LESSON PLAN & TEACHER'S GUIDE

Genome Editing and CRISPR

Adapted for PBS LearningMedia in partnership with WETA for use with

KEN BURNS PRESENTS
THE GENE
AN INTIMATE HISTORY

Aim

How might advances in our ability to change genomes impact individuals and society?

Time

This lesson can be adjusted to fill 1 or 2 classes.

Guiding questions

- What is the difference between analyzing DNA and modifying DNA?
- What are the newest techniques being developed? What is CRISPR?
- How do we make decisions about whether and how to proceed with genome editing?
- How can society ensure the promises of new genetic techniques are safe and equitably shared?

Learning objectives

By the end of the lesson, students will be able to:

- Understand that rapid changes are occurring in the field of genetics due to a combination of new insights and new techniques, including genome editing.
- Be able to explain the major points of excitement, concern and debate about CRISPR, a genome editing technique.

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- Know that genome editing holds promise as well as presents many unknowns from the perspectives of human health and ecology.
- Realize that they may have personal and societal decisions to make about genome editing.

Materials

Articles, handouts, laptop, projector or SMART board.

Standards alignment

Common Core Standards

CCSS.ELA-LITERACY.RST.11-12.1. Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.

CCSS.ELA-LITERACY.RST.11-12.2. Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.

CCSS.ELA-LITERACY.RST.11-12.4. Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 11-12 texts and topics.

CCSS.ELA-LITERACY.RST.11-12.7. Integrate and evaluate multiple sources of information presented in diverse formats and media (e.g., quantitative data, video, multimedia) in order to address a question or solve a problem.

Next Generation Science Standards

This pgEd lesson integrates some of the NGSS practices and cross cutting concepts associated with the following disciplinary core ideas. The relevant portion of each disciplinary core idea is written out below.

HS-LS1 From Molecules to Organisms: Structures and Processes

LS1.B: Growth and Development of Organisms

- The organism begins as a single cell (fertilized egg) that divides successively to produce many cells, with each parent cell passing identical genetic material (two variants of each chromosome pair) to both daughter cells. Cellular division and differentiation produce and maintain a complex organism, composed of systems of tissues and organs that work together to meet the needs of the whole organism.

HS-LS2 Ecosystems: Interactions, Energy, and Dynamics

LS2.C: Ecosystem Dynamics, Functioning, and Resilience

- If a modest biological or physical disturbance to an ecosystem occurs, it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability.

HS-LS3: Inheritance and Variation of Traits

LS3.B: Variation of Traits

- Environmental factors also affect expression of traits, and hence affect the probability of occurrences of traits in a population. Thus the variation and distribution of traits observed depends on both genetic and environmental factors.

HS-ETS1 Engineering Design

ETS1.A: Defining and Delimiting Engineering Problems

- Criteria and constraints also include satisfying any requirements set by society, such as taking issues of risk mitigation into account.

ETS1.B: Developing Possible Solutions

- When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts.

Background information and note to teachers

Recently developed techniques to easily modify DNA are bringing many new possibilities as well as dilemmas to the forefront of medicine, ethics, religion and society at large. One technique in particular, genome editing (see the Vocabulary section on page 6 for a list of helpful definitions), has attracted much attention among scientists, policymakers and the general public. Genome editing allows scientists to make changes to specific "target" sites in the genome – almost like using a molecular scalpel to alter individual sections of genetic code. One of the tools for performing genome editing, known as CRISPR (pronounced like the word *crisper*), has generated the most excitement due to its efficiency and ease of use. Researchers have used CRISPR in plants, animals and human cells; in fact, CRISPR has worked in all species examined to date.

This lesson introduces some of the recent advances in genome editing, including its potential applications for improving human health. Already, it has become a valuable tool for biomedical researchers to study disease, both in lab animals that are used as research models, and in human cells studied in petri dishes. Genome editing brings us one step closer to the possibility of "editing" the genome in patients' cells to repair a disease-causing genetic variant. While it is still early days, the hope is that genome editing technologies may one day provide a cure for genetic diseases such as sickle cell anemia, cystic fibrosis and Huntington's disease, as well as enable people to better fight off viral infections (e.g., HIV).

Much of the research on using CRISPR for treating disease is focused on introducing genetic changes in cells, such as those in blood, lungs, or brain, that would not affect the genome of the individual's future offspring. In addition to modifying these "somatic" cells, there is also a possibility of "germline editing" — that is, modifying the genomes

of cells that will become egg or sperm, or the cells in early stage embryos. Because such genetic changes could be passed on to future generations, germline editing has been the subject of particular concern and discussion by scientists, ethicists and the broader public.

Important conversations are also being had about the safety standards for emerging technologies like CRISPR, and the potential for unintended consequences. Much of the discussion we hope students will have is concerned with whether editing the genes linked to diseases or disabilities would lead to stigmatization of people who are living with those diseases or disabilities. Additionally, if as a society we agree that the use of genome editing is acceptable, how do we ensure that all individuals are aware of the potentials of these technologies, and that everyone who wants access to such technologies can afford them?

Genome editing, in particular CRISPR, has also opened a pathway to engineer the world around us for the benefit of human health, agriculture and the environment. Applications include the possibility of modifying or even eradicating disease-spreading insects, such as mosquitoes. However, not everyone agrees these applications would necessarily be a "benefit," while others worry about unintended consequences of these ecosystem-changing actions.

Genome editing brings significant potential benefits and raises profound questions. As society seeks a balance between the desire to realize the benefits of genome editing and a variety of other concerns, there will need to be broad conversations that engage all communities and ensure that diverse values and voices are heard. Researchers, bioethicists and policymakers, including a number of the scientists who pioneered CRISPR, have called for caution and the need for public consultation and dialogue that also involves patients, faith leaders, environmental activists and disability rights advocates. This lesson introduces some of the basic scientific and ethical concepts needed for informed conversation and debate.

