Demonstration of Energy Transfer and Momentum Conservation Using Gauss Rifle

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Abstract

The Gauss Rifle experiment explores the conversion of magnetic energy into kinetic energy through the collision of steel balls. The analysis of data from different configurations, including single magnet, two magnets, and three magnets, reveals the conservation of momentum, evident in the increase of final momentum compared to initial momentum. However, complete energy conservation is not achieved, as observed by the higher initial kinetic energy relative to the final kinetic energy due to energy losses. Furthermore, a direct relationship is observed between initial velocity and initial kinetic energy, while a positive correlation exists between final velocity and final kinetic energy. These findings contribute to a deeper understanding of the Gauss Rifle system, emphasizing the significance of momentum and energy conservation in its underlying dynamics.

Keywords: Gauss Rifle, Magnetic energy, Momentum, Kinetic Energy

1. Introduction

It is now possible to create a variety of simple but powerful magnetic force displays because of the development of affordable and accessible NdFeB magnets. These experiments include the "Gauss rifle," a kind of linear magnetic accelerator [1]. The magnetic cannon, often known as the Gauss gun, is a simple tool that accelerates a steel ball by transforming magnetic energy into kinetic energy. The energy conversion process is similar to other accelerating devices, including rail guns, based on electromagnetism [2]. A Gauss rifle has at least one magnet stage, though it may also have numerous succeeding magnet stages. Several ball bearings touching each other on one side of a magnet define a magnet stage. This project's first magnet stage will include a second ball bearing, which we'll refer to as the "starter" ball, on the opposite side. The starter ball must roll toward and then strike the first magnet stage in order for the Gauss rifle to fire a ball bearing. This sets off a series of events that culminate with the launcher ejecting its final ball bearing [3]. For the purpose of understanding the physics of the Gauss rifle, the process can be broken down into three phases: (i) acceleration of the ferromagnetic steel ball in the magnetic field produced by the magnet (ii) momentum propagation into the chain of steel balls, which is comparable to the propagation in Newton's cradle (iii), and (iv) ejection of the final ball escaping the residual magnetic attraction [4]. This experiment could be used in introductory physics classes to boost student motivation as they tackle an unsolved energy conservation issue. In a more traditional laboratory experiment, students might apply their knowledge of magnetism to determine by magnetic force and magnetic field measurements whether the approaching steel ball should be regarded as a permanent or an induced magnet.

2. Theory

The conservation of energy is a fundamental principle in physics, stating that the total energy of a closed system remains constant over time. In the case of the Gauss Rifle experiment, energy is initially stored in the magnetic field of the magnet and then converted into kinetic energy as the steel ball is ejected and collides with another ball.When the steel ball is ejected, the magnetic potential energy stored in the magnet is transformed into kinetic energy. The kinetic energy of the ejected ball is equal to the magnetic energy of the magnet.

According to the conservation of energy principle, the total energy of the system should remain constant. In this case, the initial magnetic energy of the magnet is converted entirely into the kinetic energy of the ejected ball. There should be no significant losses due to friction or other dissipative forces. By measuring the kinetic energy of the ejected ball and comparing it to the initial magnetic energy, you can verify if the energy conservation principle holds true. If the measured kinetic energy matches the initial magnetic energy within a reasonable margin of error, it provides evidence for the conservation of energy in the system [5]

To prove this Theory, we will use the following formula:

To find the estimated initial velocity we will use:

$$V_f^2 = v_i^2 + 2ad \tag{1}$$

In this case we let the initial velocity to be zero:

$$V_i = V_f = \sqrt{2ad} \tag{2}$$

To find the acceleration of the ball we will use:

$$a = g \sin\theta \tag{3}$$

Calculating the initial velocity, we can now take the final velocity where we will use the eq. 1.

To calculate the kinetic energy KE, we will use:

$$KE = \frac{1}{2}mv^2 \tag{4}$$

Since the Kinetic energy of the ejected ball can be considered as the transferred magnetic energy from the magnet, by measuring KE we are effectively measuring the Magnetic energy in the Gaussian system.

$$KE = B \tag{5}$$

To show that momentum is conserved in the Gauss rifle experiment we will use:

$$P_{initial} = P_{final} \tag{6}$$

$$\frac{1}{2}mv_{initial} = \frac{1}{2}mv_{final} \tag{7}$$

Since forces are an interaction between objects, the force on the initially moving ball must be the same magnitude as the force the moving ball exerts on the rest of the ball. Further, the time these forces act on each other should also be the same. The same force (magnitude) and the same time mean the other stuff will have the same change in momentum (magnitude). This is the conservation of momentum. It is a consequence of forces interacting in a closed system.

