Jochen Kuhn
Patrik Vogt *Editors*

Smartphones as Mobile Minilabs in Physics

Edited Volume Featuring more than 70 Examples from 10 Years *The Physics Teacher*-column iPhysicsLabs

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Foreword

Swiss Pocket knife, indeed! This metaphor might need some explanation for some, but it does seem right on target to me, so please indulge me while I reminisce a bit. In my younger days, I kept an actual Swiss Pocket knife with me all the time, and it seemed a critical part of the prepared physics teacher's equipment—I found myself using my it most every day to cut string or duct tape, or to open boxes or dig holes or fashion cardboard lens holders or any number of other essential physics teacher tasks. But then 9/11 happened and if you traveled much at all, you couldn't risk carrying your Swiss Pocket knife on your person and having it confiscated and yourself detained, so it went into back drawer somewhere and saw much less use than before. Now I no longer carry a knife in my pocket, but the essential piece of physics teacher equipment that has replaced it in many regards, is the cell phone, at least in my case. It is more versatile than the knife in many regards, but in my ideal world I'd have them both at my fingertips when teaching.

When Jochen Kuhn and Patrik Vogt first proposed a column for *The Physics Teacher* on the topic of using cell phones in the classroom, I can imagine there were many skeptics—after all, some teachers were still not allowing calculators in the classroom, if I remember correctly! Their first column was a beautiful piece[1] about using a cell phone to detect diffraction from an infrared remote-control device, inspiringly simple and satisfyingly packaged, but could there be enough other good ideas to generate a quality article every month? It seems even the *TPT* editor at the time, Karl Mamola, was unsure whether this idea would be sustainable as a regular *TPT* feature.

In fact, the "Column Editor's Note" that served to introduce this new *TPT* feature to readers included this caveat, "We will publish 'iPhysicsLabs' on a trial basis for a number of months; depending on reader response it may evolve into a regular *TPT* column."

However, even back in February 2012, when this first column appeared in *TPT*, Kuhn and Vogt seemed to know that this bit of technology was to be a key part of the physics teacher's tool kit for many years to come. In describing the kinds of submissions they hoped to receive, this wildly optimistic pair of physicists had

[1] Phys. Teach. **50**, 118 (2012); https://doi.org/10.1119/1.3677292

clear ideas about what would work best, writing: “The column will feature short papers (generally less than 1000 words) describing experiments that make use of the sophisticated features of mobile media devices produced by various manufacturers . . . The contributions should include some theoretical background, a description of the experimental setup and procedure, and a discussion of typical results.” Kuhn and Vogt have stayed true to this original vision, describing many dozens of clever physics experiments described within the column, and providing teachers everywhere with a host of options for tomorrow’s classroom. Some ideas came from Kuhn and Vogt directly while many others were contributed by *TPT* readers—apparently readers were so responsive that the column is still going strong after 10 years! . . . And such variety! Topics range from acoustics to mechanics to optics to electromagnetism to radioactivity to thermodynamics to astronomy to almost anything that an introductory physics teacher could imagine wanting to present in their classroom.

Their column has become one of the most long-running columns in *TPT,* being downloaded many times by teachers all over the world within a short period after appearing. In late 2013, when I inherited *The Physics Teacher* editorial role from Karl Mamola, the iPhysics column was firmly established as a regular feature with Kuhn and Vogt as Column Editors. I am so glad that they persisted these past 10 years to produce such a powerful collection of physics experiments that can be done with a pocket device. To have them all in one place, complete with an introductory piece to flesh out some of the logic behind why mobile phone media can be a key part to effective physics pedagogy, is a real benefit to the physics teaching community. Thank you, Jochen and Patrik, for sharing your knowledge and experiences in this way, and congratulations on the tenth anniversary of a truly valuable enterprise!

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Introduction

1 Smartphones and Tablet PCs: Excellent Digital Swiss Pocket Knives for Physics Education

Jochen Kuhn and Patrik Vogt

Smartphones and tablet PCs are increasingly part of our everyday life—for both the younger and the older generation. Tablet PCs are also increasingly being used in schools, although such devices have primarily been used so far as a substitute for notebooks (e.g., as cognitive tools). Smartphones, however, pose several problems in everyday school life, since for instance they can be distracting or cause disturbances. However, considering their technical possibilities, and learners' deep familiarity with the devices, targeted use of these technologies has long been identified as a possible means to enrich lessons [1].

