IA RUBRIC – SL PHYSICS

Internal assessment criteria

The new assessment model uses five criteria to assess the final report of the individual investigation with the following raw marks and weightings assigned:

Personal engagement	Exploration	Analysis	Evaluation	Communication	Total
2 (8%)	6 (25%)	6 (25%)	6 (25%)	4 (17%)	24 (100%)

Levels of performance are described using multiple indicators per level. In many cases the indicators occur together in a specific level, but not always. Also, not all indicators are always present. This means that a candidate can demonstrate performances that fit into different levels. To accommodate this, the IB assessment models use markbands and advise examiners and teachers to use a **best-fit** approach in deciding the appropriate mark for a particular criterion.

Personal engagement

This criterion assesses the extent to which the student engages with the exploration and makes it their own. Personal engagement may be recognized in different attributes and skills. These could include addressing personal interests or showing evidence of independent thinking, creativity or initiative in the designing, implementation or presentation of the investigation.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1	**The evidence of personal engagement with the exploration is limited with little independent thinking, initiative or creativity.** The justification given for choosing the research question and/or the topic under investigation does not demonstrate **personal significance, interest or curiosity**. There is little evidence of **personal input and initiative** in the designing, implementation or presentation of the investigation.
2	**The evidence of personal engagement with the exploration is clear with significant independent thinking, initiative or creativity.** The justification given for choosing the research question and/or the topic under investigation demonstrates **personal significance, interest or curiosity.** There is evidence of **personal input and initiative** in the designing, implementation or presentation of the investigation.

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Exploration

This criterion assesses the extent to which the student establishes the scientific context for the work, states a clear and focused research question and uses concepts and techniques appropriate to the Diploma Programme level. Where appropriate, this criterion also assesses awareness of safety, environmental, and ethical considerations.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	The topic of the investigation is identified and a research question of some relevance is **stated but it is not focused**. The background information provided for the investigation is **superficial** or of limited relevance and does not aid the understanding of the context of the investigation. The methodology of the investigation is only appropriate to address the research question to a very limited extent since it takes into consideration few of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of limited awareness of the significant safety, ethical or environmental issues that are **relevant to the methodology of the investigation***.
3–4	The topic of the investigation is identified and a relevant but not fully focused research question is described. The background information provided for the investigation is mainly appropriate and relevant and aids the understanding of the context of the investigation. The methodology of the investigation is mainly appropriate to address the research question but has limitations since it takes into consideration only some of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of some awareness of the significant safety, ethical or environmental issues that are **relevant to the methodology of the investigation***.
5–6	The topic of the investigation is identified and a relevant and fully focused research question is clearly described. The background information provided for the investigation is entirely appropriate and relevant and enhances the understanding of the context of the investigation. The methodology of the investigation is highly appropriate to address the research question because it takes into consideration all, or nearly all, of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of full awareness of the significant safety, ethical or environmental issues that are **relevant to the methodology of the investigation.***

* This indicator should only be applied when appropriate to the investigation. See exemplars in teacher support material.

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Analysis

This criterion assesses the extent to which the student's report provides evidence that the student has selected, recorded, processed and **interpreted** the data in ways that are relevant to the research question and can support a conclusion.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	The report includes **insufficient relevant** raw data to support a valid conclusion to the research question. Some **basic** data processing is carried out but is either too **inaccurate or too insufficient to lead to a valid** conclusion. The report shows evidence of little consideration of the impact of measurement uncertainty on the analysis. The processed data is incorrectly or insufficiently interpreted so that the conclusion is invalid or very incomplete.
3–4	The report includes relevant but incomplete quantitative and qualitative raw data that could support a simple or partially valid conclusion to the research question. Appropriate and sufficient data processing is carried out that could lead to a broadly valid conclusion but there are significant inaccuracies and inconsistencies in the processing. The report shows evidence of some consideration of the impact of measurement uncertainty on the analysis. The processed data is interpreted so that a broadly valid but incomplete or limited conclusion to the research question can be deduced.
5–6	The report includes sufficient relevant quantitative and qualitative raw data that could support a detailed and valid conclusion to the research question. Appropriate and sufficient data processing is carried out with **the accuracy** required to enable a conclusion to the research question to be drawn that is fully **consistent** with the experimental data. The report shows evidence of full and appropriate consideration of the impact of measurement uncertainty on the analysis. The processed data is correctly interpreted so that a completely valid and detailed conclusion to the research question can be deduced.

IA-3

Evaluation

This criterion assesses the extent to which the student's report provides evidence of evaluation of the investigation and the results with regard to the research question and the accepted scientific context.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	A conclusion is **outlined** which is not relevant to the research question or is not supported by the data presented. The conclusion makes superficial comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are **outlined** but are restricted to an **account** of the **practical** or **procedural issues** faced. The student has **outlined** very few realistic and relevant suggestions for the improvement and extension of the investigation.
3–4	A conclusion is **described** which is relevant to the research question and supported by the data presented. A conclusion is described which makes some relevant comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are **described** and provide evidence of some awareness of the **methodological issues*** involved in establishing the conclusion. The student has **described** some realistic and relevant suggestions for the improvement and extension of the investigation.
5–6	A conclusion is **described and justified** which is relevant to the research question and supported by the data presented. A conclusion is correctly **described and justified** through relevant comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are **discussed** and provide evidence of a clear understanding of the **methodological issues*** involved in establishing the conclusion. The student has **discussed** realistic and relevant suggestions for the improvement and extension of the investigation.

*See exemplars in teacher support material for clarification.

Communication

This criterion assesses whether the investigation is presented and reported in a way that supports effective communication of the focus, process and outcomes.

Mark	Descriptor
0	The student's report does not reach a standard described by the descriptors below.
1–2	**The presentation of the investigation is unclear, making it difficult to understand the focus, process and outcomes.** The report is not well structured and is unclear: the necessary information on focus, process and outcomes is missing or is presented in an incoherent or disorganized way. The understanding of the focus, process and outcomes of the investigation is obscured by the presence of inappropriate or irrelevant information. There are many errors in the use of subject-specific terminology and conventions*.
3–4	**The presentation of the investigation is clear. Any errors do not hamper understanding of the focus, process and outcomes.** The report is well structured and clear: the necessary information on focus, process and outcomes is present and presented in a coherent way. The report is relevant and concise thereby facilitating a ready understanding of the focus, process and outcomes of the investigation. The use of subject specific terminology and conventions is appropriate and correct. Any errors do not hamper understanding.

*For example, incorrect/missing labelling of graphs, tables, images; use of units, decimal places. For issues of referencing and citations refer to the "Academic honesty" section.

Name____________________________

Period

Grade	Criteria	Reasons/Comments
/2	Personal Engagement	
/6	Exploration	
/6	Analysis	
/6	Evaluation	
/4	Communication	

6 Total Grade = /24

1A-6

Exploring the relationship between the pressure of the ball and coefficient of restitution.

When I started thinking about possible investigations I knew I wanted to create a lab that was related to sports. After a number of ideas, I thought that changing the pressure of the ball would be a good independent variable and the rebound height of the dropped ball would be a good dependent variable. This was very interesting to me because I had just started basketball season and it's always a struggle finding a good ball to use at practice. Some balls are too bouncy and others are under inflated. My sister and I are also very particular about our soccer balls. When the ball is over inflated it's harder to control, and when it is under inflated the trajectory of the ball is altered.

I finalized my investigation to deal with the rebound height of different size soccer balls when they rebound off of different materials with different pressures, and that I should test the rebound height of the ball when it is under inflated and over inflated.

After some research I discovered that the ideal pressure for a size 5 soccer ball is 6-8 Lbs. FIFA measures the pressure of the ball in bars but for this experiment I will use lbs. In physics we usually talk about air pressure in atmospheres, but for soccer balls the pressure is usually measured in Lbs. or bar.

Coefficient of Restitution

The coefficient of restitution is a mathematical way of showing the elasticity of a collision. It can be used when two moving objects collide or when a moving object hits a stationary object. In my investigation a moving object (a soccer ball) will collide with the ground. There are many formulas to calculate the coefficient of restitution depending on the data that you are given, but the one listed below specifically deals with the height of ball bounces.

$$C_R = \sqrt{\frac{\text{Rebound Height}}{\text{Initial Height}}}$$

If the collision is perfectly elastic, meaning that no energy is transferred, the coefficient of restitution will be 1. Collisions are not perfectly elastic because energy is lost on collision. If the coefficient of restitution is 0, the collision is completely inelastic and all energy is transferred from the ball to the ground, friction, sound, heat and other forms of energy loss. This would mean that when the ball drops, it doesn't bounce back.

Energy Transfer in this experiment

The soccer ball is first raised up to a specific height. In this action energy is being transferred from the person to the ball. When the ball is resting at its maximum height all of its energy is gravitational potential. As the ball is released, gravity accelerates it towards the

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ground. As it is accelerating, the energy is transferred from potential energy to kinetic energy. The instant it hits the ground all of the energy is kinetic energy but it is quickly transferred to elastic potential energy when the ball deforms. The elastic potential energy is then transferred to kinetic energy again when the ball rebounds back up. This kinetic energy is then transferred to gravitational potential energy. At any part in the path of the ball, the energy is a combination of kinetic and potential.

When the ball rebounds back up it will not reach its original height due to energy loss. The energy loss occurs when the ball hits the ground. Energy is loss to sound and heat. When the ball loses energy it is not able to reach its maximum height.

Research Questions: What are the optimal conditions for a bouncing soccer ball to achieve the maximum rebound height?

Independent Variable: In this experiment I will be testing the impact of three different variables on the rebound height of the ball. The most important variable that I will be changing is the pressure of the soccer ball. In order to enhance this experiment I will change the surface that the ball bounces on. The three surfaces that I will be using are grass, stone and dirt. I will also be investigating if the size of the ball affects the rebound height. I will be using size 1, size 3 and size 5 soccer balls.

Dependent Variable: The dependent variable in this experiment will be the rebound height of the soccer ball.

