A Card Game Revealing the Secrets of the Stars

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Abstract

We present a card game developed by the National Institute for Astrophysics (INAF) to enhance the quality and effectiveness of educational teaching. This game explores the nuclear reactions that power stars and take place in stellar interiors, particularly the proton-proton chain of reactions. It focuses on innovative methodologies and digital solutions to increase student engagement and provide a better educational experience.
The proton-proton chain is a series of nuclear reactions in stellar cores, where hydrogen nuclei (protons) fuse to form helium. This process releases energy in the form of light and heat, while also producing positrons, neutrinos, and gamma rays. These reactions occur sequentially, using the products of one reaction as inputs for the next, and overlapping wherever the necessary reactants are present to sustain them. Understanding how these reactions occur can be challenging, and this game was designed to assist teachers in explaining the physics of stars. In fact, the game consists of a series of iterative steps in which the various cards represent different particles, and the game dynamics closely reproduce the series of nuclear reactions underlying the inner workings of stars.
In this article, we will discuss the various stages of the game design, the reasons behind the decisions that shaped its core algorithm, the artistic choices made, how the game was introduced to the public as part of a broader educational activity – reaching up to 2,000 students in 2024 – and its subsequent digital implementation using Scratch, a visual programming environment created by the MIT Media Lab to promote digital literacy and computational thinking.
The game (the cards and the digital version) is available on Play Inaf, the INAF platform for innovative teaching, particularly in astronomy and astrophysics.

Keywords: *educational teaching, gamification, astrophysics, coding*

1. Introduction

It all starts from the problem: how do you explain complex nuclear reactions to someone who is not a nuclear physicist and has no experience with fundamental interactions or elementary particles, especially in an extreme environment as the core of a star, phenomena that even for the seasoned physicist are challenging to understand.
Stars shine on us, making the night sky fascinating, and the sun brightens during the day, making life on Earth possible and enjoyable. However, the deep physical mechanisms that enable this are far from trivial.
A celestial body can be called a star from when it is heavy enough to start stable nuclear reactions in its core, burning hydrogen into helium with a self-sustained chain of reactions. This chain is called the proton-proton chain because it starts with two simple protons or hydrogen nuclei (removing the electron from the hydrogen, a process called ionization, we are left with a proton). The nuclear fusion reactions involved in the chain take place in an extreme environment, the core of stars, with temperatures reaching ten million degrees and very high densities, and involve some of the most complex particles and fundamental physics. Just having two protons to come close enough to interact requires quantum mechanics effects to happen.
So getting back to our leading problem, how do we explain this to a middle/high school student? The inspiration came from a different type of nuclear reactions, the ones that power radios and TVs in a good part of the world, in particular, from a very famous nuclear reactor, number 4 at the Chernobyl

power plant. We took the idea from the way the chain of events in Chernobyl in 1986 was explained by the physicists during the inquest. They managed to explain a very complex chain of nuclear, chemical, and physical reactions to someone who had never touched a physics book; we followed a similar methodology for our problem.
Forget all the environment, forget quantum mechanics and fundamental interactions, like everything else in the Universe, also nuclear fusion reactions follow the universal rule (applicable only to closed systems, but we assume our Universe is one) that nothing is created and nothing disappears. So what you have before a reaction must in some form appear after the reaction; the global contents of the two sides of the reactions should match. If you consider ionized atoms and particles as simple entities, a blue or green ball or a mixture of the two, with some property described by a number, see the charge of the particle or nucleus, then making a chain reaction becomes a purely logical application. The same number of green and blue on the left should be on the right, as the same total charge on the left, in the end, must be on the right-hand side of the equation, just in a different combination. If the players know what is on the right and have some hints on the process that should happen on the left-hand side then we have a perfect deduction game to play with, something all young minds from middle and high school can play.The game was showcased at the Festival della Scienza di Genova 2024 as part of the Astro-Tamagotchi experience [1,2], engaging approximately 2,000 students and receiving a positive response from the public. The use of games to engage the public into science is widely studied and used, receiving in most of the case a very positive response from the players both in terms of learning experience and engagement and motivation [3-7].