Outline of resources and activities in this lesson

Activities

This lesson includes a Do Now exercise (5-7 minutes), slideshow (30-40 minutes), scenarios activity and discussion (25-35 minutes) that accompany the clip from *The Gene: An Intimate History*.

Part 1: OVERVIEW FOR STUDENTS

Vocabulary:

There are several vocabulary words with which students may be unfamiliar. You can provide a vocabulary list, or have students look up words themselves.

Advocate – To speak or write in favor of; to support or recommend publicly.

Gene – A sequence of DNA code that determines some specific characteristic(s) of an organism.

Genome – An individual's full set of genetic information, including all genes as well as other sections of DNA that may regulate the activity of those genes.

Genome editing technologies – A set of genetic technologies that allow for making changes to a specific "target" site in the genome. Although sometimes called gene editing, the techniques can be used to modify parts of the genome other than genes.

Modify – To make partial changes to something.

Stakeholder – A person or group that has an interest in something.

Do Now exercise (5-7 minutes):

The lesson starts with two Do Now questions on slides 2 and 3 of the slideshow that ask students consider their personal interest in both learning about their own genomes and altering their genomes. (Note: Question two of the "Do Now" is hypothetical – such services do not exist at present.) Have students discuss the questions in pairs and then discuss them as a larger group. We have provided some likely ideas and questions to expect in the conversation below in the notes for Slides 2-3.

Note: This exercise assumes students have a basic understanding of genetic analysis – the process of learning about a person's individual genetic make-up. If you have not covered this topic yet with your students, you may wish to begin with pgEd's lesson Introduction to Genetics and Medicine that explores this topic.

Part 2: SLIDESHOW (30-40 minutes)

The PowerPoint slideshow illustrates the basic concepts and vocabulary for talking about genome editing and introduces CRISPR. We focus on how genome editing may one day be applied in medicine, discuss the current research being carried out primarily in animal models, and present the excitement and concerns around several examples. Each example has an ethical dimension to consider.

The slideshow is located on the pgEd website along with this lesson, and accompanying explanatory notes for the slideshow are below. The main idea of each slide is in bold along with text that summarizes the story presented in each slide. The notes provide a great deal of information to aid in answering student questions and references for teachers interested to delve deeper into these topics. The slides also pose many unanswered questions, setting up the Scenario activity where students will explore the process for collecting and assessing information about complex dilemmas.

Slide 2-3

The questions for this "Do Now" activity will help students begin to consider the topics covered in the lesson. In this "Do Now" activity, teachers should expect a wide range of answers. You may want to discuss some of the information ahead of the activity, or use this background to further add content and details to what you hear as students share their conversations.

Genetic analysis aims to inform an individual about his or her predispositions for various traits, including potential for developing diseases, by "reading" the nucleotide letters (A, T, G, C) of the individual's DNA. From there, it can also provide estimates of the likelihood of passing along certain traits to one's children. Examples of genetic analyses include the genetic tests that people might undergo before or during the course of pregnancy, or the tests for determining the basis of diseases. Increasingly, genetic analyses may involve sequencing an individual's genome. Learning about one's genetic information can come with excitement and opportunities as well as a host of questions and confusion. It can impact family members and one's own outlook, and open up new and unexpected information in terms of ancestry and health.

However, genetic analysis is just that – a look at what's in your DNA. On the horizon are technologies that may one day make it possible, after having a look at your genome, to modify or change your DNA. In theory, this could be accomplished in a number of ways, such as using a virus as a "vehicle" to send new genetic material to a cell, or techniques where existing pieces of DNA are "cut" and new ones are "pasted"

in. Once the new genetic material is inserted, the cellular machinery that copies and reads DNA would, presumably, treat it like it would any other piece of sequence.

A couple of concepts about genetic analysis and modification may be useful for students to know:

1) *Differences in the number and location of cells that need to be analyzed or modified.*

The genome in every cell in an individual's body is essentially identical - with a few notable exceptions: for example, the reproductive cells and the mutations acquired by each cell in a person's lifetime. With these caveats in mind, in theory, the DNA of virtually any cell can be analyzed to provide information about the whole body. This is why genetic analysis is often carried out on cells from easily accessible sources, such as saliva or blood. There is also ongoing research that aims to make it possible to analyze the genome sequence of single cells.

On the other hand, in order to modify traits or treat diseases, genetic changes will often need to be made to many cells at once, and the right kinds of cells. In some cases, modifying a small subset of cells may be enough (such as the stem cells in bone marrow that give rise to most of the body's blood cells). In other cases, a significant portion of cells in the relevant tissue or organ may need to be modified. This presents technical challenges for safely targeting the changes to a sufficiently high number of the right cells, and making changes to the desired part of the genome with minimal mistakes to the rest of the cell's DNA.

2) *There are two categories of genetic modifications with different ethical considerations.*

The cells in our body fall into two broad categories – somatic and germline. Somatic cells, the ones that make up the majority of our body, contain both sets of genetic materials we got from our biological parents. If you were to change the DNA of somatic cells, those genetic changes do not affect the genomes of future generations. Germline cells, such as sperm and eggs, are the cells that give rise to the offspring during the reproductive process. Changes made to germline cells, including the intended modification as well as any mistake or unexpected changes made during the process, will have the chance of being inherited in the genomes of subsequent generations. Whether a genetic change is made to somatic cells or the germline is an important distinction because of the ethical questions about making changes to a genome that will be passed on to future generations. Currently, scientists believe that genetic changes can be made to somatic cells without affecting the germline.

Slide 4 - Video clip

We recommend pausing on this slide to show students the accompanying clip from *The Gene: An Intimate History* (link also included in the slide).

