

Describing Motion with GPS

From a Straight Walk to a Two-Dimensional Campus Route

Scientific Inquiry with AI

Student Guide

Detailed Instructions & Course Material

Why This Lesson

A map can show you where you are, but a sequence of locations can tell a much richer story: how far you traveled, which way you moved, when you stopped, and how your pace changed. Those descriptions are related, but they are not interchangeable. You can walk a long way and still finish exactly where you started.

In this investigation, you will use GPS to measure your position while you walk and characterize your motion using terms such as distance, displacement, speed, and velocity that have specific meanings in physics. You will start with characterizing a straight out-and-back walk as you learn to use AI to translate the geographical coordinates provided by a GPS to the relative change in your position in meters and direction. You will then use AI to help build an application that simulates a two-dimensional campus route, make predictions, walk the route, analyze your data, and then compare the results of your simulation with your experiment. Satellite imagery will help you choose visible landmarks and connect the numerical coordinates to real places.

This lesson builds on the uncertainty lesson and your earlier HTML simulation work. Keep asking what the sensor reports, what the calculation assumes, and what observations allow you to test the model and sensor performance.

Your role is to decide what to measure, predict the patterns, and evaluate the evidence. AI can help write code, convert coordinates, and make graphs. You remain responsible for checking whether the application works as you specified and how accurately the model output describes your walk.

Learning Goals

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

Phenomena:

- Explain how GPS uses signals from multiple satellites to determine position and some of the physical limitations that contribute to the uncertainty of the measurement.
- Interpret latitude and longitude and describe the process for converting small coordinate changes to local distances.
- Distinguish distance, displacement, speed, and velocity in one and two dimensions.

Experimental Practices:

- Collect and export timestamped location data using a GPS sensor in a smartphone.
- Describe how data collection rates impact and limit different applications.
- Use AI to convert latitude and longitude measurements into position vs time graphs, and use graphs and numerical analysis to determine distance, displacement, velocity, and speed.

Habits of Mind:

- Record predictions before seeing the result; explain agreement or differences using evidence.
- Use analysis results and graphs to distinguish between a coding error, an imperfect model, an experimental artifact such as a variation in walking speed, and the uncertainty of the GPS coordinates measurement. State what your evidence can and cannot distinguish.

What You Will Need

- A charged smartphone with the phyphox app (Location/GPS sensor).
- A laptop with a browser and an AI assistant.
- This guide, GPS_Motion_Prelab_Tutor.docx, and your lab notebook.
- The supplemental files: Latitude_Longitude_Illustrated_Reading.pdf, Latitude_Longitude_Worksheet.pdf, GPS_Geographic_Coordinate_Learning_Tool.html, and GPS_Navigator_and_Path_Reader_Simulation.html.

The Core Idea

- GPS provides estimated positions in geographic coordinates. Time-stamped positions let you infer motion, but the uncertainty in the position measurements limits the accuracy and precision of the calculated motion.
- Distance adds the lengths of successive traveled segments and is a scalar quantity. Displacement compares the final and initial positions and includes direction, making it a vector quantity.
- Average speed is the distance divided by elapsed time and is a scalar quantity. Average velocity is displacement divided by the same elapsed time and is a vector quantity.
- Simulations can be a powerful tool for mapping out routes. AI provides the ability to build customized mapping tools but the tools require careful testing and validation.

Driving question. How well can a simple waypoint-and-speed model predict a campus walk, and which disagreements come from the walk, the model, or the location measurements?

Your Time Plan

When	Time	Main task
Before class 1	120 min	Build the foundation and verify your recording setup
Class 1	110 min	Measure and analyze a straight out-and-back walk
Between classes	60 min	Build, test, and save your 2D simulation
Class 2	110 min	Walk the campus route and evaluate the model
After class 2	60 min	Audit the report and complete retrieval practice

Part 1 — Pre-Class Preparation

~2 hours

Allow about two hours. Work individually; discussion is welcome, but write predictions and explanations in your own words. The prelab preparation includes learning the physics/engineering that allows GPS to determine location, exploring geographic coordinates, and learning how to characterize motion from position vs time data. Don't worry if these topics sound unfamiliar to you, the goal of the prelab is to help you learn about them.

A. How Your Phone Finds Its Position (~15 minutes)

Explore how GPS works using the link below which includes a short description with interactive graphics. Focus on the measurement idea. The description also includes the impact of relativity for those who want to understand the next level of the technology.

