Developing a teacher professional learning workshop on the general theory of relativity

Stuart FARMER

Institute of Physics, UK (Scotland)

Abstract. The development of a teacher professional learning workshop to support the General Relativity section of the Scottish Qualifications Authority Advanced Higher Physics course [1] for 17-18 year old secondary school students is described. This professional learning workshop is designed to support the development of teachers’ subject matter knowledge and pedagogical content knowledge so they are better able to provide a conceptual, non-mathematical approach to teaching curved spacetime, spacetime diagrams and evidence of the tests for General Relativity. The professional learning workshop draws on a number of resources including the educational outreach materials from the Perimeter Institute [2,3,4].

1. Background
In 2015 the Scottish Qualifications Authority (SQA) updated the Advanced Higher Physics course for final year secondary school students. This followed on from two years of a ‘pilot’ version of the course, the Revised Advanced Higher Physics course, which was taught in a small number of schools, including Robert Gordon’s College in Aberdeen where the author was Head of the Physics Department. As well as traditional topics such as rotational motion, simple harmonic motion, electrostatics, electromagnetism, and waves the previous versions of the course had contained it introduced a number of more modern physics topics such as quantum physics, stellar physics and the General Theory of Relativity (GR), see figure 1. The Special Theory of Relativity which had previously been in the Advanced Higher course was moved to an updated Higher Physics course which is usually studied by students in their penultimate year of secondary school and aged 16-17 years. The new Higher Physics course also included new topics such as the expanding universe and the Standard Model as well as the more traditional topics such as linear motion, collisions and explosions, refraction, interference, the photoelectric effect, spectra, and resistive and capacitive circuits.

Scottish physics teachers, to be registered with the General Teaching Council for Scotland to teach physics, must have a degree with sufficient physics content, a minimum of 80 credits, and in addition a teaching qualification, usually a post-graduate certificate or diploma in education. However, this means that many physics teachers have degrees in engineering or other similar disciplines which did not include the study of GR. Even if teachers have studied it, this may have been some time ago or in a more mathematical manner.

The introduction of the new course meant there was a significant need for professional learning to support teachers teach the new GR content.
Figure 1: SQA Advanced Higher Physics General Theory of Relativity course content statements [1]

2. Perimeter Institute Resources
At the Association for Science Education (ASE) Annual Conference in 2014 the author attended workshops presented by the Perimeter Institute (PI) Educational Outreach team. He immediately recognised that the PI materials addressed many of the modern physics topics in both the new SQA Higher and Advanced Higher Physics courses. At the conference the author approached Greg Dick, Director of Educational Outreach at PI, about how the resources and workshops could be made available to physics teachers in Scotland. This led to the author attending the EinsteinPlus residential course at PI in Canada in July 2014 so he could find out more about the PI resources and help make them available to Scottish teachers. It was also arranged for Greg and two colleagues to come over to the ASE Scotland Annual Conference which was hosted in the author’s department in Aberdeen in March 2015 and two of the author’s colleagues, Gordon Doig, then the Institute of Physics Scottish Education Manager, and Tim Browett, then Assistant Head of Physics at Robert Gordon’s College, attending EinsteinPlus in July 2015. A ‘training of trainers’ event was then organised in August 2015 where Gordon, Tim and the author shared their knowledge of the PI resources with eleven others experienced in delivering physics professional learning in Scotland. This prepared this larger group to deliver workshops using the PI resources, see figures 2 and 3. This group have subsequently delivered workshops on a variety of topics to physics teachers across Scotland.

3. The aims of the GR workshop
Key learning outcomes for the workshop are:
1. Develop teacher subject matter knowledge (SMK) of qualitative concepts of GR, in particular the Equivalence Principle and Spacetime Diagrams.
2. Develop teacher pedagogical content knowledge (PCK) [5,6] in relation to teaching GR in a conceptual, non-mathematical manner.
3. Introduce practical and video resources which teachers can use to illustrate and model aspects of GR.
4. Emphasize the role of modelling in science, the interplay between theory and experimental and observational evidence, and the importance of these when teaching about the Nature of Science.

