The Open Agenda

Ideas a beginning physics teacher should not take for granted

John Daicopoulos

RenegadeScience.com

Daicopoulos, John
Main title: The Open Agenda
Subtitle: Ideas a beginning physics teacher should not take for granted
[1] Education
[2] Physics

ISBN: 978-0-646-52583-9 (online, e-book)

For Dan

Who always thought I could be more
than I ever was

Table of Contents

Preface

Just how different can another physics book be and what can I do to stand out from countless other physics teachers?

In one sense it took me two short years to figure out the answer; in another sense it was closer to nineteen years. Of course the reality is it took nineteen years of stumbling through the teaching while developing the core substance to support my identity, the last two of which had superimposed upon them my obsession to produce something; but produce what? And why bother?

It began with an intention of writing, yet another, high school physics book, on my own no less – oh the horror of hubris. Not long afterwards I realized just what an burdensome task that was coupled with a most humbling thought that there were already so many well written physics texts that in no way could I contribute to the mountain substantially.

Originally my anticipated audience were high school students themselves since they were the ones with whom I had the most contact over my career, but with an early print of the first version, I was directed to re-write it with a focus on teachers – students don't read textbooks anyway, why would they read this book? Point taken. That decision, to adjust my focus, made ample sense since the idea first came to mind when I was thinking of those traits and skills I used to advise my student teachers of when mentoring them – it was reasonable to write it for them. Clearly I wanted to contribute to, and affect, physics education directly, it just took some time to settle on what and to whom I was writing. As they say the book almost wrote itself at that point, almost.

As an editor, I am abundantly aware of how easy it is for an author to miss the obvious errors in focus, pace and semantics within their own work after having created it, then reading it feverishly. As such I decided to put this version "out to the world" after three full edits on my own – enough was enough. It is not meant to be an academic text. There will be flaws in style, let alone in argument; but in my experience as a negotiator I learned that one of the best ways to influence someone is to show that you too can be influenced. So I look forward to your commentary; some of which I'll take on board for future editions, some not.

Acknowledgements

Via scuttlebutt and the media, there is some level of negativity directed at teachers' colleges with respect to their efficacy and in some cases it may be well earned; however, I was fortunate enough to have had a magnificent experience at the hands of Elgin Wolfe and Brendan Kelly at the University of Toronto. I am likely too distant a memory for either of them to remember, but their influence on my habits in teaching science and mathematics are with me still. More positive influence came at the hands of my first two department heads, Ron Columbus and John Euesden at Norwell DSS. First year teachers should be so lucky to have tough minded, good humoured and experienced teachers to lead their way through those first few chaotic years.

I want to add thanks to Peter Ridd (James Cook University) who took a chance on hiring me to teach at JCU and has encouraged me to articulate my arguments publicly more often; and to Mark Naber (Monroe County Community College) with whom I have reconnected after many years of absence from McGill University Physics. Both have provided me with necessary advice during my early versions thereby setting me on the right track.

Spirited friends know when, how and how far to push. I have many to thank all of whom share my need to be creative and risky: Greg, Ian, Trevor, Dave and John.

My family and I are adventurous people; we sold virtually everything we owned (in Canada) and moved to Australia to give ourselves a self-imposed kick in the ass for the simple purpose of shaking up our lives and careers – a little foolhardy I admit. Writing this book could not have happened otherwise; it could have happened anywhere, but not without having taken many unrelated chances along the way. I am blessed to have a wonderful family who have stood by me through numerous wanderings and adventures. I love them dearly.

What a joyous career I have had. As a rough guide, at approximately half-way through my career over 2 200 students have listened to me, argued with me, been confused by me, laughed at and with me, cried over their grades because of me, confided in me and some have even spited me – I remember many of you, but not all of you… and some more than others. Wherever you are today you should know that you are responsible for making me the teacher I am more so than anyone or anything else. I wish your triumphs far surpass all who have taught you, including me. It's your perpetual assignment to be better. Thank you for allowing me to play my part in your future.

John Daicopoulos

Introduction

How would you define culture? Some years ago a professor of mine once described it as "…all of those things that everybody knows…that everybody knows." That characterization has echoed in my mind ever since and is founded upon the underlying knowledge, quirks and rules that go without saying when living, working, communicating and socializing among a group of people who share something in common. It stems not from innate knowledge, but from knowledge that is passed on through exposure and experience. If you have ever lived in one place for a large part of your life, then moved to a completely different part of the world, or conversely had someone from afar move to your particular part of the world, then you can quickly identify with how difficult it can be adapting to a new culture.

Not surprisingly then, when we find ourselves out-of-place or out-of-sorts, we tend to ask some of the oddest questions; odd because to the locals that information is just taken for granted – it is information that everybody knows…that everybody knows – so why are you asking it? Grasping the nature of that knowledge lies at the core of understanding their comedy, their drama and their history along with finding your place in that shared future among them. Without the influence of that subconscious knowledge you face a steady stream of obstacles to understanding who, and what, defines them; however, once you have mastered their numerous nuances, sayings, mannerisms, intricacies (and delicacies) and even the accent you feel you have made it – you are now one of them, you fit in and all is well. Unfortunately, since this list of subconscious knowledge is commonly taken for granted, it tends not to be taught.

This book is about the culture of physics, or more exactly about the culture of teaching and learning physics. It is all (or at least most) of those things physics teachers think students know, or should know, plus those items we gloss over too quickly while trying to teach the content. It was written to be a concise guide, a handbook of those fundamental elements, skills and knowledge crucial for you to emphasize while you teach the physics. For young teachers, not knowing (or teaching) these basics is the first step on a long road of excruciating difficulty while teaching the physics; for the student, not knowing (or learning) these basics is a major obstacle to preventing their full immersion into the culture of physics.

The Open Agenda is not about the content of physics; there is more than an ample supply of well-written textbooks covering that material. Make no mistake about it though, this is a physics book; there are equations, ideas, and specific topics mentioned for the purpose of supporting the claims herein on how to improve your teaching of the content since it would be nearly impossible to highlight the skills necessary for teaching physics without, on occasion, talking about some of the physics along the way. Having said that, the book is written for early-career physics teachers, either presently in a university teacher-program or already employed in a secondary school teaching physics in Grade 11 or 12, (now to be referred to as senior physics, and accepting that that particular grouping of grades, 11 and 12, may not be universal). In addition to that definition, this book would also apply equally well to those teaching first-year university physics courses. Finally, although the examples are physics specific, there is much within this guide that is fundamental to the teaching of any of the sciences, and as such this book would also apply to teaching chemistry and biology in great detail. We're all in this together.

There are a number of things this book is not. There are no practice questions to solve; no end-of-chapter problems to occupy your evenings; no endless list of equations to cure your insomnia; and no appendix full of constants, terms or Greek letters to stunt your vision or make you want to break out and dance like Zorba the Greek - as I have mentioned, others have done a far more admirable job in these respects so use their resources wisely. It contains very little of the history of physics – here too, there are far better authors who have produced splendid and copious texts covering the history of physics in ways more adequate than a meager attempt on my part could muster. And lastly, it is not about pedagogy, teaching techniques for specific topics like how to solve "third law problems", nor is it about the ways to make physics "fun", although I'll talk about that topic, the making of physics "fun" to some degree later on. This book needs to be small enough to swat a fly with, or at least small enough to carry whenever and wherever you need it. Hide it in your backpack – I was never a briefcase kind of man.

Use the book in conjunction with your lesson plans, your assignment of homework, and the experiments you perform. Each chapter is short enough for you to read in one casual evening – twelve chapters over twelve nights somewhere near the beginning of your first year out. The chapters are written in a particular order that makes logical sense for teaching (and learning) physics based on my own experience, but most can be read in isolation so feel free to read them out of order if you so choose, and re-read them as necessary making notes in the margins as you need.

Our voyage begins with an analysis of the necessity for the proper use of Units in all of the measurements we make. The case for SI (Systeme Internationale) and why having one, and only one agreed upon system when teaching takes us all the way to an inter-planetary impact. The information in this first chapter may appear blatantly obvious to a graduate like yourself, but there is an underlying message within the argument that I recommend you convey through your lessons. Never lose sight of the fact that teaching physics, or any subject for that matter, is as much about teaching the material as it is about teaching how to learn the material – a good teacher does both.

We follow with Numbers; another chapter that may seem oddly obvious but it is full of the cultural nuances endemic to physics. Glossing over the concepts behind these first two chapters, or glossing over their content when you teach them is indicative of a bad habit found in many science teachers: skimming over of detail or dismissing the fundamentals to get to other (more interesting) material. Students will use every aspect of their mind and body to create roadblocks to learning; giving them just cause via our own laziness for de-valuing important details is unacceptable for a professional.

To be fair, there is a difference between the doctrinaires for the facts of physics and of the attention to detail of the process of physics. Facts can be found in books and do not require teachers; learning a process comes from personal guidance, that's where you come in to the picture. You will experience some resistance to generating even a minutia of stress among your students, get over it now. If you're too timid to step on a few toes, tangle a few minds with your words or fear putting a student in her place due to misbehaviour, then get out of the profession now. Your students will not only feed off your knowledge and experience, they will also feed off your strength of character – but only if you have one.

Learning physics is made all the more difficult when the amount of mathematics necessary to succeed is itself a roadblock to many students. In The Math They Need you'll get a brutally honest, but (I hope) comforting view of the mathematics that must be expected from a typical senior physics class. Knowing what mathematics to expect (they from you, and you from them) is half the battle; the other half is in training them to comprehend the countless mathematical equations they will encounter, and training it is since algebraic manipulation is not natural for most students no matter how much you expect it to be. Hence, the Equation Inventory Map is my offer of a technique to helping students make sense of the roll call of equations that will grow like a weed in their notebook. Tending to these equations carefully is a necessity for learning physics – so pull no punches here. Physics without equations is like auto mechanics without the tools; it would not be wise, even with the best of intentions or the strongest force. Take problems with your car to a mechanic; take problems with your wormhole to a physicist.

(To be honest, I have high hopes for this book; but this Equation Inventory Map thing frightens me because I fear it will turn into one of those items presented to teachers during professional development days where some twerp in a suit stands up telling every teacher in the room that henceforth all teachers shall teach in such-and-such a manner. More often than not during these situations I was usually sitting in the back making less than quietly sarcastic remarks while "suit" told me how to teach. Now to be fair these "suits" were well intentioned – I just disagreed with them, immensely. Successful educational reform must first come by reason and argument, then by individual acceptance and finally by group osmosis; it must become the culture, not be imposed upon the culture. Everything else is the bureaucratic bullshit you'll experience much of over your career; hip waders should be standard issue. Keep your head above the waterline, although that does not help in dealing with the stench of reform that can fill every room of a school.)

With a firm grip on the fundamentals in their grasp (even if it oozes out like jelly), and some physics content under their belts, it is time to tackle the thorny issue of deciphering those dreaded word problems. GRASP is a problem solving technique wonderfully suited to cracking most physics questions, but it's one also applicable to many other disciplines – so even if your students don't continue in physics (shocking I know) at least they can take this particular skill with them (along with $F = ma$, $E = mc^2$ and you can't push a string). Nevertheless, you will have to assign and they will have to solve a mountain of word problems before any of you are allowed out on bail.

In Pardon? you get a forlorn look at some of the faults behind what causes their calculations to go horribly wrong and how totally unaware they can be that their answers are indeed horribly wrong. It is important that you be forewarned, and to forewarn them to avoid the likelihood of answers that make no sense… unless you're a physicist living in Whoville.

In a slight departure from these prescriptive chapters, Baking a Cake is devoted to implanting within you a most insidious meme – an idea you cannot purge, and must infect others with. The focus here is the very nature of science itself: experimentation and argument. Thousands of books have been written about the philosophy and nature of science – I cannot add anything new to that debate; however, I want to harness the energy behind that debate to incorporate some of the ideas into your own philosophy of science experimentation and the writing of lab reports. Baking a Cake is necessary to making my arguments in Staking Your Claim transparent – a chapter that details the procedure for writing lab reports based on day-to-day experimental practice akin to something you would see from televisions shows such as CSI© or the MythBusters©.

When all is said and done (which means after you think you have taught them well), they are going to have to write your tests to pass the course[1]. Expert Testimony presents you with a suggested study technique to teach them – one that is based on developing their long-term confidence for problem solving while learning the content. Cultivating this level of confidence within them will take patience on both your parts, but it will help them to face (almost) any question thrown their way, today and tomorrow.

The final three chapters were not in my original plans. I had intended to include them in a later edition some time in the future; however, I came to realize two important points: 1) I might as well come out swinging with all of my arguments full bore and up front; and 2) there may never be a second edition so getting everything off my plate immediately might be prudent. The last three chapters are more chest thumping on my part.

It's not gravity damn it! neatly sums up my emphasis, and tone, for what is to be revealed within its pages regarding the topic of gravity. I am not about to give you suggestions on how to teach it, but by trying to tackle a few misconceptions centred around the topic of gravity may prove illuminating to the way you might approach teaching it in the world-of-adolescents. (There is an oddly collective mentality residing among adolescents from around the world that would make the Borg from Star Trek look like a rag-tag band of chaos mongers. Individuality exists…among individuals, but not in groups, you'll understand eventually. There is so much to love and loathe about teaching adolescents. Could you ask for anything better? I can't.)

Then it is time to delve heavily into the nitty-gritty of physics equations, in particular writing the equations of motion. In Better than Galileo we wade through the mire of the slothful equation writing of many teachers. Along the way my hopes and desires for getting all of us out of that mess will be delivered without an ounce of humility (ok maybe a little).

[1] Speaking of culture…when I moved to Australia from Canada I came to realize that students *sit* a test, they do not *write* a test. Apparently students sit, and teachers write…but never fear politicians complain… everywhere.

Lastly, The Open Agenda itself. Upon deep reflection this chapter emerged as being important enough to merit becoming the title of the book because it carries with it my profound longing for a physics curriculum established on critical thinking skills that would be taught via the historical development of physics. It will remain a perpetual work in progress for me, and if ever there is a second edition of this book it is this chapter that will warrant the most changes. To be perfectly honest it does not fit neatly into the overall flow and pragmatism of the previous chapters. There is a philosophical element behind it crucial to the underlying theme of this book, which is: there are countless minuscule elements to teaching physics that must play a foundational role in the over arching intent of teaching physics – in other words you are teaching them that the history, processes and content of physics are not separable. There are times when you will need to emphasize one over the others, but eliminating any one of them from your teaching is reprehensible.

There is double meaning in The Open Agenda title. The first is the premise that the curriculum be based upon one narrative theme permeating the class, rather than teaching a collection of distinct topics in some hodgepodge order; but the second meaning is for all teachers to be candid about our aspirations for what should happen over the course of teaching senior physics: that aspiration should be to teach physics students to be physicists. Simple. No? Over the years we have added so much "fun" and relevance to physics education that we have removed much of its grandeur, much of what really gives physics its depth. Physics and science may not be alone in this regard; but my life and this book are devoted to science. Wouldn't it be wonderful if senior English were taught with the goal of turning students into writers? To teach art with artists in mind or drama for aspiring actors? In some sense I think we do and should do more, but somehow science and physics are supposed to be taught for everyone. And that is nonsense. Your students need to feel from you that physics is the most important subject in the world – they should feel that same excitement from every teacher. It will be your passion for the minutiae that turns students on to your subject. That is my Open Agenda.

I have tried to write in a very comfortable and informal style, and was most successful writing when I pictured myself standing in front of a class; so there are numerous occasions referencing I, me, you and them. The "you" may not always fit your exact situation or ability, but teaching has always involved coalescing innumerable goals around divergent abilities and interests, within both the teacher and the students. Imagine, if you can, the book as a conversation with me, albeit one-sided for the moment. It is written, for all intents and purposes exactly as I teach; and as such it is interspersed with a number of comments which on the surface may appear dismissive about students, adolescents and their abilities. Don't be fooled. My best humour tends to be situational, spontaneous and acerbic so it may not come out as intended in print. My classroom stand-up routines, delivered through many time-honoured jokes heard by thousands of students are not worth printing; however, do not mistake this recurring commentary for negativity. Although the life-long learning shtick we hear frequently is both necessary and central to a vibrant and progressive society, there is nothing better than teaching youth. Adolescent minds are fresh, malleable, intuitive and excitingly rebellious – there is no other age I would prefer to teach.

I began this introduction by recalling how a professor of mine gave me a profoundly wise definition of culture. He was not alone with his wisdom. An education professor once confessed to the class that, "…in the world of education, while trying to give students a well-rounded education we run the risk of dulling sharpened edges." This book is about sharpening your edges in order to teach your students that which is most critical to succeeding in physics: the content.

It is a no holds-barred expression and application of my edges.

Enjoy.

1

Units

If I told you that I am 1.72 and 67 you would probably think it fair to ask 1.72 and 67 what? Innately, you know that the numbers themselves are irrelevant unless you are also told the units of measurement because knowing the units tells you both what the units are so you have a frame of reference from which to compare my number to another, and what the measured quantity was. In other words, metres tells you the number is a length…in metres; kilograms tells you it's a mass… in kilograms; and seconds tells you it's a time…in seconds. Units matter.

Regardless of how many ways there are to properly describe what physics is, ultimately it comes down to some definition revolving around the quantifiable measurements of nature: what did we measure, how did we measure it and once we have these measurements how shall we convey what they tell us about nature. That is what this first chapter is all about: Units and which ones to use in senior physics.

There are many types of unit systems with the Imperial system of feet, pounds and gallons, and the Metric system of metres, kilograms and litres being the two most common, and hopefully you'll teach some of the more common and useful Imperial-to-Metric conversions during class, none of which will be covered in this book except as a teaching a technique later on. For those of us who live in Metric only nations there is a great wealth of history behind the Imperial system that is worth learning and should not be ignored. I don't know of any metric nation that is entirely metric. Having lived most of my life in Canada I can admit to still buying homes by the square foot, and housing materials like 4 x 8 (feet) sheets of drywall. When you buy car tires anywhere in the world you buy something like 165/75R14. The 165 is the width of the tire in millimetres, the 75 is the vertical profile of the rubber in percent, and the 14 is the size of the rim, in inches. Pilots often tell you their altitude in feet. Knowing both systems is a good thing.

Nevertheless, it is vital to (learning and doing) physics that we agree upon which system of measurement to use for all of the problems, experiments and reporting we'll expect to encounter – uniformity is crucial. Therefore, in physics …all final answers and experimental data must be expressed using mks units.

What are mks units?
mks is the special subset of the Metric system that stands for metres (m), kilograms (kg but k for short) and seconds (s), therefore metres-kilograms-second, or mks for short. It is for the most part the internationally agreed upon standard that all physicists (and engineers, doctors, chemists, biologist, etc…) use when experimenting, measuring, calculating and communicating their results; therefore, if it is important enough for all of them to be consistent then it must be equally important for us to be consistent when teaching physics. (There is a cgs system (centimetres-grams-seconds), another subset of the Metric system that has fallen out of favour for most topics, especially teaching. And why mks and not cgs or any other combination is not really important to us right now, but as mentioned with respect to the Imperial system there is a wealth of history here worth learning, just not now and not here in this book. All that being said, the mks system is not used universally so we will deal with conversions later in this chapter.)

The three units of metres, kilograms and seconds are not the only base units of the mks system. The complete system includes four more:

1) The ampere, A, for measuring electric current.
2) The kelvin, K, for measuring temperature.
3) The mole, mol, for measuring the amount of a substance.
4) The candela, cd, for measuring light intensity.

(You might notice that the kilogram is the odd one out of this set because it uses a prefixed-unit, i.e. kilo + gram, kilogram. The others are base units out right as in metres and seconds. So it is important to remember that the kilogram is the proper mks base unit, not the gram.)

Using this system in physics does not mean that the only acceptable answers must be either in lengths (in metres), masses (in kilograms) or times (in seconds), but it does mean that all of the answers and data must be restricted to these units or combinations of these units called derived units. For example velocity (speed) calculated as the division of a length and a time will have to be the combination of length in metres and time in seconds only, and so a value of 16 m/s is acceptable but a value of 72 km/h is not. Note that both of these answers are in Metric, but only the former 16 m/s uses the mks subset. So 72 km/h is not mks and therefore is not acceptable, whereas 16 m/s is mks and is acceptable. All mks quantities are Metric, but not all Metric quantities are mks.

The seven base units are not the entire story though. There is another larger set of units that are also classified (defined) as both Metric and mks. Most of these are units named after (famous) scientists. Some of the more common ones to expect while teaching physics include measurements of: force in newtons (N); power in watts (W); energy in joules (J); and potential difference in volts (V).
All of these, and many others, are classified as mks because either:

1) they are simply deemed (or defined) to be mks by the great powers that be (Bureau International des Poids et Mesures). This list also includes such units as Celsius and the refractive index or;

2) they can be broken down to some combination of metres, kilograms and seconds but that we normally don't bother. For example the newton is equivalent to a kg•m/s^2 read as a kilogram metre per second squared, every individual unit in kg•m/s^2 is itself mks and therefore a newton is mks. It also important to note that mks measurements do not need to include all three units simultaneously as was shown with speed values of m/s. The requirement is that the only units used are mks units.

Be careful to note that the person's name is not capitalized when shown as the word (joule is correct, not Joule), but that the letter is always capitalized (J is correct, not j) when named after a person.

1 joule = 1 J
1 newton = 1 N
1 watt = 1 W

"The measure of power is the watt W, named after the scientist James Watt." Get it? All units named after a person are capitalized.

There is one exception. Years ago it was difficult to write the units for volume in litres because the letter l looked too much like the number 1 when printed, so the convention was amended to allow a capital L to represent the litre even though there was no Mr. or Ms. Litre. Today that is less of an issue because of the greatly improved printing techniques available; however many teachers still use a capital L because their handwriting may cause some confusion – many of my former students would agree that handwriting can make teaching confusing having once been told I had the second-worst looking boards in my school – I was gaining ground on first place though, there was hope for me, but then I left.

Not to let a little matter about the litre and its designation go by easily, a couple of scientists decided to have some fun. A fictional was story created about the famous scientist Claude Emile Jean-Baptiste Litre (1716 – 1778) for whom the unit was named. Ken Woolner and Reg Freisen wrote the original story in 1978 for the publication Chem13 News[1]. The entirely imagined history of Mssr. Litre fooled dozens of scientific journals, as well as the New York Times and the Canadian Broadcasting Corporation. The original biography itself is a great read and highly recommended for you and your students; reading about the media frenzy that resulted from it is also fascinating.

One last item to address, do not pluralize the units. It is 1 km and 10 km. Not 1 km and 10 kms. We have a standard system for a reason, everyone is to use it. And if kms is not enough to confuse the matter, you will probably see klm or klms as well (I screamed when I saw that last one on a road sign, but that's not the worst, I saw 25 kgs written on a science cart!). Stop this habit dead in its tracks in your classroom and in your life. I can be so annoying at parties.

Conversions

If physics restricts us to using only the mks subset for all data, then eventually you will be required to convert from one unit system to another, whether that means from Imperial to mks or from non-mks metric to mks. Most text books will have taken care of the majority of Imperial to Metric conversions on your behalf so realistically you'll find that converting from Imperial to Metric will play a small part of senior physics, therefore there is no listing of Imperial to Metric conversions in this book. The techniques shown here will work equally well no matter what system you are converting to or from. Let's examine a few of the important conversions necessary to teaching physics.

In order to do conversions accurately your students will need to learn, or at least be able to look up, all of the useful prefixes common to physics – there are many but please don't feel they should memorize them, just that they be able to look them up – personally I despise the image that physics, or science, is about memorizing information; it's about learning to use the information you have at hand. Having said that there are a few very common prefixes you (and they) should learn and know through practice.

[1] Ken was Professor of Physics, and Reg was the Assistant Dean of Science, at the University of Waterloo. You can read more about the entire affair at: *http://www.student.math.uwaterloo.ca/~stat231/stat231_01_02/w02/section3/fi1.2.pdf*

These include:

nano as in nanosecond (ns)	10 000 000 000 ns = 1 s;
milli as in milligram (mg)	1 000 mg = 1 g;
centi as in centimetre (cm)	100 cm = 1 m;
kilo as in kilowatt (kW)	1 000 W = 1 kW;
and mega as in megavolt (MV)	1 000 000 V = 1 MV.

