Inclined planes using the TiltTray

and

smartphone accelerometers

INTRODUCTION:

How does your smartphone know when to transition from landscape to portrait mode?

The critical tilt angle of a cell phone is the angle at which the display switches from portrait to landscape mode in viewing pictures, or for texting with more thumb space. To monitor the tilt angle, cell phones rely on internal accelerometer sensors. There are three such sensors in any phone, aligned along each of the three axes corresponding to the three spatial dimensions.

Accelerometers measure accelerations caused by motion as well as effects due to gravitational forces. When a cell phone lies *immobile* on a horizontal surface, the accelerometer only detects the effects due to gravity, which are aligned exactly along one of the three axes. If the phone is held in a *tilted* position, none of the phone axes are aligned with the gravitational acceleration vector: each axis measures only a <u>component</u> of that vector. By carefully examining these components you (and the code running on your phone) can deduce the exact orientation (tilt angle) of your phone.

DOCUMENTS:

- To do <u>BEFORE</u> the lab period:
    - *"App instructions":* installation and configuration
        - only "*basic usage*" section needed for this lab
    - Theory: *"Understanding accelerometers"*
- To do <u>DURING</u> the lab period:
    - Preparatory activity: "*discovering your smartphone's coordinate system"*
    - In this document:
        - Introduction
        - Lab procedure
        - Additional investigations (optional)
        - Follow-up questions

PROCEDURE:

Part A: Determine your phone's local coordinate system

Start by reading "Understanding accelerometers" and then carry out the preparatory activity. This will guide you in correctly identifying and labelling the unique x-y-z coordinate system for your phone. Have your teacher verify those results before continuing with the procedure here.

Part B: Examine the apparatus

The apparatus you will use with your cell phone is depicted in the picture below. It consists of a base with protractor, and a movable tray, also with a protractor and a plumb line. When raising or lowering the tray, the tilt angle is indicated on the base protractor by the needle.

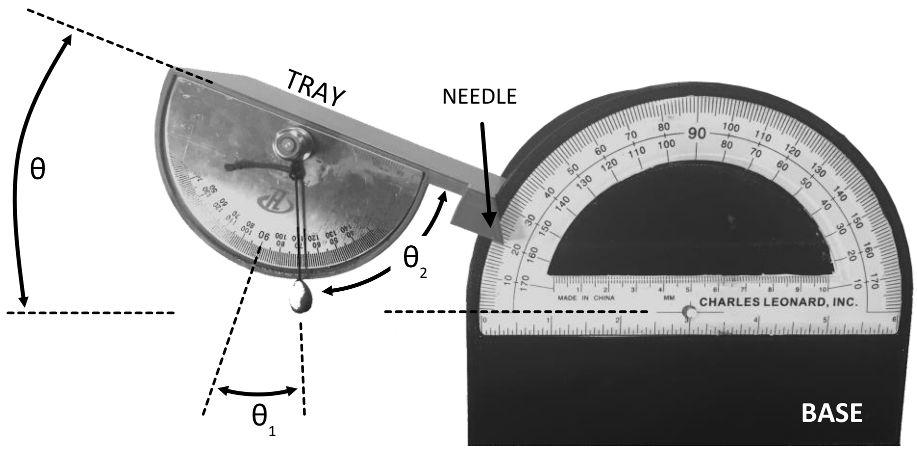


Figure 1

Start by raising the tray to an angle of $\theta = 20\,°$, as indicated by the needle. **Do not** place your phone on the tray yet; we are just examining the geometry of the apparatus itself.

Now examine the angle the plumb line makes with respect to the 90-degree line (θ_1). What angle does the string make with respect to the tray surface (θ_2)? Discuss how these relate to one another.

Part C: Components of gravity in smartphone coordinates - **theoretical analysis**

Make and model of phone: ________________

1. Below is left-side view of a smartphone sitting on the TiltTray surface. Referring to your work in "*Discovering Smartphone Coordinates*", label all 4 arrowheads with the correct axis label, using one of "+x", "-x", "+y", "-y", "+z" or "-z".

