The Rainbow Master's Guide to Introductory Physics[1]

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Abstract

Writing and grading introductory physics laboratory reports need not be crushingly dull and repetitive chores. Try encouraging some literary creativity on the part of your students!

Introduction

The discussion of laboratory reports in introductory physics courses goes back at least to 1959[2] (and further no doubt) and continues to the present, for example, recently in this journal [3]. In this article we offer a light-hearted suggestion for enlivening the preparation and grading of lab reports by reproducing, essentially *verbatim*, a selection of reports handed in by a particular student (the author) at our institution some years ago. (The use of the first person to talk about the author in the third person seems weird here. How to avoid?)

Our expectation for such reports conformed then (and still does) to the typical format: students were expected to include answers to pre-lab problems, a description of the experimental technique, a section on experimental data and analysis, a discussion of results, etc. Jed Brody, then a freshman in the introductory course, regularly enlivened

the arduous tasks of writing and grading lab reports by presenting his partly in the form of Zen dialogues. One of us (LR) thought to preserve these essays at the time (1993) in the form of a collection intended for the amusement of departmental colleagues. (Much) later this document resurfaced during a departmental move to a new building and it occurred to us (SAK & LR) that the rest of the physics community might enjoy them as much as we did. Naturally, Brody's reports also contained a complete discussion of the data, a careful mathematical analysis, and all appropriate supporting materials; for the sake of brevity, these have been omitted in the selections reproduced below.

Brody explained at the time, "I got the idea of using vaguely metaphorical dialogue from Hofstadter's *Godel, Escher, Bach: An Eternal Golden Braid*.[4]" Following his graduation from Haverford College in 1996, Brody spent two years as a Peace Corps volunteer teaching high school physics and chemistry (in French) in Benin, then received his Ph.D. (and/or M.S.?) from Georgia Institute of Technology in Electrical Engineering (true?); he is presently a physics lecturer at Emory University. We present excerpts from his reports here in the hopes of stimulating other students to higher levels of enthusiasm and novelty in their scientific writing.

Thevenin Equivalent Circuits Laboratory: Thevenin and the Rainbow Master

The sun smiles. The trees sing. A quivering arm hoists its owner up to the entrance of the cave at the peak of the mountain.

"Rainbow Master! Rainbow Master! At last have I found you! You have no idea of the cliffs I have scaled or of the caverns through which I've descended since leaving my village, Blackboxville!"

"Not so, Thevenin. I do have some idea; I know that now your altitude is 100 kilometers greater than it was when you left Blackboxville."

"Rainbow Master! What gods tell you this? I never described for you my venture up the blazing trail, my plummet down the bramble vale, my climb up ropes through fog and hail, my--"

"You don't need to. I know the altitude of Blackboxville and of my cave. Your exact path does not matter. Your route could have been incredibly labyrinthine, but I can reduce it to a simple difference in altitude."

"How wise you are! Now shall we see if your wisdom extends to electronics. This is why I have sought your aid. Evil marauders plague my village with circuits of diabolical complexity. The marauders conceal all the resistors and voltage supplies, revealing only two open wires. My digital multi-meter (DMM) cannot save me now. I despair of learning anything of these fiendish constructions!"

"Chill out. The marauders can be as complex as they like. You can foil their scheme, just as I divined your change in altitude. Listen. All the resistors and voltages sources can be

considered as a single battery supplying V_T with internal resistance R_T. The hunter who prowls the openings of the cave need not intrude to catch the prey."

"Profundity galore! That sounds great, Rainbow Master, but what in the world is the value of the slope of the line in Figure 1?" Thevenin asks, brandishing his Haverford College Introductory Physics Lab Manual.

