TeachEngineering
Ignite STEM learning in K-12

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# Lesson Template

## Part 1: Lesson Overview

| | |
|---|---|
| **Lesson Title** | **Biomechanical Analysis** |
| **Focus Grade Target** | 12th Grade |
| **Subject Area(s)** Check all subject areas that apply to this activity. [Subject area definitions] | ☐Algebra ☐Biology ☐Chemistry ☐Computer Science ☐ Data Analysis and Probability ☐Earth/Space ☐Geometry ☐Life Science ☐Measurement ☐Numbers and Operations ☐Physical Science ☐Physics ☐Problem Solving ☐Reasoning and Proof ☐Science & Technology |
| **Time Required:** | **Click or tap here to enter the Time Required.** Estimate the time required to complete the lesson in minutes; you may add a brief explanation for longer activities, such as “three 50-minute class periods”. |
| **Keywords** | **Python, Machine Learning, Artificial Intelligence, Monte Carlo, Finite Element, Extracellular matrix (ECM)** |

**Instructional Summary – 200 words**

Summarize what your activity is all about in one paragraph using the present tense. See an example.

This lesson integrates Monte Carlo (MC) simulation, Machine Learning (ML), and Finite Element Analysis (FEA) to predict and validate biomechanical behavior of extracellular matrix (ECM) structures. The lesson begins with a Monte Carlo ECM lattice (MC-ECM) generator that creates 100 unique hexagonal ECM structures, each containing 300 nodes representing collagen and elastin fibers. This MC-ECM generator produces detailed CSV datasets containing structural, mechanical, and compositional properties. Next, a machine learning system trains multiple regression algorithms (RandomForest, XGBoost, Neural Networks) to predict 3D displacement vectors from ECM node features. The system compares model performance and selects the best performer based on $R^2$ scores, saving the trained model using a Python's pickle module ( a serialized ML model that was saved as a pickle file). The ABAQUS validation based on the ABAQUS-compatible .inp files runs FE simulations on the generated ECM structures, applying realistic loading conditions and extracting nodal displacements and stress tensors. The pipeline then compares ML predictions against ABAQUS results, calculating comprehensive accuracy metrics. Finally, the system refines the ML model using validated ABAQUS data, implementing strategies like retraining or ensemble methods. This iterative process establishes a robust framework for biomechanical ECM analysis with continuous model enhancement.

**Engineering Connection – 60-100 words**

Describe how the scientific and mathematical concepts being studied in this activity pertain to real-world engineering. (Do not recap the activity summary.) Explain for the teacher how everyday engineering ties to what is being done in the lesson or activity. See an example.

# Teacher's Guide: ECM Analysis and Engineering Creativity

Engineers leverage Computational Modeling and Simulation (CMS) to predict material behavior across diverse applications. Running shoe shock absorption utilizes ECM mechanics principles, while smartphone screen flexibility mirrors tissue deformation patterns. 3D-printed prosthetics require fiber network optimization similar to biological tissues. MC-ECM analysis excels in tissue scaffold design, whereas ML-predictions optimize real-time analysis and applications. Biomedical engineers continuously advance technology to enhance performance and safety of materials interfacing with human tissue. When designing biomaterials like soft tissue, engineers consider application-specific requirements and employ varied fiber arrangements for optimal mechanical properties. Key characteristics include strength, elasticity, bio-compatibility, size constraints, tissue integration, stress tolerance, and development costs. ECM exhibits distinct fiber patterns: dense networks for load-bearing applications, sparse arrangements for flexible uses like artificial skin, and balanced structures for general tissue engineering. The ABAQUS-ML validation pipeline functions as a virtual testing laboratory, enabling engineers to evaluate thousands of designs before creating costly prototypes.

## Classroom Testing Information

Briefly describe the K-12 classroom or informal learning center testing conducted with this curriculum. Please include the date, school, location, grade level, and number of students.

Students in the SYNAPSE Lab at the Illinois Math and Science Academy (IMSA) will experience how engineers predict material performance using Computational Modeling and Simulation (CMS). They will engage with real-world applications through interactive hands-on learning research project and demonstrations. Students work through real engineering decisions by balancing competing factors like strength, elasticity, biocompatibility, size constraints, and costs. Interactive scenarios help students appreciate the complexity of creating materials that safely integrate with human tissue.

