PhET E&M Simulation Portfolio

Full-Semester Instructional Plan for Mechatronics

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Section 1: PhET Simulation Selection

The following three PhET simulations were selected to build a coherent, full-semester Electricity & Magnetism (E&M) arc for a high school Mechatronics course. The sequence moves from electrostatics through DC circuits to electromagnetism, mirroring how students encounter these concepts when building mechatronic systems with sensors, circuits, and actuators.

Simulation 1: Capacitor Lab: Basics

URL: https://phet.colorado.edu/en/simulations/capacitor-lab-basics

Description:
Students explore how plate area and plate separation affect capacitance. Two interactive screens allow investigation of the capacitance relationship ($C = \varepsilon_0 A/d$) and RC discharge behavior through a light bulb circuit. Students manipulate virtual capacitors, observe electric field lines, and track stored energy in real time.

Content Alignment

Standard	Alignment
VA CTE Mechatronics I	Explain the role of electricity and electronics in mechatronic systems; identify and describe sensors (capacitive touch/proximity sensors operate on $C = \varepsilon_0 A/d$)
VA Physics SOL PH.7	Investigate how to use the field concept to describe the effects of electric forces; key concepts include Coulomb's law and technological applications
NGSS HS-PS2-4	Use mathematical representations of Coulomb's Law to describe and predict electrostatic forces between objects
NGSS HS-PS3-2	Develop and use models to illustrate energy associated with relative position of particles; example: energy stored between two electrically-charged plates
NGSS HS-ETS1-4	Use a computer simulation to model the impact of proposed solutions to a complex real-world problem

Mechatronics Connection:
Capacitive touch sensors and proximity sensors are ubiquitous in mechatronic systems. Understanding how plate geometry and dielectric properties govern capacitance gives students the physical intuition to select and troubleshoot these sensors. The RC

discharge screen directly connects to button debounce circuits and 555-timer PWM, both of which students encounter when programming microcontrollers.

Simulation 2: Circuit Construction Kit: DC

URL: https://phet.colorado.edu/en/simulations/circuit-construction-kit-dc

Description:
A virtual free-form, node-based workspace where students build circuits from batteries, resistors, light bulbs, switches, wires, ammeters, and voltmeters. Students can toggle between lifelike component view and schematic view, measure voltage and current at any point, and observe real-time changes as they modify circuit topology. Supports series, parallel, and combined circuits.

Content Alignment

Standard	Alignment
VA CTE Mechatronics I-II	Demonstrate the use of electrical testing equipment; apply electrical measurement skills (voltage, current, resistance); explain the role of electricity and electronics in mechatronic systems
VA CTE Adv. Mfg. Task 60-61	Task 60: Explain the role of electricity/electronics in mechatronic systems; Task 61: Demonstrate the use of electrical testing equipment
VA Physics SOL PH.8	Investigate how to diagram, construct, and analyze basic electrical circuits; key concepts: Ohm's law; series, parallel, and combined circuits; electrical power; alternating and direct currents
NGSS HS-ETS1-2	Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering
NGSS HS-ETS1-4	Use a computer simulation to model the impact of proposed solutions to a complex real-world problem

Mechatronics Connection:
Every sensor, actuator, and microcontroller in a mechatronic system connects through circuits. CCK: DC is the bridge between physics concepts ($V=IR$, Kirchhoff's Laws) and the practical wiring students do on breadboards and PCBs. Research shows students who use this simulation before touching real equipment build physical circuits faster and make fewer wiring errors. The schematic view directly trains students to read the circuit diagrams they encounter in datasheets and technical manuals.

Simulation 3: Faraday's Electromagnetic Lab

URL: https://phet.colorado.edu/en/simulations/faradays-electromagnetic-lab

Description:
Five interactive screens—Bar Magnet, Pickup Coil, Electromagnet, Transformer, and Generator—let students visualize magnetic field lines, observe electromagnetic induction, and explore how changing magnetic flux produces current. The 2024 HTML5 redesign provides improved field visualization with dynamic compass needles and works on all modern browsers, tablets, and computers.

Content Alignment

Standard	Alignment
VA CTE Mechatronics I-III	Identify and describe how motors/actuators are energized by controllers; demonstrate understanding of motor control in automated systems; investigate sensors and actuators in mechatronic systems
VA CTE Electrical Tier	Rotating Electrical Motors (DC/AC); Transformers (operation, application, sizing); Solenoids; Input/Output Devices (sensors, actuators, relays)
VA Physics SOL PHII.6	Investigate and understand the interrelationships of electricity and magnetism: magnetism and moving charges; electromagnetic induction; transformers and generators; motors
NGSS HS-PS2-5	Investigate to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current
NGSS HS-PS3-3	Design, build, and refine a device that converts one form of energy into another (examples: generators, wind turbines)

Mechatronics Connection:
This simulation is the capstone. Its five modules map directly onto the devices mechatronics students build and control: DC motors, solenoids, inductive sensors, power supplies/transformers, and encoders. The Pickup Coil and Generator screens explain back-EMF—the number one cause of Arduino GPIO damage when students connect motors without flyback diodes. Understanding electromagnetic induction gives students the "why" behind the protection circuits and motor driver ICs they use in every robotics project.

