Learning about Radioactivity via Synthetic Groupwork in Introductory Physics

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The Inquiry into Radioactivity (IiR) curriculum demonstrated a significant impact on boosting student conceptual understanding of radioactivity, particularly regarding differentiating irradiation and contamination. Although IiR was originally designed to be a group-based inquiry experience, the first author has been developing an asynchronous alternative: Synthetic Groupwork-Based IiR (SynG-IiR). Although IiR was originally designed to fill a physical sciences elective for non-science majors, SynG-IiR is a condensed version designed to last not more than three hours as a stand-alone module for students in introductory physics. Here, we report that the module is comparably effective to IiR not only for asynchronous learners, but also for learners in a face-to-face course as a homework assignment to complete outside of class hours. This suggests that synthetic groupwork-based materials may be a viable option particularly for large-enrollment courses without weekly recitations (*e.g.*, in departments without Learning Assistants and with a small number of Teaching Assistants).

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I. INTRODUCTION

Students generally obtain greater learning gains when peer interaction plays a role in the classroom (*e.g.*, [1–8]). Brown *et al.* [6] argued that groupwork results in insights and solutions that might not arise without the group since groupwork enables students to explore multiple viewpoints, teasing them apart from each other, and discerning which make sense and are worth pursuing. Furthermore, whereas direct instruction and Socratic questioning can constrain a learner's search for novel solutions, groupwork offers a greater freedom in this search, which can stimulate inventiveness and creativity [7]. In recognition of these benefits, many large-enrollment physics classes in the USA have students work in groups, for example using Tutorials in Introductory Physics [8]. At the University of Alaska Fairbanks (UAF), however, Teaching Assistants are scarce, and the creation of a Learning Assistant program [9] remains an ongoing effort; currently, no groupwork opportunities exist other than what students experience in the established (heavily structured) labs. For cases such as ours, we have been developing curricular materials that simulate the groupwork experience and can plausibly provide some of the same benefits. Students complete these synthetic groupwork-based activities at their own timing (*i.e.*, asynchronously).

Hull originally created a synthetic groupwork-based learning module for use with asynchronous algebra-based College Physics 2 (AlgPhys, ~20 students) in 2023. This asynchronous module targets conceptual understanding of radioactivity and is designed to take students less than 3 hours to complete. In 2024, the asynchronous module was used for the first time also with students in calculus-based University Physics 2 (CalcPhys, ~70 students), in place of a homework assignment. By analyzing responses to a conceptual survey administered pre and post-instruction as well as responses to prompts posed in the module itself, we address three research questions:

1) How successful is the asynchronous learning module?
2) How do students perceive the module
3) How might the module be improved?

A. Student understanding of radioactivity

Among student ideas regarding radioactivity (see [10] for a comprehensive literature review or [11] for an abridged review, including [12–19]), the "undifferentiated view" has received the most attention. "Differentiated" students correctly understand that radioactive substances are distinct from the radiation they send out. Interactions of the radiation with the nuclei of victim atoms are generally negligible; as such, irradiation does not generally make other objects radioactive. Students espousing the "undifferentiated" view, on the other hand, lump radioactive material and radiation—and consequently, irradiation and contamination—together into one germ-like substance that is, for most learners, construed to be dangerous and artificial.

Many students also struggle to understand the stochastic nature of radioactivity [12,20]. In particular, many students erroneously assume that if half of a radioactive substance has decayed after one half-life, then half of each individual atom making up the sample must have correspondingly decayed [11,16,21]. Conceptual understanding of these aspects of radioactivity are important to include in the physics curriculum from a scientific literacy standpoint, as it enables citizens to make educated decisions regarding nuclear energy, nuclear medicine, etc. [10]

II. METHODOLOGY

Our asynchronous learning module is based upon Johnson's Inquiry into Radioactivity (IiR) curriculum [22], which demonstrated success at developing the differentiated view in non-science majors [18]. Although IiR was originally designed as a semester-long physical sciences elective, our Synthetic Groupwork-Based IiR (SynG-IiR, pronounced "singer") is a condensed version that learners complete in under three hours. SynG-IiR utilizes a recorded dialogue between two virtual students, Alex and Bailey, as they progress through the guided worksheets that accompany SynG-IiR. This dialogue was scripted by Hull based upon 1) personal experience of listening to in-person student responses to IiR prompts and 2) knowledge of common student difficulties documented in research literature. For each prompt in the worksheets, Alex and Bailey ask the learner for his or her own opinion. Using PlayPosit, the video stops at each of these questions and only continues once the learner submits a response.

