General relativity in German secondary schools

Ute Kraus, Corvin Zahn, Magdy Moustafa

Universität Hildesheim, Institut für Physik, Universitätsplatz 1, 31141 Hildesheim
ute.kraus@uni-hildesheim.de, corvin.zahn@uni-hildesheim.de, magdy27@hotmail.de

Abstract

This contribution describes the status quo of the incorporation of general relativity into physics classes at secondary schools in Germany. Secondary school (Gymnasium) curricula and university curricula for pre-service physics teachers (Lehramt Gymnasium) are analyzed with respect to instructional goals related to general relativity. The study includes the secondary school curricula of all 16 federal states and the university curricula of 50 universities nationwide. The general relativity content of the curricula is discussed. with a view to current physics education research on teaching general relativity at secondary school level.

1. Introduction

Relativity is one of the fundamental advancements of physics in the 20th century, the other being quantum physics. However, while quantum physics and special relativity are well established in secondary school, the same is not yet true for general relativity.

To establish the status quo of general relativity in physics classes in German secondary schools, we analyze the school curricula (Gymnasium) of the 16 federal states. We also study to what extent teachers are proficient in general relativity by analyzing the course descriptions of pre-service physics teacher education at German universities. We close with an outlook on current developments in design and testing of educational resources for teaching general relativity in secondary schools.

2. General relativity in secondary school

We have studied physics curricula with a view to the teaching of general relativity in German schools. School curricula being within the responsibility of the federal states, the study includes the curricula of all 16 states. We focus on curricula for the Gymnasium (a secondary school with grades 5 to 12 or 13, i. e., ages 10 to 17 or 18, leading to a general qualification of university entrance), since we do not expect this subject to be taught in other types of school.

The school curricula were downloaded from the official websites of the ministries of education of the 16 federal states. Supplementary documents (guidelines, model implementations) were studied where available. The documents are as at December 2017.

The general relativity content of the school curricula is summarized in tables 1 and 2. We find that four out of the 16 secondary school (Gymnasium) curricula explicitly mention general relativity as a subject taught in physics classes. In one case (Saarland), only the keyword general relativity is mentioned, as a recommended addendum to a unit on electromagnetism. This case will not be considered further. In the other three states (Bremen, North Rhine-Westphalia, Saxony), there are dedicated units on general relativity with time frames of 2, 4, 6, and 8 lessons (à 45 minutes), respectively (where in the case of Saxony, 2 and 4 lessons, respectively, are estimates based on the assumption that the time for the unit on relativity is divided equally between special and general relativity). In all three cases, general relativity is scheduled for grade 11 or grade 12 and is part of the advanced level course, only in Saxony it is part of the standard level course, too. In North Rhine-Westphalia and Saxony, general relativity is a required subject in the advanced level course.

Comparing the descriptions given in the three curricula, we find that there is a single common topic, referred to as gravitational time dilation, gravitational redshift, or experiments with atomic clocks, respectively. Topics mentioned in two out of the three curricula are the equivalence principle and the curvature of space or spacetime. Several keywords are found in only one out of the three curricula: light deflection, precession of the perihelion of Mercury, black holes, big bang theory, impact on physical world view. In conclusion, the topics to be covered strongly differ between the states, and a consensus on the content of a first short introduction to general relativity is not apparent.

In the curricula of several federal states, there are time frames with topics at the teachers' discretion. This provides additional possibilities for teaching general relativity. From personal contacts we know that this possibility is used but cannot estimate to what extent.

State	Grade & Level	Designation of the class	GR topics covered	Ref
North Rhine-Westphalia (NRW)	11/12 AL	Relativity (SR and GR), total: 24 / GR: 8 lessons (*[2]*)	Basic statements of GR: gravitational time dilation, equivalence principle; Gravitation and time measurement (describe qualitatively); gravitation, time measurement and curvature of space (illustrate using models and graphics); impact on physical world view	*[1]*
Saxony	11 AL	Introduction to relativity (SR and GR), 8 lessons	Selected aspects of GR: gravitation and curved spacetime, experiments with atomic clocks, black holes in the universe, big bang theory	*[3]*

Table 1: General relativity in secondary school, as a required subject. (GR: general relativity, SR: special relativity, SL: standard level (Grundkurs), AL: advanced level (Leistungskurs), lesson: à 45 minutes)