3. Method

The process of the Gauss rifle shot is usually described by four different steps. Firstly, A trigger ball is rolled towards the magnet. Secondly, the trigger ball gains kinetic energy due to the magnetic attraction and collides with the magnet. Thirdly, in a way akin to Newton's cradle, the kinetic energy is transferred from the trigger ball to the projectile ball. Fourthly, the projectile moves away from the magnet and its final velocity is higher than the initial velocity of the trigger ball.

For the representation of data, I will use linear square fits, also known as linear regression, to analyze the relationship between kinetic energy and magnetic energy in the Gauss Rifle experiment. Linear regression helps determine the best-fit line that represents the linear relationship between two variables. In this case, you can perform linear regression with magnetic energy as the independent variable (x-axis) and kinetic energy as the dependent variable (y-axis).

By fitting a linear regression line to the data points, I can assess the strength and direction of the linear relationship between the two energy forms. The slope of the line will provide insight into how the kinetic energy changes with respect to magnetic energy. Linear regression analysis can also help in making predictions or estimating kinetic energy values based on magnetic energy values outside of the measured data range.

To perform linear regression, I will be using various software tools such as Excel, and Python with libraries like NumPy and SciPy. These tools provide functions to calculate the regression line and determine the goodness of fit using metrics such as the coefficient of determination (R-squared value) or p-values.

4. Results and Discussion

Number of Magnets	Trials	Distance (m)	Initial Velocity (m/s)	Final Velocity (m/s)
1	1	0.637	2.067	2.924
	2	0.599	2.005	2.835
	3	0.524	1.875	2.652
			Ave: 1.982	**Ave: 2.804**
2	1	0.439	1.716	2.427
	2	0.353	1.539	2.177
	3	0.468	1.772	2.506
			Ave: 1.676	**Ave: 2.370**
3	1	0.286	1.385	1.959
	2	0.275	1.358	1.923
	3	0.294	1.405	1.987
			Ave: 1.383	**Ave: 1.956**

Table 4.1: The Initial and Final Velocity Per Number of Magnets

Number of Magnets	Average Vi Per number of magnets	Average Initial Kinetic Energy (J)	Average Magnetic Energy (J)
1	2.804	0.016	0.016
2	2.370	0.012	0.012
3	1.956	0.0079	0.0079

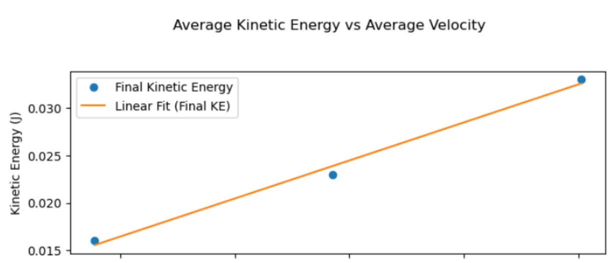
Table 4.2: The Initial Kinetic and Magnetic Energies Per Average Initial Velocities

Number of Magnets	Average Vf Per number of magnets	Average Final Kinetic Energy (J)	Average Magnetic Energy (J)
1	2.804	0.033	0.033
2	2.370	0.023	0.023
3	1.956	0.016	0.016

Table 4.3: The Final Kinetic and Magnetic Energies Per Average Final Velocities

Number of Magnets	Initial Momentum (kg m/s)	Final Momentum (kg m/s)
1	0.023	0.020
2	0.019	0.014
3	0.016	0.012

Table 4.4: The Initial and Final Momentum Calculated Per Number of Magnets



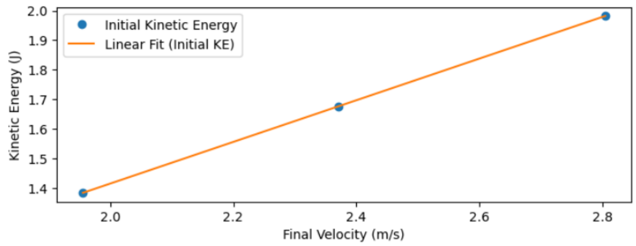


Figure 4.1 Average Kinetic Energies vs. Average Velocities

From the given data in the Gauss Rifle experiment, where we have the final velocity of the ejected ball and the corresponding kinetic energy for each trial and configuration (single magnet, two magnets, three magnets), we can draw some deduction about the relationship between final velocity and kinetic energy.