In the first part of SynG-IiR, the learner counts how many times the Geiger Muller (GM) counter clicks in a minute when various everyday objects are brought close to the detector to learn (ideally) that radioactivity is ubiquitous (although some things are much more radioactive than others). The learner also (ideally) notices the lack of a pattern in the GM counter clicking and observes that there is some variation in how many clicks are registered each minute, even though the GM counter continues to measure the same object. In the second part of SynG-IiR, the learner examines plots of minute-long readings from the GM counter in an empty classroom to see the extent by which the values vary. Finally, in the third part of SynG-IiR, the learner watches videos showing that, even after 48 hours of being close to uranium glass, a strawberry does not register an increased number of clicks on the GM counter, indicating that the radiation did not make the strawberry radioactive.

Data for this study comes from three student cohorts: 1) AlgPhys 2023, 2) AlgPhys 2024, and 3) CalcPhys 2024. Each respondent was asked on the pretest survey if they had heard the concept of half-life before. Respondents who

answered "no" were removed from the data pool. After additional data cleaning (most notably keeping only students who both completed the pretest and the post-test), 34 students across the two AlgPhys cohorts and 36 students from CalcPhys remained, leaving us with $N = 70$ respondents.

B. Assessment of the asynchronous learning module

We assessed the success of SynG-IiR via analysis of responses to a validated survey [23–26] administered pre and post-learning with the module. The survey includes three prompts to measure student understanding about the differentiated view (DIFF1, DIFF2, and DIFF3, which are each coded as "correct" or "incorrect"), three prompts regarding the ubiquitousness of radioactivity (UBIQ1, UBIQ2, and UBIQ3, also binary coded), and two prompts regarding the stochastic nature of radioactivity (STOC1 and STOC2, each coded with three ranks). Details of the DIFF and UBIQ items are available in our prior report [24] and the full survey is available in the appendix [27]. Rasch scores [28] were calculated for each respondent (ltm package in R Studio) on the pretest and post-test for the DIFF and UBIQ items independently. Since STOC items are not binary like DIFF and UBIQ items are, we used the Rasch Rating Scale Model model (a model in the Rasch family for ordered data) [29,30] instead of the standard Rasch model. In so doing, we stacked the STOC responses on the pretests and post-tests of the 70 respondents. Students who completed the survey both pre and post-learning with SynG-IiR received extra credit. All methods were approved by UAF IRB.

We addressed our first research question: **RQ1) how successful is SynG-IiR?** by looking at student improvement from pretest to post-test. We addressed our second research question: **RQ2) how do students perceive SynG-IiR?** by looking both at post-test responses to prompts asking about student impression of the learning module as well as at transcript from seven interviews of CalcPhys students conducted by Pokharel. To address our third research question, **RQ3) how might SynG-IiR be improved?**, we utilized the methodology discussed in our prior work involving alluvial diagrams [24], as well as the results from RQ1 and RQ2.

III. RESULTS

A. How successful was the learning module?

We addressed our first research question by looking at student improvement on the pretest and post-test. Prior work [24] looking only at AlgPhys students from 2023 found dramatic improvement on the DIFF prompts comparable to IiR in its original semester-long form (differentiated students increased from 20% to 80% [18]). It also found more modest improvement on the UBIQ prompts comparable with traditional face-to-face instruction (Jeidler [31] found that students predicting that a school child would make a GM counter click increased from 14% to 40%). Because the sample size was very small, this growth was measured by attributing 1 point to a student who answered all three (for example) DIFF items and 0 points otherwise. This year, with an increase in respondents, we were able to perform Rasch analysis to determine the relative difficulty of each of the three DIFF items and a corresponding Rasch score for each respondent. This allowed for a more nuanced measure of student growth in these two dimensions.

We found that DIFF2 was the most difficult of the three DIFF items (difficulty = 0.752), followed by DIFF1 (0.183) and then DIFF3 (-0.597). UBIQ2 was the most difficult of the UBIQ items (2.22), followed by UBIQ1 (-1.17) and then UBIQ3 (-1.736). Note that UBIQ2 is a complex multiple choice question, and, as such, is intrinsically more difficult. Table I shows the average Rasch score on the pretest and post-test for the DIFF and UBIQ items. Note that the pretest combined score is 0 because the pretest data was used to develop the Rasch model that the post-test data was then evaluated with. A paired-sample t-test found the growth from pretest to post-test to be statistically significant for all three student cohorts for both DIFF and UBIQ. Effect size, as determined by Cohen's d, was medium ($d > 0.5$) or large ($d > 0.8$) for all three cohorts: the difference between post-test and pretest was at least 0.5 standard deviations. Here, we see that the growth in the DIFF items and, to a lesser degree, the UBIQ items, was not idiosyncratic to a small cohort of students in 2023: in 2024, students in both AlgPhys and CalcPhys also grew in these dimensions.