## Educational Standards

In priority order, list up to four educational STEM standards that students would learn as a result of completing this lesson. If students need a prerequisite skill to complete the lesson, then list what is required.

For each standard, include the source, year, grade band, standard nomenclature (e.g., number(s)/letter(s)), and standard summary. Example: North Carolina, science, 2004, 1.01 (grades 8-8): Identify and create questions and hypotheses that can be answered through scientific investigations. ID# S1028531

Provide at least ONE from each of the following:

- Next Generation Science Standards (NGSS), Science, 2013, HS-LS1-2 (grades 9-12): Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms. ID# NGSS-HS-LS1-2
- Next Generation Science Standards (NGSS), Science, 2013, HS-ETS1-4 (grades 9-12): Use a computer simulation to model the impacts of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem. ID# NGSS-HS-ETS1-4
- Next Generation Science Standards (NGSS), Science, 2013, HS-ETS1-3 (grades 9-12): Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts. ID# NGSS-HS-ETS1-3
- Next Generation Science Standards (NGSS), Science, 2013, HS-ETS1-2 (grades 9-12): Design solutions to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering design. ID# NGSS-HS-ETS1-2

List Next Generation Science Standards (NGSS)
These standards integrate computational thinking, data analysis, engineering design processes, and mathematical modeling through authentic biomechanical engineering applications.

- **HS-LS1-2: Hierarchical Organization of Biological Systems** Structure and Function Relationships: Students develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms. The ECM fiber network patterns (dense, sparse, balanced) mirror biological tissue organization, helping students understand how structure determines function in both natural and engineered systems. Students model how molecular-level components (collagen and elastin fibers) organize into tissue-level structures (ECM networks) that provide specific mechanical functions, demonstrating structure-function relationships across biological scales.

- **HS-ETS1-4: Computer Simulation for Complex Problem Modeling** Computer Simulation for Modeling Complex Systems: Students use computer simulation to model the impacts of proposed solutions to complex problems with numerous criteria and constraints on interactions within and between systems. Both the Monte Carlo ECM generation and the machine learning prediction pipeline exemplify computational modeling to understand complex biomechanical systems with multiple interacting variables. Students use Monte Carlo simulation to generate 100 ECM structures and machine learning algorithms to predict mechanical responses, modeling complex biomaterial behavior with multiple interacting variables and constraints.
- **HS-ETS1-3: Solution Evaluation with Prioritized Criteria** Students evaluate different ECM structures and ML algorithms based on multiple criteria (coordination efficiency, mechanical properties, prediction accuracy, computational cost) while considering trade-offs in biomaterial design applications. Analyze Data from Tests to Determine Optimal Design Solutions: Students analyze data from tests to determine similarities and differences among design alternatives to identify the best characteristics of each that can be combined into a new solution. The comparative analysis of different ML algorithms (Random Forest, XGBoost, Neural Networks, etc.) and the structure-to-structure variability analysis teach students to systematically evaluate multiple solutions using quantitative metrics.
- **HS-ETS1-2: Problem Decomposition in Engineering Design** Students design solutions to complex real-world problems by breaking them down into smaller, more manageable problems that can be solved through engineering design. The biomaterial design process exemplifies this as students balance multiple constraints (strength, elasticity, biocompatibility, cost) to create optimal solutions.

List Common Core Math Standards (optional)

## Learning Objectives

Using bullet points and statement form, identify up to four main goals or student outcomes of the lesson. Learning objectives often come from the educational standards you chose above. Use **active** verbs such as "explain", "calculate" or "summarize" and avoid passive verbs such as "understand", "know", or "realize". For example:
After this lesson, students should be able to: See an example.

- Describe the flow of electrical energy through a simple circuit.
- Discuss the effects of gravity and friction in the context of their roller coaster designs.
- Solve problems involving pressure, density and Pascal's law.

After this lesson, students should be able to:

**ECM (Extracellular Matrix) Modeling:**

- Analyze the hierarchical organization of ECM fiber networks by examining how molecular-level components (collagen and elastin fibers) create tissue-level mechanical properties and functions.
- Generate Monte Carlo simulations of hexagonal lattice ECM structures with varied fiber arrangements (dense, sparse, balanced) to model different tissue engineering applications.

