

Elevator Motion: Acceleration, Velocity, and Displacement Analysis

Measurement of Changes in Acceleration and Pressure

Scientific Inquiry with AI

Student Guide

Detailed Instructions & Course Material

Why This Lesson

This investigation uses an elevator as an experimental platform to explore motion and the accelerometer and barometer in your phone as the measurement tools to interrogate that motion. In this investigation you will learn how to use both the change in acceleration and air pressure to determine how fast the elevator was moving and how far it travels. While the two sensors measure very different physical properties, they both can provide very accurate measurements. As part of the investigative process, you will also learn about using numerical integration, graphical analysis, and how to design controlled experiments.

Throughout the investigation, you will direct an AI assistant to help you understand the phenomena and analyze your data. The AI assistant will help you accumulate background understanding through prelab discussions, build code to conduct computational analysis, walk you through simulations to extend your understanding, help you make sense of the results, and assist you in communicating your findings.

Learning Goals

Upon completion of this investigation, you should be able to:

Phenomena:

- Explain the relationship between acceleration, velocity, and displacement in both physical and mathematical terms.
- Distinguish a constant sensor offset from random noise, describe the physical origin of each, and explain how each will accumulate when performing numerical integration.
- Explain how two independent sensors measuring different physical properties can be used to cross-validate velocity and displacement measurements, and describe possible explanations for disagreement based on the sensor characteristics and the physical properties measured.

Experimental Practices:

- Direct an AI coding assistant to conduct numerical integration of time series data and use graphical methods to visualize and validate the results. When appropriate, ask the AI to explain the specific numerical methods used in the analysis, or to share the code it ran.

- Design and carry out a control measurement that removes a drifting background quantity from a difference measurement.
- Compare two independent measurements of the same quantity and provide plausible explanations for the differences.

Habits of Mind:

- Test the output of any analysis — hand calculation, code, or AI-generated result — against an independent check (known value, credible estimate, secondary independent measurement) before reporting it.
- Identify when and how a control measurement can be incorporated into an experimental design to improve the precision of a measurement.

What You Will Need

- A smartphone with the free Phyphox app installed, for its accelerometer and barometer.
- A computing device with access to an AI model.
- Access to an elevator serving 3–10 floors.
- A tape measure or meter stick, for Session B pressure measurements.
- A partner for Session B whose phone reports pressure at a rate close to yours. Android phones often report about 25 samples/s and iPhones about 1 sample/s, and the control measurement is easier to align in time when both records arrive at the same cadence. (If the rates differ, you can use AI to resample both records to a common rate.)

The Core Idea

- Modern microelectromechanical systems (MEMS) accelerometers measure acceleration precisely enough that velocity and displacement can be obtained from it by numerical integration. This is the basis of inertial navigation, used in aircraft, drones, robotics, and game controllers.
- In those systems, drift, which all sensors experience at some level, is the central engineering problem; it is managed by combining the accelerometer with gyroscopes and with periodic external references such as GPS. A constant offset b in the acceleration signal accumulates as $b \cdot t$ in velocity and $\frac{1}{2}b \cdot t^2$ in displacement, so a small offset can dominate the displacement result over a long record.
- An elevator ride supplies its own boundary conditions: the car is at rest before and after the ride, and a round trip returns it to the starting floor. Those conditions supply known true values against which the bias can be detected and the accuracy of the result evaluated.
- Barometric pressure provides a second, independent path to displacement through the hydrostatic relation $dP/dh = -\rho g$.
- Introducing a control measurement into an experimental design improves the precision of the result; in the reference example of Table A1 the improvement is roughly 20×.

Worked Example: What a Good Analysis Looks Like

A reference measurement for a round-trip elevator ride is shared in Table A1 (Appendix A). Refer to that table to see what a clean result looks like at each stage of the analysis. Your own numbers will differ. Treat the table as a model of process and magnitude.