Control Variable: In this experiment there are many control variables that will be put in place to ensure our results are as accurate as possible. Control variables are used to ensure that only one variable is being changed in each experiment. Since this investigation deals with three independent variables, only one will be changing at a time. Here is a list of the control variables:

Height that the ball is dropped: The ball will always be dropped from 150cm above the test surface.

Surface that the ball is being dropped on: When I change the pressure of the ball the surface will remain the same for all trials.

Soccer ball: The size 5 soccer ball that is used will always be the same for every trial. The same goes for the size 1 and size 3 soccer balls.

Materials: Laptop, Vernier LabPro interface, Motion sensor, Meter stick, Air pressure gauge (measured in Lbs.), Air pump, Size 1 soccer ball, Size 3 soccer ball, Size 5 soccer ball, Grass area, Dirt area, Limestone Area, Pole (at least 1.5 meters high), Chair/table to help hold apparatus during data collection.

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Procedure

1. Stick a pole into the dirt surface where you will be doing the first experiment.
2. Put tape on the stick 150cm above the ground.
3. Set up the motion sensor and Vernier to your laptop.
4. Using chairs/ tables place the motion sensor approximately 175cm above the ground. Make sure it is set up beside the pole. (I had to move my pole to make it work with the motion sensor.)
5. Inflate size 5 soccer ball to 12 Lbs.
6. Hold up the ball so the middle is at the tape (150cm).
7. Start collecting data with LabPro
8. Drop ball.
9. Stop data collection when ball has bounced and returned to the ground
10. Save data.
11. Complete 3-5 trials for each ball, pressure and surface.
12. Once all trials are completed, analyze data and record in data tables.

Safety/Setup Considerations:

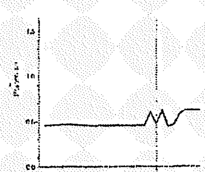
- Ensure the motion sensor is securely placed on the table. Use tape to keep it down if necessary.
- Place your laptop as far from the bouncing ball as possible to ensure it does not get hit by the rebounding ball.

Data and Processing:

I collected the data with the motion sensor and saved the data (data table and graph) on my laptop. Once I was finished collecting all the data for my investigation I analyzed each trial and recorded the initial and rebound height.

Here is a screen shot of what the graph looks like when a ball is dropped. This graph is one of practice drops, but it clearly shows what an ideal bounce would look like. The y axis shows the position of the ball from the motion sensor, not from the ground. In this example the ball starts 0.456 meters away from the sensor.

Beside seeing a visual of change in position, LabPro records the data (see next page) in a table and a graph (on the right).



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From 0.80 to 0.90 seconds, the ball is still at its original position. At 0.95 seconds the ball hits the ground, bounces back up at 1.00 seconds and returns to the ground at 1.05 seconds.

To calculate the distance it bounced up I looked at the position column. The ball starts 45.6cm from the motion sensor. It then hits the ground that is 60.2cm from the motion sensor. This means the ball dropped 14.6 cm (60.2-45.6). The ball then bounces back up *where it is now* 47.0 cm away from the motion sensor. The ball rebounded 13.2cm (60.2-47.0) after it hit the ground.

	Time (s)	Position (m)
16	0.80	0.456
17	0.85	0.455
18	0.90	0.454
19	0.95	0.602
20	1.00	0.470
21	1.05	0.623
22	1.10	0.448
23	1.15	0.469
24	1.20	0.595
25	1.25	0.623
26	1.30	0.628
27	1.35	0.626
28	1.40	0.626

The tables below show the data collected from my experiment. The processed data for this lab is the coefficient of restitution. I have included the coefficient of restitution in the raw data table so you can easily see how when the rebound height decreases, the coefficient of restitution decreases. I expected to see this relationship because a lower coefficient of restitution means the collision is more inelastic, and a lower rebound height means that more energy is lost during the collision.

Size 1 Soccer Ball

Stone	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	110.3	87.4	43.0	20.4	6.2
Trial 2(+/- 0.1cm)	107.1	85.6	42.3	23.3	4.4
Trial 3(+/- 0.1cm)	108.6	87.8	44.7	24.8	6.0
Average (+/- 0.01cm)	108.7	86.9	43.3	22.8	5.5
Coefficient of restitution (+/- $3.8x10^{-3}$)	0.9	0.8	0.5	0.4	0.2

Dirt	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	0.3	2.8	6.2	9.3	0.0
Trial 2(+/- 0.1cm)	0.0	0.0	4.7	11.5	0.0
Trial 3(+/- 0.1cm)	0.0	0.0	5.5	13.1	0.0
Average (+/- 0.01cm)	0.1	0.9	5.5	11.3	0.0
Coefficient of restitution (+/- 0.0)	0.0	0.1	0.2	0.3	0.0

Grass	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	87.3	68.6	33.9	21.2	4.0
Trial 2(+/- 0.1cm)	79.1	71.1	32.3	18.4	7.6
Trial 3(+/- 0.1cm)	82.8	74.7	29.0	18.9	6.1
Average (+/- 0.01cm)	83.1	71.5	31.7	19.5	5.9
Coefficient of restitution (+/-$3.2x10^{-3}$)	0.7	0.7	0.5	0.4	0.2

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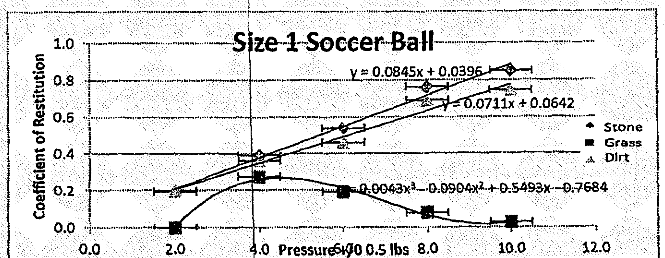

Graph 1: Coefficient of Restitution for size 1 soccer ball. The three different symbols represent different surfaces. ****Vertical error bars are too small to be visible****

Size 3 Soccer Ball

Stone	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	92.0	72.7	34.3	13.8	2.1
Trial 2(+/- 0.1cm)	92.8	72.1	41.0	25.2	1.8
Trial 3(+/- 0.1cm)	92.1	73.0	33.8	17.1	3.2
Average (+/- 0.01cm)	92.3	72.6	36.4	18.7	2.4
Coefficient of Restitution (+/-3.6x10^{-3})	0.8	0.7	0.5	0.4	0.1

Dirt	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	0.0	3.0	4.0	9.0	0.0
Trial 2(+/- 0.1cm)	0.0	2.0	6.0	8.0	3.0
Trial 3(+/- 0.1cm)	0.0	0.0	5.0	11.0	0.0
Average (+/- 0.01cm)	0.0	1.7	5.0	9.3	1.0
Coefficient of Restitution (+/- 0.0)	0.0	0.1	0.2	0.2	0.1

Grass	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	72.0	71.0	25.0	11.0	4.0
Trial 2(+/- 0.1cm)	76.0	67.0	22.0	13.0	6.0
Trial 3(+/- 0.1cm)	74.0	68.0	1.0	8.0	4.0
Average (+/- 0.01cm)	74.0	68.7	16.0	10.7	4.7
Coefficient of Restitution (+/-3.3x10^{-3})	0.7	0.7	0.3	0.3	0.2

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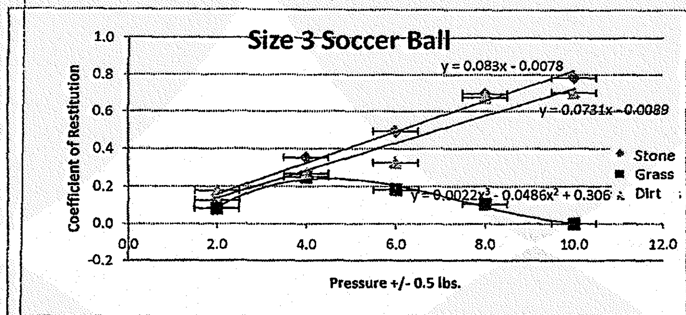

Graph 2: Coefficient of Restitution for size 3 soccer ball. The three different symbols represent different surfaces. ****Vertical error bars are too small to be visible****

Size 5 Soccer Ball

Stone	Pressure (+/- 0.5lbs.)				
Height rebounded	12.0	9.0	7.0	4.0	2.0
Trial 1(+/- 0.1cm)	87.8	73.1	41.3	17.2	6.1
Trial 2(+/- 0.1cm)	92.9	67.0	39.6	21.5	5.8
Trial 3(+/- 0.1cm)	89.3	74.7	43.2	18.2	4.2
Average (+/- 0.01cm)	90.0	71.6	41.4	19.0	5.4
Coefficient of Restitution (+/- 3.5×10^{-3})	0.8	0.7	0.5	0.4	0.2

Dirt	Pressure (+/- 0.5lbs.)				
Height rebounded	12.0	9.0	7.0	4.0	2.0
Trial 1(+/- 0.1cm)	0.0	3.0	6.0	9.0	0.0
Trial 2(+/- 0.1cm)	0.0	0.0	4.0	11.0	0.0
Trial 3(+/- 0.1cm)	0.0	0.0	5.0	13.0	0.0
Average (+/- 0.01cm)	0.0	1.0	5.0	11.0	0.0
Coefficient of Restitution (+/- 0.0)	0.0	0.1	0.2	0.3	0.0

Grass	Pressure (+/- 0.5lbs.)				
Height rebounded	12.0	9.0	7.0	4.0	2.0
Trial 1(+/- 0.1cm)	79.0	62.4	38.1	16.0	5.7
Trial 2(+/- 0.1cm)	80.8	63.1	37.8	15.4	4.3
Trial 3(+/- 0.1cm)	76.8	67.9	40.3	13.2	6.0
Average (+/- 0.01cm)	78.9	64.5	38.7	14.9	5.3
Coefficient of Restitution (+/- 3.2×10^{-3})	0.7	0.7	0.5	0.3	0.2