**Machine Learning (ML) Applications:**

- Compare multiple machine learning algorithms (Random Forest, XGBoost, Neural Networks, Ridge Regression, SVR) by evaluating their performance using quantitative metrics ($R^2$, RMSE, MAE) for predicting 3D displacement vectors in biomechanical systems.
- Execute complete ML pipelines including data preprocessing, feature scaling, train-test splitting, model training, and performance validation for multi-output regression problems.

**ABAQUS Integration:**

- Export ECM structural data to industry-standard finite element analysis format (.inp files) for computational biomechanics simulations and validation studies.
- Design biomaterial structures by systematically varying fiber network parameters and evaluating their mechanical response through computational modeling workflows.

**Validation and Engineering Design:**

- Evaluate engineering solutions by applying prioritized criteria and trade-offs (structural uniformity, computational cost) to identify optimal ECM designs for specific biomedical applications.

- Decompose complex biomaterial design problems into manageable engineering components through systematic problem-solving approaches that integrate computational simulation with experimental validation strategies.

## Prerequisite Student Knowledge

List any skills or knowledge a student must already have in order to be successful in this lesson, such as knowledge of a certain concept or topic, specific math skills, etc. Example: “A familiarity with compass directions” or “A basic understanding of gravity and friction” or “The ability to calculate median, mean, and mode.”

**Mathematics Skills:**

- The ability to calculate and interpret basic statistical measures including mean, median, standard deviation, and correlation coefficients
- Proficiency with coordinate geometry and 3D spatial reasoning (x, y, z coordinates)

**Computer Science Fundamentals:**

- Python programming concepts including variables, loops, functions, and data structures (arrays/lists)
- Familiarity with reading and interpreting data from spreadsheets or CSV files
- Experience with basic data visualization and graph interpretation

**Physics and Engineering Concepts:**

- Understanding of force, stress, strain, and basic mechanical properties of materials
- Knowledge of elastic modulus, stiffness, and material deformation concepts
- Familiarity with the relationship between structure and function in engineering systems

**Biology Background:**

- Basic understanding of cell structure and the role of extracellular matrix in biological tissues
- Knowledge of protein structure and function, particularly fibrous proteins
- Awareness of how biological materials provide mechanical support in living organisms

**Chemistry Concepts:**

- Understanding of crystal lattice structures and how atoms/molecules arrange in repeating 3D patterns
- Knowledge of hexagonal close packing and coordination numbers in crystalline materials
- Basic understanding of how molecular structure influences bulk material properties

**Scientific Method and Data Analysis:**

- Experience designing controlled experiments and identifying variables
- Ability to interpret scientific graphs, charts, and data tables
- Understanding of the concept of statistical significance and experimental uncertainty
- Familiarity with making evidence-based conclusions from quantitative data

## Part 2: Lesson Instructional Plan

### Introduction and Motivation – at least 250 words (or 1/2/ page)

Write a (minimum) half page introduction, as if you were speaking directly to the students, that helps grab the students' attention and provides an engineering context. Address the learning objectives, include vocabulary, reference worksheets and attachments, presentations, and include teacher prompts and instructions. Provide an engineering context. This could be a demo, an example or real-world context. Ask questions to engage students. See an example.

What do all of these challenges have in common?
Designing artificial skin, or creating a new heart valve, or developing the perfect running shoe that prevents injuries while maximizing performance.

They require engineers to understand and predict how materials behave at the microscopic level to create products that work flawlessly in the real world.

**Biological Architecture**
Your body is supported by an incredible invisible scaffolding called the **extracellular matrix (ECM)**. Think of it as nature's own 3D-scaffolding framework – a complex network of protein fibers including **collagen** (which provides strength like steel cables) and **elastin** (which provides flexibility like rubber bands) arranged in precise **hexagonal lattice** patterns. This biological architecture is so sophisticated that engineers spend billions of dollars trying to research it.

**Challenge Question:**
How do we predict how this microscopic fiber networks will behave when we put stress on them?
How do we know if artificial tissue will stretch properly over the next generation of bionic arm, or if our biomedical implant (Brain-Machine interface) will integrate successfully with human tissue?
This is where computational modeling meets machine learning – and where you come in as future engineers.

