LU 9.13. Motion and graphs

Overview

One of the most useful tools to understand the relative variation of two quantities (in this case, distance and time) is a graph of the two quantities against each other. In this Learning Unit , we make use of the powerful representation of graphs to describe motion quantitatively. We shall be using different graphs to understand how an object moves, or even how the fastest human being on earth makes his world records! We shall then try to understand how we, not-so-famous sprinters, run in comparison to professional athletes.

Minimum time required: Three sessions of 40 minutes each.

Type of Learning Unit: Playground and Classroom (with a minimum of 12 students)

Learning objectives:

- Learn plotting graphs.
- Understanding graphs and using them in real life situations.
- To understand the relationship between physical quantities like distance, speed and acceleration.

Links to curriculum:

- Class 7, Chapter 13- Motion and Time (speed, x-t graph)
- Class 9, Chapter 8- Motion (speed, acceleration, graph)

Science or Mathematics Pre-requisites:

- Familiarity with the concepts of distance and speed.
- Representing data using line graphs and calculating slopes.

Materials/facilities required:

Pencils, rulers, graph papers, erasers, stopwatch, meter scale, 100-meter long track (playground/corridor)

Introduction

Moving objects and people around us are among the most common sights for us in our daily life. In Physics, motion is understood in terms of two basic intuitive notions --- distance and time. The motion of an object is described and explained by quantifying how fast or slowly the object covers a certain distance, and even how this rate of motion is changing with time.

On 16th August 2009, at the 12th IAAF World Championships in Athletics, Berlin (Germany), Jamaican sprinter Usain Bolt set a new world record in 100-meter dash. He finished the race in 9.58 seconds breaking his own record of 9.69 seconds which he had set one year ago at the Beijing Olympics.

Video of the Usain Bolt's race is available here.
https://youtube.com/clip/Ugkxj3z_7aeZbBsn8Gdj6gWLtHhjyYJsTzKp

Watch the video. Usain Bolt is the fourth athlete from right in a yellow t-shirt (he is in the front in the image below). There is a timer running on the video. Try to answer the following:

Q1. From start to finish, does his speed remain same throughout the race or it increases with time?

_____

_____

Image 1: *Jamaican sprinter Usain Bolt leading the race.*

Note: If you don't have laptop or PC, you can go ahead with other tasks, this will not hamper other tasks.

Task 1: Analyzing a walk

Shabana is moving on a straight flat track. The following picture identifies six different locations (A, B, C, D, E, and F) of Shabana at different distances on the track.

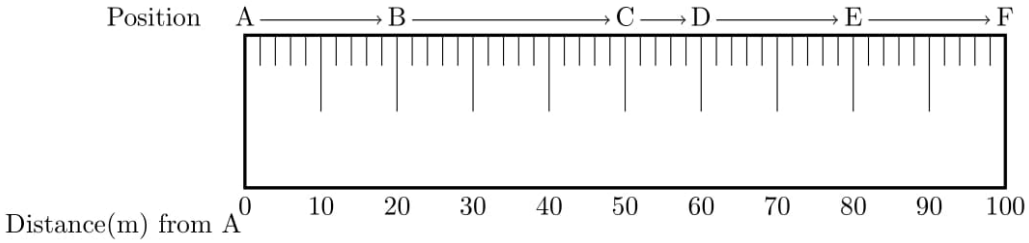


Image 2: *Positions of Shabana on a track.*

Table below shows the times at which positions of Shabana is indicated on the track. In the 3rd column write the corresponding distances of Shabana from A.

