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Development and Evaluation of a Construct Map for the Understanding of the Expansion of the Universe

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Abstract
The expansion of the universe is one of three pillars of the Big Bang theory and, therefore, an important aspect in cosmology. How the understanding hereof, including the complex concept of an expanding space, is developing, is not yet completely understood. On the basis of a hypothesis of a different study, which constructed a first structural setup of student understanding in this field, we developed it further to be able to reflect students' processes of understanding the concept of an expanding universe. The assignment of open answers of N=126 German students from 11th- and 12th-grade classes (16-20 years old) showed a good classification of these students into this construct with high interrater reliabilities.

Keywords
Construct map, expansion of the universe, cosmology, students' conceptions, learning progression

Introduction

Modern physics should be more integrated into the classroom and, apparently, better approaches for teaching certain topics such as cosmology are needed (Schecker et al., 2004). Understanding the "underpinnings of the Universe can deepen students' sense of wonder and help them appreciate where they come from" (Trouille et al., 2013, p. 1). Cosmology is a very active area of research and the interest of young people is above average as stated in the Relevance of Science Education (ROSE) study (Schreiner and Sjøberg, 2004). A core content in cosmology is the expansion of the universe as one of three pillars of the Big Bang theory, the most successful standard model in cosmology. The idea of a not static universe is "fundamental to modern cosmology" (Wallace, 2011, p. 34) and determines significantly the evolution of the universe and, therefore, has formed our modern scientific worldview. And transferring this to students through science teaching is a frequent request in science literacy discussion (e.g., American Association for the Advancement of Science, 1993; Schecker et al., 2004). But the development of students' understanding of an expanding universe is not yet completely understood. To improve this situation, the first step is usually the development of a construct map. A first attempt of a structural setup was done by Wallace (2011). In our study we developed this idea further. On the basis of open answers of N=126 German students from 11th- and 12th- grade classes (16-20 years old) we developed a construct map for the concept of an expanding universe.

Theoretical Background

The general idea of a construct map is that the development of students' understanding of a concept or characteristic follows a hierarchical order with different levels building up on each other. So a construct map is "a well thought out and researched ordering of qualitatively different levels of performance" (Wilson, 2009, p. 718) and is "designed to help conceptualize how assessments can be constructed to relate to theories of cognition" (p. 717). The different consecutive levels represent a certain level of understanding and include – except the highest level usually – related misconceptions. Examples of construct maps are for instance the model of student understanding of matter (Hadenfeldt & Neumann, 2012), of force and motion (Alonzo & Steedle, 2009), of earth in the solar system (Briggs et al., 2006) and of reading (Lin et al., 2010).

The Berkeley Evaluation and Assessment Research (BEAR) Center develops, among other things, learning progressions. "The core of all of these developments has been the construct map, which is the first building block in the BEAR Assessment System" (Wilson, 2009, p. 716). Furthermore, a key element in the acquisition of scientific literacy is a structured transmission on the basis of central concepts of the respective subject. The systematic teaching requires models of the development of students' understanding (Hadenfeldt & Neumann, 2012). Such construct maps may "ultimately provide the detail needed for teachers to track student thinking over the course of instructional units" (Alonzo & Steedle, 2009, p. 392).

Although there are a few studies investigating different aspects of cosmology such as the age of the universe, associations with the Big Bang or evidence for the Big Bang theory (e.g., Prather et al., 2003; Trouille at al., 2013), there has been very little research about students' understanding of the expansion of the universe in particular. The only present study in this area, which also includes a first attempt of a structural setup of student understanding, is that of Wallace (2011). Students at the beginning of university were asked about the meaning of an expanding universe. About one third of the students actually associated it with a universe increasing in size over time. But other major categories found are 'movements or increasing distances of single objects' and 'formation/creation of new things'. Very striking is a surprisingly large percentage (about 20%) of students stating an association with new discoveries and/or knowledge and not with the universe physically increasing in size, let alone with the expansion of space itself. The latter only being mentioned from just a few percent of the students. Wallace's construct map for the expansion of the universe and the Big Bang is shown in an abbreviated version in Table 1.

Wallace's scoring rubrics for the question about the expansion of the universe include some more details. Level 1 includes students not knowing the universe is expanding, whereas this is the case in level 2. In levels 3 and 4 the concept of an expanding space is already included with the difference in thinking that all objects and not only galaxies move away from one another in level 3. However, this model includes an additional focus on the structure of the universe including the aspects 'center' and 'edge of the universe' as well as the misconception of the Big Bang being an explosion, although it is not clear if there is a correlation. In addition, students were only assigned to the best fitting level. There was no investigation on how well students' responses fit into the construct map concerning how many levels in total fit to one open answer. An open answer can include many different aspects and, thus, could in general be assigned to several levels and not only one. Yet the major focus of the study did

Table 1: Wallace's construct map for the expansion of the universe and the Big Bang (abbreviated version).