2. The game

Having described the rationale behind it, we now go into the details of the game itself in the following.
The essential chain of nuclear fusion reactions in the proton-proton is:

- proton+proton = deuterium (1 proton, 1 neutron) + neutrino + positron
- deuterium+proton = Helium3 (2 protons, 1 neutron) + Energy (5.49 MeV)
- Helium3+Helium3 = Helium4 (2 protons, 2 neutrons) +Energy (12.96)

with the additional interaction between matter and antimatter (annihilation) of electrons and positrons, which produces energy:

- electron+positron = Energy (1.02 MeV)

These are the chain reactions we want to describe with our game. In total, we have 90 cards, protons (26), electrons (8), positrons (8), neutrons (8), deuterium (8), helium-3 (8), helium-4 (4), and energy cards (8 low energy, 8 medium energy, 4 high energy), the online version has also the neutrino card, we will explain why later on.
The cards are divided into fundamentals, which contain elemental particles mainly on the left side of the reactions, and products, which contain ionized atoms, energy, and in general what can be found on the right side of our reactions at the start of the game.
We simulate the environment of the reactions with a deck of cards that contains fundamental particles that we can find in our average stellar core: protons and electrons. In addition, in the fundamental deck there are also neutrons; they are an intruder, and their presence will be explained in a moment.
The main game is on a board, shown in figure 1, where the reactions are sketched as follows:

- X+X= Deuterium+positron+neutrino
- L1+L2=Energy
- X+Y=Helium3+Energy
- Z+Z=Helium4+proton+proton+energy

The right-hand side of the reactions contains the product cards which depict clearly the composition and electric charge of the product considered. From the composition and charge of the products, the players have to deduce who are the unknown quantities (with the who becoming evident in a moment), position the cards in their hands in the correct place on the board and pick up the corresponding products the reaction created. The products are simple compositions of unknown quantities; the players are also guided by the hints on the cards themselves, the electric charge that must be conserved, and in the end also graphically by colors. This procedure of inverse deduction is very effective, especially for students who are approaching or have just approached equations.
The game proceeds by drawing cards from the fundamental deck. This randomness, i.e. not knowing what will come out, reproduces the randomness inside the core of a star, where a particle never knows who it will meet and when. At those temperatures and densities, it can take up to several years, if not centuries for the right particles to meet and make a reaction. We were planning for a game of

about 10-20 minutes, not really centuries (the card deck to play for centuries would be so significant to become itself a star probably), but drawing 3 electrons in a row when all you need is a proton gives the correct idea that natural processes may need a lot of time as very little, all depending only on chance.
We also have the chance to pick up our intruders, the neutrons. They do not enter into the equations above but may trick the player into an easy wrong solution of the first reaction (which in practice happened). There, it is not a neutron entering the reaction, but is the second proton that mutates into a neutron to form the deuterium. The player can understand this thanks to a hint written in the proton card “I am fundamental, but I can change”. The noise induced by the neutron is helpful to stimulate lateral thinking; the simplest solution is not what often works in nature and offers the teacher the opportunity to explain how the weak interaction, which changes the proton to a neutron, is one of the strangers we have in nature, with a simple example.

