FACTA UNIVERSITATIS
Series: **Physics, Chemistry and Technology** Vol. 16, N° 3, 2018, pp. 267 - 283
https://doi.org/10.2298/FUPCT1803267R

COMPARING TEXTUAL, VISUAL AND PRACTICAL METHODS FOR TEACHING PHYSICS †

UDC 371.3 : 53 : 371.671/695

Lazar Radenković, Miodrag Radović, Ljubiša Nešić

Department of Physics, Faculty of Sciences and Mathematics, University of Niš, Serbia

Abstract. *The same material about friction was covered by the same teacher in three different ways: using only verbal and textual means of communication (text group), using visual aids (diagram group) and using simple experiments (experiment group). The conceptual understanding of each group was evaluated using a test developed for this research. The scores were similar across the groups.*

Key words: *classroom experiments, lecture demonstrations, friction, conceptual learning*

1. INTRODUCTION

Experimental work and teaching demonstrations are considered to be an integral part of everyday physics education. But in high schools in Serbia and surrounding countries, most often, they are left out. We wanted to see how simple experiments during class affected students' conceptual understanding. The chosen topic was friction because it is both important and challenging for the students. A proper understanding of friction is crucial for the transition from Aristotelian to Newtonian mechanics. However, students usually struggle with all types of friction, with rolling friction being the least understood.

We used friction examples to compare the three methods for teaching physics: textual, visual and practical. The same lesson was presented to three groups of students, in a different manner. The first group of students had the textual version of the lesson, with no drawings or diagrams. They only had access to words, in both spoken and written form.

Received August 30th, 2018; accepted January 13th, 2019
Corresponding author: Lazar Radenković
University of Niš, Department of Physics, Faculty of Sciences and Mathematics, Višegradska 33, 18000 Niš, Serbia
E-mail: lllazarrr@gmail.com
† We would like to thank Miodrag Đorđević for his assistance about statistics, and Danilo Delibašić for his helpful comments. The work of Lazar Radenković is partially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under Grant No. 174020. The work of Ljubiša Nešić is partially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under Grants No. 174020 and 176021.

The second group of students had the usual class, in which the verbal explanation is accompanied by drawings and diagrams on the board. The third group had the complete bundle – verbal explanations, diagrams on the board, and a chance to conduct simple experiments. This comparison is the main purpose of our work.

The effectiveness of teaching methods was evaluated using a conceptual test developed for this research. The scores of all the groups were very similar. The text group had the highest scores, which was unexpected considering the dry and unappealing teaching method.

In the following text, we have described:

- the sample, research conditions and procedure (section 2),
- the conceptual test, and the precautions we took to ensure a valid comparison (section 3),
- the results of testing, with our interpretations of the results (section 4),
- ideas for further research (section 5),
- the material covered in class (Appendix 1),
- the conceptual test we created for this research (Appendix 2).

2. The Research Procedure

The research was conducted during two school classes (45 min + 45 min). The first one was used for teaching and the second one for conceptual testing. The testing was conducted 9 days after the teaching class.

A total of 50 students of "Bora Stanković" gymnasium from Niš participated in this research. The students were unaware that they were part of the research and thought that it was a regular school activity. Physics was taught by one of the authors (Lazar Radenković), not just for this research, but during the whole school year. Thus, the same teacher covered the same material in the same way with all students, prior to research. All students were from two first-year science classes, learning a basic high school mechanics course. The first class had 20 students, and it was a specialized class for students particularly interested in programming. The second class had 30 students, and it was a specialized bilingual class, so that both Serbian and English were used for teaching. That means that the sample consisted of above-average students. The students were divided into three groups:

1. Text group – 20 students of the programming class (whole programming class); average grade 4.08;
2. Diagram group – 15 students of the bilingual class (half of the bilingual class); average grade 3.63;
3. Experiment group – 15 students of the bilingual class (the other half of the bilingual class); average grade 3.65.

Note that in the Serbian high school system, the lowest grade is 1 (the student failed the test), the first passing grade is 2, and the highest grade is 5.

The bilingual class was sorted by average grade and then all odd and even members of the list were assigned to the second group and third group, respectively. In this way, both the second and third group had a similar average grade. The average grade of the group was calculated using all the grades from all the students in the group (based on four out of five planned grades). We see that the first group had an average grade advantage, while the second and third group were practically equal.

Appendix 1 contains a text that resembles class activities. It is based on (Hajdusianek, 2012; Halidey et al., 2013; Pinto and Fiolhais, 2001; Young and Freedman, 2014). Only the text was used with the first group (no figures or equations). The second group received figures, and the third group could do simple experiments. At the end of the class, the material and equipment had been collected, so the students had no access to it after the class. A detailed description of the workflow with each group is given below.