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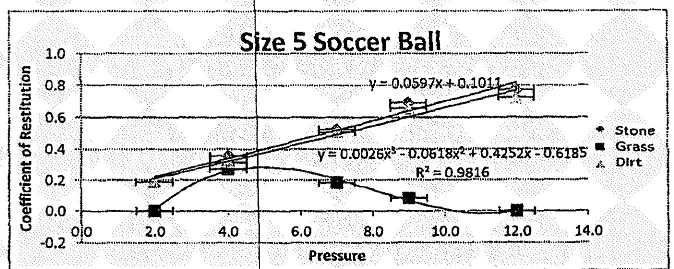
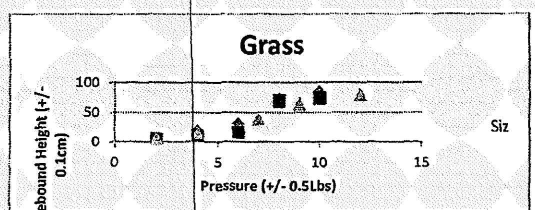
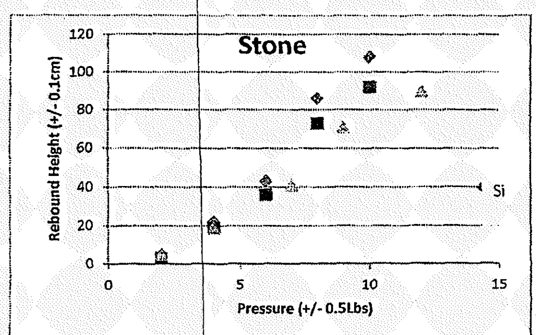


Graph 3: Coefficient of Restitution for size 5 soccer ball. The three different symbols represent different surfaces. ****Vertical error bars are too small to be visible****



Graph 4: The above graph shows the rebound height of the three balls when they are dropped on grass.



Graph 5: This graph shows the rebound height of the three balls when they are dropped on stone.

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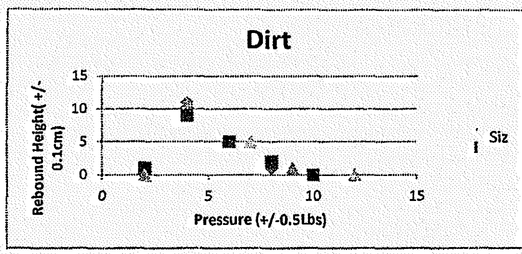

Graph 6: This graph shows the rebound height of the three balls when they are dropped on dirt.

Conclusion and Evaluation

This experiment confirms the relationship between the pressure of a soccer ball and the rebound height of the ball. I also investigated if the surface which the ball bounced on affects the rebound height. The data I have collected shows the same relationship for all three sizes of soccer balls. For grass and stone, the rebound height increased as the pressure increase. A linear trendline was used to fit the data. When the ball bounced on dirt, all three sizes responded the same way to a change in pressure. At the highest and lowest pressure, the rebound height was 0 except the size three ball rebounded 1cm when the pressure was 2 lbs. As the pressure increased by 2 lbs. the rebound high increased approximately 12cm. This was the maximum height reached by the ball when it bounced on dirt. As the pressure increased from 4 lbs. to 10 lbs. the rebound height decreased linearly.

When the soccer balls were dropped with the same pressure on the three different surfaces, the rebound height was the highest with the stone, followed by the grass and then the dirt. The rebound height was higher with the stone than the grass because there is some grass between the ball and the grass. Although the ball was not rolling on the grass, there is friction as the ball falls vertically through the blades of grass. As the ball falls on the grass the blades bend out to the side from the weight of the ball. This is evident when you look at the grass after the ball hit the ground; you can see an indent in the grass. The friction between the stone and the soccer ball is negligible in comparison with the friction presented by the grass. The ball's higher rebound height on the stone is also due to the compactness of the different materials. The stone is a much denser than the grass which means the ball deforms more as it hits the stone causing it to lose less energy when it rebounds. The grass is cushioning the ball as it hits the ground which causes the rebound height to be reduced.

When the ball bounced on dirt at low pressure our results were expected, the ball reached a very low rebound height. As the pressure increased the ball started to bounce higher, again this is what I expected. The results then veered away from my hypothesis as I continued to increase

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the pressure. When the pressure reached about 6 lbs. the rebound high started to decrease again. This can be seen in graph 6. I think that this trend was observed because as the pressure increased, the ball became firmer. When the ball became firmer it hit the ground with a greater power. This caused a bigger indent in the dirt (since it was soft) which cushioned the ball.

If energy is never created or destroyed, why do some balls bounce higher than others if they are dropped from the same height? Since they are dropped from the same height, they have the same amount of energy. My conclusion is that when an under inflated ball hits the ground, the ball is more deformed than when an over inflated ball hits the ground. When the ball is deformed to a large magnitude, a larger portion of the surface hits the ground. This means that more energy is transferred into the ground. Also since there are fewer gas molecules in the ball, it is harder for the ball to regain its original shape. When the ball deforms the area inside the ball is essentially smaller. This means that the air molecules are colliding with the side of the ball more frequently causing the ball to regain its shape. When the ball is regaining its shape and the area increases, the number of collisions with the surface of the ball decreases. This means that there are weaker forces to 'push' the ball off the ground. With a high pressure the number of molecules inside the ball is greater. This means that as the ball deforms the collisions between the molecules and the soccer ball are more powerful and at a greater frequency. This causes the ball to rebound faster and with a greater magnitude.

The dirt was not very hard packed so it 'cushioned' the balls as they fell. This was a source of energy loss. Due to the 'cushion' effect of the dirt, the rebound height was significantly lower than stone and grass. This can be seen in graph 1, graph 2 and graph 3.

Besides energy loss to sound, heat and friction as the ball hit the surface, there was energy loss due to air resistance. When the ball fell from its initial height I assumed that all the energy was transferred to kinetic but in fact some energy is transferred to the air. Therefore it is not possible to reach the initial height when it rebounds back up, even if no energy was transferred to sound, heat or friction on the ground.

The unevenness of the surfaces also caused some problems with the data collection. The ball did not always bounce in a perfectly vertical manner. It would rebound on an angle causing the motion detection to record incorrect values. Since the ball was traveling at an angle, the vertical component of it was smaller than it would have been if it bounced straight up.

When processing my data I was only concerned with the first rebound height, not the successive bounces. The data for the first rebound height seemed to follow a general trend and the trials seemed to be precise but I don't think the actually values for the rebound height are accurate. Some trials show that the second rebound is higher than the first rebound. From

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qualitative observations I know that this did not occur. This confirms that the motion sensor was not always collecting the maximum height of the rebound. This will be discussed in further detail when I explain improvements to the lab.

To improve this investigation I could ensure all the balls were made from the same brand and made from the same material. The material of the soccer balls used in this experiment were all different. The different materials have different properties that could have made them react differently on the three surfaces. The material of the size 3 soccer ball seemed worn in comparison to the size 1 and size 5 soccer balls.

Next time I would have used a dirt surface that was harder packed. Since the dirt was lightly packed every trial made the dirt harder packed for the next trial. This means that the later trials would essentially be bouncing on a different surface because the dirt would become less 'absorbent' as the ground compresses.

To improve my investigation I would set LabPro to collect data from the motion sensor every 0.01 seconds instead of every 0.05 seconds. Since the ball bounces so quickly, it could have reached hit the ground and start bouncing back up before data is collected for its maximum displacement. If the data was taken every 0.01 seconds our data would be more precise to the real displacement of the ball.

To further investigate the optimal conditions for a soccer ball I could explore the relationship between the design in the leather and rebound height. Different balls have different aerodynamics due to the different design of the ball. Some are made out of hexagons and pentagons (the traditional way) while others are made with irregular shapes. The aerodynamics of the ball affects the velocity that the ball has when it hits the ground. I would expect that at different velocities the rebound height would change.

1A-16

IA Physics Typed please.

1. A clearly written focused problem statement
    a. Independent variable
    b. Dependent variable
    c. Comprehensive list of controlled variables
2. Outline procedure (numbered list, not a paragraph, does not need to be complete sentences)
    a. Must include all measurements that need to be taken
    b. Must include "HOW" each controlled value will be controlled
    c. Must include repeat steps as needed
        i. remember you will need to change the independent variable; minimum of 5 different values, and reasonable range of values
        ii. remember you will need to repeat each measurement (minimum of five times)
            1. if the value repeats exactly the same each time this can be written in the report
3. Analysis
    a. If you are doing a lab to determine a value
        i. Starting with an equation, show the algebraic steps leading to an explanation of
            1. what is graphed on each axis
            2. how the slope is related to the value you are expected to determine
    b. For all labs, you must include everything you need to do to be able to make your graph (conversions, calculated values, etc.)
4. Raw data table
    a. Just the format of the table, labeled rows, labeled columns (specific variable names, units)
5. Processed table
    a. Just the format of the table, labeled rows, labeled columns (specific names, units)
        i. Values to be graphed must all appear on this table.
6. If possible at this time, get a single set of raw data so that you know "it works."

Also plan to take photos when you do the lab! These will be included in your final report!

1.1

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Essential idea:

Since 1948, the *Système International d'Unités* (SI) has been used as the preferred language of science and technology across the globe and reflects current best measurement practice.

1

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Nature of science:

(1) Common terminology: Since the 18th century, scientists have sought to establish common systems of measurements to facilitate international collaboration across science disciplines and ensure replication and comparability of experiments.

(2) Improvement in instrumentation: Improvement in instrumentation, such as using the transition of cesium-133 atoms for atomic clocks, has led to more refined definitions of standard units.

(3) Certainty: Although scientists are perceived as working towards finding "exact" answers, there is unavoidable uncertainty in any measurement.

