Using Scratch to enhance students' 21st century scientific thinking skills

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21st century Scientific Thinking

The "nature of science" (NOS) refers to the epistemology of science, or the values and beliefs inherent to scientific knowledge and its development (Lederman, 2006). It takes into account what is considered to be scientific knowledge (the rules or assumptions for how scientific knowledge is substantiated and evaluated) and characteristics of scientific inquiry (the process of how science is conducted). Significant research underscores the importance of teaching the nature of science and scientific inquiry in K-12 settings (e.g. Lederman, Abd-El- Khalick, Bell, & Schwartz, 2002; Sandoval & Reiser, 2004). Understanding the nature of scientific knowledge and practice is believed to be crucial for scientific literacy and critical in preparing students for higher-level science research.

Scientific inquiry as traditionally taught in science classrooms and textbooks are often equated with the step-by-step "scientific method." However, the way real-world scientists proceed in their work are far more textured than can ever be portrayed by one common method (Dunbar, 1995; Koslowski, 1996). Furthermore, scientists engage in thinking patterns that are specific to its particular socio-cultural context (Liu & Grotzer, 2009).

With the explosion of advancements in scientific knowledge and technology at the turn of the century, scientists at the cutting edge of research must adapt to new ways of interacting with their work. Recently, Liu & Grotzer (2009) identified five prominent scientific thinking patterns of the 21st century, as demonstrated by contemporary scientists working in innovative fields in the life and physical sciences that are characteristic of the century, such as bioinformatics, nanomaterials, and synthetic biology. These thinking patterns are:

- Systems thinking
- Mechanistic thinking
- Interdisciplinary thinking
- Quantitative thinking
- Distributed thinking

Systems thinking is an approach by which a system of interacting entities is analyzed as a whole, rather than by analyzing its individual constituent entities separately (Hood, 2003). This emerging systems way of thinking in the 21st century can be contrasted with the reductionist approach that dominated 19th and 20th century biology (Woese, 2004). Reductionism is an approach that dissects biological entities or systems into its constituent for analysis. Although biology has always been a science of complex systems, complexity itself has only recently acquired the status of a new concept because of the advent of computational tools and the possibility of simulating complex systems and biological networks using mathematical models to supply new ideas and solutions (Van Regenmortel, 2004; Wake, 2008). Scientists engaged in systems thinking display this integrative way of thinking, striving to understand how components interact to create a whole, and display a more nuanced perspective towards their work with greater sensitivity to context variables.

Mechanistic thinking is a way of thinking that has a mechanical or engineering undertone. This is shown through scientists' regular use of mechanical analogies to conceptualize their work, and their modular, synthetic, and purpose-driven approach towards their research problems; all of which is in the quest for greater manipulation and control over the object or organism they are working with. The display of mechanistic thinking by scientists appears to be a result of the merging of biology and engineering practices that is increasingly observed in 21st century biology, as compared to a time when most of biology—traditionally known for its pure, basic research—remain clearly demarcated from engineering—a purely applied research field. As with systems thinking, a mechanistic way of thinking is coming to the forefront now because of recent developments in new technologies and knowledge that enable scientists to manipulate biology more directly, allowing them to engineer and create novel biological systems for practical applications.

Interdisciplinary thinking is the demonstration of flexibility in utilizing methods and tools from different disciplines. Scientists are tapping increasingly more into multiple disciplines in their work, as can be seen with the merging of biology and engineering. This is not surprising given that the more problems are solved and more knowledge are gained within scientific disciplines, scientists are naturally pushed to ask more and more complex questions that cross the artificial boundaries between various scientific disciplines. With the ability to use interdisciplinary thinking skills, is the ability to flexibly adapt to new situations and aptly acquire new knowledge and skills that may be characteristic of another unfamiliar discipline, or something entirely new to the scientific community. Catalysts for the emergence of interdisciplinary thinking include is the complexity of data and questions scientists are dealing with in the 21st century, and the development of the Internet, which allows scientists to easily and serendipitously access information between disciplines.

Quantitative thinking is simply thinking with mathematics. Math is becoming more and more necessary to validate science, to increase its predictive power, and to manage the complexity and exponentially accumulating amounts of scientific data. Undeniably, math has always been some part of science. However, it is the indispensability of math to analyze and process the complex problems and large data sets of contemporary science that makes quantitative thinking a distinctive quality of 21st century science. Thinking with mathematics is a result of recent trends in system-level analysis, mass data production, and increased computing power (Bialek & Botstein, 2004; Cohen, 2004; Steen, 1988; Stewart, 2002). Much like the other patterns of thinking, the increasing employment of quantitative thinking in the 21st century is made possible with technological advancements. The ability to generate mass data in the first place starts with supercomputers with high computing power. Other technological advancements include the development of sophisticated computational approaches related to data management, statistical inferences, and mathematical modeling.

Distributed thinking is based on the theory of distributed cognition, where it is believed that cognition is not limited to an individual's mind, but can be extended beyond the individual by involving other persons and tools or technology (Perkins, 1997). Scientists employ the surround to support, share, and undertake aspects of cognitive processing, where outputs from such a distributed cognitive system would not be possible had cognition resided just in the individual. Similar to interdisciplinary thinking, catalysts for the emergence of distributed thinking include the development of the Internet and the complexity and quantity of data scientists are dealing with in the 21st century. The Internet promotes a social distribution of thinking by making it easy for scientists to collaborate and exchange ideas across space and time.