Session A — Numerical Integration and Sensor Bias (~5 hours)

Session A establishes the central relationship of the lesson: acceleration integrates to velocity, and velocity integrates to displacement. You record your own elevator ride, then direct an AI coding assistant through that integration, diagnose the sensor offset that shifts the result, and correct it. Working from acceleration $\rightarrow$ velocity $\rightarrow$ displacement reverses the displacement $\rightarrow$ velocity $\rightarrow$ acceleration sequence most commonly taught in introductory physics. The direction used here is the one modern motion control systems are built on, using MEMS accelerometers and gyroscopes.

Part 1 — Pre-Class Preparation

1.25–1.5 hours

The pre-class tutor prepares you with a working understanding of linear motion and the terms used to describe it that you will use in class. You will also conduct the elevator ride measurement using your smartphone, collecting the data that you bring to class for analysis.

A. Socratic AI Tutoring Session A (~25 minutes)

When conducting the prelab tutor, use the Scientific Inquiry with AI business account and open the prelab tutor for Session A by clicking the “Open the custom GPT” button in the prelab section on the [knowledgewithai.com](https://www.knowledgewithai.com) website. This will launch you automatically into a tutoring session in ChatGPT. Confirm you are in “Chat” mode and not “Work”. These steps will ensure the best tutoring experience and will automatically record the completion of the tutoring session.

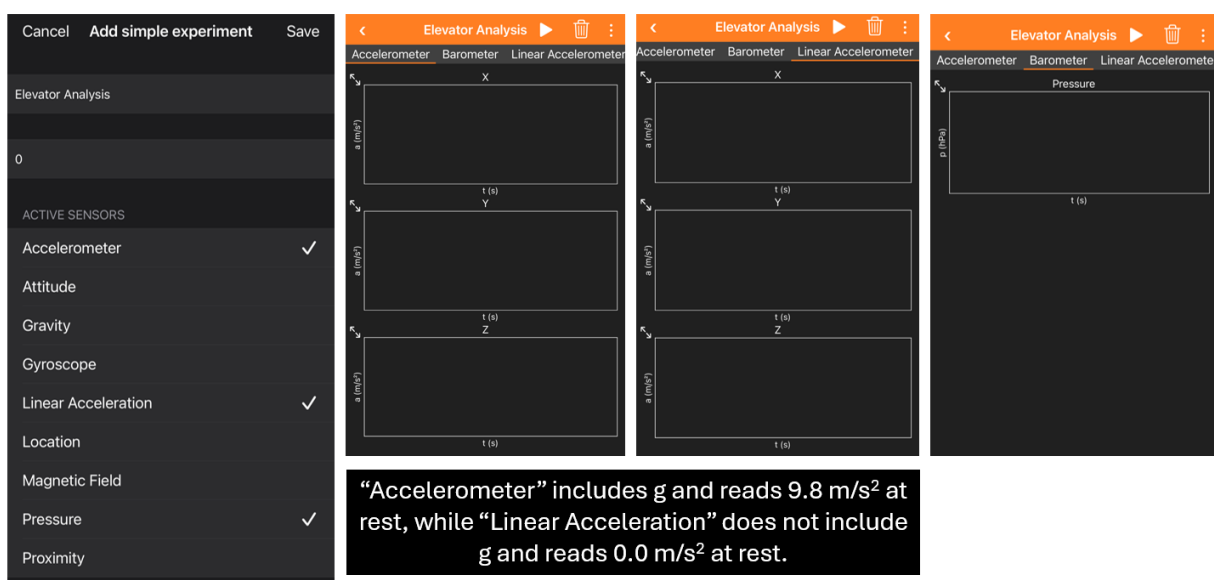
The AI tutor asks rather than explains: it opens with questions about your own experience riding an elevator, moves to diagnostic questions on how acceleration, velocity, and displacement relate, and introduces random noise and measurement bias so that the classroom analysis makes sense when you get there. You do not need prior physics; the tutor will help you build an understanding starting from your own personal background.

B. Prediction Exercise (~20 minutes)

Before making your acceleration measurement during your elevator ride, sketch the predicted acceleration, velocity, and displacement curves for a ride that accelerates, cruises, decelerates, and stops. Write this down in your notebook and bring it to class. Estimate the displacement you expect for each floor the elevator travels (you can use AI to assess if your estimate is reasonable).