Level of construct map	1	2	3	4
Universe is physically expanding in size over time	✕	✔	✔	✔
Only galaxies are moving apart from one another due to expansion	–	✕	✕	✔
Universe has no center	O	✕	✔	✔
Universe has no edge	O	✕	✔	✔
Big Bang as the beginning of expansion (not an explosion)	✕	✕	O	✔

Explanation of symbols: Student states aspect... ✔: correctly ✕: incorrectly O: correctly or incorrectly.

not lie on the development and evaluation of construct maps.

Research Questions

As shown above, Wallace's structural setup of student understanding of the expansion of the universe is not yet tested with respect to a well working assignment of students into the existing levels. The students were assigned to the best fitting level, but their answers could in general fit into more than one level. In addition, it is not clear if there is a correlation between the structural aspects 'center' and 'edge of the universe' and space expansion (see Table 1). That raises the following questions:

1. Is it possible to assign the students to just one or else two adjacent levels on the basis of a further developed and potentially adjusted construct map?

2. Is there a correlation between the misconceptions of the universe having an edge and/or center and the concept of an expanding space?

In order to answer these questions we explored students' open answers to the same question as in Wallace's study.

Method

The study is the re-analysis of data collected in a prior study on students' conceptions of the Big Bang theory (Aretz et al., 2016). Because the basis of construct maps are usually students' conceptions (e.g., Alonzo & Steedle, 2009), in this study we are looking again on part of the data concerning a new aspect, the development of students' understanding of the concept of an expanding universe. One of the questions of the questionnaire in our previous study was taken from Wallace (2011). The students were asked about the meaning of an expanding universe and their open answers enabled us to carry out the intended research.

Sample

Data taken from 11th- and 12th- grade classes (16-20 years old) in German schools was analyzed. The distribution of grades and age of the N=126 students is shown in Table 2. The data was collected from six classes in schools in three different federal states in Germany. Among the schools were five Gymnasiums and one comprehensive school (Gesamtschule). More information about the German school system and school types can be found in TIMSS 2007 Encyclopedia (2008). The distribution of students in age (but also not too large in terms of comparison), gender (about one third were female) and different parts of Germany as well as the number of participating schools represent a good basis for generalizing the obtained results.

Data collection and analysis procedures

The students were asked to answer the following question using their knowledge and/or their ideas: "Explain, in as much detail as possible, what astronomers mean when they say "the universe is expanding"." The students should also briefly indicate when they could not provide any answer at all. The survey was implemented in normal class situations under the supervision of the teacher. The data was analyzed in three steps:

1. Qualitative analysis techniques (Mayring, 2010) were used to develop a set of categories inductively. Each open answer included usually more than one statement, which were the smallest coding units. A statement can be a whole sentence or just a part of a sentence, depending on its meaning and the student's linguistic ability. The following example (translated into English) includes two statements: "Some galaxies are moving apart from each other and the universe gets cooler." Each statement was assigned to exactly one category also by an additional rater with a range of Cohen's Kappa values of [0.88–1]. In the case of the example the two statements were assigned to the cate-

Table 2: Grades and age distribution of our sample of N=126 students.

Age	16	17	18	19	20
11th grade	9,5%	12,7%	4,0%	0%	0%
12th grade	0,8%	15,8%	23,8%	8,7%	3,2%
Not specified[1]	21,4%				

1 There is no data available on the students' age from one of the six schools.

gories 'Expansion of matter' and 'Cooling of the universe' (for more details see Aretz et al., 2016). With Wallace's first attempt of a construct map at hand, we used our developed system of categories to develop the hypothesis about students' development of understanding further in more detail and with the focus on the expansion of the universe. In the next step this so built construct map, which represents actually a hypothesis about the different levels of students' mastery, although it is partly based on previous research, was tested with the help of the open answers.

2. In the second step all statements in the students' 126 open answers were assigned to the levels of the construct map. Subsequently two additional raters assigned the open answers before a comparison of the various coding was performed.

3. Finally it was analyzed to what extent the levels of the construct map fit to the students' answers. Because an open answer could consist of several statements, one open answer could be assigned to more than one level of the construct map. If the levels fit well, students should be situated in just one or else two adjacent levels of the construct map.