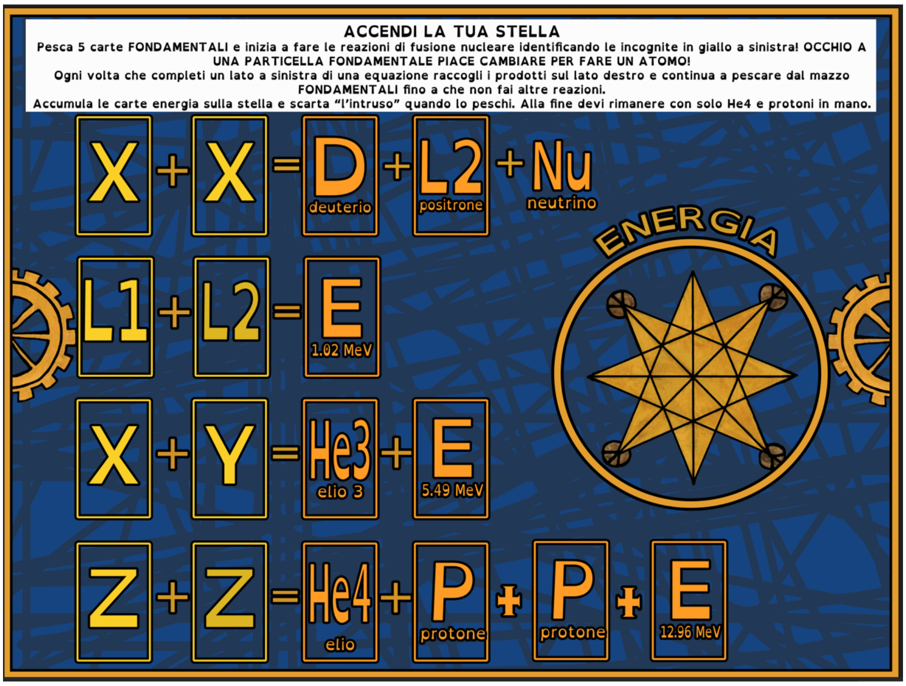

Fig. 1. Board of the game with instructions

The only card that is not present in the board version but only in the online one is the neutrino. The choice of not including a card for the neutrino is driven by the fact that neutrinos escape the star core immediately after the reaction (carrying out energy). Therefore, leaving a card on the board for them would not be correct and gives a chance to the teacher to explain to the students/players how neutrinos work, arousing their curiosity about why a card is missing. In total, we have 7 different types of particles plus 3 levels of energy: protons, electrons, and neutrons, the fundamental; Deuterium, Helium3, Helium4; and positrons, the products. The game is thought to form four Helium4 in the end, repeating the complete reaction cycle four times. We chose four since after testing it resulted in a good balance between repeating the reactions and not losing attention. Cycling helps the player memorize the reactions, repeating in their mind the reactions as a rhyme, which enables mental schemes for improving learning and memorization, and indeed perfectly reproduces the repetitiveness of the actual physical process.

3. When Teaching Science Can Teach a Lesson in Art

Being the main tools of the game, the playing cards had to be appealing, catch the attention of the players, and never be boring. We had to decide on a style choosing between abstract and modern, old fashion, fantasy, etc., but in the end, being the game a piece of the Astro-Tamagotchi experience, we decided on a manga/anime style with a Japanese heritage as the original Tamagotchi. The inspiration is the anime “The Secret of Blue Water ”, in the original *Fushigi no Umi no Nadia* by Hideaki Anno and Hayao Miyazaki, with its steampunk aesthetic and 90s big eyes, angled lines kind of style. Each card represents a particle in the game, neutrinos being present only in the online version, and as the

particles in nature, each is unique, trying to mirror the beauty of humans in the particles playing in our game.
We made a strong point that all the designs had to be done by hand, assembled, and polished with minimal computer graphics, but all the original elements were designed with paper, pencils, and markers.
We chose this avenue, though extremely time and mind-consuming with respect to using an image generation AI because it brought value to the entire experience when nowadays people are surrounded only by AI-generated images. Especially for the youngest who were born in an epoch already dominated by CGI (computer-generated imagery), this overexposure to perfectly smooth lines, eye-pleasing colors, and perfectly likable lighting, too easily produced by AI or GCI, is distorting the perceptions, especially in graphical arts. Without diminishing the values of the "artistic experiences", where AI generators recreate environments that are inspired by art, we wanted instead to show the players the actual art behind the experiences. This is why we got back to the old school by hand mangaka, with compasses, rulers, and even in the digital composition and retouching, we maintained a dirty appearance, disabling all AI helpers and just really correcting things by hand with a digital pencil instead of a carbon one. Some of the original sketches are shown in figure 2.

Fig. 2. Some of the original handmade sketches for the game

We believe the results sort of surprise the players; you have in front something imperfect, with marker signs, mistakes, and stains like in the old anime, something unexpected in a world of AI-perfect images. We hope this can remind the players that the AI in arts is just a very well-trained composer of pieces created by the human artistic spirit, which will be their duty to preserve in the future.
In figure 3 there are the final results for our cards; each has particle name, charge, composition in case of nuclei, and energy value for the energy cards. Protons, electrons, and positrons have hints for the players on their behavior. We already mentioned protons, positrons, and electrons state that if they meet their brother/sister they will start to shine. The two card characters are also meant to be brother-sister-like.

