the quantity measured), and then with a DVM ("digital voltmeter," a more recent invention, which usually can measure current and resistance as well as voltage, despite its name; both types sometimes are called simply "multimeters").

Suppose you poke the several divider outputs, beginning from the right side, where the resistors are 1kΩ. Here's a table showing what we find, at three of the dividers:

R values, divider	Measured V_{out}	Inference
1k	9.95	within R tolerance
10k	9.76	loading barely apparent
100k	8.05	loading obvious

The 8.05 v reading shows such obvious loading—and such a nice round number, if we treat it as "8 v"—that we can use this to calculate the meter's R_{in} without much effort:

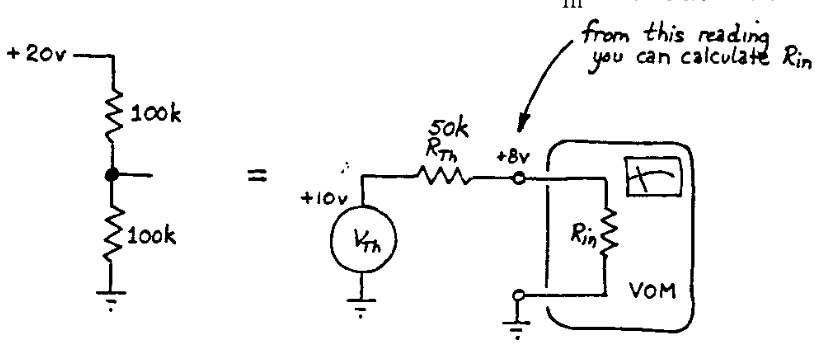


Figure N1.17: VOM reading departs from ideal; we can infer $R_{\text{in-VOM}}$

As usual, one has a choice now, whether to pull out a formula and calculator, or whether to try, instead, to do the calculation "back-of-the-envelope" style. Let's try the latter method.

First, we know that R_{Thev} is 100k parallel 100k: 50k. Now let's talk our way to a solution (an *approximate* solution: we'll treat the measured V_{out} as just "8 volts":

> The meter shows us 8 parts in 10; across the divider's R_{Thev} (or call it "R_{out}") we must be dropping the other 2 parts in 10. The relative sizes of the two resistances are in proportion to these two voltage drops: 8 to 2, so $R_{in\text{-}VOM}$ must be 4 • R_{Thev}: 200k.

If we squint at the front of the VOM, we'll find a little notation,

20,000 ohms/volt

That specification means that if we used the meter on its *1 V* scale (that is, if we set things so that an input of 1 volt would deflect the needle fully), then the meter would show an input resistance of 20k. In fact, it's showing us 200k. Does that make sense? It will when you've figured out what must be inside a VOM to allow it to change voltage ranges: a set of big series resistors. You'll understand this fully when you have done problem 1.8 in the text; for now, take our word for it: our answer, 200k, is correct when we have the meter set to the *10 V* scale, as we do for this measurement.

This is probably a good time to take a quick look at what's inside a multimeter—VOM or DVM:

How a meter works:

Depends on type.

—depends whether the basic works of the meter sense *current* or *voltage*.

- analog: senses current

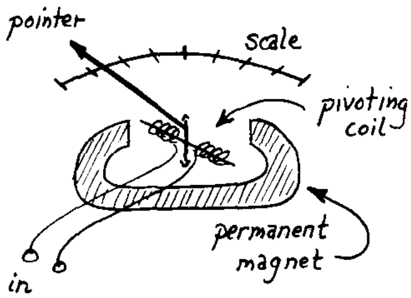


Figure N1.18: Analog meter senses current, in its guts

- digital: senses voltage

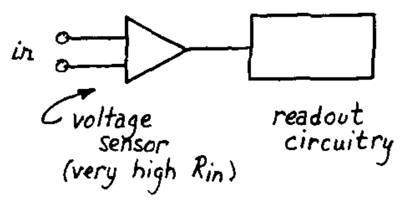


Figure N1.19: Digital meter senses voltage, in its innards

The VOM specification, 20,000 ohms/volt, describes the sensitivity of the meter *movement*—the guts of the instrument. This movement puts a fairly low ceiling on the VOM's input resistance at a given range setting.

Let's try the same experiment with a DVM, and let's suppose we get the following readings:

R values, divide	Measured V_{out}	Inference
100k	9.92	within R tolerance
1M	9.55	loading apparent
10M	6.69	loading obvious

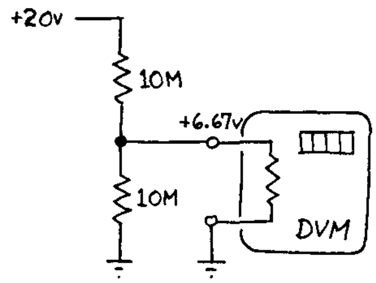


Figure N1.20: DVM reading departs from ideal; we can infer $R_{in\text{-}DVM}$

Again let's use the case where the droop is obvious; again let's talk our way to an answer:

> This time R_{Th} is 5M; we're dropping 2/3 of the voltage across $R_{in\text{-}DVM}$, 1/3 across R_{Th}. So, $R_{in\text{-}DVM}$ must be $2 \cdot R_{Th}$, or 10M.

If we check the data sheet for this particular DVM we find that its R_{in} is specified to be "≥ 10M, all ranges." Again our readings make sense.

VOM vs DVM: a conclusion?

Evidently, the DVM is a better voltmeter, at least in its R_{in}—as well as much easier to use. As a current meter, however, it is no better than the VOM: it drops 1/4 v full scale, as the VOM does; it measures current simply by letting it flow through a small resistor; the meter then measures the voltage across that resistor.

Digression on ground

The concept "ground" ("earth," in Britain) sounds solid enough. It turns out to be ambiguous. Try your understanding of the term by looking at some cases:

Figure N1.21: Ground in two senses

Query: what is the resistance between points A and B? (Easy, if you don't think about it too hard.) We know that the ground symbol means, in any event, that the bottom ends of the two resistors are electrically joined. Does it matter whether that point is also tied to the pretty planet we live on? It turns out that it does not.

And where is "ground" in this circuit:

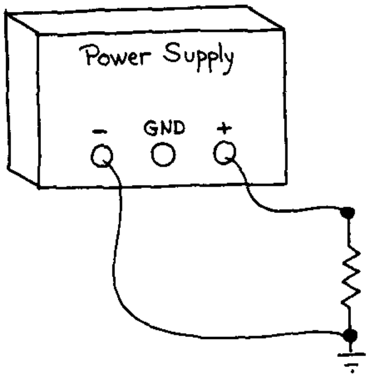


Figure N1.22: Ground in two senses, revisited

Local ground is what we care about: the common point in our circuit that we arbitrarily choose to call zero volts. Only rarely do we care whether or not that local reference is tied to a spike driven into the earth. But, ***be warned,*** sometimes you are confronted with lines that are tied to world ground—for example, the ground clip on a scope probe, *and the* "ground" of the breadboards that we use in the lab; then you must take care not to clip the scope ground to, say, +15 on the breadboard.

Generalizing what we've learned of R_{in} and R_{out}

The voltage dividers whose outputs we tried to measure introduced us to a problem we will see over and over again: some circuit tries to "drive" a load. To some extent, the load changes the output. We need to be able to predict and control this change. To do that, we need to understand, first, the characteristic we call R_{in} (this rarely troubles anyone) and, second, the one we have called $R_{Thevenin}$ (this one takes longer to get used to). Next time, when we meet frequency-dependent circuits, we will generalize both characteristics to "Z_{in}" and "Z_{out}."