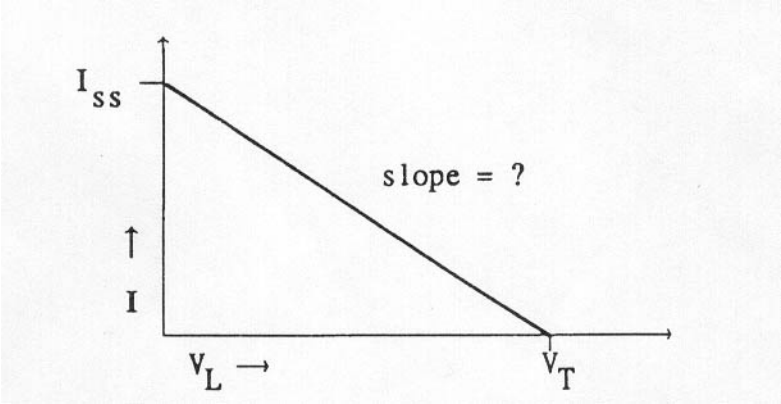

Figure 1

We probably should put the origin in explicitly on this graph. Oops.

"Even the daisies of the fields know that slope is rise over run, which in this case is - I_{ss} / V_T. (Here I_{ss} is the short circuit current.) From Equation 1, you see that this is the negative of the reciprocal of R_T:

$$R_T = V_T / I_{ss} \qquad (1)$$

"Rainbow Master, for years have I yearned to determine the internal resistance of any power supply, function generator, and DMM. If I followed the instructions in this lab manual, what assumptions would I have to make?"

"While measuring the output resistance of the power supply and function generator, you want all your current to go through these devices. You must assume that the input resistance of the DMM is relatively enormous compared to that of your load (R_L) to prevent current from entering the DMM and skewing your results. Similarly, when measuring the input resistance of the DMM, you must assume that the output resistance of your power supply is very small. The voltage drop across this output resistance is proportional to the current through it. The current depends upon the load resistance. In order for the output voltage of the power supply to be insensitive to load, the output resistance must be so small that the voltage drop across it is negligible."

"Will the gods ever forgive me for such brazen assumptions?"

"Repentance is unnecessary. The DMM's input resistance is over 100,000 times greater than the output resistance of either the power supply or function generator. This disparity justifies the assumptions."

"Rainbow Master, reality is so hard for us to know!"

"Speak for yourself. Farewell."

Thevenin Returns

Deep within a wooded ravine lurks a crooked shack. The burly man inside hears a noise and lifts his revolver.

Miles away, a large puddle resembling Thevenin sputters into Rainbow Master's cave.

"Rainbow Master! Rainbow Master! I've come back!"

"I knew you would."

"What secrets you divine! What tea leaves have you brewed, what insects have you stewed, what powers were subdued to grant you this foresight?"

"None. You forgot your umbrella, and I figured you'd return for it."

"Oh. Anyway, my real reason for returning is this: after eating some moldy bread, I had the most grotesque vision! I saw in the clouds an image of a circuit with varying voltage!"

"All things vary, nothing is constant. Night yields to day, sorrow yields to joy, potential energy yields to kinetic energy in simple harmonic motion, and yin yields to yang.

Opposites self-spawn in a perpetual cycle of change and flux. I'm sorry I don't have any more time today for profundity, or for complex number models of phasors."

Polarized Light Laboratory: Rainbow Master's Refraction

Dawn at Rainbow Master's cave. Butterflies everywhere. Somewhere in the distance a gong sounds.

"Return from your meditation. The time now has come for your enlightenment to be revealed."

Thevenin hears the mental beckoning and promptly descends from the stratosphere, where he has been levitating for some time.

"This is the hour for you to answer the three riddles."

"My mind is clear, my thoughts I steer, my body is here. All I can answer. Three impossible questions despair me not."

"Even if the three questions are--"

Rainbow Master's symphonic orchestra abruptly produces a suspenseful trill.

"-the three pre-lab problems?"

Thevenin gasps. Rainbow Master nods. Cymbals crash.

"If your soul be truly cleansed, invent and describe a procedure to determine the absorption axis of a polarizing filter."

"When unpolarized light strikes a nonmetallic surface at an acute angle," Thevenin explains sagely, "some light is absorbed. Only the light waves oscillating parallel to the surface rebound unscathed. The other components of the polarized light penetrate the surface molecules, transmit energy, and fail to reflect. Observe the light reflecting off of a table through the mysterious polarizing filter, and rotate it in front of you. When the least light gets through, the absorption axis is parallel with the polarization of the incoming light, and hence with the surface of the table."