C. Record the Elevator Ride (~20–30 minutes)

Record **one round trip** spanning 3–10 floors: up from your starting floor to the top floor of the trip, then back down to where you began. Keep the recording running while the car waits at the top floor; do not stop and restart it, and do not touch the phone. Secure the phone against a wall or corner of the car with the y-axis aligned to the direction of travel, so that it cannot move relative to the car during the recording. Include at least 3 s stationary before the ride and 3 s stationary after it. Log the accelerometer (includes g), linear acceleration, and barometric pressure channels at the same time using Phyphox’s “Simple Experiment” tool, at the maximum data collection rate for each sensor (leave the rate field set to 0, which Phyphox uses for the maximum rate). The figure below shows the Phyphox menu for adding a “simple experiment”. For the upward trip in the elevator, the y-axis linear acceleration trace should show a value near zero at rest, a positive pulse, a flat cruise back near zero, a negative pulse, and a return to near zero. A mirror image of this will be recorded on the downward return. Ideally, you do not want any additional stops on your ride, so it is best to do the experiment during a time when the elevator is not busy. It is critical that you measure the acceleration for at least 3 s before the elevator starts to move as well as after it stops. If you don’t get the measurement started in time, repeat the experiment. Take a screenshot of your acceleration graphs, then export the data using the three-dot menu ($\therefore$) → Export Data → CSV (Comma, decimal point). Phyphox saves a .zip file containing one comma-separated values (CSV) file per sensor; keep the whole .zip file. Have the .zip file and the screenshot available for class.



D. Review of In-Class Investigation (~10 minutes)

Skim the In-Class instructions so you arrive ready to work through the analysis yourself alongside the class. Note which decisions you expect to make, such as: What values do I expect for velocity and displacement? How will I determine whether an offset correction is needed? If it is, what steps will I take? Bring the exported .zip file, your screenshot, your prediction sketches, and a laptop or tablet.

Part 2 — In-Class Investigation

110 min

The class works through the analysis pipeline in parallel, each of you on your own measurement data, with the instructor gating the stages.

A. Opening Exercise (~10 minutes)

- Using your whiteboard, sketch the shape of the acceleration curve for the ride you recorded, then compare with a neighbor. Discuss what all the features represent in terms of your motion.
- On your whiteboards, illustrate numerically how you can calculate the change in velocity that occurs between two measurements of the acceleration by your sensor. You can assume that the acceleration is changing slowly compared to the 100 Hz data collection rate.

$$\text{Recall: } a = \frac{\Delta v}{\Delta t}$$

- Sketch the shape of the velocity curve for the entire ride, then compare with a neighbor.
- On your whiteboards, illustrate numerically how you can calculate the change in displacement that occurs between two sequential velocity measurements. You can assume that the velocity is changing slowly compared to the 100 Hz data collection rate.

$$\text{Recall: } v = \frac{\Delta d}{\Delta t}$$

- Sketch the shape of the displacement curve for the same ride, then compare again.

B. Co-Investigation with AI (~70 minutes)

Working with an AI coding assistant, you build the integration pipeline in four stages to analyze your linear acceleration data. This channel reports acceleration with the gravitational component already removed by your phone's sensor fusion (it uses multiple sensor inputs and software to make the correction for gravity), so it can be integrated directly and the residual sensor offset is the only constant error in the record. Reference values from a measurement made on a typical elevator appear in Table A1 (Appendix A) and are available as magnitude checks at every stage.

Stage 1 — Load and inspection (~10 minutes)

Upload the .zip file (or the linear acceleration CSV file inside it) in your chatbot window and prompt the AI to plot the y-axis linear acceleration against time. Compare the graphs to your screenshot to verify the data has been properly transferred before moving to the next step of analysis.

Stage 2 — Integrate once, without correction (~20 minutes)

Instruct the AI to integrate the linear acceleration data, with no correction, to obtain velocity, and to integrate the velocity to obtain displacement. Read the final velocity from the graph. The car is at rest at the end of the ride, so the true value is 0 m/s. If the velocity is not zero at the expected times, there must be an error in the measurement or the analysis. Evaluate the round-trip displacement using the same approach: the car returned to its starting floor, so the true value is 0 m. Record the values of the velocity and the displacement at the end of the elevator ride based on this initial analysis. Share your values using your whiteboards.