Here we will work our way to another rule of thumb; one that will make your life as designer relatively easy. We start with a goal: *Design goal:* When circuit A drives circuit B: arrange things so that B loads A lightly enough to cause only insignificant attenuation of the signal. And this goal leads to the rule of thumb:

Design rule of thumb:

When circuit A drives circuit B:

Let R_{out} for A be ≤ 1/10 R_{in} for B

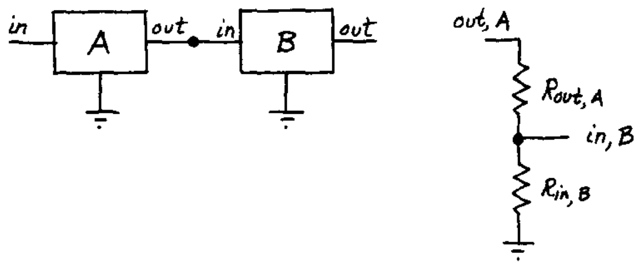


Figure N1.23: Circuit A drives circuit B

How does this rule get us the desired result? Look at the problem as a familiar voltage divider question. If R_{outA} is much smaller than R_{inB}, then the divider delivers nearly all of the original signal. If the relation is 1 : 10, then the divider delivers 10/11 of the signal: attenuation is just under 10%, and that's good enough for our purposes.

We like this arrangement not just because we like big signals. (If that were the only concern, we could always boost the output signal, simply amplifying it.) We like this arrangement above all because it *allows us to design circuit-fragments independently*: we can design A, then design B, and so on. We need not consider A,B as a large single circuit. That's good: makes our work of design and analysis lots easier than it would be if we had to treat every large circuit as a unit.

An example, with numbers: What R_{Thev} for droop of < 10%? What R's, therefore?

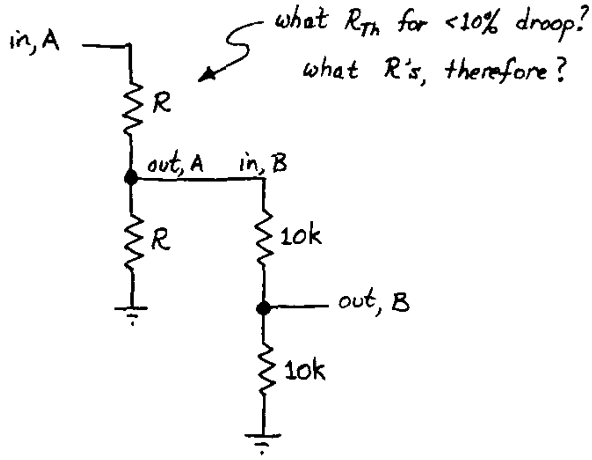


Figure N1.24: One divider driving another: a chance to apply our rule of thumb

The effects of this rule of thumb become more interesting if you extend this chain: from A and B, on to C.

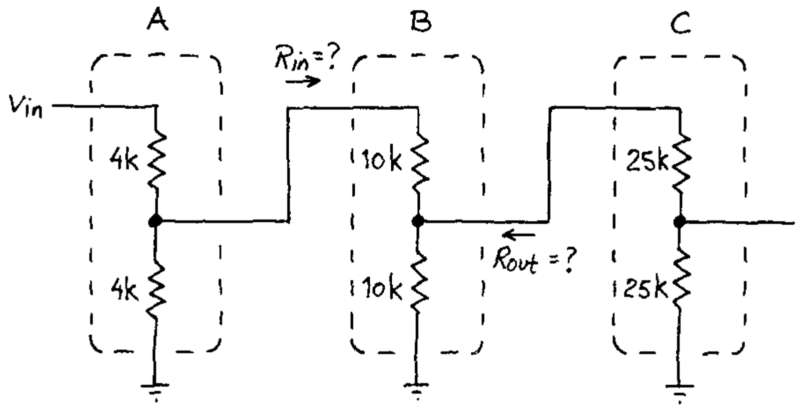


Figure N1.25: Extending the divider: testing the claim that our rule of thumb lets us consider one circuit fragment at a time

As we design C, what R_{Thev} should we use for B? Is it just 10K parallel 10K? That's the answer if we can consider B by itself, using the usual simplifying assumptions: source ideal ($R_{out} = 0$) and load ideal (R_{in} infinitely large).

But should we be more precise? Should we admit that the upper branch really looks like 10K + 2K: 12k? Oh dear! That's 20% different. Is our whole scheme crumbling? Are we going to have to look all the way back to the start of the chain, in order to design the next link? Must we, in other words, consider the whole circuit at once, not just the fragment B, as we had hoped?

No. Relax. That 20% error gets diluted to half its value: R_{Thev} for B is 10k *parallel 12k*, but that's a shade under 5.5k. So—fumes of relief!—we need not look beyond B. We can, indeed, consider the circuit in the way we had hoped: fragment by fragment.

If this argument has not exhausted you, you might give our claim a further test by looking in the other direction: does C alter B's input resistance appreciably (>10%)? You know the answer, but confirming it would let you check your understanding of our rule of thumb and its effects.

Chapter 1: Worked Examples: Resistors & Instruments

Five worked examples:

1. Design a voltmeter and ammeter from bare meter movement
2. Effects of instrument imperfections, in first lab (L1-1)
3. Thevenin models
4. R_{in}, R_{out}
5. Effect of loading

1. Design a Voltmeter, Current Meter

Text sec. 1.04, ex. 1.8, p. 10

> ***Problem: Modify a meter movement to form a voltmeter and ammeter***
>
> A 50µA meter movement has an internal resistance of 5k. What shunt resistance is needed to convert it to a 0-1 amp meter? What series resistance will convert it to a 0-10 volt meter?

This exercise gives you a useful insight into the instrument, of course, but it also will give you some practice in judging when to use approximations: how precise to make your calculations, to say this another way.

1 amp meter

"50µA meter movement" means that the needle deflects fully when 50µA flows through the movement (a coil that deflects in the magnetic field of a permanent magnet: see Class 1 notes for a sketch). The remaining current must bypass the movement; but the current through the movement must remain proportional to the whole current.

Such a long sentence makes the design sound complicated. In fact, as probably you have seen all along, the design is extremely simple: just add a resistance in parallel with the movement (this is the "shunt" mentioned in the problem):

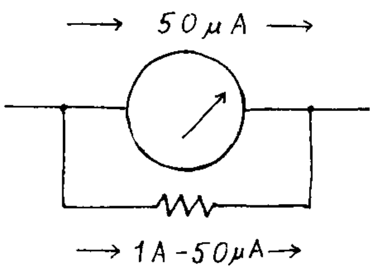


Figure X1.1: Shunt resistance allows sensitive meter movement to measure a total current of 1 A

What value?

Well, what else do we know? We know the *resistance* of the meter movement. That characteristic plus the full-scale current tell us the *full-scale voltage drop* across the movement: that's

$$V_{movement(full\text{-}scale)} = I_{full\text{-}scale} \bullet R_{movement} = 50\ \mu A \bullet 5k\Omega = 250\ mV$$

Now we can choose R_{shunt}, since we know current and voltage that we want to see across the parallel combination. At this point we have a chance to work too hard, or instead to use a sensible approximation. The occasion comes up as we try to answer the question, 'How much current should pass through the shunt?'

One possible answer is '1A less 50μA, or 0.99995 A."

Another possible answer is '1A.'

Which do you like? If you're fresh from a set of Physics courses, you may be inclined toward the first answer. If we take that, then the resistance we need is

$$R = V_{\text{full-scale}} / I_{\text{full-scale}} = 250\text{ mV} / 0.99995\text{A} = 0.2500125\Omega$$

Now in some settings that would be a good answer. In this setting, it is not. It is a very silly answer. That resistor specification claims to be good to a few parts in a million. If that were possible at all, it would be a preposterous goal in an instrument that makes a needle move so we can squint at it.

So we should have chosen the second branch at the outset: seeing that the 50μA movement current is small relative to the the 1A total current, we should then ask ourselves, 'About how small (in fractional or percentage terms)?' The answer would be '50 parts in a million.' And that fraction is so small relative to reasonable resistor tolerances that we should conclude at once that we should neglect the 50μA.