Text group

The students were told that the main goal of the class was listening and reading comprehension. This had to be done to justify the departure from the usual teaching method. The students were split into 4 teams with 5 students each. The class was structured as follows:

- the teacher read the text presented in Appendix 1 (with no diagrams); each student had to write down 5 to 10 most important things from the text (15 minutes),
- the students compared their notes inside the team (5 minutes),
- each team received a copy of the text to fill their notes (20 minutes),
- the teacher summarized the material, emphasizing the most important conclusions from the text (5 minutes).

During the entire class, the teacher approached the groups, discussed the material with the students and answered their questions. Most of the experiments performed in the experiment group had been discussed in the text group.

Diagram group

The students were divided into three 5-student teams. The material covered with this group is given in Appendix 1. During the class, the teacher asked many questions, using inquiry-based teaching, and the students consulted within the groups and answered. All the experiments done in the experiment group were discussed in the diagram group. These experiments were not performed, they were just drawn on the blackboard. For example, the teacher would ask the students “How could we prove this experimentally?”, and the students would consult within the group and then gave their suggestions. The teacher would comment on those suggestions, drew the experiments on the board, and gave explanations. At the very end of the class, each group received a copy of printed material (Appendix 1) to compare with their own notes.

Experiment group

The class was performed in the same way as in the diagram group, but students had the equipment in front of them. The equipment consisted of marbles, inclined planes, wooden blocks, etc. It was given successively, depending on the question.

The teacher asked various questions, such as “How could we prove this claim, using the equipment we have right here?” The goal was to engage the students as much as possible, using the predict-observe-explain methods described in (Crouch et al., 2004; Miller et al., 2013). After consultation and experimental trials within the teams, the students would answer. The teacher would comment on the answers, correcting if necessary.

The following experiments have been performed:

1. The experiment with a wooden block and an inclined plane. The wooden block is put on a board, and then the board is inclined to a critical angle. It is the maximum angle at which the wooden block is still stationary. For angles above the critical angle, the wooden block slides.
   If the board is inclined at the critical angle, the static friction force can still balance the parallel component of the gravitational force and keep the block stationary. However, if the block is bumped, so that it starts moving, the block will continue to slide all the way to the bottom of the inclined plane. This demonstrates that the maximum value of static friction is greater than the kinetic (sliding) friction, i.e. $\mu_s > \mu_k$.
2. The experiment with marbles and sand. The marble is released from the top of the inclined plane (always from the same position). It rolls down the inclined plane and then continues to roll on a horizontal surface. In the first case, the horizontal surface is a tray filled with sand. In the second case, the horizontal surface is a wooden desk. The students can notice that the marble travels a much shorter distance when it's rolling over the sand, leaving a trace. This is the starting point for the discussion about the role of deformations in a rolling motion.
3. The experiment with a wooden cart and cylinders. Using the inclined plane and critical angle in a manner described in the first experiment, the students can verify which is the easiest way to move the cart. The options are (listed hardest to easiest):
   a) when it’s upside down, sliding;
   b) when it's on the primitive wheels,
   c) when it upside down, rolling over the cylinders.
4. The experiment with plates and ping-pong balls. This experiment demonstrates how bearings work. Two plastic plates are placed in one another. The bottom one is held tight, while the top one is rotated. The students note the sensation. After that, ping-pong balls are inserted between the two plastic plates. Students notice that it takes no effort to rotate the top plate now. Similarly, little metal balls in bearings enable rotation between the axle of a primitive wheel and the wheel itself.

Appendix 1 shows these experiments in the context of a school class, with appropriate explanations.

The readings from the dynamometer showed unreliable and unpredictable, so we opted for the inclined plane in experiments 1 and 3.

3. Conceptual Test and Internal Validity

To test the students’ understanding of friction, we designed a conceptual test given in Appendix 2. Students had 45 minutes to complete the test. Testing had been performed 9 days after the class. The conceptual test consisted of 16 questions, where the correct answer for each question is worth one point, and 0 points otherwise. The only exception was question 13. If the friction force had been properly oriented, but with a wrong point of application (in the center of mass of the ball, instead of the ball-ground contact), the answer was scored with 0.5 points.

To maintain the internal validity of the research, we wanted to minimize the effect of all unwanted variables. We took actions to control for the effect of:

1. Previous knowledge of physics. This variable is controlled by forming groups with an equal average grade. While this was fulfilled for the diagram and experiment group, the text group had a slight advantage. We intentionally assigned them to be the text group. We anticipated the text group would have the worst score, regardless of their grade.
2. Teamwork. Since we had three equipment sets, the experiment group had to be divided into three 5-member teams. That is why we also divided the text and diagram groups into 5-member teams so that all groups had the same working conditions.
3. Students' involvement during the class. We were concerned that the students in the text group would be inactive because of the dry and unappealing presentation of the material. So, we tried to keep them active during the whole class using different tasks. These tasks include: choosing 5 to 10 most important conclusions from the text, comparing notes inside teams, and filling the notes by reading the text themselves. To complete these tasks, students must listen and pay attention to the text.
4. The time spent with the material. Performing experiments takes more time than drawing diagrams or working only with text. We wanted to eliminate the possibility for the experiment group to score better only because they spent more time studying the material. To ensure equal studying time, additional tasks were given to the text group (as described in the previous paragraph), while the diagram group had more time to think and consult within the teams.
5. Students didn't realize that they participated in the research. Informing them about the research would affect the outcome. The research was conducted during regular physics classes, so students thought that all the activities were part of the regular teaching. The division into teams and special tasks and problems were common during the school year. Also, we wanted to make sure that none of the groups knew what the other groups were doing in class. This was easily achieved for the text group since it was a separate class. The second and third group belonged to the same class, so the material was covered in two separate occasions, one for each group.

To ensure fair treatment, after the research had been done, all students had the opportunity to try out the experiments.

4. Results and Discussion

In the text group, the students' inactivity was evident, especially when the teacher read the text. Students tried to follow the text, but most of them gradually gave up and lost the motivation to participate. Those that were active, drew diagrams in their notebooks, often incorrectly. These diagrams remained incorrect even when the students received the text to check their notes. During the class, the students did ask questions, which prompted discussions and the teacher gave detailed (verbal) explanations. There was plenty of time to thoroughly cover the material and answer the students' questions.

In the diagram group, the class was dynamic and interesting. The students were motivated to participate because the questions were interesting. Also, the motivation to collaborate (inside the teams) and compete (among the teams) was much more prominent compared to the text group, even though the class was held in a similar manner. Therefore, the inclusion of diagrams spiced up the class and brought it to life. There was enough time to thoroughly cover the material and answer the students' questions.

In the experiment group, the students showed a lot of enthusiasm and were very motivated to participate. They tried things out, discussed the problems, designed trials, and, ultimately, performed the described experiments. Sometimes it seemed that all the equipment (and its non-intended usage) had been distracting students from physics explanation. With marbles, ping-pong balls, wooden carts, and boards, trays with sand, etc. in front of them, the students reacted as any 15-year-old would – they started playing! Occasional noise caused by the accidental falling of marbles, balls etc. was distracting to the teacher as well. Overall, the class required more effort to keep on track. There was barely enough time to complete the class, and the tempo was a bit rushed. Passing the equipment and setting up experiments, even as simple as the ones used in our research, took more time than expected. This could be prevented by using a physics classroom, but the gymnasium doesn't have one. Despite the mentioned problems, the class was a success. It was very enjoyable for both the students and the teacher. Many students expressed this openly, stating how much they enjoyed the class. It was evident that this class increased their motivation to study physics. This is in accordance with the results reported in (Marušić and Sliško, 2012).

The conceptual test results were calculated based on the scores of 46 students. Four students were absent and not included in the results. This affected the average grade of the groups. The corrected average grade is given in table 1. A One-way ANOVA showed no statistically significant difference for the average grade of the groups, $F(2, 43) = 0.886, p = 0.42$.

All three groups scored similarly on the conceptual test, as shown in table 1. This is confirmed using One-way ANOVA, $F(2, 43) = 0.140, p = 0.87$. The test group, in fact, had a highest score, despite the poor teaching method. We anticipated that the diagram and experiment group would score similarly because it has been reported before that laboratory work might not significantly influence lecture success (Holmes et al., 2017; Roth et al., 1997; Toothacker, 1983; Wieman and Holmes, 2015). Also, it has been reported before (Halloun and Hestenes, 1985) that conceptual test scores can be almost independent from the style of teaching. Still, we didn't expect the text group to score so high. The results can be seen in table 1 and figure 1. Note that the maximum score on the test is 16. The highest individual score was 14 points (in all three groups), and the lowest individual score was 7 points (again, in all three groups). The results for each individual question can be seen in figure 1.

A One-way ANCOVA was conducted to determine whether a statistically significant difference exists for the score of the text, diagram and experiment group, controlling for their average grade. The analysis showed no significant difference, $F(2, 42) = 0.028$, $p = 0.97$. It was previously validated using the Kolmogorov-Smirnov test that the distributions for both the average grade and test scores do not differ significantly from the normal distribution.

In conclusion, we can say that the groups were even in their average grade, and performed equally on the conceptual test, regardless of the teaching method.

Table 1 Average score for the students of each group.