**Engineering Mission**
Today, we will step into the role of a computational biomedical engineer working for a cutting-edge tissue engineering company. We will investigate designing new biomaterials for three critical applications:

- **Dense networks** for load-bearing applications like artificial cartilage
- **Sparse arrangements** for flexible applications like artificial skin
- **Balanced structures** for general tissue engineering scaffolds

Using Monte Carlo simulation (a powerful statistical method that generates hundreds of different design possibilities), we will create several unique ECM structures. Then, like engineers we will use machine learning algorithms to predict how these materials will deform under stress – a process called displacement prediction.

**Real-World Engineering Context**
Consider this real scenario: Biomedical Engineers need to design liver tissue scaffolds for drug testing. They must predict how their artificial tissue will respond to mechanical forces before expensive laboratory testing. Using the exact same techniques we will learn today – computational modeling, simulation, and machine learning – engineers can virtually test thousands of designs in hours rather than months of expensive lab work

**Learning Pathway and Tools**
Throughout this lesson, we will master four interconnected engineering skills:

1. **ECM Modeling**: You'll generate complex biological structures using computational tools, learning how molecular-level fiber arrangements create tissue-level properties
2. **Machine Learning**: You'll train artificial intelligence algorithms (Random Forest, XGBoost, Neural Networks) to predict material behavior, comparing their performance like engineers selecting the best tool for the job
3. **ABAQUS Integration**: You'll export your designs to industry-standard finite element analysis software used by aerospace, automotive, and biomedical companies worldwide
4. **Validation**: You'll evaluate your engineering solutions using multiple criteria, making data-driven decisions about which designs work best for specific applications

**Questions to Consider**
Before we dive into the technical work, let's activate your engineering thinking:

- *Why might a hexagonal arrangement be optimal for biological tissues?* (Hint: Think about honeybees and their remarkably efficient hexagonal honeycombs!)
- *If you were designing artificial skin, would you want more collagen or elastin fibers? Why?*
- *How might machine learning help doctors customize medical implants for individual patients?*
- *What happens when engineers get material predictions wrong in biomedical applications?*

You'll be working with computational modeling and simulation (CMS) tools throughout this lesson:
- **Python programming** for Monte Carlo simulation and machine learning
- **Statistical analysis** to evaluate model performance using metrics like R-squared and RMSE
- **3D visualization** to see your ECM structures in action
- **Data export protocols** for professional finite element analysis

**Your Engineering Challenge Awaits**
By the end of today's lesson, you'll have generated 100 unique biomaterial designs, trained multiple AI models to predict their behavior, and identified the optimal structures for different medical applications. You'll think like engineers, work with professional-grade software, and solve real problems that biomedical companies face every day. Are you ready to engineer the future of medicine?

## Lesson Outline

Summarize pertinent information a teacher would need to teach this lesson. Use the following format below. See an example.

**Lesson Background/Teacher Concepts - Summarize pertinent information a teacher would need to teach this lesson:**

Teachers need to understand Computational Modeling Fundamentals. Monte Carlo simulation uses random sampling to generate multiple design variations, allowing engineers to explore thousands of possibilities efficiently. Students will create 100 unique ECM structures with varying fiber arrangements (dense, sparse, balanced) to model different tissue engineering applications. The hexagonal lattice structure mimics biological efficiency found in nature, where each node connects to six neighbors for optimal load distribution.

Machine Learning Applications This lesson involves multi-output regression, where students predict three displacement values (x, y, z coordinates) simultaneously. Teachers should understand that different algorithms (Random Forest, XGBoost, Neural Networks) have varying strengths: tree-based methods handle non-linear relationships well, while neural networks can capture complex patterns. Students will compare model performance using quantitative metrics ($R^2$, RMSE, MAE) to select the best algorithm for biomechanical prediction.

Extracellular Matrix Biology The ECM is nature's scaffolding system composed primarily of collagen fibers (providing tensile strength) and elastin fibers (providing elasticity). Teachers should emphasize the structure-function relationship: molecular-level fiber arrangements determine tissue-level mechanical properties. This connects directly to the NGSS standard HS-LS1-2 regarding hierarchical organization in biological systems. Industry Integration ABAQUS is professional finite element analysis software used by aerospace, automotive, and biomedical companies. Students export their computational models to industry-standard .inp format, connecting classroom learning to real engineering workflows. This demonstrates how computational predictions guide expensive experimental testing and product development decisions.

