General Relativity as a Challenge for Physics Education

690. WE-Heraeus-Seminar

10 – 15 February 2019
Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de.

Scope of the 690. WE-Heraeus-Seminar:

General relativity is one of the fundamental advancements of physics in the 20th century. Well established and tested to high accuracy, it is the basis of modern astrophysics and cosmology. In spite of its fundamental importance, general relativity is not part of most curricula in secondary schools and in undergraduate university education.

The teaching of general relativity at the secondary school and undergraduate levels is a challenge for physics education. Novel and abstract concepts must be explained. The mathematical framework of the theory is involved and is not accessible to learners at these levels. New approaches must therefore be developed that make it possible to teach general relativity using no more than elementary mathematics.

The goal of this seminar is to promote the scientific exchange of ideas and research results on the teaching of general relativity at the secondary school and undergraduate levels. Contributions are grouped in two strands: Strand A, "Curriculum development & design", has its focus on the development of teaching materials and teaching units, strand B, "Evaluation & research on learning and instruction", has its focus on empirical tests and educational research.

Scientific Organizers:

Prof. Dr. Ute Kraus
Dr. Corvin Zahn

University of Hildesheim, GERMANY
Institute of Physics

E-mail ute.kraus@uni-hildesheim.de
E-mail corvin.zahn@uni-hildesheim.de

Program

Program

Sunday, 10 February 2019

16:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	
19:45 – 20:00	Scientific organizers	**Opening and welcome**
20:00 – 21:00	Martin Hendry	**Einstein's masterpiece: 100 years of general relativity**

Monday, 11 February 2019

08:00	*BREAKFAST*	
09:00 – 10:00	Bernard Schutz	**Intuition in physics: What is a physicist anyway?**
10:00 – 11:00	Karl-Heinz Lotze	**Various approaches to teach light deflection in gravitational fields**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Silvia Simionato	**Combining general relativity and optics to visualize light on curved paths**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:45	*LUNCH*	
14:15 – 15:15	Friedrich Herrmann	**GTR and Cosmology in the Karlsruhe Physics Course: A short description of a 15-hour course for the upper secondary school**
15:15 – 15:45	*COFFEE BREAK*	
15:45 – 17:45	Daina Taimina	**Tactile hyperbolic geometry** (workshop)
17:45 – 18:00	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
18:30	*DINNER*	

Program

Tuesday, 12 February 2019

08:00	*BREAKFAST*	
09:00 – 11:00	Ute Kraus	**Teaching general relativity with sector models** (talk with workshop)
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	**Poster flash presentations I** (3 min. each)	
12:45	*LUNCH*	
14:15– 15:15	**Poster session I: Teaching resources**	
15:15 – 15:45	*COFFEE BREAK*	

Workshop

15:45 – 17:15	Hans-Peter Nollert	**Teaching General Relativity using ruler and calculator: An interactive workshop based on the Shapiro effect**

Hands-on sessions

15:45	Matěj Ryston	**Hands-on activities for teaching curvature**
16:25	Efstratios Kapotis	**Experimentation and simulations for teaching General Relativity**
17:05	Sven Weissenborn	**Virtual sector models**

Group discussion

15:45	Markus Pössel (Chair)	**Simplifications and misconceptions in General Relativity**

Group discussion

16:45	Stuart Farmer (Chair)	**Teaching General Relativity at school - exchange of experiences**
18:30	*DINNER*	

Program

Wednesday, 13 February 2019

08:00	*BREAKFAST*	
09:00 – 10:00	Corvin Zahn	**Visualization of general relativity**
10:00 – 11:00	Andrew Hamilton	**Using general relativistic visualization to confront myths and misconceptions about what happens inside black holes**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Ellen Karoline Henriksen	**Developing learning resources and investigating students' learning in general relativity and quantum physics**
12:45	*LUNCH*	
14:15	**Excursion** Walk to local sightseeing spot. (Destination depending on the weather.)	
18:30	*DINNER*	

Program

Thursday, 14 February 2019

08:00	*BREAKFAST*	
09:00 – 10:00	David Blair	**Einsteinian reality: A challenge for school education**
10:00 – 11:00	Magdalena Kersting	**Curved spacetime: Investigating students’ conceptual understanding in general relativity**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	**Poster flash presentations II** (3 min. each)	
12:45	*LUNCH*	
14:15– 15:15	**Poster session II: Design, evaluation, programs**	
15:15 – 15:45	*COFFEE BREAK*	

Workshop

15:45 – 16:45	Roberto Salgado	**Relativity on rotated graph paper**

Hands-on sessions

15:45	Friedrich Herrmann	**Geodesic Lab - Have fun with geodesics**
16:25	Ute Kraus Corvin Zahn	**Wormholes: Interactive flight through a wormhole & 3D wormhole model**
17:05	Stephan Preiß	**Through Hildesheim at nearly the speed of light & The vehicle-through-the-garage-paradox visualized**

Group discussion

15:45	Markus Pössel (Chair)	**Simplifications and misconceptions in General Relativity**

Group discussion

16:45	Stuart Farmer (Chair)	**Teaching General Relativity at school - exchange of experiences**
18:30	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, free beverages)*	

Program

Friday, 15 February 2019

08:00	*BREAKFAST*	
09:00 – 10:00	Kimberly Coble	**Big ideas in cosmology: undergraduate students' ideas about the structure, fate, evolution, and curvature of the universe**
10:00 – 11:00	David Treagust	**Time for changing paradigms in science and in education**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Scientific organizers	**Poster awards, summary, discussions and closing remarks**
12:45	*LUNCH*	

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Friday evening for participants leaving the next morning.*

Posters

Posters

1.01	Markus Pössel	**Relative motion in general relativity: The case of cosmic expansion**
1.02	Lorenzo Galante	**From the EP to the curved space**
1.03	Hans-Peter Nollert	**Teaching General Relativity using ruler and calculator: An interactive workshop based on the Shapiro effect**
1.04	Richard Toellner	**The Milne universe**
1.05	Matěj Ryston	**Embedding diagrams and other hands-on activities for teaching curvature**
1.06	Efstratios Kapotis	**Educational experimentation and simulations for teaching General Relativity. Implementation and Evaluation**
1.07	Sven Weissenborn	**Virtual sector models (ViSeMo)**
1.08	Stuart Farmer	**Developing a teacher professional learning workshop on General Relativity**
1.09	Michael Schultz	**Teaching 2nd year undergraduates how to derive and study the geodesic equations for the Schwarzschild black hole**
1.10	Aroonkumar Beesham	**Teaching of general relativity at the University of Zululand**
1.11	Eugene Kogan	**Derivation of Schwarzschild metrics using differential forms**
1.12	Yurii Dumin	**A quasi-newtonian basis for studying the relativistic cosmology**
1.13	Floor Kamphorst	**Event diagrams – supporting student reasoning in space-time**
1.14	Essam Zoabi	**Simple mechanical model for explaining the increase of the relativistic mass**
1.15	Roberto Salgado	**Relativity on rotated graph paper**

Posters

2.01	Shachar Boublil	**Analysis and reflection on the teaching of Einstein's theory of gravity in Quebec**
2.02	Stanley Delhaye	**Design of a prototype for teaching general relativity to upper secondary students**
2.03	Ian Lawrence	**Light cones for reasoning about space and time**
2.04	Li Ju	**Gravitational waves: A vehicle for the integrated teaching of Einsteinian physics**
2.05	Chris North	**Increasing the relevance of high school studies to cutting edge gravitational wave research**
2.06	Rahul Choudhary	**Integrating Einstein-first resources with international collaboration on Einsteinian physics**
2.07	Gary Foster	**Teaching Einsteinian science at Guildford Grammar**
2.08	Richard Meagher	**Do modern high school students want to study modern physics?**
2.09	Fadeel Joubran	**Comparison between Israeli and Hungarian physics high school teachers' attitudes towards GR assimilation in the curriculum**
2.10	Stephan Preiß	**A comparison between standard courses about general relativity and a model-based approach**
2.11	Thomas Reiber	**Flying through a Kerr black hole – Visualizations**
2.12	Pierre Martin-Dussaud	**L'Agape: Renewing conferences format**
2.13	Amber Strunk	**Supporting general relativity curriculum through teacher professional development**
2.14	Magdalena Kersting (presentation) Jacqueline Bondell/ Mark Myers (authors)	**Bringing the virtual universe into the STEM classroom**

Abstracts of Lectures

(in chronological order)

Einstein's Masterpiece: 100 Years of General Relativity

M. Hendry[1]

[1]*School of Physics and Astronomy, University of Glasgow, Glasgow, UK*

Albert Einstein's General Theory of Relativity was described by Max Born as "The greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition and mathematical skill". More than a century after its publication[1] General Relativity continues to fascinate and excite new generations of physics students as they explore its remarkable predictions about the nature of curved spacetime. In this lecture I will review some of the key achievements of 100 years of General Relativity – from Mercury's perihelion advance and the first measurements of gravitational light deflection to high-precision studies of binary pulsar systems and the discovery of gravitational waves[2] – and consider where future tests of the theory might lead our understanding of fundamental physics and cosmology.

References

[1] A. Einstein, Annalen der Physik **49**, 769 (1916)
[2] B.P. Abbott et al., Phys. Rev. Lett. **116**, 061102 (2016)

Intuition in physics: What is a physicist anyway?

B. F. Schutz[1]

[1]*School of Physics and Astronomy, Cardiff University, Cardiff, Wales, UK*

My book, *Gravity from the Ground Up* [1], attempts to teach the physics of gravitation theory (Newtonian and Einsteinian) at the level of advanced high-school or undergraduate students, using algebra but not calculus, and assisted with simple computer programs. There is a heavy emphasis on connecting concepts by using analogies, examples, and plausibility arguments, on getting to results by what is often called “physical intuition”. I found that I could join up a remarkable range of gravitation theory this way, even quantitatively, and even for some quite esoteric topics, e.g. gravitomagnetism (frame-dragging). I shall argue in this talk that this should not be thought of as a “watered-down” way of teaching theoretical physics, but rather that our usual mathematical approach would benefit from having an explicitly intuitive track taught alongside it. I will support my argument by referring to recent thinking in the psychology community about the relationship between intuition and reason in human thought. Physicists commonly remark that certain legendary scientists have had ”great intuition”, for example Richard Feynman. I believe that this is not accidental, and that it should not be exceptional: it should be our goal for every student.