Many more exist and as physics rips past the boundaries of size like the very small, the very large and the very fast on a regular basis there will be many more that become common.

Some prefixes are capitalized[2] like mega (M) and giga (G) since lower case m and g are already taken. For all intents and purposes none of these prefixes should be new to them as they should have been introduced to them in junior science; nevertheless keep them relaxed at the start of this onslaught because there is so much more to come. With hope they'll discover that as they learn tiny nuggets of physics during the lessons each of these bits and bytes will find its proper place in their brain…if only for a fleeting moment.

More detail on what these prefix values indicate will be discussed later in the next chapter, but for now we need to examine one particular double conversion that occurs frequently, and doing it will help with other multiple conversions when they occur.

Double Conversions

Earlier I showed you that a final answer of 72 km/h is not an acceptable value because it is not mks. So how might we teach students to convert a km/h answer into mks, an answer of m/s? It can be done by either by converting each unit separately (from kilometres to metres, and then from hours to seconds); or by multiplying by one…really, by multiplying by one.

They will need to recall that 1 000 m is equal to 1 km, which is in fact the whole point of the prefix k; it signifies that the number in front needs to be multiplied by 1 000. So 1 000 m = 1 km. Students will need to recall that there are 60 seconds in one minute (60 s = 1 min) and there are 60 minutes in one hour (60 min = 1 h), and finally if they follow your math correctly, that means there are 3 600 s in one hour (3 600 s = 1 h). The two single conversions needed to convert from km/h to m/s are:

$$3\ 600 \text{ s} = 1 \qquad \text{(Eq.1a)}$$

[2] No there was no Mr Mega or Ms Giga though I am sure somewhere in this world those names truly exist. We are running out of letters. Prefixes are not named after anyone, at least not yet.

and

$$1\,000 \text{ m} = 1 \text{ km} \tag{Eq. 2a}$$

Now to convert from 72 km/h to m/s.[3]

First re-write the values Eq.1a and Eq.2a as ratios equal to one and in that way we really are multiplying by one, which changes nothing. In other words:

$$\frac{1h}{3600s} = 1 \tag{Eq.1b}$$

and

$$\frac{1km}{1000m} = 1 \tag{Eq. 2b}$$

Convert the hours into seconds using Eq.1b:

$$72\frac{km}{h} x \frac{1h}{3600s} = 0.02\frac{km}{s}$$

The two hours units have cancelled (one in the numerator and one in the denominator) leaving only seconds in the denominator, and 72 was divided by 3 600 leaving 0.02.

Now to convert the 0.02 km/s into a value exclusively in m/s using Eq.2b:

$$0.02\frac{km}{s} x \frac{1000m}{1km} = 20\frac{m}{s}$$

The two kilometre units have cancelled (one in the numerator and one in the denominator) leaving only metres in the numerator, and 0.02 was multiplied by 1 000 leaving 20 as the numerical answer. So 72 km/h is equal to 20 m/s, and that is a proper mks answer.

This could have been done in one whole line canceling units and calculating values all at once, as in:

$$72\frac{km}{h} x \frac{1h}{3600s} x \frac{1000m}{1h} = 20\frac{m}{s}$$

Further, you may recognize that

$$\left(x\frac{1}{3600} x \frac{1000}{1} \right)$$

[3] On a slightly off topic matter, I despise the reading of 72 km/h as 72 kilometres *an* hour, it is 72 kilometres per hour. Per. Per! PER! I know I am losing ground on this point since most people today, especially weather forecasters, say "an hour" but I refuse to budge; however, it is one of the strengths of the English language that it transforms over time. I plan to remain firmly fixed in the past as most of you leave me in your dust. Cough…hack.

is equal to dividing by 3.6 so you can use the short form

$$72\frac{km}{h} \div 3.6 = 20\frac{m}{s}$$

where 3.6 is the conversion from km/s to m/s. Therefore 3.6 km/h = 1 m/s. Although I am always hesitant providing short cuts to students, I think this one is fair enough to dole out since it appears often enough.

Let me reiterate that there should be no compulsion on their part (or yours) to memorize any of these conversions, but that they must know how find them when necessary and use them properly. Though our brains are amply suited to storing details while learning physics, leave the facts and statistics in the textbook; help them to use their spongy brains for thinking and applying, that's real teaching. Two other important items need to be addressed before moving on.

There is plenty of subjective judgment that goes on in a teacher's mind when valuing a question's worth, whether it is a four or five mark question and how exactly to distribute those potential marks to the student's solution. Will a student get one mark for showing this step, and two marks for those steps, etc…will vary for both you and me. What should match up closely between us is the overall value of any particular question to the total value of the test. No matter, providing the correct units for the answer must rank in the grading structure for each question because if students don't know whether the answer is in kg or in km then they do not know the answer – the student is wrong and deserves to pay the price in the question's grading. I have seen end-of-the-year statewide exams where the answer box already has the correct units listed for the student – that is patently unacceptable and I am disgusted that it occurs at the hands of my fellow physics teachers. There are rare occasions when it may be necessary and there are some occasions when it may be necessary to leave the answer in a non-mks form, but only if the student is told something specific to that question such as "leave the answer in km/h". In Chapter 6 there is a short discussion about the answers at the back of the book. They are often a mix of mks and non-mks units without any guidance as to which answers should or should not be in mks – that will drive your students completely around the bend. Any bit of confusion, especially when it is scattered throughout a course, hinders a student's ability to learn. My students were told to always apply the use of mks on all test answers and experimental data.

Oops

Being consistent is not only absolutely crucial it can also be painfully dangerous if not followed. There is the now infamous story about the Mars Climate Observer spacecraft launched in December 1998. It crashed into Mars (not part of its planned mission) in September 1999 due to a lack of communication between its engineers and software writers during development. One group was using the Imperial system for of all of its numerical requirements while the other group was using Metric (mks to be specific, as they should have) and because of this error the ship's maneuvering rockets fired when it was too close to Mars. The Mars Climate Orbiter Mission Failure Investigation Board report cited "…the 'root cause' of the loss of the spacecraft was the failed translation of English units into Metric units." Oops. So let us all be consistent by using the metric and mks systems. Just think of the money and insurance we could save.

And finally, if your students are not yet fully convinced that units matter ask them this simple question: "Would you rather be paid 20 dollars per hour or 20 cents per hour?" Units Matter.

Oh and by the way I am 1.72 m in height with a mass of 67 kg – but I am working on that one.

2

Numbers

Not long ago the Premier of Queensland (Australia) initiated (as politicians are apt to do) an anti-speeding campaign during the Christmas holiday season by citing statistics about how speeding was major a cause of traffic fatalities by using the usual tag-lines like speed kills and other propaganda – and every year the campaign will have surely repeat itself.

She is right though, speeding does kill; it is certainly more difficult to maneuver and stop a vehicle the faster it is moving, fair enough. Regrettably, she then proceeded to say that anybody caught speeding, "…even doing 101 km/h in a 100 km/h zone…" would be ticketed; but is going 1 km/h over the speed limit worth the effort of the ticket? Does it teach the driver enough of a lesson so he will let off the pedal the next time, or is it simply a money grab and a political stunt? More importantly, from a physics point of view, can our measuring equipment (i.e. the radar guns and the speeding vehicle's own speedometer, or even the driver's eye) actually measure precisely enough to be that accurate to within 1 km/h at 100 km/h? It is essential to observe that it requires both the radar gun and the vehicle's speedometer to be accurate in order to have a valid infraction of the speed limit. If your speedometer reads 100 km/h when you are doing 110 km/h then how will you know any better? Likewise, if the radar gun reads 105 km/h when you are actually doing 100 km/h how valid is the ticket? Although this book is not about the details of the technical instruments themselves, this chapter is about questioning the values given and what to do with those values once they are known. Having said that, I'd be wary of trying this out in a court; but let me know how it works for you.

Doing 160 km/h in a 100 km/h zone is certainly a significant difference. Doing 100 km/h in a 60 km/h is comparably significant; but is doing 101 km/h in a 100 km/h zone significant? Or even 61 km/h in a 60 km/h zone? Well, no those differences are not significant. So how do we decide whether or not a measured value is significant at all? How can we be certain with our measurements and how significant can a number read off of a device be? The radar gun and speedometer are both calculating devices just like your calculator. The values read off their screens appear after the device has done the necessary calculations and therefore has to be taken within a limited degree of seriousness; but by how much? In the world of scientific measurement we need to ask: how significant are the number of numbers shown?

In Chapter 1 we saw how to convert from km/h to m/s by dividing the original number by 3.6. In that example we calculated that 72 km/h was equal to 20 m/s because 72 divided by 3.6 was equal to 20. But what if the original answer was 110 km/h? If we divide 110 km/h by 3.6 to convert it to m/s we get 30.5555555555555555555555…with the …555… repeating forever. When do we stop writing it down?

Your students will wisely reply with "round it off." But round it off where? Is 110 km/h equal to 30.6 m/s? Or is it equal to 30.56 m/s? Or maybe it is 30.556 m/s? Or is it just 31 m/s? (We'll look at rounding techniques shortly, but the question here is where to round it off?)

To decide where to round the number we need to look at the original number from which we made the conversion to ask a simple question: What is the person (or device) that made that measurement telling us by quoting, or displaying, only those numbers? From that information we can decide how many of its digits are important, i.e. in 72 km/h there is a seven [7] and a two [2]; in 110 km/h there is a one [1] and another one [1] followed by a zero [0]. In this way we can decide on (i.e. count) the quantity of significant digits. Personally I say significant digits (sig. dig.) while other teachers say significant figures (sig. figs.). It's an insignificant difference either way – ha!

Most textbooks give a five-point plan for figuring out the quantity of significant digits in a number sequence. After detailing this five-point plan I will give you the Mr. D short method; unfortunately to understand any and all short methods you and the students need to fully understand the long method first, so bear with me right to the end. For the purposes of explaining this process numbers like 62 or 5.003 will be referred to as a number or a sequence; but individual numbers 6, 2, 5, 3, and zero will be referred to as digits.

Counting Significant Digits

Point 1 All non-zero digits in a sequence are significant (that is all of the digits from 1 through to 9 count, or matter). For example:

12 contains two significant digits; the digits 1 and 2;
483 contains three significant digits; the 4, the 8 and the 3; and
8.665 contains four significant digits; the 8, two 6's and a 5.

The rest of the points, 2 through 5, all have to do with the digit zero and its placement in the number sequence. A zero is not nothing, it is something, a placeholder and where it is placed tells us whether it is counted as significant or not.

Point 2 Zeros between non-zero digits of a sequence are counted as significant. For example:

104 contains three significant digits: the 1, 0, and 4;
3062 contains four significant digits: the 3, 0, 6, and 2; and
5.0009 contains five significant digits: the 5, four zeros, and 9.

Point 3 Leading zeros (zeros in front) in a sequence are not significant. For example:
0.32 contains two significant digits: the 3 and the 2;
0.00571 contains three significant digits: the 5, 7 and 1; and
0.0004003 contains four significant digits: the 4, two zeros and the 3. (Previous rules still apply.)

Point 3 seems odd because you would think that when a zero is a place-holder its holding of that place must be significant, especially in decimal sequences like 0.00571. Looking at number sequences greater than one, as in 359, may help with an explanation. Where are the zeros holding their places in the number 359? If you go back into the deep recesses of your memory you might remember that a number like 359 is more pedantically written as a 3 in the hundreds place, a 5 in the tens place and a 9 in the ones place; but what is in the thousands place or the ten-thousands place? Zeros of course, so why did we not bother to write them down? Because numbers like 359 would then be written as 00359 or worse yet as 00000000359. We do not write those leading zeros because they are not significant in what more information they could tell us about the number. The number's magnitude is based upon its leading non-zero digit, and nothing before it matters. Leading zeros are not significant.

Point 4 Trailing zeros in decimal number sequences are significant. All of these sequences must contain a decimal in them. For example:

3.20 contains three significant digits; the 3, 2 and zero;
50.00 contains four significant digits; the 5 and three zeros;
0.70 contains two significant digits; the 7 and the 0. (don't count leading zeros.)

Point 5 Whole number sequences (no decimals) with trailing zeros are questionable, and when in doubt go with the least. For example:

3 450 contains three significant digits; the 3, 4, and 5 – the trailing zero is questionable so go with the least;
25 000 contains two significant digits; the 2 and 5 – the trailing zeros are questionable; and finally,
3 000 contains only one significant digit; the 3, all of the zeros are questionable and when in doubt use the least.

But why should we question the trailing zeros in these cases? Are they not placeholders too? They are, but because we don't know what the number itself represents we can't be sure how important these zeros are.

If the number sequence is a measured quantity as in 3 000 metres found with a measuring tape, then there is a good chance there is some uncertainty, however small, in the measurement. By writing the number as 3 000 you are telling us that the measurement only needs to be accurate to within one metre; i.e. you are confident that a measurement of 3 001 m or one of 2 999 m provides no better information than 3 000 m – that plus-minus range of 2 m is not important. If you wanted to be more accurate, say to within 10 centimetres, then you could write 3 000 m as 3 000.0 m because now you are indicating your confidence that the measurement is not 3 000.1 m or not 2 999.9 m – that plus-minus 20 cm range is not important; but the larger plus-minus 1 m error is now important.

There are many ways to illustrate the central theme to significant digits. I know of few as effective as a military one: imagine if a missile can destroy a region as wide as a hundred metres after being launched from a distance of 3 000 m, what difference does it make whether it misses the target by 1 m or even 10 m? In other words, knowing that it will travel a distance of 3 000 is no better than knowing it will travel a distance of 3 001 m or of 2 990 m. So writing it as 3 000 m is as significant (1 sig. dig.) as it needs to be.

But what if the 3 000 was a counted quantity as in "3 000 students showed up for the school's physics night"? (…in my dreams) If a whole number with trailing zeros is a counted quantity then we say it is infinitely significant because there cannot be 3 000.1 students or 2 999.9 students unless you allow parts of students to attend school. So counted quantities are infinitely significant… and infinitely healthier for students. I think that's straight forward enough but in a terrible twist of messing with student's minds most textbooks cover these rules properly only to then write numbers like 3 000 m in questions treating them as 4 significant digits, which is incorrect; unless some poor sod laid out 3 000 individual metre-sticks!

Whew! Now that is one heavy onslaught of five points to remember and it will easily take a good chunk of a lesson to cover followed by a set of questions to practice. As for Mr. D's short method:

In any number sequence, find the first non-zero digit, count it and everything after it.

That's it. All five points rolled into one simple statement that always works. Go back and use it on each of the preceding examples making sure you apply the whole number rule when necessary – that is the only slight exception to the short method. Ah…the simplicity of it all.

Using Significant Digits

My guess is that throughout…zzzzzzz….much of what you have just…zzzzzzz…..read you might have wondered…zzzzzz…so what? What is the purpose of knowing the number of significant digits? It comes down to using those numbers in calculations: *Final answers cannot contain more significant digits than the least number of significant digits provided for in the question*.

Consider this: If a vehicle travels 32.8 m in 6.2 s, how fast is it going and how are the significant digits important in the calculation? The answer is (almost) simple and to demonstrate the solution for students we would need to calculate the speed of the vehicle by dividing the distance traveled (32.8 m) by the time interval it took to travel that distance (6.2 s):

such that the speed = 5.290 322 6 m/s according to the calculator; but where to stop writing the numbers? Looking at the original set of numbers used (32.8 and 6.2), decide which number contains the fewest significant digits (6.2 contains only two), therefore the final answer cannot contain more than two significant digits. To round off 5.290 322 6 into a number that contains only two significant digits we get 5.3. If a vehicle travels 32.8 m in 6.2 s then it is traveling 5.3 m/s. You cannot have more significant digits in the answer than in the question.

(Technically different rules apply if the numbers are being multiplied or divided compared to if they are being added or subtracted, as well as how many decimal places exist. Some teachers teach and use those separate methods and I admire them for their patience in doing so; I do not. The worst that can happen if you do not use both methods is that you will end up with a final answer containing fewer significant digits than it could be permitted to hold.)

Rounding Rules

By now you are deeply familiar with the rounding rules of mathematics. Numbers followed by a digit less than five, as in 4, 3, 2, 1 and 0 will not change the preceding number; numbers followed by five or greater, as in 9, 8, 7, 6 and 5, will round the preceding number up. So 5.29 rounds up to

5.3 for two significant digits, because the two is followed by a nine. There is another rounding rule called the odd-even rule which states that numbers followed by a 5 round up if they are odd (so 4.35 rounds to 4.4) and even numbers followed by a 5 remain unchanged (so 4.45 rounds to 4.4). Again some teachers teach (and use) this rule, all the power to them for doing so because they are more correct in using it; however, as with the different rules for using significant digits in calculations, there is little issue with not using the odd-even rule in physics since answers will vary only slightly if you do not use it. How slightly might the answers vary?

In some physics questions students will be expected to use a calculated answer from one part, say part a) to calculate another answer later on in part c); a normal requirement for multi-step problem solving very common when working with experimental data and tougher questions. In these cases it is crucial to instruct students to carry an extra one or two significant digits when possible. If the calculation for part a) works out to 4.45778 but only needs two significant digits for it to be the final answer then 4.5 is correct; but if this answer needs to be used in a calculation later on in part c) then carry it along as maybe 4.46 or 4.458 throughout the later calculations.

In many cases the difference between the value compared with the final answer is small; but in learning physics students need to know they have achieved the correct answer when in fact they are correct – it is about developing their confidence, and confidence builds upon success.

Although physics uses mathematics, physics is not mathematics, so final answers do not have to be exact to be correct. If their calculation works out to 3.6 and the correct answer is 3.7 chances are the student is correct within a minor rounding issue so there should be no need to call you over – they have done nothing wrong. If the calculation works out to 3.6 and the correct answer is 130, then they had better check their work first then call you over since they are clearly incorrect. Teach them not to round off calculations until they need them to be final answers.

100's, 1 000's and Scientific Notation

In the significant digits rules we saw that the number of significant digits in a whole number with trailing zeros is questionable unless it is a counted quantity, as in 100 ducks. How can we make 100 a three significant digit number? By using scientific notation.

You and I know that scientific notation is a method to write very large or very small numbers (i.e. very long number sequences) in a shorter form using powers of 10. Hopefully the rules for using it are familiar to them by this stage, but as a refresher you may have to make it another short lesson. Looking at it in a little detail here are a couple of examples to consider when teaching it, and yes

I know you understand it, but many of them do not and in the end there is an important learning opportunity to come…stay tuned.

The number 14 500 is equal to 1.45 x 10 000; and the number 10 000 is (1 x) 10 x 10 x 10 x 10 which is equal to 10^4 using the exponent rules. Therefore 14 500 is equivalent to 1.45 x 10^4 and that is scientific notation (with only one number left of the decimal place).

For small numbers like 0.000 048 it is slightly more elaborate and we use negative exponents. The number 0.000 048 is equal to 4.8 x 0.000 01. The number 0.000 01 is (1÷) 10 ÷ 10 ÷ 10 ÷ 10 ÷ 10 or (1 x) x 1/10 x 1/10 x 1/10 x 1/10 x 1/10 which, in either form is equal to 10^{-5}. Therefore 0.000 048 is equivalent to 4.8 x 10^{-5} which again is in scientific notation.

Fair enough, but let's return to the whole numbers ending in zero issue. To write 100 as three significant digits it would need to be written as 1.00 x 10^2, likewise to write 1 000 as four significant digits write it as 1.000 x 10^3 (or as 1.0 x 10^3 for two significant digits, etc….). This is how these numbers should be written in texts, tests and exams. More often than not they are left as 100 (or 1 000) without notifying students that they should be treated as three (or four) significant digits within the text, test or exam. That's more bad practice.

Finally, as with my comment in the Units chapter the number of significant digits provided in the answer should constitute part of the marking structure, not a big part but a part nonetheless. Here again I have seen state-wide exam markers told to essentially ignore significant digits in the student's answer unless it is grossly out of whack – that is unacceptable: it is either correct or it is wrong. It is important that they know where you stand and what is expected of them while learning physics so once standards are set and adhered to, they will find them easier to follow. When it comes to finely separating your top few students you will be grateful they have followed the rules properly.

Calculator details

To input and read scientific notation on a calculator they will need to know their own calculator's input methods and each one is different. One of my routine comments to students is: "Remember that manual that came with your calculator – find it immediately."

Your students will need to understand that the proper way to input 1.45 x 10^4 on their calculator is to use a button that probably has EE, EXP or x10^x on it. There are others, so they will have to read their manual if necessary so get them to figure it out. To input 1.45 x 10^4 type (push the buttons) 1 then decimal then 4 then 5 then EE (or EXP) and then 4. I know you think this is really lame stuff but trust me there is a point to my pedantry. The point is: how does it appear on the screen and do they understand what appears on their screen? This is of great consequence because I have seen far too many students who by now, grade 11 or so, still don't know how to read their own calculator. Every calculator will show the number 1.45×10^4 in a different way. In my years as a teacher I have seen calculators show it as:

$1.45 \text{ x} 10^4$ or

$1.45 \text{ x } 10^4$ or

1.45__4

or even

1.45^4

which is by far the worst version listed since the number 1.45^4 in proper mathematics means 1.45 x 1.45 x 1.45 x 1.45 which is not equal to 1.45×10^4. If 1.45^4 was an option provided on a multiple choice question, then a student may choose it simply because that is how it appears on their calculator. They would be wrong even though they did everything correctly! There is nothing worse than doing everything properly yet still losing a mark over a simple issue like that. Remember, success breeds confidence.

To finish off, recall our starting point: the traffic violating situation of doing 101 km/h in a 100 km/h zone. Yes it does constitute speeding but it is not significant from either a physics or policing point of view. Remember the whole point of significant digits is to convey to someone that given everything done to carry out these measurements any variation from them less than the significant digits will make little to no change to the import of the value. In other words, given all of the conditions that must be met to stop a car going 100 km/h compared to stopping a car going 101 km/h, the 1 km/h extra will make no difference to the final outcome. Given the driver's visual, mental and physical reaction times, the vehicle's braking capacity, the road conditions and distractions, going the extra 1 km/h over the limit is irrelevant – just try telling that to the police officer… or to politicians.

3

The Math They Need

"Remember all of those times in your mathematics class when you asked: where in the world am I ever going to use this stuff? Well the answer is here…in physics."

That's my quote and it's what I used to tell them on the first day. Not to frighten them, but to be honest. Mathematics is a crucial two-fifths of the effort behind solving physics problems and an invaluable component for analyzing experimental data[1]. Every physics topic, the facts and figures, the experiments, the theories, laws and models we know are only as good as the mathematical analysis behind them. Senior physics should be an unabashedly robust introduction into how we analyze the natural world using mathematics to quantify, and codify, what we observe; I believe this point so much so, that much of the rest of this book will focus on the mathematical aspects of teaching and learning physics. Now more than ever your demeanor and delivery of the lessons can weigh heavily on whether your students will panic in your class.

If you consider how much mathematics your students have studied already just to get into senior physics while adding the number of math books available to them, it had better not come as surprise that there is little more you and I could teach them in one more short lesson – we are not magicians. My emphasis throughout this chapter is simply to highlight some of the individual areas

[1] Why only two-fifths of the effort you ask? You will have to keep reading the book to find out how.

of mathematics that should be (no, must be) predominantly relevant while teaching and learning physics. Any student planning a career in physics will use far more mathematics – that's a scary thought to some, but we need to show them its beauty, power and purpose from an early stage.

Imagine reading Victor Hugo's Les Misérables in its original French writ after having spent a year, a decade, or your whole life in France compared to reading it through an English translation as an English speaking person who has never visited France; few would disagree that the difference in your experience and resonance with the story would be astounding. Furthermore, if you never do live in France, then you may never know any better. Fluency in the language of a culture is essential to understanding the culture. Translations of books from one language to another always lose some of their essence when that cultural template gets diluted, no matter how unintentionally. Being monolingual is not a dead end street though; you are always free to learn another language at any point in time, and most people would pride themselves on becoming multi-lingual.

