The final stage of the 23rd Physics tournament took place at the Davidson Institute of Science Education on March 20th, 2018. 22 teams competed in the tournament, 5 teams from Israel and 17 from abroad. The countries who took part in the tournament were Panama, Canada, Romania, Argentina, Slovenia, Angola, UK and USA.

On March 21st, 2018 there was a closing ceremony for the tournament where prizes were given to the top three winning teams.

The top three teams were:

1\textsuperscript{st} place – Gimnazija Zelimlje, Slovenia

2\textsuperscript{nd} place – Meshotaf Hof Hacarmel, Israel

3\textsuperscript{rd} place – Gimnazija Nova Gorica, Slovenia
Safes Descriptions

1st place - Gimnazija Želimlje – Skofljica, Slovenia

Gramophone

When solving the tasks, you need to establish rotation of two sound drivers: vinyl record and CDs. That’s why our safe was named Gramophone.

The controlling of the safe is provided with the microcontroller ARDUINO. Electric power is supplied by a 12 V battery.

In the beginning competitors are provided with a drinking straw.

The tasks in the safe are based on two mechanical principles, the first one on Tesla turbine principle and the second on angular momentum.
**Task one**

On a slight slope, which is inclined towards the interior of the safe, there is a simplified version of a Tesla turbine. It is made of CDs and a hollow axis, which contains a graphite pencil. With the added straw, air has to be blown into the lower part of the turbine – discs, which start spinning due to friction between air and the discs. The axis begins to climb upwards the slope and at the end we can take it out of the safe. The pencil is taken out of the axis and the discs are used as a flywheel later on.

In another compartment of the safe, there is a pad with two screws, which serve as contacts, attached to the cover door. They need to be connected using the graphite pencil. Due to good conductivity of graphite, it is enough to put the graphite tip of the pencil between the screws. The green LED turns on.

A successfully solved task allows you to proceed to the second task (when the green LED is on).
Task two

When the first task is finished, the front door is unlocked. Behind, there is a turntable, an electric motor in a hard casing and a lamp. The additional accessory is also the Tesla turbine from the first task, which you have to put on to the electric motor.

The task is finished when the turntable is rotated firstly 4 turns successively anticlockwise (the red LED will turn on) and secondly 4 turns in a row clockwise. Each opening of the front door blocks the turntable and sets partial rotation count to 0.

Important: The turntable can rotate when the front door is closed, and is blocked when the front door is opened.

The turntable rotates with the electric motor positioned in the centre of the turntable. Before that, the Tesla turbine should be set on the motor axis, forming a motor with a flywheel. The motor is activated when the photo resistor on the casing is lit with the added dynamo lamp.
The front door is closed (turntable is released). Due to external torques equal 0, the angular momentum theorem is valid.

\[ L = I \omega = \text{const.} \]

Considering the angular momentum theorem, the turntable rotates in the opposite direction than the electric motor (motor – always anticlockwise, turntable – clockwise). When the turntable performs four turns, it gets blocked by a steering mechanism for eight seconds, the motor switches off after five seconds of running and the flywheel slowly stops. The red LED is turned on and steering now counts turns in the opposite direction – anticlockwise.

The requirement is fulfilled with the front door being opened when the motor is launched and closed when the motor starts decelerating (after four seconds of rotation). Considering the angular momentum theorem here, angular momentum in the closed system of electric motor with a flywheel and turntable is retained; the turntable rotates in the same direction as the flywheel (anticlockwise).

After four turns performed in each direction, the task is solved and a key which opens the safe is dropped.

**Safe sketch**

[Diagram of the safe with side view, top view, and front view]
THE BOX

The safe crackers are given a candle, straw and marker cap filled with water. They can also use a lighter, which is attached to the top of the safe with a chain.

Task one:

The safe crackers should use the candle to illuminate a photoresistor in the corner of the safe.

In the corner, there is also a trolley, that is on one side attached to a spring and on the other to a string. The trolley can be moved along the rails to an opening in the side of the safe by pulling the string. The candle can then be inserted onto the trolley and lit using the lighter. When the string is released, the stretched spring pulls the trolley back to its original position. While moving, the trolley triggers a switch, which turns on a hairdryer.
in order to extinguish the candle. As the candle is extinguished, the photoresistor cannot be triggered by the flame.

The crackers must find out how to light the candle, after it passes the hairdryer. Above the candle there is a metal mesh. The flame cannot pass through the mesh. Before the string is released, the safe crackers have to place the lighter on the top of the mesh and let the lighter's gas flow through it. Below the mesh, it catches fire from the candle's flame. Due to the thermal properties of the mesh, the lighter's flame stays below it. Its thermal conductivity is high enough, that the amount of heat, that can get to the top of the mesh is too small for the gas to catch fire above it. The lighter can then be moved past the hairdryer, taking the flame below the mesh along with it. When the string is released, the trolley moves past the hairdryer and the candle is extinguished. The trolley has to be stopped below the lighter. Due to the flame below the mesh, the candle's wax fumes catch on fire and relights the candle wick.

The trolley can then be released and moved to its starting position next to the photoresistor. The candle's flame causes the voltage on the photoresistor to drop, which is detected by the electrical circuit. It turns on an UV LED, which reveals the combination, that opens a lock on the side of the safe. The door, required to solve the second puzzle, can then be opened.

**Task two:**

The safe crackers must interrupt the laser beam by tilting the bird located in the safe.

In the second part of the safe there is a bird. You can tilt it by creating temperature difference between top and bottom part of the bird. You can do this by wetting its head. Because you can't reach the bird you need to put the straw in the marker cap filled with water and blow over it. The fluid will be pulled out of the cap and spread towards the bird. Once its head is wet it will slowly tilt down and interrupt the laser. The electrical circuit detects this and turns on an UV LED, which reveals the combination that opens the safe.
Safe Description
Our safe consists of two compartments, one stacked on top of the other. The bottom compartment contains two sub-compartments alongside one another.