References

[1] B . F. Schutz, *Gravity from the ground up* (Cambridge University Press 2003), 490 pp.

Various approaches to teach light deflection in gravitational fields

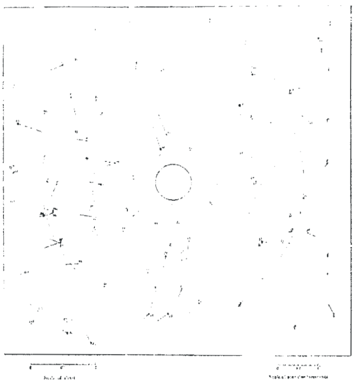
K.-H. Lotze

Wilhelm and Else Heraeus Seniorprofessor
at Friedrich-Schiller-University, Jena, Germany

In 2019 the scientific community worldwide is going to celebrate the 100th anniversary of the confirmation, by astronomical observation, of the deflection of star light by the Sun, as it was predicted by Albert Einstein in the framework of his General Theory of Relativity. The physics underlying this prediction is the same as that of other light deflection phenomena in the universe, nowadays known as gravitational-lens effect. Thus light deflection has not only been confirmed in many circumstances, but became a powerful tool of astrophysics and cosmology.

We compare and contrast various approaches to the phenomenon of light deflection by gravitational fields, in particular that of the Sun, in order to better incorporate it into to our already existing knowledge. Among them are

- ballistic light deflection (Newton 1704, v. Soldner 1801) where light, as a current of classical particles, is subjected to Newton´s law of gravitation, providing half of the deflection of light, as compared to the amount predicted later by Einstein,
- light deflection as it was predicted by the equivalence principle (Einstein 1911), leading to the same result as the ballistic approach,
- light deflection in curved spacetime based on the Schwarzschild solution of Einstein´s field equation (Einstein, Schwarzschild 1915/16), yielding the result, later confirmed by observations, twice as big as the one predicted by the ballistic and equivalence-principle approaches,
- comparison with the phenomenon of Fata Morgana on Earth, based on Fermat´s principle, which leads to the interpretation of the influence of a gravitational field upon light, as if it were a spatially inhomogeneous optical medium.



Moreover, we demonstrate how the observations of the solar eclipse of September 21, 1922 (Campbell and Trumpler, see picture) confirmed the prediction by General Relativity of a light deflection by 1.75" when extrapolated to the solar limb.

Finally we briefly explain how the classical effect of light deflection by the Sun can be incorporated into the more general gravitational-lens effect.

Combining general relativity and optics to visualize light on curved paths

S.Simionato and K.-H. Lotze

Friedrich-Schiller-University, Jena, Germany

Picture of our faculty main building taken through one of our lens. Credit: Uwe Alberti

After the travel through the theory of light deflection, thanks to the talk "*Various approaches to teach light deflection in gravitational fields*", we do a step more with this workshop introducing and combining together also optics. The aim of this process is the development of useful educational outcomes in teaching gravitational lensing. Therefore we continue with the analysis of the lens equation for the gravitational lensing phenomenon, at first for the Sun and then applying it to other celestial objects. This means not only considering different sources, but above all different cases of mass distribution for the lens. With the lens equation must be taken into consideration the deflection angle, source size, mass distribution of the lens and relative position between them. All this allows us to define the number, position, shape and size of the images produced by the gravitational lens effect.

Another important point that we want to explore is how it is possible to visualize the gravitational lens effect in a classroom. Of course with amazing images from the best telescopes, but even better together with the images produced by glass lenses and a lamp. We designed and manufactured these lenses with special shapes, specifically formulated to reproduce the images of different types of gravitational lenses. The idea is to combine general relativity with optics to obtain the same gravitational lensing phenomena that we find in the universe. In this regard we will see how it is possible to understand the shape to be given to a glass lens so that it represents a specific mass distribution and reproduces the related images.

And finally we will see in action some of our lenses, we will recreate the gravitational lensing, accompanying it with beautiful real images.

All this will be shown in detail for two cases, but the final results for some others will also be presented.

Picture of our faculty main building taken through one of our lens. Credit: Uwe Alberti

GTR and Cosmology in the *Karlsruhe Physics Course*: A short description of a 15-hour course for the upper secondary school

F. Herrmann and M. Pohlig

Karlsruhe Institute of Technology, Institut für Theoretische Festkörperphysik, Karlsruhe, Germany

The basics of a course on special and general relativity and cosmology are presented. It is a part of the *Karlsruhe Physics Course* [1]. The lecture will address some special features of our course:

1. We avoid changing the reference frame and adhere to the practice otherwise applied in physics: choose a suitable reference frame at the beginning and do not change it anymore. Consequently, Lorentz transformation, length contraction and time dilatation are not topics of the course.
2. We do not deal with the topic clock synchronization. It was discussed in detail by Einstein in his 1905 paper, but at that time he didn't know yet that in general, i.e. in curved space, two clocks cannot be synchronized anyway.
3. Relativistic kinematics is moved into the background. Thus we gain time for a detailed treatment of relativistic dynamics.
4. Light and its velocity do not play the prominent role they play in traditional courses. c is the terminal velocity for any transport, not only that of light.
5. Instead of the invariance of the velocity of light we take as initial experience the fact that mass and energy are the same physical quantity.
6. In general relativity we only treat the curvature of space – not that of space-time.
7. Instead of length changes caused by heavy celestial bodies, we consider the more descriptive volume changes.
8. The so-called twin paradox does not appear as a paradox in our course, but is a natural consequence of the fact that space and time form a unit. The "second twin paradox", in which the two twins compare their clocks after having lived at different gravitational potentials for some time, appears, after choosing a suitable reference frame, as a special case of the normal twin paradox.
9. The different horizons associated with the expansion of the universe are explained using appropriate models.

Reference

[1] F. Herrmann, *The Karlsruhe Physics Course* for the upper secondary school
http://www.physikdidaktik.uni-karlsruhe.de/index_en.html

Tactile Hyperbolic Geometry

Daina Taimina

Cornell University, Ithaca, NY, USA

Up until 1915 people thought of space as an inert stage and Newton's theory of gravity was considered the bedrock of science. Einstein's revolutionary realisation was that space is dynamic; space and time are not separate entities but form *spacetime* and gravity is the manifestation of the curvature of *spacetime*. Curvature of space determines what geometry can be used to describe this space: Euclidean geometry if curvature is zero, spherical geometry for positively curved spaces, and hyperbolic geometry for negatively curved spaces.

The theoretical discovery of hyperbolic geometry first got its actual tactile example in 1868 when Eugenio Beltrami created a negatively curved surface from paper annuli and named it *a pseudosphere*. Later the name *pseudosphere* got attached to a surface created by a tractrix rotating around its axis. However, mathematicians found more useful for theoretical purposes using different, non-tactile models such as Klein or Poincare disc models or half-plane model. Those are traditionally used in college textbooks. However, to experience deeper understanding of hyperbolic geometry, these models were not enough for Bill Thurston when he was a college student. Since in 1901 Hilbert proved that hyperbolic plane cannot be described analytically in 3-space, Thurston together with his peers at informal seminar decided to make a tactile model of hyperbolic plane and created it by gluing together paper annuli without knowing about Beltrami's paper model created hundred years earlier. I learned about Thurston's model in 1997 and decided to make it more durable by crocheting it. Crocheted hyperbolic planes have turned out to be a useful tool in tactile explorations of hyperbolic geometry giving to theoretical knowledge a different perspective.

I will demonstrate various crocheted models and will lead a hands-on exploration of the properties of the hyperbolic plane, and how manifolds and tessellations can be made. We will also create models of hyperbolic plane by gluing paper.

References

[1] Daina Taimina, *Crocheting Adventures with Hyperbolic Planes*, 2nd ed., CRC Press, 2018

[2] David W. Henderson, Daina Taimina, *Experiencing Geometry: Euclidean and non-Euclidean with History*, 3rd ed., Pearson, 2004 (4th ed. forthcoming)

Teaching general relativity with sector models

U. Kraus[1] **and C. Zahn**[1]

[1]*Department of Physics, Hildesheim University, Hildesheim, Germany*

We have created sector models as tools for teaching general relativity without going beyond elementary mathematics ([1], [2], [3]). The talk shows the potential of this toolkit. Workshop sections are integrated in the talk and provide the opportunity to try out the models.

The sector model approach aims at geometric insight into the properties of curved spaces and spacetimes. The models allow to visualize, e.g. geodesics, parallel transport, and the curvature tensor.

Sector models represent curved spaces of up to three dimensions: surfaces, 3D spaces, 1+1D spacetimes, and 2+1D spacetimes. The representation is true to scale so that inferred quantities are quantitatively correct. Models in 2D and 1+1D can be computed from the metric in an elementary way. So students can start with a metric, compute and construct a sector model, and then use the model as a tool to study geodesics and curvature.

The talk presents several examples of sector models representing different spacetimes, amongst them a Schwarzschild black hole, a neutron star, and a gravitational wave. It also describes the design and evaluation of a sector model-based course on general relativity for second year university students ([4]) .

References

[1] C. Zahn, U. Kraus, Sector models---a toolkit for teaching general relativity: I. Curved spaces and spacetimes, Eur. J. Phys. **35** 055020 (2014)

[2] C. Zahn, U. Kraus, Sector models---a toolkit for teaching general relativity: II. Geodesics, Eur. J. Phys. **40** 015601 (2018)

[3] U. Kraus, C. Zahn, Sector models---a toolkit for teaching general relativity: III. Spacetime geodesics, Eur. J. Phys. **40** 015602 (2018)

[4] U. Kraus, C. Zahn, T. Reiber, S. Preiß, A model-based general relativity course for physics teachers, Proc. ESERA Research, Practice and Collaboration in Science Education (Dublin, Ireland, 2017), ed. O. E. Finlayson et al. 978-1-873769-84-3 (2018)

Online versions of all of the above, with supplementary materials:
www.spacetimetravel.org

Visualisation of general relativity

C. Zahn, **U.Kraus**

Department of Physics, Hildesheim University, Germany

General relativity is a mathematical theory. For calculations a description based on coordinates is used. In our daily life there are no coordinate systems, we explore our environment by walking and looking around and by direct interaction. Many of the typical misconceptions around general relativity arise from the incorrect use of coordinate systems.

