Some Pillars of Physics Wisdom (A physics education research primer)

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There are many physics textbooks around full of explanations, examples and questions that you can use with classes and I'll leave you to find your favourite (*Note: my favourite physics textbook for explanations remains Paul Hewitt's Conceptual Physics. Its associated video highlight reel can be found here http://www.hewittdrewit.com/title_list.htm)*. The aim of this document is to highlight some books and papers that provide a deeper look at some of the challenges involved teaching physics and hopefully help you find your own path(s) through these. This is not always easy, and my view is that there is not a 'right' way to teach pretty much anything that can be offered without consideration for the context and a whole collection of other things. However, time and effort have been spent looking at what challenges students have in learning some parts of physics and the evaluation of some strategies and approaches. As such, a good starting point when trying to find that 'right' way for you and you class might be this body of work.

The aim of this document is to provide a starting point for where to look and to draw out some personal highlights from these readings. It focuses mainly on books although I do include some academic research papers. This bias towards books is partly an efficiency measure in that the author of the book has done a fair bit of the filtering for you. Books are often easier and cheaper (in most cases) to get hold of rather than academic research papers. In all cases, I'd suggest that these can be considered research informed with a foundation in educational research rather than the unsupported views of a single author.

In each case, I'll give you some details about the book or paper and the approach it takes as well as highlighting some interesting or notable messages. When doing so, I'll try and reproduce or summarise them in some form so that this document is useful itself. Please remember that the book or paper will have more detail and context so tread carefully if you don't plan to go beyond this document. I have chosen to take a positive approach and do not offer a critique or what I might think are difficulties/challenges or weaknesses in any book. I'm happy to have those conversations in person or by email (jad26@cam.ac.uk) if you want but will leave you to start them…

They are not presented in any hierarchical order and the amount of text for each is not necessarily relayed to its value! Many of these are more relevant for those teaching older students (16-18) however if you get your understanding of these concepts really sorted higher up then I'd hope that this would have an inevitably positive impact on what you say and do with younger students.

Five Easy Lessons – Randall Knight (book)

This book unusual in that it attempts to provide a synthesis of some of the research work done on student's alternative conceptions and challenges as well as providing some specific classroom advice for approaches to take. It feels like a book those teaching 16-18 yr. olds and in terms of content, but the overarching messages are applicable for teaching you younger students. Some chapters go beyond most causes taught to 16-18 yr. olds, but chapters 5-8, 10-11, 14-19 are the best to start with as they address the most common school-based content.

Part I of the book **Teaching Introductory Physics** is an overview of some of the main messages that have emerged physics education research leading into his 'five easy lessons' which he suggests that you should consider and try to respond to in your teaching. Knight points you to some well-chosen further reading as well as some honest and supportive commentary for those wanting to shift their teaching.

Part II (most of the book) **Topics in Introductory Physics** is split into topic-based chapters all follow the same format. These cover all the expected parts of classical physics although it does progress to quantum physics at the end. Each chapter begins with a **background information** section which draws out messages from physics education research in particular topics. Knight then identifies what he sees are some key learning objectives for students in this area and moves on to a **pedagogical approach** section that make suggestions for what you might do in class, strategies you might adopt and some questions you might want to ask.

Why this is worth reading: When reading academic research papers on education (physics or otherwise), there can be an interest and pleasure in developing a fuller understanding of the questions raised but often there can be a lingering *"so what?"* question that arises. It may well be interesting to understand how students may find it challenging to conceptualise the microscopic behaviour of electrons in a field, but you may also think *"great, but what I do with my Yr10 class when we do parallel circuits?".* This book gives you a brief review of the literature and gives you some answers to those *"so what?"* questions. It's relatively easy to see the links between the two and so as well as the specific suggestions but there is a potential extra level of empowerment that this opens up. As you become more confident as a teacher you should feel able to potentially disagree with Knight and come up with your own alternative classroom approaches that still address the learning challenges but adapted for you and your own classes.

Highlights:

A) The five easy lessons themselves are well worth considering. A deeper meaning can be lost in aphorisms but they can be easier to deal with and respond to on a daily basis. It may seem obvious but it can help to be reminded of the obvious sometimes. Be brave and put them up in your classroom for the students to see or just on a note behind the desk or in the planner.