Prerequisites and Safety Students need basic programming concepts, 3D coordinate geometry, statistical analysis skills, and understanding of crystal lattice structures from chemistry. No physical safety concerns exist, but teachers should ensure adequate computer resources and internet connectivity for computational tasks.

**Associated Activity (or Activities)** - **TeachEngineering requires an original activity with each lesson. Provide a description of your activity here:**
**Activity Description**

Teacher Preparation: Ensure all student computers have Python installed with required libraries (numpy, pandas, matplotlib, scikit-learn, xgboost). Download and verify the Monte Carlo ECM dataset file "ecm_node_data_monte_carlo.csv" is accessible on the class network or provide USB drives with the file. Test the computational scripts on at least one machine to confirm proper execution. Create student pairs and assign roles: "Design Engineer" (focuses on ECM structure generation) and "Validation Engineer" (focuses on machine learning analysis) - students will switch roles halfway through.

Student Setup (10 minutes): Students log into their workstations and open the computational environment. They should create a new project folder named "ECM_Biomaterials_[StudentName]" and download the provided Python scripts and dataset. Students verify they can access the Monte Carlo simulation code and machine learning pipeline. Each pair should designate their initial roles and prepare their engineering notebooks for data recording.

Engagement Hook (5 minutes): Display a honeycomb structure or hexagonal pattern and ask students to count connections per hexagon. Show a brief video of tissue engineering scaffolds or artificial skin being tested.

Ask the central question: "How can we predict if a biomaterial will work before expensive laboratory testing?" Explain that today they'll use the same computational methods employed by big biomedical companies like Medtronic and Johnson & Johnson to design medical devices.

Vocabulary Introduction (5 minutes): Review key terms using visual aids: extracellular matrix (show microscopy images), hexagonal lattice (demonstrate with molecular models), Monte Carlo simulation (explain random sampling concept), and machine learning algorithms (compare to pattern recognition). Emphasize that these are professional engineering tools they'll master today.

**Lesson Conclusion - Write this section as if you're speaking directly to students. Help bring it all together!**
You've just completed something truly remarkable – you've used the exact same computational tools and methods that professional engineers at major medical device companies use every single day. Think about what you've accomplished today: you generated 100 unique biomaterial designs, trained artificial intelligence to predict how materials behave, and identified optimal structures for different medical applications. That's not just impressive – that's real engineering work!

Remember when we started with that simple honeycomb pattern? Now you understand why nature chose hexagonal arrangements – they provide the perfect balance of strength and efficiency. Your Monte Carlo simulations proved this mathematically, and your machine learning models quantified exactly how these structures perform under stress. You've seen firsthand how molecular-level fiber arrangements (collagen and elastin) create the tissue-level properties that keep our bodies functioning.

The skills you've mastered today – computational modeling, machine learning, data analysis, and engineering design thinking – are shaping the future of medicine right now. Engineers using these exact methods are developing artificial organs, designing better surgical implants, and creating revolutionary treatments for diseases. Your ability to predict material behavior computationally means fewer failed experiments, faster product development, and ultimately, better patient outcomes.
(For images, see **Part 4: Photos and Images** below on how to properly reference and cite images in your submission.)

**Assessment (Pre-Activity, Formative, and Summative)**

Provide assessment tools/activities for teachers to assess the learning objectives. How do you know if the students "got it" during and after the lesson? Provide active and embedded ways (formative assessment) for the teacher to gauge what students are learning about the topic/content throughout the lesson, and a performance-based way to assess student understanding of the learning objectives at the end of the lesson (summative assessment).

Browse the TE collection for example assessment tools. [See an example.]

Pre-Lesson Assessment
**Biomedical Engineering Concept Inventory:** Administer a 10-question diagnostic quiz to gauge students' prerequisite knowledge before beginning computational work. Sample items include: (1) "Sketch a hexagonal lattice structure and label the coordination number," (2) "Explain the difference between collagen and elastin fibers in biological tissues," (3) "Define what R-squared means in statistical analysis," (4) "Describe how machine learning differs from traditional programming," and (5) "List three examples where engineers use computer simulation before building prototypes." Teachers should review responses to identify knowledge gaps and adjust instruction accordingly. Students scoring below 60% may need additional prerequisite support during the lesson.