Rainbow Master smiles. A pleasant flute concerto fills the air with vibrations within the human hearing range.

"You have answered wisely. May such wisdom prevail. If your heart be truly pure, show what the final polarization of a plane-polarized wave initially incident upon the half-wave plate at an angle of 0^{o} to the optic axis is."

"What thought this requires! Please silence those pipes; I can't concentrate! Thank you. The component of the original electric field vector, $\mathbf{E_o}$, along the slow axis will be shifted 180^o behind the fast axis component: $\mathbf{E_o} = \mathbf{E_f} + \mathbf{E_s} = \mathbf{E_o}\sin\theta + \mathbf{E_o}\cos\theta$. The final electric field vector, after the half-wave plate, **E**, then will be: $\mathbf{E} = \mathbf{E_o}\sin\theta + \mathbf{E_o}\cos(\theta - 180^o)$. Since $\sin\theta = \sin(180^o - \theta)$ and $\cos(\theta - 180^o) = \cos(180^o - \theta)$, $\mathbf{E} = \mathbf{E_o}\sin(180^o - \theta) + \mathbf{E_o}\cos(180^o - \theta)$. Thus the final angle is $180^o - \theta$. This is illustrated in Figure 3."

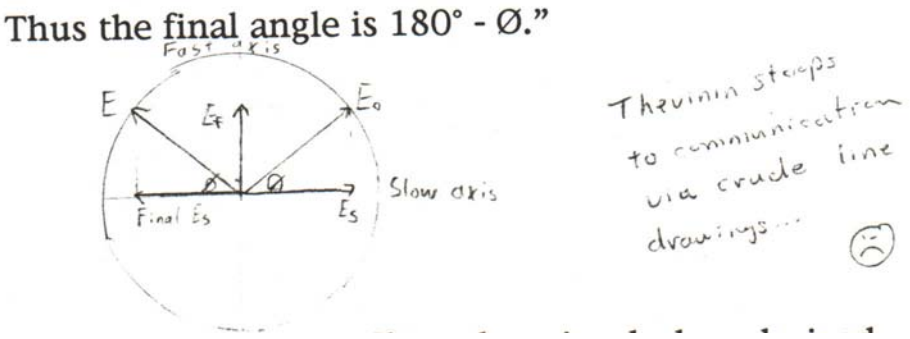

Figure 3

Do we need to provide a better version of Figure 3?

"The final question draws near. Oh, and here it is! Show that circularly polarized light results when a plane-polarized wave passes through a quarter-wave plate at 45^o to the optic axis."

Silence. Then, a soft drum roll.

"The electric field vectors of circularly polarized waves satisfy two conditions: their x and y components must be (1) equal and (2) 90^o out of phase. A plane polarized wave passing through a quarter-wave plate at 45^o to the optic axis exits with x and y

components equal in magnitude since $E_x = E \cos 45^o = E \sin 45^o = E_y$. E_x and E_y are 90^o out of phase because quarter-wave plates cause E_x to lag 90^o behind E_y, assuming that E_x is along the optic axis."

"Thevenin, I deem you worthy of this sacred artifact. Use it in good health."

"It's a polarizing filter! Awesome! There's so much to do with it that I don't even know where to begin!"

"Try determining the absorption axis."

"Right on! When viewed through the polarizing filter, the light from the fluorescent ceiling lights (beside the stalactites) that is reflected off of your lab desk looks dimmest when this transparent band is parallel with the floor. Hey, you know what? This transparent band is a handy way to remember the orientation of the absorption axis!"

"Indeed. The truth you speak."

"And if I look through the polarizer at the light reflected by the screen of the computer that you recently installed in your cave over there, I see--Wait a minute! The glare is dimmest when the transparent band isperpendicular to the floor! Why does the absorption axis switch?"

"It doesn't," Rainbow Master responds. "The glare you see results from the light originating in the ceiling lights at the other end of the cave. The axis of reflection of the light reaching your eyes is vertical, so that this reflected light is polarized vertically."

"My wisdom compared to yours is but a fig beside a galaxy."

"Indeed. But that fig is swelling, and its size may surpass the galaxy's one day. To help it on its way, observe the outside world with through the polarizing filter."