1. Keep students actively engaged and provide rapid feedback
2. Focus on phenomena rather than abstraction
3. Deal explicitly with students alternative conceptions
4. Teach and use explicitly problem-solving skills and strategies
5. Write homework and exam problems that go beyond symbol manipulation to engage students with qualitative and conceptual analysis of physical phenomena

B) The chapter on motion and kinematics (6) covers some well-trodden ground with respect to student's ideas about motion but also draws in some work on graphs and the challenges students may have. In summary:

Challenges with graphs

- Many don't know what 'Graph **a**-versus-**b**' means. Often **a** goes on horizontal and so graph is reversed
- Many think that the slope is **y/x** and not **Δy/Δx**
- The 'slope at a point' is a difficult idea. Comparing between various slopes can be problematic
- The area under graph and slope have units
- 45° slope does not necessarily have a gradient =1
- The area under a curve can be difficult to measure and understand conceptually

Challenges with Motion Graphs

- It's hard to connect a dynamic process with a static graph
- Connecting and switching between x, v and a vs t graphs together is difficult
- Axis labelling is often incomplete or unclear
- In diagrams, we often draw and show changing position along a horizontal line and then plot it along a vertical one

Teaching Physics with the Physics Suite – Edward (Joe) Redish (book)

The first thing to say is that the title may be misleading, implying that this is an instruction manual for a bought set of resources. Well, in a way it is but the plug is saved until the last 20 pages. In my view, this is perhaps the single best book available for a teacher to read who wants to get an insight into teaching and learning in physics. Unlike Five Easy Pieces, this book does not deal with specific subject content related material and so for some teachers, this is a more abstracted book.

Reddish starts by providing a context for his own work (he is a very well-known and respected 'name' in physics education research in the US). Offering an edited highlight from the closing part of this chapter should hopefully give you a good summary of what is to follow.

> *In this book, my goal is to provide a guide for teachers of physics who are interested in implementing some of the best modern methods that have been developed as a result of the community's taking a scientific approach to figuring out how to teach physics.*
>
> *It is important to realize, however, that although excellent student-centered approaches to teaching physics have been developed, none of them are "plug-and-play." Student-centered instruction doesn't mean students are left on their own to do whatever they choose. These modern approaches require that instructors provide their students with substantial guidance and learn to work with their students in new ways. That requires that the instructor be reasonably well informed about the premises and methods that are being used.*

To me, this last sentence is key - if you want an easy fix or quick lesson then you can find them all over the internet. But, if you don't know how the car is made you'll be clueless as to what to do when it breaks down.

The chapters that follow look at cognitive principles, student expectations and experiences, homework and testing, evaluating teaching as well as a few chapters on different classroom approaches (lecture, experiment, inquiry). The book also comes with a CD that has a very large number of extra supporting resources – the most valuable being a selection of conceptual understanding tests (in the action research kit section) and homework problems although many of these are now available through PhysPort: https://www.physport.org/.

NOTE: It seems possible to get a copy of the manuscript of the book free, with the author's blessing, from this site: http://www2.physics.umd.edu/~redish/Book/

Why this is worth reading: When reading research around teaching and learning there is a danger that we can get drawn into a deep but relatively narrow field. This can be great if we want to get a full understanding of a particular idea such as how practical work can be most effective or theories of motivation but it can be easy to lose sight of the big picture, and feel able to answer the question *"how does this help me be a good/better physics teacher"*. For a research-informed book that doesn't drown in endless citation (but does have the references to look further if you want) that has some meaningful and realistic messages. You'll have to join the dots between this and the lesson plans but hopefully this will not be too arduous.

Highlights:

A) Chapter 2 **Cognitive Principles and Guidelines for Instruction** attempts (and in my view succeeds well) in trying to give a distillation of some of the work done on cognition and learning. At the risk of distilling a distillation and removing all context and meaning, below is a whirlwind tour of what Reddish calls his **Implications of the Cognitive Model for Instruction: Five Foothold Principles.**

The Constructivism Principle

- Individuals build their knowledge by making connections to existing knowledge; they use this knowledge by productively creating a response to the information they receive.

The Context Principle

- What people construct depends upon the context – including their mental states.