In addition to the frequently described uses of these technologies, such as for research, as cognitive tools, or for communicating, they can also be used as experimental tools, especially in science classes. Inspired by the early article of Raymond F. Wisman and Kyle Forinash [2], we took our own first steps in this direction in 2009/2010 [3, 4] and recognized very quickly the tremendous opportunities in this idea. Following this, we wanted to extend this "lab in the pocket" idea by integrating it into well-established learning theories and systematically studying these opportunities across a broad range of physics topics. Although we did not set out to found a new direction, we wanted to establish this initiative through collaboration by inviting as many colleagues as possible to join with us. This led us to the idea for starting the "iPhysicsLabs" column in *The Physics Teacher* [5]. And now, after 10 succesful years and some breakthrough ideas delivered by different colleagues, it has been a pleasure for us to have brought together so many colleagues from all over the world to work on this fruitful topic. What is more, it seems that we are just at the

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beginning of our journey, as more and more colleagues engage with our idea by developing their own respective apps, such as the Physics Toolbox from Vieyra Software in 2013, phyphox from RWTH Aachen in 2016 [6], and PocketLab, as well as building further communities, such as SmarterPhysics by Martín Monteiro et al. and the Smarte Physik column [7].

Therefore, in this chapter, we give a summary of the basic ideas of this approach, reasons for its promise, and how it can be further developed.

1.1 Mobile Mini-Labs for Teaching and Learning

Mobile communication technologies can be used for a wide range of experiments, especially in physics, as they are equipped with different internal sensors that record physical data. These include, for example, microphone and camera, accelerometer, sensors for magnetic field strength, illumination, or brightness sensors, a gyroscope, GPS receiver, and sometimes even temperature, pressure, and humidity sensors. The original reason why the sensors were installed was of course not purposes to implement them for experiments in science education. The acceleration sensor is used, for example, to determine the device's tilt and to adjust the screen to its orientation. The magnetic field strength sensor is used as a compass to support navigation using the smartphone or to inform the user about position-specific environmental data (temperature, air pressure, humidity, etc.). However, physical data recorded by the internal sensors can be used beyond their actual function with the aid of apps, so that both qualitative and quantitative experiments are possible across a wide range of subject areas, and particularly for physics lessons. Smartphones and tablet PCs thus represent small, portable measurement laboratories that can replace confusing experimental apparatus. Furthermore, they are well known to learners in their everyday lives, which means that a high level of familiarity with their operation can be expected. Many experiments that can be carried out with mobile communication media were previously only possible with the support of computers and sensors, and some of these were expensive and difficult to operate. In contrast, experiments with the internal sensors of smartphones or tablet PCs can be carried out and evaluated more easily due to the intuitive usability of the apps, so that a stronger focus on physical content is possible.

The papers of this book discuss numerous topics of physics, and its structure corresponds to that of a typical standard work on experimental physics. We start with kinematics and dynamics (Part II), such as with ball velocity, free fall, and the Atwood machine. The reader will find impact processes in Part III, before the topic of rotation (Part IV) is addressed in detail. Topics include the direction of acceleration, angular momentum, and the SpillNot, which enables full glasses to be transported without spilling. In the following parts, deformable bodies (Part V) and pendulum experiments are discussed (Part VI), before we enter the broad field of acoustics (Parts VII–IX). Among other things, numerous variants for the determination of the speed of sound in gases and solids, as well as various everyday phenomena such as the knuckle cracking, opening wine bottles, and the physics of church bells, are presented here. Some experiments on thermodynamics (Part X), electrodynamics (Part XI), and optics (Part XII), as well as astronomy and modern physics (Part XIII), complete the edited volume.

1.2 Good Reasons for Learning with Mobile Mini-Labs

Apart from the fact that smartphones and tablet PCs are technically and practically suitable for experimental use in physics education, there are also reasons for their meaningful use based on learning theories.

First, the use of the devices as experimental tools in science lessons is didactically justified by the everyday relevance of the smartphone or tablet PC. Thus, it can be classified in well-founded theories of cognitive science, namely situated learning (e.g., [8, 9]) and context-based science education (see, e.g., [10]). The assumption here is that, in addition to the authenticity (in the sense of everyday relevance) of a topic, the authenticity of the media used in experiments also has a positive influence on learning in physics education (so-called material situatedness). Specifically, this assumption means that learners' cognitive and motivational learning success with respect to experiments in physics classes is greater when they investigate a physical phenomenon with experimental media that they use in their daily life [11].