Part 1

The top compartment has a zig-zag line cut in the top. A wine glass rests in the compartment with the base jutting out of the zig-zag while the drinking portion is pointing downward. This compartment is designed as a maze with various obstacles that a ball needs to navigate through. There are balls of various sizes and materials on one side of this compartment. The hackers must move one of the balls from the side on which it rests, through the maze and up into the chute on the opposite side of the safe.
**Explanation and Science**

To move the ball, the hackers must use the wine glass to lift the and move the ball. To keep the ball in the glass and successfully move it, the hackers must spin the glass very rapidly. Given enough velocity and a small enough radius, the force of the resulting centripetal acceleration will be larger than the force of gravity, meaning the ball will keep spinning and resist falling. This will be especially true if they choose a ball with higher $\mu$ friction (rubber ball with larger area vs. marble or smaller ball). In this manner, the hackers will be able to move the ball over the obstacles and deposit it in the chute.

**Part 2 (A and B)**

Once the ball from Part 1 slides into the chute, a little box protruding from the side will be unlocked. This unlocks the electromagnetic induction portion of the safe. This portion is divided into two sub-compartments, both of which make use of the principles of electromagnetic induction.

**Part 2 A**

The box protruding from the side unlocks and reveals a copper coil attached to wings, magnets and batteries. Compartment 2A on the box is an essentially empty compartment which contains photogates. The lasers on the photogate must be broken in rapid succession until a light illuminates on the outside of the box. To accomplish this task hackers must use the batteries, magnets and coil to create a homopolar motor that spins. This motor then must be slid into position in the box so that in turns rapidly and its' attached “wings” spin in a way that sweeps through the photogates. Once this is accomplished an LED illuminates and the instructions direct the hackers to deposit a battery in the chute. To avoid damaging the magnets or the box hackers will be asked to turn the magnets over to the team at this point.

**Explanation and Science**

The ball being dropped into the chute leads to the box being unlocked through a mixture of force-sensitive resistors, solenoid motors, and code.

The concept of a homopolar motor is based on the Lorentz Force, the force exerted by a magnetic field upon a moving electric charge. The force is given by $F=(qE+qV)B$, meaning that the entire electromagnetic force ($F$) is equal to the electric field multiplied by the charge of the particle ($qE$) plus the velocity of the particle multiplied by its charge ($qV$), all multiplied by the magnetic field ($B$). Based on the right-hand-rule (which states that if the fingers of the right hand are extended to point in the direction of $V$ and are then curled to point in the direction of $B$, then the extended thumb will point in the direction of $F$, meaning that a positively charged particle will be accelerated in the same linear orientation as the electric field but will curve perpendicularly to both the instantaneous velocity and the magnetic field), if a conductor with a current flowing through it is placed in a magnetic field that is perpendicular to the current, it will experience a force in the
direction perpendicular to both the magnetic field and the current. This force provides a torque around an axis of rotation causing the copper wire to rotate rapidly serving as a motor.

The photogates are constructed using pairs of lasers and light-dependent resistors, or photoresistors. When the light is blocked by the “wings” attached to the homopolar motor, the resistance increases. Using computer code, we are able to use this phenomenon to determine when the homopolar motor is functioning correctly, at which point the hackers will be allowed to progress to the next part of the challenge.

**Part 2 B**

When the battery is inserted into its chute and the magnet collected, another LED will illuminate another box which will also be unlocked as before. This box will contain a key unlocks the second sub-compartment (on the bottom-left). This part contains, alligator clips, capacitors, a magnet and a copper coil (which is already wired to a breadboard) and other breadboards with several incomplete circuits on it.

The first is an EMF-based capacitor charging circuit. The capacitors are off on the side (not plugged in). A magnet sealed is provided alongside a copper coil already connected to the breadboard with a pair of wires (power and ground). Hackers will need to line up the capacitors on the breadboard and shake the magnet in the coil to charge the capacitors.

Once this circuit has been completed and the capacitors charged, the capacitors must each be used to complete the remaining 4 circuits. These circuits each consist of a blacklight LED, several resistors, and power and ground wires. Only the power and ground wires are connected to the breadboard; the other components are attached to another section in the box. The charged capacitors must be used to complete these circuits, thereby illuminating the LEDs and revealing the code, which is written in blacklight paint. The hackers can then use the code to open the safe and receive their prize.

**Explanation and Science**

Faraday’s Law states that a change in the magnetic environment of a coil will create an induced voltage, or EMF, in the coil. Therefore, the magnet being shaken in the coil is an adequate voltage source for the capacitor charging circuit. Given the type of wire, coil, and magnet that is being used, this shaking-system will reach 5 or more volts very quickly.

The capacitors must be set to charge in a parallel circuit. Because of the laws of capacitors, which are in turn based on Ohm’s Law and the nature of capacitors, this means that each capacitor will have identical voltage. This means that each capacitor will have a voltage identical to the EMF.

Technically, this shaking system should not be able to charge these capacitors because the voltage that it produces is constantly changing direction just as the magnet is changing direction within the coil. This alternating current would constantly cancel itself within the
capacitors, leaving them with a negligible net voltage. To rectify this, we have included a diode in the coil circuit, which will only allow current to flow in one direction.

Once the capacitors are charged, it is a simple matter to use each of them like a battery to power the four LEDs.
The Castel of Dracula

Tales of supernatural had been circulating in Romanian folklore for centuries when Irish writer Bram Stoker picked up the thread and spun it into a golden tale.

Fringed by the peaks of the Southern Carpathian Mountains, in the enormously frightening castle is where Dracula resides. Count Dracula, an iconic character in international literature, was inspired by one of the best-known figures of Romanian history, Vlad Tepes, nicknamed Vlad the Impaler, who ruled over Wallachia.

The following objects will be given in order to crack the safe:

- Magnets
- 1 battery
- A piece of glass
The puzzles:

1. Electromagnetic force
2. Diffraction of light
3.

**Task one:**

The contestants need to build a "magnet car" by placing the 2 magnets at the post of the battery. Then, they have to rise the first “gate” that will automatically lower the second one, the opposite happens when they push the “gate”. The magnet car will move on an Aluminum foil since the contact between the 2 allows the electric current to flow. The electricity is perpendicular to the field created by the magnet, generating rotation. This rolls the "magnet car" so that it will land and will close a circuit that gives power to the laser.