![Curved Spacetime](image1)

**Figure 2:** A PowerPoint slide comparing flat and curved spacetime models

![Author and Gordon Doig](image2)

**Figure 3:** The author (left) and Gordon Doig modelling curved spacetime using a beach ball

Developing teachers’ PCK is particularly important as it is the ability of the teacher to explain complex concepts in a form understandable to the students that is the key to the successful learning of GR by the students. A deep understanding of both the SMK and PCK also better enables teachers to deal with the contingent moments that always arise from time to time during teaching.

4. **The structure of the GR workshop**

The workshop is usually delivered as a 2 hour one-off session as a twilight event or parallel conference session. In the limited time available the workshop focussed on the parts of GR with which teachers were found to require most support, curved spacetime and the Equivalence Principle.

4.1. **Section 1 – Introduction and modelling**

After a recap of the SQA Advanced Higher course content the workshop begins, as for many PI workshops, with participants observing a ‘puzzle’ situation and are asked, in small groups, to devise a model which they think explains these observations. This leads to discussion of the role of models in science, how they are used to provide explanations and make predictions but then tested against observation and changed or abandoned as a result. This provides for some explicit teaching about the Nature of Science and provides a context for subsequent discussion.

4.2. **Section 2 – Force and acceleration models of gravity**

This naturally leads into a comparison of the ‘Force Model’ and the ‘Acceleration Model’. The ‘Force Model’ of gravity is introduced using simple props such as masses on a bendy rod. This is a concept with which participants should be very familiar and provides a secure foundation from which to build. That even Newton described his ‘Force Model’ as an ‘absurdity’ in relation to the instantaneous action at a distance, is then highlighted. Evidence is then presented which shows it makes the wrong predictions, experimentally in terms of the orbit of Mercury and theoretically in violating the speed of light limit of the Special Theory of Relativity. Participants are then asked if there is an alternative model which can be used to describe the bending of the rod, and the ‘Acceleration Model’ introduced. The comparison of the models is further illustrated by the use of the PI Alice and Bob video ‘What keeps us stuck to Earth?’[4]. The introduction of the ‘Acceleration Model’ is used as a bridge between familiar
Newtonian physics and Einsteinian physics by comparing everyday accelerations, such as in a car, as well as the need to explain corresponding scenarios such as a person standing on the surface of the Earth as accelerating. This sequence leads smoothly from Newtonian physics on to Einsteinian physics, and to both curved spacetime and what Einstein described as his ‘happiest thought’, that ‘An acceleration in one direction is identical to the result of a force in the other direction’: the Equivalence Principle.

4.3. Section 3 – Spacetime diagrams
Spacetime diagrams are introduced as a means of describing a situation described in the Alice and Bob video, but in a way which builds on the use of simple descriptions and calculations using the equations and graphs for uniform accelerations in free-fall. This builds on likely secure classical physics knowledge of participants. Participants, working in groups, use masking tape to trace out the paths of objects through spacetime, and use flat and curved surfaces to compare the motion of the objects. This emphasises that the ‘Acceleration Model’ of gravity is consistent with curved spacetime and with observations.

4.4. Section 4 – Clocks in spacecraft and gravitational fields
The Equivalence Principle in relation to spacecraft in deep space and gravitational fields is then described and how this relates to light paths. The implications of this for clocks at the front and back of accelerating spacecraft are then discussed and the link is made that clocks therefore run at different rates at different altitudes in gravitational fields, see figure 4. This section is rounded off by linking this to gravitational redshift and an independent explanation from conservation of energy, again a concept very familiar to participants.

4.5. Section 5 – Modelling curved spacetime
The ‘Acceleration Model’ is summarised and participants then have the opportunity to use Lycra gravity wells and marbles to model 4-dimensional curved spacetime in 3-dimensions. Participants are asked to evaluate the pros and cons of this model and how it relates to a previous activity with a beach ball, for example, the comparison of positive and negative curvatures can be made and how this relates to the relative time dilation at different points on the curved surfaces.
4.6. Section 6 – Tests for GR

