A PERSONALIZED LEARNING TOOL FOR PHYSICS UNDERGRADUATE STUDENTS BUILT ON A LARGE LANGUAGE MODEL FOR SYMBOLIC REGRESSION

AUTHORS

Yufan Zhu, School of Computing, National University of Singapore
Zi-Yu Khoo, School of Computing, National University of Singapore
Jonathan Sze Choong Low, Agency for Science, Technology and Research (A*STAR), Singapore Institute of Manufacturing Technology
Stéphane Bressan, School of Computing, National University of Singapore

AFFILIATIONS

National University of Singapore
Ministry of Education, Singapore
Agency for Science, Technology and Research (A*STAR), Singapore Institute of Manufacturing Technology
National Research Foundation, Singapore
Prime Minister's Office, Singapore

INTRODUCTION

Interleaved practice enhances the memory and problem-solving ability of students in undergraduate courses. We introduce a personalized learning tool built on a Large Language Model (LLM) that can provide immediate and personalized attention to students as they complete homework containing problems interleaved from undergraduate physics courses. Our tool leverages dimensional analysis, enhancing students' qualitative thinking and problem-solving skills for complex phenomena.

OUR CONTRIBUTION

Our approach combines LLMs for symbolic regression with dimensional analysis via prompt engineering and offers students a unique perspective to comprehend relationships between physics variables. This fosters a broader and more versatile understanding of physics and mathematical principles and complements a conventional undergraduate physics education that relies on interpreting and applying established equations within specific contexts.

We tested our tool with equations from Feynman's lectures on physics. The tool accurately identified relationships between physics variables in most equations, demonstrating its potential as a valuable educational resource. This personalized tool enhances students' understanding of complex physics concepts, complementing traditional teaching methods.