Consider how a small bias in the acceleration measurement would impact the analysis. Take a moment to estimate how a small error might add up over time (e.g., if you accelerate at 0.2 m/s^2 you will be moving at 2 m/s after 10 s). What average bias error would be required to produce the error you saw at the velocity of your analysis? Discuss in groups and conduct the analysis manually.

Now consider the difference between bias and random noise. How would random noise on the acceleration measurement centered around zero impact the analysis?

Stage 3 — Determine and correct for bias, then integrate: acceleration → velocity → displacement (~20 minutes)

Compute the mean value of the acceleration over the stationary segment at the start of the ride. The mean value is your offset estimate for the linear acceleration data.

Instruct the AI to subtract the calculated offset from the whole acceleration record to create a corrected acceleration, then integrate the corrected acceleration to obtain velocity, and integrate again to obtain displacement. Plot the corrected acceleration and the calculated velocity and displacement on the same graph, using a secondary axis for displacement if needed to show scale.

Stage 4 — Validate (~20 minutes)

Confirm that the corrected velocity returns to 0 m/s when the elevator is known to be stationary and that the corrected round-trip displacement approaches 0 m. Compare the peak velocity and the one-way displacement against your own estimates, using any background information you can identify. Then ask the AI to refine the offset estimate so that the displacement remains constant to within 2 cm over the stationary segment at the end of the measurement, and to explain the general approach it used to do the refinement. Create a final graph of the acceleration, velocity, and displacement.

C. Peer Comparisons (~10 minutes)

Compare your peak velocity, total displacement, and offset magnitude against other students' measurements, looking for classmates who used the same elevator. Offsets differ from phone to phone because each accelerometer carries its own factory calibration residual, and because the sensor fusion that removes gravity from this channel leaves a small residual that depends on how the phone was oriented in the car. Share findings with the entire class.

D. Synthesize the Physics (~10 minutes)

Whole-class discussion returns to the core relationship. Velocity is the running integral of acceleration and displacement the running integral of velocity, so a systematic error in the measured quantity is amplified by each integration: as t in velocity, and as t^2 in displacement.

Reflect: Where Does It Break Down? (~10 minutes)

Write a short reflection on what the uncorrected and corrected displacement values showed you about the precision of raw sensor data, and on how small variations in a sensor bias might affect the use of accelerometers in different applications.

Deliverables — Session A

- Retain your conversation so you can build the post-lab report from it.
- **Submit your final graph of acceleration, velocity, and displacement from Stage 4 on the knowledgewithai.com website at the end of class.**

Part 3 — Post-Class Work

~1.75 hours

Post-class work lets you consolidate and summarize the in-class analysis. It also extends the investigation to elevator rides with different operating parameters, which is where you build on your understanding, your mathematical thinking, and your graphical analysis skills.

A. AI-Generated Report (~45 minutes)

Prompt the AI assistant for a short report describing the pipeline: how acceleration became velocity, how velocity became displacement, and where the offset correction entered. The report should include all the intermediate and final graphs that help tell the story of the analysis, and the three simulation records from B below as an appendix. Check the accuracy of every number and graph; the responsibility for validation is yours.

B. Extension Activity: Prediction Simulation (~60 minutes)

An AI was used to create a simulation for you to extend your understanding and build your problem-solving skills. Download [Elevator_Motion_Prediction_SimulationA.html](#) from the knowledgewithai.com website and open it in any web browser; no installation or account is needed. Each simulated ride is a single one-way trip: 3 s at rest, ease in, build speed, hold a cruise, ease out, then 3 s at rest. The controls are floors traveled, floor height, direction, cruise speed, maximum acceleration, jerk — the rate at which the acceleration itself changes — and sensor noise. Open the application, explore how it works and how changing the parameters changes the motion graphs. If you reveal the graphs and then move the slider bars, you can see how each variable changes the motion graphs.