Role of Digital Technology

There are three major reasons behind why digital technology should be used to enhance students' 21st century scientific thinking skills: 1) Learning is situated in the same digitally rich culture in which the thinking skills are developed and used by the scientific community, 2) Digital technologies lend well to support creative thinking, and 3) Digital fluency is critical in our media-rich participatory culture.

Situated Learning

Undeniably, the advancement of technology, especially digital technology, has greatly influenced the way scientists think and innovate in the new century. Scientists are able to simulate and manipulate much more complex problems that cuts across traditional disciplinary boundaries, all of which demanding specific thinking and working skills that will only become more salient in our increasingly digital world. Thus it is not only important for us to equip our students and future scientists with these particular thinking skills, but to do so by situating their learning in the same digitally-rich culture in which it is developed and used by the scientific community. The situated use of knowledge is necessary for deep understanding and good learning (Brown, Collins, & Duguid, 1989).

Creative Thinking

It is no coincidence that scientists are employing digital technologies to help them innovate, as digital technologies lend well to creative expression. They provide scientists with the freedom to thinker with ideas, create, and share information. Similarly, digital technologies, if properly designed and supported, may be one of the best medium to help students develop as creative thinkers (Resnick, 2007). To develop as creative thinkers, students must be provided with amble opportunities to create, and digital technologies provide the same freedoms of exploration for scientists as children, allowing them to imagine, create, play, share, reflect and imagine some more.

It is easy to recognize the important role of creativity and innovation in science (Lederman, 2006), where we often equate scientific thinking with creative thinking. However, as we move towards the Creative Society in the 21st century (Resnick 2006), the ability to think and act creatively is not only necessary for success in science learning, but success in a world that is constantly changing and adding new complexities. As seen in science, it is impossible and arguably unnecessary for students to learn everything in the ever-growing and -expanding array of scientific knowledge. Thus nothing is more important for our students than learning to think creatively, forming innovative solutions to unfamiliar situations that will continually arise in their professional and personal lives. And we can do so by leveraging new digital technologies to help students think more creatively in ways that also support scientific thinking.

Digital Fluency in New Media Culture

By interacting with digital technologies to design, create, and invent with new media, students are becoming more digitally fluent. Digital fluency involves not only knowing how to use technological tools, but also knowing how to construct things of significance with those tools (Papert and Resnick 1995). In the process of learning about scientific thinking skills using digital technologies, students learn to become more digitally fluent, which is needed to succeed in a digital society (and scientific community). Digital fluency involves skills that are needed to participate in what Henry Jenkins calls a participatory culture, in which people actively create and share ideas and media via the internet (Jenkins et al., 2006). These skills are complementary to contemporary scientific thinking skills, as scientists and students alike are all navigating information landscapes that are increasingly digital and interactive:

New Media Literacy Skills	21st Century Scientific Thinking Skills
Play Performance Simulation	Systems Thinking Quantitative Thinking Mechanistic Thinking
Appropriation	Mechanistic Thinking
Judgment Transmedia Navigation Negotiation	Interdisciplinary Thinking
Distributed Cognition Collective Intelligence Multitasking Networking	Distributed Thinking

Scratch for scientific and creative thinking

Scratch is a programming language for young people (ages 8 and up) that makes it easy to create interactive projects (e.g. stories, animations, games, simulations, music, and art) that can be shared on the Scratch website. As young people create and share Scratch projects, they learn important mathematical and computational ideas, while also learning to think creatively, reason systematically, and work collaboratively (Resnick, 2009).

Scratch (http://scratch.mit.edu) is an example of a successful educational technology with purposefully designed characteristics that are highly conducive to learning and teaching 21st century (scientific) thinking skills. The programming language of Scratch can be characterized as having a "low floor," making it easy for students and teachers to get started; a "high ceiling," allowing opportunities for increasingly complex projects over time; and "wide walls," supporting many different types of projects, so that students with different interests and learning styles can be equally engaged (Resnick, 2009). Scratch also engages children in a simulated scientific process where they are able to playfully explore design ideas and test out their ideas or mini-hypothesis incrementally and iteratively. Furthermore, since programming involves the creation of external representations of the problem-solving processes, programming provides students with opportunities of metacognitive acts, or reflecting on their own thinking, to see how they are doing it and evaluate how well they are doing it.

The low-floor/high-ceiling/wide-walls design of Scratch lends itself well to the five prominent thinking patterns of 21st century science. Scratch facilitates *systems thinking* by providing students the platform to generate science simulations where they can more easily explore the workings of complex causal systems, and how parts of a system interact with each other and with the whole. As students engage in more elaborate projects such as creating a game, the more they engage in *quantitative thinking*. Students are more eager to learn important mathematical and computational concepts, as it is associated with their personally meaningful projects (Resnick, 2009). Students are required to upon their knowledge in multiple disciplines to produce interactive content, engaging them in *interdisciplinary thinking*. Teachers can also take creative advantage of the flexibility provided by Scratch to have students create projects that cut across disciplinary boundaries, and highlight connections among different domains of knowledge. The Scratch online community highly facilitates *distributed thinking* by encouraging members to borrow, adapt, and build upon one another's ideas and projects. Member of the community can always download the source code of any project to modify, learn new programming techniques, or simply gain inspiration.