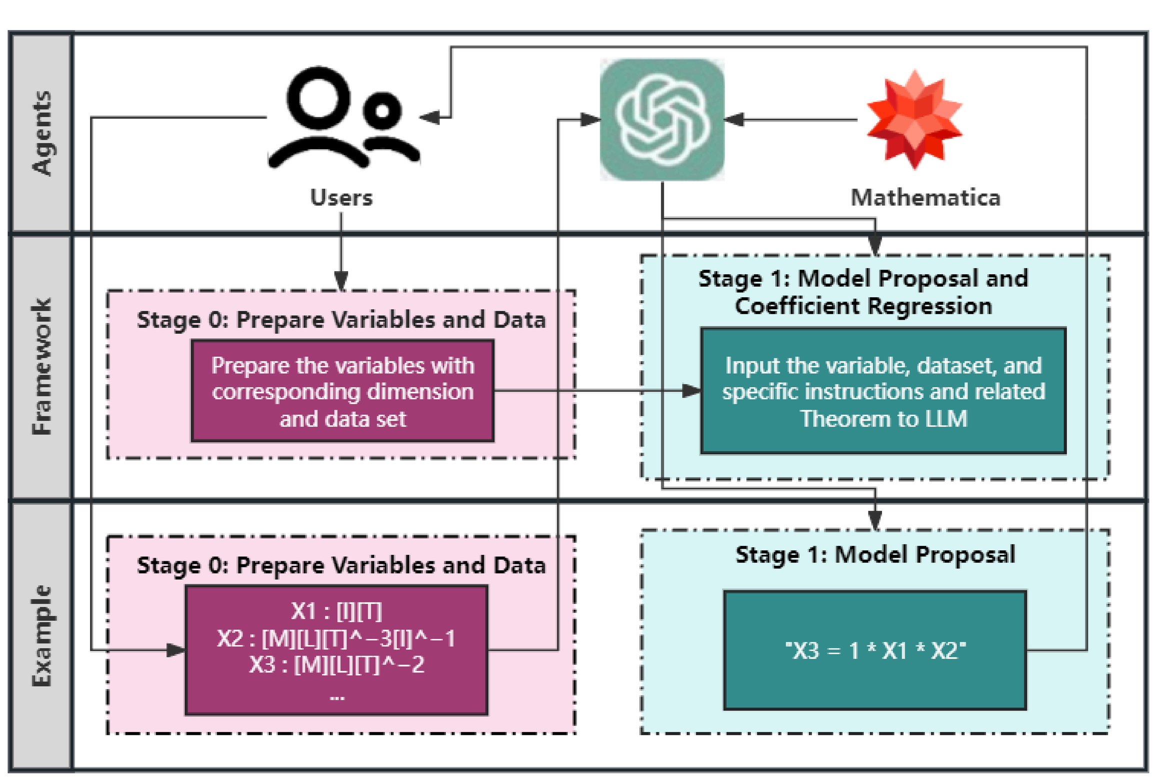
BACKGROUND

Scan Me for Full Paper

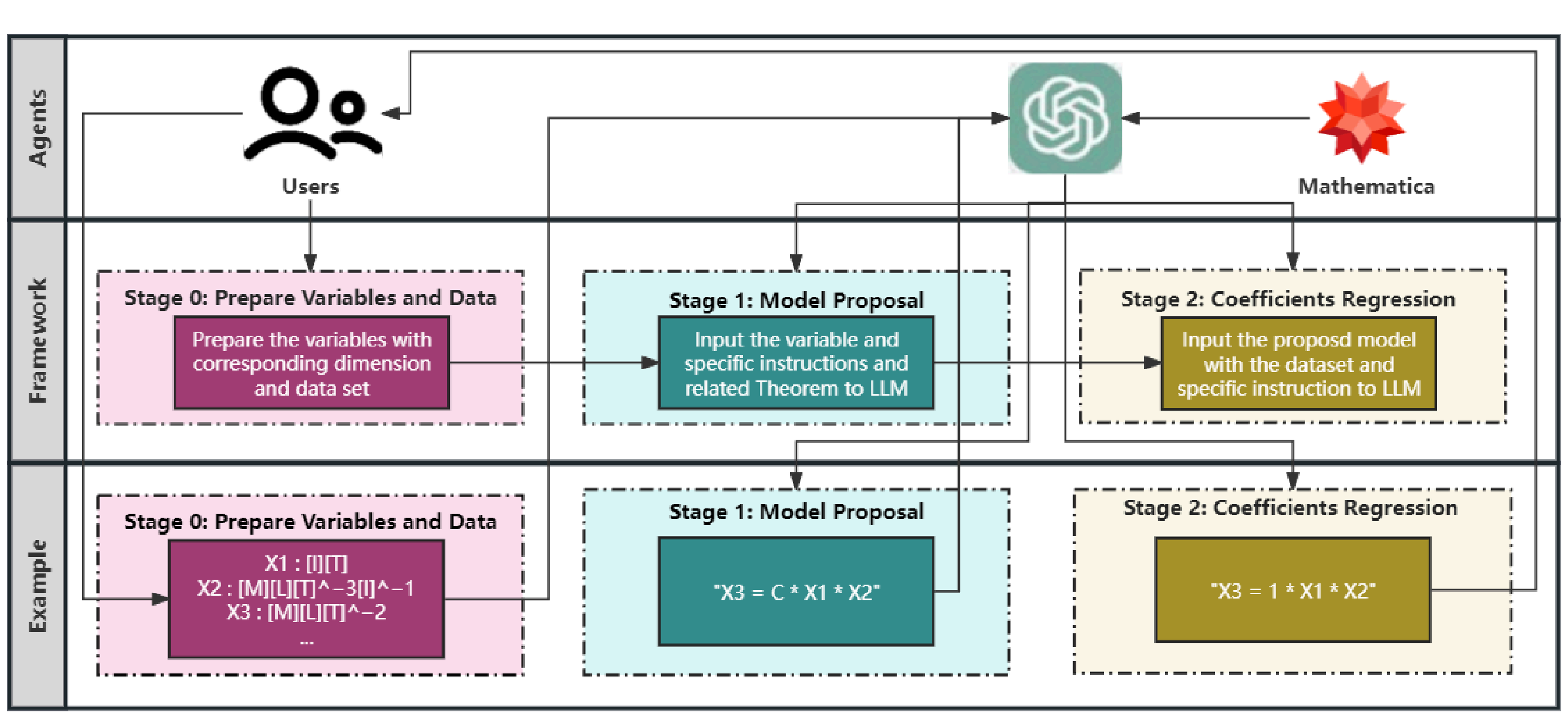
- **Symbolic Regression:** Discover explicit symbolic formulas representing input-output mappings. Find a human-readable expression $y=f(x)$y=f(x) from data. The NP-hard problem requires an extensive search for optimal mathematical expressions.
- **Dimensional Analysis**: Simplify problems by focusing on physical quantity dimensions. Established by Buckingham and Bridgman as foundational in physics. Enhances intuitive understanding of the physical. Rayleigh's Method: Relates dependent and independent variables through dimensional homogeneity, Solves for exponents to form dimensionally consistent equations:
$$R = CR_1^a R_2^b R_3^c \dots R_n^m$$
- **Large Language Models in Physics Education:** Analyze and generate text-based content, aid in problem-solving and explanations. We are solving problems, explaining concepts, and creating exercises. We need to address the challenges of accuracy, reliability, and contextual understanding.

METHODOLOGY

We developed custom prompts to guide an LLM in generating dimensionally consistent physics equations using single-stage and two-stage approaches. Our methods integrate established theorems, such as Rayleigh's method, to enhance the model's ability to generate physically meaningful expressions.