	Text group	Diagram group	Experiment group
Average grade	4.04	3.63	3.77
Average score (points)	10.17	9.80	10.00
Average score (%)	63.56	61.25	62.50

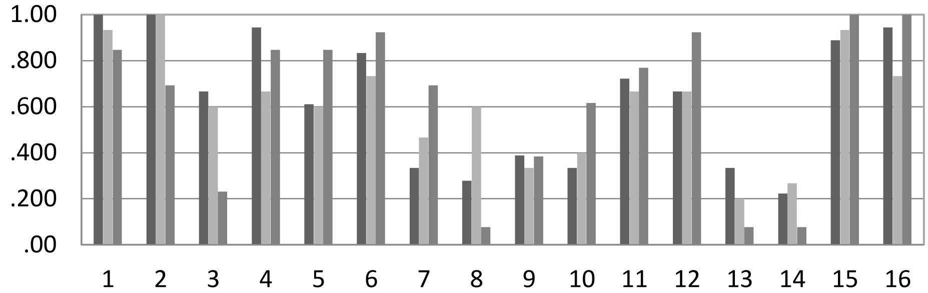

Fig. 1 The proportion of correct answers for each of the 16 questions. The bars (left to right, respectively) correspond to text, diagram and experiment group.

We tried to analyze the results for each question (figure 1), and provide rudimental explanations. Lack of post-test interviews with students to pinpoint the exact causes of the test differences is a major shortcoming of our research. It is unfortunate that the circumstances didn't allow for it. Still, based on our own observations, we tried to examine the questions with similar scores, questions with different scores, and unsuitable questions.

The score was similar (questions 1, 6, 9, 11, 15)

Question 1 dealt with examples of three main types of friction. It is a basic question, hence the similar score. Only two answers need to be known, and the third is obtained by elimination. All groups scored high with only a few students making a mistake.

Question 6 is meant to examine the students' understanding of the effects of deformation on friction. Students scored high on this question because the same example was used during the teaching class. Since "teaching to the test" is something to be avoided, we should have chosen another example for the class.

Question 9 and 11 are similar in the sense that the answer to both questions is simple and can be easily explained with one sentence. This could be the cause for the similarity in scores. However, question 9 is a bit more involved and requires a good understanding of static friction.

The question 15 is basic and can be answered without physics education, thus all groups scored similarly. A formalized variant of this question is question 5, with significantly lower scores. Here, the experiment group scored the highest probably because this question is closely related to the wooden block and inclined plane experiments (see section 2).

The score was different (questions 2, 3, 8, 10, 12, 13, 14)

The experiment group scored significantly lower on question 2, which is a simple question that has been answered by everyone in the remaining groups. This is a puzzling result, especially considering the scoring on question 5, and the aforementioned experiment with a wooden block and inclined plane.

Question 3 is very similar to question 14. Those two questions can be regarded as the same question in textual and diagram form. That's why it is surprising that the students scored low on question 14 and high on question 3. We suspect the reason for this might be the wording of question 14, which implies that there is friction force in that case, when, in fact, there is none. This question should be improved. Another explanation is that question 14 is simply a hard question, just like question 13, which has no wording issues. However, we see no apparent reason for the fact that the experiment group scored lower in the questions 13 and 14 compared to other groups.

On question 8, the diagram group scored significantly higher. This is puzzling since this is no trivial question. Students have to understand the situation without the visual cues, understand that static friction occurs, and understand that expression $f = \mu N$ applies only to sliding friction.

Question 10 examined the effect of the normal force on friction. It is not clear why the experiment group performed better on this question.

Question 12 deals with rolling motion that was thoroughly covered in the teaching material. We believe the experiment group scored the highest because they performed the experiment with a wooden cart and cylinders, which is closely related to this question.

Unsuitable questions (questions 7, 14, 15, 16)

Questions 7 and 16 should be removed from the test. The knowledge required for answering question 7 is contained in the class material, but it’s not stressed enough, and it certainly isn’t the focus of the class. It requires writing down the equations of motion and noticing the difference in moments of inertia for the ball and the cylinder. Question 16 is a trivial one. It is interesting that the second group didn’t score well on this question. We suspect they misunderstood the question.

Questions 14 should be rephrased, as stated previously. Question 15, although well understood, could also be improved. It should state *box* instead of a body, and note that the box is *sliding* with constant velocity over *rough* ground.

The rest of the questions

Question 4 checked if students understood that the familiar expression $f = \mu N$ applies only if there is sliding friction. In case there is static friction, no formula can be written without the equations of motion. It is interesting that the text and experiment group scored high on question 4 and low on question 8.

Question 13 proved to be a difficult one for all groups. Text group scored the highest, possibly due to their average grade advantage.

5. Conclusions and Further Research

Although our research is limited in scope, we believe it is interesting and worth reporting. Our results show that the demonstrations and experiments haven't significantly affected the score on the conceptual test. The most surprising aspect of the research was the fact that the text group scored so high. We did see, however, increased students' involvement when diagrams or experiments were included in the class.