Neglecting the movement current, we find the shunt resistance is just 250mV/1A = 250 mΩ. In short, the problem is very easy if we have the good sense to let it be easy. You will find this happening repeatedly in this course: if you find yourself churning through a lot of math, and especially if you are carrying lots of digits with you, you're probably overlooking an easy way to do the job. There is no sense carrying all those digits and then having to reach for a 5% resistor and 10% capacitor.

Voltmeter

Here we want to arrange things so that 10V applied to the circuit causes a full-scale deflection of the movement. Which way should we think of the cause of that deflection—'50μA flowing,' or '250 mV across the movement?'

Either is fine. Thinking in *voltage* terms probably helps one to see that most of the 10V must be dropped across some element we are to add, since only 0.25V will be dropped across the meter movement. That should help us sketch the solution:

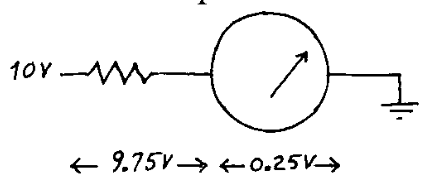


Figure X1.2: Voltmeter: series resistance needed

What series resistance should we add? There are two equivalent ways to answer:

1. The resistance must drop 9.75 volts out of 10, when 50μA flows; so R = 9.75V/50μA = 195kΩ
2. Total resistance must be 10V /50μA = 200kΩ. The meter movement looks like 5k, we were told; so we need to add the difference, 195kΩ.

If you got stung on the first part of this problem, giving an answer like "0.2500125Ω," then you might be inclined to say, 'Oh, 50μA is very small; the meter is delicate, so I'll neglect it. I'll put in a 200k series resistor, and be just a little off.'

Well, just to keep you off-balance, we must now push you the other way: this time, "50μA," though a small current is not negligibly small, because it is not to be compared with some much larger current. On the contrary, it is the crucial characteristic we need to work with: it determines the value of the series resistor. And we should *not* say '200k is close enough,' though 195k is the exact answer. The difference is 2.5%: much less than what we ordinarily worry about in this course (because we need to get used to components with 5 and 10% tolerances); but in a meter it's surely worth a few pennies extra to get a 1% resistor: a 195k.

2. Lab 1-1 questions: working around imperfections of instruments

The very first lab exercise asks you to go through the chore of confirming Ohm's Law. But it also confronts you at once with the difficulty that you cannot quite do what the experiment asks you to do: measure I and V in the resistor simultaneously. Two placements of the DVM are suggested (one is drawn, the other hinted at):

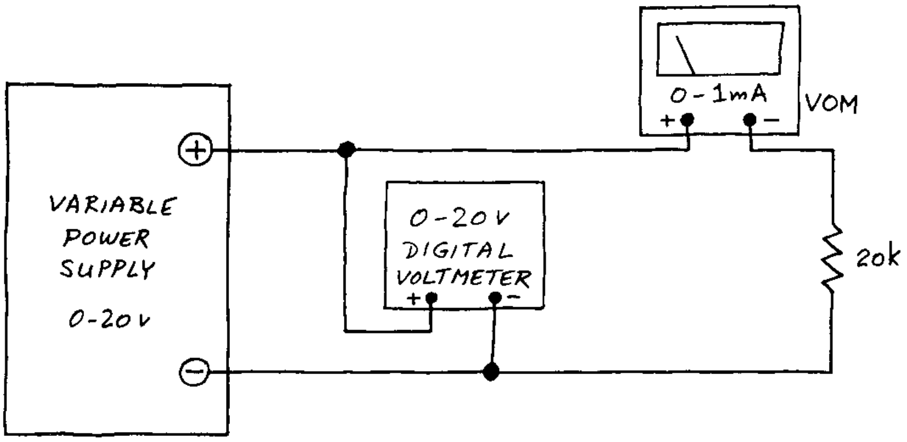


Figure X1.3: Lab 1-1 setup: DVM and VOM cannot both measure the relevant quantity

A Qualitative View

Just a few minutes' reflection will tell you that the voltage reading is off, in the circuit as drawn; moving the DVM solves that problem (above), but now makes the current reading inaccurate.

A Quantitative View

Here's the problem we want to spend a few minutes on:

Problem:

Errors caused by the Meters

If the analog meter movement is as described in the Text's problem 1.8, what percentage error in the *voltage* reading results, if the voltage probe is connected as shown in the figure for the first lab 1 experiment, when the measured resistor has the following values. Assume that you are applying 20 volts, and that you can find a meter setting that lets you get *full-scale deflection* in the current meter.

- R = 20k ohms.
- R = 200 ohms.
- R = 2M ohms.

Same question, but concerning *current* measurement error, if the voltmeter probe is moved to connect directly to the top of the resistor, for the same resistor values. Assume the DVM has an input resistance of 20 M ohms.

Errors in Voltage readings

The first question is easier than it may appear. The error we get results from the voltage drop across the current meter; but we know what that drop is, from problem 1.8: full-scale: 0.25V. So, the resistor values do not matter. Our voltage readings always are high by a quarter volt, if we can set the current meter to give full-scale deflection. The value of the resistor being measured does *not* matter.

When the DVM reads 20V, the true voltage (at the top of the resistor) is 19.75V. Our voltage reading is high by 0.25V/19.75V—about 0.25/20 or 1 part in 80: 1.25% (If we applied a lower voltage, the voltage error would be more important, assuming we still managed to get full-scale deflection from the current meter, as we might be able to by changing ranges).

Errors in Current readings

If we move the DVM to the top of the resistor, then the voltage reading becomes correct: we are measuring what we meant to measure. But now the current meter is reading a little high: it measures not only the resistor current but also the DVM current, which flows parallel to the current in *R*.

The size of *this* error depends directly on the size of *R* we are measuring. You don't even need a pencil and paper to calculate how large the errors are:

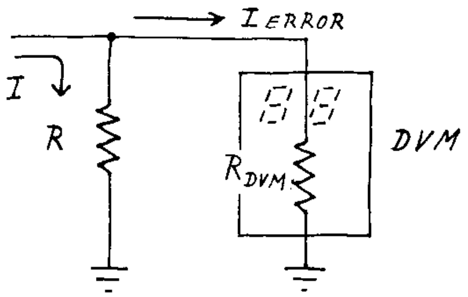


Figure X1.4: DVM causes current-reading error: how large? % error same as ratio of R to R_{DVM}

If *R* is 20kΩ	—and the DVM looks like 20M—then one part in a thousand of the total current flows through the DVM: the current reading will be high by 0.1%.
If *R* is 200Ω	then the current error is minute: 1 part in 100,000: 0.001%.
If *R* is 2MΩ	then the error is large: 1 part in ten.

Conclusion?

There is *no* general answer to the question, 'Which is the better way to place the DVM in this circuit?' The answer depends on *R*, on the applied voltage and on the consequent ammeter range setting.