"I'll take a look at the cars in the parking lot outside. When I rotate the polarizing filter, the light reflected off of various car windows appears and vanishes because the various surfaces, and hence the various planes of polarization of the light, make various angles with my line of vision. It's like a kaleidoscope!”

"Turn your eyes to the sky."

"There's this one cloud in the distance that turns really dark, like a storm cloud, when I hold the polarizing filter a certain way. None of the other clouds change."

"Why?"

"I don't know. What I do know," Thevenin boasts, "is that some sunlight, reflected toward me from air molecules, is polarized in the horizontal plane. These air molecules

must be at the right angle of a right triangle whose vertices are the sun, the air molecules and I (Figure 4). This is because the original sunlight has electric field vectors oscillating in all directions perpendicular to its motion. The air molecules are made to vibrate in these directions. Up and down vibrations send out vertically polarized light in the horizontal plane of the air molecules, since the direction of light is always perpendicular to its electric field oscillations. Horizontal vibrations radiate horizontally polarized light down to me. Oh, and to you, too, and even your symphonic orchestra."

An appreciative fugue.

“Maybe," Thevenin suggests, "the light from the air surrounding the cloud is polarized, and the change in intensity of this light as I rotate the polarizing filter creates the optical illusion that the brightness of the cloud is changing. Or maybe the cloud simply transforms from a cumulus to a stratus synchronously with my rotation of the polarizing filter."

"You could use a shave with Occam's razor. Speaking of things, which way would you orient the axis of a polarizer for sunglasses and why?"

"The absorption axis should be horizontal, since that is the orientation of plane of polarization of the sunlight. And in anticipation of your next question, I would guess that nature photographers frequently use polarizing filters for the same reason that regular people (i.e. anyone but nature photographers) use sunglasses: we want to eliminate excess

sunlight without completely blinding ourselves, and the best way to do this is to filter out the horizontally polarized light, much of which is much of the sunlight."

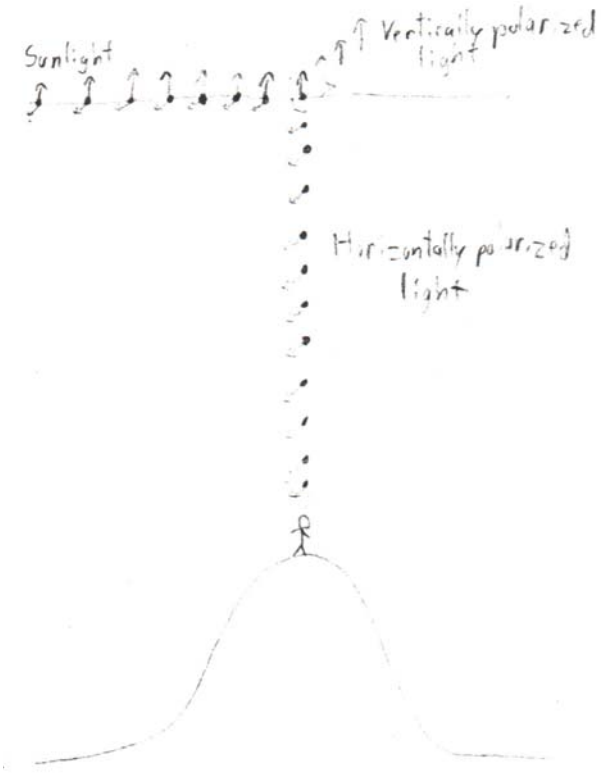

Figure 4

"We proceed. We flow with the questions in the lab manual as a leaf flows with the stream. Unless it gets caught on a rock. Direct light through two polarizers whose absorption axes are at various angles. First, orient the absorption axes at 90^{o} to each other. How much light gets through?" Rainbow Master exercises Thevenin's brain.

"Virtually none!"

"What will happen when you place a third polarizer in between these two, oriented with its absorption axis at 45^{o} to each?"

"Nothing! If anything, even less light will get through."

"Try it."

"Gasp! Wheeze! Startled interjection! More light has navigated this forbidding path! What gods do you shake, what laws do you break, what exceptions you make to let this come to pass?"