**Task two:**

They have to light up a photoresistor that is not situated in the laser beam. They'll create a diffraction system by sliding their fingers on the surface of a piece of glass situated between the laser and the wall. The laser beam will be split in 2 directions therefore activating the photoresistor which will provoke the electromagnet to pull in order for the contestants to be able to open the door.
Safe description - Argentina

Phase 1:
Stage 1:
The objective of the first stage is to extract a small amount of water that is in a container inside the safe, which cannot be accessed manually. The water will be used for the second stage and the container has a small candle stuck to it. To extract the water, it is necessary to lift the recipient and remove it from the safe, making a "thermodynamic elevator" with: an extractor (a glass recipient with a 10 micron copper wire welded to it), a battery, two cables, copper resistors and a hyssop, which are outside the box.
The contestants have to connect the battery with the cables and the copper resistor. The copper will warm up (because of the Joule’s effect) and when you get the hyssop (embedded in alcohol) on the resistance, it will set on fire. Then, they will have to light the candle with the hyssop through a hole in the roof of the box.
When the candle is lit, the 10 minute countdown will start. The contestants will have to take the extractor, and lower it through the hole in the box until it covers the candle.
The oxygen will then be consumed, leaving a partial vacuum inside the recipient, so
when they pull up the extractor, the recipient with water and the candle will come up with it.

Stage 2:
Once the water has been obtained by using the “thermodynamic elevator”, that water needs to be used to balance the water level between two cups, A and B. Cups A, B and C are connected by siphons A-B and B-C. The “key” of the challenge is that the balance between A and B will only be achieved when the water obtained from the “elevator” is emptied on the cup B. When this has been done, the following will occur:
Siphon B-C reaches it’s “breaking point” at which point it gets activated, emptying cup B and filling cup C. Then, the water need to be emptied on cup A, so that siphon A-B gets activated leveling the water levels between A and B).
If the contestants poor the water in A cup, they will need to use the emergency rescue located in A cup to retrieve the water and poor it in B cup. If this happens, the team will waste valuable time.

There is another non recommended option, which would be that instead of emptying the water in cup A, balance is tried to be reached by putting water in each cups by hand, this would require extra time and could lead to errors.
When the scale reaches equilibrium, it closes a contact, and activates an arduino nano. The arduino will start a countdown from 10 to 0 (10 seconds total), this countdown can be seen in a small seven-segment LED display that is placed in the front. Once the timer reaches 0, the arduino activates an electric lock which opens a locker. Inside the locker there is lego figure holding a two digit code, and a ferromagnetic magnet. The magnet will be used to complete phase 2, while the numbers are a part of a 3 digit code, that opens a numeric lock, which opens the safe.

Phase 2:
Stage 1:
In this stage we find a tube with an electromagnet winded around it, fixed to the roof of our safe. Inside it, there is a magnet (which will be used as a bullet) and a marble (which will be our target). There also is a magnetic switch on the floor of the safe, which is made of two screws with a gap between them. However, when a magnet is put near the switch, the screws touch each other. one of the extremes of the electromagnet goes straight to a 12v power supply. The other extreme is connected to one of the screws, and the other screw is connected to the power supply. So, when the magnet gets near the screws, the circuit is completed and the electromagnet turns on.
Since the circuit is completed, a magnetic field is created around the electromagnet, which propels the magnet (bullet) that in turn bumps a marble (target) with a code written in it that falls in a hose, which then goes outside the safe revealing the marble and it’s code.
With the previous code, plus the new one a numeric lock found outside the safe can be opened, allowing the contestants to acquire a test tube with acetone and cotton. Once the safecrackers do this, the 10 minute countdown will stop, showing that the challenge had been successfully completed. With this cotton embedded in acetone, they are able to strip a slide in a mezuzah shape, revealing a talmud quote (Megilat ב ו.). This last part is our tribute to Dr Weizmann who discovered how to produce acetone.
PHASE 2
ELECTROMAGNETIC GUN
Elements Given to Safe-Crackers

- fishing hook (string with magnet on one end and handle on the other)
- battery
- wire circle
- cart with candle
First Step: Magnetic Pendulum

A string hangs from the top of the safe, attached to the end of the string is a magnet, this is the pendulum. Hanging from a different point of the top there are four magnets piled up, these need to be retrieved in order to continue to the next step. There are also two magnets attached to each side of the safe in the pendulum’s line of movement, the players must figure out that these have to be removed for the pendulum to work. The players must use the “fishing hook” to pull up the pendulum and swing it for it to attach to the three magnets. Once the pendulum has hooked the four magnets the “fishing hook” is used again to pick up the pendulum (now with the three magnets). The players then proceed to simply take the four magnets and move on to the next step.

![Side View](image)

The Physics: A pendulum typically hangs vertically in its equilibrium position. When the mass hanging is displaced from equilibrium and then released, it begins its back and forth vibration about its fixed equilibrium position. There are two forces acting on a perfect pendulum at all times. The force of gravity acts downward on the pendulum as a result of the pendulum’s attraction to earth’s mass. The force of tension acting upward towards the point of pivot (where the pendulum hangs from) is a result of the string’s force. A regular pendulum would flow in a straight line with standard conditions; however, this is not a regular pendulum, this is a magnetic pendulum, and on the sides of the safe there are “pendulum distractions” (magnets that play as a third force on the pendulum, of course besides air resistance). The players must figure out that these have to be removed for the pendulum to work smoothly.
Second Step: Electromagnetic Bullet

With the retrieved magnets the players can now advance to work the second step. A copper wire coiled up (forming a tube) that starts at a side of the safe travels for about four inches inside the safe, at the tube’s end there is a match sitting on the base of the safe with a magnetic wire tied around the wood. The players use the given battery and fishing hook to build an electromagnetic “bullet.” The goal it to retrieve the match to move on to the next step. The players cannot simply push the magnet through the tube (this doesn’t work). The electromagnetic “bullet” is built by attaching the “s” side of the magnets to both the positive and negative side of the battery. The “bullet” goes through the tube positive side forward. The players place the “bullet” in the tube which is immediately shot through to the end of the tube were the “bullet” picks up the match (it magnetically attracts the coil on the match). The players pull the match and the “bullet” back up and proceeds to step three.

