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REPORT

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Exploring Stem Cells: A Hands-On Approach to Elementary STEM Education

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ABSTRACT

The Joint Educational Project's (JEP) STEM Education Programs at the University of Southern California (USC) present an elementary-level curriculum centered on the science of stem cells in partnership with Dr. Adam MacLean, an Assistant Professor of Quantitative and Computational Biology at USC for the broader impacts of a National Science Foundation grant. STEM (Science, Technology, Engineering and Math) fields are exciting but often opaque to those outside of them – this barrier can be challenged through the implementation of lessons designed in collaboration with scientists for use with elementary-aged children to allow them to engage with current research topics. Dr. MacLean's research focuses on computational models of adult stem cells responsible for the process of renewing organs over time in all animals. The curriculum described herein consists of four lesson plans developed from the methods and results of Dr. MacLean's research, and is aligned with the Next Generation Science Standards for 4th grade. It was piloted both virtually and in-person through the JEP STEM Education Program's WonderKids after-school program in Fall 2022, and in five 4th grade classrooms through the JEP STEM Education Program's Young Scientists Program in Spring 2024.

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The creation of this curriculum (Figure 1a–d) was motivated by two goals that leverage the fact that stem cells are a subject of leading-edge biological research, one that is sometimes misrepresented and therefore controversial. Many educators may have only encountered this topic in the context of controversies regarding embryonic stem cells of fetal origin. First and foremost was the desire to bring leading-edge scientific concepts and questions into elementary school classrooms. At the elementary level, and even in secondary and some post-secondary courses, science is often treated as a completed set of facts and methods that students must become familiar with. The reality, of course, is that science is a never-ending process, forever seeking further understanding of the world around – and in this case, within – us. By bringing lessons dealing with subjects and methods of active research into classrooms, we hope to help students understand that science is a dynamic, human field with plenty of questions left unanswered.

A secondary motivation for this project was to take the topic of stem cells and provide students and educators with a solid foundation of information on the diverse types of stem cells, focusing on non-embryonic "adult stem cells," and roles that they play in humans and other animals. We use the blood (or hematopoietic) system as an exemplary adult stem cell system with the assumption that blood is an immediately tangible and accessible topic for 4th grade students. Leveraging the accessibility of this system and our active research techniques, we are able to introduce cutting-edge and sophisticated scientific concepts such as computational modeling and cell-to-cell communication into the curriculum.

This project is an example of how a researcher and an educator can work in partnership within the broader impacts section of National Science foundation (NSF) grants. The broader impacts criterion of the National Science Foundation (NSF) emphasizes the significance of STEM education and outreach in proposed research. A key goal is to broaden

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Figure 1. (a–d) Fourth grade students at Vermont Avenue Elementary holding their stem cell blood models.

participation by increasing the involvement of underrepresented groups in STEM fields, thereby enhancing diversity. The researcher, Dr. Adam MacLean, was the Principal Investigator (PI) on the project and he partnered with the JEP STEM Education Programs to disseminate his research into a curriculum in an effort to improve scientific literacy. Two educators partnered with Dr. MacLean including Jessica Stellmann and Dr. Dieuwertje Kast. By writing this curriculum based on his research and piloting it within their educational programming, we are demonstrating a model of how other educators and scientists could work together for these large federal grants. This article will go into depth on the research itself, the pilot testing and logistics and the specifics of the four lesson curricular module.

Scientific background

Every cell in the human body begins as a stem cell. All of us, from birth until old age, have many different kinds of adult stem cells in our bodies. Adult stem cells are responsible for replenishing our bodies' organ systems with the cells they need to function. Dr. MacLean's research is focused on what determines the fate of stem cells – that is, how do processes inside the stem cell as well as influences from outside the cell (e.g., via different cells in our bodies communicating to the stem cells) act together to control what a stem cell becomes. Research conducted in the MacLean lab has revealed that cell to cell communication through chemical signals that stem cells can receive and act upon is a crucial factor in deciding their fate (Rommelfanger and MacLean 2021). Blood stem cells receive chemical signals from other (specialized) blood cells that direct them to become, for example, oxygen-carrying red blood cells, white blood cells of the immune system, or platelets (which stop bleeding via clotting). This decision depends on what our body needs at that moment, communicated via signaling to the stem cells. Beyond furthering our understanding of fundamental functions of our bodies, and the bodies of other animals, research such as Dr. MacLean's also sheds light on what can go wrong in these systems. Certain dysfunctions of stem cell systems, such as when certain types of cells proliferate and accumulate beyond normal amounts, can lead to cancer. Stem cell systems can also be perturbed by other events such as injuries or infections (Roeder et al. 2006; MacLean, Lo Celso, and Stumpf 2013; MacLean, Lo Celso, et al. 2017).