2

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Understandings:

- Fundamental and derived SI units
- Scientific notation and metric multipliers
- Significant figures
- Orders of magnitude
- Estimation

3

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Applications and skills:

- Using SI units in the correct format for all required measurements, final answers to calculations and presentation of raw and processed data
- Using scientific notation and metric multipliers
- Quoting and comparing ratios, values and approximations to the nearest order of magnitude
- Estimating quantities to an appropriate number of significant figures

4

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Guidance:
- SI unit usage and information can be found at the website of *Bureau International des Poids et Mesures*
- Students will not need to know the definition of SI units except where explicitly stated in the relevant topics
- Candela is not a required SI unit for this course
- Guidance on any use of non-SI units such as eV, MeV c^{-2}, Ly and pc will be provided in the relevant topics

International-mindedness:
- Scientific collaboration is able to be truly global without the restrictions of national borders or language due to the agreed standards for data representation

5

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Theory of knowledge:
- What has influenced the common language used in science? To what extent does having a common standard approach to measurement facilitate the sharing of knowledge in physics?

Utilization:
- This topic is able to be integrated into any topic taught at the start of the course and is important to all topics
- Students studying more than one group 4 subject will be able to use these skills across all subjects

6

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Aims:
- **Aim 2 and 3:** this is an essential area of knowledge that allows scientists to collaborate across the globe
- **Aim 4 and 5:** a common approach to expressing results of analysis, evaluation and synthesis of scientific information enables greater sharing and collaboration

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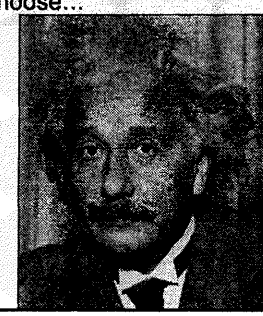
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Physics has some of the most famous names in science.

- If a poll were to be taken on who is the most famous scientist, many people would choose…

Albert Einstein
A PHYSICIST



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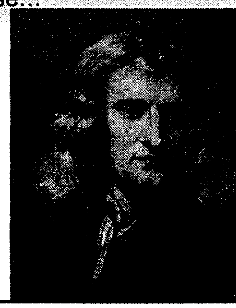
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Physics has some of the most famous names in science.

- If a poll were to be taken on who is the most famous scientist, other people might choose…

Isaac Newton
A PHYSICIST



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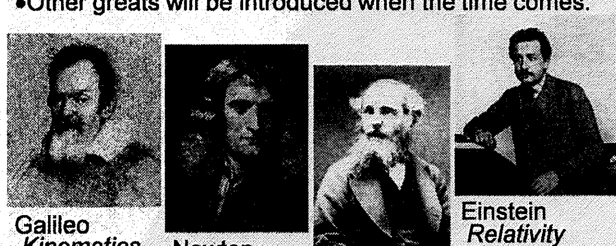
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

The physics we will study this year and next was pioneered by the following four individuals:

- Other greats will be introduced when the time comes.



Galileo
Kinematics

Newton
Calculus
Dynamics
Classical Physics

Maxwell
Electrodynamics

Einstein
Relativity
Quantum physics

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Physics is the study of forces, and matter's reaction to them.

- All of the sciences have examples of force:
- In biology, we have the bighorn sheep:

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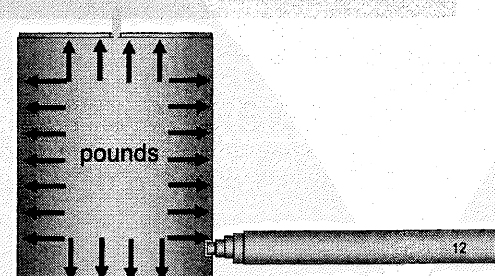
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Physics is the study of forces, and matter's reaction to them.

- All of the sciences have examples of force:
- In chemistry, we have the popping can:



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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Physics is the study of forces, and matter's reaction to them.

- All of the sciences have examples of force:
- In physics, we have the biggest forces of all:

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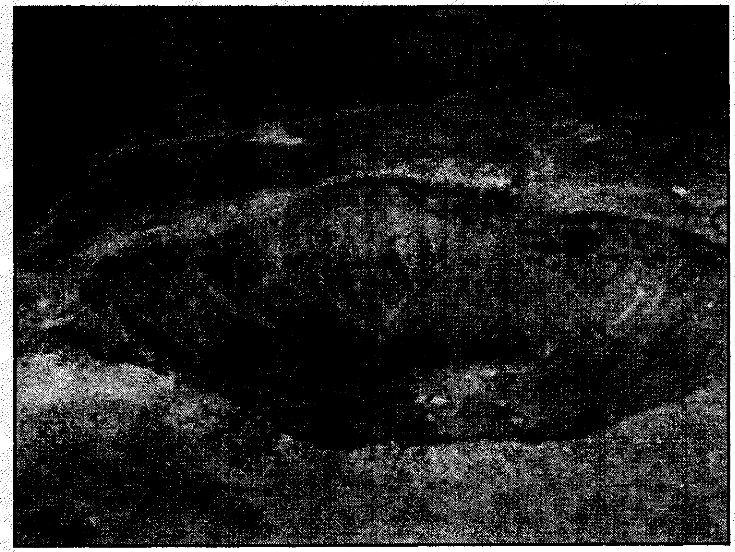
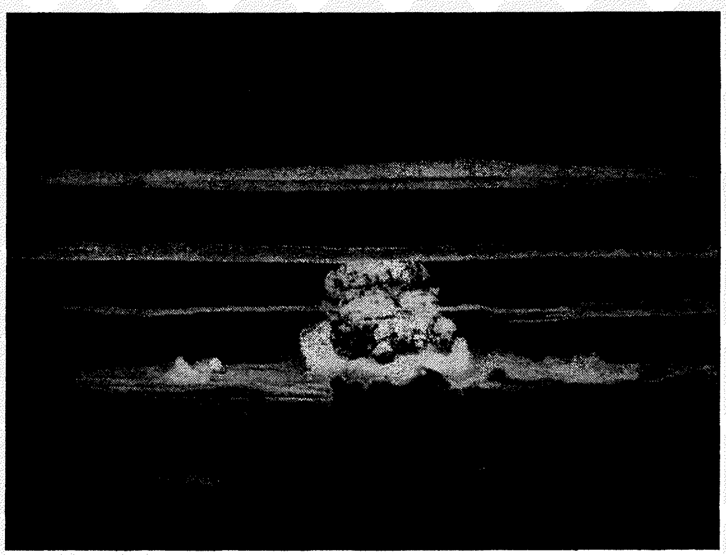
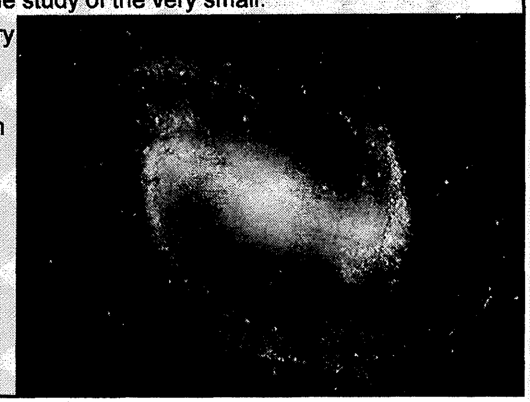




Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Physics is the study of the very small.

- And the very large.
- And everything in between.



1.1

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Fundamental and derived SI units

•The **fundamental units** in the SI system are...

- <u>mass</u> - measured in kilograms (kg)
- <u>length</u> - measured in meters (m)
- <u>time</u> - measured in seconds (s)
- <u>temperature</u> - measured in Kelvin degrees (K)
- <u>electric current</u> - measured in amperes (A)
- <u>luminosity</u> - measured in candela (cd)
- <u>mole</u> - measured in moles (mol)

FYI

•In chemistry you will no doubt use the mole, the meter, the second, and probably the Kelvin.

•You will also use the gram. <u>In physics we use the kilogram</u> (meaning 1000 grams).

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

FYI: *Blue headings* are assessment criteria put out by the IBO

Fundamental and derived SI units

PRACTICE:
Which one of the following is a fundamental unit?
A. Coulomb B. Ohm C. Volt D. Ampere

SOLUTION:
•The correct answer is (D).

FYI: "Funky print" practice problems are drawn from old IB tests

FYI

•The body that has designed the IB course is called the IBO, short for *International Baccalaureate Organization*, headquartered in Geneva, Switzerland and Wales, England.

•The IBO expects you to memorize the fundamental units.

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Learning Intentions

- You have already learned about...
  - What is physics
  - The 7 fundamental units
- What you will learn about...
  - Derived units
  - Converting between units

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

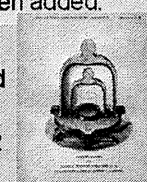
Fundamental and derived SI units

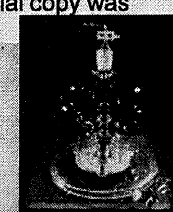
•The International Prototype of the Kilogram was sanctioned in 1889. Its form is a cylinder with diameter and height of about 39 mm. It is made of an alloy of 90 % platinum and 10 % iridium. The IPK has been conserved at the BIPM since 1889, initially with two official copies. Over the years, one official copy was replaced and four have been added.

FYI

•One meter is about a yard or three feet.

•One kilogram is about 2.2 pounds.





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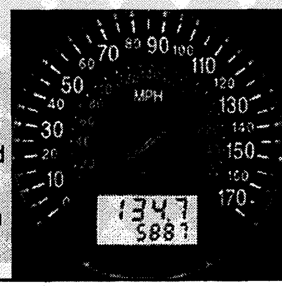
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Fundamental and derived SI units

- **Derived quantities** have units that are combos of the fundamental units. For example
- Speed - measured in meters per second (m / s).
- Acceleration - measured in meters per second per second (m / s ^{2}).



FYI

- SI stands for Système International and is a standard body of measurements.
- The SI system is pretty much the world standard in units.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Fundamental and derived SI units

- In the sciences, you must be able to convert from one set of units (and prefixes) to another.
- We will use "multiplication by the well-chosen one".