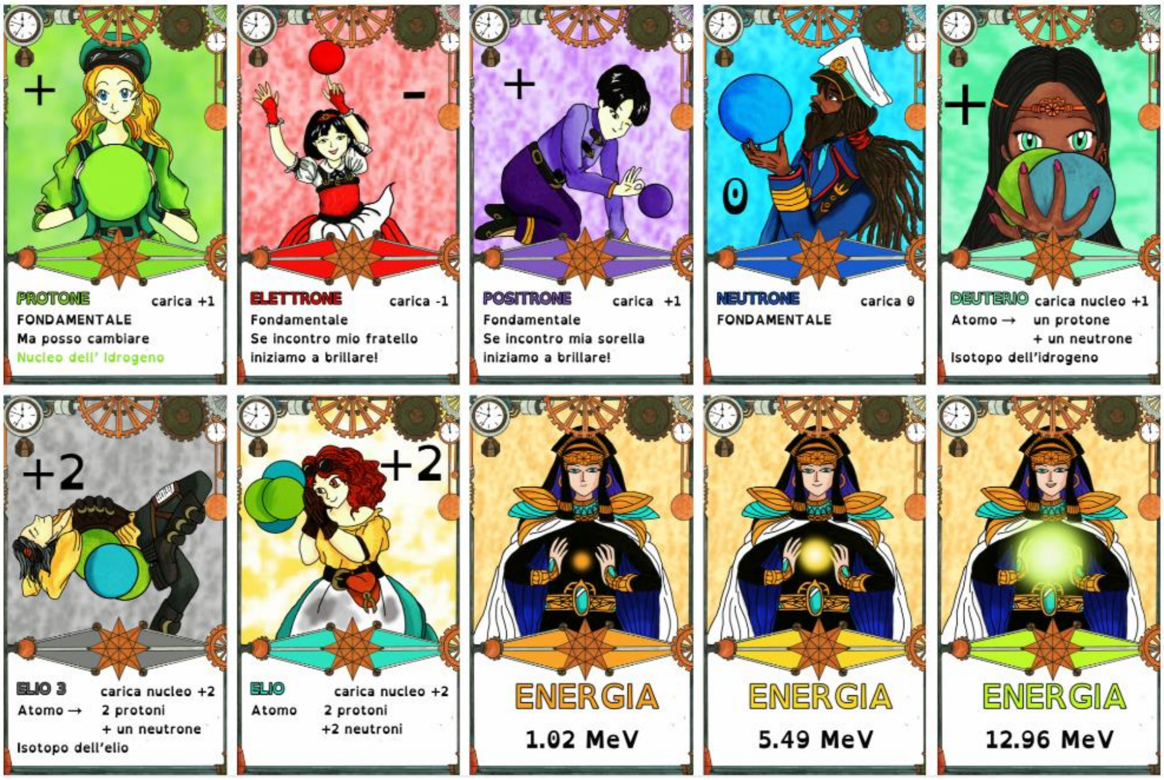

Fig. 3. Final card designs

The board maintains the steampunk style and some of the elements developed for the cards; the back of the cards follows the same approach as the board.

4. Let's Play

Let's now simulate a round of the game, our board looks like figure 4, and on the right side of the reactions we have the product cards:

- 8 deuterium + 8 positrons
- 8 low energy
- 8 helium 3 and 8 middle energy
- 4 helium 4, 4 protons, 4 protons, 4 high energy.