Slide 5

What is CRISPR? In the past decade, scientists began to develop techniques known as "genome editing." Genome editing allows scientists to make changes to a specific "target" site in the genome. One of the techniques that have generated the most excitement, due to its efficiency and ease of use, is called "CRISPR." CRISPR stands for "clustered regularly interspaced short palindromic repeats." It is akin to a primitive immune system that bacteria use to protect themselves against viruses. Scientists have since been able to take components of the CRISPR system and use it as an experimental tool.

How does CRISPR work?

CRISPR is a self-defense mechanism that bacteria use to protect their genomes against viruses. It works by making cuts to DNA at specific genomic sites. Scientists have harnessed this system for use as a tool to make targeted DNA changes in a variety of organisms, including in human cells.

Generally speaking, genome editing techniques such as CRISPR can be used to do one of two things. First, they can be used to make a gene nonfunctional (e.g., to shut down a gene that is causing disease, such as a gene that a cancer cell requires to grow). They can also be used to replace one version of a gene with another (e.g., to replace a faulty or broken copy of a gene with a working copy). Other researchers are experimenting with modified versions of CRISPR that, instead of modifying the DNA sequence at the target site, deliver additional molecular tools to turn a target gene "on" or "off."

- For a more detailed description of the mechanism of how CRISPR works, see supplemental slide #15 in the PowerPoint presentation and the notes below.
- "CRISPR's Most Exciting Uses Have Nothing to Do With Gene-Editing," by Ed Yong, January 2016, *The Atlantic*.

Slide 6

What is gene therapy? Using genetic technology to directly treat the genetic causes of diseases, known as "gene therapy," has long been an aspiration for physicians, scientists and patients. Some diseases, such as cystic fibrosis or sickle cell anemia, are relatively well-understood to be caused by variants in single genes. If the disease-

causing gene can be corrected or replaced, then the hope is to perhaps cure the disease or at least prevent the disease from worsening. However, this is more difficult for more complex conditions, such as heart disease, diabetes and many forms of cancer, which result from the interplay among many genes and between the genes and the environment.

Gene therapy has been attempted since the 1990s. So far, a limited number of gene therapy treatments have been approved by safety and regulatory agencies, such as the US Food and Drug Administration. Most of the approved treatments work by adding a new or extra copy of a gene. With advances in genome editing, it is now possible to consider more targeted approaches for gene therapy - for example, directly altering an individual's original copies of a gene. Genome editing-based gene therapy can also be used in other ways, such as adding a new gene to a specific spot in the genome or inactivating genes that may otherwise trigger immune responses to a therapy. Note that, while a number of clinical trials are in progress around the world, none of these approaches have been approved for clinical use in humans as of February 2020.

- "FDA approves first gene therapy for an inherited disease," by Laurie McGinley, December 2017, *Washington Post*.
- "Gene Therapy Arrives," by Jim Daley, January 2020, *Scientific American.*

The following two conditions may potentially be treated by gene therapy:

Cystic Fibrosis (CF): CF is a genetic disorder where thick, sticky mucus in the respiratory pathways lead to breathing problems, developmental delays and infections. CF is caused by mutations in one gene called CFTR. Treatments have been very hard to find, and CF has been one of the most anticipated targets for gene therapy. One of the main challenges for gene therapy is to be able to safely and effectively make the desired genetic changes to all the cells that need the gene to function. In the case of CF, all the cells in the lungs and sweat glands may need functional CFTR in order to properly produce mucus or other secretions. While no therapies have yet been approved for use, in recent years there have been some promising experimental results in mice and pigs, where the major symptoms of the disease have been reversed.

- "Gene therapy: promising candidate for cystic fibrosis," November 2015, *Science Daily.*
- "Gene therapy for cystic fibrosis lung disease," September 2016, *Science Daily.*

Sickle Cell Disease (SCD): SCD is a genetic condition characterized by mutations in the oxygen-carrying proteins in red blood cells, called hemoglobin. SCD causes hemoglobin proteins to stick together and lead to the red blood cells turning into a sickle shape. SCD occurs because of mutations in the "adult hemoglobin" gene, which is responsible for making hemoglobin from the time we are babies onwards through

adulthood. Gene therapy may be possible for SCD by directly repairing the mutations in this gene. Another promising approach takes advantage of a second hemoglobin gene that functions in fetuses and then gets turned off shortly after we are born. This hemoglobin gene, called the "fetal hemoglobin" gene, is not affected by mutations that cause SCD. So, one potential gene therapy would treat SCD by turning on the fetal hemoglobin gene and turning off the adult version. Experiments using this approach seem to work well in mice, and clinical trials in humans began in 2019.

- "Gene therapy for sickle cell moves closer as scientists clear unexpected obstacle," by Sharon Begley, September 2016, *STAT News.*
- "CRISPR deployed to combat sickle-cell anaemia," by Heidi Ledford, October 2016, *Nature*.
- "Sickle–Cell Patients See Hope in CRISPR," by Antonio Regalado, August 2017, *MIT Technology Review*.
- New gene therapy shows promise for patients with sickle cell disease," by Karen Weintraub, March 2019, *WBUR*.

Slide 7

Researchers have used genome editing to cure a type of liver disease in adult mice. Scientists are studying how to use CRISPR to treat diseases in animal models, as an important step in the research process towards applications in humans. For example, CRISPR has successfully been used in adult mice to reverse a liver disease called type I tyrosinemia. This disease, which affects 1 in 100,000 people, is caused by mutations in a single gene called FAH. The livers of people with this disease are unable to break down a specific amino acid, which can lead to liver failure. Scientists injected the CRISPR system along with working copies of the FAH gene into the veins of the diseased mice. In 0.4% of liver cells in these mice, the faulty FAH gene was successfully replaced with working copies. These edited cells then multiplied and replaced the cells with the faulty FAH gene, and eventually accounted for 33% of liver cells in the animals. This was enough to restore the lost function to the liver, allowing the liver to break down the proteins it previously could not – and led the research team to declare that they had "cured" type I tyrosinemia in adult mammals. While this treatment has not been tested in humans and trials are not yet underway, the concept that replacing a piece of DNA could lead to a profound improvement of a serious, often fatal genetic disorder in a mammal brings hope to many.