TABLE I. Average rasch scores and sample standard deviation on survey items administered before ("pre") and after ("post") instruction with SynG-IiR. When the p value of a two-tail t-test was less than .05, Cohen's d ("d") was calculated.

	AlgPhys23 (N = 18)	AlgPhys24 (N = 16)	CalcPhys24 (N = 36)	Combined
Developing the differentiated view (DIFF)				
Pre	0.077±0.7	0.021±0.8	-0.047±0.8	0±0.8
Post	0.959±0.6	0.521±0.9	0.638±0.7	0.693±0.7
p	3.8e-5	.01	1.1e-5	6.1e-11
d	1.173	0.576	0.820	0.843
Learning that radioactivity is ubiquitous (UBIQ)				
Pre	0.001±0.7	-0.036±0.4	0.016±0.5	0±0.5
Post	0.399±0.5	0.378±0.7	0.299±0.6	0.343±0.6
p	.004	.05	.008	1.8e-5
d	0.640	N/A	0.516	0.597

STOC1 and STOC2 were found to be of comparable difficulty (differing by about 0.1 logit—that is, log-odds). Person ability, on the other hand, scanned a range of 3

logits. Since the two STOC items were comparable in difficulty, we divided respondent ability into “low”, “medium”, and “high” if they had a total score on the two items of 0-1 points (49 respondents), 2-3 points (42 respondents), or 4 points (49 respondents). A paired-sample t-test found the growth on the STOC items from pretest to post-test to generally be statistically insignificant: the module in its current form is doing very little (if anything) to improve learners’ understanding of the stochastic nature of radioactivity. This makes the content of SynG-IiR that concerns the stochastic nature of radioactivity a prime candidate for improvement. Additional insights into how the module might be improved come from addressing our second research question, which we now do.

B. How do students perceive the learning module?

On the post-test survey, students were first asked a few questions regarding their impressions of SynG-IiR. In both years of AlgPhys, responses were generally favorable. In CalcPhys, responses were less favorable, and this difference was statistically significant, as found by a Mann-Whitney U Test on each question ($p < .05$). To discuss this difference more clearly, we pool both AlgPhys cohorts into one group.

As can be seen in Fig. 1, in response to the question “*How did you find the module on radioactivity?”,* the students who disliked SynG-IiR in CalcPhys outnumbered those who liked it (14 vs 9). In the online asynchronous AlgPhys courses, on the other hand, this trend was reversed (17 vs 8).

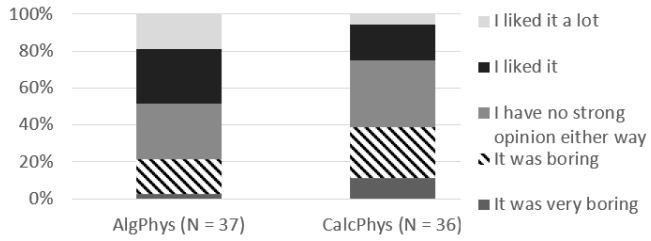

FIG. 1. Student responses on the first item of the post-test asking how students found the learning module. Similar to the other two questions on the post-test about student impressions towards the module, CalcPhys students were generally more critical of the module than AlgPhys students.

Students were also asked to provide *“any and all comments about the learning module.“* In CalcPhys, some students wrote that they prefer the think-pair-share [32]format used in lecture. More common, however, was the criticism that the module was not appropriately challenging. One student, for example, wrote “*I like the idea of doing the synthetic groupwork but it didn't feel like it had as much content as the in person or prerecorded lectures would have.*” Another student elaborated “*The videos only covered how the Geiger Mueller counter worked and that radioactive objects cannot make other objects radioactive. I would have liked to learn more about radioactivity itself. How is it caused? How does radioactive radiation effect* [sic] *objects(organic/inorganic)? How can that radiation be stopped/blocked?*” In particular, some students found the activity of flipping coins in the second part of SynG-IiR to be too childish for them, and many students complained about the tediousness of counting clicks registered by the GM counter for so many objects. These sentiments were captured also in semi-structured interviews of CalcPhys students. When asked "What did you think of the videos of Alex and Bailey about radioactivity?", one interviewee responded “*I thought that they were very interactive, I liked how they had us practice application, I liked the questions embedded…* [but] *I don't think there was as much substance as there would be* [with lecture videos]*.”*