The workshop is completed by discussing the three tests for GR proposed by Einstein, plus additional tests which are now available, and evidence which supports them are presented. Hands-on teaching strategies which can be used to visualise and illustrate some of these are introduced and participants given the opportunity to use them. These include wine glasses to model gravitational lensing [7] and another activity where masking tape is laid straight across curved surfaces to illustrate light paths in gravitational lensing. This links back to and reinforces representations of constant velocities and accelerations in the flat and curved spacetime activities from section 3. Another PI video ‘The Global Positioning System and Relativity’ [2] on the corrections for both Special and General Relativity on the clocks on GPS satellites is used to illustrate that both Theories of Relativity are not just abstract concepts but things that impact on our daily lives. The workshop concludes with the fact that the discovery of gravitational waves is as predicted by Einstein’s ‘Acceleration Model’ of gravity.

5. Analysis of the effectiveness of the workshop

As can be seen from above, the workshop is very much focussed on providing participants with SMK and PCK to allow them to teach the complex topic of GR with greater confidence, a need identified to the author by many teachers. The workshop deals with a subtle and complex scientific theory but also seeks to bring educational theories together with practice in the manner described by Timperley p11 [8] as a feature of effective professional learning. This includes breaking complex ideas down into small explicit steps, modelling both concepts and teaching, using effective questioning, and using combinations of representations [9,10]. A good example of this is when the Equivalence Principle and clocks are explored through a series of evolving scenarios in section 4. The bringing together of theory and practice, the ‘transfer problem’ [11], has been shown to be challenging for teachers.

As the workshop is normally restricted to a twilight meeting or conference session, time is always restricted and an explicit teacher educator led approach is used by the author so as to use the time as efficiently as possible. The author is playing the role of a ‘knowledgeable other’ [12] providing participants with an external stimulus of SMK and PCK. In a short workshop it is not possible to achieve the goals of realistic teacher education as described by Korthagen and Kessels [11] as the author is not able to respond to the needs of each individual participant. However, the author’s experience, from his own professional learning, teaching the topic to students and delivering workshops to teachers, allows many of the difficulties participants commonly have to be anticipated in the manner described by Korthagen and Kessels [11]. More time than that which is normally available is needed to do the topic full justice, allow a more collaborative approach [13,14], and to allow participants to reflect [15] on issues more extensively during the workshop.

One of the common misconceptions encountered in the workshop relates to why clocks at higher altitudes run at a faster rate than those at a lower altitude. Often participants associate the different rates as being due to the different gravitational field strength at the two altitudes and not due the change in altitude itself. This is also something which is implied in the PI ‘GPS and Relativity’ video [2]. As the author gained experience of the difficulties both students and teachers had with this topic he broke this section of the workshop down into smaller, more explicit steps to provide a simpler narrative.

The workshop is based on the premise that the majority, if not all, of the teachers, regardless of experience, will encounter new ways of thinking about the concepts explored in the workshop. These include ways of modelling concepts, the importance of modelling in the development of science (sections 1 and 2), practical activities to illustrate concepts (sections 3, 5 and 6), and appropriate language and explanations throughout. The author, as teacher educator, exposes the participants to new ways of thinking about concepts using a variety of methods including explicit explanation by the author, modelling of activities and explanations by the author in the manner described by [16], group discussion by participants, and question and answer sessions. A major role of the teacher educator in this workshop is to model effective teaching practice, such as the introduction of the use of flat and curved spacetime in section 3. A major part of the workshop is to ask questions and promote thinking in the teacher participants. This is firstly about the scientific concepts in terms of possible misconceptions and
difficulties, but also about how best to explain these concepts to students, including the use of a number of practical demonstrations to illustrate the concepts, thus developing the teachers’ PCK. The author asks questions of the participants, encourages the participants to discuss their own thinking during some of the group activities, and to ask questions throughout, allowing the author to identify possible misconceptions or issues the participants may be having in order that the author can respond to these using his Contingency Knowledge [17]. Unfortunately, due to the nature of the events where the workshop has been presented, there has been no structured opportunity to follow issues up with participants after the workshop, although the author is always happy to be contacted by participants.