Firstly, looking at the data points and the linear regression lines, we observe a positive correlation between the final velocity and the kinetic energy. As the final velocity of the ejected ball increases, the kinetic energy also tends to increase. This relationship is consistent across all configurations, including the single magnet, two magnets, and three magnets. Furthermore, the linear regression lines provide an estimate of the average relationship between final velocity and kinetic energy for each configuration. The slopes of the regression lines indicate the average change in kinetic energy per unit change in final velocity. A steeper slope suggests a stronger correlation between velocity and kinetic energy. Comparing the slopes of the linear regression lines for different configurations, we can see that the single magnet configuration has a relatively higher slope compared to the two magnets and three magnets configurations. This indicates that, on average, the single magnet setup exhibits a greater change in kinetic energy per unit change in final velocity compared to the other configurations.

The data and the linear regression analysis demonstrate the relationship between final velocity and kinetic energy in the Gauss Rifle experiment. The positive correlation between these variables confirms that as the final velocity of the ejected ball increases, the kinetic energy also increases. The specific configuration of the Gauss Rifle setup can influence the magnitude of this relationship, as evident from the variations in the slopes of the linear regression lines.

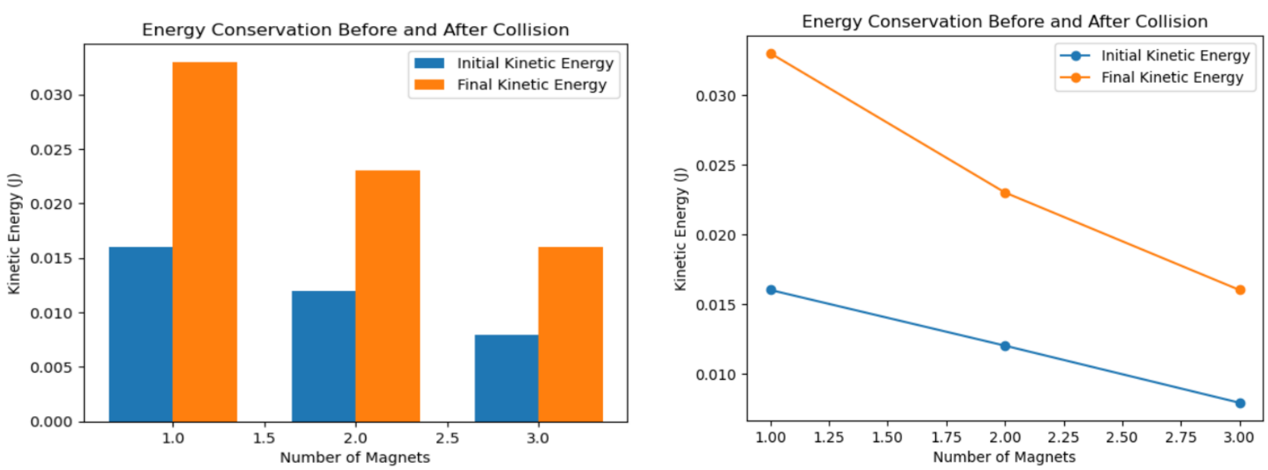


Figure 4.2: Line and Bar Graph Showing the Conservation of Energy Before and After the Collision

A relatively higher final kinetic energy in the Gauss Rifle experiment suggests that the energy transfer from the magnet to the ball was relatively efficient in the specific setup. Factors such as the strength of the magnetic field, the design of the system, and the reduction of energy losses through measures such as minimizing friction or optimizing the alignment of components may have contributed to this result. However, it is important to consider that experimental results can vary due to factors like measurement errors, uncertainties, and the complexity of the system. Achieving perfect energy conservation in the Gauss Rifle experiment is challenging, and variations in the data are expected. Therefore, while the higher kinetic energy data is interesting, it is essential to interpret the results with consideration for the experimental conditions and potential sources of variability or error.