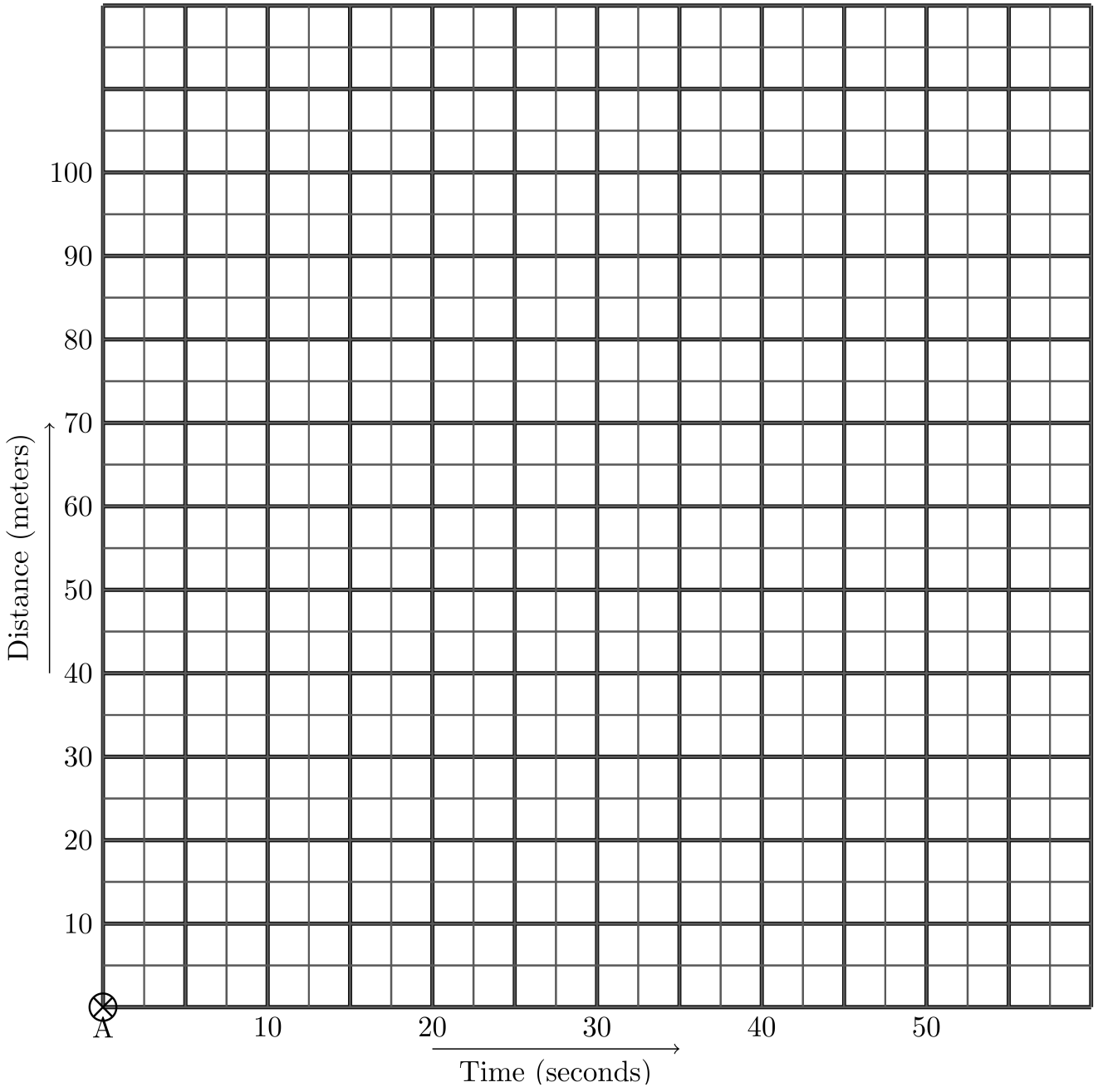
Position	Time (seconds)	Distance (metre)
A	0	
B	10	
C	20	
D	30	
E	40	
F	50	

Table 1: *Table of time for various positions of Shabana on a track.*

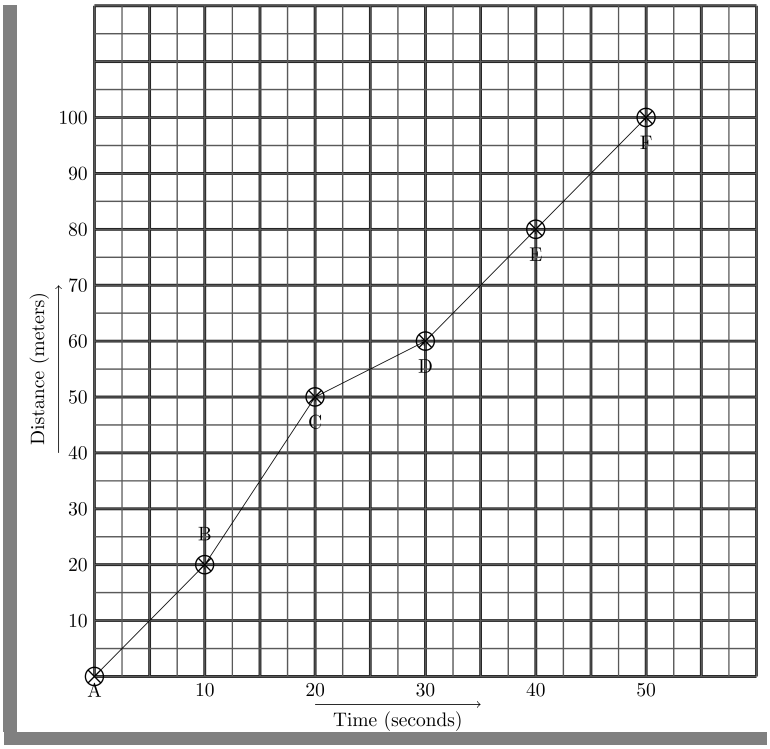
Position	Time (seconds)	Distance (metre)
A	0	0
B	10	20
C	20	50
D	30	60
E	40	80
F	50	100