The physics community is analogous to a linguistic or ethnic culture, and the best way to immerse yourself in it requires being fluent in its language. Physicists proudly speak mathematics in our culture. There are certainly many areas of physics that lend themselves to non-mathematical explanations of one degree or another; but these are limited in the clarity they can provide the learner, ultimately. As a terribly proud devotee of Shakespeare's plays my experience watching the plays, great as it is, pales in comparison to the actor's experience while playing the role; and yet the actor's familiarity, being greater than mine, imposes no remorse or inferiority upon myself and I can try my hand at acting if it so pleased me.

These next few chapters will help you to introduce the main (mathematical) elements of that cultural fluency that students will need to concentrate upon when learning physics because with fluency comes integration. It all comes down to a question of comfort really, since many of your students will feel as lost and mesmerized in your class as you would feel if dropped into a new country possessing none of the necessary linguistic skills.

Hopefully by the end of this chapter you too should be more prepared and comfortable with your own mathematical expectations while teaching them. With an increased self-confidence you'll need to impress upon them those same mathematical expectations when they learn. The material presented need only be as a refresher in one physics lesson on or about day two; it is not about teaching them the mathematics, it is about letting them know what's to come and using it with consistency throughout the rest of the course.

Basic Algebra

If I had to sum up the most important element of the mathematics needed to survive physics it has to be basic algebra: that ability to re-arrange mathematical equations correctly by isolating for one term or another. If students are poorly skilled in this element of math, they will have to sharpen that dull edge immediately; it is not the end of the world for learning physics, but it makes learning it as difficult as it can be. There will be plenty of opportunities to practice this skill over and over again during the course of the term (as well as in their mathematics classes). Let's look at few examples using some of the equations they are likely to encounter in senior physics. Remember that my point here is to illustrate the type of mathematics you must expect from them when learning physics and solving questions; this is not the forum to teach them (or me to teach you!) the mathematics for the physics.

First off, the so-called wave equation: $v = f\,\lambda$ where v is the velocity of the wave in m/s, f is the frequency of the wave motion in Hertz, Hz, and λ (lambda) is the wavelength in metres, m. It may be called the wave equation but there is no such thing as one version of an equation, in fact there are at least as many versions of an equation as there are terms in the equation. Sometimes equations are referred to as the equation for… so $v = f\,\lambda$ would be called the equation for velocity or the velocity equation, but this too is terribly lazy and inaccurate, and should be avoided at all costs, particularly by you. There are some very famous and important equations in the world of physics often referred to as the equation for…but in teaching physics we need to impart an understanding of its overall mathematical nature. Physicists understand the plurality of the expression "the equation for" to mean "the relationship between such and such, arranged so that this term is isolated"; most students will not, so do not confuse the issue for them. This particular equation relates the three terms of velocity, frequency and wavelength of a wave, and as such can be re-written to isolate each term on its own as necessary. Therefore using basic algebra, the equation $v = f\,\lambda$ can also be written as:

$$f = \frac{v}{\lambda}$$

to isolate for the frequency term f; or as

$$\lambda = \frac{v}{f}$$

to isolate for the wavelength term λ.

That is one particular equation relating the three terms v, f and λ that students will need to re-arrange mathematically as needed depending on the question. Therefore, the above three equations are not three unique equations, but one equation relating the three terms to be re-arranged as necessary.

In a very general process, consider showing them some (irrelevant) equation:

$$A = \frac{B-C}{D}$$

which can be written as either:

$$D = \frac{B-C}{A}$$

or as

$$B = C + AD$$

or as

$$C = B - AD$$

all with equal value and relevance. There is no “equation for A”, or “equation for B” etc…There is one equation, and any one of them will do. The value of a particular term A, B, C or D only comes from knowing its physical significance within the equation.

This latter set of equations illustrates another small but crucial nugget of information: many students will be overwhelmed by the onslaught of equations confronting them while learning physics. I hope these two examples have revealed the importance of teaching them one equation in any of its forms along with the necessary algebraic skills to obtaining the others. As they grimly cope with the many other equations to come, you need only teach one version while continuing to hone their algebraic skills in reaching the others – and to me, that is probably the most necessary element to succeeding in senior physics. To be clear this is not to say that the other forms should not be shown, used or mentioned, just that they should not be named or identified as anything other than the one equation re-arranged. Teach one equation, re-arrange to get the others.

It is not possible to illustrate the power and reach of algebra in all of its glory in a single lesson, that is not my point when teaching this topic; but there is one more example I use to illustrate another type of mathematical error often experienced by students while learning physics. In the energy unit you will introduce them to the concept of kinetic energy, the energy of motion, with the equation:

$$E_k = \frac{mv^2}{2}$$

where E_k is the kinetic energy in joules, m is the mass in kilograms, and v is the velocity of the mass in m/s (and 2 is well…two). Some students will incorrectly read this equation as “kinetic energy is equal to m, v squared, divided by two” rather than as the kinetic energy is equal to one-half of the product of the mass and the square of the velocity. Both are correct, but the former is a lazy method often leading to incorrect calculations. You and I know in this equation only the velocity term is squared, not the product of the velocity and mass. So if a mass of 15 kg had a velocity of 2.0 m/s then the calculation would look like:

$$E_k = \frac{(15)x(2.0)^2}{2}$$

and after squaring the 2.0

$$E_k = \frac{(15)x(4.0)}{2}$$

to finally get

$$E_k = 30J$$

Simple enough is it not? If one needed to re-calculate for a different term, say for the velocity, v, then all that is needed is to re-arrange it algebraically. Ask them to calculate the velocity of a 9.0 kg mass if it has 162 J of kinetic energy – remember the physics is not important at this early stage so you could do this question without any units at all – just do it as a math question.

Now pause and tell each and every student to calculate his or her own answer. They will re-arrange the equation then plug in the numbers to calculate it. Assuming they do it correctly it works out to:

$$v = \sqrt{\frac{2E_k}{m}}$$

and by substituting in the appropriate numbers

$$v = \sqrt{\frac{2(162)}{9.00}}$$

get v = 108 m/s. But did they get 6 or 108?

The correct answer of course is 6 m/s, not 108 m/s; unfortunately some students will get 108. But how can the same numbers give two different answers? It all comes down to the overall point of this chapter: there are details that will affect their answers that you need to keep in mind, and they need to learn, every time they work with the mathematics. In this case it is all about the order of operations. When working out (i.e. punching numbers and operations on their calculator) many students are not aware of the order of operations involved, or at least of the proper method to take into account the order of operations on their own calculator.

The square root sign encompasses the entire contents of

$$\frac{2(162)}{9.00}$$

which is 36, then taking the square root they should get 6. Some students unaware that order of operations is important, will unknowingly calculate 2x(162) then divide that answer (362) by the square root of nine (3) to get 108. They will actually work out

$$2(162) \div \sqrt{9.00} = 108$$

which is clearly incorrect.

Don't be surprised to see an even greater variety of answers since there are many ways to mess with this simple equation. Insist that every student repeat the calculation until everyone achieves 6.0 on their calculator. If they cannot do it now, they will not be able to do it later. (Ok I know there are a zillion ways to illustrate this point, but it's best to choose a mathematical example they are likely to see in a physics class. Go with your gut and choose your own emphasis.)

Looking at another, maybe simpler, example, get them to calculate the answer to:

$$A=\frac{36-12}{4}$$

Many students will find this one easy enough to do in their heads: 36 – 12 is 24; and 24 divided by 4 is 6. But if it was:

$$A=\frac{167.993-34.779}{14.9}$$

that is an equation most of us, myself included, could not do in our heads. In this case we would expect them to resort to using a calculator, and unfortunately not all calculators will understand what was intended if a student typed 167.993 minus 34.779 divided by 14.9. Some calculators will follow through with the proper order of operations by the way it was inputted in order to calculate yet another incorrect answer. Again, everyone needs to know how to use their own calculator. (By the way, the correct answer is 8.94, not 72.0. I think we've flogged this issue long enough – it is a useful activity though to make sure students know their own calculator's rules.)

There are two final points to raise before we move on to another important mathematical technique. I have emphasized this order of operations point because I have seen all too often students correctly follow through all of the necessary steps in a multi-mark question only to throw it all away at the end with a calculator error. With my marking scheme I use the dreaded red arrow and question mark to signify this type of mistake. Imagine doing the previous velocity and kinetic energy question with the student writing everything down correctly following all of the necessary steps accurately only to get v = 108 m/s from:

$$v=\sqrt{\frac{2(162)}{9.00}}$$

When marking this solution I would use a big red arrow and question mark trailing from the second last line down to the last line signifying to them that everything you have written down so far is correct except I have no idea where this final answer comes from? In other words: "you have probably made a calculation mistake". It can be terribly frustrating for a student to get so far through a difficult question only to make a minor calculation slip-up, worse yet doing it on a test and losing marks here and there; however, it is far more disparaging when it occurs while doing the assigned homework at home, all alone. When answers keep turning out to be incorrect even though the student is confident in having done all of the right steps, the frustration can be numbing. Success may breed confidence, but a lack of success is as good as dead weight.

Secondly, there will always be a debate on the use of calculators in teaching physics, although I had hoped it would have passed by now. I see no point in teaching physics without them, no point at all. Given the depth of mathematical analysis necessary for physics it seems absurd to require students to work them out by hand, or for a teacher to contrive every question so that it works out nicely with simple or whole numbers. Although I certainly do contrive the odd question to work out with simple numbers, the point of those questions is usually to illustrate some other salient physical concept, not as a mathematical exercise. Calculators are neither instruments of evil nor are they instruments of intelligence. They are just instruments. Educational bureaucrats are instruments of evil.

That equation…
There is a certain equation, well actually it is a mathematical procedure suited to solving certain types of equations, which is often neglected in senior physics, especially in grade 11. It is the dreaded quadratic equation, the mathematical process for solving binomial equations of the form:

$$ax^2+bx+c=0$$

When written like this – with a 0 on one side and all of the other terms on the other side - it can be solved for its solutions of x using the quadratic equation:

$$x=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

where a is the coefficient of the x^2 term, b is the coefficient of the x term, and c the number without a related x term – plug those numbers in, calculate (very slowly) and students get the answer(s). Or, as I have mentioned in an earlier chapter, get your students to find their calculator's manual where they may find it has a function permitting them to plug the numbers a, b and c directly into the calculator so it will work out the answer(s) on their behalf. To do this correctly their original equation must be re-arranged in the form for the calculator's function to work properly, so as learners they are not completely out of the mathematical woods; worse still, they may not be allowed to use the calculator's quadratic equation functionality on an exam or test so knowing how to solve the equation manually is always a possibility. Manually knowing how to do it is a necessity.

There is a richness that the quadratic equation adds to teaching physics – a richness that cannot be recouped when it's neglected. Students interpret mathematics as having been invented – which it is – whereas nature is based on fact; as a result they often find it difficult to grasp that the mathematics of physics does in fact tell us something genuine about the real world. We must impress upon them that the particular equations we use in physics are based on the experimental analysis of the natural world, therefore they reveal naturally true effects to us – there is reality in the mathematical solutions. I would tell my grade 11 students to expect the use of the quadratic equation a few times within the course, usually with some prior warning from myself; however, in grade 12 it needs to be in their mathematical inventory as is any other mathematical procedure like basic algebra – in reality using it may still occur only a few times or so but it is the unknown factor that makes it a wonderful learning experience to them. There is potency behind the solutions that a quadratic equation provides for problems involving projectile motion, gravitation and electrostatic that cannot be illuminated in any other way.

Let me finish this chapter by emphasizing that in the types of questions we solve, or the ones we assign them to solve, anticipate applying the mathematics they have learned, and will continue to learn, frequently while teaching. Practice does indeed make perfect. Students place a mental block in their way when it comes to using mathematics in physics – even if they have managed to set up a question properly they could still sit there stunned not knowing what to do because of their hesitancy over the mathematics. It is imperative you stress upon them to just do it – use that math they thought was irrelevant…re-arrange an equation algebraically or pull out that quadratic equation – who knows where it will take them or what new bit of information it may provide. Otherwise you may have a class that looks more like a herd of deer caught in the headlights…and you're the one driving.

4

The Equation Inventory Map

The next two chapters are probably the most crucial for establishing a student's success in learning physics for the simple reason that they focus on enabling those necessary skills for solving those inevitable word problems as in "…if two trains are headed towards each other at 100 km/h…blah blah blah. Successful problem solving comes down to using the physics and equations learnt along the way, together with the mathematics, to efficiently traverse an unknown territory – which is all one big fancy way of saying progressing from what you already know to what you need to know.

By the time students have finished grade 11 physics they will have encountered dozens of unique equations; this parade of equations will easily increase to over three dozen by the end of grade 12. The importance of and behind the list will overwhelm them if you don't do something about it early on. To help them through this muddle I have developed an Equation Inventory Map (EIM) to use throughout a course. Having a solid understanding of the concepts underlying the Equation Inventory Map will play a vital role in the next chapter when dealing specifically with the problem solving process.

The Equation Inventory Map is a real physical document to build upon over the course of learning physics to help students through the drudgery of word problems. The Equation part is pretty clear – it centres on the equations of physics. It is an Inventory because it will be a complete list, a compendium if you will, laid out precisely of all – yes all – of the equations needed to succeed, or in other words to pass your tests. Lastly, it is called a Map because, like all maps, it will help to identify where they are so they can use that information to get somewhere else; once again, to go from what they already know to what they need to know.

It will take time to accumulate all of the equations while developing the map and it will take up more than one page at the start depending on how large any one student writes, although a student can always re-write it as you go along with the teaching of the course. As a suggestion, writing a separate document for each topic learned and then assembling them all into a single text later on is probably the way to go; ultimately they can use it to create their "cheat sheet" for an exam or test. Having said that, the Equation Inventory Map is not a cheat sheet – it will help them with their problem solving and in developing a cheat sheet later on.

I, along with every other physicist and physics teacher, have an Equation Inventory Map in my head that took time to develop over my many years of learning physics, doing physics and teaching physics; it was not accomplished by memorizing one. Over time your students will get parts of it into their memory, but for now they will have to rely on the physical document by keeping it at hand because they will forget much of what you have taught them soon after you have taught it to them. An adolescent mind is akin to a flood plain: plenty of fertilizer upon which to cultivate great thoughts and ideas, which also undergoes periodic cleansing of all that was there. For some that cleansing is annual, for others it's as if they live in a tropical island with frequent evening thunderstorms. Fortunately the vital sediments never wash too far away.

There is no standard form for the map and it's always a work in progress. As long as the document contains the elements outlined, its overall design depends on personal preferences. Rigidity in education is a curse, be flexible with my suggestions.

The map consists of three columns (or rows if you prefer). The three columns are: (1) The equation…(2) contains the terms…(3) that mean.... It is entirely up to them how to separate one equation section from the other – there are no rules here, do what works best for you and for them, because it is all about helping them in the end. In the one shown here you will also notice that the equations are not numbered: 1, 2, 3…but that too may be a matter of personal preference (as mentioned in the previous chapter, I do not name or number the equations).

In addition, the equations are not identified as in the equation for…or the velocity equation for exactly the same reasons discussed – an equation is the relationship between the terms. The relationship is important, not the term on the left side of the equal sign.

I would recommend to my students that when preparing to review for a Mechanics test, they should have one of these completed maps at their side, and likewise for a Waves test, and an Electromagnetism test, etc… a complete inventory of the equations they need. Remembering that this will be a real physical document at the beginning, but one that will hopefully become a real mental document over time.

Here is the basic structure for the Equation Inventory Map:

The equation…	…contains the terms…	…that mean…
$A = \frac{B-C}{D}$	A B C D	*A is the…* *B is the…* *C is the…* *D is the…*
$E_k = \frac{mv^2}{2}$	E_k m v	E_k *is the kinetic energy (J)* *m is mass (kg)* *v is the velocity (m/s)*
$v=f\lambda$	v f λ	*v is the speed of the wave (m/s)* *f is the frequency (Hz)* λ *is the wavelength (m)*

I think you get the overall picture of what the table contains and need little more direction from me. There is the Equation (its form, variables, and what they mean) and the Inventory element because it lists all of the equations necessary, but now to turn our attention to the Map segment – the main component.

In any equation there are a number of terms, called the unknowns or variables. For example, the two equations:

$$F = ma \quad \text{Eq[3]}$$

and

$$v_2^2 = v_1^2 + 2ad \quad \text{Eq[4]}$$

consist of three or four terms, respectively. Equation[3] has the three terms F, m and a; while Equation[4] has the four terms v_2, v_1, a and d.

It is important to repeatedly emphasize to your students that any equation can be solved for an unknown term when you have the value for each of the other terms – when all of the terms are known except for one. In other words:

anytime you have two of the three terms…you can calculate the third term;
OR
anytime you have three of the four terms…you can calculate the fourth term;
OR
anytime you have four of the five terms…you can calculate the fifth term…etc.…

Therefore in Equation[3] if you have any two of the three terms F, m or a (say F and m) you'll need to use a little mathematics to calculate the term a – it's there, it just takes a little mathematical work to dig it out. To be exact, you can re-arrange the equation using algebra, to calculate a using:

$$a=\frac{F}{m} \qquad \text{Eq[3a]}$$

In Equation[4], if you know any three of the four terms v_2, v_1, a and d (say a, d and v_2 are known) then again using a little more mathematics to find v_1. It too is there, just hidden within the mathematics:

$$v_1 = \sqrt{v_2^2 - 2ad} \qquad \text{Eq[4a]}$$

To aid in illustrating the functionality of the Map, i.e. identify what we already know in a problem, consider the question: What is the mass of an object with 18 J of kinetic energy and a velocity of 4.0 m/s? Three terms are mentioned explicitly: mass, kinetic energy, and velocity. We could solve this question in one step if we had a single equation that used all three of those terms, and knowing two of the three terms (kinetic energy and velocity) we could calculate the third term. Scanning the (currently tiny) Equation Inventory Map we notice that indeed this problem can be solved using the equation:

$$E_k=\frac{mv^2}{2} \qquad \text{Eq[5]}$$

(By now you might be thinking "…so what, that much is obvious from what we already know." But this is about teaching them a process that works for all questions, not about teaching an answer to this particular question. On an end-of-year test or exam with dozens of equations staring back at them and time coming close to an end this process is about helping them focus on the task at hand.)

By using a process of listing and identification, we know the terms: E_k and v by value, and need to find the value of: m. Do we have an equation that involves each of $E_{k,}$ v and m? Yes, Eq[5] involves each of those listed, and therefore would be the one to use. (You'll see why I've listed them in the way I have in the next chapter.)

Remember I am only giving you, (you!) examples of this process with these particular equations. In reality I'd be teaching this practice early on in whichever unit was used to start the course so the examples presented to them to illustrate the process would be relevant to that topic. Many of the specific suggestions in this chapter are merely for narrative of purpose…not prescriptive or directive. Use the ideas, not the examples.

A more difficult example using the pair of equations Eq[3] and Eq[4] may help to clarify the method better: Calculate the value of v_1 if v_2 is 13, d is 4.0, F is 54 and m is equal to 9.0 (ignore the units for now, leave it as a mathematics question).

At the moment we only have Eq[4] that uses the term v_1 so we have no choice but to use it to solve the question and we can write this down. We know the value of the terms:

F = 54

m = 9.0

v_2 = 13

d = 4.0

but in order to use Eq[4] to find v_1 we must know all of the other terms and that means finding a to employ . That leaves two unknowns at this stage a and v_1 so this equation cannot be solved immediately. Either a mistake has been made with the original information, or we may need to find a somewhere else making this a two-step solution.

Two other terms F and m were provided and they are used in Eq[3]. Utilizing the Equation Inventory we can write this as: We know the values:

F = 54

m = 9.0

and need to know what a equals.

From this step hopefully they will see that indeed we do have all but one of the terms (we have F and m, but not a) so we can solve Eq[3] to give us a

$$a = \frac{F}{m}$$

so

$$a = \frac{54}{9.0}$$

and a = 6.0. Looking back to Eq[4] you can show that we really did have three of the four terms (v_2, d and a) so it too can be solved by using the a = 6.0 solution from solving Eq[3]. Therefore, we knew the value of the terms:

$v_2 = 13$
d = 4.0 and…
a = 6.0 (from solving Eq[3])

So we can find the value of the term v_1 by using:

$$v_2^2 = v_1^2 + 2ad$$

to get

$$v_1 = \sqrt{v_2^2 - 2ad}$$

$$v_1 = \sqrt{(13)^2 - 2(6.0)(4.0)}$$

$$v_1 = \sqrt{169 - 48}$$

$$v_1 = \sqrt{121}$$

knowing that v_1 now equals 11.

That is the whole point of the Equation Inventory Map – it helps them to get information once thought to be unavailable. Feeling lost (or desperate) while solving physics questions is the most likely (first) reaction many students will have when starting out – it is part of the image of physics and one we as physics teachers are not often too adept at eliminating from their minds. I teach them to use the Map for two purposes: first as an overall support system showing them there is indeed a way to get the answer requested even if at first glance it seems hopeless; and secondly, in a more practical role as a visual device or document to get them from one equation to another.

The Goal

I was known for sentencing my students to very demanding tests and as we approached that first test of the year undoubtedly panic would set in (usually as a result of the unhelpful comments from my former students). Upon the test's completion, students would invariably leave the class grumbling about how terrible I was for having put them through that most unfair ordeal, coupled with comments about me that were (likely) not very kind – although unknown to them my hearing was excellent. All that aside, there would have been a point in time, probably the day before the test where I would have advised them that "the only thing worse than the day you write my test will be the day I return it and correct it for you step by step in front of the class." That was fair warning, but what was my intention? On those most auspicious of days they would see first-hand that yes indeed there was enough information to solve for the required term(s) in each and every question – no, Mr. D did not screw up every single question. It has to be pounded into them (as you too will surely have to do) that, unless a grave error has been made in the question's wording, there must be enough information provided to solve it and that to reach the solution requires the using (the method of) the Equation Inventory Map along the way. Now to be fair, this assumption that if a question cannot be solved immediately there must be something wrong with it, is always possible; but certainly not a normal occurrence for every question that cannot be solved. (It's bad enough to err when creating their tests, but what I find worse still is the number of errors within texts. Not only in the questions themselves but also in the answers and solutions provided… Success breeds confidence, right?)

As it is a map, they should use it as a map. Admittedly it takes time to create it properly and to learn how to use it well, but if they consider the process akin to what early geographic explorers did when making maps as they explored the unknown world around them, it might help to understand its usefulness. In essence I'm talking about generating maps and then using them to efficiently and successfully guide future exploration in and around that new area. Explaining this analogy to students will at least present them with a glimpse of its objective.

It's a bit like being a tourist really. Imagine the sense of fear and trepidation you would feel if you had to drive around a new city without a map; or conversely, think of how confident you feel driving around your hometown without the need for a map. The necessary driving skills are no different whether you are in a new city or in your hometown, driving is driving, save and except slight alterations to the rules of the road and the mechanics of individual vehicles. A physical map is not necessary to get you around your hometown, you just know how to go from A to B using your driving skills along with the mental map securely formed from your past experiences; but herein lies a hidden setback: even with a very detailed and accurate tourist map in hand and sound driving skills, it is still easy to get lost and frustrated. Indeed it may be more frustrating when you have the map but still cannot get there, wherever "there" is. That is the same feeling your students are about to have as they begin this voyage through an ocean of problem solving, and every new topic you teach them is another city's road map for them to learn! The next time you get lost on vacation, think of your students.

So with the map in hand and all of the necessary driving tests passed (I trust you've figured out this is analogous to the algebra), how do you get around? One way would be to regularly ask someone for directions (unless you're male), which is a good idea to do during class time, but not a viable option for tests. The proper answer comes from a deliberate, stepwise and teachable methodology – a plan of attack, if you will, to tame a student's impatience when setting out to solve a question. That's what the next chapter is about, a specific problem solving methodology that demands a level of patience not typical to adolescents, nor of some beginning physics teachers for that matter. As such it's a technique that will also work to improve your teaching skills by making you slow down when illustrating the solutions to their homework, because far too often we make it look way too easy…which only adds to their frustration.

5

GRASP

It would be near impossible for me to think of a single more important chapter than this for reaching success in the teaching or learning of physics.