Regarding the Nature of Science, the interplay between theory and observation/evidence is emphasised during the workshop in sections 1, 2 and 6, not only in terms of emphasising the development of theories of gravitation but also how this is an important aspect of how science develops more generally. This is an issue that many participants are unlikely to have been exposed to, or to have given much thought to, during their own scientific education, initial teacher education or in-service teacher education, despite an understanding of aspects of Nature of Science being expected in many curriculum documents.

6. Conclusions and Implications
The introduction of GR into the secondary school curriculum is a challenge for the majority of physics teachers, and one that requires effective professional learning for success. As stated by Stenhouse [18] ‘Curriculum development must rest on teacher development’. The workshop was developed to address this need and has been improved incrementally over time as the author has evaluated it and incorporated additional materials when the author has become aware of these. This was partly in response to the author’s ‘wisdom of practice’ from experience teaching the topic to students and to the reaction and comments of workshop participants. Although GR is taught rarely in curricula the author has become aware of relevant materials from Norway [19] and Australia [20] which will be incorporated into the workshop in the future.

The workshop, despite being delivered as a one-off session of the nature seen as being relatively ineffective in promoting long-term professional growth of teachers [21], does aim to meet the specific need of improving the SMK and PCK of teachers tasked with teaching a new, and complex, curriculum topic with which few are familiar or confident. The workshop builds on classical physics knowledge familiar to participants and introduces the new theory in a manner that parallels the historical development of the subject, coming right up-to-date with the use of GPS and discovery of gravitational waves and imaging the black hole in M87. Emphasising the fact that predications made using Newtonian physics did not match observation supports the need to introduce a new theory, Einstein’s GR, and is designed to enhance teachers’ ability to teach about the Nature of Science. A clear rationale is provided for introducing curved spacetime rather than just doing so in what may well seem very arbitrary, disconnected, and potentially confusing manner for learners. As a one-off workshop it is probably developed as far as is reasonable and provides, in the words of Shulman [22] ‘the most useful forms of representations of those ideas, the most powerful analogies, illustrations, examples, explanation, and demonstrations – in a word, the ways of representing and formulating the subject to make it comprehensible to others’.

Much ground, including difficult conceptual ideas, is covered in the 2 hour workshop. This gives inadequate time for participants to reflect and discuss these ideas, and to think deeply about the pros and cons of different teaching strategies, models and analogies. It would be good to split the workshop across perhaps three workshops spaced some weeks apart. This would give more time during the workshops for participants to explore and discuss activities in small groups but, more importantly, give elapsed time between workshops to allow for reflection on the concepts and strategies, and opportunities to try some of the teaching activities with students before returning, providing feedback, and having deeper learning discussions based on their increased knowledge and understanding. An analysis of how this might occur appears in the ‘Change Environment’ of Clarke and Hollingsworth [21] in figure 5.
Figure 5: Analysis of a potential series of workshop using the Clark and Hollingsworth (2002) change environment.
At the end of workshops participants could be asked to identify suitable action points to follow-up as an incentive for reflective activity between workshops.

This workshop is one of a number the author has developed based on PI materials designed to support the teaching of modern physics topics in upper secondary and all have an emphasis on modelling the very small, very large, or difficult to visualise. They all highlight aspects of the Nature of Science, the historical development of scientific knowledge, and the analysis of real scientific data. Logistics and time restriction have meant that these workshops have not been delivered as a sequential programme but have been made available on demand and in negotiation with local groups of teachers or as part of larger conferences. Although some teachers have attended two or more of the workshops the changing audience has not allowed for continuity from one workshop to the next.

Working with a fixed group of teachers, a regular series of twilight workshops, fitting with their curriculum teaching sequence, would allow the input of new knowledge and teaching strategies with structured opportunities for them to use these in the classroom between workshops. Using the terminology of the Clarke and Hollingsworth [21] model, this would allow the teachers opportunities to use the external stimulus in their domain of practice, see how it might affect salient outcomes for students, and as a result this is more likely to feedback and change the teachers’ knowledge and beliefs in their personal domain. This would ensure the professional learning is also more consistent with the characteristics, described by Timperley et al. [22], Cordinley et al. [23], Darling-Hammond et al. [24] and Cordinley et al. [25], required for the professional learning to have good impact on student outcomes.

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