C. How might we improve the learning module?

Many of the students who were most critical of SynG-IiR were not opposed to the idea of synthetic groupwork per se. This suggests that a more advanced version of SynG-IiR can be developed for students in calculus-based physics. Instead of counting clicks for multiple objects, the next version on SynG-IiR will have students count clicks for just two or three objects, and then present them with measured values for the remaining objects. Later portions of IiR that address how radiation ionizes and penetrates various materials will be incorporated into SynG-IiR. In particular, IiR utilizes several computer simulations that could be brought into SynG-IiR to help students “learn more about radioactivity itself.”

As measured on the STOC items of the survey, students in both AlgPhys and CalcPhys learned disappointingly little about the stochastic nature of radioactivity. As such, we combine all data into one 70 student group for the following analysis. Examination of student responses to prompts on the module gives insight into what might have been confusing for students and what might be improved. In the first lesson, after students have been listening to the beeping of the Geiger Mueller counter, students are asked “How would you describe the time interval between the clicks?” with the desired answer being “it is unpredictable”. However, looking at responses to this prompt, it seems that many students misunderstood this question, responding with things like “It is one minute”. A follow-up prompt explicitly asking “Approximately how many clicks do you think you would need to listen to before you could predict when the next click will come?” will be added in the next version of SynG-IiR.

In prior work, alluvial diagrams were created for the DIFF questions to see which module prompts play an important role in student learning and should be further improved. Here, we create an alluvial diagram for the same purpose, but with the STOC items, for which we did not see

statistically significant gains. In the COINS prompt of SynG-IiR, the learner is asked "Do you recognize a connection between the coin flipping and the radiation measurements? What is it?" and then "Is there a cause for the variation in click count each minute?" At this point, many students wrote that there is an element of randomness involved with how many counts are recorded per minute, similar to how many coin flips will turn up heads. A student who responded this way is in an alluvium that passes through the green portion of the middle bar in Fig. 2. For example, the 15 students in the High-1-High alluvium scored the full 4 points on both the pretest and post-test STOC items and explicitly discussed the probabilistic nature of the radioactivity measurements in response to COINS. The 25 students (36%) who did not answer this way (for example, by writing "*I feel that background radiation levels are continuously changing even if it's not by much.*") are instead in an alluvium that passes through the red portion of that bar. Only 5 of these 25 students improved their score from pretest to post-test (students in the Low-0-Mid alluvium who improved their combined score on the two STOC items from 0-1 points on the pretest to 2-3 points on the post-test). On the other hand, we see that students who wrote a desirable response to COINS had at least a 50/50 chance of improving their survey score (compare Mid-1-High with Mid-1-Mid and Low-1-Mid with Low-1-Low). We can thus speculate that, should COINS be improved—for example by following them up with a visit from the TA who would give the correct answer at a point when the student is "prepared to learn" [33]—that at least half of the Low-0-Low students would instead join the Low-1-Mid alluvium.

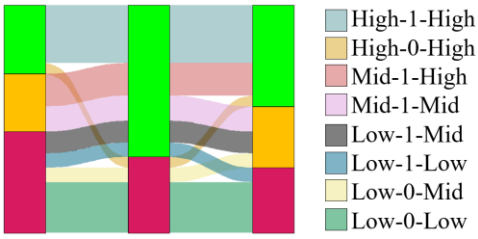

FIG. 2. Alluvial diagram for [STOCHASTIC.PRE – COINS – STOCHASTIC.POST]. Left and right columns show combined score on the two STOC items on the pretest and post-test, respectively (top: 4 points; middle: 2-3 points; bottom: 0-1 points). The middle column shows student response on the COINS prompt (top being a desirable response). Alluvia of < 3 students are not shown.

V. DISCUSSION AND CONCLUSION

In addressing our first research question, we found that most students learning with SynG-IiR successfully came to understand that radioactive objects do not, generally, make other objects radioactive. Furthermore, we found more modest growth in students realizing that everything is already a little bit radioactive. At the same time, we found that students did not grow in their understanding of the stochastic nature of radioactivity, indicating an area in which SynG-IiR can be improved (our third research question). Drawing upon the alluvial diagram-based approach discussed in our prior work [24], we identified a specific point of the module (the COINS prompt) that seems particularly important for student learning.