Arguably, insight into the theory could be gained, if it were possible to undertake a flight at almost the speed of light, visit a black hole or a wormhole, do experiments there, and so experience Einsteins theory first-hand in a coordinate-free manner. Visualizations from a first-person point of view can serve as a substitute for such an expedition by the use of modern computer graphics technology that allows the realistic and interactive simulation of a three-dimensional environment. For these relativistic scenes the classic computer graphic algorithms must be extended from three-dimensional Euclidean space to four-dimensional curved spacetime with a possibly non-trivial topology. The talk gives an overview over history, state of the art and technical aspects of first-person relativistic visualisation as well as possible applications in education.

Another type of visualization that also provides a coordinate-free way to a better understanding of the geometric structure of our spacetime is given by sector models (talk by Ute Kraus). Compared to the first-person simulations which give an impression from a local point of view, sector models present a global overview over a non-Euclidean space or spacetime and allow to explore its geometry by e.g. measuring curvature or drawing geodesics. Their representation as computer models that are manipulated in an interactive simulation, widens the scope of their application (see also the poster by Sven Weissenborn). The talk discusses the joint use of first-person visualisations ("experiments") and sector models ("theory") in teaching concepts.

References

[1] https://www.spacetimetravel.org

[2] U. Kraus, First-person visualizations of the special and general theory of relativity, 2008 Eur. J. Phys. 29 1

Using general relativistic visualization to confront myths and misconceptions about what happens inside black holes

Andrew J. S. Hamilton

JILA, Box 440, U. Colorado, Boulder, CO 80309, USA

I will use real-time interactive general relativistic visualizations to illustrate what happens when you fall into a black hole. I show that the singularity of a Schwarzschild black hole is not, as commonly asserted, a point, but rather is a surface. I show that Hawking radiation is not, as commonly asserted, emitted from the event horizon, but rather is emitted from the illusory horizon, the redshifting, dimming surface of the star and anything else that collapsed into the black hole long ago.

Developing learning resources and investigating students' learning in general relativity and quantum physics

E. K. Henriksen[1]

[1]*Department of Physics, University of Oslo, Oslo, Norway*

The Norwegian upper secondary physics curriculum for year 13 requires that students engage with general relativity and quantum physics on a qualitative level and with attention to philosophical and epistemological aspects. This requires different teaching and learning activities than those that are typical in physics instruction [1]. In project ReleQuant, we have developed web-based learning resources in general relativity and quantum physics [2] through a design-based research approach [3]: Through several iterations in collaboration with teachers and teacher students, we have tried out the resources in classrooms and collected student answers to written and oral tasks as well as student interview data.

In line with the intentions with design-based research, the project has yielded functional learning resources for use in classrooms as well as research results concerning student motivation, understanding and learning. For instance, we have looked at how small-group discussions may support learning in quantum physics [4], how students interpret the wave-particle duality for light and epistemological aspects of quantum physics [5], how students interpret the Schrödinger's cat thought experiment [6] and the rubber sheet analogy for curved space-time [7], and how general relativity may be educationally reconstructed for upper secondary students [8]. This paper reports experiences from the project and gives examples of research results and design principles used.

References

[1] M.V. Bøe, E.K. Henriksen, & C. Angell, Science Education **102** 649-667 (2018)

[2] http://www.viten.no/eng/

[3] T. Anderson & J. Shattuck, Educational Researcher **41** 16-25 (2012)

[4] B. Bungum, M.V. Bøe & E.K. Henriksen, Science Education **102** 856-877 (2018)

[5] E.K. Henriksen, C. Angell, A.I. Vistnes & B. Bungum, Science & Education **27** 81-111 (2018)

[6] H.V. Myhrehagen and B. Bungum, Physics Education **51**, 055009 (2016)

[7] M. Kersting & R. Steier, (2018), Science & Education **27**, 593-623 (2018)

[8] M. Kersting, E.K. Henriksen, M.V. Bøe and C. Angell, Physical Review Physics Education Research **14** 010130 -1- 010130 (2018)

Einsteinian Reality: A challenge for school education

David .G. Blair

[1]*University of Western Australia, Perth, Australia*

This talk will report on 7 years of trials for introducing Einsteinian physics into schools. Multiple interventions with students across age ranges from 8 to 16 have shown that students have both the interest and the capability of understanding Einsteinian reality. This talk will discuss why it is important that the conceptual language through which we understand reality should correspond with our best understanding of the universe, and why it should be taught at an early age. While simplifications have to be made, it will be shown that all students, independent of aptitude, are capable of grasping key aspects of Einsteinian reality. Short interventions in classrooms have shown that young people are capable of rapid uptake of Einsteinian concepts. Efforts are still required to determine how both mathematics and physics can be unfolded as a seamless progression throughout high school, so that science students can be motivated with an appropriate foundation for further study, while others leave school with a level of science literacy sufficient that they can appreciate the science behind both modern technology and new discoveries. My talk will include discussion of how gravitational wave detectors and their remarkable discoveries can be a very valuable tool for understanding many aspects of Einsteinian physics.

References

[1] Kaur, T., Blair, D., Moschilla, J., Stannard, W., and Zadnik, M. (2017a).Teaching Einsteinian Physics at schools: Part 1, models and analogies for relativity, *Physics Education*, Vol. **52** 065012.

[2] Kaur, T., Blair, D., Moschilla, J., and Zadnik, M. (2017b). Teaching Einsteinian Physics at schools: Part 2, models and analogies for quantum physics, *Physics Education*, Vol. **52** 065013.

[3] Kaur, T., Blair, D., Moschilla, J., Stannard, W., and Zadnik, M. (2017c).Teaching Einsteinian Physics at schools: Part 3, review of research outcomes. Physics Education, Vol. 52 065014

[4] Kaur, T., Blair, D., Burman, R., Stannard, W., Treagust, D., Venville, G., Zadnik, M., Mathews, W., and Perks, D. (2017d). "Evaluation of 14 to 15 - Year - old students' understanding and attitude towards learning Einsteinian physics", http://arxiv.org/abs/1712.02063

Curved spacetime: Investigating students' conceptual understanding in general relativity

M. Kersting[1]

[1]Department of Physics, University of Oslo, Oslo, Norway
[2] another Institute, another town, another country

The earth circles around the sun and we stay grounded on earth because of gravity. Yet, the nature of gravity eluded human understanding for centuries. It was only with Albert Einstein's theory of general relativity (GR) that physicists found a fundamental description of gravity that extends classical mechanics to cosmic scales. By describing gravity as geometry, GR offers a framework with greater explanatory power than classical mechanics: the fabric of our universe can be modelled by four-dimensional spacetime and it is the curvature of spacetime that manifests itself in form of gravity.

In the last years, physics educators have made first attempts of introducing GR to secondary school curricula: Initial efforts have focused on developing appropriate teaching approaches that rely on qualitative understanding [1], geometrical approaches [2,3], or simplified mathematical treatments [4]. However, educators still do not know much about student learning processes and the ways students develop conceptual understanding in GR. To make teaching and instruction successful, there remains the need to study students' understanding of key concepts of GR within a sound educational framework.

In this talk, I will summarise findings of my PhD-project that give insight into secondary school students' conceptual understanding in GR. I will focus on the concept of curved spacetime in particular to discuss challenges that students face when trying to understand abstract scientific concepts that are difficult or impossible to visualise. Concluding that secondary students can obtain a qualitative understanding of GR with sufficient scaffolding through interaction with teacher and peers, I will discuss how these findings can give guidance to improve learning and instruction of GR at the secondary school level.

References

[1] M. Kersting, E. K. Henriksen, M. V. Bøe, and C. Angell, General relativity in upper secondary school: design and evaluation of an online learning environment using the model of educational reconstruction. Phys. Rev. Phys. Educ. Res. **14**, 010130 (2018).

[2] C. Zahn and U. Kraus, Sector models - A toolkit for teaching general relativity: II. Geodesics. Eur. J. Phys. (2018).

[3] U. Kraus and C. Zahn, Sector models — A toolkit for teaching general relativity : III . Spacetime geodesics. Eur. J. Phys. (2018).

[4] W. Stannard, D. Blair, M. Zadnik, and T. Kaur, Why did the apple fall? A new model to explain Einstein's gravity. Eur. J. Phys. **38**, 015603 (2017).

Big ideas in cosmology: undergraduate students' ideas about the structure, fate, evolution, and curvature of the universe

K. Coble[1]

[1]*San Francisco State University, San Francisco, USA*

Powerful observations and advances in computation and visualization have led to a revolution in our understanding of the structure and evolution of the universe. Our group has been bringing these tools and advances to the classroom through research on undergraduate learning in cosmology [1-6] as well as the development of a series of web-based cosmology learning modules entitled **Big Ideas in Cosmology** [7]. Informed by our research, the modules integrate text, figures, and visualizations with short and long interactive tasks and real cosmological data, transforming general education courses from primarily lecture and book-based to a more engaging format. To explore the nature and frequency of undergraduate students' ideas, we developed a series of open-ended survey questions administered at multiple institutions (N=1535), conducted follow-up interviews (N=19), and triangulated ideas with course artifacts (N~75). In this presentation, I will primarily focus on students' ideas about the curvature and fate of the Universe, based on thematic analysis of students' responses to these instruments.

References

[1] K. Coble, M. Conlon, & J. M. Bailey, Physical Review Physics Education Research, **14**, 010144 (2018)

[2] M. Conlon, K. Coble, J. M. Bailey, & L. R. Cominsky, Physical Review Physics Education Research, **13**, 020128, (2017)

[3] K. Coble, C. T. Camarillo, L. E. Trouille, J. M. Bailey, G. L. Cochran, M. D. Nickerson, & L. R. Cominsky, Astronomy Education Review, **12**, 010102 (2013)

[4] K. Coble, M. D. Nickerson, J. M. Bailey, L. E. Trouille, G. L. Cochran, C. T. Camarillo, & L. R. Cominsky, Astronomy Education Review, **12**, 010111 (2013)

[5] L. E. Trouille, K. A. Coble, G. L. Cochran, J. M. Bailey, C. T. Camarillo, M. D. Nickerson, & L. R. Cominsky, Astronomy Education Review, **12**, 010110 (2013)

[6] J. M. Bailey, K. A., Coble, G. L. Cochran, D. M. Larrieu, R. Sanchez, & L. R. Cominsky, Astronomy Education Review, **11**, 010302 (2012)

[7] K. Coble, K. M. McLin, J. M. Bailey, A. J. Metevier, C. Peruta, & L. R. Cominsky, **Big Ideas in Cosmology**, Dubuque, IA: Kendall Hunt Publishers / Great River Learning, Inc. (2015)

Time for changing paradigms in science and in education

David F Treagust

Curtin University, Perth Australia

The parallel between paradigm changes in science and in education are indeed intriguing, having essentially the same elements – a dominant way of thinking about a particular entity and in conducting research, new evidence and ways of thinking, resistance to change and obstacles to overcome in order to move forward with new ideas and thinking. In this presentation, I will discuss paradigmatic changes in science and make a comparison with paradigmatic changes in education, particularly as they apply to teaching and learning of modern concepts of science.