Section 2: Activity Plans and Artifacts

The following three activity plans form a semester-long E&M arc within the Mechatronics course. They are sequenced to build understanding progressively: electrostatics and energy storage (Weeks 1–3) → DC circuit design and analysis (Weeks 4–6) → electromagnetism, motors, and generators (Weeks 6–9). Each plan draws from gold-star PhET activities and adapts for a CTE Mechatronics context. All four required instructional strategies—open play, prediction questions, challenge prompts, and modeling practices—are highlighted in bold and labeled where they appear.

Activity Plan 1: Capacitors —Electric Fields to Sensor Design

Simulation: Capacitor Lab: Basics (HTML5)

Timeframe: 3 class periods (50 min each), Weeks 1–3 of semester

Additional Activities: Hands-on labs with breadboards and electronic components.

Adapted from: Trish Loeblein, "Capacitor Lab: Basics — Inquiry into Capacitor Design" (Gold Star, PhET Activity #5449)

Source: https://phet.colorado.edu/en/activities/5449

Period 1: Exploring Capacitance (50 min)

Learning Goals:
Students will identify the variables that affect capacitance and discover the relationship $C = \varepsilon_0 A/d$ through guided exploration, while critically evaluating the limitations of virtual models.

Warm-Up (5 min):
Teacher holds up a capacitive touch sensor module (common in Arduino kits). Asks: "How does your phone screen know where your finger is?" Brief class discussion to activate prior knowledge.

[OPEN PLAY] Exploration Phase (15 min):
Students open the Capacitance screen of Capacitor Lab: Basics. No step-by-step instructions are given. Students freely manipulate plate area, plate separation, and the voltage slider while observing the electric field lines, charge distribution, and capacitance meter. They record observations in a "Notice / Wonder" table on their activity sheet. Teacher circulates, asking probing questions but not directing explicitly how to interact.

[PREDICTION QUESTIONS] Structured Investigation (20 min):
Students work through a series of predict-test-confirm cycles on their activity sheet:

- **"If I double the plate area while keeping separation constant, I predict the capacitance will _____ because _____."** Students test with the sim and record actual results.
- **"If I halve the plate separation while keeping area constant, I predict the capacitance will _____ because _____."**
- **"If I disconnect the battery and then increase the plate separation, I predict the voltage across the capacitor will _____ because _____."** (This is a deliberately non-obvious scenario that reveals whether students understand charge conservation vs. capacitance.)

[MODELING PRACTICES] Synthesis (10 min):
Students capture a screenshot of their simulation showing maximum capacitance and annotate it with arrows and labels explaining why that configuration maximizes C. They write the relationship $C = \varepsilon_0 A/d$ in their own words, connecting each variable to what they observed in the sim. Finally, students must list two physical realities about real-world capacitors that this virtual model *fails* to show (e.g., maximum voltage ratings, physical size limits, leakage current), building habits in critically evaluating engineering models.

Period 2: Energy Storage and RC Discharge (50 min)

Learning Goals:
Students will determine the relationships between charge, voltage, and stored energy for a capacitor, and observe RC discharge behavior.

Review (5 min):
Quick class poll using clicker questions (adapted from Loeblein's Concept Questions, Activity #3112): "A capacitor is connected to a battery. If you increase the plate area, what happens to the stored energy?" Students commit to an answer before testing.

[PREDICTION QUESTIONS] Energy Relationships (20 min):
Students investigate the Capacitance screen with the energy and voltage meters displayed. They systematically vary one variable at a time, recording capacitance (C), voltage (V), charge (Q), and stored energy (U) in a data table. Students graph U vs. V

to visually reveal the parabolic curve and are asked to predict: "If I double the voltage across the capacitor, will the stored energy double, quadruple, or stay the same?" They test and derive the relationship $U = \frac{1}{2}CV^2$ rather than just guessing the math.

[CHALLENGE PROMPT] RC Discharge Investigation (15 min):
Students switch to the Light Bulb screen. Challenge: "Charge the capacitor fully, then disconnect the battery and connect the light bulb. Your mission: design a capacitor configuration that keeps the bulb lit for the longest possible time. Record what plate geometry and initial voltage you chose and explain why." This requires students to synthesize their understanding of stored energy ($U = \frac{1}{2}CV^2$) with discharge rate.