[How Does GPS Work?](#)

A quick summary: Satellites broadcast microwave radio signals containing timing and orbital information. Your receiver uses the signal travel times and the satellites' known positions to estimate its location. A standard unconstrained solution uses at least four satellites to solve for three position coordinates and the receiver's clock offset.

In your notebooks, draw a simple sketch with several satellites and your phone. Label what travels to the phone and explain why timing matters. Then write one reason a location estimate might be imperfect.

B. Read Coordinates and Convert Small Changes (~30 minutes)

Read pages 1–4 of [Latitude_Longitude_Illustrated_Reading.pdf](#). Pages 5–6 go deeper into the topic if you are interested in more than we cover in the rest of the lesson.

After completing the reading, upload [Latitude_Longitude_Worksheet.pdf](#) to your AI along with the starter question at the front of the worksheet. The AI will guide you through a series of questions to solidify your understanding of geographic coordinates.

C. Move, Predict, and Explain (~20 minutes)

Read the short explanation of scalar and vector quantities below, then work through the three activities that follow it. Commit to your answers before opening the self-check in Appendix B. You are practicing an explanation, not racing to a correct number.

Four Words Physics Uses Carefully (~5 minutes)

Everyday speech treats distance and displacement as well as speed and velocity as near synonyms. Physics does not. The difference between them comes down to one question: is direction part of the answer? A **scalar** quantity is completely described by a number and a unit, such as 7 m, 20 s, or 0.7 m/s. A **vector** quantity is not complete until you also give a direction, such as 5 m at 53° north of east. Reporting a vector without its direction is like telling someone to walk 5 m without telling them which way to face.

Distance and displacement both sound like answers to “how far,” but they answer different versions of that question. Distance is how much ground you covered: add up the length of every segment you actually walked. Displacement is how much your position changed: final position minus initial position, with no attention to the route between them. Walk a loop back to your starting point and you have covered real distance while your displacement is zero.

Speed and velocity have a similar relationship. Average speed is distance divided by elapsed time, so it is a scalar. Average velocity is displacement divided by elapsed time, so it is a vector, and its direction points from where you started toward where you finished — a direction you may never have actually faced during the trip. Because the two use different numerators, average speed is generally not the magnitude of average velocity. They agree only when the motion stays in a straight line without reversing.

Quantity	Scalar or vector	What it tells you
Distance	Scalar	The total length of the path you actually traveled. It is never negative, and it never decreases while you keep moving.
Displacement	Vector	Final position minus initial position. It depends only on the endpoints, so it is zero for any trip that returns to its starting point.
Average speed	Scalar	Distance divided by elapsed time. How quickly you covered ground.
Average velocity	Vector	Displacement divided by elapsed time. How quickly your position changed, and in which direction.

Appendix A lists the matching calculations in east and north components.

Throughout this lesson you will write vectors as a pair of components measured from a local origin that you choose: one east number and one north number, calculated from your GPS coordinates. A negative east component means west, and a negative north component means south. When a question asks for displacement or velocity, a complete answer gives both components, or a magnitude together with a direction. When a question asks for distance or speed, one number with a unit is complete.

The Outward and Return Journey (~7 minutes)

An ideal walker goes 3 m east from A to B, then 4 m north to C. The outward trip takes 10 s in total. The walker returns along the same two legs in another 10 s. Ignore GPS error for this example.

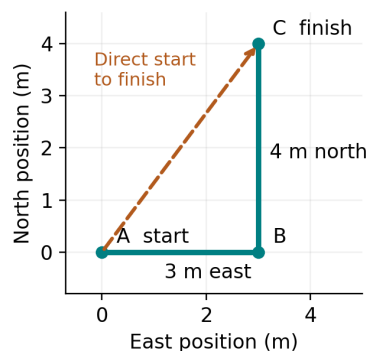


Figure 1. Equal-scale map of the two-leg outward route, with the direct start-to-finish arrow shown dashed.

Before checking: predict the distance and displacement for the outward trip, then calculate its average speed and average velocity. A direction or signed components must accompany velocity. Repeat for the complete 20 s trip. If you need a hint for the direct separation, sketch a right triangle and use $3^2 + 4^2 = 5^2$.

Graph Matching (~7 minutes)

Match each story with its east-position graph and a possible cumulative-distance graph. Explain your choices. A graph can match more than one story; one graph is impossible for cumulative distance.