In addition, students are assumed to have an enhanced experience of autonomy when using smartphones and tablet PCs [12, 13]. For example, they can use a tablet PC to independently record a self-selected movement process, directly analyze and evaluate their "own" videos (captured with their own device) using a video analysis app on the same tablet PC, and conduct similar, repetitive, or advanced experiments with a mobile medium outside of school.

In contrast to "conventional" experiments, such mobile technology can also be used to provide multiple representations for students already during and directly after the experimentation (automatic visualizing measurement data as diagrams and tables of values, formulas, vectors or images). The integration and presentation of this multimedia content is done considering of the Cognitive Theory of Multimedia Learning (CTML) [14]. Through active information processing, the coherent use and construction of multiple mental representations is to be promoted. The competent use of these multiple representations such as pictures, diagrams, formulas, and vectors—i.e., the ability to interpret external forms of representation, generate them independently, and switch between different representations flexibly and purposefully [15]—are summarized under the term of (conceptual) "representational competence" [16, 17].

The important role of representational competence for scientific thinking and learning is well documented for science in general [18] and for different individual disciplines (biology [19]; chemistry [20]; physics [21, 22], and mathematics [23, 24]). Representational competence as a prerequisite for the use of multiple representations in terms of domain-specific thinking tools is of high importance for other abilities, e.g., conceptual understanding [25, 26], "construction and reconstruction of meaning" [27], reasoning [28–30], problem solving [16, 30], and creativity

[31]. Against this background, it becomes clear why this competence is discussed for STEM subjects in general as a necessary prerequisite for the formation of deeper understanding [16, 32]. Etkina et al. [33] even mentioned it as the first of seven discipline-specific skills that should be trained.

On the other hand, research findings indicate that competent handling of representations is of considerable difficulty for learners [34, 35]. Empirical evidence for this exists from primary [34] to secondary [36] and university levels [37]. Of course, using the representation possibilities especially of smartphones and tablet PCs only makes sense if students have previously practiced converting measurement data into different forms of representation by hand. In addition, apps often offer forms of representation that are unsuitable for the data in question (e.g., bar charts, where line charts or dot plots would be necessary). This should also be addressed in class.

Since the idea of using smartphones and tablet PCs as experimental tools in the classroom is still relatively new, there are still hardly any published findings on the effectiveness of their use in this way. In the field of physics, however, it is possible to draw on the initial results of some studies published to date on this topic.

A first pilot study on the use of smartphone experiments in physics classes dealt with the topic of acoustics (secondary level 1) [11]. During two-weeks of physics lessons, the classes each worked in groups on four different learning stations with experiments convering topics of beat frequency, types of sound, sound velocity, and sound propagation. The content, scope, and difficulty of the experiments, as well as the instructional materials of the learning stations in the two classes, were identical and differed only in the experimental material used. In order to track the motivation and learning performance of the students, the necessary data were collected directly before and after the intervention as well as five weeks after the completion of this teaching sequence using curricular related tests and questionnaires. It was found that the time course of performance and the learners' knowledge differed significantly between the two groups. In the group of students who worked with smartphone experiments, performance and their self-efficacy expectations were more enhanced and stabilized, respectively, than in the group with conventional experiments. Even though motivation as a whole was not influenced differently, the motivational aspect of "self-efficacy expectation" in particular, which is significant for context-oriented learning, could thus be supported, although it is considered difficult to change.

In a second study in university introductory physics courses in mechanics, positive effects were also found when using tablet PCs for mobile video analysis on the physical concept of understanding in mechanics as well as on the students' self-concept [17, 38, 39].

The third study investigated smartphone experiments in classical mechanics at secondary level 2 (grade 11) using smartphone internal acceleration sensors [40]. Similar to the previous two studies, an quasi-experimental pre-posttest treatment-control group design was used to investigate the effects of smartphone used as experimental tools on interest, curiosity, and learning outcomes. Learners in the smartphone groups showed significantly higher interest in physics after the study. In this regard, especially such learners in this groups who were less interested at the beginning of the study benefited the most. In addition, learners in the smartphone groups showed higher curiosity. No differences in learning performance were found. This means that the use of smartphone experiments can promote interest and curiosity without reducing learning performance.