EXAMPLE: Suppose the rate of a car is 36 mph, and it travels for 4 seconds. What is the distance traveled in that time by the car?

SOLUTION:

- Distance is rate times time, or d = rt.

$$d = r \cdot t$$

$$d = \frac{36\text{ mi}}{1\text{ h}} \times (4\text{ s})$$

$$d = 144\text{ mi}\cdot\text{s/h}$$

FYI

- Sometimes "correct" units do not convey much meaning to us. See next example!

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Fundamental and derived SI units

- In the sciences, you must be able to convert from one set of units (and prefixes) to another.
- We will use "multiplication by the well-chosen one".

EXAMPLE: Convert 144 mi·s/h into units that we can understand.

SOLUTION:

- Use well-chosen ones as multipliers.

$$d = \frac{144\text{ mi}\cdot\cancel{\text{s}}}{\cancel{\text{h}}} \times \frac{1\ \cancel{\text{h}}}{60\ \cancel{\text{min}}} \times \frac{1\ \cancel{\text{min}}}{60\ \cancel{\text{s}}} = 0.04\text{ mi}$$

$$\frac{0.04\ \cancel{\text{mi}}}{1} \times \frac{5280\text{ ft}}{\cancel{\text{mi}}} = 211.2\text{ ft}$$

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Fundamental and derived SI units

- You can use units to prove that equations are invalid.

EXAMPLE: Given that distance is measured in meters, time in seconds and acceleration in meters per second squared, show that the formula $d = at$ does not work and thus is not valid.

SOLUTION: Start with the formula, then substitute the units on each side. Cancel to where you can easily compare left and right sides:

$$d \neq at$$

$$\text{m} = \frac{\text{m}}{\text{s}^{\cancel{2}}}\cancel{\text{s}}$$

$$\text{m} \neq \frac{\text{m}}{\text{s}}$$

FYI

- The last line shows that the units are <u>inconsistent</u> on left and right.
- Thus the <u>equation cannot be valid</u>.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Fundamental and derived SI units

•You can use units to prove that equations are invalid.

PRACTICE: Decide if the formulas are dimensionally consistent. The information you need is that v is measured in m/s, a is in m/s^2, x is in m and t is in s.

numbers don't have units

(a) $v = at^2$ — Inconsistent
(b) $v^2 = 3ax$ — Consistent
(c) $x = at^2$ — Consistent

FYI

•The process of substituting units into formulas to check for consistency is called **dimensional analysis.**

•DA can be used only to show the invalidity of a formula. Both (b) and (c) are consistent but neither is correct. They should be: $v^2 = 2ax$ and $x = (1/2)at^2$.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Scientific notation and metric multipliers

•We will be working with very large and very small numbers, so we will use the these prefixes:

Power of 10	Prefix Name	Symbol
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	µ
10^{-3}	milli	m
10^{-2}	centi	c
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Scientific notation and metric multipliers

•Scientific notation (commonly referred to as "standard form") is a way of writing numbers that are too big or too small to be conveniently written in decimal form.

•A number in scientific notation is expressed as $a\times10^b$, where a is a real number (called the *coefficient*, *mantissa* or *significand*) and b is an integer { … , -2, -1, 0, 1, 2, … }.

•We say that the number is *normalized* if $1 \le |a| < 10$.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Scientific notation and metric multipliers

EXAMPLE: http://en.wikipedia.org/wiki/Scientific_notation#Normalized_notation

Standard decimal notation	Normalized scientific notation
2 s	2×10^0 s
300 s	3×10^2 s
4,321.768 s	$4.321\,768\times10^3$ s 4.321768 ks
−53,000 s	-5.3×10^4 s -53 ks
6,720,000,000 s	6.72×10^9 s 9.72 Gs
0.2 s	2×10^{-1} s 200 ms
0.000 000 007 51 s	7.51×10^{-9} s 7.51 ns

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1.1

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Using SI units in the correct format

- In IB units are in "European" format rather than "American" format.
- The accepted presentation has no fraction slash.
- Instead, denominator units are written in the numerator with negative exponents. This is "SI standard."

EXAMPLE: A car's speed is measured as 40 km / h and its acceleration is measured as 1.5 m / s ^{2}. Rewrite the units in the accepted IB format.

SOLUTION: Denominator units just come to the numerator as negative exponents. Thus

- 40 km / h is written 40 km h $^{-1}$.
- 1.5 m / s ^{2} is written 1.5 m s $^{-2}$.

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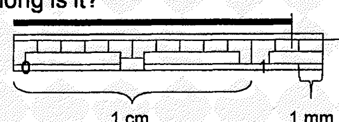
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures

- Error in measurement is expected because of the imperfect nature of our measuring devices.
- A typical meter stick has marks at every millimeter (10 $^{-3}$ m or 1/1000 m). Thus the best measurement you can get from a typical meter stick is to the nearest mm.

EXAMPLE: Consider the following line whose length we wish to measure. How long is it?



SOLUTION:

- It is closer to 1.2 cm than 1.1 cm, so we say it measures 1.2 cm. The 1 and 2 are both **significant**.

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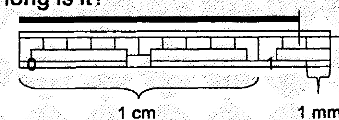
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures

- We call the "1" in the measurement below the **most significant digit**. It represents the "main portion" of our measurement.
- We call the "2" in the measurement below the **least significant digit**.

EXAMPLE: Consider the following line whose length we wish to measure. How long is it?



SOLUTION:

- It is closer to 1.2 cm than 1.1 cm, so we say it measures 1.2 cm.

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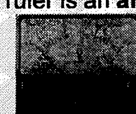
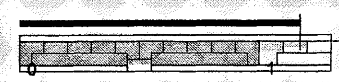
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures

- A ruler is an **analog** measuring device.



- So is a meter with a needle.
- For good analog devices you can **estimate** the last digit.
- Thus, to say that the blue line is 1.17 cm or 1.18 cm long are both correct.



- The 1.1 part constitutes the two **certain** digits.
- The 7 (or 8) constitutes the **uncertain** digit.

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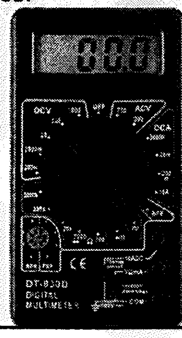
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures

- A **digital** measuring device, on the other hand, is only "good" to the least significant digit's place.

EXAMPLE:

- The meter shown here is *only* good to the nearest 0.1 V. There is NO estimation of another digit.



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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures

- **Significant figures** are the reasonable number of digits that a measurement or calculation should have.
- For example, as illustrated before, a typical wooden meter stick has two significant figures.
- The number of significant figures in a calculation reflects the precision of the least precise of the measured values.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures

(1) *All non-zero digits are significant.*	438 g	3
	26.42 m	4
	0.75 cm	2
(2) *All zeros between non-zero digits are significant.*	12060 m	4
	900.43 cm	5
(3) *Filler zeros to the left of an understood decimal place are not significant.*	220 L	2
	60 g	1
	30. cm	2
(4) *Filler zeros to the right of a decimal place are not significant.*	0.006 L	1
	0.08 g	1
(5) *All non-filler zeros to the right of a decimal place are significant.*	8.0 L	2
	60.40 g	4

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Significant figures in calculations

EXAMPLE	CALCULATOR	SIG. FIGS
Multiplication and division – *round your answer to the same number of significant digits as the quantity with the fewest number of significant digits.*		
(1.2 cm)(2 cm)	2.4 cm^2	2 cm^2
π(2.75 cm)^2	7.5625 cm^2	7.56 cm^2
5.350 m/2.752 s	1.944040698 m/s	1.944 m/s
(0.0075 N)(6 m)	0.045 Nm	0.04 Nm
Addition and subtraction – *round your answer to the same number of decimal places as the quantity with the fewest number of decimal places.*		
1.2 cm + 2 cm	3.2 cm	3 cm
2000 m+2.1 m	2002.1 m	2000 m
0.00530 m – 2.10 m	-2.0947 m	-2.09 m

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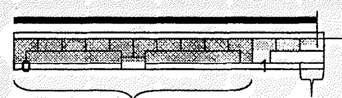
1.1

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Estimating quantities to an appropriate number of significant figures

PRACTICE: How long is this line?



SOLUTION: Read the first two certain digits, then estimate the last uncertain one.
•The 1 and the 2 are the certain digits.
•The 8 (or 7) is the uncertain digit.
•It is about 1.28 cm (or maybe 1.27 cm) long.

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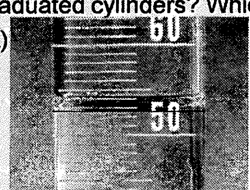
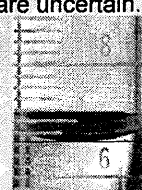
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Estimating quantities to an appropriate number of significant figures

PRACTICE: What is the reading on each of the graduated cylinders? Which digits are uncertain.

(A) 

(B) 

SOLUTION: Read to the bottom of the meniscus.

(A) reads 52.8 mL. The 8 is uncertain.

(B) Reads 6.62 mL. The 2 is uncertain.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Orders of magnitude

Mass of universe	10^{50}	kg
Diameter of universe	10^{25}	m
Diameter of galaxy	10^{21}	m
Age of universe	10^{18}	s
Speed of light	10^{8}	$m\,s^{-1}$
Diameter of atom	10^{-10}	m
Diameter of nucleus	10^{-15}	m
Diameter of quark	10^{-18}	m
Mass of proton	10^{-27}	kg
Mass of quark	10^{-30}	kg
Mass of electron	10^{-31}	kg
Planck length	10^{-35}	m

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Quoting and comparing ratios, values and approximations to the nearest order of magnitude

EXAMPLE: Given that the smallest length in the universe is the Planck length of 10^{-35} meters and that the fastest speed in the universe is that of light at 10^{8} meters per second, find the smallest time interval in the universe.