Story 1: walk 3 m east in 3 s, pause for 2 s, then walk 3 m farther east in 3 s. Story 2: walk 3 m east in 3 s, pause for 2 s, then return to the start in 3 s.

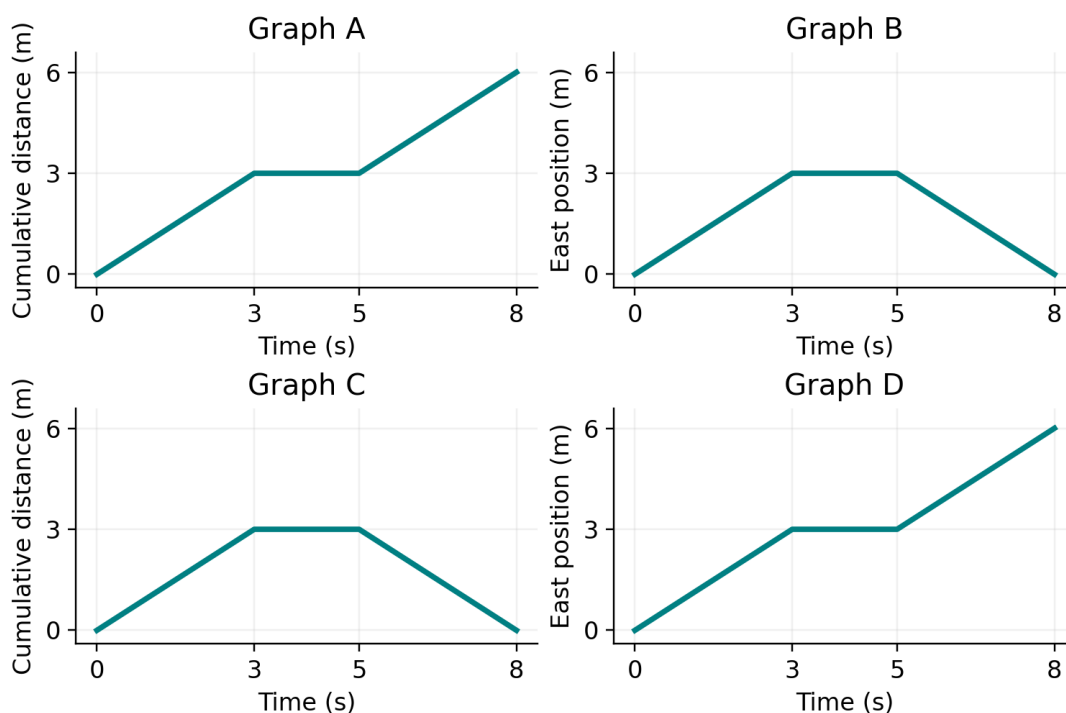


Figure 2. Four candidate time graphs. Two show cumulative distance and two show east position.

D. Socratic AI Tutoring Session (~35 minutes)

Upload GPS_Motion_Prelab_Tutor.docx to a new AI conversation. Include the prompt: “Use this document to guide my prelab conversation. Start with the opening question and wait for my response.” Answer honestly and explain your reasoning; ask questions or challenge an explanation when needed.

The tutor adapts the discussion to your needs and ends with a conceptual roadmap, an engagement score, and a chat-history JSON summary. The engagement score is practice feedback, not a course grade. Save the full conversation and the summary. Upload the JSON file to the knowledgewithai website. Bring unresolved questions to class.

E. Read a Path and Explore a Satellite Map (~15 minutes)

Open GPS_Geographic_Coordinate_Learning_Tool.html. Complete two 2-waypoint problems, one 3-waypoint problem, and one 4-waypoint problem.

Open GPS_Navigator_and_Path_Reader_Simulation.html. Locate UC Merced and identify three visible outdoor landmarks. Select the manual waypoint tab and then map a three-point route along accessible paths (see the example in Figure 3). Compare its traveled path (distance) with the direct start-to-finish arrow (displacement).