Lesson Embedded (Formative) Assessment
**Engineering Design Checkpoint System:** Implement four strategic checkpoints throughout the lesson where student pairs must demonstrate progress to the teacher before advancing. Checkpoint 1 (Monte Carlo Setup): Students explain their ECM structure parameters and predict which fiber arrangement will perform best. Checkpoint 2 (Data Analysis): Students interpret their correlation matrix and identify the three most important features for displacement prediction. Checkpoint 3 (Model Comparison): Students rank their five ML algorithms by performance and justify their choice using quantitative metrics. Checkpoint 4 (ABAQUS Export): Students demonstrate successful .inp file generation and explain how their computational model connects to real-world finite element analysis. Teachers use a simple checklist to verify understanding and provide immediate feedback.

Post-Lesson (Summative) Assessment
**Computational Biomedical Engineering Portfolio:** Students complete a comprehensive design challenge where they must recommend an optimal ECM structure for a specific medical application (artificial heart valve, burn treatment skin graft, or cartilage replacement). The portfolio includes: (1) Technical Report analyzing their Monte Carlo results with statistical justification for their chosen structure, (2) ML Model Performance Comparison evaluating all five algorithms with proper interpretation of $R^2$, RMSE, and MAE metrics, (3) Professional Presentation to a simulated medical device company explaining their design recommendation, and (4) Peer Review Process where students evaluate another team's work using engineering criteria. Teachers assess using a detailed rubric covering technical accuracy (40%), engineering reasoning (30%), communication quality (20%), and collaboration effectiveness (10%). Expected answers should demonstrate understanding that dense networks suit load-bearing applications, sparse arrangements work for flexible applications, and balanced structures serve general purposes.

Making Sense Assessment
**Reflection on Computational Engineering Skills**: Have students reflect on the science concepts they explored and/or the science and engineering skills they used by completing the Making Sense Assessment. Students should address: "How did computational modeling change your understanding of biological systems?" "What connections do you see between molecular-level fiber arrangements and tissue-level properties?" "How might machine learning help solve other engineering challenges?" and "What ethical considerations should engineers consider when designing medical devices?" This metacognitive reflection helps students consolidate their learning and recognize the broader applications of computational biomedical engineering [Making Sense Assessment.]

| **Academic Vocabulary** | **Definitions (you may source definitions from Wikipedia or Wiktionary)** |
|---|---|
| *orbit* | *The gravitationally curved trajectory of an object.* |

| | |
|---|---|
| *particle* | *A small localized object to which can be ascribed several physical or chemical properties such as volume, density, or mass.* |

See an example.

Academic Vocabulary Definitions

Extracellular Matrix (ECM): A three-dimensional network of extracellular macromolecules and minerals, such as collagen, enzymes, and glycoproteins, that provide structural and biochemical support to surrounding cells. The ECM serves as a scaffold that determines tissue architecture and mechanical properties.

Hexagonal Lattice: A regular arrangement of points in a plane or three-dimensional space where each point has six nearest neighbors arranged in a hexagonal pattern. This structure maximizes packing efficiency and provides optimal load distribution, commonly found in crystalline materials and biological tissues.

Monte Carlo Simulation: A computational algorithm that relies on repeated random sampling to obtain numerical results, typically used to model the probability of different outcomes in systems that cannot easily be predicted due to the intervention of random variables.

Machine Learning: A subset of artificial intelligence that enables computer systems to automatically learn and improve from experience without being explicitly programmed, using algorithms that build mathematical models based on training data to make predictions or decisions.

Collagen: The most abundant protein in mammals, forming a triple helix structure that provides tensile strength and structural support to tissues. Collagen fibers act like steel cables in biological materials, resisting stretching forces.

Elastin: A highly elastic protein found in connective tissue that allows tissues to resume their shape after stretching or contracting. Elastin fibers function like rubber bands, providing flexibility and resilience to biological structures.

Coordination Number: In crystallography and materials science, the number of nearest neighbor atoms or molecules that surround a central atom or molecule in a crystal lattice or molecular structure.

Multi-output Regression: A machine learning technique that predicts multiple continuous target variables simultaneously from a single set of input features, useful when the output variables are related or when computational efficiency is important.

Feature Engineering: The process of selecting, modifying, or creating input variables (features) from raw data to improve machine learning model performance by making patterns more apparent to algorithms.