![Side View](image)

The Physics: The magnet on the ends of the battery create a bar magnet with a north pole and a south pole. When you put the bullet inside the coils, it causes an electrical current to flow through the copper wire, which creates a magnetic field, which pushes the bullet along the tube. The bullet will only run one direction because of its magnetic poles.
**Third Step: Shape Memory Alloy**

With the matches retrieved from step two the players will advance to step three. A bent shape memory alloy with a box attached to its end holds the key to opening the safe. The players must understand that a memory shaped alloy has to be heated up in order for the metal to transform. First they must tilt the safe for the cart to move next to the “Lighting hole.” After, they will tilt the safe for the fire to move under the shape memory alloy. This will heat up the metal allowing it to stretch into its natural form as it brings the box with the key to a hole of the safe where the players can grab the key. The players use the key to unlock the safe.

**Side View**

*The Physics:* The Shape Memory alloy is a crystalline structure that is deformed when it is bent, but it resumes its original crystalline state when heat is applied. The heat energy rearranges the atoms to their original positions; this is a state called austenite. It reverts back to its martensite state when cooled, but still in the original position. The players must also understand that the physics behind inclined planes. An object placed on a tilted surface will often slide down the surface. The rate at which the object slides down the surface is dependent upon how tilted the surface is; the greater the tilt of the surface, the faster the rate at which the object will slide down it. In physics, a tilted surface is called an inclined plane. Objects are known to accelerate down inclined planes because of an unbalanced force.
Our safe is composed of two different sections. The first section is a circuit in which you must know to connect all the resistors (the basketball players) in parallel using alligator clips. It is important to connect them in parallel and not in series to ensure that the current is high enough to burn the fuse so that the electricity is conducted to the scoreboard rather than the fuse. Once you have completed connecting the circuit in parallel you realize that the current isn’t going through because the scoreboard which reveals the combination code does not light up. The second part of the safe is a switch which impedes the flow of the current. In essence there is a water bottle filled with distilled water and inside of it there is a test tube filled with air and water which is guided by two sticks. This mechanism acts as the switch to our electrical circuit. The tube floats in the water and is guided by the sticks using copper wire which is also conductive and allows for an electrical
current to pass through. The bottom of the sticks are wrapped with aluminum foil which and is attached to two wires which connect to the parallel circuit outside of the bottle. The goal is to bring down the tube in order to complete the circuit. According to Archimedes principle any object fully or partially immersed in a fluid, is buoyed up by a force. By squeezing the water bottle the tube will sink towards the bottom therefore closing the circuit. This allows you to understand that when you apply force to the water bottle, the water displaced by the squeeze will make its way inside the tube and compress the air within it, this increases the density of tube, causes it to sink and fall onto the pieces of aluminum, in turn completing the circuit. Once it is complete it will reveal the combination that will be the code to unlock the safe and reveal the treasure.
Our safe has the format of a house whose door possesses 4 padlocks that to open them we should obey the following steps:

1st Step: Remove the chimney to put the water in the tube, allowing them, in this way, the fluid to drain removing from the inner of the tube the egg of plastic that contains the key of the first padlock. (Hydrodynamics)

Principle of Bernoulli Law, it is based on the Mechanic Conservation Principle that states that the energy doesn’t create itself, neither disappears, it just transforms itself from one type into another or it transfers itself from one body into another.

\[ \text{Emi} = \text{Emf} \]

Where \( m = \rho V \) the fluid mass moving (water) that is poured at the upper part of the safe, prepared to match the high.
At the moment of pouring, the potential graphic energy of the fluid mass will be the maximum and the Kinetic Energy will be the minimum. As the fluid escapes, the water high reduces, as a result, the potential energy will also diminish.

\[ \Delta E_c = \frac{1}{2} \rho V (v_1 - v_2) \]

Once that, \( E_m = E_c + E_p \), so during the fluid flowing there will be the transference of Mechanic Energy from the water into the egg that contains the key inside it, and the egg is inside the safe conduct causing the movement to the safe pool.

2nd Step: Remove the slippery part of the safe to find the matrix, the comb or the ballpoint pen and the paper pieces. Rub the comb or the ballpoint pen against the woolen cloth or the hair for electrifying them and to attract the small paper pieces that contain the elements of the matrix with the respective colours. Identify the right elements of the matrix and order them according to them the pattern of colours for the opening of the second padlock. (Electrostatics and Matrix).

Principle of Coulomb Law that states the following: The interaction force between the charges is straightly proportional to the product of the charges and inversely proportional to the distance between them.

Its mathematical expression is: \( F = k \frac{(q_1 \cdot q_2)}{r^2} \)

The matter is constituted by atoms that are electrically neutrals but are constituted by particles, fundamentally protons, electrons and neutrons. Rubbing out a plastic ball-pen to a woolen cloth this friction causes electrical charge transference between the positively charged ball-pen and the woolen cloth negatively charged.
After the ball-pen charged (q1) that it will attract the pieces of paper that contain the numeration (the code) for the opening (q1).

Locate the elements of the matrix placed in the lower part of the toy car located at the garage and to order them according to the numbers according to the pattern of colours for the opening of the third padlock.

3rd Step: Identify the magnet and use it to remove the key located at the left lateral part of the safe for the opening of the fourth padlock. (Magnetism)

Principle of Magnetism Law that explains the behaviour of magnetic forces, stressing both magnets. This law establishes that same poles magnets repulse each other, while different poles magnetics attract themselves.
Safe Name: **Electric Piano**
The theme of the first puzzle is the generation of electric current in DC circuits. In order to complete the first puzzle, the safecrackers must simultaneously light three LEDs in a specific order using a provided battery, capacitor, magnet and coil of wire. In order to start cracking the safe, the competitor must first press a button that demonstrates a successful solution to the puzzle. This button will light three of the six LEDs present on the face of the safe, each with a corresponding tone. First, the competitor must determine which direction current must be applied for the three terminals, where each corresponds two LEDs but only one is correct. It is recommended that this is completed by connecting the battery into the first two terminals in either direction until the desired
note and color is displayed. For the third terminal, the student must place the bar magnet inside of the coil to induce current for a brief amount of time. The magnet will generate current in opposite directions when it is placed inside of and taken out of the coil, corresponding to two different colors and tones. Once the correct direction for the components is discovered, it is recommended that the competitor attaches the battery to the first terminal because the battery will discharge for the longest amount of time.