Lastly, there is *mechanistic thinking,* or a way of thinking that has a mechanical or engineering undertone. The Scratch grammar is designed so that users are presented with a versatile collection of graphical programming blocks that they can be snapped together to create programs, much like LEGO bricks. Connectors on the blocks suggest how they should be put together so that over the process of tinkering with these blocks, the emerging structure can give rise to new ideas and direction to the project. Not only does snapping together complimentary blocks provide an easy way into learning programming, but the idea of modularization as a problem-solving and design strategy is directly relevant to mechanistic thinking.

Design: Scratch lesson for mechanistic thinking

While the learning opportunities provided by Scratch are endless, it must be supported by good curriculum and teaching to ensure that students are maximizing their learning. I have created three lessons (one lesson per day) to help middle or high school science teachers teach mechanistic thinking with Scratch. These lessons can be used at the beginning of the school year when the scientific method is usually being presented, or can be infused during the school year, as students learn more about genetic engineering or creative thinking.

These lessons follow a constructivist approach to learning, as I have created many opportunities for active exploration, experimentation, discussion, and reflection. The lessons encourage students to discover the meaning of mechanistic thinking through their exploration of a case study, simulating how synthetic biologists think, and making connections to their own work in Scratch. Students are always encouraged to formulate their own ideas and connections before being presented with any information.

Specifically, these lessons are designed to help students 1) understand how modern scientists think mechanistically, 2) practice thinking mechanistically by simulating how synthetic biologists think in the field, and 3) recognize mechanistic thinking even when it is not in the context of science, as in their own work via Scratch.

Lesson 1

This first lesson is designed to familiarize students with the Scratch programming language so that they can create projects on it. At this point, Scratch is presented simply as a medium for expressing what they have learned, much like posters, PowerPoint presentations, and paper write-ups.

Lesson 2

This lesson is designed to expose students to the creative field of synthetic biology as a means to illustrate how scientists think mechanistically in the field. This is done by a case study of Jay Keasling, one of the pioneers of synthetic biology. By analyzing how a modern scientist work and think, students are provided with a broader view of scientific inquiry and the nature of scientific thinking.

Students will be asked to demonstrate their understanding of what they have learned so far by creating a Scratch project. This allows students to work more closely and creatively with Scratch. It also acts as a quick formative assessment for teachers of students' learning thus far. However, the real goal of this exercise is to have students engage in mechanistic thinking in their own work, which they may not recognize as it is not in the direct context of science. This will be revealed in lesson 3.

Lesson 3

This lesson is designed to have students practice thinking mechanistically by simulating how synthetic biologists think in the field via an activity (*Designing a New Microbe*) I adapted from an actual experiment conducted in 2007 (Zhang et al., 2007).

This activity presents students with a problem (need for hydrogen gas as alternative fuel) and asks students to design a microbe that can use starch and water to make hydrogen gas. Students are given a set of organism cards to work with, each card symbolizing a different type of organism (bacteria, rabbit, yeast, archea, spinach, and mouse). Proteins (molecules that can convert one molecule into another) that are unique to each organism are listed on the card. Students' engineered microbe will essentially have different proteins from different organisms, placed in a certain sequence, to end up with a final product of hydrogen gas. Students are given the *Designing a New Microbe* worksheet to help them visualize the problem better and reduce their cognitive loads (i.e. amount of information they need to carry in their heads).

The activity allows students to discover that synthetic biology is a very mind-blowing field, accomplishing things that some people never thought was possible. Students will come to appreciate how seemingly impossible feats can be possible especially when scientists are thinking creatively. By thinking and working mechanistically, scientists have more freedom then before in designing and creating novel organisms for real-world applications.

After the activity, when students have grasped a much deeper understanding of what mechanistic thinking looks like in practice, students are asked to reflect on their experience with Scratch. The goal is to have students make the connection that they themselves have been engaging in mechanistic thinking while working on their own Scratch projects. This reflective exercise encourages students to transfer their understanding of mechanistic thinking across different domains. Students will also gain an appreciation of how studying trends in scientists' way of thinking can help them in their own thinking.

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Photo courtesy: http://syntheticbiology.org/

Table of Contents

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How are scientists thinking mechanistically in the 21st century?

Understanding Goals

- The rapid advancement of technology and the accumulation of information are changing the patterns of scientific thinking and research in the 21st century.
- Designing and creating novel organisms by combining various biological components from different cells is one way scientists think mechanistically in the 21st century.
- Designing and creating Scratch projects using graphical programming blocks is one way students can display mechanistic thinking.
- Identifying characteristics of successful scientist and their thinking patterns, help us become better (science) students by applying these skills to our own learning.

Background Information

Beyond the Scientific Method

The scientific method has been commonly taught in science classrooms and textbooks as the only correct way to conduct scientific investigations. This leaves students with the impression that all of science proceeds in much the same way. Unfortunately, this view is not entirely accurate. Perhaps some scientists might conduct their work in this manner, but rarely do they use it in the stereotyped, step-by-step way that schools tend to teach it—despite the fact that scientists report their work in this way in journals.

In fact, scientists throughout history conduct their research in a variety of ways. The exact approach a scientist uses depends on the individual doing the investigation as well as the particular question or problem being studied. Furthermore, scientists often engage in thinking patterns that are specific to its particular socio-cultural context

21st Century Scientific Thinking Skills

With the explosion of advancements in scientific knowledge and technology at the turn of the century, scientists at the cutting edge of research must adapt to new ways of interacting with their work. Five prominent scientific thinking patterns of the 21st century are: systems thinking, mechanistic thinking, interdisciplinary thinking, quantitative thinking, and distributed thinking[1]. In this lesson, students will explore what mechanistic thinking.