State	Grade & Level	Designation of the class	GR topics covered	Ref
Bremen	11/12 AL	General relativity, 6 lessons	Equivalence principle, experimental tests (precession of the perihelion of Mercury, light deflection near the sun, gravitational redshift)	*[4, 5]*
Saarland	11	Fields, Section ‘‘Motion of charged particles in fields’’, 17 lessons	Reference to GR as theory of gravitation and to its significance for astrophysics and cosmology (recommendation)	*[6]*
Saxony	11 SL	Relativity of time and space (SR and GR), 4 lessons	Evidence for the impact of gravitation on light: reference to GR, gravitation and curved spacetime, experiments with atomic clocks, black holes in the universe	*[3]*

Table 2: General relativity in secondary school, as an optional subject. (GR: general relativity, SR: special relativity, SL: standard level (Grundkurs), AL: advanced level (Leistungskurs), lesson: à 45 minutes)

University	Level	Designation of module	GR topics in module description	Ref
U Bremen	M	Theoretical physics 2: mechanics and relativity, 6 credits, 4 SWS	Fundamental aspects of GR	*[8]*
U Kaisers-lautern	B	Theoretical physics 1: mechanics, electrodynamics , 8 credits, 6 SWS	GR	*[9]*
U Stuttgart	B	Relativity, astrophysics, cosmology, 6 credits, 6 SWS	Steilkurs GR, classic tests in the solar system, double pulsar 1913+16, gravitational waves, cosmology based on GR (solution of the field equations, cosmological redshift, models with cosmological constant)	*[10]*

Table 3: General relativity in pre-service teacher education, as a required subject. (GR: general relativity, credits: ECTS credit points, SWS: lessons per week (à 45 minutes, for 15 weeks), B: Bachelor studies, M: Master studies)

3. General relativity in pre-service teacher education

Since teachers’ proficiency in a subject is a prerequisite for its teaching in school, we also study the role of general relativity in pre-service teacher education. Fifty German universities nationwide offer pre-service teacher education (Gymnasium) in physics (*[7]*), see the appendix for a list. They are all included in this study. Study and examination regulations, academic guides, and handbooks of modules were downloaded from the official websites of these universities. The documents are as at July 2017.

The general relativity content of the studies of pre-service physics teachers is summarized in tables 3 and 4. Where relativity was mentioned in a module description, but without further details and not qualified as either "special" or "general", we took this to mean special relativity. This concerns physics education modules on modern physics at U Bayreuth, KIT Karlsruhe, U Köln, and U Oldenburg. These are not included in the tables. We find that nine universities offer general relativity for pre-service physics teachers. In three cases (U Bremen, U Kaiserslautern, U Koblenz-Landau), general relativity is mentioned as a single keyword with no further details, as part of a theoretical physics course on mechanics and electrodynamics. These cases will not be considered further. There remain six universities that offer courses with a substantial general relativity content. The courses are partly on the level of the Bachelor studies (4 cases) and partly of the Master studies (2 cases). In four universities (U Bonn, U Dortmund, U Jena, U Konstanz), pre-service physics teachers can take a standard general relativity course as an optional course. The time frames of these courses vary between 30 lessons and 90 lessons (à 45 minutes), where in the case of U Jena the time frame for general relativity was estimated to be half the course. The remaining two universities combine general relativity with other topics. In the case of U Stuttgart, general relativity is combined with astrophysics and cosmology. In the case of U Tübingen it is part of a course on classical field theory. From the course description, we roughly estimate 30 lessons as the time frame for general relativity in both cases. U Stuttgart stands out with a course that has a substantial general relativity content and is a required course (for students with physics as the major subject of their Bachelor studies).