- Details about this study can be found in Anne Trafton's piece "Erasing A Genetic Mutation" in *MIT News* (March 2014).
- CRISPR is also being investigated as a tool to fight other diseases in humans, such as cancer. For more, see (1) "First CRISPR trial gets green light from US panel," by Sara Reardon, June 2016, *Nature* and "CRISPR gene-editing tested in a person for the first time," by David Cyranoski, November 2016, *Nature*.

Slide 8

The case of Layla Richards symbolizes the potential promise of genome engineering for treating diseases. Diagnosed at 14 weeks old with leukemia, a type of cancer that affects blood and bone marrow, Layla Richards was 11 months old when all conventional treatments had failed. Layla became the first child to be treated for leukemia via donated immune cells that were genetically engineered specifically for her body and type of cancer - a kind of treatment called immunotherapy. The cells, called CAR-T cells, were engineered to attack Layla's cancer cells. The cells were also altered to ensure Layla's immune system would not perceive them as dangerous and reject them. The transplant was a success, and as of the most recent report in early 2017, Layla remained cancer-free.

- "A Groundbreaking Gene-Editing Therapy Eliminated Cancer in Two Infants," by Kristen Brown, January 2017, *Gizmodo*.

Slide 9

Might genome editing one day lead to a solution to global shortage of organs? In addition to carrying out gene therapy in patients, scientists are exploring other ways of using genome editing to impact human health. The following two slides look at some examples.

There is a massive shortage of organs for people who need donations, and pigs hold a great deal of promise as possible donors, as many pig organs and human organs are similar in size and structure. However, serious challenges persist for potential recipients due to risks of immune rejection and viral infection. Scientists are using CRISPR to alter pig genomes in an effort to address these issues. To prevent tissue rejection, researchers removed several pig genes that trigger a human immune response and introduced new genes that regulate blood clotting and inhibit the immune response. Additionally, the team used genome editing to disable viruses that are embedded in the pig genome (called porcine endogenous retroviruses or PERVs). By making these edits to lower the risk of an immune response or infection, people may be more likely to respond well to a transplanted organ from a pig. Increased availability of organs for transplantation could potentially save thousands of lives annually.

The pigs that have undergone genome edits are reported to be healthy and preliminary results seem to indicate that organs from these animals are significantly less likely to trigger an immune response in humans than those of unmodified pigs. To further test whether these modified pig organs will be safe and suitable for eventual transplantation into humans, the research team has started transplanting these pig organs into monkeys.

- For more, see "Eyeing organs for human transplants, companies unveil the most extensively gene-edited pigs yet," by Kelly Servick, December 2019, *Science*.

While pork producers have shown interest in joining efforts to supply engineered pig organs for human transplantation, this approach raises a number of social and ethical concerns. Animal rights activists worry about the harming and exploiting of animals. The choice of animals in which the organs are produced may present cultural or religious challenges for certain communities. There are also questions about whether the organs will be available to patients in a fair and equitable fashion. Others worry about the first group of people who agree to such a transplant – will human bodies accept these organs, long term? Will the organs actually function for a length of time that justifies the risks and expense?

Slide 10

Should genome editing be used in the hopes of reducing malaria? Each year, hundreds of millions of people get sick from diseases that are spread by mosquitoes, and outbreaks of Zika, dengue and yellow fever since the early 2010s highlight the problem. One of the mosquito-borne diseases that lead to the most suffering worldwide is malaria. In 2015, more than 200 million people had the disease, and more than 400,000 people died from it (World Health Organization: Malaria Fact Sheet).

Some scientists are investigating the possibility of curbing these mosquito-borne diseases by genetically modifying the mosquitoes, such that they become less able to either reproduce or to carry the disease-causing microbes. The general idea is to release modified mosquitoes (usually male, which do not bite and thus cannot spread disease) into the environment so that they will mate with the wild mosquitoes.

Modifying mosquitoes to change their reproductive ability and population size may have potentially unpredictable ecosystem-wide effects, e.g., on other animals that may rely on the mosquitoes for food, or plants that may depend on the insects for pollination. In order to balance the potential public health benefits with the ecological effects of this intervention, researchers, policymakers and other stakeholders are calling for more research before any genetically modified mosquito is widely released into the environment.

- "Meet the Moralist Policing Gene Drives, a Technology That Messes with Evolution," by Antonio Regalado, June 2016, *MIT Technology Review*.
- "Field trial of genetically modified mosquitoes gets approval in Florida," by Andrew Joseph, November 2016, *STAT News*.

Slide 11

CRISPR is moving fast, but are we? In April 2015, a research team in Sun Yat-sen University in China reported that they had used CRISPR to perform genome editing in human embryos. The embryos used in the research were "non-viable" and could not have developed into a fetus. Since then, other labs in China, the United States and the United Kingdom have performed genome editing in viable human embryos. Because a genetic change made to an early-stage embryo could affect all cells in the future individual, including the germ cells, this is a form of germline genetic modification. This has led to discussion and debate worldwide about whether germline editing in humans is appropriate, and whether or how society should proceed with such research and possible application.