And before we leave this question, let's notice the implication of that last phrase: the error depends on the VOM *range* setting. Why? Well, this is our first encounter with the concept we like to call Electronic Justice, or the principle that The Greedy Will Be Punished. No doubt these names mystify you, so we'll be specific: the thought is that if you want good resolution from the VOM, you will pay a price: the meter will alter results more than if you looked for less resolution:

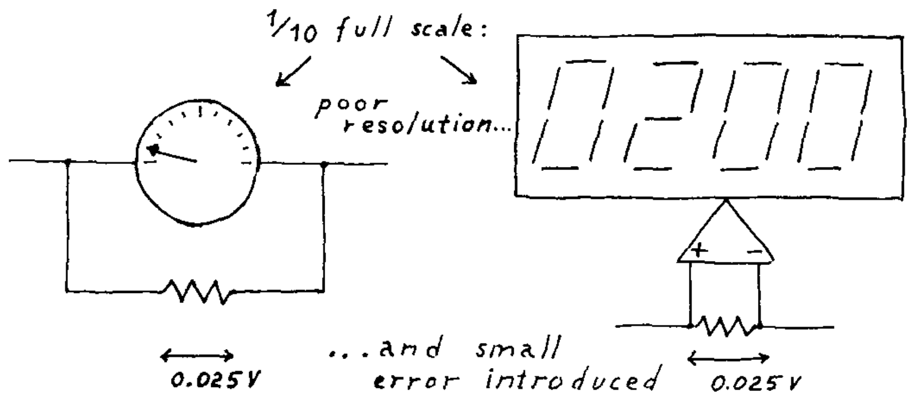


Figure X1.5: *Tradeoffs, or Electronic Justice I*: VOM or DVM as *ammeter:* the larger the reading, the larger the voltage error introduced; VOM as *voltmeter*: the larger the deflection at a given V_{in}, the lower the input impedance

If you want the current meter needle to swing nearly all the way across the dial (giving best resolution: small changes in current cause relatively large needle movement), then you'll get nearly the full-scale 1/4-volt drop across the ammeter. The same goes for the DVM as ammeter, if you understand that 'full scale' for the DVM means filling its digital range: "3 1/2 digits," as the jargon goes: the "half digit" is a character that takes only the values zero or one. So, if you set the DVM current range so that your reading looks like

.093

you have poor resolution: about one percent. If you are able to choose a setting that makes the same current look like 0.930, you've improved resolution 10X. But you have also increased the voltage drop across the meter by the same factor; for the DVM, like the analog VOM drops 1/4V full-scale, and proportionately less for smaller "deflection" (in the VOM) or smaller fractions of the full-scale range (for the DVM).

3. Thevenin Models

Problem: Thevenin Models

Draw Thevenin Models for the following circuits. Give answers to 10% and to 1%

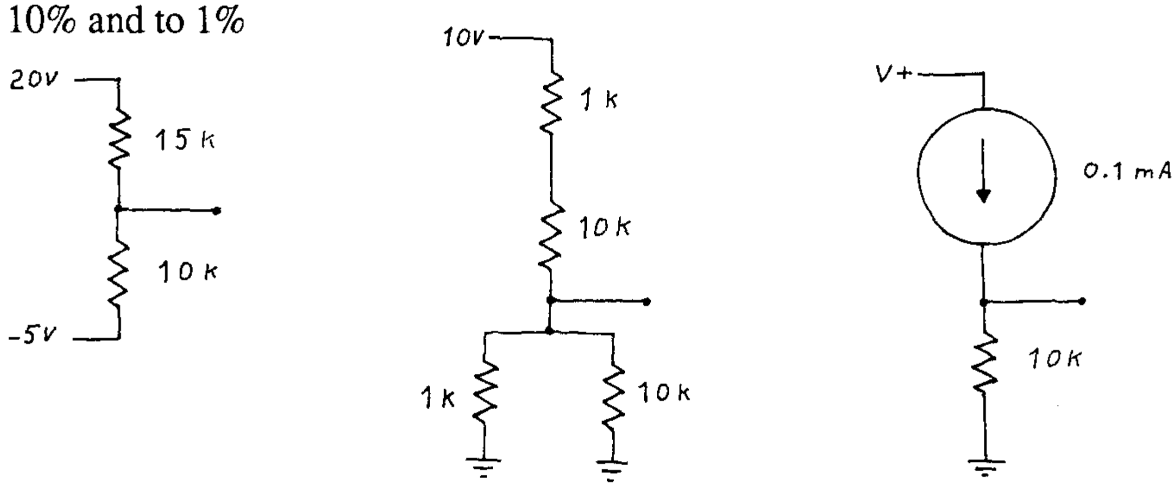


Figure X1.6: Some circuits to be reduced to Thevenin models

Some of these examples show typical difficulties that can slow you down until you have done a lot of Thevenin models.

The leftmost circuit is most easily done by temporarily redefining *ground.* That trick puts the circuit into entirely familiar form:

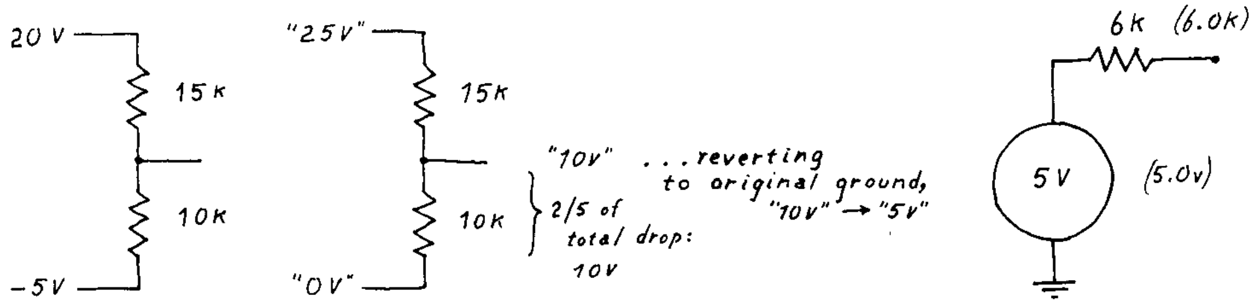


Figure X1.7: A slightly-novel problem reduced to a familiar one, by temporary redefinition of ground

The only difficulty that the middle circuit presents comes when we try to approximate. The 1% answer is easy, here. The 10% answer is tricky. If you have been paying attention to our exhortations to use 10% approximations, then you may be tempted to model each of the resistor blocks with the dominant *R*: the small one, in the parallel case, the big one in the series case:

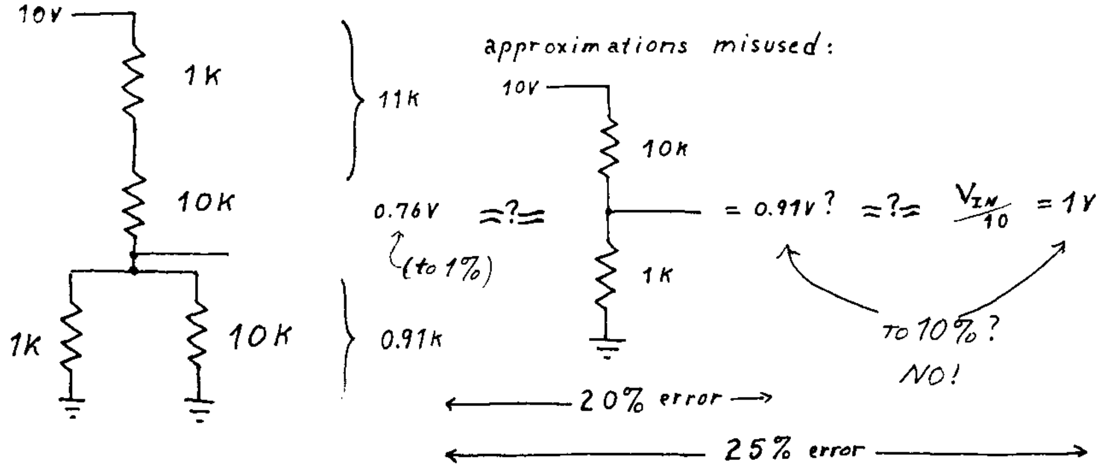


Figure X1.8: 10% approximations: errors can accumulate

Unfortunately, this is a rare case when the errors gang up on us; we are obliged to carry greater precision for the two elements that make up the divider.

This example is not meant to make you give up approximations. It makes the point that it's the *result* that should be good to the stated precision, not just the intermediate steps.