Results

The open answers of the students showed interesting conceptions concerning the meaning of an expanding universe. There existed associations with the formation of celestial bodies or orbits of planets growing over time. Many students were talking about the universe growing in size, some in the sense of an expanding space and others in the sense of matter moving in space (away from an explosion). One of the most surprising concepts was the association of expansion with new discoveries or knowledge, respectively. On the basis of the obtained categories from the students' responses of our sample and the construct map for the expansion of the universe and the Big Bang of Wallace (2011) we developed a more detailed and modified construct map with five levels as well as a level zero, which only applies for open answers (see Table 3).

The student's understanding is defined at each level. In addition, the reference of common errors in levels one to four helps to clarify the difference between levels, which indicate existing misconceptions in the corresponding level. Only the highest level (level 5) is free of misconceptions and represents expert like thinking with a scientific understanding of the concept "expansion of the universe". In level one, students connect the expanding universe to anything else but a universe growing in size or increasing distances. In level two students are aware of at least some distances becoming larger, whereas in level three they have already the idea of the whole universe growing in size. But in these levels there is no concept of an expanding space included yet. This changes in levels four and five. In level four students already know that space itself is expanding, but they still have misconceptions like space is expanding everywhere, even inside galaxies. Level five finally represents the current scientifically approved understanding of the underlying concept. At this point students have to show a deeper understanding of expansion by including at least one of the three mentioned aspects and, at the same time, not stating any misconceptions. The following students' responses (translated into English) show examples of answers from our study fitting into the corresponding category:

Level 0: "Unfortunately I can't answer that."
Level 1: "An expansion of the universe exists when 2 or more comets come together to a bigger planet."
Level 2: "That means that the distance between planets and stars is growing."
Level 3: "The matter of the Big Bang is moving in nothing by the explosion."
Level 4: "The space itself pulls somehow apart."
Level 5: "The astronomers mean by that the expansion of space, which started with the Big Bang. A proof for that is the redshift of distant galaxies. If the expansion will go on forever I don't know, but there is nothing outside of the space (so the universe)."

In comparison to Wallace's hypothesis on students' development of understanding, we modified his construct map as follows. We largely took over his levels 0 (included only in his scoring rubrics), 1 and 2, included another level between his levels 1 and 2 and replaced his levels 3 and 4 with two modified ones based on ideas emerging on the basis of our student responses. These showed an intermediate step in their thinking, e.g. by talking only about single distances becoming larger (see level 2 as the result). These kinds of statements include already the idea of a physical expansion of some kind with some objects moving apart from each oth-

Table 3: Construct map for the expansion of the universe.

Level	Description
5	Expert like thinking: Student knows the concept of an expanding space without mentioning scientifically incorrect conceptions and is able to explain correctly at least one of the following aspects: • The whole universe growing in size without having an edge or center • Galaxies remaining their size; expansion of space affects only space between galaxies • Effects on electromagnetic waves (redshift)
4	Advanced thinking: Student knows that expansion means the universe is growing in size due to space expanding itself. Common Error: Space is expanding everywhere, even between stars in galaxies. Common Error: Expansion doesn't affect the light coming from objects in the universe.
3	Everyday experiences in large scale: Student recognizes that expansion means the whole universe is growing in size. However, student believes it is due to matter moving in not changing space. Common Error: The explosion of the Big Bang distributes all matter into the universe.
2	Everyday experiences in small scale: Student recognizes that expansion means distances becoming larger. However, student believes that distances between all different kinds of objects are getting larger and/or only single objects are affected. Common Error: Some stars are moving away from each other. Common Error: Orbits are changing and distances between planets are growing.
1	Guessing: Student does not recognize the connection with a universe growing in size and/or distances becoming larger. Common Error: New discoveries expand our knowledge of the universe. Common Error: Expansion means formation of new objects like stars.
0	Tabula Rasa: Student provides no answer at all, states to have no idea or writes something unrelated to the question.

er, although yet without the conception of the whole universe being affected. In addition, we put emphasis on the differentiation between the idea of an expanding space in comparison to the idea of an expanding universe due to matter moving in space in our two highest levels 4 and 5, which wasn't clearly said in Wallace's construct map, but only mentioned in some of his explanations. For example one student's answer shown in his study, which was assigned to his level 3, didn't include any clear mentioning of space expanding itself (p. 365), but was still placed there. Furthermore, beside the expansion itself, Wallace used mainly the aspects 'center' and 'edge' of the universe for a differentiation of the levels (see Table 1). However, our data showed no connection between the idea of the universe having an edge or a center and the concept of an expanding universe. Instead the vast majority of students' in our study having been ranked even level 4 or 5 still showed the conception of the universe having a center, sometimes also or only in their answers to other questions of our previous study. For this reason we used this factor only as one possible aspect in level 5 to show a deeper understanding of the concept of an expanding space.