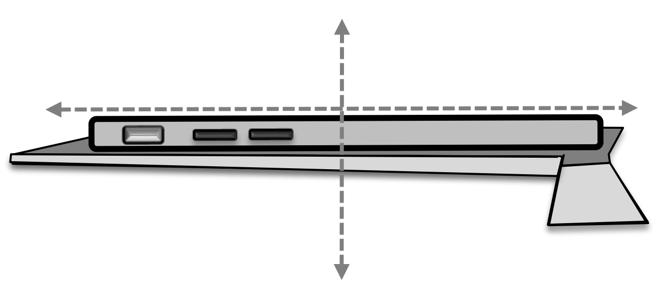


Figure 3

2. Depicted is the phone at angles of 10°, 75 ° and 0 °. The gravitational acceleration vector (magnitude of 9.81 m/s²) points straight down in all cases, but from the point of view internal to the smartphone, the components along its axes change each time. Draw the components along their respective axes, labelling them with the appropriate choice of g_x, g_y or g_z .

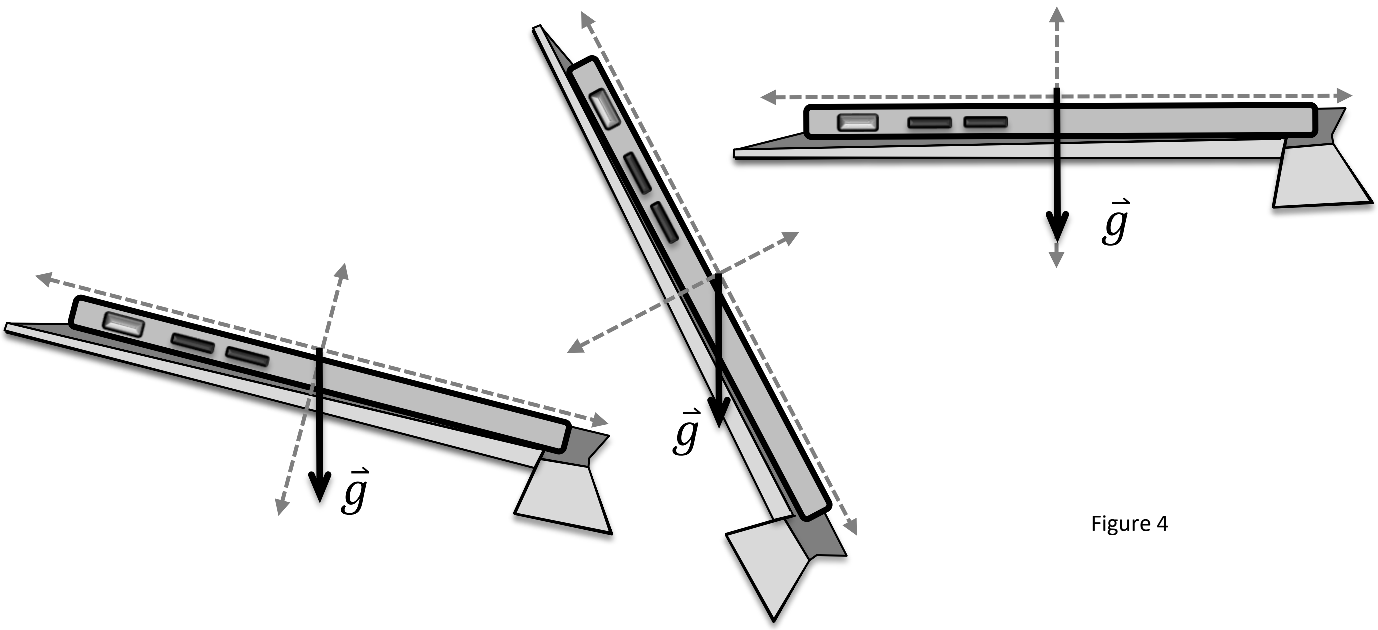


Figure 4

3. Complete Table 1 based on your **theoretical** analysis.

   a. In the two gray boxes, write the appropriate symbol (g_x, g_y or g_z).

   b. In the remaining blank spaces, use trigonometry (NOT real accelerometer data!) to determine the correct values. Make sure the sign you choose for each value corresponds to the coordinate system of your particular phone.