Mechanistic Thinking

It is a way of thinking that has a mechanical or engineering undertone. This is shown through scientists' modular, synthetic, and purpose-driven approach towards their research problems. Due to recent developments in new technologies and knowledge, scientists are able to manipulate biology more directly, allowing them to engineer and create novel biological systems for practical applications.

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[1] Liu, Y-T. D., & Grotzer, T. A. (2009). Looking forward: Teaching the nature of the science of today and tomorrow. In I. M. Saleh, & M. S. Khine (Eds.), *Fostering scientific habits of mind: Pedagogical knowledge and best practices in science education* (pp. 9-36). Rotterdam: Sense Publishers.

What is Synthetic Biology?

The thinking involved in the field of synthetic biology is the best examples of mechanistic thinking. With the rapidly emerging field of synthetic biology, blurring the lines of biology and engineering, scientists are no longer limited to working with organisms that naturally exist in the world. Scientists often think synthetically by re-designing and constructing new organisms for practical and novel applications.

Synthetic biology is an extension of genetic engineering. Some even describe it as a more sophisticated version of genetic engineering, taking into account a broader rational design perspective[2]. The engineering influence seeks out the simplicity in biological systems, and brings standardization and modular design principles to biology.

Synthetic biologists can use interchangeable parts from natural biology to assemble systems that function in new ways, never existing before in living systems, hence synthetic. Modular circuit components (e.g. metabolic enzymes or fluorescent output genes) that are well characterized and can act independently of other cellular processes are used to build synthetic biological circuits. Much like the ease of using LEGO bricks—standardized bricks that can attach to any other part—synthetic biology starts from the use of standardized biological building blocks.

The goal of synthetic biology is to both better understand how organisms function at the DNA, protein, and cell level by creating artificial biological systems, and to solve important real-world problems, the latter having caught the attention of scientists, politicians, and entrepreneurs. Promising fields of application include energy, environmental monitoring and remediation, biotech and pharmaceuticals, and materials fabrication.

As pointed out in the detailed case study of Jay Keasling (one of the pioneers of synthetic biology), another key difference between synthetic biology and genetic engineering, is the complexity of products or task the engineered organism can produce and accomplish. Genetic engineering is typically limited to having microbes produce small proteins (e.g. insulin, growth hormones) by simply inserting a single gene, from a different organism, into a microbe. However, with synthetic biology, a complex interaction of several genes can be produced in a specified sequence, much like what goes on in a chemical plant: petroleum goes in, and after a whole chain of reactions, plastic comes out.

Scratch

Scratch (http://scratch.mit.edu) is a programming language for young people (ages 8 and up) that makes it easy to create interactive projects (e.g. stories, animations, games, simulations, music, and art) that can be shared on the Scratch website. It is highly conducive to learning and teaching 21st century scientific thinking skills.

The Scratch grammar is designed so that users are presented with a versatile collection of graphical programming blocks that they can be snapped together to create programs, much like LEGO bricks (and synthetic biology!). Connectors on the blocks suggest how they should be put together so that over the process of tinkering with these blocks, the emerging structure can give rise to new ideas and direction to the project. Not only does snapping together complimentary blocks provide an easy way into learning programming, but the idea of modularization as a problem-solving and design strategy is directly relevant to mechanistic thinking.

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[2] Salisbury, M.W. (2006). Get Ready for Synthetic Biology. *Genome Technology Magazine*. Retrieved from http://www.genome-technology.com.

In this lesson, Scratch is used to have students experience thinking mechanistically in their own work. And since programming involves the creation of external representations of the problem-solving process, Scratch provides students with opportunities of reflecting on their own thinking.

Lesson Layout

These three lessons (one lesson per day) are designed to help students 1) understand how modern scientists think mechanistically, 2) practice thinking mechanistically by simulating how synthetic biologists think in the field, and 3) recognize mechanistic thinking even when it is not in the context of science, as in their own work via Scratch.

Lesson 1

Designed to familiarize students with the Scratch programming language so that they can create projects on it. At this point, Scratch is presented simply as a medium for expressing what they have learned, much like posters, Powerpoint presentations, and paper write-ups.

Lesson 2

Designed to expose students to the creative field of synthetic biology as a means to illustrate how scientists think mechanistically in the field. This is done by a case study of Jay Keasling, one of the pioneers of synthetic biology. By analyzing how a modern scientist work and think, students are provided with a broader view of scientific inquiry and the nature of scientific thinking.

Students will be asked to demonstrate their understanding of what they have learned so far by creating a Scratch project. This allows students to work more closely and creatively with Scratch. It also acts as a quick formative assessment for teachers of students' learning thus far. However, the real goal of this exercise is to have students engage in mechanistic thinking in their own work, which they may not recognize as it is not in the direct context of science. This will be revealed in lesson 3.

Lesson 3

Designed to have students practice thinking mechanistically by simulating how synthetic biologists think in the field via the *Designing a New Microbe* activity, adapted from an actual experiment conducted in 2007[3].