Some of the reasons that possibly attributed to even test scores include:

1. the applied conceptual test might not be discriminative enough. For our future research, we intend to improve the conceptual test about friction and validate it as a measurement tool using statistical methods.
2. the applied conceptual test is biased towards the diagram and text group. A more thorough comparison of students' conceptual knowledge would involve both written and practical forms of testing. Also, we noted an interesting fact in this research – some students (from all groups, not just experimental group) used their pens and other stationery for simple trials while they were doing the test. A similar variant could, therefore, involve written testing with equipment available for trials.
3. the teaching and testing class were separated by 9 days, due to technical constraints of performing this research. This period is long enough for the students to forget the concepts they learned. Alternatively, they had enough time to talk about the topics after the class and before testing.
4. all the students that participated are above-average students, to begin with.

Hopefully, we will be able to examine these assumptions in future research.

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POREĐENJE TEKSTUALNOG, VIZUELNOG I PRAKTIČNOG NAČINA RADA U NASTAVI FIZIKE

Ista lekcija o trenju obrađena je od strane istog nastavnika na tri različita načina: koristeći samo verbalni i tekstualni vid komunikacije (tekst grupa), koristeći dijagrame i crteže (dijagram grupa) i koristeći jednostavne eksperimente (eksperiment grupa). Konceptualno razumevanje učenika provereno je uz pomoć testa razvijenog za potrebe ovog istraživanja. Rezultati sve tri grupe na konceptualnom testu bili su veoma slični.

Ključne reči: *priručni eksperimenti, demonstracije, trenje, konceptualno razumevanje*

APPENDIX 1: FRICTION AND ROLLING

Usually, three types of friction are examined: static friction, sliding friction, and rolling friction.

Static Friction

If a very small horizontal force is applied to a body that is resting, it will remain at rest. For example, if we slightly pull a wooden box lying on a table, it will remain stationary. That means that the value of the active force (by which we are pulling the object) is equal to the friction force – in this case, static friction. If we slightly increase the magnitude of the active force (figure A1), the body may still be at rest. That means that the friction force must increase together with the active force. If we lower the magnitude of the active force or change its direction, the static friction force will change accordingly, so that the box remains at rest. If the magnitude of the active force is equal to zero, so will be the magnitude of the friction force.

The static friction force is described by $f_s \leq \mu_s N$, where N is the normal force and μ_s is a coefficient giving the maximum value of the static friction force, right before sliding.

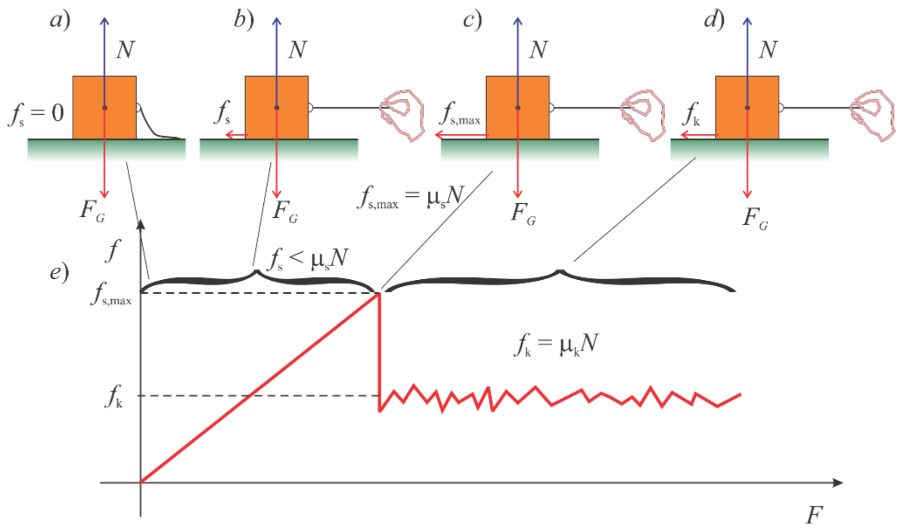


Fig. A1 a) No active force to cause friction; b) The body is still at rest, which means that the pull is balanced by static friction $f_s \leq \mu_s N$; c) The magnitude of the active force reaches $\mu_s N$ and the body starts sliding; d) The body slides and the friction force has approximately the same value $f_k = \mu_k N$; e) Graph showing how the friction force depends on the active force.

Sliding Friction

If we keep increasing the value of the active force, eventually, the body will start sliding (figure A1). Right before sliding, the static friction force has reached its maximum value. Sliding friction force has an approximately constant value, which is lower than the maximum value of the static friction.

In a narrow domain of the phenomena studied by high school mechanics, sliding friction can be assumed to be independent of the relative speed and the surface area. Sliding friction can be, therefore, represented by $f_k = \mu_k N$, where N is normala force, as before, and μ_k is a coefficient of sliding friction (also known as kinetic friction, hence the letter k in the subscript).