Sometimes you possess a book so captivating that by reading it over and over again you loosen the spine enough to keep it open on its own accord; somehow it calls out to you to pick it up and read it again. If that could happen to this book then this is the chapter to which it will normally fold open – it is that important. (Of course this is a “book” only in concept and can’t have its spine loosened, but you get my point.)

It’s probably been written often enough to make you sick, but physics is focused on problem solving. There are many problem-solving techniques available for students. This chapter will focus on the one I teach my students; the one I was taught while learning to become a teacher. The emphasis in that last statement is entirely intentional, since learning this (forthcoming) technique did not happen not until after I had finished two high school courses in physics followed by four years of a Bachelor’s degree in physics! Not until my second Bachelor’s in education did someone finally show me, itemize for me if you will, a technique for solving most, if not all, physics questions; and with minor adjustments to the definitions and process, a technique that could also be used in the design and exercise of experiments and report writing. Obviously, that lack of (early) indoctrination into an itemized problem-solving technique did not prove too much of a deterrent to me since I went on to a successful career in physics; however, I often wonder how knowing this technique might have affected some of my fellow high school students with regards to their success and enjoyment of physics had they been introduced to this process early on?

That lengthy lag in teaching any problem-solving technique is a damning indictment of the general teaching mentality of a generation ago, but one that still lingers in physics education today. The attitude was (and may still be) that good physics students just know how to solve physics problems naturally; all we as teachers had (or have) to do was teach them the physics content and all will be well. The impression was that those who struggled to successfully solve physics questions did so because they just did not understand the physics content. There is (was? I hope) an attitude that learning to solve physics questions goes hand in hand with learning physics content; it is something good physics students just magically know how to do well. That is nonsense.

I will not deny that there are students who are capable of learning certain material better than others; and yes, some students are better at "physics" than others, just as some students are better at music or art. But just as we can teach millions of students to play musical instruments well, with only a smaller number going on to becoming virtuosos or composers, we can still teach the instruments of physics (i.e. problem solving) even if a student is not going to become the next Oxford Lucasian Professor like Stephen Hawking. Students can still learn to do it; and the benefits of learning it extend far beyond physics alone. Having said that, in no way should you interpret this argument to imply my support for that motivational BS of "you can be anything you want to be if you just try." You will never find me standing in front of a group of parents or educators saying that kind of nonsense. Sometimes, reality bites…hard, and a tough skin goes a long way to defending against the pain of reality. Trust me, you don't want me to be a carpenter no matter how hard I try, which is also a big reason why I still have all of my fingers – I'll leave those tasks to others who possess the skill better, no matter how much I can learn it.

Why do we inflict word problems on them at all? The short answer is that nature itself inflicts the world upon our appetite for understanding it in much the same way: never in a clear cut or obvious manner. Sometimes we may need to dig a little deeper to discover more facts hidden behind the little information that is obvious or already known. This ability to dig a little deeper can be improved upon with training, and part of that training consists of never taking anything for granted or at face value without investigation, always assuming there is more than meets the eye and crucially that we are capable of discovering it. Although that onslaught of clichés may be annoying, they are all true aspects of why we force students to solve word problems. If we did not learn to dig beneath the surface of what we see, hear, touch, feel, and taste then we would still be picking nits off of our closest relatives while swinging from trees on the African Savannah. Knowing that we can delve more deeply than what nature has provided on the surface defines us as humans.

This particular problem-solving technique is based on a simple premise: somewhere in the question, somewhere in the world around us, the information to solve for the required term(s) or questions is provided. Breaking up the process in broad terms we need to ask:

What information is given?
What exactly am I required to find?
How will I analyze the given information with the tools at available to find the required term(s) or answer the question?

You may have noticed that there is nothing particularly scientific about this process; it can be used for many non-scientific problem-solving endeavours. Nevertheless, we need to give some credit to scientists here, at least to Galileo who is (usually) the one credited with clarifying or codifying the scientific process roughly outlined in this problem solving technique; however, there are other similarly itemized techniques in dispute resolution, group dynamics and change management.

It will take you longer to teach, explain and perform this five-step process first time than it will take them to use it in practice afterwards – that's normal. Nevertheless, you will find that over time they'll use the process in a less and less formalized manner as long as you use it continuously too.

Step one: GIVEN

Teachers may not be perfect, but in the vast majority of word problems assigned all of the information needed to solve the question…is in the question. The realization that there is indeed enough information to solve the question is an important insight for students to grasp, in fact, denying this reality is one of the main (self-imposed) stumbling blocks of students. And so this step (GIVEN) is about students writing down all of the information provided in the question; and note I wrote…writing down…not just finding it and placing it in that special place in their brains from where adolescents tell people "I know…" Insist they write it down, all of it.

Instruct them to read the question all of the way through to get an idea of what topic it may be dealing with, whether it's an optics question, a kinematics problem, etc… In addition, within specific topics like kinematics it may be a constant motion problem or one that involves acceleration – read it slowly. This first reading emphasizes the overall mental perspective important to the issue at hand.

For example: An object rolling with a velocity of 25 m/s stops in 120 m. Calculate its acceleration.

This example is about an object moving with some initial velocity coming to a stop over a long distance – something like a driver slowing a car while approaching a stop sign. That is the overall perspective they need to comprehend before starting the problem. I loathe saying "picture" it or making some mention of reality. Trying to get a "picture of reality" from every physics question is a lost cause, especially for adolescents. The real leap of physics success comes when they picture the reality from the mathematics. When it happens, it is a joyous moment for both of you. Nevertheless, I am human and often make the very mistakes I caution against. Suck it up.

Then get them to re-read the question writing down the obvious numerical information literally as they read it (remember you should be doing this on the board for the first time with them, but they will need to do these steps on their own). The question states that the object has…a velocity of 25 m/s…STOP READING, write it down:
$v_1 = 25$ m/s,
and continuing to read we get that it …stops in 120 m…STOP READING and write down:
$d = 120$ m.

Done? No, there is more information provided that is not necessarily apparent. The question states that the object…stops…so that means it has stopped moving, is at rest, has come to rest, etc… There will be many times when it will be necessary to convert word statements into mathematical ones and this is a common one. Therefore, we also know its final velocity is zero, so:
$v_2 = 0$.

That is all of the numerical information provided in the question; however, remember our previous chapters on units and numbers? At this point it is a good idea to check that all of the data conforms to mks units and if not, then change them now. There will be situations when you will ask them to…leave the units unchanged…or times when non-mks units are carried through the question, this is the point at which they need to figure it out – remember, when in doubt use mks units. This is also the time to decide how many significant digits the final answer will have. Looking at the numbers provided we would see that our final answer could have no more than two significant digits. Do not use word statements like "rest" and "stop" to guide the significant digit routine, use only the numbers provided.

In addition there may be underlying information that is assumed to be known; this is information that (over time) they will be expected to know even when it is not given at all, namely constants (I sometimes call this assumption-information, but not as a general rule). The most common example is the acceleration due to gravity, $g = 9.8\ m/s^2$. Any time an object is thrown up, down, sideways, or anyway there is the assumption-information that g must be used when solving it; it may not be provided except that a question refers to something being…thrown or…is falling. From that bit of information students would need to be aware of the necessity to write down: $g = 9.8\ m/s^2$ as part of the GIVEN stage. So at the end of step 1 we have:

GIVEN
$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$

Step two: REQUIRED

This is probably the simplest part of the process: what exactly are you asked, i.e. required, to find in the question? In the example provided: calculate the acceleration it cannot be any more obvious; unfortunately that may not always be the case and some problems will require multiple steps. Nevertheless, write the sought after term both as a term and in words, so:

REQUIRED
acceleration, a = ?

We now have:

GIVEN
$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$

REQUIRED
acceleration, a = ?

Step three: ANALYSIS

Step three…three…step three, not step one! Unfortunately this step is from where most students start solving questions, skipping past steps one and two as if they did not exist. I'll make my argument regarding why this is terribly ineffective later on in this chapter, suffice it to say, once steps one and two are completed properly students have completed (most of) the physics. Steps three to five are simply the finishing touches to solving the problem. As I say to my students: when you get to the Analysis stage, you've completed the physics, the rest is math.

This is where the Equation Inventory Map comes into play. Look back at what we know from this example so far:

GIVEN
$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$

REQUIRED
acceleration, a = ?

We have the four stated terms v_1, d, v_2 and a; and knowing three of them v_1, d, and v_2 can we find the fourth term a? In other words: do we have an equation that will permit us to find the acceleration if we know v_1, d, and v_2? The answer is yes we do: (Of course you will have taught all of the necessary equations already. But even more likely you will best teach GRASP very early on in the course so this particular type of question may be too difficult to use as a question to teach the GRASP process. Ultimately, it makes no matter really, teach it when they are about to solve their first set of numerical word problems. This particular choice of example is one of the narrative elements of this book, not one of its prescriptive parts. It's the idea that matters here, not the example.)

The objective of this step is to identify what equation (or equations) to use from our knowledge (i.e. inventory) given the values we have (v_1, d, and v_2) and what we are required to find (the acceleration, a). Get them to visually scan through the EIM for the necessary equation, with the hope that eventually this visual scanning of the physical document will become a mental scan through their knowledge. At this ANALYSIS step, and only at this step, should they ask: What equation do I use? This is not the question they are to ask themselves immediately after reading the problem; nor should you ask it when showing the solution. Pound this into their heads, stomp around the room, whatever it takes…I do. Have some fun in your class, I try to turn my frustrations into humour although it may not always work to alleviate their aggravations it does break some of the monotony. Therefore, the Analysis step will look like this:
ANALYSIS

$$v_2^2 = v_1^2 + 2ad$$

$$a = \frac{v_2^2 - v_1^2}{2d}$$

All we have done is to use algebra to re-arrange the original equation isolating for the term needed, in this case isolating for the acceleration a. We now have every term on the right side of the equation (v_2, v_1 and d). Step three ends with having an equation ready to be solved. It was a mathematical step, no physics at all. (If a problem involves multiple steps that require first solving for one term, then using that answer and the previous information to solve for the final term, then repeat steps three and four until you get the final answer. It's important to teach this process as a guideline, not a rule. Rules confine them, GRASP is about freeing them.

Our three steps will look like:

GIVEN
$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$

REQUIRED
acceleration, a = ?

ANALYSIS
$$v_2^2 = v_1^2 + 2ad$$
$$a = \frac{v_2^2 - v_1^2}{2d}$$

Step four: SOLUTION
Now we can calculate the answer by substituting the numbers we have into the final equation. So we would write:
SOLUTION
$$a = \frac{v_2^2 - v_1^2}{2d}$$
$$a = \frac{(0)^2 - (25)^2}{2(120)}$$
$$a = 2.6$$
(The units would be m/s^2. I have not carried the units through the example since it's not relevant to my purpose although I think it is better to do so for them. It can be cumbersome at times so be careful. It may add to a student's level of confusion when written less neatly by hand as:
$$a = \frac{(0\frac{m}{s})^2 - (25\frac{m}{s})^2}{2(120m)}$$

But when the units are carried through you can do a more accurate units analysis to find out that the final answer should indeed be m/s^2.) We now have:

GIVEN
$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$

REQUIRED
acceleration, a = ?

ANALYSIS

$$v_2^2 = v_1^2 + 2ad$$

$$a = \frac{v_2^2 - v_1^2}{2d}$$

SOLUTION

$$a = \frac{(0)^2 - (25)^2}{2(120)}$$

$$a = 2.6$$

Step five: PHRASE

They might think the question is done; but that would be presumptuous. In the final stage demand they tell you that they have actually found the answer and here it is in this sentence (phrase). This is also the time to ensure that the units are mks (or otherwise if requested) and that the number of significant digits is also correct. So finally we have:

PHRASE
The acceleration is 2.6 m/s^2.
A simple phrase is all that I require, but use whatever matters to you.

Putting it all together:

An object rolling with a velocity of 25 m/s stops in 120 m. Calculate its acceleration.

GIVEN
$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$
REQUIRED
acceleration, a = ?
ANALYSIS

$$v_2^2 = v_1^2 + 2ad$$

$$a = \frac{v_2^2 - v_1^2}{2d}$$

SOLUTION

$$a = \frac{(0)^2 - (25)^2}{2(120)}$$

$$a = 2.6$$

PHRASE
The acceleration is 2.6 m/s^2.

To do a quick re-cap of what it would look like without the words:
Example: An object rolling with a velocity of 25 m/s stops in 120 m. Calculate its acceleration.

$v_1 = 25$ m/s
d = 120 m
$v_2 = 0$
acceleration, a = ?

$$v_2^2 = v_1^2 + 2ad$$

$$a = \frac{v_2^2 - v_1^2}{2d}$$

$$a = \frac{(0)^2 - (25)^2}{2(120)}$$

$$a = 2.6$$

The acceleration is 2.6 m/s^2.

Given + Required + Analysis + Solution + Phrase = GRASP. It's a simple name and pertinent name to help remember the steps. Now to be honest, the original process I was taught was called GRASS replacing the P of Phrase with S for Sentence or Statement, which makes little sense for problem solving since you can't GRASS a solution, but you can GRASP it. Anyway having school administrators learn that I was teaching my students to use grass may not have gone over very well, though it would have been funny to see the looks on their faces.

Therefore, solving physics problems can be categorized as itemizing the information provided, knowing what is to be calculated then doing some mathematics to find it. Of course, knowing the underlying physics content is very important to successfully solving the problems; but you only have to teach them this process once early on in the course then apply it repeatedly when correcting any questions in front of the class. Having been taught this technique is one less hurdle to jump while they are learning the content. Who would have thought a technique could be that simple? That simplicity is why it is a process that can and should be taught explicitly.

The power and elegance of GRASP

I have often told my students that the difference between the way I solve a problem compared to the way they solve a problem is that my first response is to step back whereas their first response is to jump in. "Jumping in" is best represented with the proverbial "what equation do I use" statement right off the bat, a question not to be asked until the ANALYSIS stage. Students need to learn to stop, step back and slow down which is what the first two steps of GIVEN and REQUIRED force them to do, literally and figuratively. The physics part of this problem-solving technique ends at the ANALYSIS stage – if the first two steps are not done well, then it is only a math question - not a physics one. That may sound satisfactory, but physics questions are often worded in such a way that there is not enough information clearly mentioned to solve them without knowing some of the physics behind the question. No matter how you cut it, a strong comprehension of the content is necessary to answering the question. Using GRASP gives them the time to contemplate the physics. The GIVEN and REQUIRED steps are the most important steps even though they seem the simplest, the most unnecessary. Let me explain.

Often during class time when students are working on problems a student would call me over from across the room in a mild state of panic with "Mr. D, Mr. D. I need your help." Then by the time I get there it becomes "…oh that's ok I figured it out." Now normally I would tell them that they've figured it out because my presence near them makes them smarter - at which point they normally roll their eyes at me; but why does this delayed revelation happen so enough? Think about it this way, in the five to ten seconds it takes me to walk across the room the student (i.e. the student's brain) has had time to process some of the information – by waiting for me, the student was forced to stop or at least slow down their thinking process. Too often students, and teachers for that matter, think that answers must be forthcoming in an instant. They think that at the end of reading a question they should immediately have the entire process mapped out in their head with all of the mathematical calculations charted. That is ridiculous. In the forced pause of waiting for me to arrive their brain might process some tidbit or nugget of information momentarily out of their mental reach. GRASP enables them to create their own forced pauses by taking the time to write down what is given and what is required, and that, I think, is the power and elegance of GRASP… when it works.

Finally, during class work periods I would endeavor to stick to the regimen of not helping students solve a particular problem until they had written down the GIVEN and the REQUIRED information into their notes; in other words a blank page with the question number written on it results in an equally blank stare from me. In reality if I had to adhere to this philosophy I would never have accomplished anything, so even after 17 years of teaching this method, even to my junior students before they took physics, they might still jump to "which equation do I use?" when they get to physics, and I still bang my head against the board. Ouch.

6

Pardon?

Speaking of banging my head against a wall, this chapter lists just a few of my (least) favourite things about problem-solving; or more exactly, what drives me crazy about students and their answers.

I did it my way

Some physics questions are worded in such a way that there is one and only one way to solve them given the information provided – one solution and one correct answer. In the GRASP example from the previous chapter there is, actually, another way to solve the problem using the complete set of kinematics equations (I trust you knew that) and since you would have likely taught that complete set of equations over the course of the kinematics topic, the available (kinematics) Equation Inventory Map would have included at least six equations giving students ample opportunity to solve for the acceleration using more than one method – more than one correct solution, but still only one correct answer. Having options from which to choose a solution is always good.

So what if you solved a problem one way on the board and a student did it another way? When this situation occurred in my class and a student proudly announced (usually in front of the whole class) "I did it another way and got the same answer. Is that ok?" My usual reply in as polite a tone as I could must was: "So what?" Of course it is acceptable to solve a question using another procedure than the one used on the board, as long as that other way is a legitimate method using proper physics and mathematics. In many cases this is simply student hubris. “See how smart I am to do it this way and I’d like to let everyone in the class, especially you the Teacher know.”

It’s annoying, but you’ll need to be open to their options while being patient with their conceit for two reasons:

1) you set the tone in the class not only for the academic nature of what is being learned, but for the decorum surrounding how everything is being learned – your response to behavioral matters will remain as much a part of your shared history with them as your teaching skills will be, their memories of your behaviour will last longer than their mortgages.

2) Teachable moments are memorable moments. Dissecting a student’s own solution may yield some tidbit of information you had neglected to mention to the rest of them. In short you may realize that your method, though correct, fails to demonstrate some salient point that your other method missed; and that next time, you may use the student’s method for that very reason.

You have to be open to the possibility of amending your teaching style from the way students learn. Sometimes a student is right. And besides, a professional will always adapt and amend future lesson plans based upon the questions and confusions raised from previous lessons. You may never be able to preempt all of their questions and thoughts on a specific topic, but trying to do so day by day, and year over year, is the sign of someone who cares more about how they learn and less about how you teach.

Given that most students will naturally bond (i.e. work together) with others for academic assistance, when a partner does it another way there is no better opportunity for each of them to learn from that alternative. If a student had not even considered solving the problem in another way, then opening their minds to an optional method may prove to be beneficial because it may be shorter, easier, or more elegant. Individual students learn to do similar things in different ways. It would be great if we could show every possible solution to every assigned problem – the learning opportunity behind this prospect would be utterly staggering, but it’s very unlikely given time the constraints placed on all of us.

It may be best to recommend that your students confirm the validity of their solutions by checking with you during a work period or sometime when you really can be open to optional solutions. Students who show off, brag, or bother other students with their way can be terribly distracting or disheartening to the other students; however, there are wonderful learning opportunities here, so play your cards well and with some courtesy you can have one of those teachable moments we all live for. Remember the more options you, and they, have for solving word problems the better for everyone.

Go ask B-O-B

Many years ago a student introduced me to BOB, Back-Of-Book, and for most textbooks this is where the answers can be found (although some texts place them at the end of the question or on the side of the page, both of which are good ideas). Before a student calls me over to review or confirm an answer, I ask that she has checked with BOB first. Should BOB declare the answer is 3.6 whereas her answer is 3.7 then quite likely she is correct with some minor rounding or significant digit issue skewing the value, so “chill or check your calculations again.” Unfortunately, if her answer is 415 and BOB’s is 3.7, then yes, she is probably wrong.

You will discover soon enough that some textbooks have the occasionally incorrect answer listed which is immensely frustrating for everyone; however, the number of incorrect answers is far fewer than the number of times a student will be wrong. Get them to check their solutions first. Good books provide more than just the answers, they include a solutions manual with (usually one version of) a solution laid out in step-by-step detail. This availability will help with the study technique to be mentioned later.

Are You Serious?

There is this word problem I have asked often on tests. It’s about an airplane taking off from a runway and can be solved using either kinematics, dynamics or work and energy equations; it has multiple solutions where the student gets to decide how best to solve it – multiple solutions but only one answer. I never tell my students which method to use. I leave it open to them.

There really is no best way to solve this question; just different ways each taking a different amount of time depending on the student’s strengths. One method may involve what I call brute force – i.e. the long way (but not the wrong way), another requires a (free-body) diagram, and a third way involves what I call finesse. Finesse solutions are elegantly beautiful methods because they allow some students to reveal their deep rooted understanding for problem-solving usually resulting in a less time consuming process, which is part of the finesse thereby leaving more time for the more difficult questions that may lurk later on in the test. It is extremely difficult to teach finesse solutions in class, let alone in this small book – but it can be taught – it is something you should demonstrate as much as possible when solving (specific) problems. “Here’s the finesse/short way to solve this question… Now isn’t that beautiful?”

Nevertheless, every method to solving this question gives the same answer, assuming the work was done correctly, and no method will (or should) merit the giving of special or bonus marks – there is one and only one correct answer. The difficulty with this question, I had always presumed, was in solving the problem – doing the physics (and math) to get the correct answer. Nope, I was wrong…. big time wrong. Let me briefly outline the question.

It is about a plane. A plane, with a given mass starting from rest at one end of a runway using its engines to apply a force while reaching a certain velocity necessary for take-off. Then off she goes…. All of the necessary values to calculate the answer are provided.

It is a plane…you know what a plane is right? A plane is bigger than a bird but smaller than a planet. Now most of us have never paused to wonder how long a runway is; however, I would hazard to guess you would be able to remember an image of one in your head given that you have either been to an airport or at least seen photos of a runway while a plane was taking off or landing. You would think that that mental image would be some guide to the validity of their answers – nope!

I would be given answers that ranged from 2.5 m to 2 500 km for the length of the runway! 2.5 m is about the length of a car, and 2 500 km is approximately the distance from the most southerly tip of Texas to the Canada – US border! The correct answer, given the numbers provided, was 2 500 m or 2.5 km, so at least you can see where the numerical value of 2.5 or 2 500 comes from, but their choice of units was terribly out of whack.

For a 2.5 m runway the inherent acceleration would not only tear the engines off the plane, it would likely tear the skin off most of the passengers while turning their eyeballs into pancaked blobs on the back of their skulls – which is not good for return business. For a runway of 2 500 km you could just about imagine hearing the captain coming over the intercom saying "…don't worry ladies and gentlemen we'll get this baby off the ground eventually….oh look we're passing Kansas City…on the ground…anyone know a nice diner for lunch?"

This issue here, of course, is what would possess a student to write down an answer like 2.5 m or 2 500 km? Quite probably it was anxiety, nerves, or the stress of writing a test; but all it would have taken is a little pause of thought to ask: "does my answer make sense?" So teach that – pause, relax, reflect – before writing down any answer and ask "does this answer make sense?" Computers and calculators may be susceptible to garbage-in – garbage-out, but students are prone to the latter. Both of you will need some patience and humour to get passed these discrepancies. Nevertheless, do not take garbage-out answers for granted, there may be a reason behind them.

To be fair, you will teach many topics where the units and the quantities have very little "common sense" resonance to a student's everyday life experiences; put another way, although we all have some idea whether certain values like a snail moving at 250 m/s, an 8 g elephant or 150 kg flea are gibberish, there are some topics like energy, momentum and others that will not resonate with their common sense notions of the world. Never fear though, as you progress through teaching senior physics they will recognize an unreasonable answer more and more often, and hopefully you will all have a good laugh over it.

7

Baking a Cake

It comes as no surprise to me that many distinctly human activities such as art, literature, mythology and science share many common traits, especially in the way they are used to describe what we see or desire to see in nature. It's no surprise because they are all performed by… wait for it… humans, and not surprisingly we share common traits with each other, therefore there will be similarities in our descriptions of nature whether scientific or artistic. This realization seems to slip the minds of the many people I meet who want to remind, nay enlighten me of the similarities between the disparate worlds of quantum physics and ancient worldly "wisdoms" like Zen. I don't share their fascination. The fact that there may be, at times, a shared use of the words and phrases to describe the invented world of myth and faith with the real world of nature is simply an artifact of language, not a correlation between what is being described.