JEP STEM Education programs

The USC JEP STEM Education programs consist of three STEM Education programs – the Young Scientists Program, the Medical STEM Program and Wonderkids. The Young Scientists Program (Grades 1–2, 4–5, and SDC 3–5) and the Medical STEM Program (Grade 3). These two programs are inquiry-based, hands-on STEM education outreach programs operated by the USC Joint Educational Project in partnership with classroom teachers across 7 schools in the South Los Angeles community during the school day. Our 1st- 5th grade science curriculums function as effective supplements of current science instruction in Los Angeles Unified School District (LAUSD) schools. They incorporate Next Generation Science Standards (NGSS), as well as LAUSD and statewide grade-level science learning standards, with the ultimate goal of strengthening science literacy and promoting interest in scientific careers. Their primary objectives are to present hands-on, accessible and engaging science lessons to the children attending schools in our community, assist in alleviating the potential fear and stress that is often associated with studying science, and helping students apply what they learn in the classroom to the real world and to their own lives. The programs are free for the schools and all curriculum, supplies and one science instructor (an undergraduate student pursuing a STEM degree at USC) are provided to participating teachers. The third-grade program, the Medical STEM Program, is being funded by the Keck School of Medicine and the content is more medically inclined, but teacher commitments remain the same.

The WonderKids after-school program is one of several STEM-focused programs within JEP (Kast, Singh, and Kast 2018). WonderKids seeks to empower the young people of South Los Angeles to believe in themselves and their ability to pursue any career they want, as well as to expose them to the great breadth of opportunities and fields within the STEM umbrella. Two versions of the WonderKids program are currently operating. The first is a virtual format that allows K-5 students from across JEP's 14 partner elementary schools to participate in the program via zoom for 2 h each week. The other is an in-person after school program that operates at a smaller number of JEP's partner elementary schools. Both versions of the program feature hands-on activities and visits from STEM professionals (supplies are mailed to students in the virtual program in order to maintain a hands-on curriculum).

Pilot test #1: WonderKids after-school program

In Fall 2022 two partner schools were chosen to host the in-person trial stem cell curriculum, in addition to it being trialed in the virtual program (Figure 2). WonderKids participants are kindergarteners through fifth graders from South Los Angeles that attend Title I schools. For our virtual program, 58 students registered for the Fall 2022 program. Forty students participated in the in-person offerings (15 at 32nd St Magnet, 25 at

Figure 2. Dr. Adam MacLean assists WonderKids' students at Norwood St. Elementary with figuring out the best balance of blood cells in a stem cell simulation game created by his research group.

Figure 3. YSP Coordinator and TA Alexander Zambidis teaches blood stem cells to fourth graders at Vermont Ave Elementary.

Norwood Street Elementary). Across both versions of the program, 100% of our students identify as BIPOC (Black, Indigenous and people of color).

Dr. Adam MacLean was a guest speaker and facilitator for some of the sessions implementing this curriculum in both the virtual and in-person settings – he attended the second session of the virtual program's "Stem Cells" week, and the sessions focused on Lessons 3 and 4 (see lesson descriptions) at the Norwood in-person site. Students at the 32nd St. site were visited by one of Dr. MacLean's graduate students, Jesse Kreger, for their Lesson 4 session. This provided the students the opportunity to learn directly from a scientist and how their research and how it connects to themselves and their everyday life. It also allowed Dr. MacLean to observe the effectiveness of the lessons in communicating the concepts, methods, and results of his work. We assessed student learning via administration of pre-tests before and post-tests after the two lessons presented in the virtual program and the four lessons presented in the in-person program.

For the after-school WonderKids Implementation, pre- and post-tests were administered to 13 students at 32nd st and 9 students at Norwood. It was found that 20.5% more students were able to adequately answer the question "What are stem cells" on the post-test than on the pre-test. At Norwood, nine students were tested and an improvement of 55.5% more students answering adequately was observed. Due to the logistical restrictions of the virtual program, only Lesson 1 and Lesson 4 (see lesson descriptions) were taught. Of the 8 students in the Kindergarten-2nd Grade age group given the assessments, 32% more of them were able to adequately answer the question "What are stem cells?" on the post-test; 60% more of the 5 students in the 3rd-5th grade age group were able to do so. Since the first pilot test in an elective after-school STEM program went well, we proceeded to do another pilot test during the instructional day with our STEM education staff and a select few of our classroom teacher partners.

