IB Guide to Writing Lab Reports

Standard and Higher Level Chemistry

Error Analysis

Please read carefully and keep this handy reference for future use in writing exemplary lab reports.

IB Guide to Writing Laboratory Reports

Explanations, Clarifications, and Handy Hints

The nature of science is to investigate the world around you. An inquiring mind is essential to science. Experiments are designed by curious minds to gain insight into wonder-producing phenomena. Hopefully, this process of designing experiments, doing experiments, thinking about experimental results, and writing lab reports will tremendously benefit YOU!

IB Chemistry is the challenge you have chosen. Congratulations! IB learners strive to be:

- Inquirers
- Knowledgeable
- Thinkers
- Communicators
- Principled
- Open-minded
- Caring
- Risk-takers
- Balanced
- Reflective * the IB learner profile

This process will challenge your thinking skills more than you can imagine. We need to emphasize again and again; all of this work is about YOU growing as a student. In addition, we invest valuable time into lab experiences because we all LIKE doing lab experiments! Hands-on learning opportunities are engaging and rewarding. Laboratory experiments are about *thinking* and *doing* and *thinking* some more.

> "I hear and I forget.
> I see and I remember.
> I do and I understand."
> -- Confucius * see page 32 for more Confucius quotes

The International Baccalaureate program values the laboratory as an integral part of learning chemistry. Your lab portfolio will comprise 24% of your official IB grade. Your teachers also value the lab and designate 30% of each marking period grade to be based on your lab experiences. So, lab is BIG.

IB has designated particular criteria to be included in a formal lab report, and each criterion has distinct aspects that will be evaluated. Not all lab reports in IB Chemistry will be “formal” lab reports, and not all “formal” lab reports will be assessing all of the designated criteria. We will pace the expectations of the course to keep your workload manageable. We do appreciate your time.

This Guide will help you understand the IB requirements and maximize your learning.

Specific Points Graded for Each Lab Report Criteria

Design: D
- Defining the Problem
- Controlling variables
- Developing a method for collection of data

Data Collection and Processing: DCP
- Recording Raw Data
- Processing Raw Data
- Presenting Raw Data

Conclusion and Evaluation: CE
- Concluding
- Evaluating Procedure(s)
- Improving the Investigation

Design

	Aspect 1	Aspect 2	Aspect 3
Levels	*Defining the Problem*	*Controlling Variables*	*Developing a Method for Collection of Data*
Complete	Formulates a focused problem / research question and identifies the relevant variables	Designs a method for the effective control of the variables.	Develops a method that allows for the collection of sufficient relevant data.
Partial	Formulates a problem / research question that is incomplete or identifies only some relevant variables.	Designs a method that makes some attempt to control the variables.	Develops a method that allows for the collection of insufficient relevant data.
None	Does not identify a problem / research question and does not identify any relevant variables	Designs a method that does not control the variables.	Develops a method that does not allow for any relevant data to be collected.

Aspect 1: Defining the Problem

Only a few experiments in IB Chemistry will require you to create your own research problem. Usually the labs you will be asked to do will already have clearly specified research questions and procedures. But when you design your own experiment, the first step is to recognize the nature of the problem before you. When the Design criterion is assessed, you will be given an open-ended problem or a general aim of the lab such that your inquiry is guided. For example, the research question might be presented to the whole class in the form of

"Investigate the Volume of a Drop".

You will need to recognize that certain factors will influence the volume of a drop. This is the nature of the problem. You will form a research question that is specific and relevant to your individual experiment. For the experiment "Investigate the Volume of a Drop", your research question could be

"Determine how the size of the opening of the dropper affects the volume of a drop of water".

Your current understanding of science theories provides a background for your research question. Relevant theory needs to be presented. (e.g., What do you know about water that makes you to wonder about how the size of the opening could affect the volume of a drop of water? You could discuss surface tension, intermolecular bonds, adhesive and cohesive forces, capillary action, and other physical properties of water.) Your understanding of theory impacts the research question you choose.

You might be asked to formulate a hypothesis (prediction) in light of any independent variables that have been chosen. Such a hypothesis must contain more than just an expected observation. It must also include a proposed relationship between two or more variables, or at least an element of rational explanation for an expected observation. Often a hypothesis is formulated in a statement;

“if *y* is done, then *z* will occur because…………...”.

Answering the “because” in this hypothesis is an important part of the criteria being evaluated. The known theory is presented in the beginning of a lab report to substantiate your hypothesis as reasonable. Theory supports the “because” in your hypothesis. In addition to your research question, theory also relates to your explanation of your hypothesis. Theory used by a curious mind is the foundation of experimentation.

Your hypothesis will relate two variables that might have an effect on each other. Other variables that might affect the outcome are also mentioned, even if they are not to be specifically investigated.