SOLUTION:

•Speed is distance divided by time (speed = d / t).

•Using algebra we can write t = d / speed.

•Substitution yields $t = 10^{-35} / 10^{8} = 10^{-43}$ seconds.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Quoting and comparing ratios, values and approximations to the nearest order of magnitude

EXAMPLE: Find the difference in order of magnitude of the mass of the universe to the mass of a quark.

SOLUTION:
- Make a ratio (fraction) and simplify.
- 10^{50} kilograms / 10^{-30} kilograms = 10^{80}.
- Note that the kilograms cancels leaving a unitless power of ten.
- The answer is 80 orders of magnitude.

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

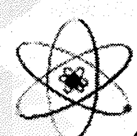
Quoting and comparing ratios, values and approximations to the nearest order of magnitude

PRACTICE:

The ratio $\dfrac{\text{diameter of a nucleus}}{\text{diameter of an atom}}$ is approximately equal to

A. 10^{-15}. B. 10^{-8}. C. 10^{-5}. D. 10^{-2}.

SOLUTION:
- Diameter of nucleus is 10^{-15} m.
- Diameter of atom is 10^{-10} m.
- Thus 10^{-15} m / 10^{-10} m = $10^{-15-(-10)} = 10^{-5}$.
- The correct answer is (C).



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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Quoting and comparing ratios, values and approximations to the nearest order of magnitude

PRACTICE:

The mass of an atom of the isotope strontium-92 (^{92}Sr) is of the order of

A. 10^{-23} kg. B. 10^{-25} kg. C. 10^{-27} kg. D. 10^{-29} kg.

SOLUTION:
- The "92" in ^{92}Sr means 92 nucleons.
- The mass of nucleons (protons and neutrons) is of the order of 10^{-27} kg.
- 92 is of the order of 10^{2}.
- Thus $10^{2} \times 10^{-27}$ kg = 10^{-25} kg.
- The correct answer is (B).

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Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Quoting and comparing ratios, values and approximations to the nearest order of magnitude

PRACTICE:

The volume of the Earth is approximately 10^{12} km^3 and the volume of a grain of sand is approximately 1 mm^3. The order of magnitude of the number of grains of sand that can fit in the volume of the Earth is

A. 10^{12}. B. 10^{18}. C. 10^{24}. D. 10^{30}.

SOLUTION:
- $V_{Earth} = 10^{12}$ km^3 = $10^{12} \times (10^{3})^{3} = 10^{12+9} = 10^{21}$ m^3.
- $V_{sand} = 1$ mm^3 = $10^{0} \times (10^{-3})^{3} = 10^{0-9} = 10^{-9}$ m^3.
- $N_{sand} = V_{Earth} / V_{sand} = 10^{21} / 10^{-9} = 10^{21-(-9)} = 10^{30}$.
- The correct answer is (D).

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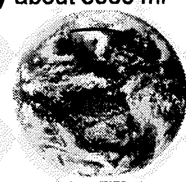
Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Estimation revisited

- Another form of estimation is to solve complex problems with the simplest math possible and obtain a ballpark figure as an answer.
- If at all possible, only powers of ten are used.

EXAMPLE: NY and LA are separated by about 3000 mi and three time zones. What is the circumference of Earth?



SOLUTION:

- Since 3000 mi = 3 TZ, 1000 mi = 1 TZ.
- There are 24 h in a day.
- Earth rotates once each day. Thus there are 24 TZ in one circumference, or 24×1000 mi = 24000 mi.

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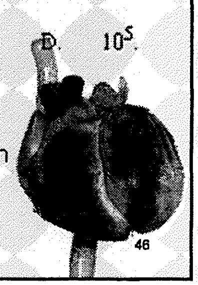
1.1

Topic 1: Measurement and uncertainties
1.1 – Measurements in physics

Quoting and comparing ratios, values and approximations to the nearest order of magnitude

PRACTICE:
The number of heartbeats of a person at rest in one hour, to the nearest order of magnitude is

A. 10^1. B. 10^2. C. 10^3. D. 10^5.



SOLUTION: The human heart rate is about 75 beats per minute. This is between 10^1 (10) and 10^2 (100).

- But 1 hour is 60 min, which is also between 10^1 (10) and 10^2 (100).
- Then our answer is between $10^1 \times 10^1 = 10^2$ and $10^2 \times 10^2 = 10^4$.
- The correct answer is (C).

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1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Essential idea:

Scientists aim towards designing experiments that can give a "true value" from their measurements, but due to the limited precision in measuring devices, they often quote their results with some form of uncertainty.

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Understandings:

- Random and systematic errors
- Absolute, fractional and percentage uncertainties
- Error bars
- Uncertainty of gradients and intercepts

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Nature of science:

Uncertainties: "All scientific knowledge is uncertain. When the scientist tells you he does not know the answer, he is an ignorant man. When he tells you he has a hunch about how it is going to work, he is uncertain about it. When he is pretty sure of how it is going to work, he still is in some doubt. And it is of paramount importance, in order to make progress, that we recognize this ignorance and this doubt. Because we have the doubt, we then propose looking in new directions for new ideas."

– Feynman, Richard P. 1998. The Meaning of It All: Thoughts of a Citizen-Scientist. Reading, Massachusetts, USA. Perseus. P 13.

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Applications and skills:

- Explaining how random and systematic errors can be identified and reduced
- Collecting data that include absolute and/or fractional uncertainties and stating these as an uncertainty range (expressed as: best estimate ± uncertainty range)
- Propagating uncertainties through calculations involving addition, subtraction, multiplication, division and raising to a power
- Determining the uncertainty in gradients and intercepts

1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Guidance:
- Analysis of uncertainties will not be expected for trigonometric or logarithmic functions in examinations

Data booklet reference:
- If $y = a \pm b$ then $\Delta y = \Delta a + \Delta b$
- If $y = a \cdot b / c$ then $\Delta y / y = \Delta a / a + \Delta b / b + \Delta c / c$
- If $y = a^n$ then $\Delta y / y = | n \cdot \Delta a / a |$

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Theory of knowledge:
- "One aim of the physical sciences has been to give an exact picture of the material world. One achievement of physics in the twentieth century has been to prove that this aim is unattainable." – *Jacob Bronowski.*
- Can scientists ever be truly certain of their discoveries?

Jacob Bronowski was a mathematician, biologist, historian of science, theatre author, poet and inventor. He is probably best remembered as the writer of The Ascent of Man.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Utilization:
- Students studying more than one group 4 subject will be able to use these skills across all subjects

Aims:
- Aim 4: it is important that students see scientific errors and uncertainties not only as the range of possible answers but as an integral part of the scientific process
- Aim 9: the process of using uncertainties in classical physics can be compared to the view of uncertainties in modern (and particularly quantum) physics

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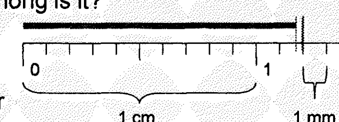
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

- Error in measurement is expected because of the imperfect nature of us and our measuring devices.
- For example a typical meter stick has marks at every millimeter (10^{-3} m or 1/1000 m).

EXAMPLE: Consider the following line whose length we wish to measure. How long is it?



SOLUTION: It is closer to 1.2 cm than to 1.1 cm, so we say it measures 1.2 cm (or 12 mm or 0.012 m).

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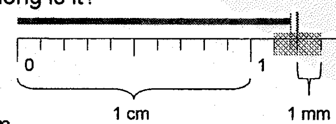
1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

- Error in measurement is expected because of the imperfect nature of us and our measuring devices.
- We say the **precision** or **uncertainty** in our measurement is ± 1 mm.

EXAMPLE: Consider the following line whose length we wish to measure. How long is it?



SOLUTION: It is closer to 1.2 cm than to 1.1 cm, so we say it measures 1.2 cm (or 12 mm or 0.012 m).

FYI • We record L = 12 mm ± 1 mm.

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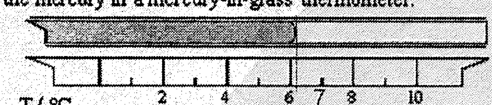
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

The diagram below shows the position of the meniscus of the mercury in a mercury-in-glass thermometer.



Which of the following best expresses the indicated temperature with its uncertainty?

A. (6.0 ± 0.5)°C
B. (6.1 ± 0.1)°C
C. (6.2 ± 0.2)°C
D. (6.2 ± 0.5)°C

SOLUTION:

- 6.2 is the nearest reading.
- The uncertainty is certainly less than 0.5.

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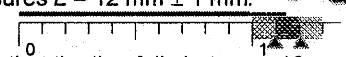
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

- **Random error** is error due to the recorder, rather than the instrument used for the measurement.
- Different people may measure the same line slightly differently. You may in fact measure the same line differently on two different occasions.

EXAMPLE: Suppose **Bob** measures L = 11 mm ± 1 mm and **Ann** measures L = 12 mm ± 1 mm.



- Then **Bob** guarantees that the line falls between 10 mm and 12 mm.
- **Ann** guarantees it is between 11 mm and 13 mm.
- **Both** are absolutely correct.

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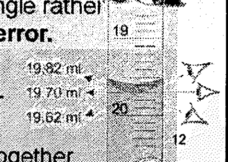
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

- **Random error** is error due to the recorder, rather than the instrument used for the measurement.
- Different people may measure the same line slightly differently. You may in fact measure the same line differently on two different occasions.
- Perhaps the ruler wasn't perfectly lined up.
- Perhaps your eye was viewing at an angle rather than head-on. This is called a **parallax error.**

FYI

- The only way to minimize random error is to take many readings of the same measurement and to average them all together.



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1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

Systematic error is error due to the instrument being "out of adjustment."

•A voltmeter might have a zero offset error.

•A meter stick might be rounded on one end.

Now Bob measures the same line at 13 mm ± 1 mm.

Furthermore, every measurement Bob makes will be off by that same amount.

FYI

•Systematic errors are usually difficult to detect.