Pilot test #2: Young Scientists Program

The YSP is JEP STEM Education Program's largest and longest-running program, serving over 2,500 students in 1st-5th grade across seven of JEP's partner schools. YSP's model involves our "teaching assistants," paid undergraduate students (typically STEM majors) from USC, entering LAUSD classrooms during the instructional day to present NGSS-aligned, hands-on STEM lessons. The classrooms that YSP partners with are all part of Title 1 schools within LAUSD, and of the students YSP serves, between 83–92% identify as BIPOC, with 78–89% identifying as Hispanic/Latinx specifically (EdData 2024).

Due to the close alignment of the presented curriculum with the 4th grade NGSS, one of the STEM program's teaching assistants, Alexander Zambidis, was selected to pilot the full curriculum in the five 4th grade classrooms he teaches in as a part of YSP in Spring 2024 (Figure 3). The LAUSD teachers for Zambidis' classes were cautiously intrigued by the unit's lesson plans. When asked about their thoughts regarding teaching students of their grade level about stem cells prior to this pilot, one educator responded "Stem cells are relevant to our science curriculum LS1-From Molecules to Organisms Structures and Processes. I didn't consider teaching about stem cells before. I didn't know how to present the subject in an engaging way."

According to these LAUSD educators, this pilot implementation of the stem cell curriculum by Zambidis was a success. In an end of unit evaluation, all respondents replied with "Strongly Agree" to statements declaring each lesson as interesting and effective, as well as to the statements "The stem cell unit as presented in my class included information that served my student's educational needs" and "The stem cell unit as presented in my class included activities that were engaging to my students." The unit was even able to bring skeptical educators on board, with one teacher saying "At the beginning I was hesitant regarding the lessons, but after seeing the students interest and understanding of the concepts, my opinion changed. I think that for being a pilot program the lessons were well developed with specific learning activities in an engaging meaningful manner."

As a part of the YSP implementation a pre-test was given to the students in each class that included questions relating to the stem-cell specific lesson objectives of all four lessons to assess what, if any, knowledge they had about stem cells prior to instruction. The decision to focus on only the stem-cell specific lesson objectives for the pre-test was made to keep the time required to administer the pre-test as short as possible, in deference to the fact that each classroom session Zambidis had with the students is only 1 h long. At the conclusion of each lesson, a post-test was administered that included questions relating to that specific lesson's objectives. The evaluations questions for each lesson are provided in the included resources (linked below). By comparing student responses to questions that appeared on both the pre-test and post-test(s), we were able to gauge whether or not student understanding was improving after each lesson. You can see the summarized results of the pre- and post-test data below in Table 1.

Overall, the results indicate that student understanding of stem-cell concepts was indeed increasing following instruction, evidence that the lesson plans are capable of meeting their objectives. It is worth noting that the questions assessing the lesson objectives for Lesson 1, where post-test results show minimal positive and even slight negative change, were both TRUE/FALSE format questions and that both were answered correctly by a very high percentage of students on both pre- (1. 90.9%, 2. 86.4%) and post-tests (1. 96.6%, 2. 84.8%). In the future, we would implement versions of these questions that included an answer option of "I don't know" in order to minimize correct answers through random guessing in order to better assess whether or not student understanding is meaningfully changing.

Table 1. Objectives chosen for pre- and post-tests were restricted to stem cell focused objectives in order to minimize time spent on evaluations, given the time constraints of our programs.

Lesson Objective[a]	Change in Percentage of Correct Responses from Pretest to Post-test.
Lesson 1. Objectives 1 and 2.	1.+5.7% 2.−1.6%
Lesson 2. Objective 3.	+38.7%
Lesson 3. Objective 1 and 3.	+34.1%
Lesson 4. Objective 1.	+22.3%

[a]For the full text of Lesson Objectives, see Table 2.

Curriculum description

The curriculum we created was divided into four lessons based on main themes from MacLean's research. Specifically,

- Lesson #1: Adult stem cells
- Lesson #2: Blood stem cells
- Lesson #3: Cell-to-cell communications
- Lesson #4: Computational modeling of stem cells

All of the lessons were written by Jessica Stellmann in collaboration with Dr. Adam MacLean and Dr. Dieuwertje Kast. They are presented in 5E format and include hands-on activities that are NGSS aligned. A summary of each lesson's learning objectives and associated standards is presented in Table 2. Each of the lessons are described below.