Mechatronics Bridge (10 min):
Teacher demonstration: connect a physical 100µF capacitor to an LED and 330Ω resistor on a breadboard, charge it, and disconnect the power supply. Students observe the decay. Teacher explains: "This is exactly what happens inside a button debounce circuit on your microcontroller. The RC time constant determines how long the capacitor holds charge — and that's what prevents your microcontroller from reading a single button press as multiple rapid-fire clicks." Students connect simulation observations to physical behavior.

Period 3: Capacitive Sensors Design Challenge (50 min)

Learning Goals:
Students will apply capacitance principles to explain how proximity sensors work and document a sensor configuration for a specific advanced manufacturing application.

[CHALLENGE PROMPT] Sensor Design Task (35 min):
Working in pairs, students receive this design brief:

- *Scenario:* An automated semiconductor milling machine requires a non-contact proximity sensor to act as a homing switch. This sensor must detect the approaching metal gantry plate to prevent the end-effector assembly from crashing into the end rails.
- *Task:* Because the approaching metal gantry essentially acts as a second conductive plate, altering the effective distance (d), use the simulation to model how a capacitive sensor would behave as the gantry approaches. Capture annotated screenshots and document:
    - How does decreasing the distance (d) between the sensor and the approaching metal plate change the capacitance reading?
    - What specific capacitance threshold (in picofarads) would you program into the machine controller to trigger the "STOP" command? Why?

- What physical environmental factors in a machining environment could cause a false reading or alter the effective area (A)?

[MODELING PRACTICES] Gallery Walk and Reflection (15 min):
Student teams post their annotated sensor designs. The class conducts a gallery walk with sticky-note feedback. The teacher evaluates the artifacts not just for physics accuracy, but for iterative storytelling through technical documentation—how clearly and professionally the engineering decisions are communicated to an outside observer.

Activity Plan 2: DC Circuits — Virtual Connections to Physical Wiring

Simulation: Circuit Construction Kit: DC

Timeframe: 5 class periods (50 min each), Weeks 4–6 of semester

Adapted from: Trish Loeblein, "Circuit Construction Kit — Series of Three Activities" (Gold Star, PhET Activity #3121) and "Concept Questions for Physics Using PhET" (Gold Star, Activity #3112)

Sources: https://phet.colorado.edu/en/activities/3121 | https://phet.colorado.edu/en/activities/3112

Period 1: Discovering Circuit Fundamentals (50 min)

Learning Goals:
Students will build simple circuits, use virtual multimeters to measure voltage and current, and discover the relationship $V = IR$.

[OPEN PLAY] Free Build (15 min):
Students open Circuit Construction Kit: DC and are given one instruction: "Build a circuit that makes a light bulb glow. Then build a different circuit that makes it glow brighter." No component list or wiring diagram is provided. Students explore the component palette, discover how to connect wires, and figure out that a complete loop is required. Teacher circulates, noting common struggles (e.g., open circuits, short circuits) for later class discussion.

[PREDICTION QUESTIONS] Ohm's Law Investigation (20 min):
Students build a single-resistor circuit with a battery, resistor, ammeter, and voltmeter. Activity sheet prompts:

- "Predict: If I double the battery voltage, the current through the resistor will _____." Test and record.
- "Predict: If I replace the resistor with one of twice the resistance (same voltage), the current will _____." Test and record.
- Students compile data in a table and derive V = IR from their measurements.

[MODELING PRACTICES] Schematic Literacy (15 min):
Students toggle between the "lifelike" component view and the "schematic" view in the simulation. For each of three provided schematics (drawn on the activity sheet), students build the corresponding circuit in the sim, toggle to schematic view to verify it matches, and record voltage/current readings. Teacher explains: "In mechatronics, every motor driver, sensor module, and microcontroller board comes with a schematic. This is the language we use to communicate circuit designs."

Period 2: Series Circuits (50 min)

Learning Goals:
Students will predict and verify voltage and current behavior in series circuits and apply Kirchhoff's Voltage Law.

[PREDICTION QUESTIONS] Series Resistor Investigation (25 min):
Students build a two-resistor series circuit. Before taking any measurements, they predict:

- "Will the current be the same through both resistors, or different? Why?"
- "Will the voltage across each resistor be the same, or different? Why?"
- "What will the sum of the individual voltage drops equal?"

Students place ammeters and voltmeters, test their predictions, and reconcile any discrepancies. They then add a third resistor and repeat, building toward Kirchhoff's Voltage Law: the sum of voltage drops around a loop equals the source voltage.