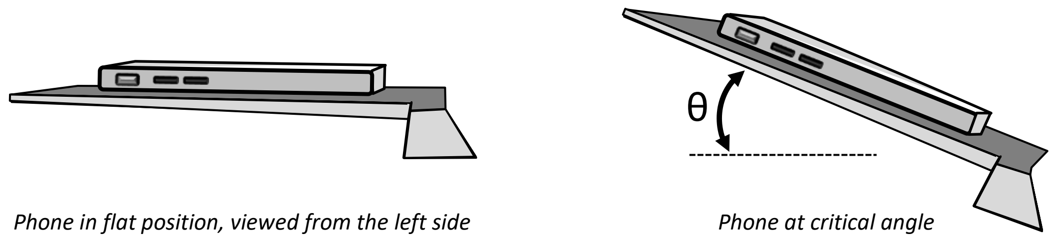
angle θ (degrees)	components of $\vec{g}$ (m/s²)	
	long axis	camera axis
10		
75		
0		

Table 1 – *Components of gravity using trigonometry*

Show one sample calculation

Part D: Determine the critical tilt angle of your phone

1. Place the tray flat again at an angle of zero degrees.
2. Start with your phone active, and displaying your texting app or browser in **landscape** mode.
3. Place your phone on the tray facing upwards, with the left side of your phone oriented to be visible when looking at the protractor side of the apparatus.
4. Raise the tray until your phone *just* switches to portrait mode.
5. Closely watch the needle position to determine the exact angle at which this switch takes place. Make it as accurate as possible. Record this value.



Phone in flat position, viewed from the left side *Phone at critical angle*

Figure 2

Part E: Components of gravity in smartphone coordinates - **from accelerometer data**

1. You will now find the components of gravity based on accelerometer data using Table 2 as a guide. Columns 2 and 3 are the accelerometer data that you will soon collect. Columns 4 and 5 represent your interpretation of that data as components of gravity along the same axes but in the opposite directions.
   a. In the 4 gray boxes of Table 2, therefore, write the appropriate symbol (a_x, a_y or a_z; g_x, g_y or $g_{z,}$).

      (*The symbols in columns 4 and 5 should be identical to those used in Table 1.*)

   b. Fill in the value for your critical angle in the appropriate cell of column 1.

2. Set the tray flat at zero degrees. Place your phone on the tray screen side up, with the “mouth side” touching the bar at the axle. Start the accelerometer app. Record the acceleration values for the long axis and the camera axis (columns 2 and 3). Repeat for all angles listed.
   (The units of the column are m/s^2, so multiply your readings by 9.8.)

3. Carefully review Topic 4 of “*Understanding Accelerometers*” before proceeding. Keep in mind that the x-y-z axis names used in Topic 4 do not necessarily correspond to those in your phone. For each angle in Table 2 below, determine the components of $\vec{g}$ with respect to the inclined phone coordinate system (columns 4 and 5).

4. Finally, use the components of the gravitational vector to express the gravitational vector in polar form (last two columns). Report the angle as θ_2: the angle you identified in Part B of this document (refer to Figure 1).

5. Compare the angles in the first and last columns. Are they the same? Should they be?

6. Compare your data from Table 2 with your theoretical predictions in Table 1. What is the largest deviation (not % deviation) of the experimental values from the theoretical values ?

Table 2 – Components of gravity from accelerometer data   Make and model of phone: ________________

angle θ (degrees)	accelerometer vector 'a' (m/s^2) component form		gravitational vector 'g' (m/s^2) component form		gravitational vector 'g' polar form	
	long axis	camera axis	long axis	camera axis	magnitude (m/s^2)	angle θ_2 (degrees)
0						
10						
(critical)						
75						

ADDITIONAL INVESTIGATIONS:

1. Suppose the tray is set to an incline angle of 45 degrees. What would you expect the readings for the accelerometer components to be in this case? Try it out to verify.

2. In your experimental work so far, the edge of the phone closest to the protractor axis is the "mouth side". Turn your phone by 180 degrees and place the "ear side" closest to the axis. Predict which results in Parts 3 and 4 will be different. Carry out the experiment and report on the actual results.