It may be that our capacity for language and prose has been surpassed by our capacity for science thereby deferring the best practice of description to the lesser forms of analogy and metaphor, none of which can ever be as comprehensive in illuminating the natural world. Case in point is the apparent discrepancy between whether light is a particle or a wave. It's not difficult for you and I to understand that light is both a particle and a wave because that's what experiment and theory show simultaneously and mathematically. The problem lies in the forced dichotomy between our still ancient vocabulary of particle and wave and the quantum world as it really is. In other words, behavior in the quantum world cannot be forced to choose between particle or wave since it's not either particle or wave. We need a better way than the application of the words particle or wave to describe what we observe. That's why I, and other scientists, have such confidence in the conventions of mathematics and science, our set of syntax and semantics, respectively. Up until now, much of the content of the previous chapters covered the syntax of science, the mathematics; now it is time shift to what I call the semantics of science: experiment.

Not unlike other professions teaching can be a very individual enterprise, and no matter how much training and professional development you get from colleagues, in the end you are alone in the class with your students – when push comes to shove…it's your call. Although the rules and criteria for performing a high-quality experiment are clearly set out within our scientific conventions, the rules for writing up the report based on that experiment can be a very private affair for a senior physics teacher. Each of us has had our own collection of professors all of whom have taught us slightly different tenets with respect to experimental report writing; and concurrent to that you'll develop a new set of experiences based upon the particular colleagues, schools and situations you will come upon over your career. From these encounters you can make your own judgments to decide what merits a good experiment and its report. The arguments over the next few pages are intended to influence your judgment with respect to what I believe amounts to best practice along with some finicky rules for writing the report. In my (not-so) humble opinion these will prove to be a conclusive set of rules that I believe ought to be taught by all teachers and adopted by all students, with small situational variations – heck, why else would I write them. If you follow them, incorporating some minor variations along the way, then I don't think you can go wrong.

The focus of this book has been to outline some of the crucial elements necessary for succeeding in teaching (and learning) senior physics, unfortunately, it cannot cover every aspect of experimental techniques – that topic needs to be exhaustively referenced within your classroom textbook, if it is not then find one where it is and use it. Furthermore, you need to spend sufficient time covering the precise aspects and procedures of each experiment and its associated safety procedures before students can perform the experiment. As domineering as it may sound, you must command the respect and discipline of your students before embarking on any experiment for the safety of all involved. I cannot teach you how to acquire that command here, except to say that it is a duty of all teachers – without that command you do not belong in the class, to put it bluntly.

To me there is little point in performing a classroom experiment unless it is to be written up as a formal lab report for grading (Although my definition of formal may differ from yours). Clearly there is a necessity for teachers to perform demonstrations and for students to participate in and perform their own demonstrations to illustrate vital concepts during a lesson; but my arguments here are not about demonstrations. These arguments below are about how to perform an experiment skillfully (the details of the act of the experiment) then using those details when writing a proper report (in the next chapter).

In an ideal world we would be able to assess each student's laboratory abilities by grading both the report and their technical performance for every experiment; however, you need to face the fact that students will be assessed on their report writing more than on anything else about the experiment. It is simply a reflection of our capabilities within an industrialized school system. Truly individual attention is a farce try as we all do, but do try nonetheless. Therefore, having them comprehend the substantive elements of a good lab report is both a realistic and assessable goal.

In senior physics we tend to perform experiments of two types: recipe labs and design labs. And yes variations and gradations to these definitions exist, but that's not important right now.

Recipe Labs

Recipe labs are those where you, or the textbook, tell students what they are about to do (Purpose); what equipment to use (Materials); the entire set of instructions (Procedure) and what to do with data in the end (Observations) along with the direction to a common "answer" (Conclusion). This is why the term recipe fits so well, it sounds similar to the directions for baking a cake; if everyone performs all of the following steps, with all of this material provided then all of us will observe the same thing and come to the same conclusion. Ta da!

In a recipe lab students are never going to discover anything new about nature that is not already known (and has been known for probably a hundred years too). So there needs to be a point, of which they are abundantly aware, in having them perform these types of experiments. The emphasis behind these kinds of experiments should rest heavily on having them personally:

1) confirm some constant which is crucial to physics (measuring the acceleration due to gravity as 9.8 m/s^2 for example);
2) make a particularly revelatory observation (witnessing the conditions for Total Internal Reflection);
3) learn to use some specific piece of equipment or practicing a special laboratory procedure (titrating an acid); or
4) get up off their butts to do some activity-based science.

Items 1 and 2 are confirmation-type experiments, 3 are procedural-/technical-type experiments, and 4 are so-called hands-on science stuff.

After the experiment is performed the next stage usually includes copying copious parts of the textbook like the Purpose, Materials etc… This aspect of report writing is what I call the "make-work-project" stage. A "make-work-project" is akin to using employees to move furniture from one part of the office to another part today, and then having them move everything back again tomorrow so they look busy for the boss. I'm no fan of this feature of report writing. Admittedly, it does serve some purpose in the junior grades in developing their overall realization of why they have just preformed a particular experiment, or in itemizing the techniques and materials used by name and detail, or by directing their lack luster data analysis skills, and maybe in emphasizing the need to come to a conclusion at all, hence the point of doing the experiment. But these skills should have been taught and learned in those junior grades, not highlighted or repeated in senior physics which should be our focus. There is nothing to learn by copying anything from the textbook; copying is assigned to keep them busy at their desks. It is a waste of time, honest. Experiments should emphasize: Do Think Claim. More on this later.

The latter half of their report writing project requires them to follow another set of instructions on how to display the data and what questions from the text are to be answered based on the data collected, and it's at this stage where many students hit the wall of confusion. To put it more bluntly, it's when the proverbial shit hits the fan because every textbook and every teacher assumes the experiment was performed well enough to have collected the appropriate i.e. correct, data; and therein lies a serious problem: the questions are all based on the supposition that the students have the correct data, but what if they don't? The data, graphs and observations have to be correct in order to follow through and answer the directed questions thereby making sure everyone attains the same conclusion at which point the entire class will heave a collective "ah ha. Eureka!" In your dreams.

It is unlikely that after every recipe lab every student, or group of students, will have all of the correct data; and hence, what happens next is as near to mental chaos as you can reach. Confused students will call you to their desks having discovered that a specific question cannot be answered properly given the data. "The question asks us to explain why the variable increases but ours decreases. What do we do?" Now it becomes incumbent upon you to find out why their data does not match with the expected result, what went wrong in their experiment, what to do with the data at hand and whether their experiment should be repeated to get the right data[1] (and on whose time) or, you need to instruct them on how to answer the questions that now make little sense at all given the data available – it is a nightmare for everyone involved and it will happen often. It is the major flaw behind all recipe labs.

[1] Which is really bad science!

So far I have not presented a pretty picture of experiments, so should we stop doing them? Not at all, but we do need to change the way we do them.

Design Labs (or Inquiry-based learning)

Lab activities are always a good distraction for a science class, but without veering into too much of a discussion on the philosophy of science, recipe labs are not the way to go – they are not real science. Unfortunately the educational community (of which I consider myself a part and therefore accept some of the blame) has spent a good portion of the previous generation forcing science education into becoming a solely hands-on endeavour; that practice has, for the most part, turned modern day science-classes into a high-octane explosive sideshow, more entertainment and less enlightenment regrettably. Classroom activities serve a crucial function in science education, but as with the mathematical elements on their own they do not amount to science. Science is the only objectively itemized method of looking at nature through an activity-based, data-collecting process to analyze evidence upon which to make a claim – and that is the whole point of doing an experiment: to make a claim. So how can we keep senior science classes activity-based while presenting a more truthful portrait of science? By using design labs and including a few ideas from television of all places.

I would bet there is a high probability that you and many of your students are fans of the MythBusters© and of the investigative genre of police dramas such as CSI© or NCIS©. Ever wondered why? What is it about these shows, that is so captivating? I believe the answer is more subtle than a mere attraction for the wiz-bang scientific techniques and equipment used. What occurs over the course of an episode is not only exciting, engaging and analytical, but is inherently deductive in nature – it epitomizes the fundamental practice of science. Invariably, all of us wish our science class could be more like those shows, and so we should, but it is not about the elaborate or expensive equipment, though I bet you would love to use them – it is the process of what happens during the shows that is fascinating. We all want science class to be more, well…more investigative. To be fair no school will have the equipment or budget of these shows, and given the safety issues involved in many of the episodes it is highly unlikely you will ever come close to re-enacting the science and technology of what happened – in short, you and I will not get to meet Adam and Jamie on their level with any regularity; however, the excitement of that process of investigation should not be lost from our science classes.

A design lab is more in tune with those same fundamental elements of science portrayed in the MythBusters© and CSI©, not perfectly, but more than any recipe lab ever could. There are multiple ways of devising design labs, so the directions given here are highly adaptable to your situation.

A Design Lab example

Here is the outline of a design lab I have given often. There is nothing particularly unique about it, and I have given this one to both grade 11 and 12 classes with only slight modifications depending on what may have been taught immediately prior to the experiment. The modifications are not only dependent upon the different depth of the material presented, but also dependent upon the fact that many of my grade 12 students would have been my grade 11 students and might have done the experiment already. Nevertheless, giving it again with modifications was still a useful activity for them.

> Friction is the retarding force created at the boundary between two materials or objects. The value of this force varies depending on the surfaces of the two materials involved. The coefficient of friction is a measure of the amount of friction that will exist between these two bodies when in contact. Your assignment is to design and perform an experiment that will determine the coefficient of friction between two materials. You may determine either the static or kinetic coefficient of friction, but you must specify.
>
> Your report must include the following:
>
> ***Apparatus***: List the apparatus needed to repeat your Procedure. You may assume the use of any apparatus likely to be found in a typical school.
>
> ***Procedure***: Make a short outline of the procedural steps to be followed. Diagrams may be useful. Repeat the experiment for at least 3 pairs of materials.
>
> ***Observations***: Design a table to record the measured values. Present the data in a visually pleasing and informative format. Hint: no graphs are needed for this lab.
>
> ***Analysis***: Analyze the data to calculate the value for each pair of materials. Only one final coefficient of friction is required for each pair of materials.
>
> ***Conclusion***: What exactly did you find? Include your estimate of the authenticity of the data and conclusion.

This particular version is written the way it would have appeared for a grade 11 class that would have just been introduced to friction in the previous one or two lessons, in addition they would have been inexperienced with the purpose or objective of design labs; as a result there is a large amount of guidance in the latter half of the guidelines. For a grade 12 class there would be far less guidance written throughout the document since most students would have completed many design labs prior to this point, and therefore know what to expect in this regard.

The grade 12 class would probably only get:

> Friction is the retarding force created at the boundary between two materials or objects. The value of this force varies depending on the surfaces of the two materials involved. The coefficient of friction is a measure of the amount of friction that will exist between these two bodies when in contact. Your assignment is to design and perform an experiment that will determine the coefficient of friction between two materials. You may determine either the static or kinetic coefficient of friction. Begin.

A grade 12 class would also know more techniques for discovering the co-efficient.

If you look at the focus of the lab, it is to figure out the coefficient of friction between any two materials – I have not specified what those two materials should be, and therefore I have absolutely no idea what the coefficient of friction will be unless I have tested every pair of materials available in my class. (No I have not done this – I do have a life outside of class, and you should ensure you have one to.) In other words, I do not know what the "answer" is, how could I? So the point of this activity is for the students to design the lab, perform the experiment and ultimately convince me of their conclusion, i.e. of their claim. All design labs should be like this: a very open ended search for specific results yet still tightly focused on the validity of those results. In addition, there is no one correct way to perform the lab, so a number of valid procedural options exist. Some options are easier, some are faster and some are very difficult to carry out. None of my design labs have an answer known ahead of time. All that matters in the end is:

- Does the procedure, as written, actually permit the correct data to be collected?
- Can other experimenters have confidence that the procedure and analysis performed actually allow for the conclusion claimed to be reached?

That is the rationale behind a design lab. It is also the premise behind all good science.

Finally, on a more pedantic note, students would have had only 75 minutes from reading the directions in order to design, perform, analyze, write it up and hand it in. On some occasions they would be given notice that a design lab will be done tomorrow, at other times it would be a surprise. No day in advance to prepare notes, tables or plan ahead.

With those restrictions in mind, we need to look at how the report itself should appear.

8

Staking Your Claim

With the MythBusters© and CSI© series each episode concludes with the hosts or actors making a claim from what they've discovered after having gone through the motions of their investigations. In the MythBusters we get to hear if the hosts have decided upon a confirmed, plausible or busted claim, which usually follows after a few moments of involved and reasoned banter over the observations and data (all mixed with a healthy dose of humour). Having watched the entire process through and through (save and except for television editing) we too can decide for ourselves if their claim of confirmed, plausible or busted is valid – and if you've ever visited their blog sites you'll see that many disagree. While in CSI© shows we observe the officers confront the guilty person with a ton of over-whelming evidence with the perpetrator subsequently spilling his guts with the truth. If only.

Unfortunately, the reality is both of these scenarios are just the beginning. If we chose to, we could perform our own equivalent MythBusters investigations that may well dictate our own inclination in developing a dissenting claim based on differing observations. As for the real world of crime investigations, the evidential claim of guilt now requires the officers to present their findings not only to the prosecuting lawyers to decide whether or not to proceed with a prosecution, but also to present their findings in a public court of law that will involve the inclusion of much debate and further questioning. That stage of open public debate is also a crucial stage to science and can only happen once you've made your claim in a written report.

At the end of the previous chapter I introduced a sample design lab that mentioned the important sections necessary for most lab reports: apparatus, procedure, observations, analysis, and conclusion. That rough guide will provide the template to specifying the important elements to bear in mind when writing the report[1].

Let's recall the scenario we are dealing with. Having just performed an experiment to discover a specific answer to a very specific question (the experiment's purpose), the experimenter i.e. the student must tell everyone:

1) what has been done; and
2) what has been found; and
3) how to repeat the experiment to verify what has been found; and finally
4) how confident they are in what has been found.

That is a lot of "ands" but they are necessary to highlight the purpose of doing an experiment, especially in design labs. So with that in mind, writing the report should be focused on achieving these goals by telling us: what was measured, how it was measured, the results of what was measured, the conclusion from what was measured, and the level of confidence in that conclusion.

In the classic beginning to a report it's expected to be filled with such items as the Purpose, Aim, Hypothesis, and/or Question telling everyone why the experiment was done at all. But for a design lab the student was already told what to do and why (by me), so I have never understood the compulsion for writing that information – that's part of the "make-work-project" mentality "…just write it down to busy your time." Furthermore, it makes no difference whether it is a recipe lab or a design lab since you, the teacher, gave the direction for the experiment both times. If you have a craving for them to write the Purpose, then by all means go ahead and tell them to write it down; but as mentioned earlier, I see no point in performing an experiment without an expected report being handed in for grading, so in getting them to write the Purpose they will simply copy the Purpose from somewhere else. Unless paraphrasing short sentences is a part of your grading structure it makes little sense to me…remember this is senior physics, not junior science.

Now to be completely fair, if they are doing an experiment entirely from scratch, in other words you have decided that they can have a choice in what investigation to study (given some boundaries),

[1] Throughout this project I have been very honest such that in many instances I support ideas abhorrent to the educational status quo, including its pedantic quips and propaganda; this lab report section is probably no different. I hope many teachers will see the value in what I argue for on these pages. Many of you will not.

or you are directing them towards some type science fair project where they are compelled to show that they are abundantly aware of the entire scientific process, then yes by all means they had better write down something resembling the Purpose, Aim, etc…But this book is not about science fair projects, it is about what should happen in a classic senior physics class. Therefore there is no need to include any of the Purpose, Aim, or Hypothesis in the reports. For purely pedantic purposes I suggest including a title page or prominent title section so that everyone, especially you, knows what is being handed in and by whom.

By eliminating the Purpose, Materials, and Procedure sections from a recipe lab there is much less writing than before. In fact, those sections would easily have taken up at least half a lab report through the writing and space used alone; but my abhorrence to writing those segments goes far beyond a distaste for "make-work-projects". It stems from a belief that the wasted time and effort that goes into composing these sections deters from the ultimate purpose of the experiment: to collect and analyze data for the purpose of making a conclusion or claim, and that's no easy task so why compound that mission with unnecessary items? So what should be included?

Start with the Materials. Whether you call it Materials or Equipment or Apparatus is terribly irrelevant and requiring the use of a particular term is being overly precise, or to be more blunt anally retentive. Writing the section as a list, being sure to include all of the important apparatus used, may not be exactly scientific, but it does make grading it easier for you. Emphasize that other experimenters will be expecting to use similar equipment when repeating the experiment with the aim of trying to reach (and hopefully support) the original conclusion. Direct them not to be silly by including items like rulers, pencils, and graph paper, etc...These should be obvious. You cannot measure the length of something without a ruler or some other device like a tape measure. (You are not the only one who can be anally retentive.)

In some instances it may be necessary to include an item like a ruler, especially if an electronic range finder is also used. Let's say the point of the experiment was to look at how accurately one can measure various lengths. In this case the point of the experiment are the measuring devices themselves so it is crucial to include them; but if one is measuring lengths, like how far something rolls, then it may be obvious what was used.

The Materials

The Materials list should not include the specific value of lengths or masses. For example: 5.0 kg mass, 10.0 kg mass, 15 kg mass. Including this information in the list of Materials is informing others that in order to repeat the experiment they too must use those exact masses [5.0, 10.0 and

15 kg]. It is far more likely that those masses were used because they were the only ones at hand; and since the conclusion will state some generalized concept such as “X increases as the mass increases” the materials need to be general as well. Write only: various masses ranging from... or something similar. That allows the next experimenter to verify the generality of the conclusion while including the specific masses used later on in a table of results or on a graph. This is not about hiding the values of the masses used, it is about stressing what detail is vital to reaching the same generalized conclusion. And yes there are also times when you might need to be specific here as well, so be open to that possibility.

The Procedure

The Procedure is probably the most important section of the lab report; therefore it should be the most detailed. Why is it the most crucial element? For the simple reason that it is here where the fundamental elements of the scientific process are upheld – so yes, it really is that important. It is in the Procedure where the authors (I love thinking about my students as the authors) not only exhibit the means by which the data was gathered, but also the manner in which it was analyzed and therefore the value anyone can place on the final conclusion. Do not let your students take this section for granted; likewise you should be equally assertive when grading this section.

There are two grammatical formats permissible when writing the Procedure: writing in past tense, i.e. telling readers what was done; or writing in future tense, i.e. prescriptively telling readers how to repeat the experiment. I have no preference for either one, but if you give them the option to choose either one, then demand they be consistent throughout the report. Having said that, the best reading format is the prescriptive one because telling others what to do is more authoritative. It works for me, can’t you tell.

Insist that students be clear, specific and detailed with the Procedure, numbering the steps using a list[2], and similar with the Materials section do not include silly items such as:

1) go to the front of the room and collect the equipment. Or
2) Get a ruler. Draw a line for the axis, blah, blah…

They should include only the necessary steps to repeat the scientific and technical aspects of the experiment. This is also an optimum time for the use of diagrams. Drawing a detailed and itemized diagram of the equipment as it should be set up properly, permits students to write shorter procedural steps such as:

Set up the equipment as shown in Diagram 1.

[2] Similar to the Materials, a list is easier for them to itemize and easier for you to grade. Ultimately, you can choose for yourself if you would prefer they use a paragraph style instead.

This will surely save many lines of do this, then do that, then clamp another thingy there beside that thingy… Make sure all of the important equipment shown in the diagram is also listed in the Materials.

Since an experiment is all about keeping some quantities constant (the controls) while varying other items (the variables), students will need to repeat individual steps within the Procedure. This is one of those cultural elements mentioned in the Introduction to this book; repeating procedural steps is obvious for you and me, but not so much to them. It may not be written into academic papers as "…we repeated this step ten times…", but it is a given factor behind all of them. Getting your students to write it down helps to emphasize its significance. You might suggest:

10) Keeping X constant, repeat Steps 3 - 6 five times by changing Y while measuring Z for each unique Y.

Before ending the Procedure segment there is one more item that should be included in a senior physics lab report: what to do with the data.

A senior physics lab report must outline what to do with the data once it has been accumulated; that is to say, force them to write a few lines detailing how to analyze the data. That may be a self-evident process in scientific reports (another part of the culture of physics), but permitting them to presume it's too obvious to be written is mistaken. This report is about them: their experiment, their data, their claim, and how they came up with their claim. Insisting that they explain themselves goes to the very depth of their understanding, or lack of it.

Describing what to do with the data may read as simply as: tabulate the data; graph the results; analyze the graph for any relationships and develop the/an equation describing the relationship. Far too often students, and teachers, think the point of doing the experiment is to do the experiment; which is wrong. The point of an experiment is to develop a claim founded upon the procedure and the data, and therefore it needs to be justified at all levels.

Observations

It is crucial students present their raw data in its original, but neatest, form. In academic circles this is not done as directly as I insist upon it for my students, but in a senior physics class we might be talking about a 10 pairs of numbers…maybe, not terabytes of data streamed from complex devices. The best format is in a table. Below are my preferences for table design and layout, but make your own decisions relating to anything specifically different from what is mentioned here.

To illustrate, we need to use the data from a simple experiment from which to develop a table and the remaining report sections. (This particular set of experimental data is used in my class for a number of reasons other than explaining how to write lab reports, but that's not relevant here.)

"An experiment was performed to measure the average speed of a runner over a period of four seconds. It was done by having the runner start at some origin, the beginning, and then dropping a stone on the ground every second as required. Afterwards, the distance of each successive stone from the origin was measured and the data looks like this: at 1.0 second the first stone was 2.35 m from the origin, at 2.0 seconds a stone was 3.75 m from the origin, at 3.0 s it was at 6.33 m, and finally at 4.0 s it was at 7.70 m." From this small set of data we can develop the general rules to follow for all tables, even those far more complex and lengthy. Here is the completed table that I'll be using to highlight what matters in proper table design:

Table of distance and time

Table # 1

Time t (s)	Distance x (m)
1.0	2.35
2.0	3.75
3.0	6.33
4.0	7.70
±0.1	±0.03

The table has both a title (Table of distance and time) and a label (Table # 1); make sure this is done for every table (and diagram) so it can be referenced in the report as in: Looking at Table # 1 we see that… Some people prefer the title and label at the bottom, I prefer them at the top; it doesn't matter. To explain why to title or label at all, you might suggest they imagine a textbook where every diagram, table, figure and picture is missing its title/label then to imagine how difficult it would be to follow the text references. One would rightly wonder why any of the images were there at all and if they were connected to anything mentioned in the text. Label all of the diagrams, tables and graphs.

The table is boxed in all around. This is a small but ingeniously simple way to highlight it making it stand out from the rest of the report. Note also that none of these guidelines requires a computer or printer to accomplish; remember, my students had only 75 minutes to complete all of this on a design lab, so hand-written reports were commonplace.

The top line of the table includes:

- the name of each measured quantity (Time, Distance);
- the variable used to represent each measured quantity (time is t, distance is x) and;
- the units used for each (time in seconds s, distance in metres m).

In one line the reader has the vital information AND there is no need to write the units over and over again. Looking down the columns, you see that neither an "s" or an "m" is repeated for each value given. That is the point of writing them on the top line! Do not write them again. Have you noticed that writing reports my way is actually shorter than what you may be used to – I am trying to help you and them.

Potential Inaccuracies (Uncertainty)

The bottom row of the table [±0.1, ±0.03] contains an expression of the uncertainties inherent in each measurement; let's call this the uncertainty statement. An uncertainty statement must not be interpreted by them or you as a reference to being wrong; it is unconscionable to infer, or teach, experimental uncertainty as an error on their part or by being incorrect. Therefore the better term is uncertainty. All experiments contain uncertainties no matter who performed the experiment or what equipment was used. It is not a reflection of incompetence, but it is a fact of life in science (There will be more about this in the Conclusion section of this chapter). The problem with the word "error" is that it implies there is a "correct" answer blowing in the wind similar to making a mistake on a mathematics problem. That is a poor interpretation of the scientific method. Nevertheless, we do talk about error-bars and error analysis in science, so the term is not entirely unpalatable. I would suggest you avoid using it when teaching, but even I find it difficult to do so. I admire those who can avoid the term consistently.