This activity presents students with a problem (need for hydrogen gas as alternative fuel) and asks students to design a microbe that can use starch and water to make hydrogen gas. Students are given a set of organism cards to work with, each card symbolizing a different type of organism (bacteria, rabbit, yeast, archea, spinach, and mouse). Proteins (molecules that can convert one molecule into another) that are unique to each organism are listed on the card. Students' engineered microbe will essentially have different proteins from different organisms, placed in a certain sequence, to end up with a final product of hydrogen gas. Students are given the *Designing a New Microbe* worksheet to help them visualize the problem better and reduce their cognitive loads (i.e. amount of information they need to carry in their heads).

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[3] Zhang Y.H., Evans B.R., Mielenz J.R., Hopkins R.C., Adams M.W. (2007). High-yield hydrogen production from starch and water by a synthetic enzymatic pathway. *PLoS ONE 5*: e456.

After the activity, when students have grasped a much deeper understanding of what mechanistic thinking looks like in practice, students are asked to reflect on their experience with Scratch. The goal is to have students make the connection that they themselves have been engaging in mechanistic thinking while working on their own Scratch projects. This reflective exercise encourages students to transfer their understanding of mechanistic thinking across different domains. Students will also gain an appreciation of how studying trends in scientists' way of thinking can help them in their own thinking.

Lesson Placement

These lessons can be used at the beginning of the school year when the scientific method is usually being presented. Alternatively, this lesson can be infused during the school year, as students learn more about genetic engineering or creative thinking.

These lessons follow a constructivist approach to learning, encouraging students to discover the meaning of mechanistic thinking through their exploration of a case study, simulating how synthetic biologists think, and making connections to their own work in Scratch. Students are always encouraged to formulate their own ideas and connections before being presented with any information.

Lesson Plan: Day 1

Materials

- Computers with Scratch installed
- Scratch Resources

Prep Step

- Review lesson plan, background information and understanding goals
- Obtain computers with Scratch installed for students to work on
- Make copies of Scratch Resources (not provided)

Explore

Step 1: Introduction to lesson

Introduce the lesson by giving students a sense of what they will be doing and where they are headed, by telling students, "This will be a three-day lesson where we will be exploring how scientists think, and more specifically what mechanistic thinking looks like in practice. In this process, we will also be learning Scratch. We will tie everything together at the end of the third day."

Step 2: Playing with Scratch

Depending on the level of your students and any future goals you wish to achieve with Scratch, structure the class so that students are comfortable navigating around the Scratch environment, and are able to get started on their own Scratch project by the end of the class. Please provide students with any Scratch resources you see fit. Check out the ScratchEd's resource search (http://scratched.media.mit.edu/resources/search) for more info. Some good examples found in ScratchEd of Scratch lesson plans (video tutorials, PowerPoints, and worksheets) include:

- Having Fun with Computer Programming and Games
  (http://www.lero.ie/educationoutreach/secondlevel/scratchlessonplans/)
- A TeachNetUK Project: 6 Lessons on Getting Started with Scratch
  (http://www.teachnet-uk.org.uk/2007%20Projects/ICT-Scratch/Scratch/pages/8_schemeofwork.html)
- Scratch Lessons: Shall We Learn Scratch Programming for Tweens
  (http://www.shallwelearn.com/scratchprogrammingforkidscategory)
- Designing Animations and Games—A Creative Introduction to Programming
  (http://www.cs.uni-potsdam.de/~romeike/UEWettbewerb/index-english.htm)

Make sure to also introduce students to the Scratch online community, and let them know that they can download the source code of any project to help them see how others are using the Scratch programming language to create projects.

Review, Extend, and Apply

Step 3: Scratch Assignment

End the day by informing students that they will apply what they have learned today to create a mini-Scratch project for an assignment after the next day's lesson. Emphasize to students that the goal is not to create a complex programming project, but to use Scratch creatively as a medium for creative expressing not matter how simple the project is. Encourage students to play with Scratch on their own time, and make it clear that you highly encourage them to borrow, adapt, and build upon the ideas and projects of others (this is *not* considered cheating).

Lesson Plan: Day 2

Materials

- 21st century scientist case study of Jay Keasling
- Student notebooks or journals

Prep Step

- Review lesson plan, background information and understanding goals
- Make copies of 21st century scientist case study of Jay Keasling (p. 8)

Explore

Step 1: What is scientific thinking?

Ask students to describe what they think is scientific thinking. Collect a representative list of students' thoughts on the board. Ask students to explain or expound on the meaning behind what they are saying. After reviewing the list, ask them, " Do you think all scientists come to their discoveries in the same way," "Do scientists display all these characteristics at all times?" It is important to point out to students that scientists have various methods going about their experimentation and work, and depending on the type of work they are doing, scientists don't always share the same methods. Furthermore, scientists engage in thinking patterns that are specific to its particular socio-cultural context, and one of which is mechanistic thinking.

Engage in a discussion with students on how might the explosion of advancements in scientific knowledge and technology at the turn of the century, change the way scientists at the cutting edge of research interact with their work.

Step 2: Analyze case study of a 21st century scientist

Let students know that they will be learning about the field of synthetic biology as a means to illustrate how modern scientists work and think. Specifically, they will be studying Jay Keasling, one of the pioneers of synthetic biology.

Hand out the case study on Jay Keasling. Have students work in groups of 3-4 students to identify any patterns of thinking that the scientist displays. Make sure to ask students to specifically identify what part of the case study justifies their claims. Have students write the class findings in their journals/notebooks.