Lesson #1: Adult stem cells

The first lesson defines not only what stem cells are but drives home the idea that cells, despite being so small, play a crucial role in organ systems. The lesson includes a Play-Doh model of how different kinds of cells make up different tissues and organs which in turn comprise our bodies' organ systems such as our skin, or our circulatory system (Figure 4). Students construct a representation of how cells are the building blocks of tissues, organs, and organ systems by first making model cells out of Play-Doh, then combining several of these cells into model tissue and combining several model tissues into a model organ before illustrating where in the body that organ is located and the system it is a part of. This repeated building up of different structures, starting each time with modeled Play-Doh cells, reinforces the fact that cells are a building block for our bodies' systems. This

Table 2. Summary of learning objectives and associated standards for each lesson.

Lesson Name	Lesson Objectives	NGSS Standards and Common Core
Lesson 1 – Adult stem cells	1. Students will independently construct a representation of how cells are the building blocks of tissues, organs, and organ systems. Following this lesson, students should be able to identify the various levels within the body's structures (cells, tissues, organs, organ system) within various organ systems. 2. Students will discuss the purpose of adult stem cells within various organ systems. Following this lesson, students should be able to identify that the role of adult stem cells in organ systems is to replace dead cells, so that the tissues, organ and organ system can continue to function.	NGSS: 4-LS1-1. Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction.
Lesson 2 – Blood stem cells	1. Students will identify each of the five components of blood and their function 2. Students will create a model of blood by including each of the five components (plasma, red cells, white cells, platelets and stem cells) 3. Students will explain that blood stem cells differentiate into red, white or platelets and that there are stem cells in the blood.	NGSS: 4-LS1-1. Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction. Common Core: 4.NF.7. Compare two decimals to hundredths by reasoning about their size. Recognize that comparisons are valid only when the two decimals refer to the same whole. Record the results of comparisons with the symbols $>$, $=$, or $<$, and justify the conclusions, e.g., by using the number line or another visual model. Common Core: 4.NF.3.d. Understand a fraction a/b with a $>$ 1 as a sum of fractions 1/b. Solve word problems involving addition and subtraction of fractions referring to the same whole and having like denominators, e.g., by using visual fraction models and equations to represent the problem.
Lesson 3 – Cell-to-cell communication	1. Students will learn that cells communicate with each other through chemical signals. 2. Students will be able to identify that the chemical that carries the signal is called a ligand, and the part of the cell that gets the signal is called the receptor. 3. Students will learn that this communication is very important for stem cells to change and become a differentiated cell.	NGSS: 4-LS1-1. Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction.
Lesson 4 – Computational modeling of stem cells	1. Students will visually understand the impact that stem cells have on differentiated red and white blood cells, and the ideal balance between blood cell types in a healthy organism. 2. Students will discuss the use of computer simulations in investigating difficult and/or costly questions.	NGSS: 4-LS1-1. Construct an argument that plants and animals have internal and external structures that function to support survival, growth, behavior, and reproduction. Common Core: 4. MD.2. Use the four operations to solve word problems involving distances, intervals of time, liquid volumes, masses of objects, and money, including problems involving simple fractions or decimals, and problems that require expressing measurements given in a larger unit in terms of a smaller unit. Represent measurement quantities using diagrams such as number line diagrams that feature a measurement scale. K12CS: 3-5.AP.10. Compare and refine multiple algorithms for the same task and determine which is the most appropriate.

activity is accompanied by lecture material focusing on the role of stem cells in replenishing the different cells that make up our organs. Some of the specific concepts this lesson aims to cover include: Adult stem cells are undifferentiated cells (cells that do not have a specific function) that reside among differentiated cells (cells that do have a specific function, e.g., a skin cell) in a tissue or organ. They have the ability to renew themselves and differentiate into specialized cell types. They primarily exist to repair and renew the tissues in which they reside (Lo Celso and Scadden 2011; Clevers 2015).

Lesson #2: Blood stem cells

The activity for lesson 2 is a model of the five components of the blood: plasma, red blood cells, white blood cells, platelets, and stem cells, within a water bottle (Figure 5a–d). The plasma is represented by the light corn syrup base. The other four components are represented by candy. The 60–80 red candies or cinnamon imperials are red blood cells, the white blood cells are represented by 2 lima beans, 3 white large sprinkles are platelets, and one tiny white sprinkle represents a blood stem cell. The numbers are based