[MODELING PRACTICES] Circuit Diagrams (15 min):
Students draw a schematic of their 3-resistor series circuit by hand, label all component values, and annotate with measured voltages and currents. They write a sentence explaining why series circuits are used for LED strings (same current through each LED ensures uniform brightness) and why series resistors are used as voltage dividers in sensor circuits.

Physical Build (10 min):
Students replicate their 3-resistor series circuit on a physical breadboard using real resistors, a power supply, and a multimeter. They compare physical measurements to simulation values and discuss sources of discrepancy (tolerance, contact resistance).

Period 3: Parallel Circuits & The Transistor Bridge (50 min)

Learning Goals:
Students will verify parallel circuit behavior and design a transistor switching circuit to safely control high-current loads.

[PREDICTION QUESTIONS] Parallel Investigation (25 min):
Students build a two-resistor parallel circuit. Prediction prompts:

- "Will the voltage across each branch be the same or different?"
- "Will the current through each branch be the same or different?"
- "Predict: Adding a parallel branch will cause total circuit current to _____ (increase / decrease / stay the same)."

Students test each prediction with ammeters at the junction and at each branch. They discover that current splits at a junction and reconvenes — Kirchhoff's Current Law.

[CHALLENGE PROMPT] Circuit Design Challenge (20 min):
"Your microcontroller can safely supply a maximum of 20 mA per GPIO pin. However, you need to power a high-brightness LED array (5 LEDs in parallel, requiring 100 mA total at 5V) for an automated vision inspection station. If you wire this directly to the GPIO pin, you will fry the board. Design a circuit that uses the microcontroller pin *only* to send a low-current control signal to a logic-level NPN transistor (like a 2N2222). The transistor will act as a switch, pulling the heavier 100mA load directly from the main 5V power supply. Calculate the required current-limiting resistors for the LEDs. Build and test the LED array in the simulation to verify the 100mA current draw, then diagram the full transistor circuit."

Debrief (5 min):
Class discussion bridging this concept to robotic actuators: "This exact logic is how a 3.3V microcontroller safely controls a heavy stepper motor within industrial robotics or an automated LED array for computer-vision quality control processes. The logic board only talks to the driver; the driver handles the heavy current."

Periods 4–5: Combined Circuits and Troubleshooting (100 min total)

Learning Goals:
Students will analyze combined series-parallel circuits, practice systematic troubleshooting, and develop perseverance to debug physical hardware blind by relying on their peers' documentation.

Period 4 — Combined Circuits (50 min):
Students work through increasingly complex combined circuits provided on their activity sheet. For each circuit, they predict all voltages and currents using $V = IR$ and Kirchhoff's Laws, build them within simulation, and verify. For the final 20 minutes, each team physically builds their most complex simulated circuit on a breadboard. They must verify it works perfectly and record the "baseline" voltage and current readings at key test points.

[CHALLENGE PROMPT] Period 5 — The Sabotage and Swap (35 min):

Phase 1: The Sabotage (10 min):
Teams are instructed to introduce one intentional, realistic fault into their working physical circuit (e.g., a disconnected jumper mimicking a broken wire, a blown LED, or swapping a 220Ω resistor for a 10kΩ resistor to mimic a failed component). To simulate industrial systems where wiring is hidden inside cable drag chains or enclosures, they place a strip of masking tape over the center wiring of the breadboard, leaving only component legs exposed.

Phase 2: The Swap & Solve (25 min):
Teams rotate to a different workbench. They are handed the original "baseline" documentation for that station's circuit. Using *only* a physical multimeter to probe the exposed legs, they must diagnose the hidden fault. They must stick with the problem, documenting their systematic process: what test point they measured, how it deviated from the baseline, and what specific fault they diagnosed using KVL/KCL.

[MODELING PRACTICES] Circuit Documentation & Debrief (Last 15 min of Day 5):
Teams reunite with the original builders to confirm if their diagnosis was correct. Students create a complete, clean schematic of the circuit they successfully debugged, including component values, baseline measurement points, and a brief written explanation of the fault they uncovered. This artifact is added to their engineering documentation as a reference for future team-based problem-solving.

Activity Plan 3: Electromagnetism — Magnetic Fields to Motors

Simulation: Faraday's Electromagnetic Lab (HTML5)

Timeframe: 4 class periods (50 min each), Weeks 7–9

Adapted from: Trish Loeblein, "Magnets — Introduction" (Gold Star, Activity #2826), and "Induction — High School Version" (Gold Star, Activity #2827)

Sources: https://phet.colorado.edu/en/activities/2826 | https://phet.colorado.edu/en/activities/2827

Period 1: Magnetic Fields and Electromagnets (50 min)

Learning Goals:
Students will predict the direction and strength of magnetic fields around bar magnets and electromagnets and compare the two.