University	Level	Designation of module	GR topics in module description	Ref
U Bonn	M	General relativity and cosmology, 7 credits, 5 SWS	Aims: Understanding GR and its cosmological implications. Contents: Relativity principle, gravitation in relativistic mechanics, curvilinear coordinates, curvature and energy-momentum tensor, Einstein-Hilbert action and the equations of the gravitational field, black holes, gravitational waves, time evolution of the universe, Friedmann-Robertson-Walker solutions	*[11, 12]*
U Bonn	M	General relativity for experimentalists, 7 credits, 5 SWS	Aims: The students shall learn the basics of GR and be able to apply it to applications such as experimental tests of GR, GPS, astrophysical objects and simple issues in cosmology. Contents: Review of SR, curved spacetime of GR, experimental tests of GR, GPS, black holes, gravitational waves, introductory cosmology	*[11, 12]*
TU Dortmund	M	General relativity, 6 credits, 4 SWS	Equivalence principle, principle of covariance and tensor analysis, covariant formulation and gravitational effects, curvature and curvature tensor, field equations, Schwarzschild metric, tests of GR, stellar structure and gravitational collapse (Oppenheimer-Volkoff equation, Kruskal metric, Eddington-Finkelstein metric, black holes)	*[13]*
U Jena	B	Relativistic physics (SR and GR), 4 credits, 4 SWS	Fundamental ideas of GR, Riemannian geometry, physical laws in Riemann space, field equations, Newtonian limit, Schwarzschild solution, classical GR effects, spherically symmetric stellar models, black holes	*[14]*
U Koblenz-Landau	B	Theoretical physics 1: mechanics, electrodynamics, 7 credits, 4 SWS	GR	*[15]*
U Konstanz	B	General relativity, 10 credits, 6 SWS	Introduction to SR, Riemannian geometry, field equations, predictions of the theory for static fields and comparison with experiments (precession of the perihelion of Mercury, light deflection, gravitational redshift, Shapiro time delay, Lense-Thirring effect), gravitational waves, stellar models (white dwarfs, neutron stars, black holes), cosmology (big bang)	*[16]*
U Tübingen	B	Classical field theory, 9 credits, 6 SWS	Equivalence principle, fundamentals of Riemannian geometry, field equations, Schwarzschild solution, gravitational waves	*[17]*

Table 4: General relativity in pre-service teacher education, as an optional subject. (GR: general relativity, credits: ECTS credit points, SWS: lessons per week (à 45 minutes, for 15 weeks), B: Bachelor studies, M: Master studies)

4. Discussion and Outlook

Among the 16 German federal states, two stand out by featuring general relativity both in school and in pre-service teacher education. Both Bremen and North Rhine-Westphalia have a substantial general relativity contribution in school. U Bremen provides an introduction to general relativity that is presumably short, but is part of a required class for pre-service physics teachers. In North Rhine-Westphalia, two universities (out of 11), U Bonn and U Dortmund, offer general relativity as an optional subject to pre-service physics teachers.

General relativity has been newly introduced into various school curricula in recent years, both in

Germany and internationally, e. g. in Korea, Norway, and Scotland. Concurrently, there is increasing activity in physics education research on the teaching and learning of general relativity in school. This is partly triggered by the increasing role of general relativity in school curricula, and partly based on the conviction that general relativity is a fundamentally important part of the contemporary physical world view that every student should have the opportunity to get acquainted with.

Examples of recent work in general relativity education research include

- an online module designed for Norwegian upper secondary schools ([18]), also available online in English at [19]
- a course for secondary school students centered on student activities using models and analogies ([20], [21])
- courses for secondary school and pre-service teacher education based on the true-to-scale representation of curved spacetimes by sector models ([22], [23], [24]), with teaching resources available online at [25].

An important issue is pre-service teacher education in general relativity. Standard courses in general relativity are aimed at future theoretical physicists and involve learning an extensive mathematical apparatus. Since pre-service teachers in Germany study two subjects plus education science, the time available for studying physics will as a rule not allow for such a comprehensive general relativity course. Teacher education requires a shorter course, focussed on conceptual understanding and on the significance of relativistic phenomena in physics and astrophysics. Physics education research into this question should greatly help to pave the way for establishing general relativity in secondary schools.

Information on any omissions or mistakes in the data presented in this overview is very welcome.

5. References

[1] (NRW) Kernlehrplan für die Sekundarstufe II Gymnasium/Gesamtschule in Nordrhein-Westfalen, Physik, 2014

[2] (NRW) QUA-LIS NRW, Physik, Inhaltsfeld: Relativitätstheorie (LK), 2014 (Umsetzungsbeispiel schulinterner Lehrplan)

[3] (Saxony) Lehrplan Gymnasium, Physik, in Kraft 08/ 2011

[4] (Bremen) Physik. Bildungsplan für die Gymnasiale Oberstufe – Qualifikationsphase, 2008

[5] (Bremen) Handreichung zum Bildungsplan für das Gymnasium – Qualifikationsphase, 2008

[6] (Saarland) Gymnasiale Oberstufe Saar, Lehrplan Physik, 2008

[7] Studien- und Berufswahl 2016/17, Meramo Verlag, 2016

[8] (U Bremen) Physik für das Lehramt an Gymnasien und Oberschulen, Webseite des Instituts für Didaktik der Naturwissenschaften, Modul TP L2, Stand 5.4.2013