Next, the student must charge the capacitor with the battery and place it on the next terminal so it lights the second correct LED and plays the correct second tone. The student should know that capacitors discharge in a short time, which in this case is roughly ten seconds, so they must be quick to complete the next step. Finally, the competitor needs to place the magnet in (or pull it out of) the coil such that it produces current in the correct direction and lights the final LED. If this is done correctly, the lights will blink and a success tone will play. A display will indicate that this puzzle is complete and the team will be given a pen magnet and fur for the next puzzle.

The theme for the final puzzle is magnetic and electrostatic attraction. There are two tracks, both only accessible by a small hole the size of the pen magnet on the side of the box. In one track there is a plastic ball and a metal ball, as well as a large magnet. The pen magnet must be used to hold the large magnet, then pull the metal ball to the end of the track. Because the plastic ball is positioned between the magnet and metal ball, it will also be carried to the end where the two balls will fall through a hole out of the safe.

Before the plastic ball is placed inside of their corresponding holes on the top of the second track, the plastic ball must be charged using the fur. After rubbing the two for a few seconds, the balls must be placed in the box such that the plastic ball is now behind the metal ball with respect to the hole for the pen magnet. The magnet will be used to pull the metal ball once again, but this time it will attract the plastic ball because of its charge. The electrons on the plastic ball will be attracted to the positive charges of the metal ball via electrostatic induction, causing the plastic ball to follow the metal ball. Even though the two balls will touch, the plastic ball should not lose a significant amount of charge because it is not a conductor. If this does occur, however, or the competitor does not sufficiently charge the ball, a hole exists such that the plastic ball can be easily pushed out of the safe. If the two balls are correctly moved to the goal end of the track, they will fall into a hole with a laser and photoresistor, which the Arduino used to control the first puzzle of the safe will use to determine success of the team. If this is done, the LCD will display the combination to the lock on the back of the safe, granting them a successful attempt at cracking the safe.
Green Valley HS
Henderson, NV, USA
Electric Piano

Laser
2 bottles will block for End

LED screen

Exit hole for start of puzzle

Piano Puzzle
Our box basically consists of two principles of physics, which would become magnetism and gas expansion.

**How to crack it, and its elements**

The start of our box consists of a rolled copper filament called solenoid in conjunction with a battery and a pair of spherical magnets. The magnets must be stuck on each of the end of this battery in the right configuration. This will create a current in loops through the solenoid which will in turn form a magnetic field which will propel the magnets and therefore the battery forward. In the middle of the solenoid, a laser will pass which makes contact with a photo sensor. Once the beam of light is interrupted by the battery passing through the solenoid,
a lock will open, which will give access to a nine-volt battery and cables, which starts the second puzzle.

This second part of our box contains steel wool, alcohol, a test tube, a balloon, and cotton. The nine-volt battery is placed in contact with the steel wool via the wires, which causes the steel wool to burn. This will ignite a small cotton ball dipped in alcohol that is under a test tube filled with alcohol. This will cause the alcohol to evaporate and inflate a balloon that is tied to the top of the test tube. This will cause a second laser to be interrupted that will open the lock of the top lid. (The right measurements were found to assure that this puzzle is completely safe).

Sketch
**Description of the safe: Geared up**

**Gears:**

On this side, there is a “driver” gear in the top right hand corner. This gear has a 3D printed plastic handle on it which allows the teams to turn the gear. The gear is connected to the side of the safe using bearings which are screwed on. This means that the gear can turn easily with no resistance. More importantly, it also means that the gear can be replaced if it breaks or needs to be removed for travel. The teams must then use the provided cogs to make a path to the “driven” gear which is housed within a 3D printed enclosure. A bearing is used here so that the final gear can turn freely and steadily. The point of the enclosure is to stop the teams from being able to turn the final gear with their hands to reveal the code.
The penultimate gear which is required to complete the path, is locked behind a padlock in a cupboard on the opposite side of the safe. In order to retrieve this gear, the team must solve a simple physics question, the answer to which will be the code of the padlock. The question focuses on the GCSE knowledge of the Gear Ratio and Input/Output speed equations. This is the idea that the more teeth an output cog has, the less rotations it will make per rotation of the input cog. In order to answer the question you need to simply rearrange the equations and substitute in the numbers that you have been given in the question.

The final gear is connected to an **electromagnetic generator** which creates an alternating current when the gear is turned. An electromagnetic generator’s purpose is to take kinetic energy and convert it into electrical energy. It does this by spinning a coil of wire between the poles of a magnet, or spinning a magnet inside a coil of wire. According to Fleming’s right hand generator rule, which we learnt at GCSE, a current will therefore be induced due to the motion of the coil in a magnetic field. This is because the conductor (in this case the wire) is cutting the magnetic field lines at angles ranging from 90° to 0° (perpendicular to parallel). The current produced is directly proportional to the rate at which the magnetic field lines are cut. However, this induced current is an alternating current because for every 180° of the rotation of the magnet, the direction of the magnetic field in relation to the motion reverses, causing the current to change direction.

The generator is part of a **relay circuit** which starts a motor thus turning a bolt with a nut on it. The nut has a code stamped into it. When the motor rotates the bolt, which is held in place by a coupling, the nut slides up or down depending on the direction of rotation of the motor. A relay is effectively a little electromagnetic switch. Inside it has an electromagnet and a tiny switch. When the current connected to the electromagnet is great enough, a magnetic field is induced which attracts the switch towards the closed position, closing a new (separate) circuit on the other side of the relay. We have connected the motor to the switch side of the relay (with a different battery) so that when the current is generated by the electromagnetic generator, it will be AC when entering the relay, but DC in the new circuit on the other side, enabling the motor to turn in only one direction and reveal the code. This can then be input into the padlock on the top of the safe, to open the lid and reveal the laser section.