Table T1: *Table of time for various positions of Shabana on a track.*

Represent the motion of Shabana as a distance v/s time graph by marking its distance from the starting point (A). Use the values from the table above to plot at the remaining locations (B, C, D, E and F). Location A is already indicated in the graph by ⊗. Join the successive points by straight lines.



Graph 1: *Shabana's distance v/s time graph.*



Graph T1: *Shabana's distance v/s time graph.*

You may have to explain different sections of graphs, scales, etc.

By looking at the nature of the graph, during which interval, Shabana most likely is

i) the fastest: _____

ii) the slowest: _____

iii) faster than the previous interval: _____

Students may be given to identify the slope of the graph by looking at the values of time and distances between the two intervals.

i) The segment joining the positions B and C is the steepest or in other words has the maximum slope. Hence Shabana is moving fastest between 10 to 20 seconds.

ii) Using the same argument, it can be concluded that Shabana is moving slowest between C and D (20 to 30 seconds).

iii) BC and DE are faster than AB, and CE respectively.

While we do not know the details of motion of Shabana between the given points, we can still learn a lot about the overall motion of Shabana by calculating its average speed between each consecutive pair of points.

Calculate the average speed in each interval between successive points and fill the below-given table. To help you, calculation of average speed between A-B is given in the third column.

Discuss with your friends the distinction between instantaneous speed and average speed. Here we can get only the average speed and not the instantaneous speed.

Time interval (seconds)	Change in position	Average speed (metre/second)
0-10	(A-B)	(20-0)/(10-0)=2
10-20	(B-C)	
20-30	(C-D)	
30-40	(D-E)	

40-50	(E-F)	
0-20	(A-C)	
0-50	(A-F)	

Table 2: Calculation of average speed

Time interval(seconds)	Position	Average speed (metre/second)
0-10	(A-B)	(20-0)/(10-0)=2
10-20	(B-C)	(50-20)/(20-10)=3
20-30	(C-D)	(60-50)/30-20)=1
30-40	(D-E)	(80-60)/(40-30)= 2
40-50	(E-F)	(100-80)/(50-40)=2
0-20	(A-C)	(50-0)/(20-0)=2.5
0-50	(A-F)	(100-0)/(50-0)=2

Table T2: Calculation of average speed

Average speed can be calculated between any intervals and it may be different from the instantaneous speed of a smaller interval. For example, the average speed in the first two segments (0-10,10-20) are 2 and 3 m/s respectively. But the average speed of the combined time interval from 0-20 second is 2.5 m/s.
Also you may draw students' attention to the concept that in a given time, a steeper line segment covers more distance. This indicates a higher speed.

During which time interval(s) is its average speed

(a) Maximum?_____

(b) Minimum?_____

(c) greater than what it was in the previous time interval? _____

Speed can be found by the formula distance/time. For example, the speed between 0-10 sec is 20/10=2m/s.

(a) The minimum speed is between 20-30 sec.

(b) Maximum speed is between 10-20 sec.

(c) 10-20 and then 30-40 sec.

Kindly notice that in the previous part, you have drawn the same conclusions without calculating the average speeds.

Task 2: Analyzing Bolt's run

In this exercise, we will try to analyze Bolt's 2009 run (refer to Introduction for the video).

During the race, a camera was running parallel to Bolt and recorded time every 10 meters. The time record at every 10 m distance is given below.

Distance (m)	Time (s)
0	0
10	1.89
20	2.88
30	3.78
40	4.64
50	5.47

60	6.29
70	7.10
80	7.92
90	8.75
100	9.58

Table 3: *Usain Bolt's running data*

Four different graphs are given below. The scales and labels of the y-axis are not given.