Critics emphasize the technical and ethical issues with making changes to the genome that can be passed down to offspring. There are concerns that any unforeseen effect in the editing process can become inherited. Other questions are being asked — do we have the right to alter the genome of our future generations? Would the editing of certain diseases or disabilities lead to stigmatization of people who are living with those diseases or disabilities? And who gets to decide what are considered diseases or disabilities that should be edited? Are there religious questions and perspectives that can inform the discussion? At the same time, proponents of germline editing emphasize the benefits in terms of alleviating suffering. These include the potential to eliminate diseases such as Huntington's disease, a debilitating neurological condition caused by a single gene variant. They also argue that humans have long been altering the lives and genetics of our offspring without their explicit consent, through procedures such as genetic counseling and preimplantation genetic diagnosis.

- "A debate: Should we edit the human germline?" by Patrick Skerrett, November 2015, *STAT News*.
- "Gene-editing research in human embryos gains momentum," by Ewen Callaway, April 2016, *Nature*.
- "God and the genome: A geneticist seeks allies among the faithful," by Andrew Joseph, October 2016 *STAT News.*

Slide 12

What is the path forward? The following two slides introduce the classroom activity that allows students to practice gathering information to make informed choices and policy decisions on a personal and societal level.

In December 2015, the United States National Academies, the United Kingdom Royal Academy, and the Chinese Academy of Sciences convened scientists, social scientists, ethicists, and other stakeholders for an International Summit on Human Gene Editing in

Washington, DC. A statement released at the end of the summit emphasized that it would be "irresponsible" at this time to proceed with the clinical use of germline editing, but did not recommend banning the technique, instead suggesting that research should continue. Since then, a number of meetings and working groups have continued to move the conversation forward.

In February 2017, an expert panel convened by the US National Academies issued its report on human genome editing. It recommended that clinical research on germline modification to treat "serious disease or condition" should be allowed to proceed once a number of criteria are met, including more research on safety and efficacy, stringent oversight, and continuing public conversation about societal benefits and risks. At the same time, the report urges that genome editing for nonmedical "enhancement" should not proceed without further societal discussion.

Currently, germline modification is illegal in many European countries and in Canada, and federal funding in the US cannot be used for such work. As of February 2020, researchers in the UK, Sweden and China have gotten approval to perform genome editing in human embryos for research purposes only (in addition, existing laws or guidelines in these countries only allow research on embryos up to 14 days after fertilization).

Slide 13

Claims of CRISPR being used to edit genomes of twin girls. In November 2018, Dr. Jiankui He of Southern University of Science and Technology in Shenzhen, China announced that two children had been born whose genes were edited in the embryo stage. In an attempt to confer immunity to HIV infection, he genetically modified the CCR5 gene in embryos created via in-vitro fertilization (IVF). The current report is the first one of human beings being born with their DNA purposely altered in a lab to possess certain traits. He presented the research at the Second International Summit on Human Genome Editing, two days after the news broke.

In addition to the issues that this case raised about informed consent and the ethics of germline modification in humans, there are also scientific questions to consider. While changing CCR5 may confer immunity to some strains of HIV, a person could still be infected by other strains. There is also growing evidence that the genetically modified CCR5 gene might have unintended consequences, such as an increased susceptibility to infection by influenza and West Nile virus. This story highlights the challenges of using CRISPR and other genome editing tools, given that our biology is highly complex and that scientists' understanding of genetics is ever-evolving.

- For a deeper dive into this story, see pgEd's lesson on "Claims of CRISPR Being Used to Edit Genomes of Twin Girls Born in 2018".

- "He Jiankui, embryo editing, CCR5, the London patient, and jumping to conclusions," by Henry T. Greely, April 2019, *STAT*.
- "Gene edits to 'CRISPR babies' might have shortened their life expectancy," by Sara Reardon, June 2019, *Nature*.

Before beginning the activity in Part 3, students should be aware of where regulation of genetic modification currently stands. These materials are up to date as of February 2020. As this is a rapidly developing area, you will find the most updated version of this lesson plan on pgEd's website.

Slide 15 - Supplemental Slide

How does CRISPR work? When used as an experimental tool for genome editing, the CRISPR system has two main components:

1. A targeting system that finds the right place in the genome to cut. This is achieved by a molecule called a guide RNA (gRNA), which has the same genetic sequence as the target genomic site.

2. A component for making the actual cut to the DNA. This consists of a DNA-cutting enzyme (the technical term is a "nuclease") called Cas9.

When both of these components are delivered into a cell, the gRNA will bind to the target genomic site through complementary base pairing (meaning, A's will bind to T's and G's will bind to C's). In the process, the gRNA helps bring in Cas9 to the target site to make a cut to the DNA double helix. The cell's natural DNA repair mechanism will close this gap, but because the process is not perfect, a few DNA bases will be added or deleted. This renders the original gene – e.g., a gene variant linked to cancer, or one related to HIV infection – nonfunctional.

CRISPR can also be used to replace an undesired version of a gene (e.g., one that causes a disease) with a desired copy. In this case, the desired version of the target gene can be placed into the cell along with the gRNA and Cas9. The cell will then use this alternate sequence as a template to repair the broken DNA through the process of "homologous recombination," copying the new sequence into the genome.

Part 3: CLASSROOM ACTIVITY (25-35 minutes)

This activity asks students to use critical thinking and research skills. How do you collect information to make complex decisions? What expertise or viewpoints should you seek out as you develop your position on an issue? How do you assess its veracity? What sorts of data might cause you to change your mind?

Each group is assigned to play the role of an elected official, who is asked to make a recommendation on a situation that involves genome editing. The students are not given all the information needed to make an informed decision. They are asked to create a list of 6+ questions that they have after reading the scenario, and then create a list of four people whom they would seek out to ask their questions.