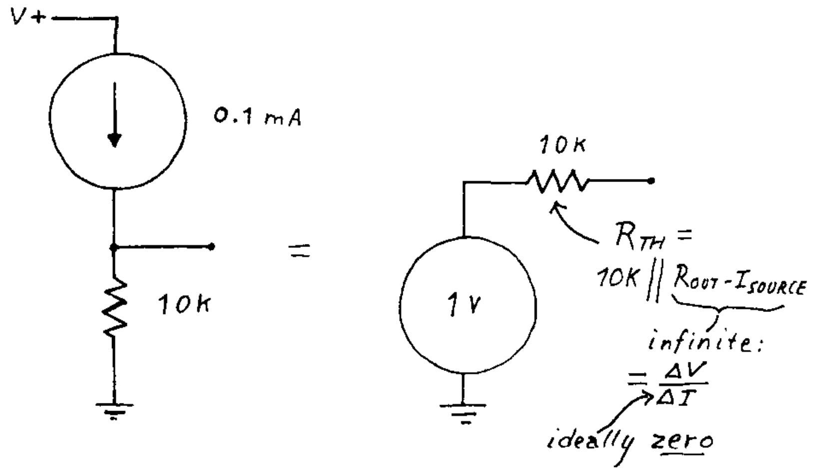


Figure X1.9: Current source feeding resistor, and equivalent Thevenin model

The *current source* shown here probably looks queer to you. But you needn't understand how to make one to see its effect; just take it on faith that it does what's claimed: sources (squirts) a fixed current, down toward the negative supply. The rest follows from Ohm's Law. (In Chapter 2 you will learn to design these things—and you will discover that some devices just do behave like current sources without being coaxed into it: transistors behave this way—both bipolar and FET.)

The point that the current source shows a very high output impedance helps to remind us of the definition of impedance: always the same: ΔV/ΔI. It is better to carry that general notion with you than to memorize a truth like 'Current sources show high output impedance.' Recalling that definition of impedance, you can always figure out the current source's approximate output impedance (large versus small); soon you will know the particular result for a current source, just because you will have seen this case repeatedly.

4. 'Looking through' a circuit fragment, and R_{in}, R_{out}

Problem: R_{in}, R_{out}

What are R_{in}, R_{out} at the indicated points?

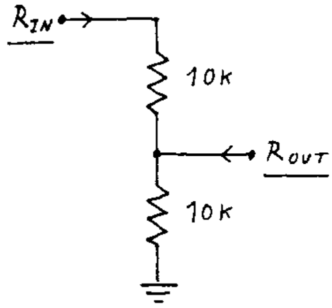


Figure X1.10: Determining R_{in}, R_{out}; you need to decide what's beyond the circuit to which you're connecting

R_{in}

It's clear what R_{in} the divider should show: just $R_1 + R_2$: 10k + 10k = 20k. But when we say that are we answering the right question? Isn't the divider surely going to drive something down the line? If not, why was it constructed?

The answer is Yes, it *is* going to drive something else—the *load.* But that something else should show its own R_{in} high enough so that it does not appreciably alter the result you got when you ignored the load. If we follow our *10X* rule of thumb (see the end of Class 1 notes), you won't be far off this idealization: less than 10% off. To put this concisely, you might say simply that we assume an *ideal* load: a load with infinite input impedance.

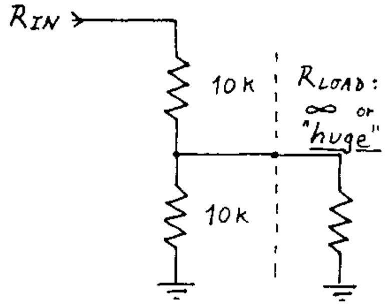


Figure X1.11: R_{in}: we need an assumption about the load that the circuit drives, if we are to determine R_{in}

R_{out}

Here the same problem arises—and we settle it in the same way: by assuming an ideal source. The difficulty, again, is that we need to make some assumption about what is on the far side of the divider if we are to determine R_{out}:

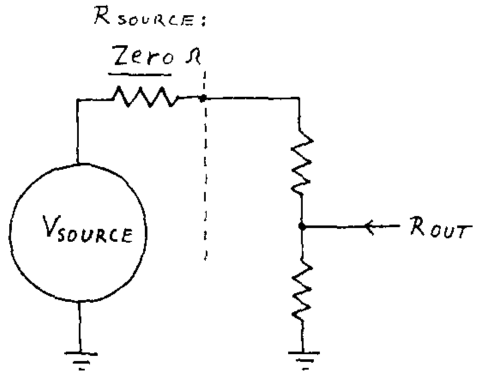


Figure X1.12: R_{out}: we need an assumption about the source that drives the circuit, if we are to determine R_{out}

4. Effects of loading

Problem: Effects of loading

What is the voltage at X—

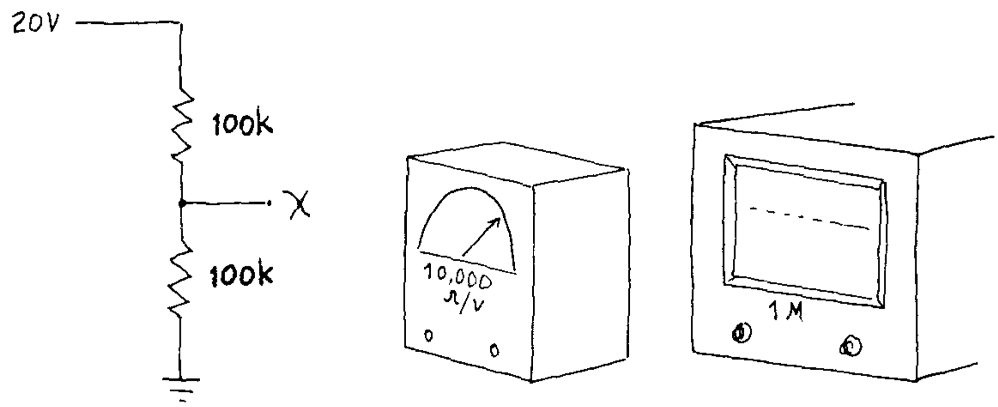


Figure X1.13: V_{out}: calculated versus measured

with no load attached?

When measured with a VOM labeled "10,000 ohms/volt?"

When measured with a scope whose input resistance is 1 MΩ?

This example recapitulates a point made several times over in the the first day's class notes, as you recognize. *Reminder*: The "...ohms/volt" rating implies that on the 1-volt scale (that is, when 1V causes full deflection of the meter) the meter will present that input resistance. What resistance would the meter present when set to the 10 volt scale?

We start, as usual, by trying to reduce the circuit to familiar form. The Thevenin model does that for us. Then we add meter or scope as *load*, forming a voltage divider, and see what voltage results:

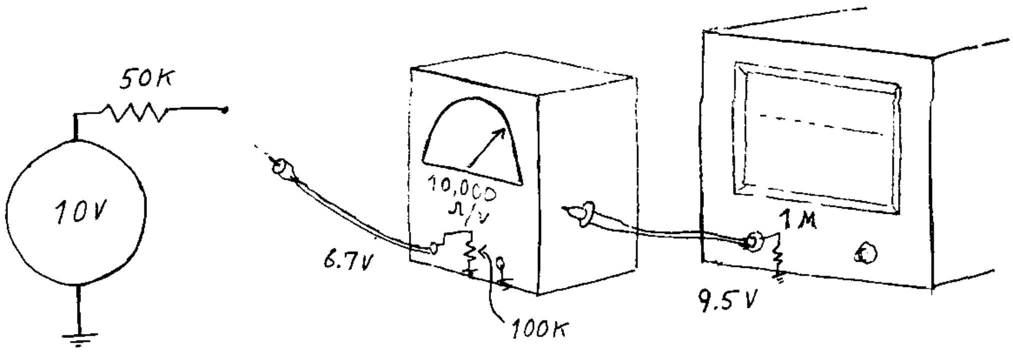


Figure X1.14: Thevenin model of the circuit under test; and showing the "load"—this time, a meter or scope

You will go through this general process again and again, in this course: reduce an unfamiliar circuit diagram to one that looks familiar. Sometimes you will do that by merely redrawing or rearranging the circuit; more often you will invoke a model, and often that model will be Thevenin's.