ABAQUS: Professional finite element analysis software used for simulating the physical behavior of materials and structures under various loading conditions, widely employed in aerospace, automotive, and biomedical engineering industries.

R-squared ($R^2$): A statistical measure representing the proportion of variance in the dependent variable that is predictable from the independent variables, ranging from 0 to 1, where higher values indicate better model fit.

Root Mean Square Error (RMSE): A measure of the differences between predicted and observed values, calculated as the square root of the average of squared differences, providing error magnitude in the same units as the original data.

## Worksheets and Attachments

List the names of any documents you will use as part of this lesson such as **presentations, handouts, assessments**, etc. Please also provide **answer keys** for all handouts/assessments. **Upload these documents separately along with this template.**

Clearly label each lesson and include the lesson name in the file (for example, all-about-bridges-homework-assignment.docx. TeachEngineering accepts most files in an **editable format** including Microsoft Word (.docx) Microsoft Excel (.xlsx) Microsoft PowerPoint (.pptx), JPEG files (.jpg) and Portable Network Graphics (.png) and others. If you have any questions, please contact your editors at TeachEngineering.

See an example.

**Supporting Documents and Materials**

**Computational Code Files:** • Monte_Carlo_ECM_Generator.py - Complete Python script for generating 100 ECM hexagonal lattice structures • ML_Displacement_Prediction_Pipeline.py - Machine learning code for training and comparing five algorithms • ecm_node_data_monte_carlo.csv - Dataset containing node-level structural and mechanical properties

**Student Handouts:** • ECM_Engineering_Notebook_Template.pdf - Structured worksheet for recording computational results and analysis • ML_Algorithm_Comparison_Chart.pdf - Table for students to track model performance metrics • ABAQUS_Export_Checklist.pdf - Step-by-step guide for generating .inp files • Biomedical_Applications_Reference_Sheet.pdf - Examples of dense, sparse, and balanced ECM applications

**Assessment Materials:** • Pre_Lesson_Concept_Inventory.pdf - 10-question diagnostic quiz on prerequisite knowledge • Engineering_Design_Checkpoint_Rubric.pdf - Formative assessment checklist for four lesson checkpoints • Computational_Portfolio_Assessment_Rubric.pdf - Detailed scoring guide for final design challenge • Making_Sense_Reflection_Questions.pdf - Metacognitive assessment prompts

**Instructional Presentations:** • ECM_Introduction_Slides.pptx - Lesson opening with honeycomb demonstration and real-world context • Machine_Learning_Concepts_Presentation.pptx - Visual explanation of algorithms and evaluation metrics • Professional_Engineering_Applications.pptx - Industry examples from Medtronic, Johnson & Johnson

**Technical Reference Materials:** • Python_Installation_Guide.pdf - Computer setup instructions for required libraries • ECM_Vocabulary_Glossary.pdf - Illustrated definitions of key technical terms • NGSS_Standards_Alignment_Document.pdf - Detailed connection between activities and learning standards • Troubleshooting_Common_Errors.pdf - Solutions for typical computational issues students encounter

## Part 3: Supporting Activity Information

### Lesson Scaling, Extensions, and Enrichment

**Personalized Medicine Design Challenge:** Students research specific patient conditions (osteoarthritis, burn injuries, heart valve disease) and modify their ECM parameters to create patient-specific biomaterial designs. They investigate how age, lifestyle, and genetic factors might influence optimal fiber arrangements, then use their trained ML models to predict performance for different patient demographics.

**Multi-Scale Biomechanics Investigation:** Extend the analysis to include cellular-level interactions by modeling how individual cells attach to and remodel ECM structures. Students can explore how mechanical forces at the tissue level influence gene expression and protein synthesis at the cellular level, connecting their computational models to biochemical pathways.

**Scientific Method**"How do we know when our computational models are 'good enough' to replace expensive laboratory experiments? What are the risks and benefits?"

**Artificial Intelligence:** "How might automation and AI change the role of biomedical engineers in the next 20 years?" "What ethical responsibilities do engineers have when their designs directly impact human health and quality of life?"

See an example.

### References

List all references used to create the activity, especially the background knowledge section.
Consider using a modified MLA format. Provide in A-to-Z order according to authors' last names or website banner page name, whichever appears first in citation.