With this developed construct map at hand, the open answers of the 126 students were assigned to the different levels described above by two additional raters without providing further text than the explanations in the construct map. Comparison of the coding showed high interrater reliabilities. Overall, the range of Cohen's Kappa values was [0.94-1] (comparison with first rater) and [0.77-1] (comparison with second rater).

Finally we analyzed the fitting between the levels of the construct map and the students' answers. Because an open answer can include more than one statement, it was possible to assign more than one level to one open answer. Twelve of these answers couldn't be assigned at all. One example hereof is (translated): "It develops by and by…". From the remaining 114 students, 91,2% could be assigned in each case to exactly one level of the construct map (see Table 4). The number of statements per student ranged from one to six with most of them providing up to three statements. Seven open answers (6,1%) included statements of adjacent levels of the construct map. Three answers (2,6%) were assigned to level one and three.

Discussion

In this study we described at first the development of a construct map for the concept of an expanding universe. Although it is based on previous research, this construct map is still a hypothesis of the development of students' understanding and therefore needs to be tested further and eventually also adjusted in an iterative process. With our sample we were able to show that, with high interrater reliabilities, most of the students' open answers could be assigned to exactly one of the levels of the construct map. Although in some cases this is trivial due to just one existing statement per student, taken out the students in level 0, who stated to have no idea, about 50% of the remaining students occurring in Table 4 provided more than one statement. The following assignment by two additional raters showed promising results for the application of the construct map, which, nevertheless, should be verified again with a larger sample size.

If one assumes that the progression of understanding is following the structure of a construct map, students should be situated in just one or else two adjacent levels. We showed that this seems to be the case for the vast majority of our sample. Only three students didn't fit into this assumption. One example of these three answers is the following (translated): "The universe increases due to mass which expands. Also new galaxies etc. form". The first sentence was assigned to level 3 and the second one to level 1. Here, interviews most likely would have helped to figure out in more detail, what the students' underlying thinking was behind that statement, and then maybe he or she could have been assigned differently.

Despite the first success with this construct map, it still has to be validated with a larger sample size. Furthermore, the prognostic validation is not yet verifiable. Currently it is not yet clear if students follow exactly along these developmental stages – what doesn't exclude skipping one level in between. In addition, in comparison to other construct maps, like the one for students understanding of "Earth and the Solar System (ESS)" (Briggs et al., 2006), it is not possible to assign a level of the construct map presented here to a certain grade. This is not feasible because the expansion of the universe belonging to cosmology is not part of all curricula and where it is, it can differ very much in content and grade. Therefore, students are assumed to have their knowledge or ideas, respectively, mainly from informal learning (Aretz et al., 2016). A construct map as well as a learning progression is an assumption about student thinking and it's development and as such "expresses a current idea […], which can – and should – be revised in response to new information about student thinking" (Alonzo & Steedle, 2009, p. 393).

Table 4: Assignment of students' open answers to the levels of the construct map.

Level of construct map	5	4	3	2	1	0	1/2	2/3	3/4	1/3
Absolute number of students	1	9	36	13	18	27	3	3	1	3
Corresponding Percentage[1]	1%	8%	32%	11%	16%	24%	3%	3%	1%	3%

1 Based on the 114 assignable open answers, rounded to the nearest percent (therefore, the sum is not exactly 100%).

Conclusions and outlook

The construct map presented in this article for the concept of an expanding universe seems to be promising. Although it could still be revised in the future on the basis of new research in that area, the construct map can now fulfill several purposes. It illustrates the progression of student thinking and, therefore, it can be used as the basis for the development of learning progressions in that field. This construct map could be one of several construct maps for a learning progression in cosmology. Details and illustration about potential relationships between construct maps and learning progressions are shown for example in Wilson (2009). Where this field of physics is part of the curricula it might even be possible to assign the levels of the construct map to certain grades, which would also be very helpful for designing learning progressions.

In addition, the construct map can serve directly for systematic teaching by providing a tool for instructors to plan their lessons accordingly. It can make them aware of students' thinking and prepare them for existing misconceptions. Furthermore, the construct map can serve as the basis for the construction of assessments, which will allow instructors to evaluate their students' current level of understanding as well as the progression during instruction. This construct map allows for example the development of Ordered Multiple-Choice Items (OMC) ¬– the second principle according to Wilson (2009) of the BEAR Assessment System. Because each answer option in these OMC items corresponds to one level of the construct map they will provide more diagnostic information closer to open ended items without loosing the efficiency of conventional MC items. The application of tests including such items makes it possible to assess students' cognitive level of understanding in teaching environments in a quick way, to follow students' progression along the way and to improve instruction and its outcome.

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