This question can be answered without any calculation. If students choose incorrect graphs, there's no need to correct students' answers immediately. Allow them to answer next few questions and then revisit this discussion so that they can identify and correct their mistakes themselves.

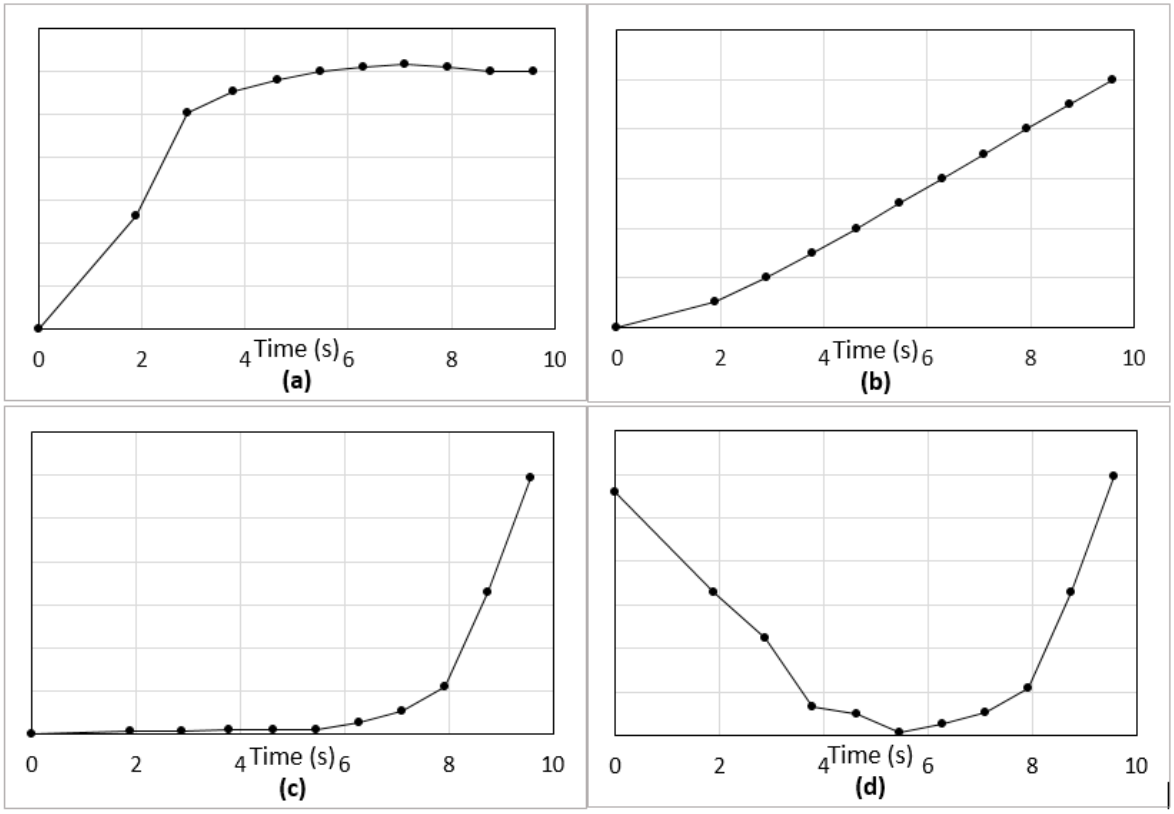


Figure 1: *Graphs with y-axis missing*

Q2.1. Identify which graph is distance versus time for the Usain bolt's run.

Graph (b) represents distance vs. time, which is the only graph that effectively illustrates the change in distance over time. Graph (a) is incorrect because it only shows a significant increase in distance up to 5 seconds, after which the change is minimal. Similarly, Graph (c) is inaccurate as it shows no change in displacement for the first 6 seconds. On the other hand, Graph (d) inaccurately portrays a significant distance at the beginning, which is incorrect, as the runner started from rest at the initial distance of zero. All of this must be explained with reference to the above graphs and the video.

After Identifying distance vs time graph, from the remaining three graphs

Q2.2. Identify which graph is speed versus time.