Abstracts of Posters

(in order of presentation)

Poster 1.01

Relative motion in general relativity: the case of cosmic expansion

M. Pössel[1]

[1]*Haus der Astronomie and Max Planck Institute for Astronomy,*
Königstuhl 17, 69117 Heidelberg, Germany, poessel@hda-hd.de

When is the relative speed of two objects? In special relativity, with its preferred inertial reference frames, the answer is straightforward. For general relativity, any answer involves judgement calls about how to generalize the concept of relative speed, and thus about conventions and definitions – as is inevitable in matters of generalization from one framework to a more general framework. (A famous pedagogical example, where the ambiguities inherent in the process have led to heated discussions, is the generalization of the concept of mass from classical mechanics to special relativity). I present arguments in favor of defining relative motion in terms of the parallel transport of four-velocities along geodesic segments between the events on two world-lines whose relative speed is to be determined. From a pedagogical point of view, this has the advantage of allowing students to understand the cosmological redshift as a special-relativistic Doppler shift. It also allows students to understand the apparent energy loss of photons of the cosmic background radiation as a matter of viewing one and the same photon from two reference frames which are in relative motion. In both cases, the explanations are in line with students' previous knowledge about special relativity. While the full general-relativistic version of this definition of relative speed requires advanced knowledge of general relativity, toy models can serve to introduce instructive examples to an undergraduate and even to a high-school audience: the Milne universe or, alternatively, toy models based on a small number of inertial systems in relative motion within special relativity.

References

[1] M. Pössel 2018a, Eur. J. Phys. in press, arXiv:1811.09524 [gr-qc]
doi: 10.1088/1361-6404/aaf2f7
[2] M. Pössel 2018b, arXiv:1812.11589 [gr-qc]

Poster 1.02

From the EP to the curved space

L. Galante[1] , **I. Gnesi**[2]

[1]*University of Torino, Torino, Italy; INFN, Torino, Italy; Enrico Fermi Historical Museum of Physics and Study and Research Centre, Rome, Italy.*
[2] *Unical, Arcavacata di Rende, Italy; INFN LNF Gruppo Collegato di Cosenza, Italy; Enrico Fermi Historical Museum of Physics and Study and Research Centre, Rome, Italy.*

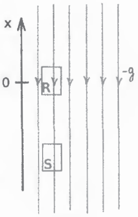


Fig.1

The EEP is a bridge between the Doppler effect and the gravitational Redshift [1] leading to the conclusion that two separate points in a uniform gravitational filed experience a redshift:$\lambda_R = \lambda_S \cdot (1+\beta)$. Where λ_R is the wavelength (WL) of a signal received at a distance x above the emitter S and $\beta = -\frac{g}{c^2}x$ is proportional to the distance x separating R and S and to the intensity g of the gravitational field (Figure 1). Considering the two WLs as distance elements dx, the redshift formula gives the opportunity to establish how an observer, embedded in a uniform field, perceives lengths of objects at a distance x above or below him: $dx' = (1 - \frac{gx}{c^2}) \cdot dx$. Where dx' represents the perceived length of an object with length dx placed x meters away from the observer (above $x > 0$ or below $x < 0$). We thus have: $dx' = g(x) \cdot dx$, where $g(x) = 1 - kx$ and $k = \frac{g}{c^2}$. Since the gravitational field has no components along the y and z axes, we can define the space metric as a diagonal matrix with elements: $1 - kx, 1, 1$. Receiving signals from above, or measuring distances above him, the observer finds a contration ($0 < g(x) < 1$), since signals are "falling" to him. On the other hand, if the signal comes from below the observer experiences an expansion ($g(x) > 0$). Starting from the classic formula for the acoustic Doppler effect and going throught the EEP we can achieve a simple derivation for the space curvature induced by a uniform field. The mathematics involved is quite simple (straight lines and parabolae). Furthermore the acoustic Doppler effect is probably taught in every country at secondary school level and can be easily verified with gym activities. For example running toward an acoustic source with a tablet which perfomes the spectrogram of the received signal (Figure 3).

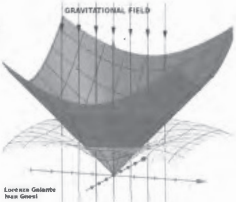


Fig.2. The green surface repesents how the red cone would be perceived by the observer placed in the origin.

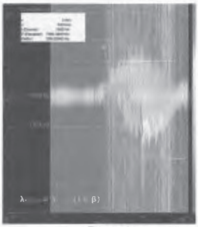


Fig.3. The Doppler effect measured running with a tablet.

References

[1] S. Carroll, **Lecture notes on GR**, p. 102 (1997)

Poster 1.03

Teaching General Relativity using ruler and calculator: An interactive workshop based on the Shapiro effect

H.-P. Nollert

University of Tübingen, Germany

Unfortunately there are no experiments about General (or even Special) Relativity suitable for the classroom. This tends to give Relativity the appearance of a theory which is very abstract and hard to comprehend.

As a kind of second-best approach this poster describes a workshop which is based on an actual measurement, the Shapiro effect. After participating in this workshop, students will be able to compute a realistic value for this important test of General Relativity using nothing more than a ruler and a pocket calculator. On the theoretical side, dealing with the scale of a map is basically all that is required.

The core concepts behind the workshop are the meaning of a map and of its scale, i.e. the metric. Other aspects of the theory, such as geodesics, the role of coordinates, field equations, etc. can be introduced at the discretion of the teacher, but are not required for a successful participation in the workshop.

The workshop proceeds with these major steps:

1. Introduction: What is the Shapiro effect?
2. Establish the metric as the scaling of a world map
3. Using the metric of the equatorial plane of a non-rotating black hole
4. Extend the concept of scale/metric to gravitational time dilation
5. Use the metric of space-time in the vicinity of the Sun to obtain a realistic value for the Shapiro effect

Poster 1.04

THE MILNE UNIVERSE

by Richard Toellner

Berufliches Gymnasium St. Klara, Weggentalstr. 24, D-72108 Rottenburg

"Is the Universe finite or infinite?" This question asked by participants of an astronomy workshop at the Gymnasium Josephinum in Hildesheim ended up to a model which turned out to be very similar to the Milne universe[i]. By testing this model in two advanced courses in physics the students had to learn about different topics like special relativity, Bohr model, background- and blackbody radiation.

A Minkowski diagram of the universe

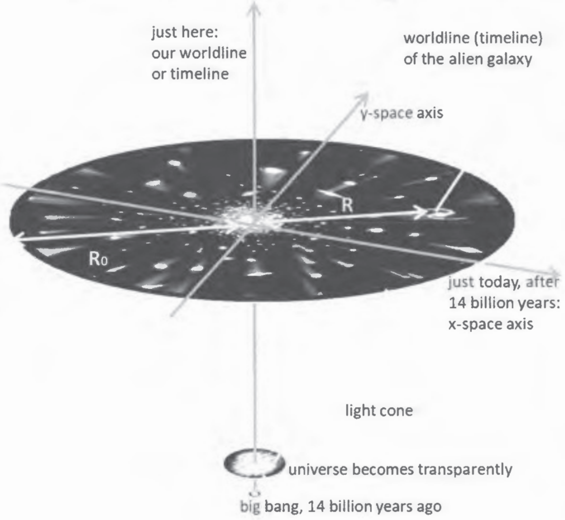


Figure 1:
The space is expanding during the time.
The „worldline" marks the position of a resting observer.
The ratio R/R_0 is equal to the recession velocity v/c of the alien galaxy according to Hubble's law.
In this scetch the aliens would have 80% of speed of light!
However, the situation ist symmetric relative to us as special relativity shows.

Time goes slower on the aliens' timeline (Lorentz transformation). If they are as old as we are (14 billion years) then their just-today-axis (x-space axis) ist not parallel to the x-space axis of us. But it has the same radius R_0, exactly as we do.
Therefore, the situation ist symmetric and the universe ist finite with radius R_0.
If we mark all 14 billion year points in proper time on every worldline crossing our x-y-space area we will get a rotation hyperboloid converging to the light cone.
Therefore, the universe ist infinite.
The universe is both, finite and infinite, at the same time.

---

[i] Explaining cosmology with special relativity: Piecewise inertial frames as toy models for cosmic expansion, by Markus Poessel_Haus der Astronomie and Max Planck Institute for Astronomy, Koenigstuhl 17, 69124 Heidelberg, Germany (Dated: March 11, 2017)

Poster 1.05

Embedding Diagrams and Other Hands-on Activities for Teaching Curvature

M. Ryston[1]

[1]Department of Physics Education, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

Curvature is a key concept in General Relativity, illustrated best by the very succinct formulation of GR by Hartle [1], which begins: '*Gravity is curvature of spacetime,...*'. As such, it is beneficial to spend some time developing the idea of curvature when teaching GR. However, as it is the case with most of relativity, curvature is a very abstract concept, the mathematics describing it is nontrivial and furthermore, most students do not encounter curvature in the mathematical sense before they study GR.

To overcome this difficulty of understanding curvature when presenting secondary school students with GR, we use ordinary objects and 3D-printed models of general shapes, such as spheres, cones and most importantly the Flamm's paraboloid[1] (more commonly known as the embedding diagram for the equatorial plane of Schwarzschild spacetime) to illustrate some basic concepts of curvature and how it relates to, for example, the motion of planets around a star. There are also other teaching aids such as small "motorbikes" that have been made using a 3D printer to allow the students to make simple tangible "experiments" in the area of GR.