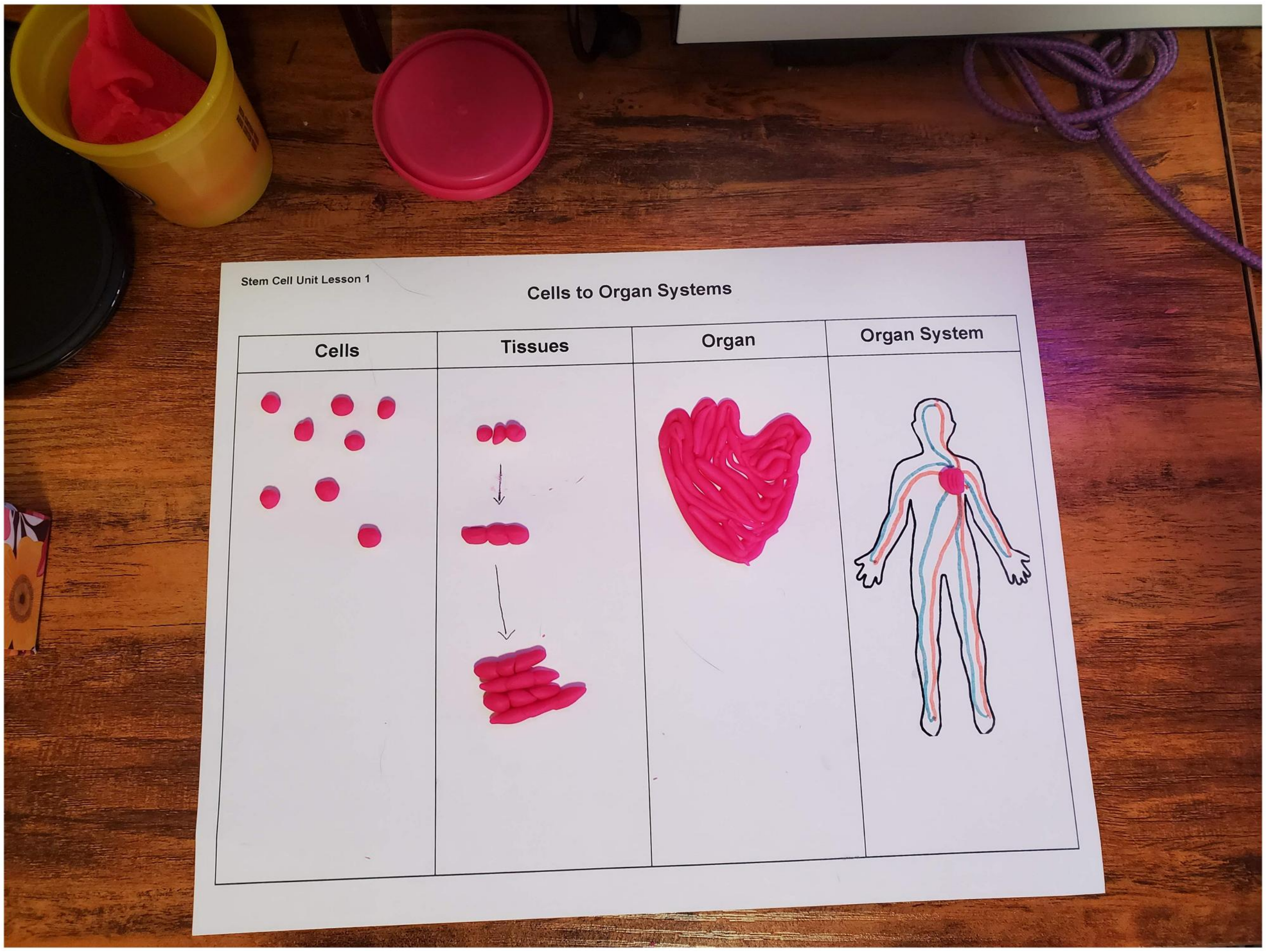

Figure 4. Completed Lesson #1 worksheet using Play-Doh.

on the real ratios of these in the blood. This activity familiarizes students with the different components that make up human blood, as well as the proportional rarity of blood stem cells among other cell types. Alongside assembling the model, lecture material prompts students to continue to engage with the concept introduced in lesson one. Through this lecture and discussion, they learn that adult stem cells become specialized cell types, such as red blood cells, platelets, or one of several different kinds of white blood cells, depending on the body's needs (Figure 6a,b) (MacLean, Lo Celso, et al. 2017).