We addressed our third research question also by considering findings to our second research question, **how do students perceive SynG-IiR?** We found that students taking asynchronous AlgPhys generally reported finding SynG-IiR to be enjoyable. Students in the face-to-face CalcPhys class, on the other hand, generally reported preferring more traditional instruction. It should be noted, however, that much of the criticism from the CalcPhys students was not about the idea of synthetic groupwork per se, but rather that the content discussed in SynG-IiR was not sufficiently rigorous.

With advances in AI technology, synthetic tutors like Khanmigo and aiPlato are expected to play an increasing role in education [34–36]. There are several benefits found in groupwork, however, that should not be forgotten. From a Vygotskian perspective, students learn best within a Zone of Proximal Development [37]. Groupwork allows weaker students to learn from someone who is not so advanced, and so the explanations of the stronger students are more likely to resonate. On the post-test survey, a AlgPhys student wrote *"…the module was very helpful to my understanding as it walked me through not just from the perspective of someone who already knows what I don't*". In the interviews, a CalcPhys student said "*I did like being able to, like, think through with them, I feel like it helped a lot.*" These reports serve as an existence proof that the benefit of learning within a Zone of Proximal Development is something that students can actually recognize in synthetic groupwork.

We are not the first to have students consider an exchange between fictitious classmates. For example, Tutorials in Introductory Physics [8] and Conflicting Contentions Tasks in Tasks Inspired by Physics Education Research [38] have students do this, as does the Modules for Interactive Teaching [39] project in biology education research. To the best of our knowledge, however, we are the first to create an environment in which those fictitious classmates respond to the learner's responses as if the learner were a group member. Our work has been specific to student learning about radioactivity, but we will investigate the creation and assessment of synthetic groupwork for other physics topics. Although synthetic groupwork is most appropriate for asynchronous classrooms, we have shown that it can be used to benefit also in-person physics learners when administered as homework. For physics classes like ours, where a low instructor:student ratio impedes in-person groupwork, synthetic groupwork is a viable alternative.