A series of such simple experiments including some generally known ones (such as folding a section of paper to create a cone, drawing curves on a beach ball, etc.) has been put together to present the concept of curvature to secondary school students. The poster will introduce these activities as well as some experience from presenting the activities to students.

References

[1] HARTLE, James B. General relativity in the undergraduate physics curriculum: An unconventional overview of relativity theory. *American Journal of Physics*. 2006, 74(1): 14. DOI: 10.1119/1.2110581. ISSN 00029505. Available at: http://link.aip.org/link/AJPIAS/v74/i1/p14/s1

---

[1] Coincidentally, this paraboloid has become the icon and the go-to graphical representation of GR, therefore it is important to include it in our exposition of GR.

Poster 1.06

Educational experimentation and simulations for teaching General Relativity. Implementation and Evaluation

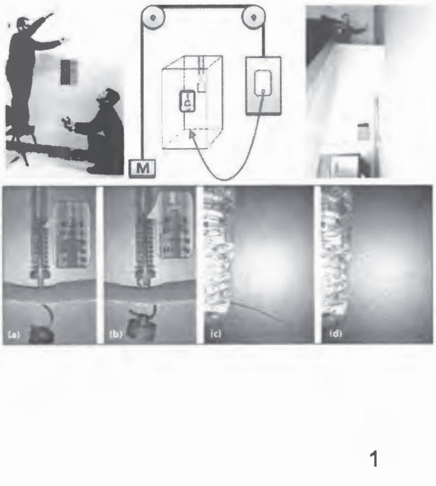
E. Kapotis[1] **and P. Tsakonas**[2]

[1] *National and Kapodistrian University of Athens, Athens, Greece*
[2] *University of Piraeus, Piraeus, Greece*

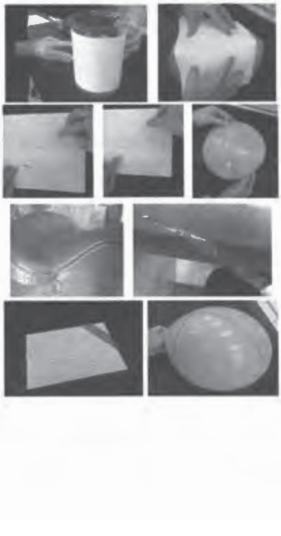
Bearing in mind common misconceptions and points of difficulty of the theory of General Relativity, we implemented a series of experimental configurations, implemented with readily available and/or simple-cheap materials, in order to support teaching to second grade and undergraduate students. We completed our approach by designing and developing a series of interactive Learning Objects (LOs) simulating phenomena and principles of General Relativity that cannot be approached with actual experimentation by students. These open source LOs, published over the internet, are suitable for aiding teaching in the classroom, e-learning programs and self-study through code modification.
Our educational proposal incorporates experimentation and teaching methodologies aiming to facilitate students in overcoming conceptual difficulties, recorded in previous work of other researchers or of our own. We tested the proposed material on 50 undergraduate students of the Faculty of Primary Education in National and Kapodistrian University of Athens. The evaluation process was carried out in terms of learning outcomes, compared to traditional teaching approaches. We recorded a statistically significant higher level.

Indicative real experiments:

Einstein's elevator for the Study of the Equivalence Principle (self-construction)

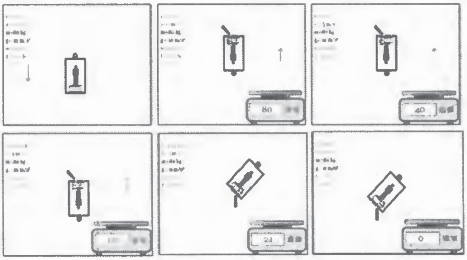


Curvature and shortest path location in curved spaces

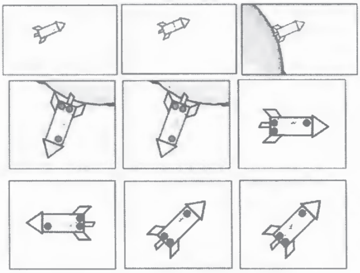


Indicative interactive computer simulations:

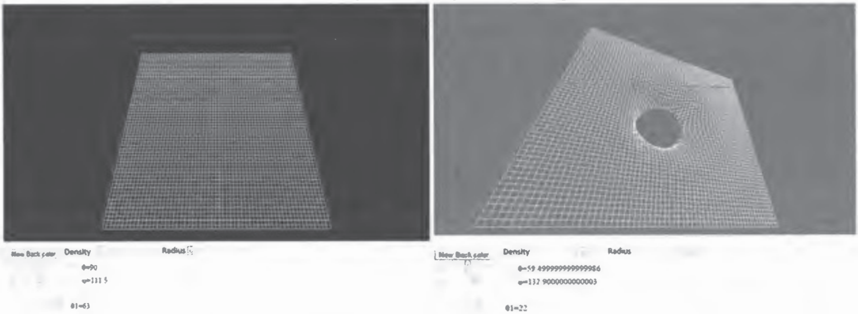
Einstein's elevator



Particles and photons trajectories - Clock rate



Curved space-time paths tracing



θ=90
φ=111.5
θ1=63

θ=59.499999999999986
φ=132.9000000000003
θ1=22

References

[1] E. Kapotis & G. Kalkanis, The Physics Teacher, **54(7)**, 404-407 (2016)

[2] D. Gousopoulos, E. Kapotis & G. Kalkanis, ESERA Conference Proceedings, **1**, 169-175, (2015)

Poster 1.07

Virtual Sector Models (ViSeMo)

S. Weissenborn[1], **Norman Görsch**[1], **Ute Kraus**[1] **and Corvin Zahn**[1]

[1]*Hildesheim University, Hildesheim, Germany*

Despite general interest in and fascination for, the theory of general relativity has not yet entered high school education. Explanations commonly given in edutainment programs may further broad understanding of the subject, but often they are not as precise and accurate as required for a school environment. To face this deficit, a novel approach, based on so-called sector models, makes it possible to teach the basic principles of the theory of general relativity to high school students without the need for higher mathematics ([1], [2], [3]). The presented project complements the existing work with a new digital realization, giving faster, location-independent access to the virtual variant and adding purpose-built methods.

To ensure the effectiveness for learning of the digital course materials, the research for this approach is founded on design-based research concepts, iteratively cycling through design, practice, analysis and redesign, thereby utilizing data-gathering methods, e.g. questionnaires for teachers and the technique of probing acceptance ([4]).

References

[1] C. Zahn, U. Kraus, Sector models —-a toolkit for teaching general relativity: I. Curved spaces and spacetimes, Eur. J. Phys. **35** 055020 (2014)

[2] C. Zahn, U. Kraus, Sector models —-a toolkit for teaching general relativity: II. Geodesics, Eur. J. Phys. **40** 015601 (2018)

[3] U. Kraus, C. Zahn, Sector models —-a toolkit for teaching general relativity: III. Spacetime geodesics, Eur. J. Phys. **40** 015602 (2018)

[4] W. Jung, Probing Acceptance, A Technique for Investigating Learning Difficulties, in: R. Duit et al. [eds.]: Research in Physics Learning: Theoretical Issues and Empirical Studies, Kiel: IPN, pp 278 – 295 (1992)

Poster 1.08

Developing a teacher professional learning workshop on General Relativity

S Farmer[1]

[1] *Institute of Physics, London, UK*

The development of a teacher professional learning workshop to support the General Relativity section of the Scottish Qualifications Authority (SQA) 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 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].

References

[1] SQA, Advanced Higher Physics Course/Unit Support Notes, (2015)
[2] Perimeter Institute, GPS and Relativity, (2010)
[3] Perimeter Institute, Revolutions in Science, (2013)

Poster 1.09

Teaching 2nd Year Undergraduates how to Derive and Study the Geodesic Equations for the Schwarzschild Black Hole

Michael T. Schultz

Utah State University, Logan, Utah, USA
Department of Mathematics and Statistics
Email:

A major obstruction for beginning undergraduate students interested in General Relativity is the sheer difficulty of the necessary computations and differential equations involved. My poster demonstrates my experience and curriculum developed for teaching 2nd year undergraduate students about General Relativity in an Ordinary Differential Equations class. My curriculum teaches students about the calculus of variations, Noether's Theorem, and how to compute the geodesic equations for the Schwarzschild Black Hole. Using the computer program Maple, my students solve the reduced geodesic equations for freely falling bodies constrained to lie in a spacelike two-plane and plot the resulting geodesics in 2+1 dimensions. This allows for a discussion of properties of the event horizon for an external observer and illustrates important consequences of General Relativity and Black Hole physics, all accessible and understandable to students at this level.

Teaching of general relativity at the University of Zululand

A. Beesham[1]

[1]*University of Zululand, Kwa-Dlangezwa, South Africa*

At the University of Zululand, there are two modules in which relativity is taught as part of a three year B Sc degree. The Department of Physics teaches a module entitled "Mechanics, Special Relativity and Properties of Matter" at the second year level. An introduction to special relativity is provided, which involves the Lorentz transformation, Doppler effect, energy and momentum and space-time diagrams. Approximately 12 lectures and 12 tutorial periods are spent on the module, so it is a very elementary introduction.

The Department of Mathematical Sciences offers a third year module "Tensor Analysis" comprising 36 lectures and 36 tutorials. The topics covered are tensors, electromagnetism, Christoffel symbols, Riemann, Ricci and Einstein tensors and coming up to the field equations of general relativity. A textbook that we have found very useful is "Flat and Curved Spacetimes" by Ellis & Williams, which is written at a very elementary level, but has 3 appendices which are suitable at the senior undergraduate level. After the student has mastered calculations by hand, we introduce them to computing using maple and grtensor.

We discuss the problems students face in making the transition from Newtonian mechanics to special relativity and ways in which we can help them to overcome this hurdle.
The abstract should be headed by a **title**, **name(s) and complete address(es) of the author(s).** Please underline the name of the author who will present the paper and leave a 3.0 cm margin on top and 2.5 cm margin on all other sides. As font you should use Arial or Helvetica, 12pt with a line spacing of 16pt. The abstract can contain Figures, Tables and References, but the length of the abstract should not exceed **one** DIN A4 page. Please note that coloured abstracts will be converted to black-and-white.