Possible findings from case analysis: Jay Keasling

Keasling is a pioneer of synthetic biology—a field that designs and constructs new organisms for useful purposes. He is most known for creating a microbe that produces a drug to treat malaria (making drugs from bugs). Some of his characteristics as a scientist include:

- *Creative and imaginative:* wanted to invent new tools that can turn cells into chemical plants, take in something very simple and spits out something complicated and valuable, coming up with other applications of synthetic biology (use microbes to break down pesticides, make biodegradable plastics, create fuels from plants)
- *Critical thinking:* thought about how to design and create microbes to produce artemisinin much quicker and cheaper, how to integrate genes from different species into a microbe to fabricate the drug

- *Seek and integrate information:* integrated methods and concepts from engineering and biology, leading to synthetic biology
- *Supported with significant resources:* did research at universities and received grant money
- *Practical-minded:* microbes will churn out anti-malarial drug for a fraction of its current cost, making it accessible to much more of the world, these microbes could save millions of lives
- *Strong disciplinary understanding:* studied biology and chemical engineering extensively, leading to his PhD and professor position at UC Berkeley

Step 3: What is mechanistic thinking?
Introduce students to the idea of mechanistic thinking as a prominent thinking pattern in the 21st century.

Mechanistic Thinking

Mechanistic thinking is a way of thinking that has a mechanical or engineering undertone. This is shown through scientists' regular use of mechanical analogies to conceptualize their work, and their modular, synthetic, and purpose-driven approach towards their research problems. The display of mechanistic thinking by scientists appears to be a result of the merging of biology and engineering practices that is increasingly observed in 21st century biology, as compared to a time when most of biology—traditionally known for its pure, basic research—remain clearly demarcated from engineering—a purely applied research field. A mechanistic way of thinking has come to the forefront of 21st century science because of recent developments in new technologies and knowledge that enable scientists to manipulate the object or organism they are working with more directly, allowing them to engineer and create novel biological systems for practical applications.

Let students know that the work synthetic biologists do, often require them to think mechanistically. Now that students are given a definition of mechanistic thinking, have students revisit their case study analysis and explore how synthetic biologists might think mechanistically.

Review, Extend, and Apply

Step 4: Scratch Assignment
Ask students to create a mini-Scratch project to demonstrate what they have learned so far (the project does not have to be all inclusive; students can choose to focus on just one thing they learned either about scientific thinking, mechanistic thinking, or synthetic biology). Emphasize to students that the goal is not to create a complex programming project, but to use Scratch creatively as a medium for creative expressing not matter how simple the project is. Encourage students to work with partners and collaborate by borrowing, adapting, or building upon the ideas and projects of others (this is *not* considered cheating).

Detailed Case Study
Jay Keasling
(1964 – present)

> ***Best known for:*** *pioneering the new field of synthetic biology, which designs and constructs new organisms for useful purposes. He is also most known for creating a microbe that produces a drug to treat malaria (making drugs from bugs).*

Jay Keasling was raised on a farm, and spent his childhood exploring the practical side of biology, chemistry, and engineering. This background eventually led him to work in the rapidly growing field that uses living organisms like bacteria for various practical purposes, such as food processing, agriculture, and medicine.

In the early 1980s, genetic engineering became popular because you can "convince" microbes to produce insulin, growth hormones, and other valuable proteins by simply inserting a single gene, from a different organism, into bacteria. However, Keasling believed that genetic engineering isn't harnessing the full power of these cells. The production of molecules isn't always so simple; it requires a complex interaction of several genes (not just one) being produced in a certain sequence. So Keasling wanted to invent the tools that would allow him to create these kinds of genetic assembly lines. Thus, what goes on in a cell is a lot like what goes on in a chemical plant: petroleum goes in, and after a whole chain of reactions, plastic comes out.

Keasling went to college studying biology and chemical engineering extensively, and got his Ph.D. in 1991. He is now a professor at the University of California at Berkeley. He spent his first 10 years at UC Berkeley building the new tools he would need to turn cells into chemical plants. He also invented powerful chemical switches (like a light switch) that allowed him to control when he wanted to "turn on" and "turn off" protein production in cells. This way of borrowing techniques from engineering and figuring out how to manipulate microbes came to be call synthetic biology.

After years of perfecting his biological tool kit, Keasling wanted to find a real-world use for it. In 2002 he learned of the dire need for artemisinin, a compound derived from the sweet wormwood plant, which is 90 percent effective against the parasite that causes malaria and has few side effects (malaria kills some 3 million people a year). However, extracting the drug from sweet wormwood is a slow and expensive process. Keasling figured he could design and create microbes to produce artemisinin much quicker and cheaper. Rather than wait months for sweet wormwood to grow on farms, Keasling wanted to create it simply by pouring sugar in a tank full of microbes that can use the sugar to make the drug via a chemical pathway he has designed—he wanted to integrate genes from different species into a microbe to fabricate the drug for malaria.

In 2006, Keasling's team (comprised of graduate students, post-docs, and research assistants) published their success of the production of artemisinin. It is expected to lower the cost of artemisinin production from a dollar per gram to just 10 cents. He was awarded a $43 million grant from the Bill and Melinda Gates Foundation, and awarded DISCOVER magazine's first ever Scientist of the Year Award.

Fighting malaria is just one part of Keasling's larger agenda to explore the potential of synthetic biology. In his laboratory, students are engineering microbes to break down pesticides, make biodegradable plastics, and create ethanol and other fuels from plants.

Jay Keisling biography adapted from:
Zimmer, C. (2006). "Scientist of the Year: Jay Keasling." *Discovermagazine.com*. Retrieved from http://discovermagazine.com/2006/dec/cover.