For now we need to look at what should be considered when writing the uncertainty statement. There are two kinds of uncertainty to consider: systematic (or technical) ones relate to the measuring equipment used or the manner in which the experiment was performed; random ones relate to the way in which the values were measured by the experimenter. Systematic uncertainty tends to force values towards a specific direction away from the precise value. In other words, one piece of equipment used may be calibrated incorrectly leading to all of its measured values being either too high or too small. A good example is a ticker-tape timer[3]. It may be designed, and read, to deliver a dot every $1/60^{th}$ of a second, but may in fact deliver a dot at every $1/61^{th}$ of a second; therefore all of its values will be out of synch from the expected reading by (roughly) the same amount.

[3] I despise ticker-tape timers. I think they should be collected, melted down and turned into something more useful like toilet paper holders.

Likewise, the experiment itself may have an unknown design flaw leading to certain measured values being too high or too low from the accurate readings. In our experiment in this chapter, there is an inherent design flaw with dropping a stone when told to drop it. Is the time considered to be used when the timer tells the runner to drop, or when the rock is dropped, or when the rock hits the ground? These are design flaws that need to be understood and addressed (this is one of the other ways I use this data, in having a discussion on improving experimental design).

Random uncertainties are essentially more human ones. They result from misreading the numerical values from a piece of equipment and can vary from reading to reading, hence the randomness. Probably the most common version of this stems from poor readings of length measurements using a ruler or measuring tape. The problem is not with the tape itself, since that would be systematic, but with the person reading the tape itself, i.e. the student. The student must decide where the edges of the object are and from there make the measurements, and that act of deciding is wrought with randomness; sometimes it's too far, sometimes it's too short. Another version of randomness often mentioned in texts is parallax with the best example being trying to measure the amount of liquid in a graduated cylinder. The accuracy of the measurement depends on whether the reader is at the correct horizontal level with the liquid's meniscus. If either too high or too low at any one reading, then the results themselves will be too low or too high, respectively, for each reading. For simplicity's sake let's roll all of these sources of uncertainty into one.

Returning to our hypothetical runner experiment we would likely have used a stopwatch for the time and a metre stick or measuring tape for the distance. Although most stopwatches are devices accurate enough to show hundredths of a second [0.01s] it is unlikely that students could call out to the runner when to drop the stone accurately enough to merit knowing what the time was to within a hundredth of a second. So no matter what the stopwatch says or how it was read it when the call to "drop the stone" is given, every value will be off from exactly a whole second. How much uncertainty away from that whole second is what students need to identify. Similarly with the distance; even though the measuring tape may be accurate to within millimeters [0.001m] the size of the stone itself, and whether it bounces, slides or rolls, will not merit an accuracy as small as 0.001 m. Students will always need to make a judgment call on what the last accurate digit of the reading will be, and considering all of these issues (and many more) there are too many reasons to not have complete confidence in each measurement of time and distance made. It might be better to interpret this lack of confidence more so as a measure of the authenticity of the data tables, and therefore stating it clearly in the uncertainty statement at the bottom is crucial when making later judgments about the validity of the conclusion.

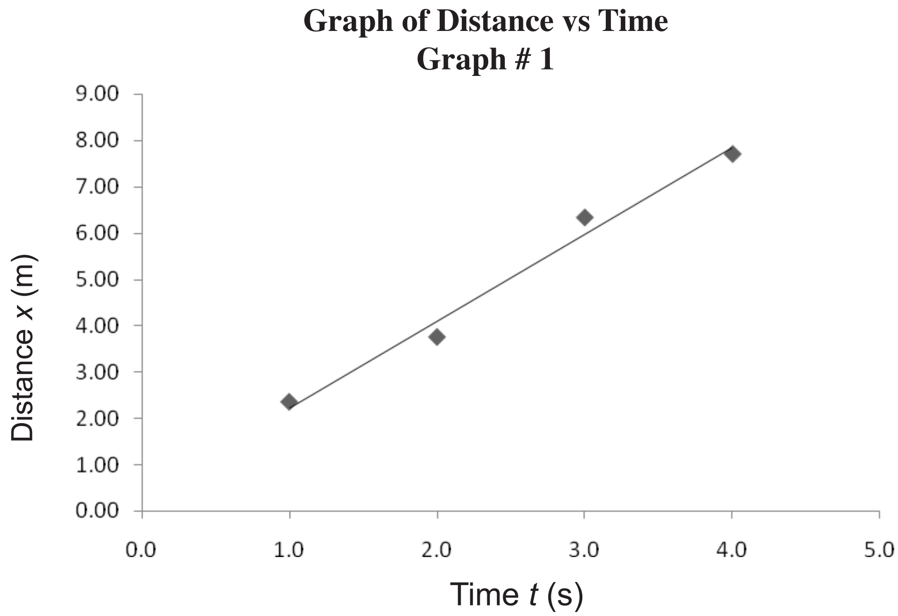
There are very precise and detailed methods for following through with these uncertainties to properly develop an accurate analysis of the quality of data with respect to the final result; however, teaching these rules of data analysis are not important in senior physics. So why bother with any of this at all? Because it is crucial that students be totally aware of the fact that uncertainty plays an important role in scientific experiments and expressing that uncertainty is a part of scientific integrity. Nothing you teach at this stage of physics should weaken the significance of scientific integrity; scientific integrity is essential to the foundation and advancement of science. So although following through with proper data analysis may not be necessary, it is important students are aware of uncertainty, and its sources, in order to make mention of it in their reports. At this stage you should be focused on instilling a sense of purpose and honesty, even though total accuracy is a distant dream.

Before moving on, hark back to the values expressed in each column with reference to the uncertainty mentioned at the bottom. In the Time column the uncertainty statement is ±0.1 s (one decimal place), and for the Distance column it is ±0.03 m (two decimal places). Now look at each individual value in the column above; there is no value with more decimal places than in its uncertainty statement. There is no time value of 2.00 seconds nor, a distance value of 6.153 m. Tabular values cannot contain more decimal places than claimed in the uncertainty statement. If the time's uncertainties are no better than 0.1 s, then a time value of 2.00 s cannot be valid because there is definite uncertainty in the first decimal place and therefore no certainty in the second decimal place.

Graphs

Tables are nice, but graphs are better. Graphs show the reader, visually and quickly, that there is indeed a (mathematical) relationship between the terms labeled along the axes, or whether one exists at all. The immediacy inherent in graphs surpasses the most elegant tables or the most verbose prose. Having said that, all graphs need to be taken with a grain of salt until the assumptions used to develop the data are known, but nevertheless, they fit the adage "…a picture is worth a thousand words…" perfectly. The graph of the data from our average speed experiment (Graph 1) will suffice in explaining the details of graph design.

First, notice that the graph has both a Title (Graph of Distance vs Time) and a Label (Graph # 1) just as the tables require. Each axis has the same labels as the table's column names, variables used and their units: Distance x (m) and Time t (s). The numbers written on each axis use the same number of significant digits and decimal places as the column value: three significant digits and two decimal places for Distance, and two significant digits and one decimal place for Time.



Consistency is important for developing confidence in claims. All graphs should be developed from the data provided for and shown in the attached tables. And yes, proper academic reports do not make this requirement for the same reasons mentioned before: terabytes of data are just too much to show, but the original data is always available.

Although in this case the graph is drawn by a computer, there should be no preferential grading for that. For design labs the students must do the graph by hand on graph paper provided; so as long as it is neat, well drawn, and properly labeled it should not matter. In addition, I insist that each, hand drawn, graph covers a single page. This gives the most space for all of the labeling. For computer/printer graphs two per page is acceptable since they can be far more detailed and nicely drawn.

All four points from the original data are plotted, and then a line is drawn. The line is purposefully drawn by the experimenters to prove to the reader that there is indeed a (linear, straight line) trend following from that set of data, the trend line, or line-of-best-fit. (If the set of plotted points appeared to be following a curved path, then by all means insist they draw a smooth curved line… and no this is not the time to mention the fact that available spreadsheet software exists because this discussion is still about design labs with only 75 minute periods, or less. Four data points are not necessarily enough to distinguish a curved line from straight line, but you know that, so if it is necessary for them to know at this point then elaborate and expand on this point yourself. Likewise, this book is not the time to cover the methods for "straightening" a curved line, but if necessary then teach it to them.)

There are two items to direct their attention to them immediately:

1) The line is not drawn through the origin [0,0] (where and when the runner started) or beyond the last point. If the line is to be drawn through the origin, then that data point [0,0] should have been included along with the data set, which is fine, otherwise you may have to tell them that there is some particular reason to "force-fit" the line through the origin. Likewise, they should not continue the line past the last data point they have, which in this is case [4.0, 7.90]. The line-of-best-fit should only appear where they have confidently collected data. Showing the line outside of that range, at either end, is speculation and extrapolation. It may be necessary as part of the experimental analysis, but should be marked using dashed lines or in another colour or referred to somehow explicitly.

2) When the line-of-best-fit is drawn…absolutely never, ever connect the dots. NEVER.

(My students would quickly learn that connecting-the-dots is one of the greatest sins they could commit in my class. It follows closely behind pronouncing km as "call-o-meters" and not "keel-o-meters"! AAAGGGGHHHH! Do you pronounce kg "keel-o-grams" or "call-o-grams"? Huh? Do you?! No! Keel-o, Keel-o, Keel-o! I needed to get that off my chest.)

Data has just been collected with its inherent uncertainty acknowledged (remember the bottom of the table?); each and every data point then has some uncertainty surrounding it, so any particular data point cannot be entirely accurate. The line-of-best-fit is exactly that, the line that best fits in a representative way how the data is behaving as an overall trend. The line may not go through any of the data points at all; looking at my graph you see it entirely misses three of the four points – and so what?

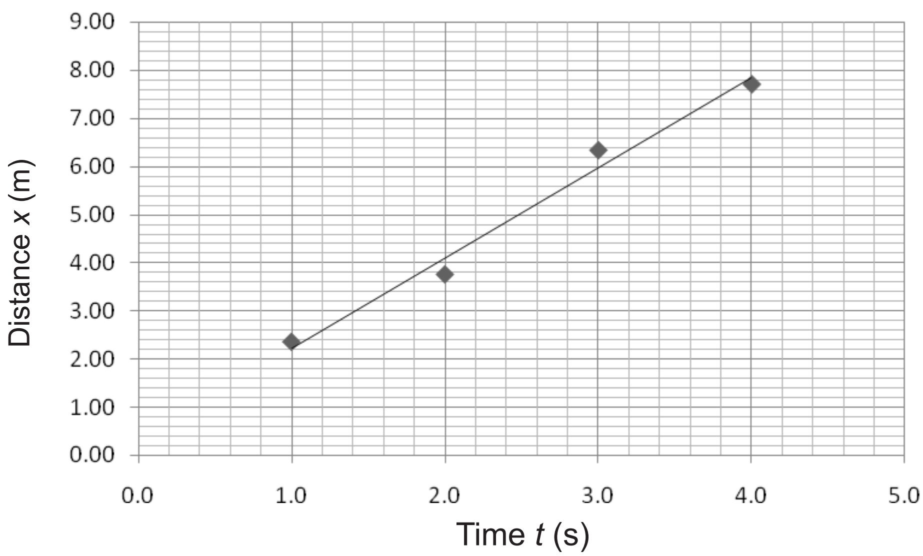
The line-of-best-fit is supposed to represent what the data would look like if the experiment was repeated a thousand times with all of the points plotted. That specific line is used to imply "with a thousand repeated data sets this is what the trend would be, where it would go from, go to and how steeply". It is perfectly acceptable for the line-of-best-fit to actually go through the odd point or two, just do not let them force it through points; however, a line-of-best-fit that does go through (some) points is a good way of assessing the quality of the data, and hopefully the quality of the conclusion following.

Another way of making this point is to imagine that once the line-of-best-fit is drawn, the data points no longer exist and they can be ignored for all intents and purposes. If someone else repeats the experiment (the hope is) they will find that their data sets cluster around that same drawn line – no one can reasonably expect to collect the exact same data, but one can anticipate they will come to the same conclusion (i.e. the same line-of-best-fit) that was originally developed. That is good science; but remember this is still high school and most experiments will incur significant uncertainty, so consistently accurate data should flag a few warning cells in your brain. Do not let them lie or fabricate data to make it fit a line.

Analysis

The analysis of the data begins with a by ignoring the data points and using the line-of-best-fit to calculate the (in this case linear) relationship between the two terms. I have re-drawn the original graph (now Graph # 2) but this time adding smaller grid lines to assist in making my point.

Graph of Distance vs Time
Graph # 2



To calculate the linear relationship from a line we need to calculate its slope, or gradient, using the equation[4]:

$$slope = \frac{x_2 - x_1}{t_2 - t_1}$$

where the points [t_1, x_1] and [t_2, x_2] are points from the line, not from the original data set. Students should choose any two data points from the line, but why not suggest points that cross grid lines – although it does not matter – but make sure the points are on the line. We can choose [1.2 s, 2.8 m] and [3.2 s, 6.0 m]. So our slope calculation would be:

$$slope = \frac{6.0m - 2.8m}{3.2s - 1.2s}$$

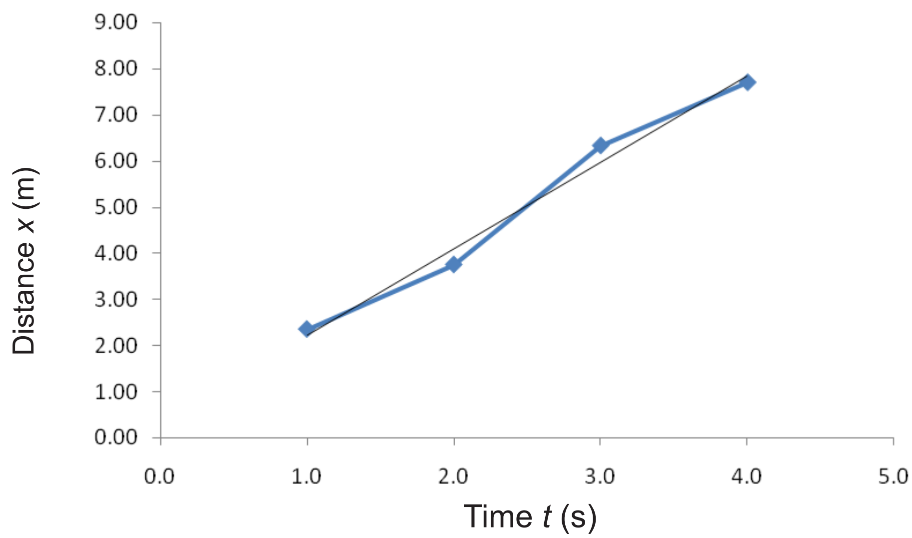
$$slope = \frac{3.2m}{2.0s}$$

$$slope = 1.6m/s$$

This value represents the trend of the data set. In other words, if someone repeated the experiment numerous times, the claim is that the trend of all of other data sets would cluster around 1.6 m/s, give or take an uncertainty to be stated later.

What would be wrong with using values from the original data set to calculate the slope? Once again the graph is re-drawn (now Graph # 3) but this time there are two lines: a jagged one from connecting the dots and another is the proper line-of-best-fit. You can see clearly that if one chooses any particular pair of successive data points there is a very small chance that the slope calculation would work out to be 1.6 m/s. If you look at any of the blue lines none of them matches the slope of the line-of-best-fit. That should be proof enough for never connecting the dots. Remember to emphasize that once the line-of-best-fit is drawn, they are to make all calculations from that line and not from the original data set.

Graph of Distance vs Time
Graph # 3



The Conclusion… of the report, not of my book

For some bizarre reason students think the Conclusion should be long, and the longer it is the better chance at more marks – garbage! The Conclusion should be one of, if not the shortest parts of the report. The authors really need to tell the reader two things only: what was calculated for the final result, and how much confidence the authors have in that final result. This is their chance to make a claim and support it with their data and its analysis. Knowledge does not come from data, knowledge comes from the way the data is interpreted and is expressed in the overall confidence in the experiment.

For the runner experiment we were looking to measure the runner's speed over four seconds. So the very first line of the Conclusion should be a statement attesting to that: The runner's average speed was 1.6 m/s. For another common senior physics experiment you might be calculating the acceleration due to gravity, therefore: We found the acceleration due to gravity to be 9.5 m/s^2. Whatever it is, it should be kept simple; if there are multiple results then why not use another table.

Do not let your students repeat statements in reverse. There is a TV commercial running that compares the financial situation of two people using two different methods of saving their money. The commercial states: "His savings are higher… Her savings are lower." Well of course her savings are lower! The truth of the second statement follows from the first statement. You cannot have two people compared with one having something lower, if the other's is not higher, that's obvious – unless you are in marketing. This need to fill space with print is part of a student's innate flair of equating the number of words with quality. There are many ways to make a point. Make it and move on.

The latter part of the Conclusion should be about their level of confidence in the claim by stating the amount of authenticity they believe the claim contains, in both a general and specific fashion. I have already mentioned that this book will not probe deeply into data analysis – that is best left for early university and beyond. Nevertheless, you need to come clean with a reasonable expectation of what depth of analysis should be expected from them regarding their final claim, and make sure you convey this to them. The uncertainty declaration, probably based on simple significant digits analysis, could be included in the first statement: The average speed of the runner was 1.6 m/s, ±0.3m/s; or included separately justifying how or why that number of ±0.3m/s was provided.

Other types of uncertainty statements will need to describe where they may have gone wrong (We should have used…instead of a…to achieve greater accuracy); or ways to improve (The reader should consider repeating the experiment, with Device A instead of Device B). The point of this is simply to get them to do a self-evaluation of their experimental design and report on it. With a little focus on afterthought at this stage in their lives, they might develop a sense of value in the review process for the construction of other experiments in the future.

Lastly, the entire point of an experimental report is to generate an opportunity for making a claim based on the procedure used and the evidence discovered. It is about providing the support for an argument the authors are using to base their claim, it is not about the visual appearance of the argument. Ultimately the appearance needs to be clean, neat and presentable, but nothing more. We have become a frilly society where the marketing of a product or idea is more important than the value or quality of the product or idea itself. This is not wholly the fault of our market driven society;

it is also the fault of our educational system, particularly our elementary and junior grades where the emphasis is more often on appearance than substance – but senior physics is not elementary science. Content and argument are king and queen.

With design lab periods being as short as 75 minutes, student reports had to hand-written; however, for recipe labs computer-generated reports were expected. Apparently that meant it was time to switch their brains from being content focused into art-class mode; now that in and of itself is not an issue, art is sometimes of value in physics, but I cannot tell how much of an endeavor it will take you to tell, nay compel, students to spend more time worrying about what they were writing rather than on what it looked like. Does anybody actually read lucida blackletter or braggdocio?

9

Expert Testimony

I obtained my bachelor's degree in physics at age 23 after a long love affair with every little aspect I could plunge my mind into. There was no doubt then that a career in physics was going to play a significant part of my future identity, and so with excellent grades in high school off to university I went…whereupon I failed my first mid-term and was devastated beyond my imagination.

It was nothing more than great fortune that I was living with two graduate students, one studying for his MBA and the other for his Medical Degree - no intellectual slouches there; their advice was to me was to relax, my academic life was not over and my new found career plans of building hospitals in the heart of war torn nations, though laudable, was not yet necessary. There was still time to recover from this setback. But what was the problem? Why had I done so well in high school, and yet begun so poorly in university? The solution lay between a mix of time-management and study skills.

If you recall from a previous chapter, in the process of making my argument that problem solving s a skill that needs to be taught to adolescents explicitly, I had mentioned that everyone (namely, my teachers and fellow students) had just assumed "good" physics student knew how to solve problems innately[1]; therefore, no one had taught us how to prepare for difficult tests. Other than

[1] Problem solving skills are certainly not restricted to physics, or science, of course. Problem solving goes by a number

some pedantic mention of "you had better study" there was no specific direction, suggestion or advice on how to prepare for writing a test. I cruised through high school conquering what were (assumed to be) difficult tests when in fact they were not – at least not as challenging as they should have been. Early on in my teaching career I resolved to write difficult tests with a view of using that avenue in and of itself as another part of the learning process. The keyword throughout this being to learn, learning to prepare for tests – it takes time to learn it and do it, it is not an overnight process, but as with algebra or problem solving it can be taught.

I rarely held back on difficulty, knowing full well that no matter how difficult my tests were, my students would face more difficult tests in subsequent years - holding back would be a disservice. I did give fair tests, although I suspect it was not until much later in the year after most of my students had succumbed to these regular intellectual beatings before they realized that. "Your tests were fair but tough" was probably the greatest compliment my students could have given me, even if given indirectly only.

There are many study guides available (this chapter being yet another one) and there were probably many available when I was in high school as well. Unfortunately I had not read any of them and paid the price for that negligence in first-year university; and yet in a bizarre twist of reality, not having read any of them forced me to cultivate my own method of studying – and quickly.

Do not assume your students know how to study based on the simple fact that up until now they have been successful enough to have passed the prerequisite courses for getting into senior physics. Take nothing for granted about their previous education; even if it was excellent, adolescents retain skills year upon year like a sponge retains water – under a little pressure it may spill out or evaporate over time. The details behind my approach are representative of why I became a teacher, the call behind my calling if you will. It does not demand genius or intelligence to acquire, but like learning to use GRASP it is a mechanical, step-wise method that can work even for someone with no interest in teaching.

Successful study techniques may be as individual as the student; however, there some techniques that most educational psychologists agree do not work: one of which is rote memorization. Therefore,

---

of other names, including dispute or conflict resolution. In my later teaching years this (learned) skill would prove personally and professionally productive. I became the Chief Negotiator for my teachers' federation (OSSTF, Ontario Secondary Schools Teachers' Federation) dealing mostly with the labour relations between my colleagues and our school board. My ability to deal with numbers (i.e. finance), analyze detailed and complex situations, and write logical contract language was crucial. But my conflict resolution skills did not stop there; I became a mediator, studied a number of dispute resolution techniques and earned a Diploma in Peace and Conflict Studies from Conrad Grebel College, at the University of Waterloo. See, you never know where physics and its related skills may take you.

the best answer to the question: “What should I memorize for the test?” should be “…nothing…” Any heavily laden problem solving discipline like physics which is constantly doling out new problems based on new equations, ideas, and models cannot be conquered through memorization at all because no one can memorize for every foreseeable problem. Things change. Panic strikes. Shit happens. As Dorothy said “…we’re not in Kansas anymore Toto.”

Now learning at a senior physics level is not the same as learning in a junior science course, although here too I wish junior science were taught through less memorization. Clearly the level of difficulty would have to be less than expected from a senior physics course; but nevertheless with a level of difficulty in tune with students’ resilience to being pushed and stressed slightly beyond their capabilities. Too often we’re afraid of pushing our students beyond their limits or of upsetting their mental poise. But that is the very nature of a problem: it upsets our balance, our routine and our confidence; without the practice of knowing what to do when that confidence is disturbed you cannot know how to proceed passed it. I can’t account for where my lack of fear of upsetting my students arose, maybe it is the bowl of nails I eat for breakfast every morning, whatever it is you need to find it.

The vast majority of the test questions you design will be problem based, even those that are not mathematical in nature are still problem based and can be solved with the help of GRASP; a good quality test will have just a little factual recall inherent to it, and memorizing information should be of little importance. In addition, only a few of the test questions need to resemble ones previously assigned in class; all questions need to be “solvable” given what’s been taught, but not identical to what they’ve seen.

Think like an expert

In keeping with the entire theme throughout this book, this particular study technique is the one I suggest and describe to my students, though ultimately it is their choice as it is yours to suggest another one. Elements of this system will work when applied with other study techniques, so feel free to pick it clean for whatever you can.

Being successful on tests and evaluations comes down to having the confidence of facing whatever is thrown your way. That is how I feel when walking into a classroom full of eagerly awaiting physics students. “Lay it on me. I can work my way through whatever questions are tossed at me.” Now that does not mean I know everything, but whatever questions or problems are asked of me, even outside of the assigned problems or classroom material, can be worked through to a correct answer or reasonable solution. For instance if asked a question about a car’s mechanics, I may not know all of the factors affecting a vehicle's engine performance, but at least my students will hear me work (and walk) my way through to something logical and plausible given what I do know about cars and physics. That ease of flow with information and process comes with confidence, a confidence that takes time to develop[2]. You need to cultivate that confidence within them when they are preparing for tests. I am not going to waste time and space telling you to encourage them to be neat and tidy with clearly ordered notes from which to study; or to have done as many of the previously assigned homework questions as possible; or to have copied all of the solution methods shown for the questions they could not solve. A student cannot study from a weak base. My suggested study technique assumes students have been paying attention – if not, this method will bury them in a deep hole very quickly. So how does one prepare for the great unknown? You think like an expert, that's how. Teach them to study like they already know everything as if they are the expert, they are the physics teacher.