The Change Principle

- It is reasonably easy to learn something that matches or extends an existing scheme, but changing a well-established schema substantially is difficult
- It's hard to learn something that we don't almost already know
- Much of our learning is done by analogy
- Good examples are very important
- It is very difficult to change an established mental model

The Individuality Principle

Since each different individual constructs his or her own mental structures, different students have different mental responses and different approaches to learning. Any population of students will show significant variation in a large number of cognitive variables

- People learn differently.
- There is no unique answer to the question: What is the best way to teach a particular subject?
- Our own experiences may not be the best guide for what we should do with our classes.
- Students know themselves and what they know pretty well, perhaps we should ask them?

The Social Learning Principle

- For most individuals, learning is most effectively carried out via social interactions.

B) Chapter 5, **Evaluating our Instruction** may seem somewhat out of place in the narrative but is quite key, and an important part of the whole book. You'll know that having a good idea for teaching something in a certain way is the start of a process rather than an end in itself and where possible we should look to evaluate the effectiveness of what we do. This chapter talks through some well used and tested tools for capturing students understanding and attitudes. They are on the CD that comes with the book and even if there is some light cut and pasting you can quickly have some worthwhile tools to help you try and get some meaningful feedback when evaluating your own teaching.

Peer Instruction – Eric Mazur (book)

An even more misleading title and in some ways just a short essay on one teaching approach and a book of questions. Eric Mazur teaches Physics and Harvard and provides a strong case for reviewing how we teach. The argument he makes is that lecturing is problematic and not that successful and so we need to take an alternative approach. He proposes a peer instruction model that may be familiar if you've read about flipped classrooms. At the heart of what Mazur promotes is that we should take as much advantage as possible of student-to-student interaction in class and spend less time lecturing. He uses well-targeted questions that aim to address a single concept or ideas as a focus for the student interaction.

The first 40 pages of the book outline his approach, thinking and provide some data from his evaluation of its effectiveness. It's short and accessible and even if you don't change your whole approach it's a worthwhile read and has merit. The rest of the book consists of a very large bank of questions. Most of them match content taught to those over 16 but there are some good questions for students younger than that.

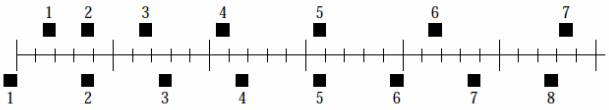
Why this is worth reading: In some ways, you can get the arguments from peer learning elsewhere but what is presented well is the whole story and his thinking behind it and as a process of professional reflection, change and evaluation of that. The course he is talking about is a US undergraduate course but this is applicable and achievable here.

Ultimately, buy this for the questions and I'd recommend you do so if you are teaching A level. The CD that comes with the book has them all in digital format and so even just as a timesaver exercise it's worth this. ***So, James, why include a book of questions on this list?*** To be honest, firstly because the questions are good and comprehensive in coverage but secondly the process that is explained in the book in terms of evaluation and analysis of the effectiveness is something feasible that you may wish to consider and replicate in your own classrooms.

Highlights:

For fun, I'll throw in a pair of questions from the tests

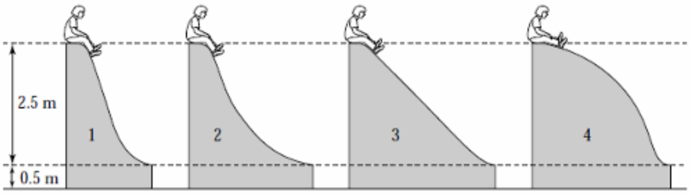
19. The positions of two blocks at successive 0.20-s time intervals are represented by the numbered squares in the following figure. The blocks are moving toward the right.



Do the blocks ever have the same speed?

___ 1. No.
___ 2. Yes, at instant 2.
___ 3. Yes, at instant 5.
___ 4. Yes, at instants 2 and 5.
___ 5. Yes, at some time during the interval 3 to 4.

10. A young girl wishes to select one of the *frictionless* playground slides illustrated below to give her the greatest possible speed when she reaches the bottom of the slide.



Which of the slides illustrated in the diagram above should she choose?

___ 1. Slide 1
___ 2. Slide 2
___ 3. Slide 3
___ 4. Slide 4
___ 5. It doesn't matter, her speed would be the same for each slide.