[OPEN PLAY] Bar Magnet Exploration (10 min):
Students open the Bar Magnet screen. No explicit instructions — they freely move the magnet,

observe the compass needles, toggle the field line visualization, and flip the magnet. They record in a "Notice / Wonder" table what they observe about field direction, field density near vs. far from the magnet, and what happens at the poles.

[PREDICTION QUESTIONS] Electromagnet Comparison (20 min):
Students switch to the Electromagnet screen. Prediction prompts:

- "Predict: If I increase the current through the coil, the magnetic field strength will _____."
- "Predict: If I reverse the current direction, the field will _____."
- "Predict: How will the electromagnet's field pattern compare to the bar magnet? (Same shape / different shape / no field)"

Students test each prediction, toggle field lines on/off, and move the compass around both the bar magnet and electromagnet to compare. They discover that an electromagnet produces the same dipole field pattern as a bar magnet but is controllable.

[MODELING PRACTICES] Field Diagrams (15 min):
Students draw field line diagrams for both the bar magnet and electromagnet side by side, labeling N/S poles, field direction, and areas of high vs. low field density. They write a comparison paragraph explaining how electromagnets are "programmable magnets" — a concept central to solenoid valves, relay switches, and electromagnetic brakes in mechatronic systems.

Mechatronics Bridge (5 min):
Teacher shows a relay module and a solenoid valve from the lab. "Both of these are electromagnets controlled by microcontrollers. Now you understand the physics behind why applying current makes them activate."

Period 2: Electromagnetic Induction (50 min)

Learning Goals:
Students will identify conditions that produce electromagnetic induction and predict how changes in those conditions affect induced current.

- **[OPEN PLAY] Pickup Coil Discovery (10 min):**
  Students open the Pickup Coil screen and freely move the bar magnet near the coil. They observe the light bulb and voltmeter responding. Challenge: "Can you make the bulb glow without touching the coil to the magnet?" Students discover that movement is required — a stationary magnet inside the coil produces no current.

- **[PREDICTION QUESTIONS] Variables of Induction (25 min):**
  Systematic investigation with predict-test-confirm:
  - "Predict: Moving the magnet faster through the coil will cause the induced voltage to _____."
  - "Predict: Increasing the number of loops in the coil will cause the induced voltage to _____."

- "Predict: Using a stronger magnet will cause the induced voltage to _____."
- "Predict: Reversing the direction of magnet motion will cause the voltmeter to _____."

Students compile their findings into a summary statement: "Electromagnetic induction depends on _____, _____, and _____." Teacher introduces Faraday's Law conceptually: the induced voltage is proportional to the rate of change of magnetic flux through the coil.

[CHALLENGE PROMPT] Minimum Conditions (10 min):
"What is the absolute minimum condition needed to produce induction? Test at least 3 different scenarios and determine: is it the magnet that matters, the coil that matters, or something else entirely?" Students discover that relative motion (changing flux) is the key — not the magnet or coil alone.

Exit Ticket (5 min):
"A student says: 'A magnet sitting inside a coil will continuously generate electricity.' Do you agree or disagree? Explain using evidence from your investigation."

Period 3: Transformers and Generators (50 min)

Learning Goals:
Students will explain how transformers step voltage up/down and how generators convert mechanical energy to electrical energy.

Transformer Screen (20 min):
Students explore the Transformer screen. They vary the number of loops in the primary and secondary coils and observe the effect on the output voltage. Prediction: "If the primary coil has 4 loops and the secondary has 2 loops, the output voltage will be _____ compared to the input voltage." Students discover the turns ratio relationship and connect it to why power supplies for mechatronic systems use step-down transformers (wall outlet 120V AC → 12V or 5V DC).

[OPEN PLAY] Generator Screen (15 min):
Students open the Generator screen and turn the faucet to spin the magnet inside the coil. They observe the voltmeter showing alternating current. Students freely explore: What happens when you change the water flow rate? What happens when you change the number of coil loops? The magnet strength? Teacher connects: "This is the same principle inside a wind turbine, a hydroelectric dam, and the alternator in a car."

[MODELING PRACTICES] Energy Flow Diagrams (15 min):
Students create energy flow diagrams for three mechatronic devices: (1) a DC motor (electrical → magnetic → mechanical), (2) a generator (mechanical → magnetic → electrical), and (3) a transformer (electrical → magnetic → electrical at different voltages). They annotate each diagram with observations from the simulation. Teacher connects:

"Motors and generators are the same device run in opposite directions — and that's why spinning a motor shaft generates a voltage (back-EMF)."

Period 4: Motors, Back-EMF, and Protection Circuits (50 min)

Learning Goals:
Students will connect electromagnetic induction to DC motor operation and design motor protection circuits for microcontroller projects.