A fourth study analyzed the learning efficacy of using tablet PC-based video analysis of motion in the subject area of mechanics in secondary level 2 physics classes [41]. Again a quasi-experimental field study was conducted in a pre-posttest design with control and intervention groups. The study included two essential topics of mechanics: uniform motion and accelerated motion. The results demonstrated significantly higher learning performance related to understanding physics concepts through the use of tablet PC-based video analysis compared to traditional instruction in both topics, with the larger effect in the more cognitively demanding topic of accelerated motion [42, 43]. These results could be reproduced by a further study from Hochberg et al. [44].

These first studies on the use of smartphones and tablet PCs as experimental tools did not, of course, allow any general transferable findings, for reasons such as their small number of participants and the limitation of topic reference and addressee group. However, they have provided indications of initial trends and of questions that are still valid and currently being investigated in further studies with a larger number of participants, different groups of addressees (schools and universities) and other subject areas.

1.3 Summary

In this introductory chapter, we described why smartphones and tablet PCs are particularly well suited for experiments in physics education. Furthermore, we explained with reference to established learning theories why students can be expected to learn better with them. Initial studies show positive learning and motivation effects.

Of course, this is only possible if teachers develop suitable instructions and implement them appropriately into their lessons. A logical conclusion from this is that such examples must be integrated even more strongly into teacher training. The following chapters describe numerous tested experiments that can also be used very well for this purpose.

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Part II

Kinematics and Dynamics

Determining Ball Velocities with Smartphones

2

Patrik Vogt, Jochen Kuhn, and Denis Neuschwander

The use of a smartphone's microphone for quantitative analysis in the field of "acoustics" will be discussed in coming chapters of this book, including the analysis of different sources of sound (Chap. 48) [1], the determination of the speed of sound in various gases (Chap. 43) [2], and the examination of acoustic beat frequency phenomena (Chap. 49) [3]. Acoustic data logging can also be very useful in teaching mechanics, for example, to determine *g* on the basis of bouncing balls (Chap. 12) [4] or on the basis of the Doppler shift [5] (for an overview, see Ref. 6). This chapter adds further to the applied acoustics repertoire and presents an experiment on the determination of the mean velocity of driven or kicked balls.

2.1 Theoretical Background and Execution of the Experiment

Determining the mean velocity of driven and kicked balls by means of acoustics is not new. It has already been discussed by measuring the speed of a soccer ball using a sound card and an external microphone [7]. The basic principle is easy to understand: a sound signal results from kicking the ball. Then this signal is registered by the microphone with a slight delay. The same effect is valid for the ball's impact on the wall. If the microphone's distance from the kicker is identical to its distance

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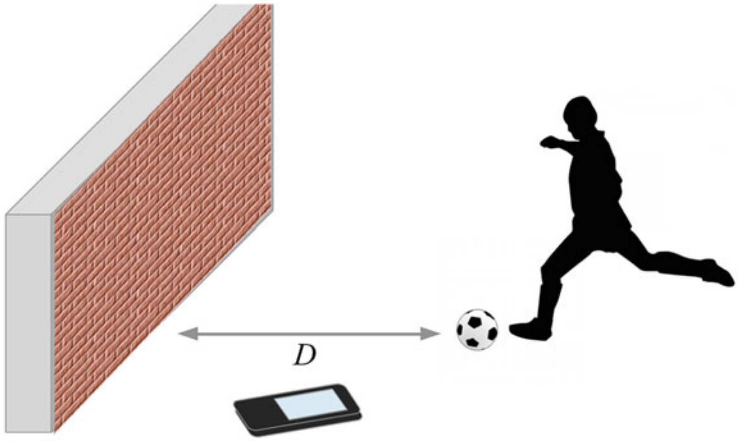

Fig. 2.1 Experimental setup

Fig. 2.2 Screen shot of the Oscilloscope App. The first peak shows the impact of the ball on the table-tennis paddle, the second one shows the impact on the wall. The time difference can be found in the app (see red circle)

from the wall, the ball's flight time is the same as the period of time that passes between both registered sound signals (Fig. 2.1). Dividing the person's distance *D* from the wall by the measured time will reveal the mean velocity of the ball in a very precise way. A smartphone using an oscilloscope app [8] has many advantages over computers, e.g., a higher mobility and a constant availability. The screen shot of the Oscilloscope App in Fig. 2.2 shows the measurement of a driven table-tennis ball with a distance of 2 m from the wall. The mean velocity of 10.9 ms^{-1} results from the actual flight time of 183.8 ms. The following paragraph contains the outcome of several series of measurements. Five different sports have been chosen (table tennis, beach paddle ball, soccer, badminton, and volleyball) to investigate the influence of gender and age on the mean velocity of a driven ball.[1] Calculating the mean value from 10 measurements for each person's performance was necessary in order to gain the highest possible accuracy.