Lab 1: DC Circuits

Reading:	Chapter 1, secs 1.1 – 1.11. Appendix A (don't worry if there are things you don't understand) Appendix C
Problems:	Problems in text. Additional Exercises 1,2.

1-1. Ohm's Law

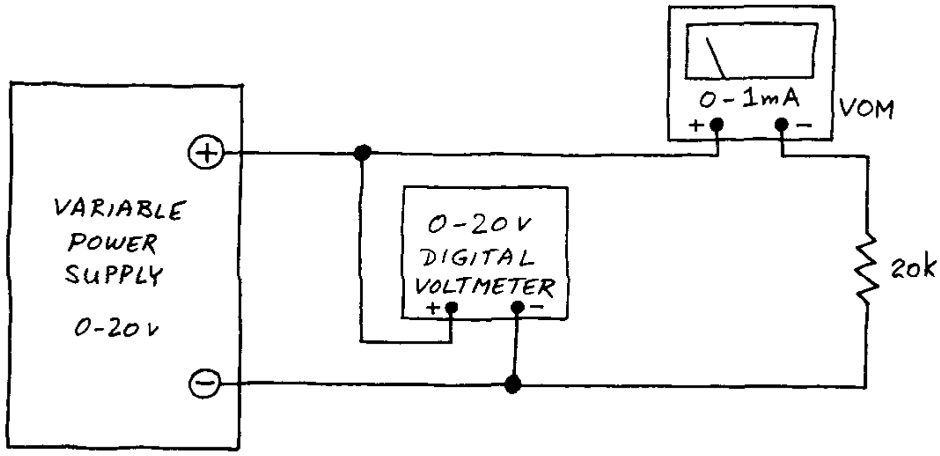


Figure L1.1: Circuit for measurement of resistor's **I** vs **V**

First, the pedestrian part of this exercise: *Verify that the resistor obeys Ohm's law*, by measuring **V** and **I** for a few voltages.

A preliminary note on ***procedure***

The principal challenge here is simply to get used to the breadboard and the way to connect instruments to it. We do not expect you to find Ohm's Law surprising. Try to build your circuit *on the breadboard*, not in the air. Novices often begin by suspending a resistor between the jaws of alligator clips that run to power supply and meters. Try to do better: plug the resistor into the plastic breadboard strip. Bring power supply and meters to the breadboard through jacks (banana jacks, if your breadboard has them); then plug a wire into the breadboard so as to join resistor, for example, to banana jack. Below is a sketch of the poor way and better way to build a circuit.

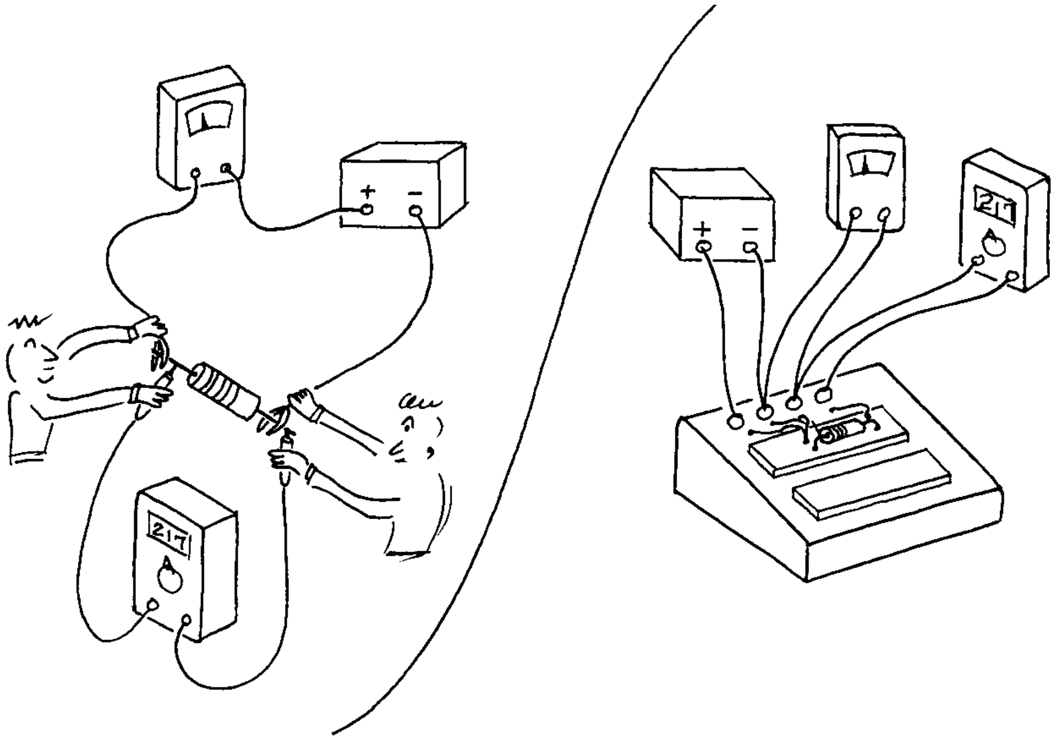


Figure L1.2: Bad and Good breadboarding technique: Left: labor intensive, mid-air method, in which many hands hold everything precariously in place; Right: tidy method: circuit wired in place

Have your instructor demonstrate which holes are connected to which, how to connect voltages and signals from the outside world, etc.

This is also the right time to begin to establish some conventions that will help you keep your circuits intelligible:

- Try to build your circuit so that it looks like its circuit diagram:
  - Let signal flow in from left, exit on right (in this case, the "signal" is just **V**; the "output" is just **I**, read on the ammeter);
  - Place *ground* on a horizontal breadboard *bus* strip *below* your circuit; place the positive supply on a similar bus *above* your circuit. When you reach circuits that include negative supply, place that on a bus strip *below* the ground bus.
  - Use ***color coding*** to help you follow your own wiring: use ***black*** for ground, ***red*** for the positive supply. Such color coding helps a little now, ***a lot*** later, when you begin to lay out more complicated *digital* circuits.

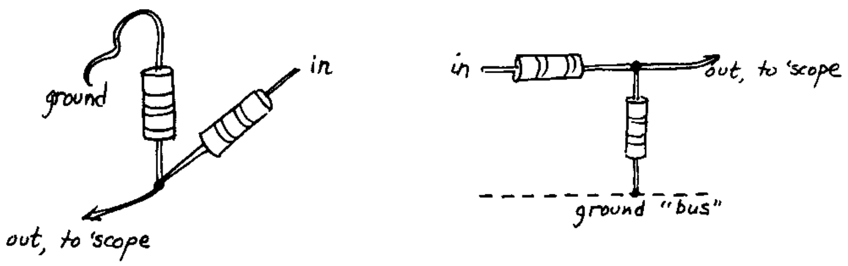


Figure L1.3: Bad and good breadboard layouts of a simple circuit

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Use a variable regulated dc supply, and the hookup shown in the first figure, above, Fig. L1.1. Note that voltages are measured ***between*** points in the circuit, while currents are measured ***through*** a part of a circuit. Therefore you usually have to break the circuit to measure a current.

Measure a few values of **V** and **I** for the 20k resistor (*note:* you may well find *no 20k resistor in your kit.* Don't panic. Consider how to take advantage of some 10k's.) Next try a 10k resistor instead, and sketch the two curves that these resistors define on a plot of I vs V. You may be disinclined to draw these "curves," because you knew without doing this experiment what they would look like. Fair enough. But we encourage you to draw the plot for contrast with the devices you will meet next—which interest us just because their curves do *not* look like those of a resistor: just because these other devices *do not* obey Ohm's Law.