Graph (a) represents speed vs. time. Graphs (c) and (d) are inaccurate. Graph (c) falsely indicates speed at

the beginning, where it was nearly zero for the first 6 seconds. Graph (d) incorrectly shows speed decreasing to zero between 4 and 5 seconds and then increasing, which doesn't align with Usain Bolt's run. In reality, the runner accelerated initially and then attempted to maintain speed until the last second. Therefore, graph (a) accurately represents the scenario. This analysis is supported by reference to the above graphs and the accompanying video.

The time rate of change of speed is known as acceleration.

Q2.3. From identified speed vs time graph, find in which time interval does he accelerate the most?

From graph we can see that slope of speed vs time graph (fig. (a)) is highest between 2 and 3 seconds, more accurately during the time interval 1.89 s-2.88 s. Hence acceleration is maximum in that time interval.

Task 3: Plotting your friend's run

This activity requires minimum 12 students. Gather your friends and come to the playground. One of you has to run a 100-meter race and the rest of the friends will record the timing at every 10 meters. In other words, we have to record your running timing and produce a data table similar to Bolt's performance shown in Part 2(a). Ideally, collect the data for two runners. Runners may run fast or slow depending on their capacity.

One of the method to conduct this is as follows:

1) Identify a 100/50-meter flat track.
2) Starting from 0 meters, ask your friends with a stopwatch to stand every 10 meters till 100 meters. You will need 11 students for this. Set stopwatches in counter mode. We will call these students *Markers.* You can also use stopwatch mode on a mobile phone.
3) Decide a convenient method to operate/synchronize clocks. Make the students aware of the least count of the clock. Use minimum possible least count.
4) Draw a line on the track at equal intervals each, say 5/10m each and markers should stand at the intervals. One of you can play the role of Usain Bolt. We will call her/him *Runner.* As soon as the runner starts the race all the *markers* should start their stopwatches. The *Markers* have to stop their respective stopwatches when the *Runner* crosses their interval line.
5) After the race, record the timing from each stopwatch in the following table.
6) Calculate the speed for each interval.

For more than 1 runners, you may use the extra tables given in the appendix at the end of this unit.

Distance (m)	Time (s)	Distance interval(m)	Time interval(s)	Average speed (m/s)
0	0	-	-	0

Table 4: Students' running data for speed

Plot speed vs time for the runner and compare with Usain Bolt's performance plot.

Answer the following questions.

Q1. Is the shape of your graph similar to his performance? If not, then what are major qualitative differences?

_____

_____

The graph may not be the same as Usain Bolt's performance. You may notice the difference in the slope of distance vs time curve. In addition, since the data collection is not as sophisticated as the one used in 100 m dashes, data may appear zigzag. Possible errors may be due to the reaction time of markers, or in the synchronization of clocks.

Q2. What is the maximum speed that the *runner* has achieved and during which time interval?

_____

Q3. Is the *runner's* speed continuously increasing during the race?

_____

We can calculate average acceleration from speed in the same way we have calculated speed from distance.

Q4. Can you now calculate the acceleration of the runner at different times and enter the values in the table on the previous page?

Average speed (m/s)	Time (s)	Time interval(s)	Acceleration (m/s^2)
0	0	-	0

Table 5: Students' running data for accleration

Q5. Can you identify the differences between the maximum acceleration of your friend and that of Usain Bolt?

Note that the acceleration can be negative or positive depending upon the change in velocity. In the obtained graph, acceleration decreases at the end. That indicates that the speed is decreasing for that time interval. Certain quantities have directions associated with them, for example, velocity and acceleration.

Task 4: (Possible extension) Perimeter of your school

Without using any meter tape, estimate the approximate total perimeter of your school playground. You can only use a stopwatch and a standard 30cm ruler for this activity. Briefly describe your measurement technique.

Measurement technique:

Draw the shape of the playground:

Total perimeter:

Further reading

- "Simple Models for the 100 meter Dash", Priyanka deSouza and Vijay A. Singh, Resonance, 17, 592-602, (2010); https://www.ias.ac.in/describe/article/reso/017/06/0592-0603
- "Student difficulties in connecting graphs and physics: Examples from kinematics", Lillian C. McDermott, Mark L. Rosenquist, *and* Emily H. van Zee, American Journal of Physics 55, 503 (1987); https://doi.org/10.1119/1.15104

Appendix: Table for recording runner's data

Distance (m)	Time (s)	Distance interval(m)	Time interval(s)	Average speed (m/s)
0	0	-	-	0

Distance (m)	Time (s)	Distance interval(m)	Time interval(s)	Average speed (m/s)
0	0	-	-	0