[9] (U Kaiserslautern) Studienanleitung Lehramt Physik (u.a.), WiSe 2016/17, Modul TP1

[10] (U Stuttgart) Modulhandbuch Studiengang Bachelor of Arts (Lehramt) Physik HF, Stand: 3.4.2017, module 59030

[11] (U Bonn) Modulhandbuch LA Master Physik, Stand: 25.4.2014

[12] (U Bonn) Module-Handbook Master in Physics, SS 2017, 02/2017, course physics754, course physics768

[13] (TU Dortmund) Modulhandbuch Master Physik für Lehramt an Gymnasien und Gesamtschulen und für Lehramt an Berufskollegs, Stand 06/2010, Modul V1.3_GY

[14] (U Jena) Modulkatalog Bachelor of Science - 128 Physik, PO-Version 2013, Stand 25.4.2017, Modul 128BX521 Relativistische Physik

[15] (U Koblenz-Landau) Modulhandbuch Physik für Lehramtsstudiengänge, Stand: 15.9.2015, Modul 03PH1109

[16] (U Konstanz) Veranstaltungsverzeichnis und Vorlesungskommentar, FB Physik, WiSe 2016/17

[17] (U Tübingen) Modulhandbuch Lehramt Physik in den Studiengängen Lehramt Physik an Gymnasien und Lehramt Sozialpädagogik/Pädagogik und Physik an beruflichen Schulen, Stand 1.12.2014, Modul BMTPKFT

[18] M. Kersting, E. K. Henriksen, M. V. Boe, C. Angell, 2018, Design and evaluation of an online learning environment using the model of educational reconstruction, Physical Review Physics Education Research **14** 010130

[19] The ReleQuant project, University of Oslo, www.viten.no/relativity

[20] T. Kaur, D. Blair, J. Moschilla, W. Stannard, M. Zadnik, 2017, Teaching Einsteinian physics at schools: part 1, models and analogies for relativity, Physics Education, **52** (6) 065012, arXiv:1704.02058[physics.ed-ph]

[21] T. Kaur, D. Blair, J. Moschilla, W. Stannard, M. Zadnik, 2017, Teaching Einsteinian physics at schools: part 3, review of research outcomes, Physics Education, **52** (6) 065014, arXiv:1707.03729[physics.ed-ph]

[22] C. Zahn, U. Kraus, Sector models—A toolkit for teaching general relativity: I. Curved spaces and spacetimes, 2014, EJP **35** 055020, arXiv:1405.0323[physics.ed-ph]

[23] C. Zahn, U. Kraus, Sector models—A toolkit for teaching general relativity: II. Geodesics, 2018, arXiv:1804.09828[physics.ed-ph]

[24] U. Kraus, C. Zahn, Sector models—A toolkit for teaching general relativity: III. Spacetime geodesics, 2018, arXiv:1804.09765[physics.ed-ph]

[25] C. Zahn, U. Kraus, Relativity visualized, www.spacetimetravel.org , www.tempolimit-lichtgeschwindigkeit.de

Appendix

List of universities included in this study, grouped by federal state. Baden-Württemberg: U Freiburg, U Heidelberg, KIT Karlsruhe, U Konstanz, U Stuttgart, U Tübingen, U Ulm. Bavaria: U Augsburg, U Bayreuth, U Erlangen-Nürnberg, U München, TU München, U Regensburg, U Würzburg. Berlin: FU Berlin, HU Berlin. Brandenburg: U Potsdam. Bremen: U Bremen. Hamburg: U Hamburg. Hesse: U Darmstadt, U Frankfurt, U Gießen, U Kassel, U Marburg. Lower Saxony: U Braunschweig, U Göttingen, U Hannover, U Oldenburg, U Osnabrück. Mecklenburg-West Pomerania: U Rostock. North Rhine-Westphalia: TU Aachen, U Bielefeld, U Bochum, U Bonn, U Dortmund, U Duisburg-Essen, U Köln, U Münster, U Paderborn, U Siegen, U Wuppertal. Rhineland-Palatinate: TU Kaiserslautern, U Koblenz-Landau, U Mainz. Saarland: U Saarbrücken. Saxony: U Dresden, U Leipzig. Saxony-Anhalt: U Halle-Wittenberg. Schleswig-Holstein: U Kiel. Thuringia: U Jena.