Rolling friction

Let's examine a ball that's rolling without slipping on flat horizontal ground (figure A2). Based on our experience, we know that the ball will eventually stop, which leads us to the conclusion that the friction force is acting in an opposite direction from the ball's velocity. This conclusion explains the ball's translational motion. However, if we examine the rotation of the ball around its axis, then a friction force with this direction would cause angular acceleration! That means that the ball should decelerate its translation and accelerate its rotation, which is both theoretically and practically impossible.

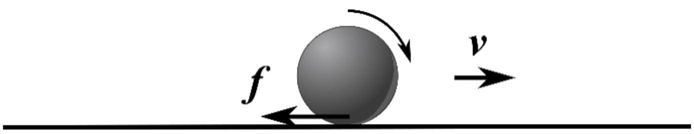


Fig. A2 The ball rolling on a horizontal ground.

Friction force can be assumed to be in the same direction as velocity, with a good justification. Since the ball is rotating, the lower part of the ball tends to go backward and since there is no slipping, that means that the friction force must be acting in the direction of the motion of the ball to prevent sliding. The same can be said for walking when the foot is in contact with the ground. Note that friction is not always opposed to the motion of the body itself – friction prevents *relative motion of contact surfaces*. However, in this case, the friction force would simultaneously cause angular deceleration and linear acceleration, which is impossible.

To explain this paradox, the deformation of the ball and/or the ground has to be considered. The deformation must be asymmetric, i.e. different from the front and back side of the rolling ball. To prove this, let's first examine the perfectly elastic and symmetrical deformation, shown in the figure A3, left. The sum of all interactions left and right of the center of the ball is represented by forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$, respectively. If deformation is perfectly elastic, the forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ have the same magnitude and they are symmetric about the vertical line dividing the ball in half. That means that the resultant force $\boldsymbol{F}_1 + \boldsymbol{F}_2$ goes through the center of the ball, and has a zero torque (moment arm is equal to zero). Since the ball slows down, there must be a torque that decelerates its angular speed – something perfectly symmetric deformations cannot account for.

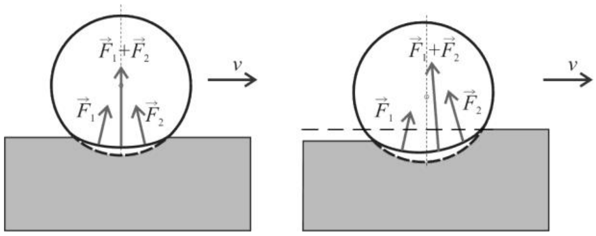


Fig. A3 Elastic and non-elastic deformation during rolling.

On the other hand, if the ball is rolling on sand, the sand behind it will be compressed (figure A3, right), and asymmetric deformations will occur. The resultant force $\boldsymbol{F}_1 + \boldsymbol{F}_2$ doesn't go through the center of mass and its torque will slow down the rotation. Its horizontal component will also slow down the translation. The ball is slowing down as we expect. Another way to look at this is using conservation laws. The ball keeps losing it's using kinetic energy (both translational and rotational) on ground deformations, and it slows down. This is the reason why it is harder to push the ball on deformable ground (for example sand or earth) than on rigid ground (such as a wooden desk, or concrete). Your teacher found out about this the hard way, by pushing the car over a lawn.

The rolling of a rigid ball on a rigid ground needs to be examined. This is the case where both the deformation of both the ball and the ground can be neglected. Let us, therefore, examine the motion of the ball in two cases: (a) down the inclined plane; (b) on the horizontal plane. All the time, we are assuming that the ball rolls without slipping. That means that the point of contact between the ball and the ground is still, and static friction occurs. It is important to keep in mind that the static friction force depends solely on the applied active force.

Inclined plane. If there was no friction, the ball would slide down the inclined plane with no rotation. Since the ball accelerates its rotation, there must be a torque (from the friction force) to cause it. The active force here is the parallel component of the gravitational force, so the friction force is acting in an opposite direction (figure 4).

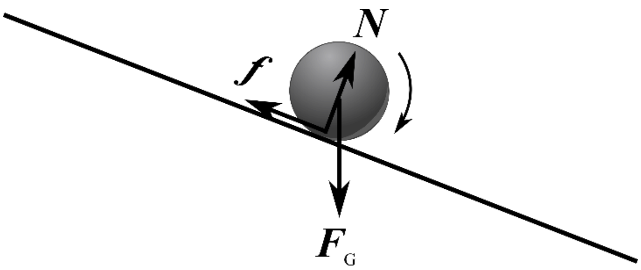


Fig. A4 The ball rolling down the inclined plane.

Translational motion is described by following scalar equations:

$$F_{\mathrm{Gp}} - f = ma,$$

$$F_{\mathrm{Gn}} = N,$$

and the rotational motion is described by:

$$M = I\,\alpha \quad \Rightarrow \quad fR = \frac{2}{5}mR^2\alpha.$$

The ball rolls without slipping, so $a = R\,\alpha$. The acceleration a can be calculated by solving these equations. It should be stressed that $f = \mu N$ is *an incorrect* equation for the magnitude of the friction force, since the static friction force is acting in this case, not the sliding friction force.