The application is designed to allow you to save your sketch and then reveal the simulated graphs. Each export is a single PDF carrying the ride settings, the locked prediction sketch, and the

revealed curves. The ride report at the end of the file is written only when the graphs have been revealed, so reveal before exporting. Include three exported records in the appendix of the report from A above. Export the PDF immediately after revealing, before you move any slider: moving a slider after the reveal clears your sketch.

Record 1 — Prediction of User Defined Elevator Ride (~20 minutes)

Set the parameters for a ride, click “Sketch my prediction,” and sketch the predicted curves on the locked axes of both tabs (Acceleration & Jerk; Velocity & Displacement). Then reveal and export. The sketch tool locks at the moment of reveal, so the sketch in the exported PDF is the one you committed to beforehand.

Record 2 — Prediction of Random Elevator Ride (~20 minutes)

Use “New Random Conditions” to create a new ride. Carefully sketch your predictions on both tabs before revealing the graphs. Export your PDF immediately after revealing, before moving any slider.

Record 3 — Match your own ride (~20 minutes)

Set the controls so the simulation reproduces the elevator ride you measured and analyzed in class, then export the third record. The simulation models a one-way trip, so match the upward leg of your ride and set Direction to Up. Adjust the settings to reproduce the graphs from your analysis:

- **Floors traveled.** Counted during the ride.
- **Average floor height.** The one-way displacement from your Session A analysis divided by the number of floors.
- **Cruise speed.** The height of the flat stretch in the corrected velocity curve.
- **Maximum acceleration.** The height of the acceleration plateau, read off the corrected acceleration trace.
- **Jerk.** The plateau height divided by the time the trace takes to climb from zero to it, which is the slope of the acceleration during the ease-in.
- **Sensor noise.** Roughly the standard deviation of your acceleration during the stationary segment before the ride (ask the AI to compute it).

Set the Accelerometer reading toggle to “Gravity removed” so the simulated trace sits on the same footing as the linear acceleration channel you analyzed in Session A. Compare the simulated curves against your measured ones and account for the differences.

Deliverables — Post-class Session A

Nothing is submitted after Session A. Keep your report, with the three simulation PDF records in its appendix. After Session B you will extend this report and submit the combined version.

Session B — Alternative Measurement Modality using Pressure Sensor (~5 hours)

Session B starts by analyzing the “acceleration (with g)” time series data using the workflow you developed in Session A. That serves as verification and reinforces the analysis method. You then use your barometric sensor data to calculate the change in altitude and the maximum velocity of the elevator. Converting a pressure change into an altitude change first requires determining the relationship between the two variables at your location. In addition, you will develop an experimental design that uses a second phone as a control to correct for small changes in the background pressure that occur within your measurement period.

Part 1 — Pre-Class Preparation

~1 hour

The pre-class work gives you the basic physics and nomenclature of pressure, and leads you through a discussion of how controls are used in experimental design.

A. Socratic AI Tutoring Session B (~25 minutes)

When conducting the prelab tutor, use the Scientific Inquiry with AI business account and open the prelab tutor for Session B by clicking the “Open the custom GPT” button in the prelab section on the [knowledgewithai.com](https://www.knowledgewithai.com) website. This will launch you automatically into a tutoring session in ChatGPT. Confirm you are in “Chat” mode and not “Work”. These steps will ensure the best tutoring experience and will automatically record the completion of the tutoring session.

The tutor is focused on helping you learn four topics:

- Using control measurements in experimental design (~12 minutes), opening with everyday examples and narrowing to a pressure measurement: a single-phone measurement at two elevations drifts with the background pressure of the room, while a two-phone measurement holds one phone at a fixed reference elevation as the second moves.
- Pressure as a physical quantity: what it measures, the units used to report it, and the magnitude of the force the atmosphere exerts on a person.
- The hydrostatic relation $dP/dh = -\rho g$ and the conversion constant it supplies.
- The barometric channel as an independent check on an accelerometer displacement estimate.

If you would like to review the key information later, ask the AI to prepare a one-page summary of the session.