3. Repeat Parts 3 and 4 with your phone placed perpendicularly to the tray surface instead of parallel to it. What are the new axes along which accelerometer readings will be non-zero?

FOLLOW-UP QUESTIONS:

1. Consider a cell phone on a horizontal surface, being accelerated to the right (along its "right-left" axis). If the accelerometer "ball" has a mass of 2.0×10^{-6} kg, and the wall of the box is pushing on it with a force of 5.0×10^{-6} N, determine the magnitude of the acceleration reported by the device.

2. For each of the pictures below, complete Table 3 (next page) by predicting what the accelerometer readings would be for each axis. Be sure to include the sign.
   (Remember, the accelerometer vector points equal
   and oppositely to the gravitational acceleration vector.)

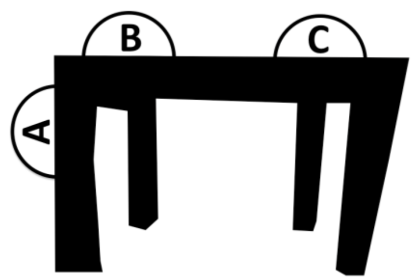
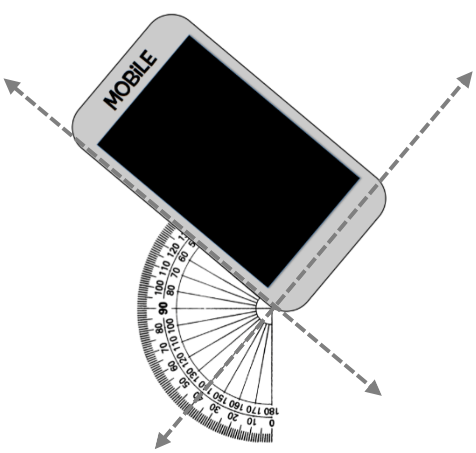
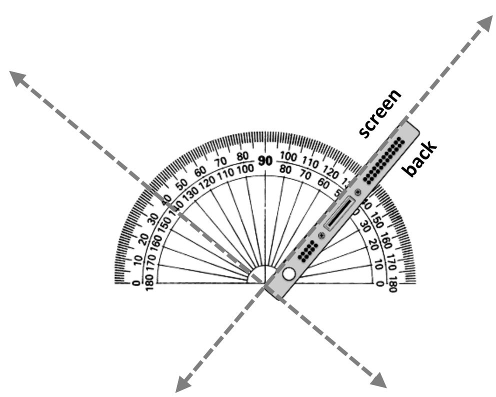


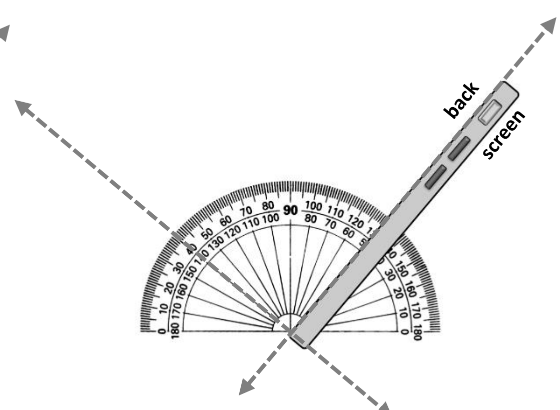
Figure 5



A



B
[Mouth-side view]



C
[Left-side view]

TABLE 3: Predictions of accelerometer readings based on images.

ACCELEROMETER READING

image	x (m/s^2)	y (m/s^2)	z (m/s^2)
A			
B			
C			

3. For each of the accelerometer readings below, draw a picture indicating the cell phone orientation.

ACCELEROMETER READING

label	x (m/s^2)	y (m/s^2)	z (m/s^2)
A	0	0	9.8
B	9.8	0	0
C	9.76	0	0.85
D	8.5	0	4.9

4. At what angle should the cell phone be held for the x- and y- components of the accelerometer to be equal? Draw a diagram as part of your explanation.