2.2 Experiment Analysis

The results for the different sports are shown in Table 2.1. Typical distances during regular play for each sports activity were used. The maximum mean velocities were achieved in badminton (averaging 81.8 ± 4 km/h). Since the amount of the random sample was relatively small and the subjects were amateurs, the results cannot be considered valid for competitive sports. We saw notable differences between the speeds generated by males and females.

Three soccer teams were separately analyzed in order to examine the influence of age on the mean velocity: a boys' team with group members aged 11–13, a second boys' team with group members aged 15–17, and a men's team with an average age of 24.2 years. As expected, the ball's velocity increases with age in the studied groups (see Table 2.2).

Research shows that studying acoustic phenomena with mobile devices integrated in a more sophisticated instructional setting could also increase learning [9].

Table 2.1 Results for the different sports (*N* is the sample size, *SD* is the standard deviation)

Velocity in km/h			
		Male	Female
Sport (distance)	*N*	11	9
Table tennis (2 m)	Mean	65.5	44.5
	(*SD*)	(12.5)	(9.5)
Beach paddle ball (3 m)	Mean	74.7	50.2
	(*SD*)	(13.5)	(10.0)
Soccer (5 m)	Mean	67.7	42.1
	(*SD*)	(8.9)	(10.4)
Badminton (3 m)	Mean	81.8	55.7
	(*SD*)	(12.8)	(17.8)
Volleyball (5 m)	Mean	53.4	35.6
	(*SD*)	(10.7)	(5.9)

[1] Due to numerous students playing sports in their free time, they can easily conduct measurements for physics or science classes.

Table 2.2 Velocities in soccer depending on age (*N* sample, *SD* standard deviation)

		Boys' team (11–13 years)	Boys' team (15–17 years)	Men's team
N		9	10	10
Age (mean)		12.2	16.4	24.2
Velocity in km/h	Mean	52.9	79.1	88.5
	(*SD*)	(6.1)	(4.3)	(5.5)

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An Experiment of Relative Velocity in a Train Using a Smartphone

3

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When we travel in a train moving at a certain velocity, we observe the stationary objects outside are moving backwards. These stationary objects seem to move due to a relative velocity [1, 2]. Consider that the stationary object outside the train is a man standing on the stationary floor watching a woman moving on a train. The woman on a train will see the man moving backward with a similar velocity as her. In kinematics, this magnitude of relative velocity will always be the same whether the man is far away from or near the train, as long as he stands on the stationary floor [1, 2].

But in reality, an observer inside the train will see that each outside object has different velocities according to its distance to the train. The closer the object to the train, the larger the relative velocity of the object as perceived by the observer's eyes. When the objects are far away from the train, they seem to be moving slower than the nearby object.

Several papers have involved smartphones to support physics experiments [3–7]. This chapter aims to provide a simple method using a smartphone app to analyze and theoretically prove that any stationary object outside a moving train at any distance has a similar relative velocity to the train.

3.1 Methods

There were several components required to perform this experiment:

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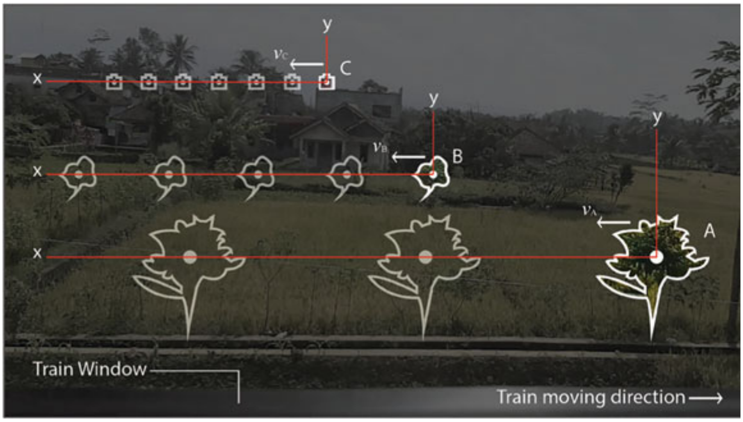

Fig. 3.1 Video shot for objects' motion analysis

1. An Android smartphone capable of recording a video for analysis.
2. VidAnalysis app for Android that can freely be downloaded from the Google Play Store.
3. Microsoft Excel to plot the data and create a graphical analysis.