[PREDICTION QUESTIONS] Back-EMF Investigation (15 min):
Using the Pickup Coil screen, teacher poses: "Your microcontroller sends a signal to a motor controller through a transistor. The motor spins. Now the Arduino turns the signal OFF. Predict: what happens in the coil of the motor at the instant it stops receiving current?" Students use the simulation to model this: they move the magnet away from the coil quickly and observe the voltage spike. Teacher explains: "That voltage spike is back-EMF, and it can destroy your microcontroller's GPIO pin or transistor if you don't protect against it."

[CHALLENGE PROMPT] Motor Driver Design Challenge (25 min):
Working in pairs, students receive this design brief: "You are designing a mechatronic system that uses a 12V DC motor controlled by an ESP32. The motor draws 500 mA under load. Design a complete motor control circuit that includes: (a) a transistor or MOSFET to switch the motor (since microcontroller GPIO can only supply 40 mA), (b) a flyback diode to protect against back-EMF, and (c) a decoupling capacitor to smooth power supply noise. Draw a complete schematic, label all component values, and explain the purpose of each component using what you learned from the simulations." Students sketch their designs and present to the class.

[MODELING PRACTICES] Reflection and Documentation (10 min):
Students write a one-paragraph reflection: "How do the principles of electromagnetic induction I explored in the Faraday simulation connect to the motor protection circuit I designed?" These reflections are added to their engineering documentation.

Section 3: Instructional Strategies Summary

The table below maps where each of the four required PhET instructional strategies appears across the full set of activity plans.

Strategy	Capacitor Lab (Plan 1)	CCK: DC (Plan 2)	Faraday's EM Lab (Plan 3)
Open Play	**Period 1**: 15-min free exploration of Capacitance screen; Notice/Wonder table	**Period 1**: "Build a circuit that makes a bulb glow brighter" with no instructions	**Period 1**: Bar Magnet free exploration; **Period 2**: Pickup Coil discovery; **Period 3**: Generator screen
Prediction Questions	**Period 1**: Predict-test-confirm for capacitance variables; **Period 2**: Energy clicker questions and $U=\frac{1}{2}CV^2$ predictions	**Period 1**: Ohm's Law predictions; **Period 2**: Series circuit V/I predictions; **Period 3**: Parallel branch predictions	**Period 1**: Electromagnet field predictions; **Period 2**: All four induction variable predictions; **Period 4**: Back-EMF predictions
Challenge Prompts	**Period 2**: Longest-lit bulb RC challenge; **Period 3**: Capacitive sensor design for limiting and homing machine gantry	**Period 3**: Transistor bridge circuit for high-current mechatronics load; **Period 5**: Physical “Sabotage and Swap” fault diagnosis	**Period 2**: Minimum conditions for induction; **Period 4**: Motor driver design with back-EMF diode
Modeling Practices	**Period 1**: Annotated screenshots with $C=\varepsilon_0 A/d$ and model limitations; **Period 3**: Gallery walk of sensor designs focused on technical documentation	**Period 1**: Schematic literacy toggle exercise; **Period 2**: Hand-drawn series circuit diagrams; **Period 5**: Complete circuit documentation of debugged physical board	**Period 1**: Side-by-side field line diagrams; **Period 3**: Energy flow diagrams for motor/generator/transformer; **Period 4**: Back-EMF reflection

Section 4: Narrative Reflection

Context

What course did you have in mind as you created this portfolio?

This portfolio was designed for a high school Mechatronics course at the Grace Hopper Center (GHC), part of Arlington Public Schools (APSVA) in Arlington, Virginia. Next year, I am transitioning away from teaching Digital Electronics and Computer-Integrated Manufacturing to focus entirely on launching Mechatronics I and II. This integrated pathway effectively combines the logic, circuitry, and manufacturing principles of those previous courses into one cohesive arc focused on digital fabrication, computational design, sensors, instrumentation, and embedded programming on microcontrollers.

The typical student profile includes:

- **Grade level:** 10th–12th graders.
- **Prior knowledge:** Students have completed at least one foundational engineering or technology course, which is required for all entering Arlington Tech freshmen (Full-time, 1000 student STEM program at GHC). Most have basic experience with breadboard wiring and microcontroller programming from prior content within their freshman year and during the beginning weeks of Mechatronics I, with younger students having limited formal physics background.
- **Special considerations:** CTE students at Grace Hopper Center are diverse in academic preparation. Some are highly skilled STEM-track students pursuing engineering degrees from top universities; others are career-focused who are entering the workforce through apprenticeships after graduation. Some have IEPs or 504 plans requiring visual support and extended time. Overall, the simulation-first approach benefits all students because it provides a safe, consequence-free environment for exploration with immediate visual feedback for deeper foundational knowledge.
- **Class context:** Class sizes are typically 18–24 students. My classroom operates as a collaborative learning environment where students work in teams to solve complex technical problems. They all have personal MacBooks and access to broad swaths of materials, components, testing instrumentation, and fabrication tools for bridge activities.