B. Estimation of Displacement using Pressure (~25 minutes)

Make a rough measurement of how pressure changes with elevation, using the Pressure tool in Phyphox (under Raw Sensors): hold the phone still on the floor for about 10 s and record a typical value of the pressure, then hold it still at a height of about 2 m for another 10 s and record a typical

value again. Use the difference to determine the relationship in Pa/m. Then, using your own measured value, answer this question: given the displacement you measured in Session A from acceleration, what pressure change would you expect to find in the data you recorded during your elevator ride? Be prepared to show that calculation at the start of class — don't worry about the accuracy at this point, just the concept. You will make a far more accurate measurement of this relationship in class.

C. Review of In-Class Investigation (~10 minutes)

Review the investigation you will conduct in class. Try to identify a partner whose phone has a data collection rate similar to yours. If your team has two different data collection rates, you can still work together but will need to get help from your AI assistant to create evenly spaced data for analysis. Bring the .zip data file from your Session A elevator ride; its barometer record is analyzed in class.

Part 2 — In-Class Investigation

110 min

You start by analyzing the acceleration (with g) versus time data using the workflow you established in Session A. You then work in pairs to determine the hydrostatic relationship using an experimental design with a control measurement. That relationship converts your pressure versus time data into displacement versus time. You fit the slope of the displacement graph during the constant-velocity cruise to determine velocity, and finally compare the displacement and velocity obtained from the two different physical measurements.

A. Activation (~15 minutes)

- Your instructor sets conditions using the Elevator_Motion_Prediction_SimulationA.html, and the class commits on whiteboards to how the acceleration, velocity, and displacement curves will change before the reveal.
- Students share the results of their pre-class measurement of the hydrostatic relationship.
- Instructor leads an investigation of how data sampling rates can limit experimental investigations.

B. Co-Investigation with AI (~75 minutes)

The investigation runs in four stages.

Stage 1 — Acceleration (with g) cross-check (~20 minutes)

Use the Session A workflow on the acceleration (with g) channel. This channel reports proper acceleration, so a stationary phone with one axis vertical reads about 9.8 m/s^2 on that axis rather than zero. Use the workflow you developed in Session A to correct for the acceleration offset, determine velocity and displacement, and create a motion graph which includes all three variables. Compare the maximum velocity and total displacement you obtain against your linear acceleration results from Session A, and account for any difference.

Stage 2 — Measure without a control (~15 minutes)

Working in pairs with a single phone, measure the pressure at two elevations, using the largest height difference you can measure accurately to ± 1 cm. Repeat the pair of readings 2 minutes later. Share results with the class on whiteboards and discuss the origin of the variation.

Stage 3 — Add the control (~25 minutes)

Repeat the same two-elevation measurement using two phones logging pressure at the same time. One phone stays at a fixed reference elevation for the whole measurement while the second is moved to the target elevation; repeat this several times within the same experimental data set so you have multiple measurements to work with. (Consider what happens if you do not start the phones together.) Describe your experiment to an AI and determine the best way to calculate the change in pressure per meter using your full data sets from the two phones. Once you decide on a method, ask the AI to perform the analysis and provide a graphic illustrating the results of the analysis. Be prepared to share your method with the class. Compare values across the class on whiteboards (report in Pa/m).

Stage 4 — Apply the measured constant to the elevator ride (~15 minutes)

Use AI to create a pressure vs time graph for your barometer data collected during the elevator ride. Convert the pressure-against-time data into altitude using the constant you measured in Stage 3. Does your height reach a plateau at the end of the ride? How does it compare to the height you determined from your acceleration data? Determine velocity from the slope of the altitude trace during the constant-velocity cruise phase. Create graphs showing the fits and the slope values.

C. Critique and Reflect (~20 minutes)

- Use AI to create a comparison table showing the height and maximum velocity for all three data sets. Write a short discussion comparing them and say why you might have more trust in any one of them where they differ.
- Using your own numbers: how much did adding the control change the spread in your measurement, and what physical quantity did it remove?
- In most science classes a control means holding a variable constant. Background pressure is not something you can hold constant. Explain what your control did instead, and why that works.
- Name a measurement where this approach would fail — where a second, simultaneous reference would not remove the disturbance — and say what makes it fail.