Lesson #3: Stem cells communication game

In this week's lesson, students begin to build upon the stem cell information from the weeks prior, now learning about the fundamental ideas of cell differentiation. They transition from what stem cells are and examples of them from weeks 1 and 2 to how they interact with the other cells of our body in week 3. In this lesson, students act out how ligands, a specialized chemical from red and white blood cells, reach and connect to the receptors of stem cells to induce differentiation. The students do so using hula hoops and color-matched gloves. Students with white or red gloves act as ligands, starting the game holding on to a hula hoop of the same color representing either a white or red blood cells respectively. Other students are holding a different color hula-hoop, representing our blood stem cells which could be later signaled by a ligand to become either a white or red blood cell. The goal of the game is for ligands to move about the classroom and grab on to a blood stem cell, illustrating how ligands can signal to stem cells what cell they can differentiate into. The instructor uses a spinner or other criteria to determine which ligands can move for a predetermined amount of time (ex. "If your birthday is in April, move for three seconds"). Once all of the blood stem cells have been signaled by a ligand, the game is over.

Figure 5. (a–d) The process of putting together the blood model bottle.

Lesson #4: Computational modeling of stem cells

The curriculum's final lesson takes the ideas taught in the three previous weeks and applies them to the world of computational biology. In this lesson, students work with a computer simulation to model how the development of stem cells affect progenitors and ultimately blood cell dynamics. Created in collaboration with the MacLean lab, this model provides an interactive and controlled environment where students