Horizontal ground. Now, let's examine what happens when the ball rolls on a horizontal ground. If we treat the horizontal ground as a special case of an inclined plane (when the angle is zero), the friction force would be directed parallel to the ground, opposite to the ball motion (figure A2). However, that would lead to a problem described at the beginning of this section in which the friction force paradoxically decelerates translation and accelerates rotation.

The answer lies in the fact that the static friction force has no predetermined magnitude and direction. The active force will determine the magnitude and direction of the static friction force. Remember the example in which we're pulling the box (figure A1).

When the ball rolls down the inclined plane, the friction force is a consequence of the parallel component of the gravitational force. When the ball rolls on the horizontal ground there is no active force which acts parallel to the ground, so no static friction occurs. Therefore, the surprising conclusion is that no friction force is acting on the ball that is rolling on a horizontal ground (figure A5). Therefore, the center of mass of the ball keeps moving uniformly, by inertia, because no force is changing that state of motion. Also, the ball keeps rolling with uniform angular velocity because no torque is changing that state of rotation.

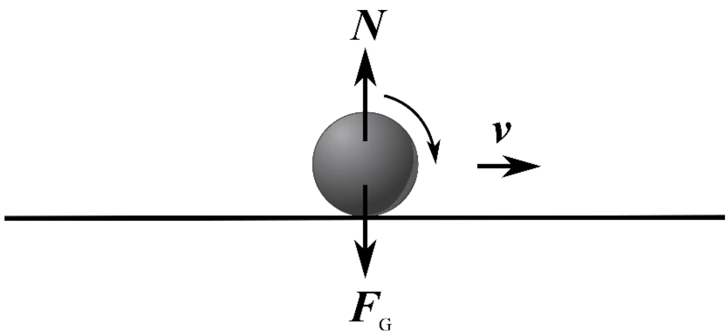


Fig. A5 The free body diagram for a rigid ball rolling on a rigid horizontal ground.

In reality, the ball will stop because of the impurities between it and the ground, the deformation on a microscopic level, air resistance and similar effects.

We conclude, therefore, that rolling friction occurs *only* when the ball and/or the ground deforms. If the ball and the ground are perfectly rigid, static friction occurs.

The wheel as a technological revolution

From the previous discussion, it can be seen why rolling is a preferred method for moving an object, especially compared to sliding. A primitive wheel takes advantage of the rolling phenomena. A primitive wheel consists of an axle made from wood or metal that goes through a hole in the middle of the wheel. The axle is fixed, and the wheel is rotating around it. When this wheel is used, there is no sliding between the wheel and the ground, but there is sliding between the wheel and the axle. The primitive wheel is effective because the sliding happens on a much smaller distance than if there were no wheels.

The most effective way to move a load would be if there was no sliding, but only rolling. This can be done if small cylinders are used instead of wheels. To demonstrate this, we'll be using a wooden cart with primitive wheels, a few wooden cylinders and a dynamometer (figure A6). In the first case, the wooden cart is sliding upside down on its flat surface. The dynamometer will show the maximum value for the friction force. In the second case, the cart is being moved on its primitive wheels. The dynamometer will show significantly lower values. Finally, in the third case, the cart is turned upside down, but cylinders are inserted between the flat surface and the ground. The dynamometer will show the least value. If dynamometers are not available, the inclined plane can be used by noting a critical angle for each situation.

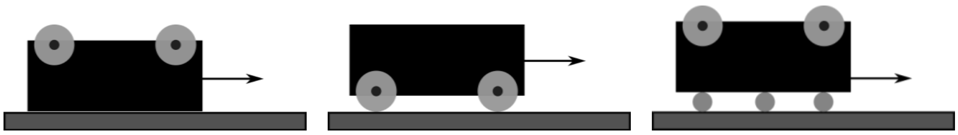


Fig. A6 Pulling a wooden cart in different ways.

Even though the resistance is the least when cart moves using the cylinders, they're impractical, mostly because they must be repositioned all the time. To solve both the problem of sliding with the primitive wheels and impracticality of cylinders, modern bearings are used (figure A7). With bearings, small balls are inserted between the wheel and the axle that can roll when the wheel rolls. How bearings work can be shown by using this simple demonstration. If we put two plastic plates into one another and keep the lower plate stationary and try to rotate the upper plate, we will see that it is necessary to use a significant amount of force. That corresponds to sliding. If we insert ping-pong balls between the plates and try again, we will see how much easier it is to rotate the upper plate. That corresponds to the usage of bearings.

Fig. A7 Diagram of a wheel with bearings.