Excerpts of interview w/ Jay Keasling

See responses to these questions at
Zimmer, C. (2006). "Scientist of the Year: Jay Keasling." *Discovermagazine.com*. Retrieved from http://discovermagazine.com/2006/dec/cover.

1. You arrived at UC Berkeley in 1992 with training as both a chemical engineer and a biologist. What did you hope to do?

Interview content removed due to copyright restrictions.

2. Why hadn't anybody tried to engineer cells that way before?

Interview content removed due to copyright restrictions.

3. How did you get involved in your antimalaria project?

Interview content removed due to copyright restrictions.

Lesson Plan: Day 3

Materials

- *Designing a New Microbe* worksheet
- Organism cards
- Student notebooks or journals

Prep Step

- Review lesson plan, background information and understanding goals
- Photocopy *Designing a New Microbe* worksheet (p. 28)
- Cut out organism cards (each group of 3-4 students will have a set of cards) (p.29)

Explore

Step 1: Designing a New Microbe

Introduce today's activity by saying, "You will be simulating how synthetic biologists think mechanistically by doing an the activity that is actually modeled after a real experiment done by scientists in 2007."

Divide students into groups of 3 or 4. Each group receives a set of organism cards. Each student receives a *Designing a New Microbe* worksheet. Remind students that proteins (or enzymes) are molecules inside cells that convert one molecule into another (e.g. the make-believe molecule *How* is converted to the molecule *Home* by Protein T in bacteria).

Following the directions of the handout, have students create a kind of assembly line that integrate proteins from different organisms into a microbe that uses water and starch (inputs) to ultimately produce hydrogen (output).

Possible answers to *Designing a New Microbe*

There are two possible pathways that can lead to hydrogen production:

1. Starch & water → Protein G → Protein P → Protein D → Protein R → Protein T → Protein F → Protein H →Hydrogen
2. Starch & water → Protein G → Protein P → Protein D → Protein H → Hydrogen

Guide students along by encouraging students who have already figured out how to attempt the problem to reveal and share with the class how they are thinking through the problem. Stop students periodically to ask, "How are you thinking through this problem? What is your goal, and how is your thinking helping you reach that goal?" Students may find either working sequentially forward or backward to fill in the worksheet to be easier.

Note to teachers: The hydrogen production pathway from starch and water is a shorten version of the actual 2007 experiment for learning purposes. The organism types and molecule names are true to the experiment. Protein names are made up for simplicity.

Step 2: Discuss students' findings

Have students tell you what they found as you write their findings on the board. Students may have discovered by now that there are two paths that lead to hydrogen production. Students might recall that Jay Keasling have done something similar by making an antimalarial drug from sugar using synthetic biology.

Students may have also discovered that no proteins from the mouse organism were used for the design of their new microbe. Ask students, "what do you think is the purpose of having a mouse organism when we didn't need it?" Help students understand how in reality scientists have hundreds of organisms to choose from, some of which are irrelevant to their work. In fact, a common skill that scientists share is being about to identify and pull together important and relevant information.

The activity allows students to discover that synthetic biology is a very mind-blowing field, accomplishing things that some people never thought was possible. Students will come to appreciate how seemingly impossible feats can be possible especially when scientists are thinking creatively. By thinking and working mechanistically, scientists have more freedom then before in designing and creating novel organisms for real-world applications.

Review, Extend, and Apply

Step 3: How do you think mechanistically?

Ask students to reflect on their experience with Scratch and how they might have engaged in mechanistic thinking in their own work. Helps students make the connection that they themselves have been engaging in mechanistic thinking while working on their own Scratch projects.

The Scratch grammar is designed so that users are presented with a versatile collection of graphical programming blocks that they can be snapped together to create programs, much like synthetic biology. Connectors on the blocks suggest how they should be put together so that over the process of tinkering with these blocks, the emerging structure can give rise to new ideas and direction to the project. Not only does snapping together complimentary blocks provide an easy way into learning programming, but the idea of modularization as a problem-solving and design strategy is directly relevant to mechanistic thinking!