**Optical Fibres:**

The optical fibre side of the safe has been created so that the teams are presented with a grid of holes, and 5 questions above them. The team are also given at the beginning, 5 optical fibres of different lengths. There is a push button on the side of the safe in the top left corner, which turns on the first LED in the bottom right hole of the grid. Each hole has a number underneath, some of which are answers to the questions. One end of the first optical fibre must be pushed into the hole with the initial LED, and then the other end must be pushed into the hole with the
answer to question 1. This will then cause another hole to light up and so the process repeats with the second optical fibre, and the second question. When the final optical fibre is pushed into the hole with the answer to the final question, an LED will turn on behind a section of black theatre gauze. This type of gauze, when pulled taught, seems opaque when you look from a well-lit area, into a darker area. By turning on an LED behind the gauze, the gauze becomes slightly transparent as the area behind it is better lit. This means that you can then see the first half of the final code to unlock the trophy. To join together the answer for one question to the beginning of the next, we have used hidden optical fibre within the safe. However, at a couple of points we needed to boost the strength of the light (as some is lost at the optical fibre connections, and so we used LDR circuits to turn on LEDs when they detect the light from the optical fibre.

The optical fibres are able to transfer light from one end to the other by utilising the concept of Total Internal Reflection (TIR) which minimises energy loss. TIR is when all the light hitting the surface of a medium (from higher refractive index to lower refractive index) is reflected instead of being refracted through the medium. When the angle (called the angle of incidence) to the normal (an imaginary line drawn perpendicular to the surface of the medium) of the ray of light is bigger than the critical angle, the light is totally reflected. The critical angle is defined as the angle of incidence beyond which rays of light are no longer refracted but totally reflected. This means that none of the light is lost through refraction out of the side of the optical fibre. Instead it is totally internally reflected off the inside of the optical fibre over and over again as it travels through it. The low critical angle means the teams are able to bend the optical fibre through great angles, before it will break.

A Light Dependant Resistor (LDR) is a variable resistor that varies its resistance according to the amount of light it detects. The more light that it detects, the lower its resistance. This causes the current in the circuit to vary, and thus varies the power of the components in the circuit. The LDR circuits are similar to the circuits used in street lamps, but reversed. We created our own modified LDR circuits so that we could customise their sensitivity according to the brightness of the light. The main premise of our LDR circuit is that when the LDR detects an increase in the light, an LED turns on. In order to achieve this we used the concepts from Kirchhoff’s laws to create a potential divider circuit. This means that as the LDR lowers its resistance, it has a lower potential difference. This then causes the LED to have a higher potential difference, thus resulting in it turning on. In order to achieve the effect of the potential divider circuit, we also had to use a transistor to create the parallel branches of the circuit.
Lasers:

The top section of the safe contains a laser puzzle which can only be accessed by unlocking the lid using the code produced by completing the gears. In one end of the laser section there are 2 holes with laser diodes in them, and in the opposite end, there are 2 more holes both housing LDRs (joined in series). We have designed the positions of the two holes on the opposite end, so that they are not directly opposite the lasers. This means you must use at least some of the supplied equipment in order to bend/reflect the lasers into the holes. In front of the first laser are three 3D printed diffraction grating holders at different distances to the LDR. You are supplied with 3 different diffraction gratings (300, 600 and 1200 lines/mm) and must choose which one to use, and which holder to slot it into. The correct choice will result in one of the dots from the laser being directed straight onto one the LDR.

In front of the second laser are two polarising filters with a space in between them. The second polarising filter is oriented perpendicular to the first. The first polarising filter causes the laser to diminish by half its brightness, and the other polarising filter cuts out the laser entirely. The teams are suggested to consider Bell’s Theorem in order to get the laser through the polarising filters. They are supplied with a mini third polarising filter which is stuck into a 3D printed frame so that it can stand up on its own. In front of the two polarising filters are two prisms which are secured in “prism holders”. These are connected to bearings which can rotate smoothly. This is to allow the teams to use the prisms’ ability of TIR to reflect the laser light (like a periscope) onto the second LDR. When both LDR’s have a laser on them, another LED lights up behind some more theatre gauze and reveals the second half of the code to unlock the trophy. The trophy, which we designed and 3D printed, is stored in a cupboard on the side of the safe.

Diffraction gratings are filters which have multiple parallel slits across a very short distance. The 3 we are using have a slit spacing of 1/300mm, 1/600mm and 1/1200mm. Diffraction gratings create a line of dots perpendicular to the direction of the slits and the way they achieve this is through wave interference. The waves are diffracted as they pass through the slits, causing them to spread out and so are able to interact (because all laser light from the same laser diode has the same wavelength) and interfere with each other. Where the trough of one waveform meets the peak of another waveform, there is destructive interference and no light can be seen as the amplitude of the resultant wave is 0. On the other hand, where the peaks of two different waveforms meet, there is constructive interference and a brighter light can be seen as the amplitude is 2 or more times greater than that of the original waveform. When a screen is placed near the diffraction grating, a line of dots appears because there are various points (at that distance from the diffraction grating) where there is both constructive and destructive interference. As you increase the number of slits per mm, the dots become further apart because there are more waveforms emerging from the diffraction grating which are able to interfere, and so there is more chance of there being resultant destructive interference than constructive interference.
A polarising filter (or Polaroid) works because of light’s behaviour as a wave. Light is a form of electromagnetic radiation, which means it is a transverse wave and has oscillations perpendicular to the direction of energy transfer. These oscillations can occur at any angle between the x and y axis, given the direction of energy transfer is along the z axis. A polarising filter allows light through which has a component of its oscillations in a direction perpendicular to the slits in the filter. This means that when a polaroid with horizontal slits is placed in front of a light source, then only light with vertical oscillations can travel through, and vice versa. Therefore by basic understanding, if you place a second polarising filter in front of the first one, but you orientate the second one at 90° to the first one, then no light will be able to travel through as the first polaroid will block all the oscillations in one direction, and the second will block all the other oscillations.

Bell’s theorem is an idea used to try and explain the phenomenon that when you place a third polarising filter at an angle roughly in the range of 22.5° and 45° in between the two polaroids, somehow, the light travels all the way through all 3 polarising filters. This happens even though you have not changed the oppositely oriented first and second polarising filter. One possible explanation is that this happens because when the light passes through the first filter, only the light with components perpendicular to the first filter’s slits is affected. One of the possible explanations is that after each polarising filter, the light’s direction of oscillation is changed and as a result 50% of the remaining light is stopped by the polarising filter each time. This would result in having 25% of the light left at the end. Another possible explanation is that the process of being filtered by the middle polaroid affects the polarisation of the light and so there is no possible way to calculate the amount of light that will be filtered by the next polarising filter.