The single-stage approach instructs the LLM to simultaneously propose dimensionally consistent equations and determine their coefficients by fitting the provided data. **The two-stage approach** first generates dimensionally consistent equations and then fits the coefficients using a given dataset.



PERFORMANCE EVALUATION

we used the GPT-4 model with a Wolfram Alpha plugin for enhanced computational capabilities, applying it to 26 equations from the Feynman Lectures on Physics. We assessed the LLM's performance using two metrics: the number of prompts required for generating dimensionally consistent equations and accurately regressing coefficients, and the Mean Absolute Percentage Error (MAPE)

	Methodology						
	Single-stage General Dimensional Analysis	**Two-stage General Dimensional Analysis**		**Single-stage Rayleigh's Method Analysis**	**Two-stage Rayleigh's Method Analysis**		**AI Feynman**
Successfully discovered in One Shot	17/26	22/26		17/26	23/26		26/26
Average No. of Prompts Needed to	Regress expected equation	Propose dimensionally consistent equation	Regress expected coefficients	Regress expected equation	Propose dimensionally consistent equations	Regress expected coefficients	N.A.
	1.885	1.154	1.192	1.308	1	1.192	N.A.
MAPE	105.86%	22.88%		9.95%	3.77%		≈ 0%
Average Time Taken	2m33s	56s	2m42s	2m17s	1m6s	2m40s	18m50s

The Single-stage General Dimensional Analysis method showed robust performance with a success rate of 17/26, while the Single-stage Rayleigh's Method required fewer prompts. The Two-stage methods, particularly the Two-stage Rayleigh's Method, had the highest success rate (23/26), demonstrating superior efficiency and accuracy, with lower Mean Absolute Percentage Error (MAPE) and prompt counts. The Two-stage Rayleigh's Method, combining established dimensional analysis and multi-stage prompting, emerged as the most effective, highlighting its practical utility in complex symbolic regression tasks.

Compared to the baseline AI Feynman, which has a higher success rate but is time-intensive. Our four methodologies consistently discovered equations within 5 minutes. This efficiency makes our tool more user-friendly and accessible, allowing students to receive timely guidance and support tailored to their learning paces.

CONCLUSION

Our research underscores the potential of Large Language Models (LLMs) as innovative and accessible tools in undergraduate physics education. By leveraging prompt engineering and integrating scientific methods like Rayleigh's Method, LLMs enable personalized, data-driven learning experiences that deepen students' understanding of physical phenomena. This approach enhances critical thinking and analytical skills, essential in modern science. Consequently, LLMs emerge as valuable assets in undergraduate physics education, offering new avenues for learning and exploration.

FUTURE WORKS

Future research will focus on applying our methodologies to more intractable systems, pushing the boundaries of what LLMs can achieve in complex physics problems. We plan to test different mathematica plugin and LLMs to enhance response accuracy and speed. Expanding our evaluation to include a broader range of benchmarks will help validate the robustness of our tool. Additionally, we aim to gather feedback from students to refine and improve the tool's effectiveness in real-world educational settings.

ACKNOWLEDGMENT

This research is supported by the Singapore Ministry of Education, grant MOE-T2EP50120-0019, and by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) program as part of the program Descartes.

RELATED WORKS

- Khoo, Z.-Y., Low, J.S.C., Bressan, S. (2023). A Comparative Evaluation of Additive Separability Tests for Physics-Informed Machine Learning. Accepted at the 25th International Conference on Information Integration and Web Intelligence (iiWAS2023).
- Khoo, Z.-Y., Rajiv, G., Yang, A., Low, J.S.C., Bressan, S. (2023). Celestial Machine Learning: Discovering the Planarity, heliocentricity, and Orbital Equation of Mars with AI Feynman. Accepted at the 25th International Conference on Information Integration and Web Intelligence (iiWAS2023).
- Khoo, Z.-Y., Yang, A., Low, J.S.C., Bressan, S. (2023). Celestial Machine Learning. In: Strauss, C., Amagasa, T., Kotsis, G., Tjoa, A.M., Khalil, I. (eds) Database and Expert Systems Applications. DEXA 2023. Lecture Notes in Computer Science, vol 14147. Springer, Cham.
- Chavelli, F., Zi-Yu, K., Low, J.S.C., Bressan, S. (2023). Assessing the Effectiveness of Intrinsic Dimension Estimators for Uncovering the Phase Space Dimensionality of Dynamical Systems from State Observations. In: Strauss, C., Amagasa, T., Kotsis, G., Tjoa, A.M., Khalil, I. (eds) Database and Expert Systems Applications. DEXA 2023. Lecture Notes in Computer Science, vol 14146. Springer, Cham.