When studying for a test the (real) student should imagine herself as the expert physics teacher who is about to interpret (by imagination only) every question read from the text as if it were being asked to her as the teacher doing the question at the board. The (real) student pictures herself as the focus of attention for the class so that as she is solving the problem on her page she imagines herself speaking (in her head) with the same assurance the physics teacher would. As the teacher she would have to follow all of the rules for significant digits, mks, rounding techniques, drawing diagrams when necessary, and especially using GRASP. This is just the beginning. (I also highly recommend they re-do previously assigned problems and examples because they can hear my voice and confidence when I showed them the solution, eventually their own voice should command their studies.)

As the problem is being solved the student should imagine having to explain every step just as a physics teacher would. Every time a new step is reached it needs to be explained to the (imaginary) students and the class is very engaged in everything being done, so they ask many questions: "Where did that number come from? Why did you do that? What happened to the x term? Etc…

Each step in a solution needs to be justified. Any time there is the slightest pause in their own thoughts, the (real) student should stop explaining to herself why one procedure was done instead

[2] To be brutally honest you need to develop that same level of confidence within yourself. Laugh off your own classroom errors…after you have corrected them. There will be times when an answer eludes you, never show trepidation especially in the face of discipline. Adolescents are like a pack of hungry wolves; they can smell your disquiet tomorrow. They will circle your bewilderment and cowardice until they consume it looking for more. Your first year may be hell; I remember coming home from each day, having a nap to relieve my stress, making dinner, and then staying up late always trying to be one step ahead of them the next day. It worked from time to time, but always got better each day, week and year.

of another. There is no need for anything to be memorized at all, if there is doubt over a particular step or technique go back to find notes from the class to help. During my own classes I might remind them about… "Remember when we learned…" or "Remember how we got…" You get my point. Each student needs to validate and defend everything done. That's what you and I will have to do, so why not them.

To successfully follow this I-am-an-expert method successfully students must practice it during the teaching of the unit rather than leaving it all for the end – the crash course as they say, and for more good reason, since most students will crash and burn with late studying. This kind of studying cannot be effective when begun the night before a test, it's a very time consuming process and it is much better to put the time in learning and utilizing this method well ahead of the test date.

Being resourceful

There is nothing worse than wasting good resources, and I don't mean our natural resources. There are many useful educational resources available to students when learning physics, or any subject for that matter. The most important resource is you. You need to teach with such a style and demeanor that each and every student feels it is his or her right to take advantage of your availability in the class as much as possible. The vast majority of students taking senior physics will not have someone at home to help them with their physics homework, and because of that crucial absence you will soon become aware of the unfortunate reality that many students will get home, open their book, start off at the first assigned question and then get stumped. Now what? Well, probably they'll struggle a bit, look up the answer from BOB, plead with someone at home (who will giggle saying that they are no hope as well), call a friend, (buy a vowel, ok I am kidding with this one), you know what I mean. Then finally when all else fails they move on the next question leaving that one undone[3]. But what if it happens again…and again…on that same night?

Success breeds success, but so too does frustration breed frustration and eventually resignation. Provide your students with as much time as possible in class to do their assigned questions; you are their best resource. This is their opportunity to still get stumped with questions, but now they are able to ask for assistance from you (or their fellow students) thereby cultivating some of the confidence they need to finish the rest of the work at home. Getting bogged down solving problems is a dreadful feeling common to learning physics. Do not let them waste their available class time.[4] If you are not their best resource, then why are you there?

[3] In some sense moving on to the next question is not such a bad idea. Getting stumped is bound to happen on a test and knowing when to cut your losses and move on is an important skill.

[4] "Should make better use of the available class time," was probably my most used report card comment and for good reason. The only comment more important would have been… "Behavior is interfering with learning." I think that says it all with respect to most learning difficulties. Oh I can hear the howls…

The next best resource is the textbook. You must impress upon your students the notion that it be used as more than just a source of questions and answers (otherwise it would be about a tenth of its cost, size and mass thereby not requiring an SUV to lug it around). There is more in there from which to learn. In an odd twist, good teaching practice can become a substitute for utilizing the textbook, yes I did write substitute. In some sense that is a good thing – teaching should be much more of a dialogue between students and teacher, as opposed to a monologue by the teacher; but most students, and some teachers, use the book for little more than a Q and A list. Someone, another physicist or physics-teacher, has gone to a lot of trouble to write all of that information – read it, learn it, nurture confidence from it!

Following with the I-am-the-expert study method, the textbook can provide a rich source of how to appear…smart. What do I mean? As part of their home studying, suggest students read through the text and examples as if they were the teacher standing in front of the class using those words and doing those examples – sounding like the expert. They should stop themselves when unsure about an idea, just as a student might question the teacher. Some student texts also provide a source of solutions, not just answers. Reading through them with the same I-am-the-expert method helps to develop a deeper understanding of the physics cam be yet another good idea.

The Equation Sheet

It has become quite rare to take a physics test today without being permitted to use an equation sheet, cheat sheet or whatever you call it. An equation sheet is a valuable test tool as long as the questions are written from a level of difficulty worthy of having access to the equations.

Ultimately you have to define the rules under which they can create an equation sheet; however, here are some general things to keep in mind. The equation sheet should only contain the most important equations, terms, and constants needed for a particular topic (all of them for the final exam[5]). It is not a copy of the Equation Inventory Map, but it can be generated from it. Hopefully by test time students will have learned the meanings of the terms in each equation and how to manipulate them using algebra, so the equation sheet should simply be a well laid out list possibly in the order the material was taught, but that amount of literalism is not necessary. Insist that it be visually neat, clean, concise and ordered – not numbered, ordered – mechanics equations here, then optics equations there, etc...

[5] Exams, tests, evaluations, assessments, blah blah blah…Call them what you will they all mean the same thing. I've worked in two jurisdictions where considerable effort was made to expunge and exorcise the word exam from the school vocabulary. That is one way the education system wastes our money…there are other ways, many, many other ways.

Do not permit each equation to be written in multiple algebraic forms since it only clogs up the page and more importantly it clogs up their brain – remember they're going to be very stressed when using it. Just in case I have not been entirely clear above, let me repeat certain words: insist, and do not permit. You must set the limits on their equation sheet, on its design, its content and its use. Students will compete to see how much they can cram on their page; if they need an electron microscope to read it then there is too much there. Therefore, to eliminate these issues from my classes I provided the equation sheet, the same one for every one, choosing what went on it. If possible hand it out a few days before the test for them to become comfortable with what's on it and where. If there are any errors or omissions picked up corrections can be made; if that happened during the test then the correction was written on the board for all to see. That was a fairer system for everyone involved. I ran the class, no one else did.

Nevertheless, find your own scheme. You may choose to permit labels or names for the terms and equations, or to forbid diagrams and statements – you decide; I would not permit any diagrams or statements; equations only. But having said that, here too I have seen jurisdictions permit anything, literally anything to be written on the student's cheat sheet…and then provide the most perfunctory, plug-and-chug type of exam as to be a complete joke. Giving marks for writing the correct equation, marks for definitions that were easily written on the cheat sheet or marks for diagrams copied off of the cheat sheet is all disgraceful and unacceptable. This is part of the "let's make sure our students feel good about themselves" educational philosophy. We need to know who is better than whomever and this kind of marking and use of cheat sheets will never achieve that. I should have given you a SOAPBOX WARNING.

An equation sheet must not be treated as a support like a crutch, but as a tool like a wrench. The whole point of using the Equation Inventory Map throughout the topic was to become comfortable with the mathematics of problem solving while learning the physics; it was not about memorizing the equations then, and still it is not.

Test days

I can't speak for every physics teacher (try as I do), but the good ones will write challenging tests with such regularity that it points students to the means for improvement. A good test encompasses a few simple questions (plug-and-chug, regurgitate) that precede progressively more and more difficult problems. An even better test format will mix these up so students learn to read ahead itemizing difficult questions from the easier ones, but that can be challenging. Taking a few minutes to read the whole test first and writing something like E (easy) and H (hard) in the margins as an aid is a sign of poise. Some exams have a formal "reading time" prior to the start; otherwise encourage your students to make their own reading time. The most difficult questions are the ones students believe they have not seen before – I say believe because students can put up their own mental road blocks at times if a question does not sound like ones they have already solved. If you recall, I mentioned some of my students dreaded the test de-brief days more than the test days themselves (ok, the anxiety of getting their grade may have had more weight). Let me now explain why.

I had the self-appointed role of pushing my students to their intellectual limits by placing a few very challenging questions on my tests – most hated that self-anointed role and probably still do. The questions were challenging in one of two ways: either they were similar to previously assigned questions but worded as to appear completely different; or they were new questions requiring multiple steps connecting seemingly unrelated terms. This is really not the time or place to explain or detail these nuances because that would require specific examples of what had been previously assigned; however, it amounted to questions that merged what was once taught as disparate concepts. Either way, many students left the test periods very upset and usually grumbling foul things about me saying: “we’ve never seen that question before! How unfair!” Unfortunately, this preconception of what should merit a typical test format, i.e. simple regurgitation of what has been done, is exactly what they’ve been taught to expect up until now. “I do many questions in class and at home, I write the test with the same type of questions on it just with different numbers, I regurgitate the solutions and presto I do well, pass the course and now I know physics!” That is not my style. There are legitimate “type” questions in physics, questions that follow from a repetitive pattern of information and solution, like Newton’s Third Law problems. But it’s the ones that follow a pattern of wording, that are poor question types leading to poor tests.

The day I returned the tests for the debriefing showed the students that yes indeed they had seen these questions before. The de-brief is when I solved each and every test question showing a full solution, where the marks were granted or lost, what concepts were used and sometimes other possible methods. I did this for every question on every test; it is well worth the time and effort and is as much a learning opportunity as the previous three or four weeks spent teaching the material in the first place. “See…that was #3 on page 88, or #10 from your homework…and this question involved a bit of #12 and #24 from the Review pages… but I changed… to… instead of…” You get the picture. That is what a good test should do – push them. Being tough minded is not equivalent to being cruel or unfair. I have never been pleased to see the anguish on my student’s faces, or happy to see tears well up in their eyes during or after a test; but I am forever confident in knowing that I have been fair and reasonable, and most importantly, that they have learned to learn, and that is worth the ordeal of teaching. I am not alone in this stance; but sadly teachers who share my resolve are a diminishing breed. Damn there goes my soapbox again.

It is very easy to become despondent with yourself on these days, to which I can attest. Sometimes teaching them the material and techniques is not enough for them to know how to answer the questions – welcome to teaching. The stress and anxiety of tests can overwhelm them no matter how much grounding was provided, so teaching them how to prepare for and write tests is at least as important as the material taught. There is a poise and clarity of purpose that we need to instill which does not stem from solving easy questions. Over the semester it was my hope they would learn to feel, with confidence that"…yes indeed I have seen this material before…and I have the skills to solve it." This simple thought can go a long way to helping them gather their composure, take a one-minute break, and start again with Given, Required, etc… At the very least leaving the question aside and moving on to another (hopefully) easier question returning to this one later.

We can be our own worst enemies too. Imagine how demoralizing it is to them when, after spending many minutes struggling through a question you announce that a mistake has been made in its wording (it will happen from time to time). Be very conscious of ensuring that questions are well worded and that somewhere in their studies they have come across the material to solve every problem. Surprises are grave for both of you.

Finally, do not expect perfection, expect improvement, individually and as a class. I dragged many (some would say most) of my students to the brink of mental anguish with my tests. A good teacher will bring them there regularly and then bring them back. A good student will learn to expect it, then prepare for it.

10

It's not gravity, damn it

When I arrived in Australia, there was a minor educational skirmish being played out in the press over whether physics students should be allowed to use equation sheets or calculators on exams (to be honest I can't really remember what it was, but it was some nit-picking issue like this). Into this navel gazing arose the issue (come to think of it, this may have been the catalyst), of whether students should be taught to use the acceleration due to gravity as 9.8 m/s^2 or 10 m/s^2, and therefore something about memorizing information or mental mathematical skills, or the accuracy of answers blah blah blah... What was most disturbing throughout this debate was not that it was led and championed by physics teachers themselves, but that each teacher assumed that only one of 9.8 m/s^2 or 10 m/s^2 was correct. From my perspective either choice is petty, and the important point is buried within this debacle that needs to be addressed.

Let's imagine a typical physics question requiring the use of the acceleration due to gravity as 10 m/s^2 [down] and assuming 2 significant digits (since significant digits are not immediately relevant for my argument here).

Ex: An object is thrown upwards with a velocity of 25 m/s. How long does it take for it to be moving downwards at 5.0 m/s?

This is a rather simple and common kinematics question that can be solved easily with GRASP. (Now I know you know the answer already, but that's not the point. In fact that's exactly my point…that that's not my point…just wait you'll understand in a moment.) Using GRASP we have:

$$\vec{v}_1 = 25m/s[Up]$$

$$\vec{v}_2 = 5.0m/s[Down]$$

$$\vec{a} = g = 10m/s^2[Down]$$

$\Delta t = ?$

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t}$$

and by re-arranging this equation we get

$$\Delta t = \frac{\vec{v}_2 - \vec{v}_1}{\vec{a}}$$

to solve. Using the values given we get:

$$\Delta t = \frac{5.0m/s[Down] - 25m/s[Up]}{10m/s^2[Down]}$$

for a final answer of $\Delta t = 3.0$ s. Easy, isn't it.

If we had used 9.8 m/s^2 instead of 10 m/s^2 the answer would be 3.1 s, which is a mere 3% difference from the first answer. Does that matter? No it doesn't, especially since the difference of 0.2 m/s^2 itself (from 9.8 to 10) amounts to only a 2% difference at best. For most of the classroom experiments your students will perform to calculate the acceleration due to gravity, they will be hard pressed to get values that precise. So neither value has any particular preference over the other. There will be moments during problem solving when you will undoubtedly use g = 10 m/s^2 in order to do a quick mental calculation. So why should it matter which constant is used in any question?

You need to choose what the assumed value in your class shall be. My students are told that the value to use is always 9.8 m/s^2 unless they are told otherwise and clearly. It should be entirely up to you in your own assessments; just make sure they know what is expected of them, especially on national or statewide exams. There are times when it is necessary to contrive a question's data in order to prefer the use of 10 over 9.8, just make sure you tell them to "…use g = 10 m/s^2." In these circumstances, we are trying to convey some salient point not correlated to an exact value, or to express a "back-of-the-napkin" type of calculation or solution that only physicists enjoy doing. (Here come the letters…)

At one point in the original 9.8 vs 10 debate somebody, I believe it was a teacher in fact, wrote that it was important to use 9.8 instead of 10 because students needed to be accurate. "Imagine if they were designing a bridge…" the argument went "…would we not want that bridge to be sound, safe and sturdy? That could not happen without using the acceleration due to gravity as 9.8." Let me be totally candid here, if you're getting your students to design real bridges where real people like myself are to drive across, then please tell me where you live so I can avoid driving there. Give me a break. The majority of physics problems are composed of numbers used to elicit skills, not specific values.

Hark back to the example and notice that nowhere had I mentioned the situation was to take place on earth. What if it took place on the moon? Has anything of consequence changed at all? No. In fact regardless of whether you use 9.8, 10 or even 1.6 m/s^2 (for the moon) the question's solution is exactly the same. Exactly the same! And that's what teaching physics is all about – solving problems, not solving that problem. Indeed, it is still the same question if it had said: "An object is rolled up an inclined ramp at 25 m/s. Calculate the time it takes to be going 5.0 m/s downwards if the acceleration down the ramp was 1.6 m/s^2." Same, same, same! It's critical to appreciate that it is our obligation, nay compulsion, to teach the techniques for finding the solutions to problems, not to teach the answers to problems.

Lazy Physics

When learning complex topics like physics, it is comforting for students to resort to short-handed or incorrect statements when speaking and writing. (Does the phrase quantum leap come to mind?) Likewise when teaching, it is very easy for us to permit them the leeway to be lazy; however, in regards to the acceleration due to gravity, we should give no ground. By "give no ground" I speak with respect to the use of the term "gravity" alone instead of the phrase "acceleration due to gravity."

9.8 m/s^2 is not gravity!

It's the acceleration due to gravity. Due to gravity. Due. Due to gravity!

This book may not be the best avenue to make sure you understand that (not-so-subtle) difference of fundamental physics, though I would hope you already know the difference between gravity and the acceleration due to gravity. If you don't, then drop this book and run scared. Accept no laziness in your class, by you or by them. You have to set the example here.

There is one other element of lazy physics to address before ending this chapter, and that too deals with the poor use of a word. In my class it is called it the d-word: deceleration.

You, every physicist and I know the gravity (pardon the pun) behind the word deceleration. We know that the use of the word deceleration implies a certain frame of reference from which we can interpret that a deceleration implies a negative acceleration. So far so good you might be thinking, but for students they interpret a deceleration as a property that can only decrease the velocity of an object…and that is patently incorrect. Who can blame them really, if you look at the vast majority of questions involving accelerations, they involve increases in velocity; but a negative acceleration can increase or decrease the velocity of an object depending on the direction of motion of the object and the direction of the negative acceleration. How does nature know to use a deceleration when an object is thrown upwards, but switch to an acceleration when the object stops and then begins to fall downwards? Does nature know that the object is "at the top" and that now it's time to switch? Obviously, it does not.

There is one acceleration with one value all the way throughout the entire motion of the object. It may be negative, but it is negative everywhere and all of the time. You already knew that; but they will not. This physical detail highlights a fine line within teaching: it's about teaching students something they don't know, it's not about teaching them something you know. Certainly there is a complementary relationship between these concepts, but good teaching is focused on the former while being dependent on the latter.

11

Better than Galileo

It may not come as much of a surprise to you, but on occasion, there has been a little friction between myself and some of my colleagues regarding how to teach physics. Accepting that I may have at times come on too strongly in my defense of what I purport to be good and right about my techniques, I have never met another physics teacher with whom I have not had the pleasure to teach alongside. There have been times when I have stepped on toes, trodden into another's territory, and tested someone's patience with me. Sometimes I have committed all of these crimes to one and the same person. I have disagreed with their teaching styles and their pedagogy, but never with their intentions, their abilities or their passion for teaching physics. As with every other discipline we have shared our common interest, passion, and (yes) culture with thousands of students. We have watched many of the same television shows, read many of the same books, and continue to marvel at the same obscure observations and quirks of nature that others pass merrily by. Save and except my family, I am probably happiest when I am in the company of my colleagues; however; there is one last poke in the eye to deliver… A last jab dealing with one specific issue: the Galilean equations of motion.

There are two significant, along with two minor, issues to focus our attention, each of which involves the way the equations are written and therefore the way they are taught and used. To be as concise as possible the equations at hand are laid out in the table showing them as they are commonly written and taught, and as I write and teach them.

Table 1: The Galilean Equations of Motion

The common way	My way
$v = \frac{x}{t}$	$\vec{v} = \frac{\Delta\vec{x}}{\Delta t}$
$a = \frac{v_2 - v_1}{t}$	$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t}$
$x = \frac{v_1 + v_2}{2} t$	$\Delta\vec{x} = \frac{\vec{v}_1 + \vec{v}_2}{2} \Delta t$
$x = v_1 t + \frac{1}{2} a t^2$	$\Delta\vec{x} = \vec{v}_1 \Delta t + \frac{1}{2} \vec{a} \Delta t^2$
$x = v_2 t - \frac{1}{2} a t^2$	$\Delta\vec{x} = \vec{v}_2 \Delta t - \frac{1}{2} \vec{a} \Delta t^2$
$v_2^2 = v_1^2 + 2ax$	$\vec{v}_2^{\,2} = \vec{v}_1^{\,2} + 2\vec{a}\Delta\vec{x}$

The two critical items to observe are:

1) the use of vectors and the vector symbol on each of the terms (except for t), and

2) the use of the "delta" term Δ.

I believe it is "bad" teaching to write these equations without using both vectors and Δ, and why that is so, is the focus of this chapter. I am not alone in my disdain for the lazy form of these equations[1], but fear those who agree with me fully are a dying breed, or at least a retiring breed. In all fairness, some teachers write the equations as vectors but without the delta symbol; others use the delta symbol but without the vectors, while still others use neither. For the proper teaching physics you need to use both all of the time. (There is a proviso to this statement in the next chapter.)

The two minor issues involve the use of x or d or s to represent the displacement; and whether to use v_1 and v_2 compared to u or v to represent velocities. Let us consider these latter two minor issues of displacement and velocity first.

[1] When I set out to write this book I strove to write as much of it from my own experiences and practice; however, I wish to recommend a particularly superb book: Arons, Arnold B. Teaching Introductory Physics, Part I (John Wiley and Sons Inc., New York, 1997). This tome of a book is the most complete and well presented archive of what every physics teacher should know before entering the classroom, at least as far as the academic side is concerned. Arons does a far better job at justifying much of what I have argued for in this chapter. Buy the book. If you are not convinced with my arguments, then Arons certainly will convince you. In actual fact, I am just putting my own personal spin on his far more admirable work.

I use the term displacement exclusively with regards to kinematics and dynamics topics, and before doing so there certainly would have been a proper introduction into the differences between distance and displacement, along the "why" and "when" those differences matter. From that point onward the use of the word distance is set aside for other topics such as waves and light. Though I guess you could argue for the use of displacement there too, and you would be right, it is just a word after all is said and done.

First, it is of no consequence which letter is used to represent the displacement. It matters little to students whether you use x, d, or s, just be ready to explain how the letter x or s can represent a displacement; but as with other similar issues of labeling it is important they know what to expect from you and that you be entirely consistent throughout the course. My personal use of x is but an artifact of my educational past, although its use is far more universal than that of the other two letters. Having said that, being able to recognize an equation by its identity, regardless of whether it uses x, d, or s, is a valuable skill all students should learn. In other words, recognizing that:

$$\Delta\vec{x} = \vec{v}_1\Delta t + \tfrac{1}{2}\vec{a}\Delta t^2$$

or

$$\Delta\vec{s} = \vec{v}_1\Delta t + \tfrac{1}{2}\vec{a}\Delta t^2$$

or

$$\Delta\vec{d} = \vec{v}_1\Delta t + \tfrac{1}{2}\vec{a}\Delta t^2$$

are all the same equation is as important as recognizing what the equation itself allows us to find. It is the same as recognizing that $P = Qr^2$ is no less the relationship between mass and energy than $E = mc^2$ is, as long as P represents the energy, q the mass, and r the speed of light in all of the appropriate units. In some regards it makes ample sense to use letters that have some literal relevance to the terms described (E for energy, m for mass, etc…) but there are only twenty-six letters in the English alphabet and far more than twenty-six terms and constants in nature so there would have to be overlap; however, this technicality on the irrelevant use of letters should not translate over to the use of letters when teaching about velocities.

It is difficult for adults, even those of us who have learned and loved physics, to recall just what an onslaught of equations, terms, definitions and ideas senior physics can be to an adolescent. I see no reason to complicate this already difficult process by requiring them to learn the difference between u and v when it would be just as easy to teach the use of v_1 and v_2 (or v_i and v_f) to represent the initial and final velocities. Just look at them, they make such good sense. The 1 or i meaning first or initial, and the 2 or f for the second or final – how much more simply can you write it so that students comprehend it? Whether to use v_1 and v_2 compared to u and v to represent the initial and final velocities, respectively, remains a deeply ingrained and personal distinction for every physics teacher. I was taught with u and v but then quickly switched over to v_1 and v_2 after seeing the glaze form over my student's eyes upon starting to teach. These are adolescents we are talking about and they need all the help we can give them; if hormones were flammable, then spontaneous combustion would be as real as the pimples on their faces. Do not lose sight of the fact that you are there to teach physics, not just talk physics. If in the end they do not understand the terms involved then in a sense we have failed them – so we need to adjust what how we teach.