Classroom set-up:

Divide students into four to eight groups (depending on class size) and assign each group one of the four scenarios provided. (If you have 8 groups, two groups will have each scenario.) Distribute 3 handouts to each group: (1) a description of the assignment, (2) their assigned scenario, and (3) a worksheet for them to complete. At the end of the activity, have each group present their scenario to the class, explain the questions they have about the scenario, and the stakeholders who they think are best-suited to provide answers.

We have included accompanying notes for teachers, as they help students to navigate this activity. You may find these notes below on pages 18-21 of this document. Do not hand out the information to students, as they should be working in groups to come up with these lists.

Scenario 1

Should genetically modified mosquitoes be released into the environment to combat Zika virus? While the World Health Organization declared in November 2016 that the Zika epidemic was no longer a global health emergency, the Pan American Health Organization continues to regularly publish updated statistics about the infection.

In November 2016, a ballot measure in the Florida Keys area was passed that could give the go-ahead for the first trial of genetically modified mosquitoes in the US, although the measure was defeated in the community of Key Haven, where the trial would actually occur. In October 2017, the Food and Drug Administration transferred the approval powers for the mosquito trials to the Environmental Protection Agency, which must complete its review within 12 months. As this story evolves, you will find the most updated version of this lesson plan on pgEd's website.

Sample questions:

1. How far can mosquitoes travel? Can they spread their genetic modifications to areas outside the test zone?
2. How long do mosquitoes live?
3. Who pays for the development of the mosquitoes?
4. How will the success or failure of the mosquito trial be determined?
5. The FDA examined the possible impact on humans, endangered species, and also looked at how likely they are to fly outside the test zone. But what if they impact an animal that is not endangered right now, but becomes endangered in the future?
6. Why do they think this experiment with mosquitoes will work? Has it worked elsewhere?

Potential people involved (stakeholders):

1. A doctor treating patients with Zika or malaria
2. A person who was part of the FDA study
3. A local environmental expert who studies insects
4. Public health official from the health department
5. Citizens who live in the test area
6. People who have survived or are currently affected with a mosquito-borne illness

Scenario 2

Should adults seek genome editing as a treatment for their liver disease? This scenario is inspired by the study discussed in slide #7 of the lesson, where scientists used CRISPR to "cure" type I tyrosinemia in mice. Unlike our scenario, however, to our knowledge, all of the mice in the real-world study survived the CRISPR procedure.

Sample questions:

1. Why do scientists study human diseases and treatments in animals?
2. When scientists tested the genome editing technique in animals, for how long did they study the impact of the treatment on the animals' health?
3. After liver function was restored in the test animals, did any of them become sick again from the liver disease?
4. Did the test animals have any other negative heath issues that might be related to the edited cells?
5. Is the procedure reversible? If the new genes make animals sick, could they be replaced?
6. Is there any chance that the genetic changes may be passed on to the patients' children?
7. If patients sign up, are they told that they may not in fact be cured?
8. Who, if anyone, is responsible if those who sign up for the clinical trial get sicker, or even die?

Note: Many of the questions that might arise could be about clinical trials. If you or your students want to read more, please see Clinical Trials at the NIH.

Potential people involved (stakeholders):

1. Person who invented this technique
2. Doctors who have run genome editing experiments in humans in the past
3. People suffering from liver disease
4. Someone who is an expert on organ donations
5. A lawyer who can answer questions about who might be at fault if the treatment causes more harm than good
6. A health insurance organization who could explain who might pay for these sorts of treatments

Scenario 3

Is it acceptable to edit the genome of human embryos to treat genetic diseases? This scenario addresses a topic that is hotly debated and contested worldwide, across many fields of expertise. The sorts of discussion you will have will be highly dependent on students' backgrounds in genetics, reproductive biology, bioethics, history, disability and religion. It is important to note that genome editing of embryos is not approved for clinical use in the United States as of February 2020. We present this scenario as there are advocates for the genome editing of embryos, and there is a possibility that we will see these techniques used in the future, regardless of regulatory guidelines.

Part of this conversation could be informed by a basic familiarity with Phase 1 clinical trials, which is a framework in the US and elsewhere to study safety and efficacy of new medical devices, techniques and drugs.

Sample questions:

1. How do you decide when a technique is safe enough to try in humans?
2. An adult could agree to having their genes changed and live with the risks or benefits. Are there different considerations when the subject of genome editing is a potential child with no say in the matter?
3. Are there laws that allow or forbid this sort of research?
4. Could changing the genes of an embryo cause unexpected problems if the embryo does develop into a baby?
5. How is this research being paid for? Does it matter if public money such as taxes is used versus if it is privately paid for?
6. Is genome editing a better option than investing more money in inventing new medicines or making our social systems better accommodate people with differing abilities?

Potential people involved (stakeholders):

1. Scientists who developed the technology and tested it on animals
2. A group of religious advisors who could speak to the question of "Are humans 'playing God?'"
3. People who have lost children to childhood cancers, or have a history of that type of cancer in their family
4. A historian who can talk about changing genes through the lens of historical episodes such as the American Eugenics movement
5. Doctors who can talk about treatment options other than genome editing
6. People who have survived/thrived/are living with genetic differences

Scenario 4

Is the use of genome editing for non-medical "enhancement" acceptable or not? This scenario addresses a topic that is hotly debated and contested worldwide, across many fields of expertise. The sorts of discussion you will have will be highly dependent on students' backgrounds in genetics, reproductive biology, bioethics, history, disability and religion. It is important to note that the genetic basis for many complex, non-medical traits, including athleticism and intelligence, has not been fully worked out. There are still many questions regarding the relative importance of genetic vs. environmental influence, the extent to which differences in these traits are genetically determined, or the specific genes that affect these traits.