Deliverables — Session B

- Retain your AI conversation for the construction of the post-lab report.
- **Submit the comparison table for all three data sets on the knowledgewithai.com website at the end of class.**

Part 3 — Post-Class Work

~2.25 hours

Post-class work audits the cross-validation, extends the investigation of correcting for offset bias using a simulation, and connects the pressure-altitude relationship to a system deployed commercially.

A. AI-Generated Report (~60 minutes)

Combine the results from Session B into the report you created for Session A by prompting the AI assistant to merge them. Check all the information for correctness — nothing should be in the report that you did not read and verify. Include key graphs, your calculation of the hydrostatic relationship, and the final table comparing the results for all three methods. Include your assessment of the three methods, what you trust, and what might have caused differences if they exist. Write that final summary yourself rather than generating it with AI.

B. Extension Activity: Postlab Simulation (~20 minutes)

Download `Elevator_Bias_and_Motion_SimulationB.html` from the `knowledgewithai.com` website and open it in any web browser. This simulation is different from the simulation tool you used after Session A. Every generated ride carries a new random sensor offset that stays hidden until it is revealed, so you locate it the same way you did with your own recording in Session A. Generate a ride, enter your offset guess, and then reveal the true bias. Add two screenshots to your report as an appendix: (1) the Correct the Bias tab showing your offset guess and the revealed true bias, and (2) the Error Propagation tab showing how a leftover offset error grows in velocity and displacement.

C. NextNav Technology and Business Evaluation (~30 minutes)

Research the Pinnacle barometric vertical-location service operated by NextNav, which determines which floor of a building a 911 caller is on using the pressure-altitude relationship from this lesson. The Federal Communications Commission requires wireless carriers to deliver vertical location within ± 3 m for 80% of qualifying calls, and Pinnacle meets that requirement through a network of fixed reference stations that model local pressure conditions — the Stage 3 control measurement operated at metropolitan scale. Consider: how might pressure-based altitude measurement be useful in emergency response, and what does that suggest about the value of the NextNav technology and business model? You may use AI to help assemble the analysis, and you are encouraged to draw on academic literature. Be prepared to speak to your conclusions in the next class session.

D. Retrieval Practice / Course Review (~30 minutes)

Spend approximately 30 minutes on integrated course review using the customized AI-enhanced retrieval tool, which supports spaced repetition and interleaving across the full course. Items drawn from this lesson review both sessions and cover integration, offset correction, control measurements, and cross-validation.

Deliverables — Post-class Session B

The bold items should be submitted using the knowledgewithai.com website.

- **Combined Session A and B report described above in Part 3A, with the Simulation B screenshots from Part 3B in its appendix.**
- Notes on NextNav technology to discuss in class.
- **Retrieval Tool Practice**

Appendix A — Reference Measurements

Table A1. Reference measurements that can serve as sanity checks on magnitude and process. Every building, elevator, and phone placement produces different results, and your values will differ.

Session	Quantity	Reference value
A	Ride configuration	5-floor round trip
A	Peak velocity	≈ 1.83 m/s upward; ≈ -1.83 m/s downward
A	Uncorrected round-trip displacement	≈ 17.86 m (true value 0 m)
A	Offset refinement	$\approx 5 \times 10^{-4}$ m/s ² change to the first-pass offset estimate from the stationary segment
A	One-way displacement after refinement	≈ 17.91 m one way, not verified against an independent measurement of the floor-to-floor distance; residual round-trip displacement under 2 cm
B	Uncontrolled pressure measurement	Single phone, $\Delta h = 1.716$ m, read at two different times: 20.6 Pa and 21.4 Pa
B	Controlled pressure measurement	Same $\Delta h = 1.716$ m with a fixed control phone: a repeatable 19.0 Pa (≈ 11.1 Pa/m)
B	Larger-scale control example	Corrected precision improved by roughly 20 $\times$ (0.389 hPa uncorrected vs. 0.018 hPa corrected)
B	Acceleration (with g) cross-check	Consistent with the linear acceleration result to within a percent
B	Barometric velocity (self-measured constant ≈ 11.1 Pa/m)	≈ 1.79 m/s upward; ≈ -1.77 m/s downward, consistent with the accelerometer values