**Click or tap here to enter text.**

## Part 4: Contributor, Supporting Program, Acknowledgements, and Classroom Testing

### Contributors

Ashwin Mohan, Ph.D., Joseph Michaelis, Ph.D., Shafigh Mehraeen, Ph.D.,
Hamed Hatami-Marbini, Ph.D.

### Supporting Program

**Click or tap here to enter text.** If this instruction was developed as part of a special program, list the name of the supporting program and/or organization.

Example: Research Experience for Teachers (RET), Center for Bio-mediated & Bio-inspired Geotechnics (CBBG), in partnership with Arizona State University, Georgia Institute of Technology, New Mexico State University, University of California-Davis, and the National Science Foundation.

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### Acknowledgements

**Click or tap here to enter text.** This curriculum was developed under National Science Foundation RET grant number ABC-XXXXXXXX. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## Part 4: Photos and Images

### Lesson Photos

**TeachEngineering requires a minimum of two original photos per lesson.** This helps teachers visualize the nature of the lesson. We don't expect nor require expert photos—smartphone photos work fine! However, we would like to see how teachers and students engage in the lesson—and you may use photos from your associated activity. (There are five placeholders below for photos, but we encourage you to add as many as you like.)

You may supplement your images with additional content sourced from the internet as long as they are licensed for public use (see Requirements and Tips for Using Images). Note: if authors plan on submitting photos that include their students, the author is responsible for securing the appropriate permissions from parents, guardians, or administrators. TeachEngineering classifies photos into two categories:

**Images** are photos or illustrations that enhance the lesson's visual appeal. Reference where you want the image to go in the lesson by simply saying **(Insert Image 1)** in the text above and attach the photo in a box below.

**Figures** may be photos or illustrations as well as diagrams or drawings that specifically reference a topic within the text. For example, in explaining the parts of a cell or how a suspension bridge works, a figure may reference that explanation. Figures may also be used to help explain how to build a tool or a machine. Reference where you want the image to go in the lesson by saying **(Insert Figure 1)** in your text above and attach the photo in a box below.

How to format images and figures; see below for a finished example:

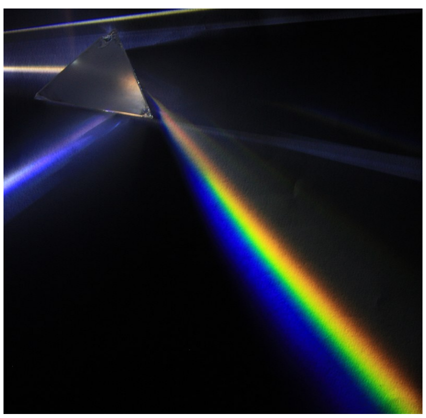

**Image 1:** Insert into Procedure under "Day 1"

**Image file**: lesson01-image1-prism.jpg

**ADA Description**: A glass prism sits on a black background; a light source shining through the prism is demonstrating refraction of white light into the visible light spectrum.

**Source/Rights**: 2009 D-Kuru, CC BY-SA 3.0, Wikipedia, source link.

**Caption**: Why does white light diffract into the colors of a rainbow when it shines through a prism?

**Click the center of the box below to upload an image.**

**Image 1 / Figure 1:** *Enter the location of where you want the image or figure in the text by saying* (Insert Figure 1) *here.*
**File name:** *The photo must be included as an attachment and must have the exact same name as you type here.*
*Example: lesson05-image1-pilot.jpg*
**ADA Description:** *Write this text as if describing key elements of the image to a blind person.*
**Source/Rights:** *Include copyright or identifying information for any images used. Images pulled from the Internet should be either in the public domain or licensed for use through Creative Commons (CC-BY or CC-SA); you must still attribute them to the person or website from which they were pulled as well as provide a* ***direct link*** *to the image.*
**Caption:** *This text will appear directly below the Image. This should not be the same text as used for the ADA Description.*

**Image 2 / Figure 2:** *Enter the location of where you want the image or figure in the text by saying* (Insert Figure 1) *here*.

**File name:** *Example: activity05-image1-pilot.jpg*

**ADA Description:**

**Source/Rights:**

**Caption:**

**Image 3 / Figure 3:** *Enter the location of where you want the image or figure in the text by saying* (Insert Figure 1) *here*.

**File name:** *Example: activity05-image1-pilot.jpg*

**ADA Description:**

**Source/Rights:**

**Caption:**