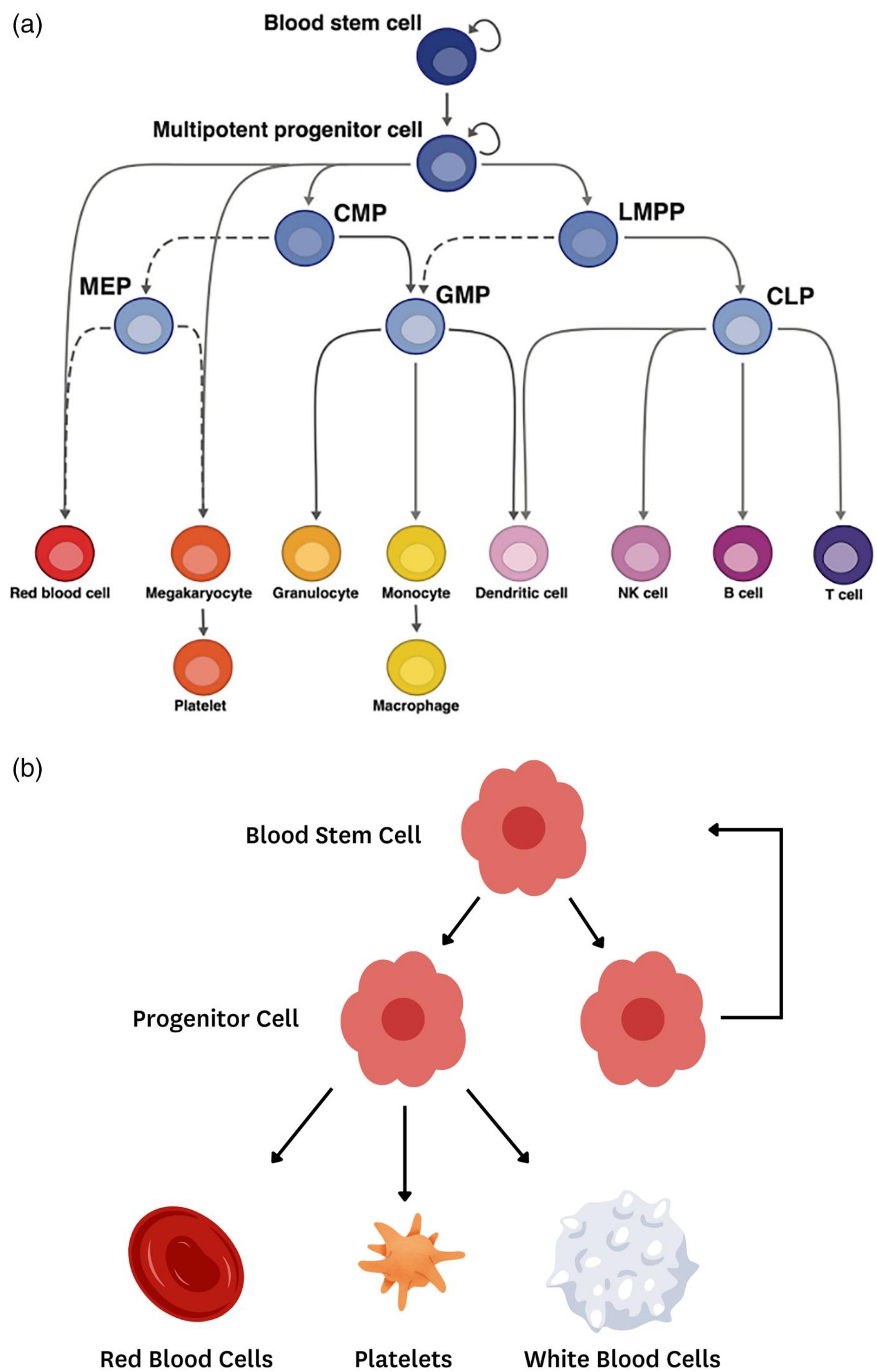

Figure 6. (a) (Top): The stages of blood stem cell differentiation and the suite of specialized cells that blood stem cells produce. Figure is based upon MacLean, Lo Celso, et al. (2017) with newer insights incorporated (Kucinski et al. 2024). See MacLean, Lo Celso, et al. (2017) for further details and full legend. (b) (Bottom): Simplified figure based on concepts presented in (Top) for use in this curriculum.

can modulate various parameters including stem cell death rate and red blood cell death rate to observe the effect on an organism's overall health. The resulting cell numbers are displayed on a bar graph, line graph, and illustrative model. Most importantly, the cell death parameters directly affect the central character (Strawberry Superhero) which stands in the top right of the screen and has a sad, neutral, or happy face depending on whether the ratio of stem, progenitor, and red blood cells would make an organism unhealthy, neutral, or healthy (Figure 7).

In addition to experimenting with the model, students document the different variables and processes that the model is built with, to reinforce and apply