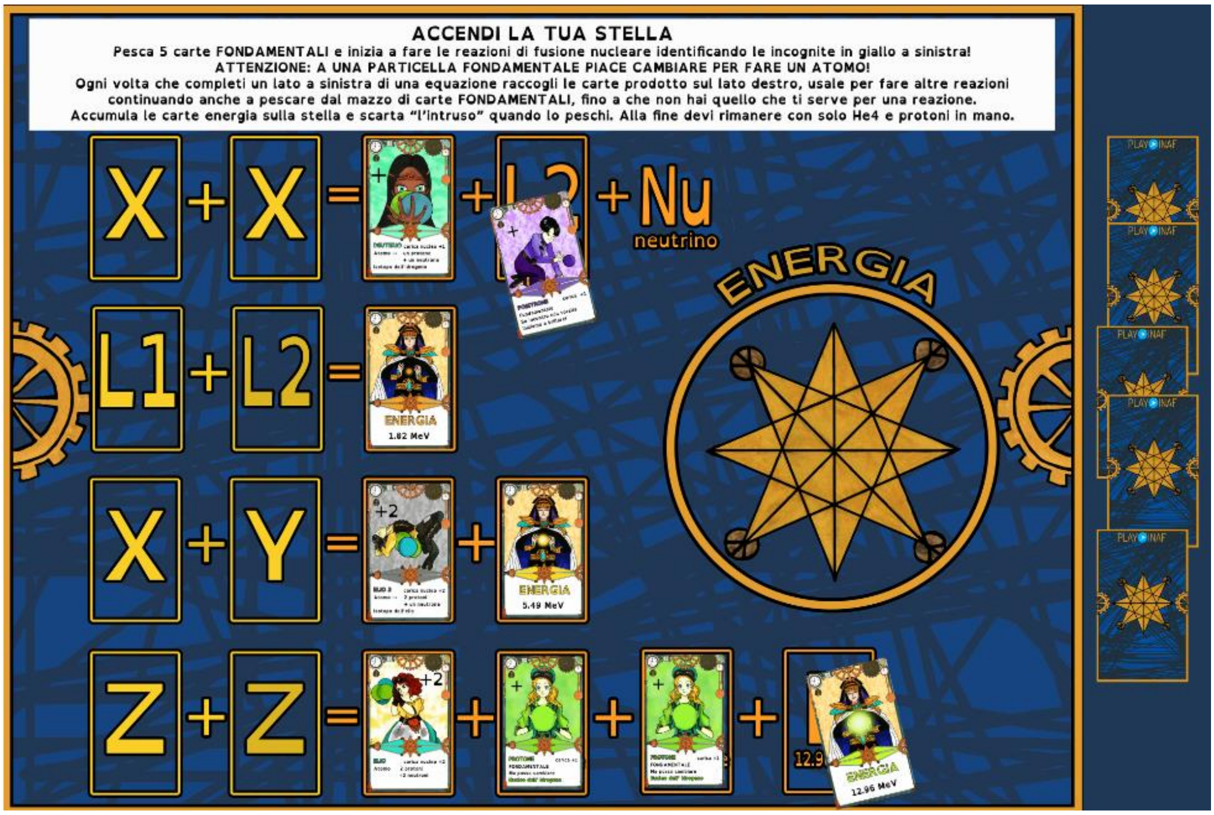

Fig. 4. Board in the configuration to start the game

We start by drawing 5 cards from the fundamental deck. Once we understand who are the reactants, it is a matter of using the drawn cards to make the reactions by positioning them in the correct place in the left-hand side of the reactions on the board. Every time a reaction is completed, we have to take one of each product from the board, put the energy cards into the energy circle, and use the products to do the reactions. There is no order on how the reactions can take place, exactly as in nature; once the products are there, whatever the reaction can start. The only independent at first is the P+P one simply because we need products to perform the other three.
Once the first is done we have a deuterium and a positron in hand, depending if we draw an electron or another proton we can proceed with the second reaction which produces only energy or proceed with the third which gives us a helium 3. At this point we need to wait to draw the right cards to repeat the same reactions to produce another helium 3. Once we have two we can perform the final fusion reaction and produce the helium 4 and a lot of energy. The final reaction also produces 2 protons, with whom we can restart the whole cycle again from the first reaction. At this stage, the player understands not only the reaction chain but also how it self-sustains in the star interiors, with the final product you also produce the original reactants you need to restart the chain. At the end of the entire cycle what we are left with are Helium 4 and energy (plus 2 protons but that do not react anymore) which is what is left of a star core once the hydrogen has been exhausted. The end of the game teaches how star cores begin as huge spheres of hydrogen and end up being made of helium. This stage of the life cycle of a star is probably the main one after its birth, it may take billions of years to reach for the smaller stars like our sun, or mere millions for the most massive stars. The common point to all is that once the star reaches this stage it is entering the final stages of its life, the ending of the game can therefore serve as a cue for the teachers to discuss the evolution of stars, as was done in the Astro-Tamagotchi [1].