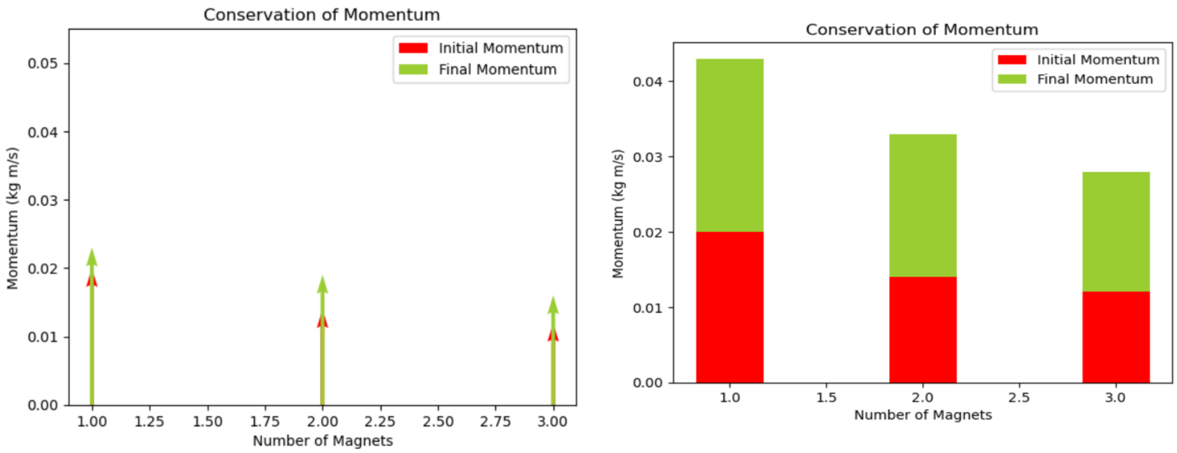


Figure 4.3: Graph Showing the Momentum Vector as Arrows and the Bar Graph Showing the Initial Comparison of Initial and Final Momentum

From the given data on momentum and energy conservation in the Gauss Rifle experiment, we can draw some conclusions regarding the relationship between the number of magnets, momentum conservation, and energy conservation.

Looking at the momentum data, we observe that the initial momentum values are lower than the corresponding final momentum values for all configurations (single magnet, two magnets, three magnets). This indicates a gain in momentum during the collision process, suggesting that momentum is conserved in the system. The increase in momentum can be attributed to the transfer of momentum from the magnets to the ejected ball, as it gains velocity and moves in the opposite direction. In terms of energy conservation, we can consider kinetic energy as a proxy for energy. The kinetic energy values indicate that the initial kinetic energy is higher than the final kinetic energy for most configurations. This suggests that energy is not fully conserved in the system, and there are energy losses during the collision process. Factors such as friction, air resistance, and imperfect energy transfer contribute to these energy losses.

The disparity between momentum conservation and energy conservation can be attributed to the specific design and dynamics of the Gauss Rifle experiment. While momentum is more likely to be conserved due to the system's closed nature, energy conservation is affected by various factors that can introduce inefficiencies and energy dissipation. It is important to consider that the experimental conditions, setup, and measurements may introduce variability and uncertainties in the data. The observed trends in momentum and energy conservation provide valuable insights into the principles of the Gauss Rifle experiment. However, achieving perfect conservation in real-world experiments can be challenging due to practical limitations and factors that affect energy transfer and dissipation.

Overall, the data highlights the importance of considering both momentum and energy conservation in the context of the Gauss Rifle experiment. It reinforces the understanding that momentum is conserved, while energy conservation is influenced by various factors, leading to energy losses during the collision process. These insights contribute to a deeper understanding of the dynamics and principles underlying the Gauss Rifle experiment.

5. Conclusion

The Gauss rifle exhibits a representation of energy and momentum conservation. From the accumulated data, we can conclude that momentum is conserved during the collision process. The final momentum values are higher than the initial momentum values, indicating a gain in momentum as the ejected ball moves in the opposite direction. This observation aligns with the fundamental principle of momentum conservation.

However, the data also suggests that energy conservation is not fully achieved in the system. The initial kinetic energy is generally higher than the final kinetic energy, indicating energy losses during the collision process. Factors such as friction, air resistance, and imperfect energy transfer contribute to these energy losses.

References

[1] (PDF) the Gauss Rifle and magnetic energy - researchgate, https://www.researchgate.net/publication/243715504_The_Gauss_Rifle_and_Magnetic_Energy (accessed Jul. 15, 2023).