"When the polarized light from the first filter passes through the second," Rainbow Master professes, "resolve the electric field of the approaching light into two vectors: one perpendicular to the absorption axis of the middle filter, and one parallel with it. Only the parallel vector endures. Follow the same procedure when this light braves the last polarizer. When the absorption axis of the middle polarizer is at 45^{o} to each of the other two, the amount of light exiting the entire apparatus is at a maximum.

"Thevenin, look at your watch."

"Aw, is it time for lab to end already?"

"No, your dedication has been rewarded with an extended duration of lab work. I meant, look at your watch through a polarizer."

"Oh. Hey! The digits disappear when the absorption axis of the polarizer is vertical."

"Actually," Rainbow Master discloses, "the numbers stay as they are. The rest of the screen blackens to join them."

"It's a good thing that the light is vertically polarized. If it were horizontal, you'd have to take off your polarized sunglasses to view your watch! And you look so good in your polarized sunglasses, Rainbow Master."

The theme from *Grease*, in D minor.

"I thank you. Now can you explain how Liquid Crystal Devices (LCD) devices work?" A random harmonic tremolo.

“Maybe," Thevenin speculates, "there is a vertical polarizer near the top surface of the screen. The polarized light passes through the LCD, rotating in the areas containing electric fields. The light reflects off of a mirror in the bowels of the watch. The light again passes through the LCD, and the light rays that rotated before rotate a little more. These rays cannot escape, since they are no longer polarized in the same direction as the

surface polarizer. The rest of the light, its original vertical polarization intact, passes right back out through the surface. The black digits on my watch appear where electric fields have dizzied and ensnared the light." (Figure 5)

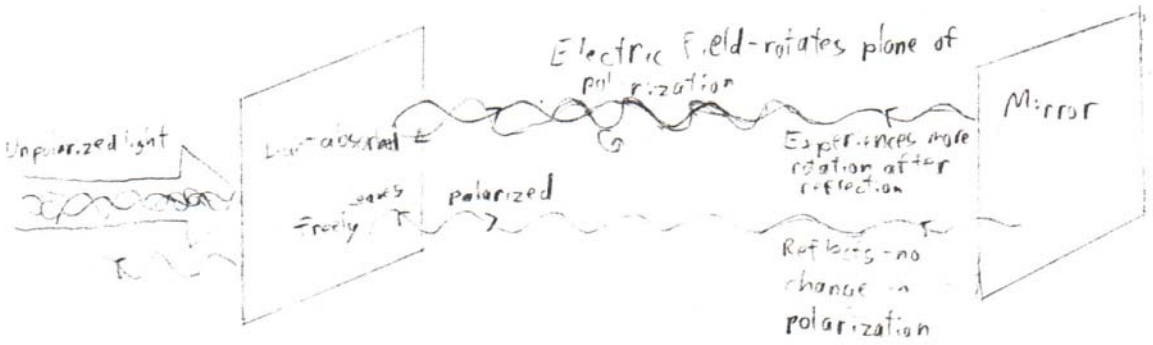

Figure 5

"Thevenin, you tread the trail toward enlightenment. Here, my usefulness to you is over. I move on to higher worlds, higher realms. I seek the light and follow the light through many paths at once."

"Rainbow Master, do not leave me!"

"I am leaving, but that which I leave is not you. Come with me, Thevenin."

"Where are we going?"

"Of that, I am as uncertain as the position of a particle whose momentum is very well known. Before our eyes, the days arise. Behold blue skies! Onward!"

Enshrouding the cave is silence. The symphonic orchestra is still. A rainbow leaps across the sky.

We (SAK and LR) miss Thevenin and the Rainbow Master and are still wondering about that burly man.

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[1] Alternate title: A Suggestion for Reducing the Tedium of Writing and Grading Introductory Lab Reports.

[2] Howard Lassiter, Am. J. Phys. 27, 166 (1959).

[3] Taoufik Nadji and Michael Lach, The Physics Teacher 41, January 2003 p. 56.

[4] Douglas R. Hofstadter, Gödel, Escher, Bach : An Eternal Golden Braid (Vintage Books, New York, 1980).