5. Star-klondike!

The structure of the game is prone to be transformed into an online game; in this case, it is not a small group experience but a much funnier version of the classical solitaires as klondike. The significant difference is that this solitaire does not only entertain and, as the live version, teaches how the star interiors work, but can also be enjoyed from a common laptop. The main differences are simply a different design organization of the board, which needed the spaces for the drawn cards, and the

presence of the neutrino card, figure 5, which in the online version can simply fly away when the first reaction is completed, maintaining the physical correctness.
The application has been developed using Scratch, a high-level, block-based visual programming language developed by the MIT Media Lab, to introduce young students to coding in an engaging and intuitive way. Through its block-based interface, users can create interactive stories, animations, and games while developing essential computational thinking skills such as problem-solving, logical reasoning, and creativity. Moreover, as with all projects shared on the Scratch platform, anyone can look inside the code to understand the implementation choices made by the programmer. Additionally, users can remix the project—that is, create a copy on the platform as a starting point for further modifications—fostering learning, experimentation, and creative collaboration.
The online version of the game can be found on the Play Inaf website at this URL:
https://play.inaf.it/accendi-la-tua-stella/

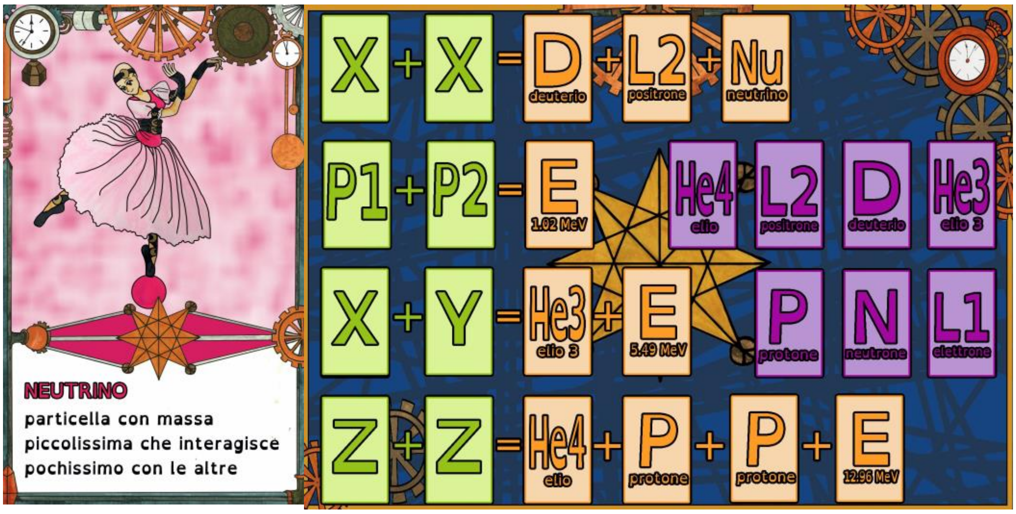

Fig. 5. The neutrino card on the left and the online game board on the right

6. Future Perspectives: Levels!

The proton-proton chain is not the only nuclear reaction chain taking place in the star interiors. Depending on the type, and what is called the population which sort of indicates if stars are the grandparents, parents, or children of other stars, stars can produce energy also through a more complex chain of reactions called CNO, involving not hydrogen as the proton-proton but carbon, oxygen, and nitrogen. This chain of reactions is more complex since it involves different types of atoms and several steps, it would be impossible to make it in a clear way in the live-board game. Nevertheless, it can be a challenge in the online version, as the second level of our game. Once completed the proton-proton chain, the player can try the second, most challenging level. In this way, the students interested in going a bit in-depth can also learn more complex nuclear reactions in the same way as in the first level. We are now in the developing phase of this second level and on the very long term thinking also more, including, for example, the game studying the reactions taking place in the almost-stars, the brown dwarves, and in the giant ones, which end up making the heavy elements in the Universe.

7. Conclusions

At first, we thought that explaining nuclear fusion reactions taking place in star interiors to middle/high school students was an impossible challenge. Instead, the complete decontextualization from the nuclear physics environment enables the players to use simple deduction and logic capabilities to understand what is happening inside a star that makes it shine. The game's appearance is purposely different from what is usually found in science teaching to stimulate curiosity towards this strange steampunk card game in the middle of a science festival. Once the players overcome the first challenge of understanding how the reactions work, they become the interior of the star, waiting for the right particles to meet in their hands for pure chance, do the reaction, take the products, and wait again for a lucky draw, do a new reaction and so on, until they have fully understood how a complex physics phenomenon works just playing with cards.

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