Note: There are smaller banks of this type of questions available for 11-16 yr. olds. The ESPE project from York has developed a selection here across some of the common topics taught to students aged 14-16 (forces/electricity and matter). These are a little tricky to track down these days but if you want copies please email me. The Best Evidence Science Teaching (BEST) project at the University of York is has developed and expanded these ideas considerably with a suite of questions and extra resources for 11-16 teaching, all available free from here:
https://www.stem.org.uk/secondary/resources/collections/science/best-evidence-science-teaching

A final warning: Writing these types of questions is harder than you think! Coming up with what I call the 'right wrong answer' is not an easy job.

Teaching Introductory Physics – Arnold Arons (book)

The 'big one' in more ways than one. My copy is 5cm thick and it costs around £100 and so perhaps not something that you'll go for straight away but you might track down a cheap copy or find a generous benefactor. As with some of the other books here, the original market was US undergraduates however many of the messages for teachers are worth listing to and there is very significant overlap with A-level specifications. Once inside, it turns out to be three books in one

Part I: A Guide to Teaching for Learning and Understanding

The main attraction in my view. A look at teaching and learning in the traditional core physics topics at A level (kinematics, dynamics, momentum, energy, electricity, waves, early modern physics [Bohr, Photos, Special Relativity]). There is a discussion on learning, the challenges students face and corresponding teaching approaches.

Part II: Homework and Test Questions

200 pages of often tricky question, no answers. The questions are good and tightly focused on single concepts where possible. To some extent, Mazur's book will provide sustenance here but you don't get part I. Broadly speaking these cover the topics in part I above but also included are some questions on *Scaling and Ratio Reasoning*.

Part III: Introduction to Classical Conservation Laws

Heavier going for some but a look at momentum, kinetic theory, thermal equilibrium. 'heat', and energy. Again with ideas and questions but moving towards the limits of most A-level courses and so not as relevant as Parts I and II are.

Why this is worth reading: For me, it is **Part I** that is the strongest section here. Within it is an enormous amount of insight and thought on the teaching of physics. Not quite a life's work but certainly more than a lifetime of wisdom than I think I'd ever be able to come up with. Some of it is a bit heavy going but worth the effort. It's like getting to chat with the wise old professor of physics education that helps steer your thinking and nudge you in the parts where you are not quite sure or thought you were. I'd suggest that this one is perhaps best to think about reading if you have been teaching for a few years and want to give your own thinking and teaching some challenge. You'll need to know your specification well to be able to pick out what will be directly relevant to your teaching.

Highlights:

A) The first chapter **A Guide to Teaching for Learning and Understanding** starts with what Arons calls the 'underpinnings'. It's a short section of 20 pages or so but he lays down what he feels are some foundations for the study of physics that if not addressed early and well in the study of physics may well cause significant problems later on.
An abbreviated list of some of Arons' underpinnings

- Area, Volume
- Ratios and Division
- Arithmetical reasoning involving division
- Graphs and arithmetical reasoning
- Scaling and Ratio
- Elementary Trigonometry
- Horizontal, Vertical, North, South, Noon, Midnight (measurement and reference)
- Interpreting and algebraic statements

This is worth highlighting and consideration for two main reasons. The list itself is interesting and enlightening. Perhaps of greater significance is that it raises a question for us as physics teachers as to what the 'toolkit' is that is needed to do physics is and when/if/how we equip our students with it. We can disagree with the list, but what is on ours and what do/can/should we do about it is a valuable question to ask.

B) Perhaps not a 'highlight as such, but to offer a feel of how Arons approaches things.

3.17 STRINGS AND TENSION

Many textbooks bring forth the word "tension" and start using it as though everyone must know what it means without operational definition. The student is confronted with the familiar problem in which one string is stretched by opposite forces of 50 N at each end while a second string, with one end attached to a wall, is pulled with a force of 50 N. The student wonders how it is possible for the tension in the string to be the same in each case and is unable to see why it is not 100 N in the first string.

There are two difficulties superposed here. One is that, when this situation is first encountered, many students have not fully assimilated the third law and, not drawing an adequate force diagram of the string, fail to see that the two situations are identical as far as the forces on the strings are concerned. The other difficulty, however, is that "tension" has not been defined.