[2] D. Kagan, "Energy and momentum in the Gauss Accelerator," AIP Publishing, https://pubs.aip.org/aapt/pte/article-abstract/42/1/24/274145/Energy-and-Momentum-in-the-Gauss-Accelerator?redirectedFrom=fulltext (accessed Jul. 15, 2023).

[3] "Build a gauss rifle!: Science project," Science Buddies, https://www.sciencebuddies.org/science-fair-projects/project-ideas/Phys_p081/physics/gauss-rifle (accessed Jul. 15, 2023).

[4] Magnetic cannon: The physics of the gauss Rifle - hal.science, https://hal.science/hal-02408779/document (accessed Jul. 15, 2023).

[5] [1] Magnetic cannon: The physics of the gauss Rifle, https://hal.science/hal-02408779/document (accessed Jul. 15, 2023).

Appendix I: Sample Calculation

Acceleration:

$$a = g \sin\theta$$
$$a = 9.81 \sin(20)$$
$$a = 3.355 \frac{m}{s^2}$$

Sample Calculation for Estimate Initial Velocity:

Note: we let $V_i = 0$

$$V_f = \sqrt{2ad}$$

1 magnet:

Trial 1:

$$V_f = \sqrt{2(3.355)(0.637)}$$
$$V_f = 2.067 \text{ m/s}$$

Sample Calculation for Final Velocity:

Note: We will use the value we obtained as initial velocity:

$$V_f = \sqrt{v_i^2 + 2ad}$$

1 magnet:

Trial 1:

$$V_f = \sqrt{2.067 + 2(3.355)(0.637)}$$
$$V_f = 2.924 \text{ m/s}$$

Sample Calculation for $KE_{initial}$

$$KE_{initial} = \frac{1}{2} m v_{inital}^2$$
$$KE_{initial} = \frac{1}{2}(0.00833)(1.982)^2$$
$$KE_{initial} = 0.016\, J$$

Sample Calculation for KE_{final}

$$KE_{final} = \frac{1}{2} m v_{final}^2$$
$$KE_{final} = \frac{1}{2}(0.00833)(2.804)^2$$
$$KE_{final} = 0.033\, J$$

Sample Calculation for momentum:

$$P_{initial} = P_{final}$$
$$mv_{initial} = mv_{final}$$
$$(0.00833)(1.982) = (0.00833)(2.804)$$
$$0.020 = 0.023$$

Appendix II: Code Listings

Average Kinetic Energy Vs. Average Velocity

Linear Square Fits

```
import numpy as np
import matplotlib.pyplot as plt
from scipy import stats

# Data
num_magnets = np.array([1, 2, 3])
average_velocity = np.array([2.804, 2.370, 1.956])
final_kinetic_energy = np.array([0.033, 0.023, 0.016])
initial_kinetic_energy = np.array([1.982, 1.676, 1.383])

# Linear regression for final kinetic energy
slope_final, intercept_final, _, _, _ = stats.linregress(average_velocity, final_kinetic_energy)
line_final = slope_final * average_velocity + intercept_final

# Linear regression for initial kinetic energy
slope_initial, intercept_initial, _, _, _ = stats.linregress(average_velocity, initial_kinetic_energy)
line_initial = slope_initial * average_velocity + intercept_initial

# Plotting
fig, (ax1, ax2) = plt.subplots(2, sharex=True, figsize=(8, 6))

# Plot for final kinetic energy vs final velocity
ax1.plot(average_velocity, final_kinetic_energy, 'o', label='Final Kinetic Energy')
ax1.plot(average_velocity, line_final, label='Linear Fit (Final KE)')
ax1.set_ylabel('Kinetic Energy (J)')
ax1.legend()

# Plot for initial kinetic energy vs final velocity
ax2.plot(average_velocity, initial_kinetic_energy, 'o', label='Initial Kinetic Energy')
ax2.plot(average_velocity, line_initial, label='Linear Fit (Initial KE)')
ax2.set_xlabel('Final Velocity (m/s)')
ax2.set_ylabel('Kinetic Energy (J)')
ax2.legend()

plt.suptitle('Average Kinetic Energy vs Average Velocity')

plt.show()
```