We required a smartphone to directly record and analyze the motion of several objects outside the train in a certain time as illustrated in Fig. 3.1. For the analysis process, we have made calibration of the distances performed within the VidAnalysis app with a known length placed in the path of the object movement. The resulting time and *x*-distance data of the objects' movement can then be exported to Excel for graphical process.

3.2 Results and Conclusion

The result of video analysis using a smartphone and graphical analysis using Excel is shown in Fig. 3.2.

The three objects shown in Fig. 3.2 have almost similar velocities. They have about 28.4 m/s of average relative velocity to the train with a mean absolute deviation 0.184. Theoretically, this velocity is also the moving train's velocity. Consider the objects A, B, and C outside the train moving with a velocity of $\boldsymbol{v}_{\mathrm{T}}$ as illustrated in Fig. 3.3.

Figure 3.3 shows the position vector of objects A, B, and C expressed mathematically as in Eqs. (3.1–3.3).

$$\boldsymbol{r}_{\mathrm{TA}} = \boldsymbol{r}_{\mathrm{T}} - \boldsymbol{r}_{\mathrm{A}} \tag{3.1}$$

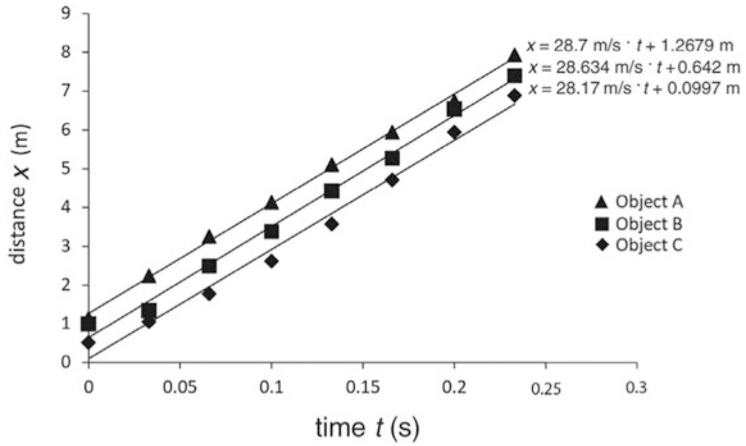

Fig. 3.2 Time (in seconds) and distance (in meters) plot of three stationary objects located at various distances from the moving train

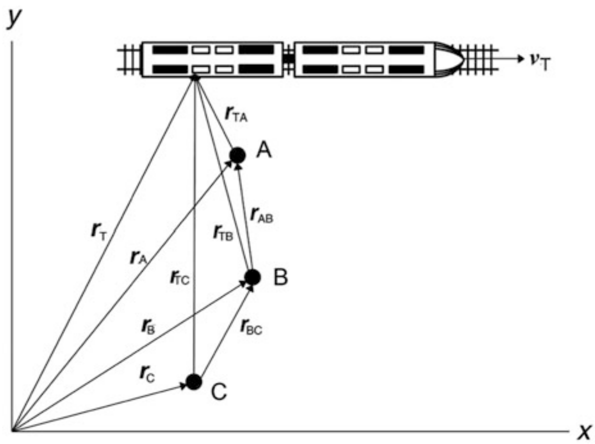

Fig. 3.3 Vector analysis to theoretically find the relative velocities of objects A, B, and C outside a moving train

$$\boldsymbol{r}_{\mathrm{TB}} = \boldsymbol{r}_{\mathrm{T}} - \boldsymbol{r}_{\mathrm{B}} \tag{3.2}$$

$$\boldsymbol{r}_{\mathrm{TC}} = \boldsymbol{r}_{\mathrm{T}} - \boldsymbol{r}_{\mathrm{C}} \tag{3.3}$$

While the train is moving, position vectors $\boldsymbol{r}_{\mathrm{A}}$, $\boldsymbol{r}_{\mathrm{B}}$, and $\boldsymbol{r}_{\mathrm{C}}$ are constant to the origin; thus, we have Eqs. (3.4–3.6):

$$\boldsymbol{v}_{\mathrm{TA}} = \frac{\mathrm{d}r_{\mathrm{T}}}{\mathrm{d}t} + \frac{\mathrm{d}r_{\mathrm{A}}}{\mathrm{d}t} = \frac{\mathrm{d}r_{\mathrm{T}}}{\mathrm{d}t} \tag{3.4}$$