References

[1] G. F. R. Ellis, Flat and Curved Spacetimes, Clarendon Press (2001).

Poster 1.11

Derivation of Schwarzschild metrics using differential forms

E. Kogan

Bar-Ilan University, Ramat-Gan, ISRAEL

The differential forms provide a more efficient method to calculate curvature than the more traditional method of first working out the Christoffel symbols. The Christoffel symbols are 3-indexed objects. While the connection 1-form ω also nominally carries 3 indices, the indices are of two types, and so in reality, one has to handle either a 1-indexed object or a 2-indexed object, depending on how you look at it. Besides, the 1-form is antisymmetric in its indices, while a Christoffel symbol is symmetric in its two lower indices. In general, an antisymmetric object (lots of vanishing components!) is much easier to deal with than a symmetric one.

Schwarzschild metrics was the first exact solution of Einstein equations in vacuum. It remains, arguably, the most important such solution and, certainly, the most important metrics for teaching General relativity. In spite of the fact that the form of the metrics turns out to be quite simple, the derivation of it, at least the traditional derivation using the Christoffel symbols, is quite long and cumbersome. We present the derivation of Schwarzschild metrics using differential forms, which is substantially shorter and, as our experience shows, is well accepted by the students.

A Quasi-Newtonian Basis for Studying the Relativistic Cosmology

Yu.V. Dumin

Sternberg Astronomical Institute of Lomonosov Moscow State University,
Universitetskii prosp., 13, 119992 Moscow, Russia
Space Research Institute of Russian Academy of Sciences,
Profsoyuznaya str., 84/32, 117997 Moscow, Russia
E-mail: dumin@sai.msu.ru

The main problem in teaching cosmology at the undergraduate level is usually to make the first step—namely, to derive Friedman equation from the Einstein equations of general relativity—because the most of the undergraduate students are unfamiliar with the corresponding mathematical technique of differential geometry. However, a reasonable way to get around this obstacle can be a quasi-Newtonian derivation of the Friedmann equation for a flat three-dimensional space. This is actually a quite rigorous mathematical treatment, since the general relativity equations are reduced to the Newtonian law of gravity in the weak-field limit. Next, the equations of state for the various kinds of matter can be derived from the special relativity and thermodynamic arguments. At last, the most important properties of the inflaton potentials and the corresponding equations of state of the scalar fields are obtained exploiting some similarities with the Lagrangian formulation of classical mechanics, which is familiar to all physical students from the Course of Theoretical Physics.

As follows from our teaching experience in the Moscow Institute for Physics and Technology (MIPT) since the late 1980's, the above-listed methodology can provide a reasonable basis for studying the physical cosmology—including the inflationary models—by undergraduate students specializing in various branches of physics.

Poster 1.13

Event Diagrams – Supporting Student Reasoning in Space-Time

F. Kamphorst[1], **M. J. Vollebregt**[1], **E. R. Savelsbergh**[1] **and W. R. van Joolingen**[1]

[1]*Freudenthal Institute, Utrecht, the Netherlands*

Like General Relativity, Special Relativity Theory also deals with counterintuitive results and concepts that are far from daily life experience. Both theories revolutionized our conceptions of time and space. The educational challenges for these theories may therefore have a common ground, which means that research in SRT and GRT-education can draw on each other for finding solutions for these problems.

Relativistic phenomena are hard to imagine, since they are far from our daily lives. Reported learning difficulties with these concepts are that students view the relativistic phenomena to be apparent or that they stick to a classical view [1, 2]. Most of these phenomena are direct consequences of strict reasoning with the light postulate. Student understanding of the light postulate, as well of other relativistic phenomena can be enhanced when students understand the relation between the two.

Both drawing and thought experiments have been proposed to close the gap between student understanding and hard to imagine physical concepts. Drawing allows students to make their incoherent thoughts explicit and visible [3], so students can communicate their ideas and to reflect on them. Thought experiments allow both students and scientists to study a phenomenon and its consequences in an idealized, isolated context [2].

The Event Diagram is a representation of space time that allows students to visualize the position of objects and events [1]. With slight modifications, the ED becomes not only a representation of space-time, but also a reasoning tool that supports students to perform thought experiments themselves. By drawing light propagation in the ED, students can explore phenomena like signal travel time and the time and place of events. This way, students can discover that relativistic phenomena are a consequence of the light postulate. We will present this reasoning tool, as well as some results of students working with the diagrams.

References

[1] Scherr, R. E. (2001). An investigation of student understanding of basic concepts in special relativity. Washington: Unpublished Doctoral Dissertation.

[2] A. Velentzas, K. Halkia, International Journal of Science Education **35**, 3026 (2013)

[3] S. Ainsworth, V. Prain, R. Tytler, Science **333**, 1096 (2011)

Poster 1.14

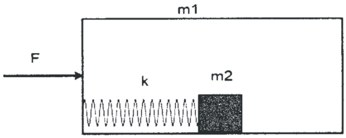
Simple Mechanical Model for Explaining the Increase of the Relativistic Mass

Dr. Essam Zoabi[1] & Dr. Fadeel Joubran[1]

[1] The Academic Arab College of Education in Israel, Haifa, Israel

The concept of velocity dependent mass, relativistic mass (RM), consider as problematic from pedagogical view and even physics view [1]. Moreover, even Einstein was not in favor of using RM, except in his earliest works.
As lecturers and according to [2], we know that one of the difficulties in teaching the special theory of relativity that our pre-service teachers face, is to perceive that velocity affect mass and even increase it according to: $m(v)=\frac{m_0}{\sqrt{1-v^2/c^2}}$

We introduce here a simple mechanical model that demonstrates how mass can vary with speed.
The model is composed of a box of mass m_1 found on horizontal frictionless surface. Inside this box there is a block of mas m_2 which is connected to one end of a massless spring, and the other end of the spring is connected to the wall of the box (see figure).



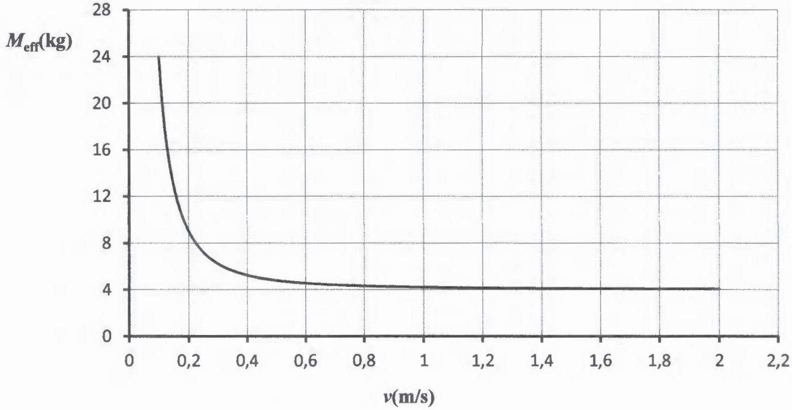
When we apply an external horizontal force F on this system and a work of $W=F\Delta x$ is performed a long a displacement of Δx, we can show that the following relation is fulfilled:

$$(1)\qquad F\Delta x=\tfrac{1}{2}\left(\frac{m_2^2a^2}{kv^2}+M\right)v^2=\tfrac{1}{2}M_{\text{eff}}v^2$$

Where:

$M=m_1+m_2$ is the mass of the system , $a=\frac{F}{m_1+m_2}=\frac{F}{M}$ is the acceleration of the system k is the spring constant. M in our model represents the rest mass (m_0) and M_{eff} represent RM of special theory of relativity. According to Eq (1) M_{eff} depends on velocity.

The following graph shows the variation of the effective mass vs. velocity for the following values: $m_1 = m_2 = 2\,\mathrm{kg}$, $k = 20\,\mathrm{N/m}$, and $F = 4\,\mathrm{N}$.



We conclude that the effective mass changes with velocity. But, in contrary to the relativistic mass it starts from high value and decrease with the velocity to the real mass $M = m_1 + m_2$. Our future challenge is to find a form of interaction between the two masses, m_1 and m_2 that leads to the result that the mass increases with the velocity.

References

[1] Oas, G. https://arxiv.org/abs/physics/0504110v2 . (2005)
[2] Hunkoog, J. New Physics: Sae Mulli. Vol. 64, No. 3,(pp. 281-289). (2014)

Poster 1.15

Relativity on Rotated Graph Paper

R. Salgado[1]

[1] Department of Physics and Astronomy, Colgate University, Hamilton, NY 13346, USA

We demonstrate a method for constructing spacetime diagrams for special relativity on graph paper that has been rotated by 45 degrees. We show that many quantitative results (elapsed times and lengths) can be read off a spacetime diagram simply by counting boxes, using very little algebra. This has been used to teach relativity to undergraduates in an algebra-based introductory class. In addition to solving textbook examples with our method, we show some recent results extending the idea to piecewise-uniformly-accelerated observers.

References

[1] R. Salgado, Am. J. Phy. **84,** 344 (2016)
[2] https://www.geogebra.org/m/HYD7hB9v

Poster 2.01

Analysis and reflection on the teaching of Einstein's theory of gravity in Quebec

S. Boublil and C. Pouliot Ph.D

Laval University, CRIRES, Quebec City, Canada

My Master thesis makes use of the first phase of Michel Artigue's [1] methodology of didactic engineering. This phase is associated with an in-depth epistemological study of content, teaching methods, students' conceptions as well as research conducted in recent years on teaching Einstein's theory of gravity (Norway, Germany, Australia, and others). We also study the current curriculum and textbooks used at various levels in Quebec high schools. We view this approach as a necessary step to unraveling the complexity of the subject as well as the limits to what can learned in classrooms. This theoretical phase prepares us to continue our research at the Ph.D. level which includes an experimental part with more practical solutions (teaching sequences) on how to teach Einstein's theory of gravity.

The ideas developed in Einstein's theory of gravity (principle of equivalence, postulates of special relativity, space-time, spectral shift, acceleration, mass, the geometry of space, etc.) are not included in Quebec's high school curriculum and are seldom dealt with in CEGEPs (preuniversity program). In our province, like elsewhere in Canada, the number of students majoring in physics is in decline. Our research suggests that teaching modern physics should start with Einstein's theory of gravity (general relativity), as it allows students understand relations between many physical notions taught in school. Such an approach would augment student's interest and motivation in physics.