Three Types of Variables in an Experiment

1) The *independent variable* is the variable you set or determine. Hence this variable stands independently in your experiment. You set this variable.
2) The *dependent variable* is the variable that responds to the independent variable. Hence this variable is dependent on the independent variable in your experiment.
3) The *controlled variables* are all of the reasonable potential variables that you are keeping constant or unchanged throughout the duration of the experiment. You try very hard to control all of these variables to be unwavering while you gather data.

Aspect 2: Controlling the Variables

You will then need to design a method that allows you to control these variables. “Control of variables” refers to the manipulation of the independent variable and the attempt to maintain the controlled variables at a constant value. The method should include explicit reference as to how the control of variables is achieved. The method should be clearly described in sufficient detail so that it could be reproduced by someone else from the information given. It is conventional to write sequential, numbered steps to communicate a procedure.

Your designed procedure must guarantee that the independent variable remains independent, the dependent variable remains dependent, and the controlled variables truly remain constant. Be specific in the listing of required supplies. Materials and equipment needed in the investigation are to be designated by quantity and size (i.e. 3 − 50mL beakers) and chemicals designated by quantity and concentration (i.e., 25 mL of 1.0 molar hydrochloric acid or 10 grams of iron filings). The experimental set-up and measurement techniques are to be described. A labeled drawing of your set-up and / or protocol is often helpful and highly recommended.

Numbered steps in your procedure should be clear and specific to allow for the replication of your experiment by another person. The conscious effort to keep controlled variables constant should be evident in your procedure. Your procedure also should be appropriate to the level of uncertainty needed. For example, don't use a beaker to dispense a precise volume of liquid. On the other hand, don't use the analytical balance that masses to ± 0.0001gram when only an approximate mass is needed. (Think!) You can allow for the collection of sufficient data by having a large enough range of values for your independent variable and having repeated trials. Specify and justify any assumptions underlying the procedure. Think through potential problems in advance, and demonstrate in your lab report your plan to master these difficulties.

Aspect 3: Developing a Method for Collection of Data

In the design of your method of data collection, you need to pay attention to the need of sufficient, relevant data. The definition of "sufficient relevant data" depends on the context. The planned investigation should anticipate the collection of sufficient data so that the aim or research question can be suitably addressed and an evaluation of the reliability of the data can be made. Example considerations when assessing sufficiency of data could be the following:

- The plan includes the duplication of data collected in multiple trials (at least 2-3 trials).
- When planning the levels of the independent variable values, 5 is the minimum number when practical.
- If a trend line is to be plotted through a scatter graph then at least 5 data points are needed.
- When doing titrations, the plan should show appreciation of the need for a trial run and repeats until consistent results are obtained.

Data Collection and Processing

	Aspect 1	Aspect 2	Aspect 3
Levels	*Recording Raw Data*	*Processing Raw Data*	*Presenting Raw Data*
Complete	Records appropriate quantitative and associated qualitative raw data, including units and uncertainties where relevant.	Processes the quantitative raw data correctly.	Presents processed data appropriately and, where relevant, includes errors and uncertainties.
Partial	Records appropriate quantitative and associated qualitative raw data, but with some mistakes or omissions.	Processes quantitative raw data, but with some mistakes and/or omissions.	Presents processed data appropriately, but with some mistakes and/or omissions.
None	Does not record any appropriate quantitative raw data **or** raw data is incomprehensible.	No processing of quantitative raw data is carried out **or** major mistakes are made in processing.	Presents processed data inappropriately **or** incomprehensibly.

Aspect 1: Record Raw Data

Data collection skills are important in accurately recording events and are critical to scientific investigation. Data collection involves all <u>quantitative</u> and <u>qualitative</u> **raw** data, such as tabulated measurements, written observations, or drawn specimens. Raw data is the actual data measured. This will include associated qualitative data. The term "quantitative data" refers to numerical measurements of the variables associated with the investigation. Associated qualitative data are considered to be those observations that would enhance the interpretation of results. Qualitative data is defined as those observed with more or less unaided senses (color, change of state, etc.) or rather crude estimates (hotter, colder, blue, finely powdered, etc.), whereas quantitative data implies numerical observations, i.e., actual measurements. Both types of data are important and required.

Students will not be told how to record the raw data. The design and formatting of the data tables are evaluated aspects of collecting data. Designing a data table in advance of the experiment is confirmation that you know what data is relevant to collect during the experiment. Never erase original recorded data---instead neatly cross out the error with a single line.

Raw data must be presented for grading. Raw data is the unaltered measurements and observations you record during the course of the experiment on the original paper you took in the lab. Your teacher will initial your paper. This raw data sheet is the only data sheet to include in your lab report. In other words, do not recreate a more legible format of the data sheet for your lab report. Plan ahead and make your original data table appropriate for easy interpretation.