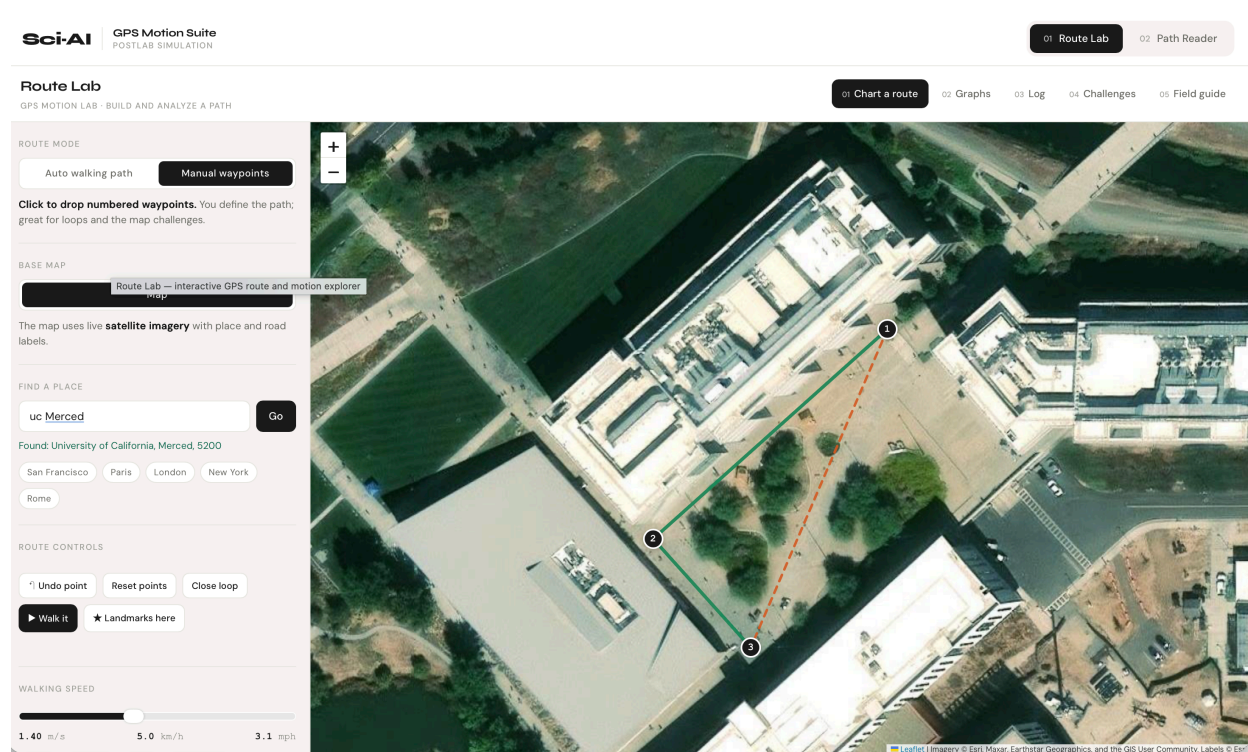


Figure 3. Example three-waypoint route traced on the satellite map in the GPS Navigator and Path Reader simulation.

Explore the features of this tool. You will build your own version of a route mapping tool later in the lesson.

F. Review of In-Class Investigation (~5 minutes)

Skim both class sessions and the between-class build. Write one decision you expect to make about your route and one about the analysis. Confirm that you can find your files and reopen the supplied HTML tools.

Part 2 — In-Class Investigation

~4.75 hours

The Investigation, Stage by Stage

The investigation runs across two class sessions. During the first class period you investigate a simple motion pattern where you will assess GPS measurement capabilities and develop an approach to use AI to conduct the analysis. Between classes you build a GPS simulation application that allows you to choose a path and produce graphs of latitude and longitude as well as a full suite of motion graphs (displacement, distance, velocity, and speed vs time). In class, you will test the results of your simulation against a real campus walk. The stages below orient the decisions you need to make and the evidence you should keep; your instructor sets the live pacing and may adjust the order.

Class One — A Straight Out-and-Back Walk (110 minutes)

In this session you will walk out and back along a straight path. You will predict, measure, analyze, and compare. Each individual will make their own measurements and conduct their own analysis.

Stage 1 — Predict (10 minutes)

Explain distance versus displacement to a partner. Predict graphs for a straight out-and-back walk from point A to point B and back to point A with pauses at each position. Create separate graphs in your notebooks for latitude, longitude, distance, displacement, speed, and velocity vs time.