Effects of the instruments on your readings

Now that you have done what we called the pedestrian part of the experiment, consider a couple of practical questions that arise in even this simplest of "experiments."

A Qualitative View

The voltmeter is not measuring the voltage at the place you want, namely across the resistor. Does that matter? How can you fix the circuit so the voltmeter measures what you want? When you've done that, what about the accuracy of the current measurement? Can you summarize by saying what an ideal voltmeter (or ammeter) should do to the circuit under test? What does that say about its "internal resistance"?

A Quantitative View

How large is each error, given a 20k resistor. Which of the two alternative hookups is preferable, therefore? Would you have reached the same conclusion if the resistor had been 20MΩ?

(You will find this question pursued in one of the Worked Examples.)

Two Nonlinear Devices: *(Ohm's Law Defied!)*

1-2. An incandescent lamp

Now perform the same measurement (**I** vs **V**) for a #47 lamp. Use the 100mA and 500mA scales on your VOM. <u>Do not exceed 6.5 volts!</u> Again you need only a few readings. Again we suggest you plot your results on the drawing you used to show the *resistor's* behavior. Get enough points to show how the lamp ***diverges*** from resistor-like performance.

What is the "resistance" of the lamp? Is this a reasonable question? If the lamp's filament is made of a material fundamentally like the material used in the resistors you tested earlier, what accounts for the funny shape of the lamp's **V** vs **I** curve?

1-3. The Diode

Here is another device that does not obey Ohm's law: the **diode**. (We don't expect you to understand how the diode works yet; we just want you to meet it, to get some perspective on Ohm's Law devices: to see that they constitute an important but *special* case).

We need to modify the test setup here, because you can't just stick a voltage across a diode, as you did for the resistor and lamp above[1] You'll see why after you've measured the diode's **V** vs **I**. Do that by wiring up the circuit shown below.

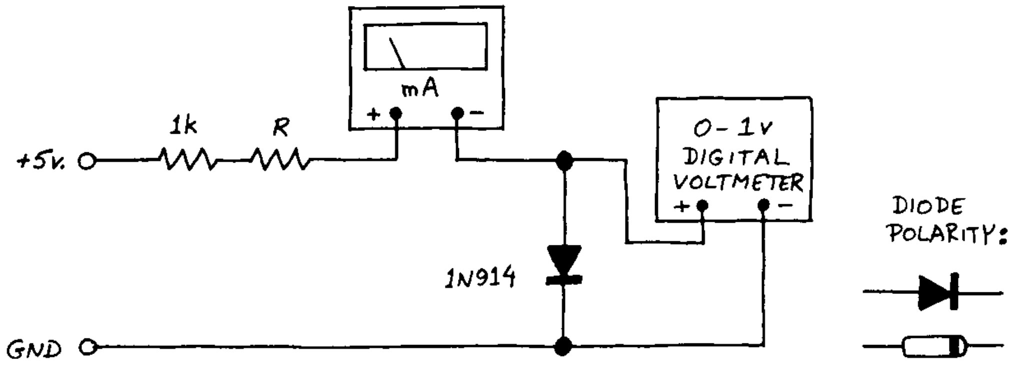

Figure L1.4: Diode VI measuring circuit

In this circuit you are applying a *current*, and noting the diode voltage that results; earlier, you applied a voltage and read resulting current. The 1k resistor limits the current to safe values. Vary **R** (use a 100k variable resistor (usually called a *potentiometer* or "pot" even when wired, as here, as a variable resistor), a resistor substitution box, or a selection of various fixed resistors), and look at **I** vs **V**, sketching the plot in two forms: linear and "semi-log."

First, get an impression of the shape of the linear plot; just four or five points should define the shape of the curve. Then draw the same points on a *semi-log* plot, which compresses one of the axes. (Evidently, it is the fast-growing current axis that needs compressing, in this case.) If you have some semi-log paper use it. If you don't have such paper, you can use the small version laid out below. The point is to see the pattern. You will see this shape again in Lab 5 when you let the scope plot diode and transistor characteristics for you.

1. Well, you *can*; but you can't do it twice with one diode!

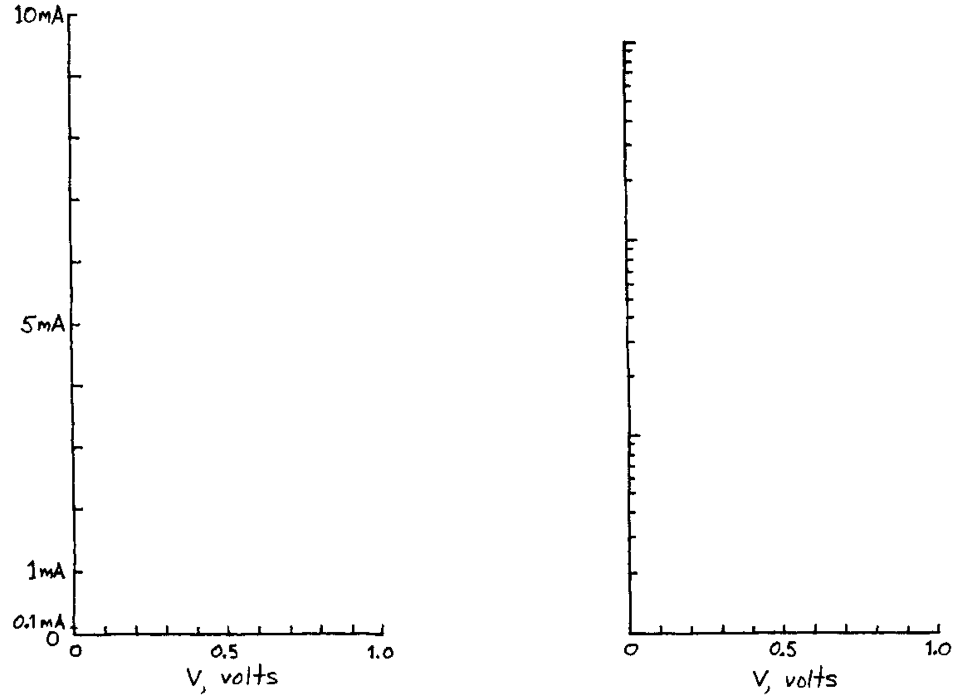

Figure L1.5: Diode I vs V: linear plot; semi-log plot

See what happens if you reverse the direction of the diode.

How would you summarize the **V** vs **I** behavior of a diode?

Now explain what would happen if you were to put 5 volts across the diode (**Don't try it!**). Look at a diode data sheet, if you're curious: see what the manufacturer thinks would happen. The data sheet won't say "Boom" or "Pfft," but that is what it will mean.

We'll do lots more with this important device; see, e.g., secs. 1.25-1.31 in the text, and Lab 3.

1-4. Voltage Divider

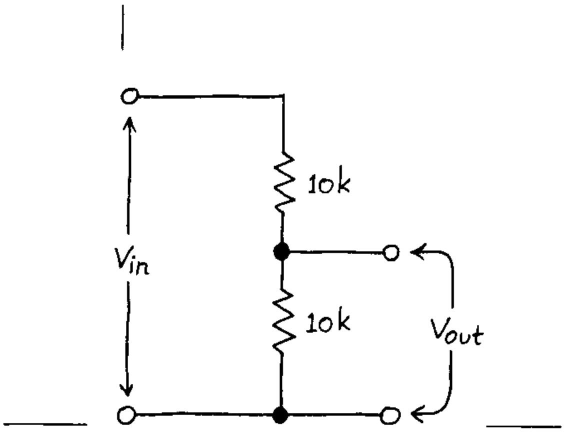

Figure L1.6: Voltage divider

Construct the voltage divider shown above (this is the circuit described in Exercise 1.9 (p. 10 of the text)). Apply V_{in} = 15 volts (use the dc voltages on the breadboard). Measure the (open circuit) output voltage. Then attach a 10k load and see what happens.