Prisms use the same process of TIR as used in the optical fibres. The glass used in the prisms has a higher refractive index than the air around it, and so this means that light moves towards the normal when entering the prism and away from the normal when leaving the prism. This can be calculated using the formula: \( n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \). The fact that a prism has a 90° angle in it means that the laser can enter the prism along the normal and therefore has an angle of incidence of 0. This means that it is not refracted inside the prism, and then when the laser hits the back side of the prism, the angle of incidence is much larger than the critical angle, and the laser is totally internally reflected.
How To Solve The Safe:

Gears:
The answer to the physics question for the gears is 060. That is the number of teeth that can be worked out when you calculate the gear ratio of input speed / output speed. This gives you a gear ratio of 1.2. Then you can use the gear retrieved from the cupboard to make the path from the first gear to the last gear. Finally, turn the first gear using the handle and the code will be pushed out of the safe on the opposite side of the safe. Use that code to unlock the lid of the safe.

Optical Fibres:
The answers to the question are as follows and only require simple GCSE knowledge recall:

Question 1: 3 x10^8 m/s

Question 2: 273 K

Question 3: 330 m/s

Question 4: 0.2 A (P=IV)

Question 5: 19.44 m/s (70 x 1000 to convert from km to m, then divide 3600 to convert from hours to seconds)

The final hole (and answer to the 5th question) is the top right hand corner hole of the grid. The code revealed is 28_ _

Lasers:
The required diffraction grating is the 300 lines/mm one, and it must be put into the holder nearest the laser.

The 3rd polaroid must be placed in between the 2 polarising filters, on one of its corners. Depending on the orientation, one of the corners will let the most laser light through.

The prisms must be rotated until the laser is reflected directly onto the LDR.

When this section is solved the code _ _73 is revealed. This can be put together with the other code to form 2873 which can be put into the final padlock to unlock the safe and get the trophy.
Photos:

Figure 1: Sketch of the empty gear side of the safe.

Figure 2: Picture showing completed gears solution. Not including enclosure for final gear.

Figure 3: Sketch of the optical fibre side of the safe.

Figure 4: Picture showing completed optical fibre solution. Not including the new design.

Figure 5: Sketch showing the laser side of the safe. Location of items (e.g. diffraction grating) are just for reference and are not correct.
“Safety in Numbers”

Photo and diagram:
How to crack the safe:

- The students attempting to crack the safe are given two items which they need to solve both parts of the puzzle. The first is an iron nail and the second is a plastic key. The iron nail is used for its paramagnetic properties in the first puzzle.
- By moving the nail around the box casing, you discover that some of the plastic counters have cube magnets underneath them, causing the counters to jump to the nail.
- Then you must, using these items, rotate a foam board blocker around, in order to clear the path of two lasers. Stuck onto this blocker is a penny washer.
- Insert the nail into the hole directly above this washer, and magnetise it using the cube magnets.
- This gives enough attractive force for the barrier to be rotated ninety degrees. This clears the path of the laser, allowing it to shine directly on to the second box. This contains two metal levers, two pathways and two LDRs.
- In order to solve the puzzle all you must do is get the two beams to shine onto the two LDRs.
- The difficulty comes from the fact that one of these levers is in the open position, while the other is in the closed position, and simple magnetic attraction using the key, with magnets in one of 7,776 (6x6x6x6x6) random arrangements, would simply close this one while opening the other.
- However, if arranged in a halbach array, similar to a fridge magnet this problem is solved. The N poles must be arranged so that they are rotating in a ninety degree pattern, repeating in a continuous pattern.
- In this way it causes constructive and destructive interference of the field lines, causing amplification on one side and a negligible magnetic field on the other.
- This allows you to move only the closed lever, allowing the light beams to cause a reduced resistance, automatically reducing the resistance.
- For ease of drawing, I have only depicted the numbers on the side, however, identical numbers can be found on the safe as well. These are removable and contain small, cubic, permanent magnets attached to glued-on brass washers, for ease of release.

- These are the lasers we used. They are within the UK’s maximum safe power of 1 mWatt for class two lasers.

- This 6 mm coach bolt is all that the crackers are provided with. Made from zinc coated, medium carbon steel, it is ferromagnetic and crucial for solving the rest of the safe.

- Made of brass-board in order to be as light as possible, this piece exists to block the lasers passing through the first puzzle. The piece can be lifted due to the metal washer which can be attracted to the keyarded magnetised steel coach bolt.

- This is the second and more complex of the two puzzles. Designed to make use of the Holbach array, this puzzle requires the back arm $\alpha$ made of wrought iron to be attracted to the magnets, held in a removable key in the middle. While the second arm $\beta$ is left in an open position allowing the lasers to reach both LDFs $\delta$.

- The two LDFs we use have been wired up to cause that a signal to open the safe only if both lasers detect laser. LDFs detection due to the photovoltaic effect, where more $\epsilon$ are known lost by photos converting a hypercurrent, the more light there is.

- The door runs off a simple servo that rotates a bar through ninety degrees. In the closed position, this bar is stuck behind a piece of wood so that the door cannot open unless the safe has been cracked.
1- Safe Concept Description

A. **Description of Physics Concepts:**

**Piezoelectricity** - Piezoelectricity is the appearance of biased charges on opposing faces of a piezoelectric material when mechanical stress is applied. We use a piezoelectric material as a voltage source in our safe. Examples of piezoelectric materials include some crystals, ceramics, and biological materials. These materials exhibit piezoelectricity because of their specific atomic structure. The applied stress leads to the change in the position of the atoms, resulting in the formation of net dipole moments that cause polarization, and an electric field, respectively. We use the principle of piezoelectricity in our safe to trigger a coil, which creates a magnetic field.