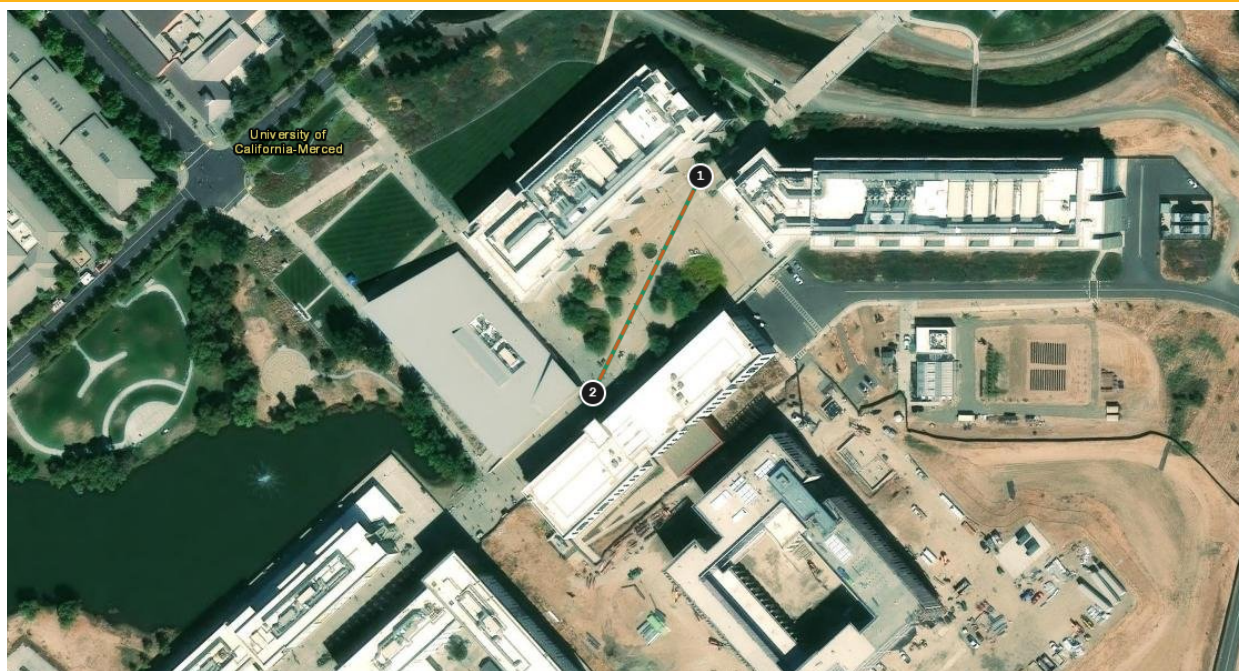


Figure 4. Example straight out-and-back route between two well-defined campus landmarks.

Stage 2 — Plan and Record Your Walk (25 minutes)

Plan the walk: Choose well-defined locations for Point A and Point B. You want to know where you started and stopped within one meter. Use pauses of approximately 20 s stationary at A initially, a steady walk to B, approximately 10 s stationary at B, a walk back to A at a noticeably different comfortable and constant pace, and approximately 10 s stationary at A before stopping data collection. The pauses will be very useful as you visualize and interpret your data. Start and finish your walk as close to the original position as possible – this will allow you to keep the uncertainty of your actual walk small compared to the precision of the GPS measurement. Walk a straight path and walk a route as close as possible to that of others in the class – this will allow a comparison of your distance measurement to your classmates.

Collect the data: **Turn off the Wi-Fi on your phone before conducting this measurement.** This will ensure that only the GPS signals are used for determining your position. Smartphones often use Wi-Fi to help in determining location. Use the location sensor in phyphox to collect data while conducting your planned walk. Capture screen shots of your latitude and longitude data and export your data file as a .csv file.

Stage 3 — Confirm Your Data and Trim the File Before Analysis (10 minutes)

Before conducting any analysis, it is important to verify your file has been successfully exported and uploaded to the AI. However, you need to make one small adjustment to your data before graphing and analysis. The first 5–10 seconds of a phone's GPS record are often inaccurate, and you will want to use AI to remove the first 10 seconds from the file. You collected 20 seconds at the beginning of your experiment to account for this issue. Once you have made this modification, prompt the AI to graph the latitude and longitude versus time and confirm the data matches what you observed in phyphox.

phyphox automated analysis is not reliable: The exported file will include additional data columns where it has conducted analysis of the various motion parameters. These calculations will include the initial latitude and longitude measurements that may not have been accurate. We will ignore those calculations and perform our own analysis after removing the initial data points.