Energy Conservation Before and After Collision

Line Graph:

```
import numpy as np
import matplotlib.pyplot as plt

# Data
num_magnets = [1, 2, 3]
initial_kinetic_energy = [0.016, 0.012, 0.0079]
final_kinetic_energy = [0.033, 0.023, 0.016]

# Plotting
plt.plot(num_magnets, initial_kinetic_energy, 'o-', label='Initial Kinetic Energy')
plt.plot(num_magnets, final_kinetic_energy, 'o-', label='Final Kinetic Energy')
plt.xlabel('Number of Magnets')
plt.ylabel('Kinetic Energy (J)')
plt.title('Energy Conservation Before and After Collision')
plt.legend()
plt.show()
```

Bar Graph:

```
import numpy as np
import matplotlib.pyplot as plt

# Data
num_magnets = [1, 2, 3]
initial_kinetic_energy = [0.016, 0.012, 0.0079]
final_kinetic_energy = [0.033, 0.023, 0.016]

# Set the width of the bars
bar_width = 0.35

# Plotting
plt.bar(np.array(num_magnets) - bar_width/2, initial_kinetic_energy, width=bar_width, label='Initial Kinetic Energy')
plt.bar(np.array(num_magnets) + bar_width/2, final_kinetic_energy, width=bar_width, label='Final Kinetic Energy')
plt.xlabel('Number of Magnets')
plt.ylabel('Kinetic Energy (J)')
plt.title('Energy Conservation Before and After Collision')
plt.legend()
plt.show()
```

Momentum Conservation

Arrow as momentum vectors

```
import matplotlib.pyplot as plt

# Data
num_magnets = [1, 2, 3]
initial_momentum = [0.020, 0.014, 0.012]
final_momentum = [0.023, 0.019, 0.016]

# Plotting
fig, ax = plt.subplots()

# Plotting initial momentum vectors
ax.quiver(num_magnets, [0] * len(num_magnets), [0] * len(num_magnets), initial_momentum, angles='xy', scale_units='xy'

# Plotting final momentum vectors
ax.quiver(num_magnets, [0] * len(num_magnets), [0] * len(num_magnets), final_momentum, angles='xy', scale_units='xy',

ax.set_xlabel('Number of Magnets')
ax.set_ylabel('Momentum (kg m/s)')
ax.set_title('Conservation of Momentum')

ax.legend()
ax.set_ylim(bottom=0)

plt.show()
```

Bar Graph

```
import numpy as np
import matplotlib.pyplot as plt

# Data
num_magnets = [1, 2, 3]
initial_momentum = np.array([0.020, 0.014, 0.012])
final_momentum = np.array([0.023, 0.019, 0.016])

# Plotting
width = 0.35
fig, ax = plt.subplots()

ax.bar(num_magnets, initial_momentum, width, label='Initial Momentum', color = "red")
ax.bar(num_magnets, final_momentum, width, label='Final Momentum', bottom=initial_momentum, color = "yellowgreen")

ax.set_xlabel('Number of Magnets')
ax.set_ylabel('Momentum (kg m/s)')
ax.set_title('Conservation of Momentum')
ax.legend()

plt.show()
```

APPENDIX III: STUDENT DECLARATION

Activity 1 and 2 – Computational Physics II

Name: Abraham Prosia	Year and Section: BS Physics 3-2
Student Number: 2020-08300-MN-0	Date: June 10, 2023

Student's Declaration

I hereby declare and confirm the following, regarding the exam noted above:

1. To the best of my knowledge, I am officially eligible to take this exam.

2. I hereby confirm that I am aware of the lecturer's instructions for the exam and that I completed the exam in compliance with these instructions.

3. I hereby confirm that I completed the exam alone, without consulting with or the assistance and cooperation of any other person.

4. I hereby confirm that I completed the exam within the required time framework, as noted in the lecturer's instructions; I submitted the exam at the end of the allotted time, and I did not abuse the time extension awarded to students with this accommodation.

5. I am aware that the file that is the exam that was uploaded by me to the course site in accordance with the instructions related to the exam is the only file that will be checked and for which I will receive a grade.

6. I am aware that in the efforts to maintain exam integrity I may be required by my lecturer, after submitting the exam and before receiving the grade, to explain some of my answers.

I am aware of the importance of conducting exams with integrity and fairness and according to the lecturer's instructions, and I hereby confirm that I will comply with the above requirements. I am aware that non-compliance with these instructions and unfair conduct constitute a disciplinary offense in accordance with the university's student handbook, with all that it entails, including the possibility of suspension from studies.

Abraham Prosia
Signature above printed name

July 15, 2023
Date