One simple approach is to lead the student to imagine "cutting" a stretched string at some point along its length and drawing the forces acting on the two segments. (Not only is this a good exercise in using the third law, but it also introduces students to the examination of forces in the *interior* of objects. Up to this point all forces and force diagrams have usually been confined to external effects, and the realization has not been formed that one can, in imagination, "cut through" an object and show the forces at the selected cut.) Having drawn the equal and opposite forces acting on the two segments at the cut, one can give the name "tension at the cut or section" to the magnitude of the force acting on either segment. Tension and compression in rods or columns can then be defined in a similar way.

Having defined tension in this way, it is now a relatively simple matter, inviting valuable phenomenological thinking and visualization, to examine the tension in a massive rope (or chain or rod) as the object is accelerated by a force at one end. It is not necessary to solve quantitative problems! As one examines the tension "chunk-by-chunk" through the length of the object, it becomes apparent, through application of the second law, that it must decrease continuously from a value equal to that of the applied force at one end to zero at the other. One can then leave for homework the further problem of how the tension varies when a rope is accelerated with two opposing forces, unequal in magnitude, at each end.

Whilst not as comprehensive as the book, if you want an insight into Arons and his views on Physics education then the following paper is a good read that draws out some important messages for teachers. http://www.physics.indiana.edu/~hake/AronsAdvMeth-8.pdf

Oersted Medal Lecture 2001: Physics Education Research-The Key to Student Learning : Lillian McDermott (academic paper)

American Journal of Physics: Volume 69, Issue 11, Pages 1127-1137 http://dx.doi.org/10.1119/1.1389280 **(academic paper)**

This paper is over 20 years old and based mainly on research work with undergraduates but even considering these possible limitations, it offers such a rich source of ideas for consideration I'd suggest that it should be required reading.

Why this is worth reading:

I don't know of a document as short as this that is able to stimulate so much professional dialogue and discussion about teaching and learning in physics. Lillian McDermott has spent many years researching teaching and learning in physics as well as developing some highly regarded curriculum materials, this paper acts as a summary of her work and thinking at that point and as such is about as dense as it can get whilst still being readable.

Highlights:

At only 10 pages long it is all worth reading but the two most directly relevant parts are **Some research-based generalisations about learning** and then the '*so what*?' answer where she works through each of these and provides **Some research-based generalisations about teaching**. The generalisations part of the title is an important reminder that this is the start of a process, not the solution offered up for us to just copy in our classrooms. The list is shown below, with each point on the learning list followed by one of the suggestions for teaching. Perhaps some or all of this is familiar but certainly a challenge to try and respond to and address them all. That is part of the joy of teaching though.

Some research-based generalisations about learning **and teaching**

- Facility in solving standard quantitative problems is not an adequate criterion for functional understanding. Questions that require qualitative reasoning and verbal explanation are essential for assessing student learning and are an effective strategy for helping students learn.
- Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. Students need repeated practice in interpreting physics formalism and relating it to the real world.
- Certain conceptual difficulties are not overcome by traditional instruction. Persistent conceptual difficulties must be explicitly addressed in multiple contexts.
- A coherent conceptual framework is not typically an outcome of traditional instruction. Students need to participate in the process of constructing qualitative models and applying these models to predict and explain real-world phenomena.
- Growth in reasoning ability often does not result from traditional instruction. Scientific reasoning skills must be expressly cultivated.
- Teaching by telling is an ineffective mode of instruction for most students. Students must be intellectually active to develop a functional understanding.

Perhaps some or all of this is familiar but certainly a challenge to try and respond to and address them all. There is more detail in the paper but the fun bit of coming up with the specific answers for our own class is left to us.

Note: This paper, published by the American Journal of Physics is kept behind a paywall for subscribers and members of the American Association of Physics Teachers (AAPT). I heartily recommend joining the AAPT but some wise searching may find a copy around in cyberspace.

Concluding Thoughts:

Hopefully, the summaries and highlights above provide some stimulus for thought, consideration and action as well as discussion with colleagues. I would like to think that this is the start of a process rather than an end in itself. A final thought to end this short primer, something from an Arons in a paper in 1984 where he tried to draw together many of the threads of his work that exist in his book Teaching Introductory Physics (see above) and in the others. It's a few years old now but as we move forwards the haze only partly clears.

> *I fully anticipate that future advances in cognitive research will analyze, reconstruct, merge, separate, and reassemble in various more orderly ways, the insights I have attempted to describe. For the time being, I simply present what I have been able to discern through the still surrounding haze.*

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