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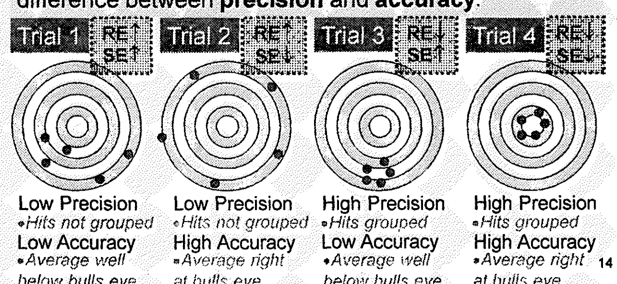
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

•The following game where a catapult launches darts with the goal of hitting the bull's eye illustrates the difference between **precision** and **accuracy**.



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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Random and systematic errors

PRACTICE:

An ammeter has a zero offset error. This fault will affect

A. neither the precision nor the accuracy of the readings.

B. only the precision of the readings.

C. only the accuracy of the readings.

D. both the precision and the accuracy of the readings.

SOLUTION:

•This is like the rounded-end ruler. It will produce a systematic error.

•Thus its error will be in accuracy, not precision.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Absolute, fractional and percentage uncertainties

•**Absolute error** is the raw uncertainty or precision of your measurement.

EXAMPLE:

A student measures the length of a line with a wooden meter stick to be 11 mm ± 1 mm. What is the absolute error or uncertainty in her measurement?

SOLUTION:

•The ± number is the **absolute error**. Thus 1 mm is the absolute error.

•1 mm is also the **precision**.

•1 mm is also the **raw uncertainty**.

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1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Absolute, fractional and percentage uncertainties

•**Fractional error** is given by

fractional error

$$\textit{Fractional Error} = \frac{\textit{Absolute Error}}{\textit{Measured Value}}$$

EXAMPLE:

A student measures the length of a line with a wooden meter stick to be 11 mm ± 1 mm. What is the fractional error or uncertainty in her measurement?

SOLUTION:

•*Fractional error* = 1 / 11 = 0.09.

FYI •"Fractional" errors are usually expressed as decimal numbers rather than fractions.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Absolute, fractional and percentage uncertainties

•**Percentage error** is given by

percentage error

$$\textit{Percentage Error} = \left(\frac{\textit{Absolute Error}}{\textit{Measured Value}}\right) \cdot 100\%$$

EXAMPLE:

A student measures the length of a line with a wooden meter stick to be 11 mm ± 1 mm. What is the percentage error or uncertainty in her measurement?

SOLUTION:

•*Percentage error* = (1 / 11) · 100% = 9%

FYI •Don't forget to include the percent sign.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Absolute, fractional and percentage uncertainties

PRACTICE:

A student measures the voltage shown. What are the absolute, fractional and percentage uncertainties of his measurement? Find the precision and the raw uncertainty.

SOLUTION:

•Absolute uncertainty = 0.001 V.

•Fractional uncertainty = 0.001/0.385 = 0.0026.

•Percentage uncertainty = 0.0026(100%) = 0.26%.

•Precision is 0.001 V.

•Raw uncertainty is 0.001 V.

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Absolute, fractional and percentage uncertainties

PRACTICE:

A student measures a distance several times. The readings lie between 49.8 cm and 50.2 cm. This measurement is best recorded as

A. 49.8 ± 0.2 cm.
B. 49.8 ± 0.4 cm.
C. 50.0 ± 0.2 cm.
D. 50.0 ± 0.4 cm.

SOLUTION:

•Find the average of the two measurements:

(49.8 + 50.2) / 2 = 50.0.

•Find the range / 2 of the two measurements:

(50.2 – 49.8) / 2 = 0.2.

•The measurement is 50.0 ± 0.2 cm.

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1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Propagating uncertainties through calculations

- To find the **uncertainty in a sum or difference** you just add the uncertainties of all the ingredients.
- In formula form we have

uncertainty in sums and differences

If $y = a \pm b$ then $\Delta y = \Delta a + \Delta b$

FYI

- Note that whether or not the **calculation** has a + or a -, the **uncertainties** are ADDED.
- Uncertainties NEVER REDUCE ONE ANOTHER.

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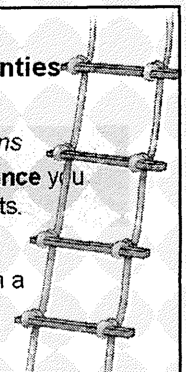
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors



Propagating uncertainties through calculations

- To find the **uncertainty in a sum or difference** you just add the uncertainties of all the ingredients.

EXAMPLE:

A 9.51 ± 0.15 meter rope ladder is hung from a roof that is 12.56 ± 0.07 meters above the ground. How far is the bottom of the ladder from the ground?

SOLUTION:

- $y = a - b = 12.56 - 9.51 = 3.05$ m
- $\Delta y = \Delta a + \Delta b = 0.15 + 0.07 = 0.22$ m
- Thus the bottom is 3.05 ± 0.22 m from the ground.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Propagating uncertainties through calculations

- To find the **uncertainty in a product or quotient** you just add the percentage or fractional uncertainties of all the ingredients.
- In formula form we have

uncertainty in products and quotients

If $y = a \cdot b / c$ then $\Delta y / y = \Delta a / a + \Delta b / b + \Delta c / c$

FYI

- Whether or not the **calculation** has a × or a ÷, the **uncertainties** are ADDED.
- You can't add numbers having different units, so we use fractional uncertainties for products and quotients.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

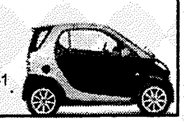
Propagating uncertainties through calculations

- To find the **uncertainty in a product or quotient** you just add the percentage or fractional uncertainties of all the ingredients.

EXAMPLE: A car travels 64.7 ± 0.5 meters in 8.65 ± 0.05 seconds. What is its speed?

SOLUTION: Use *rate* = *distance* divided by *time*.

- $r = d / t = 64.7 / 8.65 = 7.48$ m s^{-1}
- $\Delta r / r = \Delta d / d + \Delta t / t = .5 / 64.7 + .05 / 8.65 = 0.0135$
- $\Delta r / 7.48 = 0.0135$ so that
- $\Delta r = 7.48(0.0135) = 0.10$ m s^{-1}.
- Thus, the car is traveling at 7.48 ± 0.10 m s^{-1}.



1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Propagating uncertainties through calculations

PRACTICE:

The power dissipated in a resistor of resistance R carrying a current I is equal to I^2R. The value of I has an uncertainty of ±2% and the value of R has an uncertainty of ±10%. The value of the uncertainty in the calculated power dissipation is

A. ±8%. B. ±12%. C. ±14%. D. ±20%.

SOLUTION:

- $\Delta P / P = \Delta I / I + \Delta I / I + \Delta R / R$

$\Delta P / P = 2\% + 2\% + 10\% = 14\%$.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Propagating uncertainties through calculations

PRACTICE:

When a force F of (10.0 ± 0.2) N is applied to a mass m of (2.0 ± 0.1) kg, the percentage uncertainty attached to the value of the calculated acceleration $\frac{F}{m}$ is

A. 2%. B. 5%. C. 7%. D. 10%.

SOLUTION:

- $\Delta F / F = 0.2 / 10 = 0.02 = 2\%$.
- $\Delta m / m = 0.1 / 2 = 0.05 = 5\%$.
- $\Delta a / a = \Delta F / F + \Delta m / m = 2\% + 5\% = 7\%$.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Propagating uncertainties through calculations

PRACTICE:

The radius of a loop is measured to be (10.0 ± 0.5) cm. Which of the following is the best estimate of the uncertainty in the calculated area of the loop?

A. 0.25% B. 5% C. 10% D. 25%

SOLUTION:

- $\Delta r / r = 0.5 / 10 = 0.05 = 5\%$.
- $A = \pi r^2$.
- Then $\Delta A / A = \Delta r / r + \Delta r / r = 5\% + 5\% = 10\%$.

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

- IB has a requirement that when you conduct an experiment of your own design, you must have **five variations** in your **independent variable**.
- And for **each** variation of your independent variable you must conduct **three trials** to gather the values of the **dependent variable**.
- The three values for each dependent variable will then be averaged.

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1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•This is a well designed table containing all of the information and data points required by IB:

The "good" header

Average Rebound Height
Word Name
h / cm
Symbol / Units
$\Delta h = \pm 2.0$ cm
Uncertainty

Sheets n / no units $\Delta n = \pm 0$	3 Trials: Rebound Height h_i / cm $\Delta h_i = \pm 0.2$ cm			Average Rebound Height h / cm $\Delta h = \pm 2.0$ cm
Independent (manipulated)	Trial 1	Trial 2	Trial 3	Dependent (responding)
0	54.8	55.1	54.6	55
2	53.4	52.5	49.6	52
4	50.7	48.7	48.6	49
6	49.0	47.1	48.5	48
8	45.9	45.0	44.6	45

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Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•In order to determine the uncertainty in the dependent variable we reproduce the first two rows of the previous table:

Sheets n / no units $\Delta n = \pm 0$	Rebound Height h_i / cm $\Delta h_i = \pm 0.2$ cm			Average Rebound Height h / cm $\Delta h = \pm 2.0$ cm
	Trial 1	Trial 2	Trial 3	
0	54.8	55.1	54.6	55
2	53.4	52.5	49.6	52

•The uncertainty in the average height h was taken to be **half the largest range** in the trial data, which is in the row for $n = 2$ sheets: $\frac{53.4 - 49.6}{2} = 2.0$

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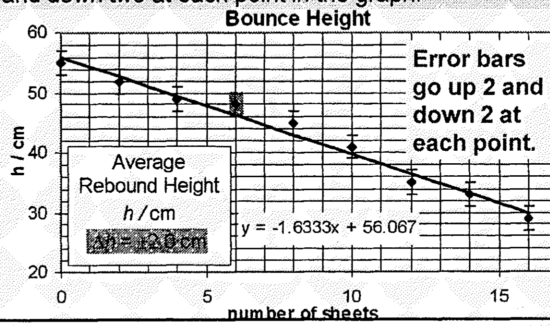
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•The size of the **error bar** in the graph is then up two and down two at each point in the graph:



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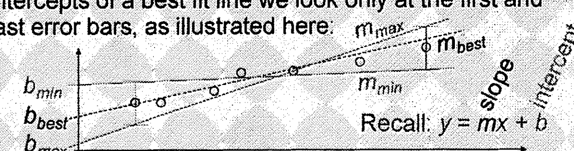
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•To determine the uncertainty in the gradient and intercepts of a best fit line we look only at the first and last error bars, as illustrated here:



$m_{best} \pm \Delta m = m_{best} \pm \left(\frac{m_{max} - m_{min}}{2} \right)$ slope & uncertainty

$b_{best} \pm \Delta b = b_{best} \pm \left(\frac{b_{max} - b_{min}}{2} \right)$ intercept & uncertainty

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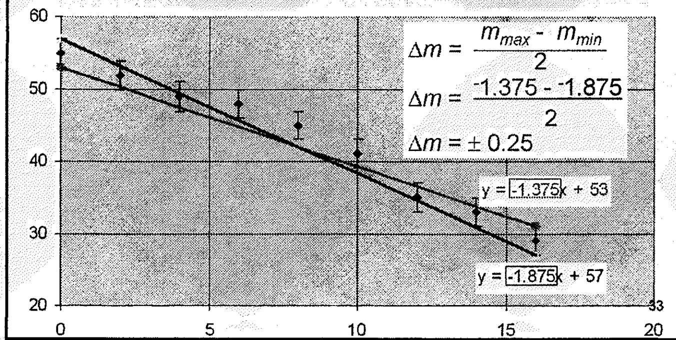
1.2

Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•The **slope uncertainty calculation** is shown here:



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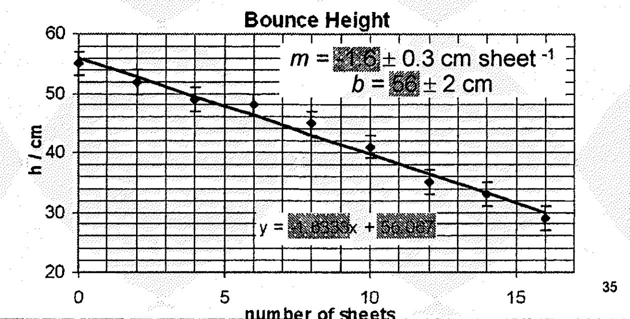
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•Finally, the finished graph:



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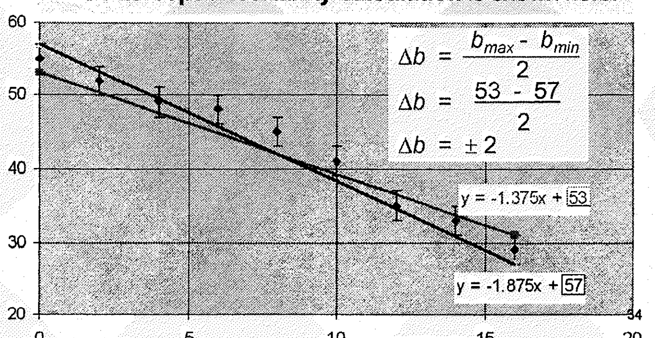
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

•The **intercept uncertainty calculation** is shown here:



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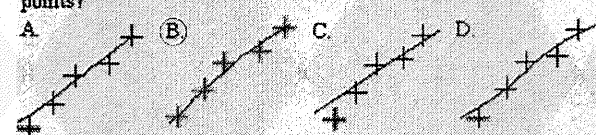
Topic 1: Measurement and uncertainties
1.2 – Uncertainties and errors

Uncertainty of gradient and intercepts

EXAMPLE:

Which one of the following shows the best-fit line for the plotted points?



SOLUTION:

•Look for the line to lie within all horizontal and vertical error bars.

•Only graph B satisfies this requirement.

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Topic 1.1 – Measurements in physics **Formative Assessment**

NAME: ________________________________ TEAM:__

THIS IS A PRACTICE ASSESSMENT. Show formulas, substitutions, answers (in spaces provided) and units!

1. Find the difference in order of magnitude for the following comparison: The size of the atom to the size of the nucleus. 1. ______________

2. Find the order of magnitude for the following calculation: The time it takes light to transverse a quark. 2. ______________

3. Which equation must be wrong? Note that t is in s, v is in m s^{-1}, a is in m s^{-2}, x is in m, F is in kg m s^{-2} and m is in kg. 3. ____
   a. $a = v^2 / x$ c. $a = v^2 / t$
   b. $v = at$ d. $a = F / m$

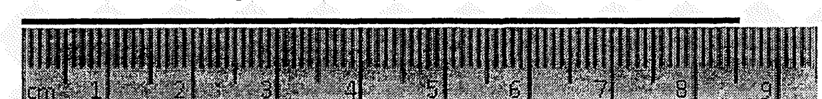
4. Convert 484 mi s h^{-1} to feet. Be sure to show each well-chosen one. 4. ______________

5. Estimate how many kilograms are in a 225-pound man. 5. ______________

6. Using the technique of the well-chosen one, convert the quantity 125 km into its equivalent in mm.
   6. ______________

7. Estimate the amount of time it takes light to travel from a batter to your eye if you are seated in center field at Miller Park, 315 feet away. 1 meter is about 3 feet. 7. ______________

8. Find the line's length to the maximum number of significant figures allowed by the centimeter ruler.



8. ______________

9. Determine the number of significant figures in each of the following.

(a) 0.0015 ___ (b) 0.15 ___ (c) 1.500 ___ (d) 1.0005 ___

(e) 1.00050 ___ (f) 0.00010000 ___ (g) 6.35×10^{6} ___ (h) 160×10^{-21} ___

10. Compute the following quantities to the correct number of significant figures.

(a) 5.0000×2 (b) 5.0000×2.0 (c) $2.5\times10^{-2} - 2.5$ (d) $2.5\times10^{-2} - 2.50$

__________ __________ __________ __________

(e) $2.5\times10^{-2} - 2.500$ (f) $5.0000 \div 2$ (g) $2.5\times10^{-2} - \pi$ (h) $2.50\times10^{-2} \div 4.50$

__________ __________ __________ __________

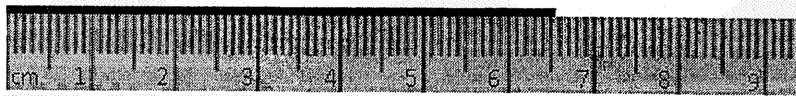
WS1

Topic 1.2 – Uncertainties and errors **Formative Assessment**

NAME: ______________________________ TEAM:__

THIS IS A PRACTICE ASSESSMENT. Show formulas, substitutions, answers (in spaces provided) and units!

For questions 1. through 4. consider the line shown here:



1. What is the measured length of this line in mm? Use the amount of significant figures a wooden meter stick is capable of supplying. 1. ______________

2. What is the precision of this measurement? 2. ______________

3. If the above line is one side of a perfect square, what is the area of that square, taking into account the correct number of significant figures and the correct units? Note that area is length times width, and the length equals the width in a square. 3. ______________

4. What is the raw uncertainty in your answer from problem 3? 4. ______________

A student measures a line to be 3.8 cm ±0.1 cm.

5. Find the absolute uncertainty in the measurement. 5. ______________

6. Find the raw uncertainty in the measurement. 6. ______________

7. Find the fractional uncertainty in the measurement. 7. ______________

8. Find the percentage uncertainty in the measurement. 8. ______________

9. A flagpole is placed on the roof of a house. A student measures the flagpole to be 4.25 m ± 0.05 m. The same student measures the height from the ground to the base of the flagpole to be 6.40 m ± 0.15 m. If the flagpole is mounted vertically upward (straight up), how far is the tip of the flagpole above the ground. Be sure to use significant figures and include a raw uncertainty with your answer. 9. ______________

10. A car travels 250 m ± 15 m in 12.2 s ± 0.2 s. Calculate its speed. Be sure to use significant figures and include a raw uncertainty with your answer. 10. ______________

WS2

A table of data was created by a student during an experiment in which a paper helicopter was dropped from various heights.

11. Complete the last column of the table.

12. Does it appear that the student has done the right number of trials and variations to satisfy the internal assessment requirements of the IBO? Be sure to explain very clearly your reasoning.

Height H / m $\Delta H = \pm 0.1$ m	Fall Time T_i / s $\Delta T_i = \pm 0.2$ s			Average Fall Time T / s
	Trial 1	Trial 2	Trial 3	ΔT_i = ______
1.0	1.4	1.7	1.6	
1.5	2.0	2.2	1.8	
2.0	2.4	2.7	2.7	
2.5	3.1	3.7	3.4	
3.0	3.9	3.8	4.2	

12. ______________________________

13. Create a graph which plots *Average Fall Time vs. Height*. Be sure to label the graph properly.
13. ___See graph___

14. On the same graph sketch the vertical error bars on each point. 14. ___See graph___

15. On the same graph sketch in your line of best fit. 15. ___See graph___

16. Calculate the slope of the line of best fit. Be sure to include the units. 16. ______________

17. From your graph, determine the intercept. Include its units. 17. ______________

18. On the same graph sketch in the maximum and minimum slopes, using the first and last error bars as your guide. 18. ___See graph___

19. Calculate the minimum and maximum slopes. Be sure to include the units. 19. ______________
____

20. Calculate the uncertainty of the slope. 20. ______________

21. What are the intercepts of the lines representing the minimum and maximum slopes?
21. ______________
____

22. Calculate the uncertainty of the intercept. 22. ______________

23. State, in words, the slope (and uncertainty) of your graph and its physical meaning.

24. State, in words, the intercept (and uncertainty) of your graph and its physical meaning.

WS3