**Resonant Frequency** - Every system has a natural resonant frequency, or frequency at which the system will oscillate when external stimuli is applied. The resonant frequency occurs when the amplitude of the oscillation, or the extent of displacement
in response to each oscillation, is at a maximum. A system’s resonant frequency amplitude can be enhanced using the principle of superposition through constructive interference. This phenomenon is called mechanical resonance. It relies on applying a force that matches that of the motion of the mass. We use the principle of mechanical resonance in our safe to allow a weight spring system to reach an amplitude great enough to reach a magnet, completing a circuit to allow access to the next part of the safe.

**Granular Segregation** - Granular matrices exhibit patterns of behavior similar to those of fluids when exposed to mechanical stimuli. When vibrated at a specific frequency, the granular media may organize and form a crystal lattice matrix. If the frequency changes, the granular matrix may start behaving like a fluid and mix in a convective pattern, “liquify”, “bubble” or “boil”. Flow within a granular matrix inside a control volume like a cylinder may result in sorting of particles due to size and not density, where larger particles may rise to the top of the matrix or sink depending on the frequency of external mechanical motion that is applied to the control volume. In our safe we use the principle of granular sorting to move a heavy magnetic ball of greater diameter and density than the surrounding matrix, to the top of a control volume column.

**B. Description of The Safe**

**Puzzle #1: The Piezoelectric Tower**

The burglars are given piezoelectric material. The burglars apply pressure at a certain frequency on the piezoelectric material to generate a voltage that is directed to an amplifier. The amplifier applies a larger current to a coil to create a magnetic field. The burglars must figure out a frequency that creates constructive interference, to oscillate a mass suspended on a spring at a resonant frequency with an enhanced amplitude. The objective is to reach a state of mechanical resonance. Only when this is achieved does the mass and its attached magnet extend far enough into the coil to close a magnetic circuit. This closed circuit opens a latched compartment, giving access to a string that is attached to the granular convection tube.
Puzzle #2: The Granular Convection Tube

The burglar pours the granular material into the granular segregation tube which is oscillated by the string from the latched compartment attached to the bottom. The cylinder is housed in a cactus structure and is suspended from the cactus housing by a spring. Using the string, the burglar manually vibrates the cylinder. This vibrational motion coupled with the spring attached to the top will create conditions for granular segregation and buoy the heavy magnetic ball to rise upwards. The magnetic ball completes a circuit when it reaches the top of the cylinder, which opens the prize chamber.

Design Sketch
The first step for cracking our safe is making the windmill turn, which will physically create a force of tension on the string. Then the string pulls the screw that is keeping the door in place. In order to do this, the safecrackers must blow on the
windmill through the gap between the plexiglass and the wooden structure. The windmill will rotate and create a force of tension on the string that is attached to it. This causes the string to be pulled. The string that is being pulled is attached to the screw. Through a pulley system, the screw, which is stuck through the hole of two intersecting L-brackets, will be pulled out, removing the blockage and allowing the door to be opened. When the door is opened, the cracker retrieves a pump, a tube, and a cork from the inside.

Following this, the burglar must remove the ping pong ball which is covering a hole at the bottom of a tennis ball canister. The ping pong ball is sitting in the bottom of a tennis ball canister. The ball is blocking a hole, which is needed for a later step. In order to remove the ball, the burglars must pump air into the tennis ball canister through the top. The ping pong ball will then rise up and fly out of the cannister. This step is done using Bernoulli's Principle, which states that in fluid dynamics an area of higher velocity will cause that area to have lower pressure, and an area of lower velocity causes the area to have higher pressure. To apply this to the ping pong ball, when pumping air on top of the ball, it causes the velocity of the air beneath the ball to be smaller than the velocity above the ball. The reason for this difference in velocity above and beneath the ball is because air deviates as it reaches the ball. The air deviates and is spread around the ball. The vector velocity splits up into multiple vectors with different directions around the ball. Each individual vector beneath the ball is less than the vector on the top. Therefore, the velocity on the bottom is less than the velocity on the top of the ball. Bernoulli’s principle explains that beneath the ball there will be higher pressure than above the ball because the velocity beneath the ball is less than the velocity above the ball. This difference in pressure above and beneath the ball generates lift, since air particles in areas of higher pressure travel to areas of lower pressure. As a result, the ping pong ball is lifted up and out of the tennis ball canister.
The next step is to block the hole with the cork to properly create the vacuum. This hole is positioned in the wall that is separating the final chamber from the chamber with the windmill. To properly create a vacuum, the compartment must be air-tight. Due to the hole through the divider, a vacuum cannot be created until it is blocked. Placing the cork through the hole allows the compartment to become airtight, allowing for the creation of a vacuum.

The final step is to create a vacuum in the chamber at the other side of the divider. Creating a vacuum will cause the door to open inwards. There is a screw drilled through the wooden door and through the plexiglass. When the door opens, the screw is removed from the plexiglass and the burglars are able to slide up the plexiglass. The safe is now open.

The reason that the door opens is because of Boyle’s Law. Boyle’s law relates volume and pressure in the equation $V_1P_1=V_2P_2$. This equation means that volume and pressure are inversely proportional to each other. When volume increases, it causes the pressure in that chamber to decrease and vice versa; when pressure increases, it causes the volume of that chamber to decrease and vice versa. The goal is to decrease the pressure in the chamber to increase the volume and open the door. In order to do this, the burglars must place the tube through the mouth of the pump. Then insert the tube through the two holes that line up in the tennis ball canister and put the mouth of the tube onto the hole in the safe. Make sure that the tube is placed directly on the hole without allowing any air to escape. Then, ensure the pump is on deflate and pump out all the air in the chamber. Pumping air out of the chamber decreases its air pressure. Boyle’s law states that when pressure decreases, the volume wants to increase. Hence, the door opens inwards, which increases the volume of the chamber.

In addition, there is another reason why the door opens when removing the air in the chamber. Pressure is force over area. Using the pump, remove the air from the chamber. The change in pressure causes a force to appear in the direction of the change. The change in pressure inwards makes a force appear inwards. The change is pulling the air out, therefore the door wants to follow the direction of the change in pressure.
Now that the door is open, the bolt is removed from the plexiglass. The safecracker can now slide the plexiglass upwards and open the safe.

Front View
When door is open:
Once the door swings inward, the bolt will come out of the doorknob on the acoustic door cover, allowing the cover to slide up and permit access to the door, thus solving the safe.