Now measure the short circuit current. (That means "short the output to ground, but make the current flow through your current meter. Don't let the scary word "short" throw you: the current in this case will be very modest. You may have grown up thinking "a short blows a fuse." That's a good generalization around the house, but it often does not hold in electronics.)

From $I_{Short\ Circuit}$ and $V_{Open\ Circuit}$ you can calculate the Thevenin equivalent circuit.

Now build the Thevenin equivalent circuit, using the variable regulated dc supply as the voltage source, and check that its open circuit voltage and short circuit current match those of the circuit that it models. Then attach a 10k load, just as you did with the original voltage divider, to see if it behaves identically.

A Note on Practical use of Thevenin Models

You will rarely do again what you just did: short the output of a circuit to ground in order to discover its $\mathbf{R_{Thevenin}}$ (or "output impedance," as we soon will begin to call this characteristic). This method is too brutal in the lab, and too slow when you want to calculate R_{Th} on paper.

In the lab, I_{SC} could be too large for the health of your circuit (as in your fuse-blowing experience). You will soon learn a gentler way to get the same information.

On paper, if you are given the circuit diagram the fastest way to get R_{Th} for a divider is always to take the *parallel* resistance of the several resistances that make up the divider (again assuming R_{source} is ideal: zero Ω). So, in the case you just examined:

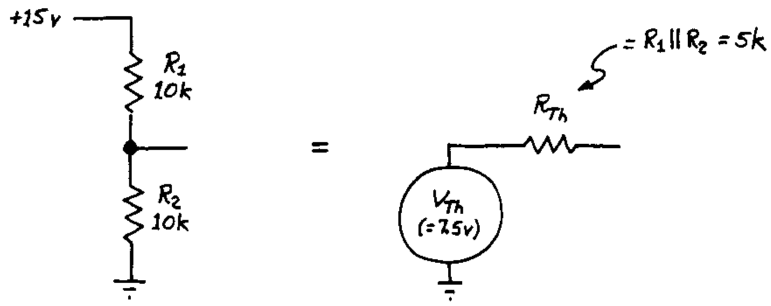

Figure L1.7: R_{Th} = parallel resistances as seen from the circuit's output

1-5. Oscilloscope

We'll be using the oscilloscope ("scope") in virtually every lab from now on. If you run out of time today, you *can* learn to use the scope while doing the experiments of Lab 2. You will find Lab 2 easier, however, if today you can devote perhaps 20 minutes to meeting the scope.

Get familiar with scope and ***function generator*** (a box that puts out time-varying voltages: waveforms: things like sine waves, triangle waves and square waves) by generating a 1000 hertz (1kHz, 1000 cycles/sec) sine wave with the function generator and displaying it on the scope.

If both instruments seem to present you with a bewildering array of switches and knobs, don't blame yourself. These front-panels just *are* complicated. You will need several lab sessions to get fully used to them—and at term's end you may still not know all: it may be a long time before you find any occasion for use of the *holdoff* control, for example, or of *single-shot* triggering, if your scope offers this.

Play with the scope's sweep and trigger controls. Specifically, try the following:

- The vertical gain switch. This controls "*volts/div*"; note that "div" or "division" refers to the *centimeter* marks, not to the tiny 0.2 cm marks);
- The horizontal sweep speed selector: *time* per division.

  On this knob as on the vertical gain knob, make sure the switch is in its ***CAL*** position, not ***VAR*** or "variable." Usually that means that you should turn a small center knob clockwise till you feel the switch *detent* click into place. If you don't do this, you can't trust *any* reading you take!)

- The trigger controls. Don't feel dumb if you have a hard time getting the scope to trigger properly. Triggering is by far the subtlest part of scope operation. When you think you have triggering under control, invite your partner to prove to you that you ***don't***: have your partner randomize some of the scope controls, then see if you can regain a sensible display (don't overdo it here!).

  Beware the tempting so-called "normal" settings (usually labeled "**NORM**"). They rarely help, and instead cause much misery when misapplied. Think of "normal" here as short for ***abnormal***! Save it for the rare occasion when you know you need it. "**AUTO**" is almost always the better choice.

Switch the function generator to square waves and use the scope to measure the "risetime" of the square wave (defined as time to pass from 10% to 90% of its full amplitude).

At first you may be inclined to despair, saying "Risetime? The square wave rises instantaneously." The scope, properly applied, will show you this is not so.

> *A suggestion on triggering:*
>
> It's a good idea to *watch* the edge that *triggers* the scope, rather than trigger on one event and watch another. If you watch the *trigger event*, you will find that you can sweep the scope fast without losing the display off the right side of the screen.

What comes out of the function generator's **SYNC OUT** or **TTL** connector? Look at this on one channel while you watch a triangle or square wave on the other scope channel. To see how SYNC or TTL can be useful, try to trigger the scope on the peak of a sine wave *without* using these aids; then notice how entirely easy it is to trigger so when you *do* use SYNC or TTL to trigger the scope. (Triggering on a well-defined point in a waveform, such as peak or trough, is especially useful when you become interested in measuring a difference in *phase* between two waveforms; this you will do several times in the next lab.)

How about the terminal marked **CALIBRATOR** (or "CAL") on the scope's front panel? (We won't ask you to *use* this signal yet; not until Lab 3 do we explain how a scope probe works, and how you "calibrate" it with this signal. For now, just note that this signal is available to you). *Postpone* using scope probes until you understand what is within one of these gadgets. A "10X" scope probe is *not* just a piece of coaxial cable.

Put an "offset" onto the signal, if your function generator permits, then see what the **AC/DC** switch (located near the scope inputs) does.

Note on AC/DC switch:

Common sense may seem to invite you to use the ***AC*** position most of the time: after all, aren't these time-varying signals that you're looking at "AC"—alternating current (in some sense)? ***Eschew*** this plausible error. The ***AC*** setting on the scope puts a capacitor in series with the scope input, and this can produce startling distortions of waveforms if you forget it is there. (See what a 50 Hz square wave looks like on AC, if you need convincing.) Furthermore, the AC setting washes away DC information, as you have seen: it hides from you the fact that a sine wave is sitting on a DC offset, for example. You don't want to wash away information except when you choose to do so knowingly and purposefully. Once in a while you *will* want to look at a little sine with its DC level stripped away; but always you will want to *know* that this DC information has been made invisible.

Set the function generator to some frequency in the middle of its range, then try to make an accurate frequency measurement with the scope. (Directly, you are obliged to measure *period*, of course, not frequency.) You will do this operation hundreds of times during this course. Soon you will be good at it.

Trust the scope period readings; distrust the function generator frequency markings; these are useful only for very *approximate* guidance, on ordinary function generators.

Try looking at pulses, say 1μs wide, at 10kHz.

1-6. AC Voltage Divider

First spend a minute thinking about the following question: How would the analysis of the voltage divider be affected by an input voltage that changes with time (i.e., an input *signal*)? Now hook up the voltage divider from lab exercise 1-4, above, and see what it does to a 1kHz sine wave (use function generator and scope), comparing input and output signals.

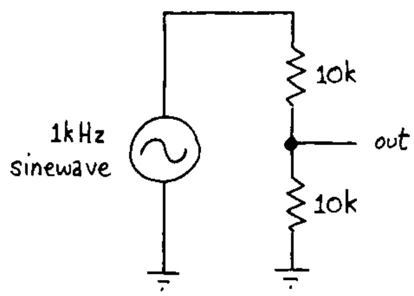

Figure L1.8: Voltage divider applied to a time-varying signal

Explain in detail, to your own satisfaction, why the divider must act as it does.

If this question seems silly to you, you know either too much or too little.