Sample questions:

1. How do you decide when a technique is safe enough to try in humans?
2. How do you decide whether a trait is medical or non-medical (in other words, whether a procedure is a treatment or an enhancement)?
3. An adult could agree to having their genes changed and live with the risks or benefits. Are there different considerations when the subject of genome editing is a potential child with no say in the matter?
4. Are there laws that allow or forbid this sort of research?
5. Are people more likely to take on risks for something that could cure a devastating disease than something that could improve their athletic ability? Does the government have the responsibility of "protecting people from themselves"?
6. How is this research being paid for? Does it matter if public money such as taxes is used versus if it is privately paid for?
7. Is this an ethical use of medical resources?
8. To what extent could CRISPR or other similar techniques affect complex traits like intelligence or athleticism?
9. If someone was harmed by genome editing for "enhancement," and needed more medical attention as a result – could someone be sued? Who would have to pay?

Potential people involved (stakeholders):

1. Scientists who developed the technology and tested it on animals
2. Religious advisors who could speak to the question of "are humans "playing God"?"
3. People with diseases that they feel are underfunded and neglected in terms of medical research
4. A historian who can talk about "improving" genes through the lens of historical episodes such as the American Eugenics movement
5. Leaders of for-profit companies looking to offer such genetic enhancement services
6. Employee of the Food and Drug Administration who can talk about safety of medical procedures

Part 4: ASSESSMENTS & HANDOUTS

Homework assignment:

Here are some ideas for extending the lesson and assessing student understanding:

- Have students answer one or more of the questions they have posed or write out what they suspect they might hear from one of the "experts" they identified.
- Have students read an article by one of the leading scientists in the CRISPR field and then complete a written reflection: "Eight questions to ask before human genetic engineering goes mainstream," by Dr. George Church, February 2016, *Washington Post*.

"Genome Editing and CRISPR" quiz answer key

(see page 30 for quiz)

1. What is the difference between analyzing and modifying one's DNA?

Analyzing DNA aims to reveal the genetic information that a person has, so as to predict or better understand the traits or diseases that she or he may develop. Modifying DNA involves actively trying to change an individual's genome.

2. Why would a person want to make changes to the genome?

Answers could include: (a) to replace a gene variant that causes diseases; (b) to change a disease-causing gene variant in an embryo to prevent it from being further passed down a family; (c) to solve a problem such as mosquito-borne illnesses; or (d) to "improve" traits that are not related to illness but to things like athletic performance, intelligence, etc. (even though the genes related to these traits are not fully known).

3. True or False? CRISPR is a method to edit or change part of a person's genome by cutting out, replacing or adding pieces to the DNA sequence.

True

4. A potential benefit to genetically modifying mosquitos is:

b. Mosquitoes will spread fewer cases of serious diseases, including malaria and Zika.

5. Some people have concerns about modifying human embryos because:

d. All of the above.

Genome Editing and CRISPR

STUDENT HANDOUT

Name: _____ Date: _____

Your assignment: You are an **elected official**, and a situation has been presented to you. You need to make an informed recommendation about what to do, but you do not have all the information you need. How do you get the information you need? Read your assigned topic, and ask yourself: **What else do I need to know? Who should I ask?**

Create a list of at least six questions (or more) that you have after reading the scenario. Then create a list of four people to whom you would like to ask your questions. How do you decide what recommendations to make on the use of these technologies?

Think about information you might need - viewpoints from experts on the medical, health and environmental questions. You might have ethical questions best answered by a bioethicist (a person who thinks about the moral and ethical issues related to scientific advances), a philosopher or a religious leader. Do you want to hear from people directly affected, from experts, from concerned neighbors and citizens? You do not need to list people by name. Instead, you can simply identify them by their profession, such as doctor, lawyer or religious leader, or by where they might work (for example, employee of a drug company). Use the handout for creating your lists.

During the group class discussion, be prepared to explain your questions and why you believe your list of people will provide the information you need.

Scenario 1

Name: _____ Date: _____

Should genetically modified mosquitoes be released into the environment to combat Zika virus?

Zika fever has infected tens of thousands of people since 2015. This disease is caused by the Zika virus, which can be carried by mosquitoes. A person can become infected with Zika when he or she is bitten by a mosquito carrying the virus. More than two thousand babies born to infected mothers have a condition called microcephaly. Microcephaly causes babies' heads to be smaller than expected, and babies with microcephaly often have smaller brains that might not have developed typically (www.cdc.gov).

In total, mosquito-borne illnesses, which also include malaria and dengue fever, infect a billion people annually and are responsible for almost a million deaths every year. Millions of dollars are spent on various approaches to mosquito control, such as nets, medicines, pesticides, and efforts that reduce the kind of environments (such as small ponds of water) where mosquitoes can breed. While these methods can be very effective in some cases, millions of people still suffer and die every year.

Another way to fight mosquito-borne illnesses might be through the use of genetically modified mosquitoes. In August 2016, the Food and Drug Administration (FDA) in the United States concluded that a type of genetically modified mosquito could be safely tested as part of the effort to combat Zika infections. In this case, the plan is to insert an extra gene into the mosquito genome. The inserted gene produces a chemical that interferes with genes necessary for reproduction, leaving the mosquito offspring unable to reproduce. As a result, the number of mosquitoes – which spread disease – is expected to drop significantly. The FDA considered the available scientific studies looking at many factors relevant to the mosquitos' introduction into the environment. These factors include the risks to human health, threats to endangered species, and the likelihood of the mosquitoes flying outside of the test zone. At the end, the FDA made a preliminary determination that "no significant environmental impact" is expected.

There is now a proposal before you, the elected official, to release the genetically modified mosquitoes within a 2-square mile area where people have already been infected with Zika. Prepare a list of questions and a panel of people to discuss whether or not the project to release the genetically modified mosquitoes should go forward.