[1] S. A. Pathak, B. Kim, M. J. Jacobson, and B. Zhang, Learning the physics of electricity: A qualitative analysis of collaborative processes involved in productive failure. Int J Comput Support Collab Learn **6**, 57 (2011).
[2] M. Kapur and K. Bielaczyc, Designing for productive failure. Journal of the Learning Sciences **21**, 45 (2012).
[3] K. Loibl, I. Roll, and N. Rummel, Towards a theory of when and how problem solving followed by instruction supports learning. Educ Psychol Rev **29**, 693 (2017).
[4] T. Sinha and M. Kapur, When Productive Failure Fails. in *Proceedings of the Annual Meeting of the Cognitive Science Society* (2019), pp. 31–36.
[5] B. Kim, S. A. Pathak, M. J. Jacobson, B. Zhang, and J. D. Gobert, Cycles of exploration, reflection, and consolidation in model-based learning of genetics. J Sci Educ Technol **24**, 789 (2015).
[6] J. S. Brown, A. Collins, and P. Duguid, Situated cognition and the culture of learning. Educational Researcher **18**, 32 (1989).
[7] Manu. Kapur, Examining productive failure, productive success, unproductive failure, and unproductive success in learning. Educ Psychol **51**, 289 (2016).
[8] L. C. McDermott and P. S. Shaffer, Tutorials in Introductory Physics. *Tutorials in Introductory Physics*, 1st ed. (Prentice Hall, Upper Saddle River, NJ, 2002).
[9] V. Otero, S. Pollock, and N. Finkelstein, A physics department's role in preparing physics teachers: The Colorado learning assistant model. Am J Phys **78**, 1218 (2010).
[10] M. M. Hull, A. Jansky, and M. Hopf, Radioactivity, Radiation, and Particle Physics in General. in *The International Handbook of Physics Education Research: Learning Physics*, edited by M. F. Taşar and P. R. L. Heron (AIP Publishing, Melville, New York, 2023), pp. 9.1-9.28.
[11] M. M. Hull and M. Hopf, Student understanding of emergent aspects of radioactivity. International Journal of Physics & Chemistry Education **12**, 19 (2020).
[12] H. M. C. Eijkelhof, Radiation and risk in physics education. Radiation and Risk in Physics Education, 1990.
[13] P. L. Lijnse, H. M. C. Eijkelhof, C. W. J. M. Klaassen, and R. L. J. Scholte, Pupils' and mass-media ideas about radioactivity. Int J Sci Educ **12**, 67 (1990).
[14] H. Eijkelhof and R. Millar, Reading about Chernobyl: the public understanding of radiation and radioactivity. School Science Review **70**, 35 (1988).
[15] E. E. Prather, Students' Beliefs About the Role of Atoms in Radioactive Decay and Half-life. Journal of Geoscience Education **53**, 345 (2005).
[16] C. W. J. M. Klaassen, H. M. C. Eijkelhof, and P. L. Lijnse, Considering an alternative approach to teaching radioactivity. in *Relating Macroscopic Phenomena to Microscopic Particles: A Central Problem in Secondary Science Education* (Utrecht CDP Press, 1990), pp. 304–316.
[17] R. Millar, School students' understanding of key ideas about radioactivity and ionizing radiation. Public Understanding of Science (n.d.).
[18] N. DeKay and R. Maidl, Identifying & resolving problematic student thinking about ionizing radiation. in *Proceedings of the 2012 National Conference on Undergraduate Research* (Ogden, UT, 2012).
[19] A. Johnson and R. Maidl, Students Coming to Understand Ionizing Radiation-A Radiation Literacy Challenge. in (National Association for Research in Science Teaching 2014 Annual Conference, Pittsburgh, PA, 2014).
[20] M. M. Hull, A. Jansky, and M. Hopf, Probability-related naïve ideas across physics topics. Stud Sci Educ 1 (2021).
[21] A. Jansky, Die Rolle von Schülervorstellungen zu Wahrscheinlichkeit und Zufall im naturwissenschaftlichen Kontext, University of Vienna, 2019.
[22] A. Johnson, Radiation and Atomic Literacy for Nonscientists. Science IBI Series Winner **342**, (2013).
[23] E. S. Holzinger, The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended, MS Thesis, University of Vienna, 2022.
[24] M. M. Hull, M. Jeidler, and E. S. Holzinger, Simulated Groupwork in an Asynchronous Course Learning about Radioactivity. in *Physics Education Research Conference Proceedings* (2023).
[25] M. M. Hull, A. Jansky, and M. Hopf, Does confidence in a wrong answer imply a misconception? Phys Rev Phys Educ Res **18**, 020108 (2022).
[26] M. M. Hull, A. Jansky, and M. Hopf, Radioactivity as "quintessentially eternal": two survey prompts. Proceedings of the GDCP (Gesellschaft Für Didaktik Der Chemie Und Physik) 2021 Conference 184 (2022).
[27] Appendix. (2024). https://tinyurl.com/5cbzff5e

[28] T. Bond and C. Fox, Applying the Rasch Model. Fundamental Measurements in the Human Sciences. *Applying the Rasch Model. Fundamental Measurements in the Human Sciences*, 2nd ed. (Erlbaum, Mahwah, NJ, 2007).
[29] D. Andrich, A rating formulation for ordered response categories. Psychometrika **43**, 561 (1978).
[30] B. D. Wright, Two-item testing? in *Rasch Measurement Transactions*, edited by https://www.rasch.org/rmt/rmt122b.htm (1998), pp. 627–628.
[31] M. Jeidler, The Influence of "The Radiation Around Us" on Student Conceptual Understanding and Interest, MS Thesis, University of Vienna, 2024.
[32] C. H. Crouch and E. Mazur, Peer instruction: Ten years of experience and results. Am J Phys **69**, 970 (2001).
[33] D. L. Schwartz and J. D. Bransford, A time for telling. Cogn Instr **16**, 475 (1998).
[34] S. Khan, How AI Could Save (Not Destroy) Education. TED (2023).
[35] aiPlato, Democratizing 1-on-1 education. Https://Aiplato.Ai/ (2023).
[36] R. P. dos. Santos, Enhancing physics learning with chatgpt, bing chat, and bard as agents-to-think-with: A comparative case study. ArXiv Preprint ArXiv:2306.00724 (2023).
[37] L. Vygotsky, Interaction Between Learning and Development. in *Readings on the Development of Children*, edited by Gauvain and Cole (Scientific American Books, New York, 1978), pp. 34–40.
[38] D. P. Maloney, C. Hieggelke, and S. Kanim, nTIPERS: Tasks to help students "unpack" aspects of Newtonian mechanics. in *AIP Conf Proc* (American Institute of Physics, 2010).
[39] RIT, Modules for INteractive Teaching (MINT). (2008).