Stage 4 — Convert Positions and Describe Motion (35 minutes)

Direct AI to convert geographical coordinates into distance and displacement and then graph both on the same graph vs time.

Use AI to estimate the velocity on a steady part of each walking leg by fitting a line to the displacement versus time graph. Have the AI graph the fits and highlight the times where the fits were computed. Report the fitted interval and slope in m/s.

Calculate the instantaneous velocity and speed. Plot each separately vs time. Explain why the data is noisy. Is the average value consistent with the velocity you calculated from the slope? Ask the AI to compare the two approaches (average of instantaneous velocity vs slope) and recommend the most accurate method.

Stage 5 — Audit the Results and Examine Uncertainty (20 minutes)

Calculate the displacement between points A and B manually using the method and conversion factors you used in the prelab to verify the AI analysis.

Compare the distance and displacement between point A and point B. Are they the same? If you walked a straight line, would you expect them to be the same?

The distance traveled at any point in time is calculated by cumulatively adding up the distance traveled between each successive location. Describe how the uncertainty of the location measurement could be responsible for the difference between distance and displacement that was calculated by the AI. Work with the AI to determine possible approaches to correct for this error and implement the correction.

Reflect on the First Investigation (10 minutes)

Which result was most affected by GPS scatter: endpoint displacement, accumulated distance, or short-interval speed? What evidence supports your answer?

Between Classes — Build and Verify Your Simulation (60 minutes)

Use your experience creating simulations and using the GPS Navigator (from the prelab) as a foundation to build your own GPS simulator.

Develop the Specification for Your Simulation

Write a specification for a simulation that lets you trace a walking route on a satellite map. Your specification should describe:

- how the route gets defined (clicking waypoints, entering coordinates, etc.)
- which variables you want to control (walking speed, etc.)
- any additional features worth including, such as location search, route editing, animated playback, ability to include pause points, or create a trip summary

The simulation should output graphs of latitude, longitude, distance, and displacement versus time. You should also specify that all the information be exported in a .csv file that can be used for comparison to experimental data. During the next class you'll collect your own GPS data and compare it to these results.

Be creative and make your simulation both fun to use and physically accurate.

Check Two Different Things

Check	Evidence you should save
Does it run	Reopen the HTML; test buttons, reset, imagery, plots, and export.
Are calculations correct	Verify a known-answer case independently, including a pause and turn. Compare displayed and exported values.

Class Two — The Campus Route Test (110 minutes)

This session tests your saved prediction against a real campus walk. Agree on a shared plan while retaining each person's explanation and audit record.

Stage 1 — Peer Review the Application (20 minutes)

Exchange applications with a partner. Test each other's code operationally and provide suggestions for improvements. Code owners should then make any changes they determine are desired.

Stage 2 — Plan and Walk a Campus Route (25 minutes)

Plan a route on the satellite map and choose recognizable, accessible waypoints. The route should be at least 200 m but can be longer if you desire. Walk the route and take note of any modifications

from the planned route. Attempt to walk the entire route at a constant pace throughout and only pause if that was part of the plan and the simulation allows you to include pauses.

Stage 3 — Compare Predicted and Measured Motion (30 minutes)

Export the data from your experimental walk and analyze your data in a similar way you did in your straight line walk. Create graphs of latitude, longitude, distance, and displacement. Fit the displacement data over several intervals to determine average speeds.

Map out your actual walk using your simulation and include your average walking speed. Run the simulation on the route and generate the graphs for comparison.

Determine the best approach for comparing your experimental and simulated data.

Stage 4 — Investigate a Disagreement (25 minutes)

Evaluate the differences between the experimental and the simulated data. Consider walking pace, path changes, rounded turns, pause timing, location scatter, map placement, or a coding error.

Make any adjustments in the simulation that you believe might have caused the mismatch and rerun the simulation. Discuss the effectiveness of those changes.

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

Discuss, then answer individually: What additional measurements would you like to make to verify the accuracy of the experimental analysis? What changes would you make in the simulation to improve your ability to match the experimental data?

Part 3 — Post-Class Work

~1 hour

A. Generate and Audit Your Report (~30 minutes)

Assemble a concise report from your existing notes and figures, about two to three pages plus selected figures. AI may help draft it; audit every number, unit, caption, and claim. Include:

- Your question, route, equipment, sampling intervals, event timing, and model assumptions.
- The analysis of your experimental data
- The results of your simulation
- A comparison of the experimental data and the simulation with a discussion of the basis for any disagreement.
- A short individual reflection on the accuracy of both approaches and a discussion of how you would validate the results if you had more time.