Scenario 2

Name: _____ Date: _____

Should adults seek genome editing as a treatment for their liver disease?

Imagine some patients with a type of life-threatening liver disease that has a genetic cause. They want scientists to use genome editing as a treatment for adults with this disorder. Your job is to determine if the genome editing treatment is ready to be tested in humans. The proposed treatment would use genome editing to replace the faulty gene in the patients' liver cells with a version of the gene that will function properly. The treatment has been tested in animal experiments, and was found to successfully restore liver function in most of the tested animals. However, not all the animals survived the procedure.

The people before you want to be the first group to try the genome editing approach for their liver disease. These patients who seek to be part of the first human trial are adults, many of whom feel they are out of options.

Prepare a list of questions and a panel of people to discuss whether or not adults should be able to use genome editing for this sort of genetic liver disease.

Scenario 3

Name: _____ Date: _____

Is it acceptable or not to edit the genome of human embryos to treat genetic diseases?

There is a group of genetic disorders that cause fatal childhood diseases. To avoid having children with these genetic disorders, some parents choose to use a procedure called in vitro fertilization (IVF) followed by genetic testing. Typically, in the first step of IVF, women receive hormone injections to produce multiple eggs, after which the eggs are harvested. The eggs are then fertilized by sperm in a petri dish to make embryos, which are then transferred to a woman's uterus. If the goal is to identify embryos that do not have specific genetic conditions, doctors would screen the embryos before they are implanted into the woman – in other words, they would analyze the embryos' DNA to look for variants of the gene(s) that cause the genetic disorder. While the genetic testing of IVF-produced embryos has been done for decades, the procedure is controversial. The controversies include worries that parents are interfering with their potential child's traits, concerns about what happens to embryos that are not implanted, and the fact that these technologies are not available to everyone because they are expensive.

Now imagine that a group of parents is before you, and proposes to not only screen embryos, but also wants to go a step further. That is, they propose to use information obtained from screening the embryos to then identify and "repair" faulty genes in the embryos that are linked to a known genetic disorder. The parents argue that this procedure will decrease the number of children suffering from deadly genetic diseases.

At the same time, you are aware that there are many people who are strongly opposed to genetically modifying humans. These include many religious organizations, as well as different groups that advocate for patients or for people with disabilities.

Prepare a list of questions and a panel of people to discuss whether or not we should be able to use genome editing to alter human embryos with the goal of treating genetic disorders.

Scenario 4

Name: _____ Date: _____

Is the use of genome editing for non-medical "enhancement" acceptable or not?

Imagine a future where it is possible to modify a person's DNA to "improve" non-medical traits – in other words, the modification is not for the purpose of curing or preventing diseases. This sort of genetic "enhancements" could include improved muscle mass and the ability to move oxygen to one's muscles more efficiently – traits that are valuable to elite athletes. Other potential enhancements might include modifying genes to decrease the chance of needing glasses. And while scientists have not yet identified genes that are clearly related to intelligence, some people might hope that these genes, if they were ever found, could also be enhanced through genetic technologies.

Some groups might believe that, if people want, they should be able to "improve" their own DNA. They think the government should not have any say on why or how genome editing might be used. They believe it is a private matter of personal choice, like many other medical decisions. Additionally, you are aware that there are many people who are strongly opposed to genetically modifying humans, in particular for non-medical traits. These include many religious organizations, as well as different groups that advocate for people with disability.

Prepare a list of questions and a panel of people to discuss whether or not we should be able to use genome editing for enhancement purposes.

Genome Editing and CRISPR

STUDENT WORKSHEET

Name: _____ Date: _____

A) Questions you have after reading the scenario:

1.

2.

3.

4.

5.

6.

B) Four people to whom you want to ask your questions:

1.

2.

3.

4.

Genome Editing and CRISPR

QUIZ

Name_____ Date_____

1. What is the difference between analyzing and modifying one's DNA?

2. Why would a person want to make changes to the genome?

3. True or False? CRISPR is a method to edit or change part of a person's genome by cutting out, replacing or adding pieces to the DNA sequence.

   True False

4. A potential benefit to genetically modifying mosquitos is:
   a. Mosquito bites will be less itchy.
   b. Mosquitoes will spread fewer cases of serious diseases, including malaria and Zika.
   c. Scientists will be able to create better insect repellent.

5. Some people have concerns about modifying human embryos because:
   a. Scientists might hurt future generations, because they do not know how a genetic change could affect children in the future.
   b. People who live with a disability or genetic condition could face increased discrimination if they are seen as "passing up" the chance for a genome editing "cure."
   c. We do not presently agree on what conditions or disabilities could be edited, nor have we agreed on who gets to decide (such as politicians, parents, doctors, religious leaders or scientists).
   d. All of the above.

ADDITIONAL RESOURCES FOR TEACHERS

Additional resources for teachers

- Many of the ethical issues in this lesson are discussed in this lengthy but compelling article: "Should you edit your children's genes?" by Erika Check Hayden, February 2016, *Nature* (open access).
- "CRISPR: A Gene-Editing Superpower" (video) by SciShow (2016).
- "Gene Editing and CRISPR: How Far Should We Go?" (video and lesson plan) by KQED Learn, PBS LearningMedia.

Related pgEd lesson plans

pgEd has two additional lesson plans on genome editing:

- Claims of CRISPR Being Used to Edit Genomes of Twin Girls Born in 2018
  Aim: How can we navigate news headlines to understand emerging genetic technologies and their social and ethical implications?
- Engineering the World Around Us: Genome Editing and the Environment
  Aim: How might genome editing be used to address the environmental issues we are facing?

pgEd regularly updates our lessons to reflect the latest developments in science and society and to include more voices in our materials. For more information, visit our lesson plan page and join our mailing list to find out about our latest offerings.