Few researchers are working on this topic leaving us with many open questions: how and at what level Einstein's theories can be taught? What are the difficulties in teaching Einstein's theory of gravity to students of different levels? What teaching theories, methods, and models are to be adapted?

References

[1] M. Artigue, "Ingénierie didactique," *Rech. en Didact. des mathématiques*, vol. 9, no. 3, pp. 281–308, 1988.

Poster 2.02

Design of a prototype for teaching general relativity to upper secondary students

Dr S. Delhaye[1,2], Dr L.G.A. de Putter - Smits[2] and Prof. B.E.U. Pepin[2]

[1] *Jan van Brabant College, Helmond, The Netherlands*
[2] *Eindhoven School of Education, Eindhoven, The Netherlands*

Together with quantum physics, general relativity is one of the major modern theories in contemporary physics. General relativity is not part of the standard upper secondary school physics curriculum in the Netherlands. The goal of our design based research project, is to develop and evaluate curriculum materials on general relativity for upper secondary physics classes, with the research question: What does a design of a prototype for teaching general relativity to upper secondary students in the Netherlands look like?

The design of the materials is based on a set of design principles. These design principles in turn, are based on a literature study, a cursory textbook analysis and three expert rounds with didactical and content knowledge experts. From the literature study and textbook analysis it became apparent that it is possible to teach general relativity at secondary or even primary level [1]. The explanations have to be specifically aimed at the students' skill and comprehension levels [2]. The use of visuals, like graphics, images and animations, increases student engagement and can lead to enhanced learning results. The use of models and visualization techniques can further aid in helping students wrap their heads around the various abstract concepts. Four key concepts of general relativity were proposed based on similar key concepts identified by other authors [3]. These are 1) The principle of equivalence; 2) The principle of relativity; 3) Geodesics and 4) Spacetime and curvature. During two expert rounds, the design principles and the ultimate design itself have been improved and validated. Based on the literature review and the expert rounds, the following design principles have been formulated: *The module* 1) contains appealing contexts, 2) is close to the level of mathematics that can be expected of an upper secondary student, 3) is presented in an age appropriate way, 4) is visually supported, 5) contains hands-on experiences, 6) enables students to study the materials independently from the teacher, 7) is embedded within the current physics curriculum, 8) is appealing and encourages students to read and study the curriculum materials and 9) is structured in a consistent and coherent way.

References

[1] Pitts, M., Venville, G., Blair, D., & Zadnik, M., Research in Science Education **44** (3), 363-388 (2014)

[2] Haddad, W. D., & Pella, M. O., The Journal of Experimental Education **41** (1), 22-32 (1972)

[3] Hartle, J. B., American Journal of Physics **74** (1), 14-21 (2005)

Poster 2.03

Light cones for reasoning about space and time

I. Lawrence

Institute of Physics, London, United Kingdom

A major issue is to figure out a model of space and time and how this has changed from Newton to Einstein.

The poster will sketch out an approach to a two-week long teaching sequence to illuminate some of the central insights of Special and General Relativity based on reasoning with light cones. Light cones will be developed as a representation based on the two postulates of Special Relativity and then used to illustrate the slower ticking of clocks in a gravitational field based on physical evidence rather than on the metric(judged too complex derive from Einstein's field equations). The aim is to illuminate and reify rather than to prove – much like current approaches to Newtonian equations.

For Einstein there are a multiplicity of local witnesses only. There is no global witness to who we can appeal for a privileged point of view. The model of space and time instructs one witness in the procedures to be followed to reconstruct an accurate picture of what another witness will view. These transformations are more complex than the Galilean, but the principle is the same - this is the game that we're playing. It seems essential to establish this epistemological understanding, which is best expressed using a local, rather than global geometry. In characterising the transformations, which are more commonly known as the metric, we should follow Einstein's lead and focus firmly on time. This is not simple and some of the issues in representing duration will surface as a part of thinking about designing the sequence.

The key to the metric is time, determined by the dual postulates of the universal speed and the universality of physics.

From this simple start we might hope to build a didactical path that enables access to reasoning about all or some of the following, within the alllocated time-frame: natural motion; free fall; parabolic motion in uniform gravitational fields; satellite motion in radial fields; black holes; gravitational waves. Just how far teachers and children get will depend on the affordances available before explicitly starting to work on Einstein's approaches.

There will remain a few questions, as the work is in the early stages.

Poster 2.04

Gravitational waves: a vehicle for the integrated teaching of Einsteinian physics

L. Ju and David Blair

University of Western Australia. Perth, Australia

Gravitational wave detectors have enabled observation of black holes, neutron stars and precision testing of Einstein's theory of general relativity. They operate by directly measuring the Riemann curvature tensor. They have opened a new window for us to observe the universe. The detectors operate in the quantum regime, in which noise is optimised through detailed understanding of radiation pressure, quantum uncertainty and quantum entanglement. As such gravitational wave astronomy provides an ideal vehicle and motivation for teaching the full breadth of Einsteinian physics at all levels from primary school to tertiary. This poster will identify the interrelating elements of Einsteinian physics as applied in gravitational wave astronomy, show how they are related, and suggest possible stages in which they could be introduced, developed, and extended into advanced training.

Poster 2.05

Increasing the relevance of high school studies to cutting edge gravitational wave research

C. E. North[1]

[1] *School of Physics and Astronomy, Cardiff University, Cardiff, UK*

As part of the Gravitational Physics research performed at Cardiff University, as part of the LIGO-Virgo Collaboration [1], we designed and delivered a school workshop. The aim is to provide them with information about gravitational waves, and let them investigate, building on skills and knowledge they have developed at school. The content was developed in collaboration with UK-based teachers through the National Space Academy, using cutting edge simulation data [2]. To date, the workshop has been run with around 300 16-18 year old students in schools around the UK.

The evaluation results, of around 200 students in all four regions of the UK, show that they not only feel more knowledgeable about gravitational waves, but that they also feel that their school studies are more relevant to cutting-edge science than they did before the workshop (see Figure 1).

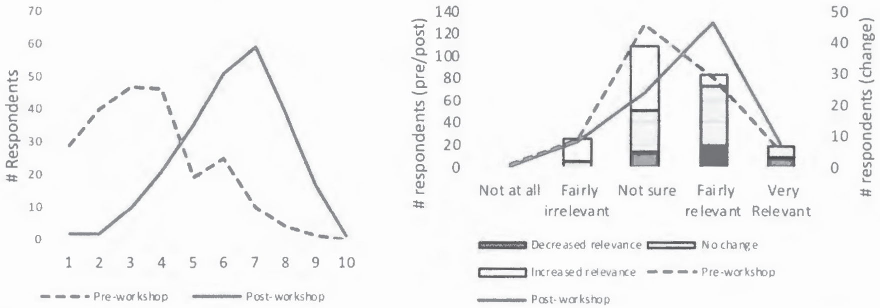


Figure 1 Left: students' assessment of how well they understand gravitational waves, before and after the workshop. Right: students' assessment of how relevant their studies are to gravitational waves before (dashed line) and after (solid line) the workshop, and whether that that relevance increased or decreased (shaded bars) as a result of the workshop.

References

[1] LIGO Scientific Collaboration & Virgo Collaboration, Phys. Rev. X (in press) https://arxiv.org/abs/1811.12907

[2] M. Hannam et al., Phys. Rev. Lett. **113**, 151101 (2014)

Poster 2.06

Integrating Einstein-First Resources with International Collaboration on Einsteinian Physics

Rahul Choudhary[1], Ute Kraus[2], Corvin Zahn[2], Magdalena Kersting[3], Alex Foppoli[1], Tejinder Kaur[1], Ron Burman[1], Marjan Zadnik[1], David Blair[1]

[1]University of Western Australia, Western Australia 6009
[2]University of Hildesheim, Germany
[3]University of Oslo, Norway

There is worldwide interest in introducing Einsteinian physics concepts early in school because of its distinct paradigm shift compared to Newtonian physics. Researchers around the world are developing resources to introduce this early in schools. A group of researchers and science educators are working in close collaboration to introduce Einsteinian physics in schools. The so called Einsteinian physics education research collaboration recently integrated their resources developed independently and trialled it on school students. The resources consist of models, analogies, digital resources, films, 2D and 3D models and craft sheets.[1] [2] [3] When tested on high school students, the initial result shows it to be feasible to introduce at a high school level. Teachers' response where also collected through survey questionnaires. The evaluated response and student performance will be presented in the poster.

References

[1] Kaur, T. et al., Teaching Einsteinian physics at schools: part 1, models and analogies for Relativity. *European Journal of Physics Education* ***52***(6), (2017)

[2] Zahn, C., & Kraus, U., Sector models – A toolkit for teaching general relativity part 1: Curved spaces and spacetimes. *European Journal of Physics,* ***35****(5), (*2014)

[3] Kersting, M. et al., General relativity in upper secondary school: Design and evaluation of an online learning environment using the model of educational reconstruction, *Physical Review Physics Education Research* ***14***, (2018)

Poster 2.07

Teaching Einsteinian Science at Guildford Grammar

Gary Foster

Guildford Grammar School Western Australia; 11 Terrace Road Guildford 6953

Guildford Grammar School is an Independent K-12 co-educational secondary day and boarding school situated in the Swan Valley in Guildford Western Australia.

The lower school science curriculum is based on the Australian Curriculum (the Western Australian version), however, in science there is the opportunity to introduce modules of specialist science topics through our special Catalyst Curriculum. Two of these elective units are:

1. History of the Solar System
2. History of the Universe

Within these Astronomy electives students have the opportunity to study Einsteinian Science concepts which are introduced and taught as a part of these unit programs.

It is anticipated that more of these units will be introduced in the future and possibly a unit dedicated exclusively to Einsteinian Physics.

It is also possible that these elective units might be extended into Year 10 and the Preparatory (Primary) School in the future.

Einsteinian physics is taught also within the Year 12 Physics ATAR course curriculum.

Poster 2.08

Do Modern High School Students Want To Study Modern Physics?