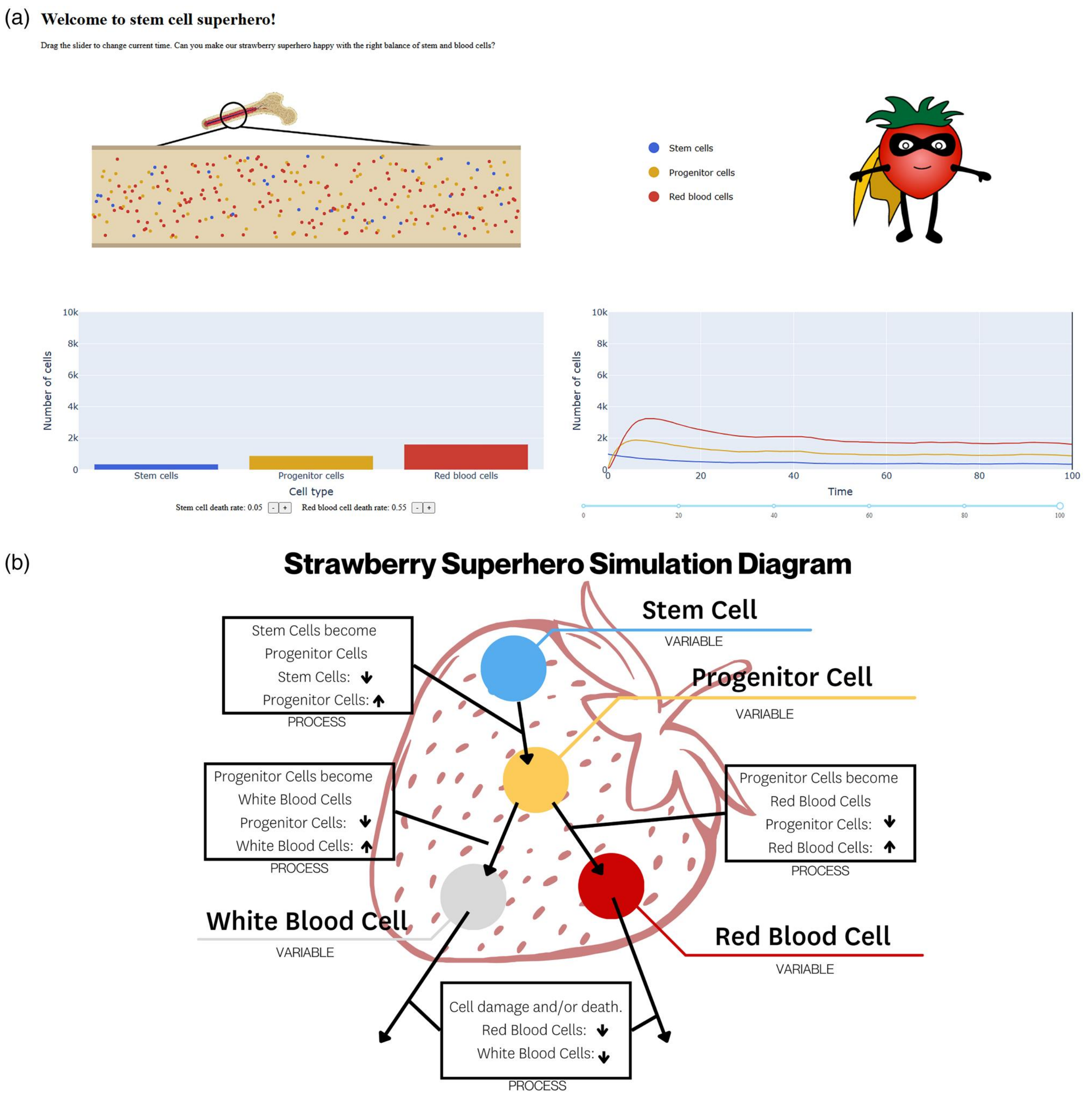

Figure 7. (a) An example of model output where the chosen rates result in a success — a happy Strawberry Superhero. The top left panel illustrates what the numbers of model cells would look like in the body. The bottom left represents the number of each kind of cell as a bar chart. The bottom right shows a line graph depicting how the number of each kind of cell changes over the time of the simulation. (b) Answer key for Lesson 4 worksheet documenting the variables and processes represented in the computation model. Up and down arrows represent an increase or decrease in the number of cells, respectively.

their understanding of the stem cell processes at play while also teaching them the thought processes that go into constructing computational models. This activity not only teaches students the importance of quantitative analysis of stem cells but also provides a segue into the importance of computer simulations in scientific research (Figure 8).

Accommodations for diverse learner needs

The use of varied learning accommodations is especially important when implementing lessons on an intricate topic such as stem cell biology. JEP STEM Education's Young Scientists Program (YSP) lessons are designed to bring novel science instruction to Los Angeles Unified School District (LAUSD) classrooms with a strong emphasis on the scientific and engineering practices which at its core relies on collaboration. Throughout each lesson, Zambidis had students work together to create their own hypotheses, perform experiments, share their findings, and come up with conclusions. This allowed students to reinforce the lesson material through engagement with their peers. Further, the elementary school students in schools around USC are primarily Latinx (89%), with a significant portion being English Language Learners (ELL) (40%), predominantly Spanish speakers. For this reason, it was imperative that the information presented was provided in English and Spanish. This meant all slides, activity worksheets, and pre- and post-tests were made for all students, not only those who could speak English. All four lessons utilized use of visual, auditory, and tactile learning strategies. Visual aids were particularly helpful in illustrating how complex the cellular level is. From ligand to receptor interactions to stem cell differentiation, picture and video content presented effective ways to explain the microscopic world while also catering to visual learners. Individually, these learning accommodations cater to a distinct subset of the student population, collectively, they synergize to widen the scope of opportunities for learning new content.

Future directions

The Young Scientists Program was founded to give supplemental science instruction in the elementary schools around USC. We do this by facilitating interactive, engaging, and educational lessons for students in 1st through 5th grade. This year we aimed to tackle stem cell biology in select 4th grade classrooms and found some success. Our post-test data show that stem cell biology can be effectively taught in the fourth grade, where students were able to successfully answer a variety of questions including how stem cells differentiate in the blood, how stem cells communicate with other cells, and that there is a healthy balance of stem cells compared to other cells. Each of these concepts opens the door to the greater world of stem cell biology, one that is consistently growing year-over-year in its research and clinical applications.

The curricular implementation presented several challenges. For example, 4th grade students have a limited understanding of cell biology and require dedicated time to reinforce the connection between the lesson content and how it materializes in their own body. This disconnect became apparent in the activity for lesson three, which when facilitated in the future, will require additional scaffolding to bridge this gap. The nature of this activity lends itself to be game-like which distracts the students from what each part of the activity ultimately represents. To successfully achieve the learning goals in future iterations, careful attention must be paid to how the different items in the activity are explained, giving ample opportunity for students to ask questions about each component as needed. As a result of our learnings, suggestions for when and how to scaffold the activity for students have been added to the Lesson 3 lesson plan (linked below). Despite this hurdle, students were able to successfully answer post-test questions related to cell-to-cell communication. Moving forward, educators can use the teaching principles exemplified in this article to push students to engage in fields of science that are not included in traditional science curriculum in the elementary grades. Exposing students at a young age to complex scientific concepts like stem cell biology and computational modeling not only broadens their understanding of the world around them but also instills a curiosity and excitement for learning that can last a lifetime. By breaking down seemingly complex ideas in developmentally appropriate ways, educators can continue to inspire the next generation of scientists, innovators, and critical thinkers.

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