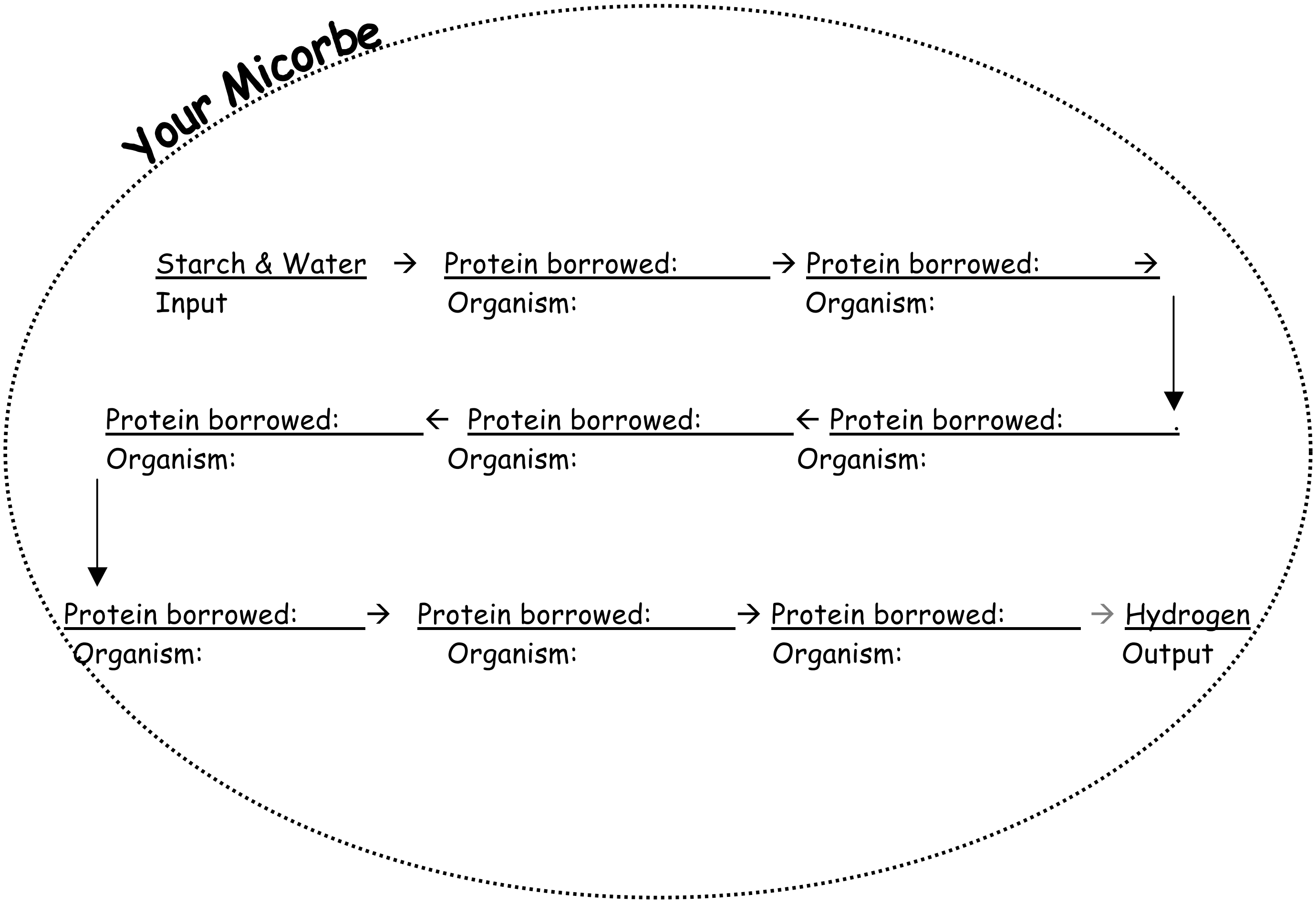
Go on to discuss how they can apply scientists' patterns of thinking to our own thinking in science class and daily life.

Name_____________________________ Date ____________

Designing a New Microbe

Task: Gas prices have reached its all time high! Thus scientists are trying to think of ways to produce alternative fuels, such as hydrogen gas, in a much cheaper and quicker way. You are a scientist and you are familiar with six different organisms. Based on what you know, can you come up with a way to generate hydrogen from starch and water by designing a microbe that borrows different mechanisms/proteins from different cells? Fill in the blanks with protein names and the organism that the protein was taken from.

Materials: Each team has a set of cards, each card symbolizing a different organism. On the card, you will see the name of the organism, a picture of the organism, and proteins that is unique to them. Proteins (or enzymes) convert one molecule into another.



Starch & Water → Protein borrowed: → Protein borrowed: →
Input Organism: Organism:

Protein borrowed: ← Protein borrowed: ← Protein borrowed: .
Organism: Organism: Organism:

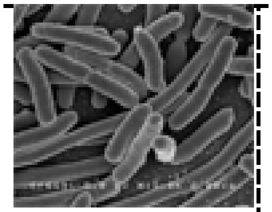
Protein borrowed: → Protein borrowed: → Protein borrowed: → Hydrogen
Organism: Organism: Organism: Output

Experiment adapted from:
Zhang Y.H., Evans B.R., Mielenz J.R., Hopkins R.C., Adams M.W. (2007). High-yield hydrogen production from starch and water by a synthetic enzymatic pathway. *PLoS ONE 5*: e456.

Organism Cards (one set)

Teachers: Please make as many copies as the number of groups of students. Cut the cards out and shuffle before handing to students.

Bacteria



Source: NIH

- Protein T uses *[X5P]* to make *[S7P]*
- Protein F uses *[S7P]* to make *[NADPH]*

Rabbit

Photo: US Fish and Wildlife Service.

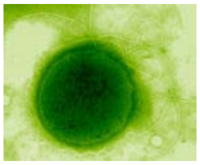
- Protein G uses starch and water to make *[G-1-P]*
- Protein P uses *[G-1-P]* to make *[G-6-P]*

Yeast

Public domain image. (Source: Wikimedia Commons)

- Protein D uses *[G-6-P]* to make *[NADPH]* and *[R5P]*

Archea



Courtesy of Angels Tapias (License CC BY).

- Protein H uses *[NADPH]* to make *Hydrogen*

Spinach

Public domain image. (Source: Wikimedia Commons)

- Protein R uses *[R5P]* to make *[X5P]*

Mouse

Source: NIH

- Protein X uses *[T8P]* to make *Hydrogen*

Experiment adapted from:

Zhang Y.H., Evans B.R., Mielenz J.R., Hopkins R.C., Adams M.W. (2007). High-yield hydrogen production from starch and water by a synthetic enzymatic pathway. *PLoS ONE 5*: e456.

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