What is your level of familiarity with PhET's E&M simulations now compared to before taking this course?

Before completing both the *PhET E&M* and *Introduction to PhET Simulations for STEM Education* courses, I had never worked with PhET simulations. My previous simulation experience was strictly functional and outcome-driven. I used TinkerCAD and Wokwi to verify breadboard connections and test C++ code for ESP32 projects, or Multisim to develop schematics for testing logic gate structures from truth tables and K-Maps. I used these primarily as verification tools or teacher-led demonstrations projected on a screen.

My understanding of what a simulation can achieve pedagogically has shifted entirely. I now understand the profound value of using physics-engine simulations for constructivist meaning-making. If we only look at photos or datasheets, the underlying physics of electronics is entirely lost in abstraction. PhET provides a dynamic environment where students can actively interact with abstract concepts, building their own foundational understandings. That deep physics knowledge then translates to deeper and transferable understanding of sensors, motor controllers, GPIO pins, and actuators from first principles.

Instructional Approach

Why did you select the simulations you chose?

The three simulations—*Capacitor Lab: Basics*, *Circuit Construction Kit: DC*, and *Faraday's Electromagnetic Lab*—were selected because they directly map to the three foundational E&M pillars that mechatronics teams must understand to design functional systems:

1. **Capacitor Lab: Basics:** Addresses the electrostatics and energy storage principles behind capacitive sensors (like capacitive homing sensors) and RC timing circuits (debounce, PWM).

2. **Circuit Construction Kit: DC:** The core circuit literacy tool. Every sensor and actuator connects through circuits governed by Ohm's Law and Kirchhoff's Laws. The schematic view directly trains students in the technical communication language they need to document and share designs with their teams. The simulation is also node-based, which helps students develop a foundational understanding of connections before adding the spatial complexity of physical breadboards.

3. **Faraday's Electromagnetic Lab:** The capstone that explains how motors, solenoids, transformers, and generators work. Since every mechatronic system involves actuators, students need to understand electromagnetic induction to design safe motor control circuits—especially understanding the back-EMF that causes catastrophic hardware damage.

These three simulations also align strongly with Virginia CTE Mechatronics competencies (explaining electricity/electronics in mechatronic systems, demonstrating electrical testing equipment, understanding motors/actuators), Virginia Physics SOL standards (PH.7, PH.8, PHII.6), and NGSS performance expectations (HS-PS2-4, HS-PS2-5, HS-PS3-2, HS-PS3-3, HS-ETS1-4). The alignment details are documented in Section 1.

What are your activity plans and how do they fit together to build student understanding?

One of my top-level goals is teaching students how to stick with difficult technical problems longer. These three plans form a deliberate learning progression designed to build that technical perseverance:

- **Weeks 1–3 (Capacitor Lab):** Students begin with electrostatics and energy storage. The progression moves from free exploration to structured investigation to an applied design challenge (capacitive homing sensor). This early placement builds intuition about electric fields that supports later circuit analysis.
- **Weeks 4–6 (CCK: DC):** Students begin learning about circuit design by gaining deep practice with $V=IR$, Kirchhoff's Laws, schematic literacy, and systematic troubleshooting. The simulation-to-physical-breadboard bridge, culminating in a blind "Sabotage and Swap" physical troubleshooting challenge, forces teams to rely on one another's technical documentation to solve problems.
- **Weeks 7–9 (Faraday's EM Lab):** By this point, students are about to wire motors in their projects. Before damaging components because of back-EMF (or near-misses), they can build preemptive knowledge in simulation. The Faraday simulation finally gives them the "why" behind the protection circuits they are using.

Use of Instructional Strategies: Each strategy was deployed for a specific pedagogical purpose:

- **Open play** begins every new simulation encounter. Following PhET's research, I avoid giving step-by-step exploration instructions. Instead, students explore freely and record observations in "Notice / Wonder" tables. This activates curiosity, surfaces prior conceptions, and gives students ownership of their learning trajectory. Open play is especially effective with CTE students who are accustomed to hands-on exploration.
- **Prediction questions** are embedded throughout all three activity plans as predict-test-confirm cycles. Having students commit to a prediction before testing with the simulation forces them to engage their mental model rather than passively observing. When predictions are wrong, the discrepancy creates productive cognitive conflict that deepens understanding. I use both individual written predictions (activity sheets) and whole-class clicker polls for different purposes.
- **Challenge prompts** appear in every activity plan, typically in the later days when students have foundational understanding. These are deliberately open-ended and require synthesis: designing a capacitive sensor, designing an Arduino LED circuit with real specifications, diagnosing hidden circuit faults, and designing a motor driver with back-EMF protection. These challenges connect PhET simulation work to authentic mechatronics engineering tasks.
- **Modeling practices** run throughout as students create annotated screenshots, hand-drawn schematics, energy flow diagrams, and written explanations. In CTE education, documentation is a professional skill. Students are not just doing physics — they are learning to communicate their understanding in the formats used by engineers and technicians (schematics, annotated diagrams, technical writing).

Addressing Common Student Learning Challenges: CTE students often struggle with abstract physics concepts disconnected from application. Every activity plan includes explicit "Mechatronics Bridge" moments where I connect simulation physics to tangible devices students use in the lab (capacitive touch sensors, breadboard circuits, relay modules, motors). The simulation-first approach also addresses the common challenge of fear of equipment damage — students can short-circuit a virtual battery without consequences, building confidence before touching real components.

Synthesis

How does the portfolio reflect a change in your instructional approach when teaching about E&M?

Example 1 — From functional verification to constructivist inquiry: Previously, I used tools like Wokwi strictly to verify if code or wiring was correct before a build. Through this course, I learned that simulations are most effective when students use them to construct meaning, not just check work. My activity plans now begin with open play and use the simulation as a student investigation tool.

Example 2 — Adding the prediction cycle: Before this course, I sporadically used prediction questions. I would ask students to "observe what happens," but not require commitment. The predict-test-confirm framework changed this. Requiring a written prediction before testing dramatically increases cognitive engagement because students suddenly have a stake in the outcome.

Example 3 — Connecting simulations to mechatronics applications: Previously, simulation work (like Multisim logic gates) and hands-on project work were bound together for utility, rather than uncovering abstractions. This portfolio integrates them: students explore abstract physics in the simulation, then immediately apply it toward tangible mechatronics design problems, like sizing a flyback diode for a motor.

How does your portfolio reflect what you have learned in this course about E&M topics and/or PhET simulations?

Example 1 — Capacitor Lab deepened my own content knowledge:
Before this course, I understood capacitors as circuit components but had not deeply explored how plate geometry governs capacitance ($C = \varepsilon_0 A/d$) or how that principle underlies capacitive sensors. The Capacitor Lab simulation made this relationship visual and manipulable in a way that a textbook equation cannot. This deepened understanding directly shaped Activity Plan 1, where I ask students to design capacitive sensors, which is a challenge I would not have been equipped to create before.

Example 2 — Faraday's Lab explained back-EMF in a way my students need:
My students have damaged Arduino pins by connecting motors directly to GPIO pins without flyback diodes. Before this course, I taught back-EMF protection as a rule ("always use a diode with motors") without fully explaining the induction physics. The Faraday simulation's Pickup Coil screen lets students see the voltage spike that occurs when a magnetic field collapses — making the abstract threat concrete. Activity Plan 3,

Day 4 now gives students the physics foundation to understand why protection circuits are necessary, not just that they are required.

Example 3 — I learned that PhET's pedagogical design is itself a model of good CTE instruction:

PhET's emphasis on student-driven exploration, making the invisible visible, and connecting abstract models to real-world phenomena aligns perfectly with the project-based learning philosophy I use in my mechatronics program. This course did not just give me three simulations — it gave me a framework (open play → prediction → challenge → modeling) that I can apply to any simulation or hands-on investigation in my CTE courses.

Conclusion

Ultimately, this portfolio represents a fundamental evolution in how I approach mechatronics education. The shift from using software merely for functional verification to leveraging it for constructivist inquiry directly supports my core pedagogical mission: teaching students how to solve difficult technical problems in collaborative teams.

For more than a decade in adventure education, I saw firsthand that navigating remote rivers or granite rock faces requires the exact same durable human capabilities as debugging a complex motor control circuit—perseverance, ambitious goal-setting, and a willingness to stick with a frustrating problem. By introducing these dynamic PhET simulations before the physical build, I am providing a vital, consequence-free training ground. It is here that students can safely make mistakes, reconstruct their understanding of invisible forces, and develop the technical confidence necessary to take shared responsibility for extraordinary outcomes within the lab and beyond.

Sources

PhET Simulations

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- Virginia CTE Resource Center — Mechatronics I, II, III
- Virginia CTE Competency List — Advanced Manufacturing Systems II (Course 8427)
- Virginia Science Standards of Learning — Physics (2018)
- NGSS Performance Expectations — All DCI
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