Vectors and Δ

To make my case for utilizing both vectors and the Δ symbol when working with the Galilean equations I make but one simple statement: by not using them you are teaching incorrect physics, or to put it more bluntly: "the equations are wrong."

Let's look at another equation for a start; the one relating the mass, speed and kinetic energy of an object:

$$E_k = \frac{mv^2}{2}$$

where the mass is m (in kg), the speed is v (in m/s) and the kinetic energy is E_k (in J), each of these variables is a single instantaneous quantity. That equation relates those terms at any and all instants in time. The time may in fact last for hours or days if none of the terms changes, and therefore the value itself (in this case E_k) is the instantaneous value at each and every instant. That is not the situation for the Galilean equations of motion.

The previous chapter had an example with an object being tossed upwards at 25 m/s, then falling at 5 m/s downwards 3.0 s later; but which three seconds? Well…any three seconds as long as they were the three seconds that followed the instant after the object was tossed upwards at 25 m/s. The time answer of (3.0 seconds) would be the same if you lined up a hundred students each of whom tossed an object upwards at 25 m/s at some pre-determined time successively following their neighbour's toss. It could also be done at anytime, and anywhere (as long as $g = 10\ m/s^2$). It is the interval of time that matters not the instant of time itself. The object changed its motion from 25 m/s upwards to 5 m/s downwards over a time interval of 3.0 s – not at the 3.0 s instant of time. There is nothing significant to the 3.0 s of time except in its relation to these initial conditions.

Everything in that question is about a series of events that occurred over a period of time, it had a start time and a finish time, and the interval will always span 3.0 s. The scenario is about a series of events over a time of three seconds, not about something happening at an instant of time, namely at 3.0 seconds. There is no universal clock of time, and therefore there is nothing absolute about the terms in the Galilean equations except that they all relate to values spanning events over time.

I would be prepared to give some ground on the use of Δ, but only if one repeatedly explains and uses the phrases "over the time interval" or "across that displacement" or some other set of similar statements; but being that diligent over the term of a whole course is much easier said than done. By not using the Δ symbol properly, or by neglecting to teach that those equations describe events over time, one cannot expect to prepare students for solving some of the more difficult kinematics questions they will be expected to face. Finally, by using the Δ symbol we permit a much easier flow-on through to the future use of calculus in physics.

Finally, the vectors… Unless you are going to contrive every single kinematics question into being a one-dimensional, non-backtracking[2] type of problem, there is absolutely no way that any of the Galilean equations written vector-less could be used properly. Actually, if you are going to contrive every single kinematics question to be a one-dimensional, non-backtracking type of problem, then what is the point of teaching kinematics anyway? Those are the best kind of questions! The ones that are the most fun to solve, with the most revealing physics buried deep within them. So if you are going to do them, then do them properly.

And how will you treat accelerations? How can one teach the concept of acceleration accurately without the use of vectors? Simply put it is not possible and well as being patently incorrect; all accelerations involve forces and all forces are vectors. There is no proper way to solve questions using the equation:

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t}$$

unless you contrive all of the problems – again, what's the point then?

Look at the equation:

$$\Delta\vec{x} = \vec{v}_1\Delta t + \tfrac{1}{2}\vec{a}\Delta t^2$$

The terms are what they are, and where they are (mathematically) for all of the correct and proper physical reasons. In other words the "+" sign in front of the $\frac{1}{2}\vec{a}\Delta t^2$ is there because that entire term is to be added, summed, to the $\vec{v}_1\Delta t$ previous term; but not because the acceleration is positive. The plus sign and the acceleration vector are not mutually related; they are independent of each other and must remain so.

In some instances to help out struggling students I suggest they replace variables with spaced brackets that they then fill in with the values found in the Given stage of GRASP. The above equation might then get written in the next step as:

$$(\_\_) = (\_\_) \cdot (\_\_) + \tfrac{1}{2}(\_\_) \cdot (\_\_)^2$$

whereby the student then "fills in" the spaces with the values given. In this respect it is sometimes easier for them to visualize that the "plus" sign is not attached to the acceleration and if the acceleration was negative the sign in front remains a "+" until they get to the Analysis stage where they begin solving the mathematics.

To explain it another way, consider an example from dynamics. When dealing with questions involving the Net (or Resultant) force, students will invariably have to write an equation resembling:

$$\vec{F}_{Net} = \vec{F}_{applied} + \vec{F}_f$$

Ignoring the specifics of the equation for now, if the question required the solution for the applied force $\vec{F}_{applied}$ you will discover, far more often than your patience will allow, that many students will transpose the terms and simultaneously substitute vector values all in one step. For example, if the friction term $\vec{F}_f$ was negative, as it often is, students will incorrectly write:

$$F_{\mathrm{applied}} = F_{\mathrm{Net}} + F_{\mathrm{f}}$$

having substituted the "-" with a "+" and then transposing the terms. That will be a recurring and difficult habit to overcome on their part; however, it is one you must overcome through the proper use of vectors.

Let me add one final cause for insisting on using the vector symbols in all of these kinematics equations. Imagine a projectile motion question where an object has both horizontal motion (Left – Right) as well as vertical motion (Up – Down). The best way to solve these questions is to separate the problem into two one-dimensional problems with time-of-flight being the only common variable in each dimension. Inevitably, students will mix terms from one dimension (say Left-Right) into the other (Down) when solving the equations. As a self-correcting method to verifying their mathematics, if they were using each equation in its vector form, AND carrying the vector directions through each line of the calculation (or at least in the first line), then they would be able to check if they are at least remotely correct in their mathematics. How?

There is no way (in senior physics) that any of those quantities should have vectors of mixed direction within them. Therefore in a projectile motion question, a line that looks like:

$$\Delta\vec{x} = (12\,\tfrac{m}{s}[Right]) \cdot (4.5s) + \tfrac{1}{2}(9.8\,\tfrac{m}{s^2}[Down]) \cdot (4.5s)^2$$

should never exist because there is a [Right] term 12 m/s [Right] mixed with a [Down] term 9.8 m/ s^2[Down]. This short method of checking for errors holds true for each of the kinematics equations. It is a great way for students to learn a self-checking process while solving physics problems. Every little bit helps them, so why not teach it.

You need to set a high quality standard throughout your course, your notes, and your board work. If you are consistent with the proper way to write these equations, most students will follow suit, they are more than capable of doing so. Show you believe in them by not holding back.

12

The Open Agenda

"It is, in fact, nothing short of a miracle that the modern methods of instruction have not yet entirely strangled the holy curiosity of inquiry." Albert Einstein.

Einstein was not the only one to recognize the need for restructuring the (then) modern methods of physics instruction. The entire physics community pulled together during the Sixties and Seventies by targeting their efforts, such as improving textbooks, to transform what was a mostly intellectual pursuit into today's richly dynamic physics courses. We have, however, reached new level of mediocrity requiring an equally targeted and sustained effort of reformation. In short, I am terribly displeased with what passes as physics curriculum. In some respects I am talking about the syllabus, i.e. the topics we teach in our physics classes; however, there is more to this essay than just the topics. It is about the direction and aim of what should be expected over the course of teaching physics. For that reason I prefer to call this a curriculum, even though the word syllabus appears from time to time.[1]

That displeasure with the curriculum should not imply a belief that today's curriculum is somehow wrong or even ineffectual; just that it has removed the thrill of inquiry from an otherwise well intentioned prospect. Actually if you really want the truth, physics education has been neutered,

[1]This is a revised essay that originally appeared in Australian Physics September/October 2006 Volume 43 Number 4. A Publication of the Australian Institute of Physics.

come to think of it so has most of science. (I say most only because teachers of the other disciplines need to speak for themselves, but I suspect many would agree.)

Einstein's concern has been so well addressed that today's secondary school physics syllabus has become misguided in its singularly minded approach in demonstrating that physics has relevance… to students. The prevailing educational mantra (coming from mostly outside of physics) is, to put it simply, that if physics cannot be shown to be immediately applicable to adolescents then it has no value to them. The curricular focus has been on making each individual topic and concept instantly pertinent to students rather than on showing that how we do and learn physics is more essential than the application of physics. Therefore, in our great drive to make physics relevant we have in fact castrated its innate essence – we have moved away from Einstein's observation.

To be fair, physics has stood its ground and remains one of the most content-rich subjects in spite of an educational shift towards activity-based pedagogy. Activity-based pedagogy rests on the premise that (any) physical activity in the classroom be the primary avenue for student engagement in the scientific process; unfortunately this narrow focus on "hands-on" activity has diminished the true nature of physics (and of science in general). The relevance to students of the practicality of physics is not to be understated for enhancing student learning; but neither should it be the primary narrative in that engagement. It is beyond me why any of the historical, practical, locally relevant or topical aspects of physics needs to be codified into a curriculum document thereby forcing it to be taught explicitly – if you are not raising these issues on a regular basis, then find the time to do so; but not as a project, or special day out. These need to be part of the conversation that is teaching; they need to "come up" not as contrived talking points, but as captivating asides. "By the way did you know…?" (More on this later in the essay).

There is a huge public appetite for the kind of physics that is not immediately applicable, especially for some of the more pure elements like cosmology or particle physics. The highly positive attention shown for the 2005 International Year of Physics, the terrific audience support of deeply physics-based television programs such as Brian Green's Elegant Universe, or the media hype behind the Large Hadron Collider have shown that physics can be fashionable and media savvy. Although we should be loath to cater our courses to passing fads, as is the educational way, we need to take advantage of these sporadic peaks of interest – and you need to take advantage of them when they happen in and around your community. To act on this opportunity, physics teaching needs a new narrative, a curriculum with an open agenda of teaching how physics succeeds in discovery and progresses through defeat and contradiction. A physics curriculum focused on scientific inquiry, not on engineering skills.

The Open Agenda

It is easy to characterize a scientific experiment as an activity designed to collect data based upon some stated hypothesis; but that begs the question: what was the origin of the hypothesis itself? Did a scientist awake some morning to randomly make a hypothesis; arrange the necessary equipment and then conduct an experiment for some casual purpose? Clearly we know that is not true, unfortunately students seem to think this is indeed how it happened, and still happens.

Prior to the hypothesis behind an experiment there was a known departure point of ignorance within, or surrounding, an accepted theory requiring a specific refinement, or a recognized state of discord between two competing theories requiring a resolution. This latter condition, the one of conflict resolution between theories, should become the primary narrative of physics teaching. This “open agenda” syllabus, as I shall call it, should encompass much more than problem solving; it should aim to emphasize a process-centred approach to the identification and resolution of scientific conflict.

A process-centred approach should not be confused with a student-centred outcomes based approach – that method drives me up around the bend. The process at hand here is that of learning to do physics not the process of how a student learns to do physics. This is not to be indifferent to the wide variety of ways our students learn. There have been great advances in cognitive and meta-cognitive psychology destined to improve the methodology of physics teaching and these developments are not to be dismissed. Indeed we need more empirically based direction in teaching research, not less. In case there is any confusion, or accusations of fence sitting,

All courses should be taught with the intent of turning students into masters of that discipline. I want my son to be taught English by a teacher with passion that pours from her skin in the hope of turning him into a great writer; a music teacher with the gumption to drive my son to becoming a virtuoso; and science teachers who want to feed the promise of a great (future) scientist. I teach with that passion and direction. So should you.

The open agenda methodology requires no new teaching techniques, special equipment or Professional Development days. It is simply a new pedagogical focus to the overall aim of teaching physics. It approaches an entire Grade 12 course with a clear and ordered (i.e. open) agenda so that a single narrative runs through the course. The chosen physics topics are necessary and crucial elements to the teaching of that agenda; but it is the order of the topics presented via the over arching and prevalent theme running through the course that is itself the agenda.

The Syllabus

How would this open agenda unfold? Here is one version of a proposed syllabus in its order of study; "one version" because I accept that there may be other possible sets of topics that succeed in the same overall goal. I hope to hear from other physics teachers on this matter and look forward to their examples. There is little point in itemizing every topic's list of details since you and I are physicists, but the major points that should be covered within each one are addressed.

1. Uniform Motion. Begin with a brief introduction into critical thinking and the foundations of scientific theories (My starting point is the use of Michael Shermer's Baloney Detection Kit[2]). This is to spotlight the agenda for the remaining course, then using that focus to get directly into the physics content. Develop a robust description of measuring time intervals; analyzing position and displacement by emphasizing their necessary vector and "change in" (Dx) nature (as noted in the previous chapter); graphical and algebraic aspects of uniform motion; measuring the length of (relatively slow) moving objects; kinetic energy and momentum (without a study of collisions); how and why we need to use frames of reference; finally closing with an in-depth study of relative motion in one and two dimensions. Note: no accelerated motion.

2. The Nature of Light. Develop the theoretical and experimental framework on the nature of light tracing its history from the particle model to the wave model; the Doppler Effect; Young's experiments; diffraction; and polarization. Ending with the conflict statement: If light is a wave, then it should behave like other waves…so what is it waving in and why can we not discover that material? This mode of questioning carries on with the open agenda goal – we have discovered a conflict, how can/has physics resolve(d) it?

3. Electromagnetism. Experimentally and qualitatively reviewing the multiple connections between electrostatics and magnetism (fields, force rules, charges/poles, and materials); delving deeply into the theoretical implications of Oersted, Coulomb, Faraday, Hertz, Ampere, etc… detailing the empirical account of Maxwell's equations (without the calculus) along with the necessary symmetry of the displacement current. Another conflict now arises between two physical foundations: the mechanical (frame of reference) method for measuring the speed of light (see #1) and the electromagnetic method without the need for a frame of reference. How can/will/did physics reconcile this conflict between Galilean mechanics and Maxwell's electrodynamics?

4. Special Relativity. First, a highly qualitatively description of how special relativity resolves the conflict between the mechanical and electromagnetic effects of motion; historical elements; then a

---

[2] Shermer, Michael and Pat Linse, The Baloney Detection Kit (The Skeptic Society, Altadena, California, 2001), p. 3.

quantitative analysis of the relativistic equations for time, length, mass and energy; laying out the supporting evidence of special relativity spiraling back over the previous content to reinforce how physics arrived at this point via the resolution to a variety of scientific conflicts.

What about changes in uniform motion?

5. Non-uniform motion. Graphically and algebraically defining acceleration; its necessary vector nature; its fundamental distinction from velocity; acceleration due to gravity and Galileo's analytical achievements; free fall; simple projectile motion; inertial and non-inertial frames of reference (in a non-dynamic manner); acceleration's independence on a frame of reference; and circular motion.

6. Forces. Defining force more as a function of Newton's First Law than as pushes or pulls; free-body-diagrams; defining mass; Newton's other two laws; defining inertial and non-inertial frames of reference with respect to forces; re-visiting kinetic energy and momentum, but now with a focus on collisions; the natural forces and why we quest for their unification. Ending with a qualitative discussion on the conflict between gravity and how we define forces? Why can you not feel gravity when it is the only force acting on you?

7. Gravitation. Introduction to local and universal gravity; free-fall, weight and weightlessness in gravitational terms; astronomical studies using gravitation; gravitational potential energy and escape velocity; Kepler's laws. Ending the unit with an analysis of the conflict between Newtonian gravitation and special relativity. "How fast does gravity travel?"

8. General Relativity and Cosmology[3]. In qualitative terms explain how general relativity has overcome the conflict between Newtonian gravitation and special relativity; its geometric and observational predictions, verification; its operational description of gravity; (some of) the mathematics of space-time using simple geometry; advances in observational astronomy. As with special relativity, this treatment of general relativity allows for a complete spiraling back over the entire content tieing up loose ends – closing the open agenda and finishing the narrative.

Introducing general relativity into secondary education is not such an outlandish idea; it was little more than a generation ago that special relativity and quantum physics were not part of the regular high school physics program, and yet now they are staples of it.

This syllabus still leaves ample opportunity for productive and quantitative problem solving through an activity-rich program of study, i.e. you can still do plenty of experiments to keep your students busy. We should expect nothing less of a strong physics course.

[3] Bergmann, Peter G,. The Riddle of Gravity. Charles Scribner's Sons. New York 1968

On another stream, the open agenda is not a history course; this is all about physics, not the history of physics. Any teacher worth her pay would introduce historical elements into a good classroom discussion, but always with the direction to teaching the physics content. I cannot imagine teaching universal gravitation without including vital biographical information about Newton; but I am not teaching Newton's biography, it is about teaching how Newton developed his ideas from his experiences and strengths. The same holds in virtually every topic in physics.

Nevertheless, there are countless curricula in dozens of jurisdictions requiring historical aspects of physics be taught – and that is good, except for the fact that many teachers and administrators interpret this as some need to impose upon students "projects" designed to incorporate biographies of famous scientists. That may be fine in earlier grades, but not in Grade 12.

What about Grade 11?

A Grade 11 course of study should introduce students to the fundamentals of physics with its primary focus on the essential tools of experimentation, the concepts of physical laws and scientific theories, the algebraic manipulation of equations married with problem solving skills, and the multiple applications of physics in our daily lives. In short it should be a preparatory "physics is fun" syllabus that could stand alone if necessary.

To be specific, the topics should be chosen from: geometric optics, sound and waves, electricity and magnetism, bodies in equilibrium, thermal physics (a neglected topic in my opinion), fluids, and nuclear and atomic physics, and maybe some astronomy. You may notice a pair of commonly taught physics topics missing from this list: kinematics and dynamics. It is not a misprint, as I would argue for the complete elimination of kinematics/dynamics prior to Grade 12 – yes you read that correctly: no kinematics or dynamics in Grade 11 physics. The true nature of kinematics or dynamics is both too subtle and too complex an idea for most Grade 11 students to grasp, and requires more than the cursory study it presently merits at the earlier grades including Grade 11.

Furthermore, it can be the greatest turn-off to students first setting out while learning physics. True, many students can solve the assigned kinematics problems, and there are a great many fun physics questions to solve in kinematics, but these matters alone are not worth the lost opportunity that can arise when kinematics (and dynamics) is taught to Grade 12 students. There are far more interesting and experimentally rich topics from which to design a Grade 11 course.

Potential Setbacks

There are considerable difficulties to address before implementing this type of a narrative approach to the curriculum. First, trying to fit an appropriate quantum study into this framework has proven to be problematical, mostly in terms of course content and time restrictions. Without a decent quantum element covered in the overall course, trying to convince the greater physics community of its value may be a challenge; however, as Arons[4] points out for any suitably designed syllabus "…it is impossible to include all the conventional topics of introductory physics. One must leave gaps, however painful this may seem… The selected story line [read open agenda] would develop the necessary underpinnings and would leave out those topics not essential to understanding the climax." I agree, though painfully, and am looking forward to hearing from colleagues on how to incorporate quantum physics into this open agenda format - there is no compulsion on my part to keeping it out, I just haven't figured out how to fit it in.

Secondly, there is a distinct lack of secondary level texts written with this narrative in mind. Admittedly this dilemma stems from the fact that there is no commensurate state-sponsored curriculum with this narrative in mind, and therefore no author or publisher would be bothered producing a text that does not accompany a syllabus since there is no money in it. Who would buy it? Therefore brand new texts are required and that is an expensive proposition.

Thirdly, can we entrust the future, let alone the present, teacher cadre to deliver this more intensive syllabus? In Australia the Who's Teaching Science Report published for the Australian Council of Deans of Science cited similar problems of confidence. The report's authors state[5]: "Nearly 43 per cent of senior school physics teachers lacked a physics major, and one in four had not studied the subject beyond first-year. This, coupled together with the reported difficulties in attracting physics teachers (40 per cent of schools surveyed), paints an alarming picture. No matter how good their pedagogical skills, teachers who lack knowledge in their discipline are manifestly unprepared." Notwithstanding, we need to ensure that our teachers (that means you) "fit" the syllabus, not to fit the syllabus to our available teacher cadre. Most people, especially young children, share our innate sense of curiosity with science; however, only those who can instill a cause and purpose behind that curiosity should venture into the world of education.

Teaching physics solely as a technical tool rather than as an intellectual adventure is a dead weight proposition; our constant reliance on practical aspects (i.e. real-world relevance) has diminished the educational promise of all of the sciences. As good as any one syllabus is in specifics, we have become complacent with its overall goal. Just as the physics community addressed Einstein's concern generations ago, we need to re-visit that concern now.

---

[4] Arons, Arnold B, Teaching Introductory Physics, Part I (John Wiley and Sons Inc., New York, 1997), p. 265.
[5] Harris, Kerri-Lee et al. Who's Teaching Science: A Report Prepared for the Australian Council of Deans of Science, (Centre of Higher Education University of Melbourne, Melbourne, 2005), p. 9.

In closing

Except for my hopes of being a loving father and husband, teaching physics defines me – it is the only identity that truly matters to me and as a result I can be a reckless advocate for my brand of physics education. That recklessness has led me to the realization, nay the revelation, that "going with the flow" within the educational community is of no personal or professional use to me. Consider it this way, when you "go with the flow" inevitably you end up in an ocean: one-among millions, small and unheard. That is not my teaching style.

Hopefully you will adopt much of the advice herein while planning your lessons and developing your courses, though I am sensible enough to know you will be dismissive of some of the guidance. Preferably the former will outnumber the latter. Nevertheless, there should have been something within these pages for everyone to agree upon, or at least to start talking about.

This has been an (almost) exhaustive retrospective regarding those fundamental elements of physics essential for you to know before, and while, you teach the content. Some teachers will disagree with much of what has been written, likely countering that it has gone too far or that it is not necessary to be "that tough" while teaching. I would disagree, but then again teaching can be an enormously personal affair. It is hoped that most of my colleagues will find that I have not gone far enough, and I trust to hear from them in this regard.

With respect to the content of physics, something that has been avoided, here too there are many concepts that could have, or should have, been expanded upon. For example, though it is difficult to teach the finesse method for answering questions, it is not impossible. A future edition (maybe a part II?) of this book may cover some specific topics in physics and the techniques (finesse or otherwise) for teaching them. You will need to be heavily acquainted with having already tried to teach that detailed subject matter, or those particular equations and models before that can happen. Remember, knowing the content should not be confused with teaching the content. So take advantage of what and who are around you early on in your career. I was blessed with some very strong willed and experienced Department Heads when I began teaching. Their assistance and influence has stayed with me to this day. There are thousands of resources available to you; most of them are human (i.e. your colleagues). Find them to harvest their ideas and experience.

Until then, you will have to stumble, stutter, stare blindly and learn to do adapt many of the ideas mentioned here for yourself and for your students; you are both on an intellectual maturity curve: they are mastering the learning process, you are mastering the teaching process and when those tracks meet the feeling is mutually rewarding. Just as you might suggest they "step back and pause" when stumped with a question, you might need to do likewise when stumped with an explanation. I have often told my students that I too had to stop on a test or exam, write RELAX at the top of the page, put my head down, and zone out for a moment or two; although that is probably not a good idea to do in class I think you get the picture: you (and they) need patience.

Most first-year teachers will arrive to class under enormous stress. Converting that stress into the "butterflies" of nervous anticipation takes you well on your way to being a successful physics teacher. May those butterflies never leave you; they are the impetus that ensures we say, do and cover all of the material needed to teach, inspire and thrill with passion. So chill. Some teachers will grasp teaching a field as difficult as physics without the need for diligence, practice and focus. I was not one of them and I suspect neither are you. This book is a guide for teachers like us.

And lastly, this book is by no means meant to be a textbook for you or for your students. There is nothing in here that should take more than a part of a lesson to teach but once. These past chapters are not lessons plans in and of themselves, but nuggets of knowledge (memes if you will) to be carried throughout a course, highlighted within lessons and used regularly as the means by which the transfer of ideas, the content of physics, is conducted. Make no mistake about it though, in physics content is king, and my aspirations are that that content be taught via the narrative referred to in the final chapter The Open Agenda – through the magnificent story of nature that is the grandeur of physics, never as the rote memorization of facts or equations.

The physics community is a wondrous thing, but it is not a closed entity. This book is but a small overture into some of the bits and pieces of our culture of (teaching and learning) physics. Practice, adapt and implement the suggestions regularly. Re-visit the ideas presented as often as you need, remembering that the more often you do so early on in your career, the less often you will need to do so later as they become a part of your routine, of your identity. The next stage of your cultural immersion begins when you no longer need this book, when you just know all of those things that everybody knows…that everybody knows.