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

Use the course retrieval tool, or ask AI for one question at a time mixing this lesson with the uncertainty and simulation lessons. Answer from memory before receiving feedback. Revisit

coordinate signs, the four motion quantities, noise, sampling, independent checks, and verification versus validation. Save brief review notes.

Everything You Turn In

Before class one

- Tutor chat and JSON summary

After class two

- Final HTML Simulation
- Audited report with reflections
- Retrieval tool practice

Appendix A — Calculation Reference for Local Motion

Use these relationships to direct and audit an analysis. Angles in the two local conversion equations are in degrees; distances are in meters. Choose a local origin with latitude ϕ_0 and longitude λ_0 . Near Merced:

$$\text{north} \approx 111000 \times (\text{latitude} - \phi_0)$$

$$\text{east} \approx 88500 \times (\text{longitude} - \lambda_0)$$

These rounded factors are adequate for this campus-scale lesson. The optional appendix in the illustrated reading derives them from circle geometry and the small-angle approximation. Long journeys require spherical great-circle or ellipsoidal geodesic methods. Ignore elevation for this approximately level horizontal-motion investigation.

Quantity	How to calculate it	Meaning and units
Displacement	Final position minus initial position	Vector: east and north components, in m
Displacement magnitude	Square root of $\Delta\text{east}^2 + \Delta\text{north}^2$	Direct endpoint separation, in m
Recorded path distance	Sum of the lengths between successive recorded positions	Nonnegative scalar, in m; affected by sampling and noise
Average velocity	Displacement components divided by elapsed time	Vector components, in m/s
Average speed	Path distance divided by elapsed time	Nonnegative scalar, in m/s

For a short interval between two samples, divide each position change by the actual timestamp difference. The resulting vector is an interval-average velocity; its magnitude is a short-interval speed estimate. It is not an exact instantaneous velocity. A phone-provided speed column may use a different method, so label it separately if you compare it.

For the straight walk, let $\mathbf{u}$ be a unit vector from A toward B. Signed position is $q = \text{east} \times u_e + \text{north} \times u_n$. The slope of q versus time estimates signed velocity along that line. In 2D, fit east and north separately over the same straight, steady interval to obtain two velocity components.

A Small Independent Check

An ideal object has these positions: at 0 s, (0, 0) m; at 3 s, (3, 0) m; at 7 s, (3, 4) m; at 12 s, (0, 0) m. It moves straight between points. Segment lengths are 3, 4, and 5 m, so distance is 12 m. Final displacement is (0, 0) m. Average speed is 1 m/s and average velocity is (0, 0) m/s. The return-leg velocity is (-0.6, -0.8) m/s, whose magnitude is 1 m/s.

Checks do not prove everything. Passing these arithmetic relationships would not reveal an incorrect timestamp column, a shifted satellite map, or a logger that missed part of the walk. Combine numerical checks with raw plots and observation notes.

Appendix B — Prelab Self-Check

Use this page only after recording your own answers to the motion activity in Part 1C. If your answer changes, keep the original and add one sentence explaining the revision.

The Outward and Return Journey

Outward A to B to C: distance = 3 + 4 = 7 m. Displacement = (3 m east, 4 m north), with magnitude 5 m and direction about 53° north of east. Over 10 s, average speed = 0.7 m/s and average velocity = (0.3 m/s east, 0.4 m/s north), with magnitude 0.5 m/s. The average velocity points directly from A to C; it does not trace the path.

The full out-and-back trip follows the same two legs in reverse. Distance = 14 m in 20 s, so average speed = 0.7 m/s. Displacement and average velocity are zero. Zero average velocity does not mean the walker stood still during the trip.

Graph Matching

Story 1 matches east-position graph D and cumulative-distance graph A. Story 2 matches east-position graph B and also cumulative-distance graph A. Both journeys cover the same distance at the same rates and pause at the same time, but their endpoint positions differ. Graph C cannot describe cumulative distance because it decreases. A pause produces a flat section in both distance and position.

At a corner, velocity changes even if speed stays constant because velocity includes direction. At an ideal instantaneous corner in a piecewise straight simulation, there is no single velocity at the exact turning instant; use the incoming and outgoing legs. A real walker changes direction over a finite time.