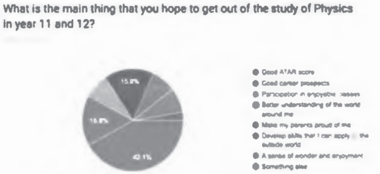
R. Meagher

Mt Lawley Senior High School, Perth, Australia

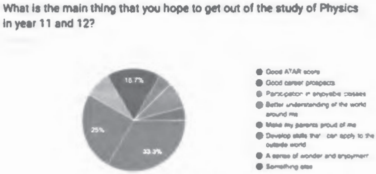
High school students select and study Physics courses for a variety of reasons. As a member of the Einstein First research group and partner investigator with the Einsteinian Physics Education Research (EPER) Collaboration I have been able to expose my staff to professional learning opportunities and our classes to educational interventions with the goal of researching to determine the most effective methods of presenting concepts of General Relativity to school students.

The purpose of this research is to measure the impact of various strategies on the student's understandings of these concepts. Whilst all members of the research groups are in agreement as to the necessity to teach these aspects of Einsteinian Physics, by innovative methods, earlier than traditionally in a student's education, and desire to collect evidence to convince educational authorities of the validity of this necessity I felt that investigation of the attitudes of the students who are studying Physics Courses could also provide some valuable insights. Why are they studying Physics? What do they want from the study of a Physics Course? What questions would they like answered through the study of Physics? Do they actually want to study Einsteinian Physics? To answer these, and other, questions I collected responses from groups of students before and after a series of 6 lesson interventions (2 x Time and Gravity, 2 x Curved Space, and 2 x Quantum Weirdness) in the classroom.

My poster will present and analyse the data collected, as well as make suggestions for subsequent research.



Before Intervention



After Intervention.

Poster 2.09

Comparison Between Israeli and Hungarian Physics High School Teachers' Attitudes Towards GR Assimilation in the Curriculum

Dr. Fadeel Joubran[1] & Mr. Laszlo Varnai[2]

[1] *The Academic Arab College of Education in Israel, Haifa, Israel*

[2] *Padányi Katolikus High school, Veszprém. Hungary.*

On the assumption that any successful change on the curriculum is largely dependent on teachers being positive about it [1], we assessed and compared between 134 physics high school teachers' attitudes, 71 from Israel and 63 from Hungary.

Teachers' attitudes in the two countries were compared by means of an online questionnaire with Likert-type in five issues: degree of past and current GR knowledge, expectations of obstacles in implementing GR in the classroom, degree of importance teaching GR as mandatory, degree of importance teaching GR as internal elective and coping with mathematics difficulty.

We found that the majority of the Israeli and Hungarian physics high school teachers, 69% and 83% respectively, have studied GR in the past. However, regarding to the current knowledge, only 18% and 23% of the Israeli and Hungarian physics high school teachers, respectively, think that their knowledge of GR is good.

Israeli physics high school teachers think that the main obstacle of teaching GR is time pressure, however, the Hungarian physics high school teachers think that the main obstacles of teaching GR are content knowledge and student responsiveness.

When we asked the teachers about the degree of teaching GR as mandatory, only 22% and 26% of Israeli and Hungarian teachers, respectively agreed to its importance. However, when we asked the teachers about the degree of teaching GR as elective or internal, 62% and 36% of Israeli and Hungarian teachers, respectively agreed to its importance.

When we asked the teachers about the gap between GR mathematics and elementary mathematics, 56% and 57% of the Israeli and Hungarian, respectively think that GR could be teachable in high school despite its mathematics complexity.

Regarding the comparison between the two countries, we think that there are some similarities and other differences in teachers' attitudes, due to sociocultural issues and educational system in the two countries [2].

We think that both researchers and education decision makers should take in account teachers' attitudes in any curriculum changes proposal.

References

[1] Foppoli, A., Choudhary, R., Blair, D., Kaur, T., Moschilla, J. and Zadnik, M. Phys. Edu. 54, 1, 015001. (2019).

[2] Jones, M. G., & Carter, G. Handbook of research on science education (pp. 1067–1104). (2018)

Poster 2.10

A comparison between standard courses about general relativity and a model-based approach

Stephan Preiß[1], Thomas Reiber[1], Ute Kraus[1] and Corvin Zahn[1]
[1]*Hildesheim University, Hildesheim, Germany*

The general theory of relativity is one of the foundations of today's physical worldview and should therefore be part of the education of physics teachers and also of the school curricula. We developed a general relativity course for pre-service physics teachers that is model-based and conceptual rather than mathematical. We present a detailed comparison between the contents of a standard course about general relativity (e.g. based on [1]) and our approach. The course is comparatively short, uses only elementary mathematics, and has a focus on the basic concepts and on the physical phenomena. We also present an evaluation of the course based on written exam papers of students at Hildesheim University over several years of teaching the course. The teaching strategy relies on the fact that general relativity is a geometric theory. Graphic constructions are used to study the properties of curved spacetime. This is made possible by the use of sector models [2,3] as tools to represent curved spaces and spacetime true to scale. The evaluation is focussed on students' ability to construct and use sector models.

References

[1] J. Hartle, *Gravity*, San Francisco, Addison Wesley, 2003
[2] C. Zahn & U. Kraus, European Journal of Physics **35 (5)**, article id. 055020 (2014)
[3] U. Kraus & C. Zahn, Astronomie und Raumfahrt **3/4**, 43-49 (2016)

Poster 2.11

Flying through a Kerr black hole – Visualizations

T. Reiber[1]

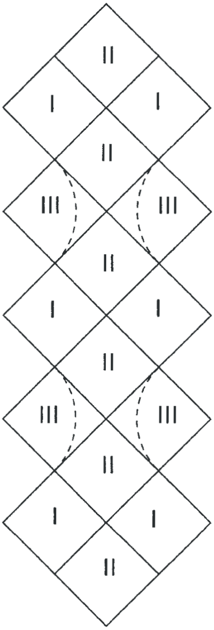
[1]*Hildesheim University, Hildesheim, Germany*

Image-based visualization is an intuitive and rather direct way for teaching general relativity. It is being developed since many years [1,2,3].

We use ray tracing to calculate images and videos in slow Kerr spacetime. In contrast to most of the existing simulations, integration of the light rays is not stopped at the (outer) horizon – causing a “shadow” of the black hole in the calculated image – but continued in a "maximal analytic extension" (see diagram) of Kerr spacetime as first described by Robert Boyer and Richard Lindquist [4] and Brandon Carter [5].

The maximal analytic extension of Kerr spacetime is geodesically complete (with the exception of those geodesics hitting the ring singularity) and contains infinitely many asymptotically flat “exterior” parts (labeled I and III in the diagram).
In extended Kerr spacetime, an observer may pass through event horizons to reach a different asymptotically flat part.

For the visualization we use a background scenery placed at r = ±∞ in the asymptotically flat regions of extended Kerr spacetime.



References

[1] U. Kraus, European Journal of Physics **29**, 1-13 (2008)
[2] A. J. S. Hamilton and G. Polhemus, New Journal of Physics **12**, 123027 (2010)
[3] T. Müller, European Journal of Physics **36**, 065019 (2015)
[4] R. H. Boyer and R. W. Lindquist, J. Math. Phys. **8**, 265 (1967)
[5] B. Carter, Physical Review **174**, 1559 (1968)

Poster 2.12

L'Agape: renewing conferences format

P. Martin-Dussaud

Aix-Marseille Université, Marseilles, France

L'Agape is the name of a format of a physics summer-school. It was invented in 2018 by a group of young physicists (PhD students and post-docs) who wanted to renew the usual format of summer-schools and conferences.

Disappointed by the quality of renowned international physics conferences, facing both the difficulties to afford the fees and to stay awake during talks, l'Agape was first thought modestly as an attempt to create a joyful moment for students to talk freely about theoretical physics, and to re-arouse childish curiosity for these topics. It notably took inspiration from the Rethinking Workshop, another alternative format created in 2013, which took place during several years in a cabin of the Austrian mountains [1].

The goal of this summer-school is to share deep discussions about physics and its foundations in an open and creative way for an intense time of learning, reflection and enlightenment – and all in a joyful atmosphere. To that goal, it proposes an innovative format of summer-school that mixes various activities to improve the quality of discussions and to make learning easier. In all aspects, l'Agape is entirely organised by and addressed to young theoretical physicists (PhD students and post-docs). With up to 17 participants, l'Agape sees a partition between more in-depth courses given in the mornings by some of the students themselves, and radical, open and creative activities in the afternoons (like scientific escape-game, philosophical walks, scientific tales writing...).

The first edition took place in July 2018 in Mézeyrac, a small village lost in the French countryside [2]. Next edition of l'Agape is currently under preparation for July 2019.

References

[1] rethinking-workshop.org
[2] lagape-2018.sciencesconf.org

Poster 2.13

Supporting General Relativity Curriculum Through Teacher Professional Development

A. Strunk[1]

[1]LIGO Hanford Observatory, Richland, WA 99352, USA

Physics curriculum in secondary schools continues to focus on pre 20th century physics. While movements to incorporate modern topics such as particle physics and quantum mechanics into curriculum have met with some success inclusion of General Relativity has been slow and in many schools nonexistent. In the United States many physics teachers lack a physics degree. Even those who have a degree in physics, both inside and outside of the United States, have generally completed minimal, if any, courses in General Relativity. The complex nature of the math necessary to fully understand General Relativity combined with teachers' lack of training makes it hard to successfully introduce the content. Curriculum development is only one piece of the puzzle in addressing the lack of General Relativity in schools. High quality teacher professional development is also needed to assist in the ultimate goal, developed curriculum being successfully realized in classrooms. In July of 2018 LIGO Hanford Observatory hosted its first International Physics and Astronomy Program for Educators. Twenty four teachers from eight countries spent a week learning from experts, and each other. This poster will describe the program, its impact, and what was learned for future programs.

Poster 2.14

Bringing the Virtual Universe Into the STEM Classroom

Magdalena Kersting
(presentation)

Jacqueline Bondell, Mark Myers
(authors)

Swinburne University of Technology, John St. Hawthorn, VIC 3122 Australia

OzGrav developed a Schools Program combining scientific modelling with interactive virtual reality. Mission Gravity allows students to collaborate in teams, creating models of stellar evolution via collecting and analysing data from virtual trips to stars. Students use the principles of Physics and interactive VR to model how stars evolve using virtual scientific tools. To develop this program, OzGrav focused on designing a science lesson that effectively incorporates VR into student-centred activities while aligning with curriculum standards, ensuring pedagogical integrity, respect for the scientific process, and relevant incorporation of VR technology.