APPENDIX 2: CONCEPTUAL TEST ABOUT FRICTION

1. Connect the following phenomena with basic types of friction:

a) walking (foot on the ground)	1. rolling friction
b) breaking (rubber brake plate in contact with the rim of a bicycle wheel)	2. static friction
c) roller skating (rubber wheels in contact with the ground)	3. sliding friction

2. Static friction has the maximum values immediately before the body starts sliding.
TRUE FALSE

3. If a rigid ball rolls without slipping on a rigid horizontal ground with constant velocity:
a) sliding friction occurs;
b) rolling friction occurs;
c) static friction occurs;
d) no friction occurs.

4. Which statement is correct:
a) The static friction force always has a value given by the expression $f = \mu_s N$.
b) The static friction force is not predetermined, and its magnitude and direction are obtained by solving equations of the particular situation.

5. Static friction is
a) greater than sliding friction;
b) less than sliding friction;
c) equal to sliding friction.

6. It is easier to push the car:
a) on the pavement.
b) on the lawn.

7. A ball and a cylinder of the same mass are rolling without slipping down the same inclined plane. Friction force will be the same in both cases.
TRUE FALSE

8. A ball is rolling without slipping down the inclined plane, all deformations being negligible. The friction force is described by equation $f = \mu N$.
TRUE FALSE

9. The friction force between two bodies in contact can be equal to zero, even though the contact surface is rough.

TRUE FALSE

10. The sliding friction force between the body and the ground is greater when the ground is:

a) horizontal.
b) inclined.

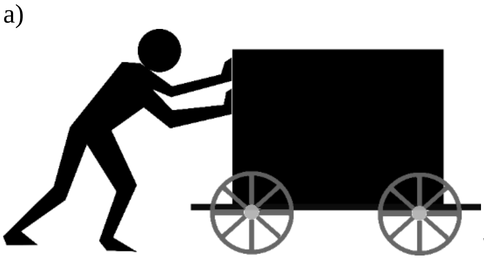
11. The invention of the primitive wheel completely eliminated sliding friction and replaced it with rolling friction.

TRUE FALSE

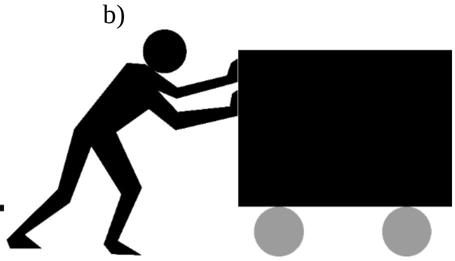
12. An ancient Roman slave had the task to transport a very heavy load along the gravel road on a hot sunny day. In the first case, the load is on the cart with primitive wheels. In the second case, wooden logs are put under the load. In the third case, the load is on a wooden sled.

Rank these situations from *easiest to hardest* to push.

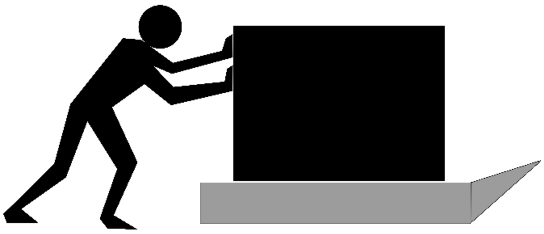
a)



b)

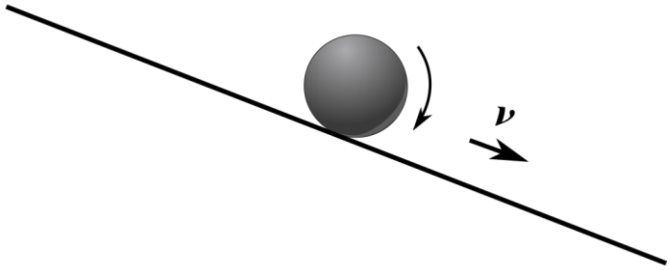


c)

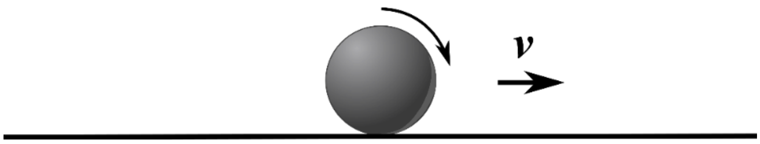


Answer: _________;___________;__________

13. Draw the friction force in the given picture. The ball rolls without slipping and the deformation of the ball and the ground are negligible.



14. Draw the friction force in the given picture. The ball rolls without slipping and the deformation of the ball and the ground are negligible.



15. Does it take less effort to:
a) push the body and move it from rest;
b) push the body to keep it moving with constant velocity?

16. If we push a wooden cart over the following surfaces, in which case will the sliding friction be the least?
a) ice;
b) sand;
c) sandpaper;
d) tarmac;
e) lawn.