Uncertainties are associated with all raw data and an attempt should always be made to quantify uncertainties. For example, when students say there is an uncertainty in stopwatch measurements because of reaction time, they must estimate the magnitude of the uncertainty. Within tables of quantitative data, columns should be clearly annotated with a heading, units and an indication of the uncertainty of measurements. The uncertainty need not be the same as the manufacturer's stated precision of the measuring device used if your use of the instrument reflects a different precision. Significant digits in the data and the uncertainty in the data must be consistent. This applies to all measuring devices. The number of significant digits should reflect the precision of the measurements.

There should be no variation in the precision of raw data. For example, the same number of decimal places should be used if the measuring device is consistent. The level of precision for calculated results should be consistent with the precision of the raw data.

The recording of the level of precision would be expected from the point where the students take over the manipulation. For example, you will not be expected to state the level of precision in the concentration of a solution prepared for you.

The following points should be included in data collection:

1. Data *tables* are always required. All data is tabulated for organization.
2. Only original, raw data tables are evaluated. Do not re-copy your data.
3. Give an identifying title on the data table. More comprehensive experiments have multiple data tables. For example, Data Tables could be titled :

<u>Table 1: Number of Drops of Various Liquids in One Cubic Centimeter</u>

or

<u>Table 2: Observations Upon Mixing Solutions Containing Different Ions</u>

4. Data tables should have headings with units and uncertainties on each column and/or row. ***Note the formatting of the heading on Table 1 and follow this example;

Table 1: Change of Temperature as Naphthalene is Cooled

Time / s (± 1 s)	Temperature / ^{o}C (± 0.5 ^{o}C)	Temperature / ^{o}C (± 0.5 ^{o}C)
	Trial 1	Trial 2
0	*92.0*	*91.5*
30.	*87.5*	*88.0*
60.	*83.5*	*84.0*
90.	*81.0*	*81.0*
120.	*79.5*	*79.0*
Leave room here to write qualitative data		

5. Any recorded measurement must reflect the precision of the measuring device used.
6. Collect both qualitative and quantitative data. Plan ahead and leave space for your required qualitative data.
7. Qualitative data should be recorded before, during and after the experimental procedure. For example, initial colors of solutions, colors of precipitates, colors of final solutions, textures of solids, odors, duration of reaction, and more should all be recorded in qualitative data.
8. Units of measurement are only indicated in the headings of the columns or rows.
9. Calculations are not to be put in data tables.
10. Subsequent calculations are usually clearer if data is arranged in columns instead of rows. For example, you probably find it much easier to interpret Table 2 instead of Table 3

Table 2: Determination of the Mass of 50 Drops of Water Delivered from a Dropping Pipette

	Trial 1	Trial 2	Trial 3
Mass of beaker with water / g (±0.01 g)	*58.33*	*58.45*	*58.42*
Mass of empty beaker / g (±0.01 g)	*56.31*	*56.40*	*56.38*

Table 3: Determination of the Mass of 50 Drops of Water Delivered From a Dropping Pipette

Trial	Mass of beaker with water / g (±0.01 g)	Mass of empty beaker / g (±0.01 g)
1	*58.33*	*56.31*
2	*58.45*	*56.40*
3	*58.42*	*56.38*

Aspect 2: Processing Raw Data

Data Processing is what you do to the raw data once you have collected it. Processing data means to perform calculations on the data or to convert tabulated data into graphical form. You should notice that both the accuracy and thoroughness of your data processing is evaluated.

You will often have several calculations to perform on your data. The data should be processed such that the pathway to the final result can be easily followed. This is most apparent when sets of calculations are *annotated* to provide the reader with insight into your intent. Data processing involving many calculations can be simplified to show just one sample calculation (per type of calculation) and then Result Tables can organize resulting calculations in a tabulated order. Result Tables also need clear titles with heading on each column. Be sure to show the uncertainties of these results based on your propagation of error.

You are expected to decide upon a suitable presentation format for your calculations (for example, spreadsheet, table, graph, chart, glow diagram, and so on). There should be clear, unambiguous heading for all calculations, tables, or graphs. Graphs need to have appropriate scales, labeled axes with units, and accurately plotted data points with a suitable best-fit line or curve. You should present the data so that all stages to the final result can be followed. Inclusion of metric/SI units is expected for final derived quantities, expressed to correct significant figures. The treatment of uncertainties in graphical analysis requires the construction of appropriate best-fit lines.

The following points should be included in PROCESSING calculations and graphs:

1. Only work out one example of each type of calculation. Identical calculations do not need to be demonstrated.
2. Format of work and answers includes formulae, rearrangement of formulae, and values substituted into rearranged formulae (including units and significant figures).
3. Show all steps, explaining the method if it is necessary.
4. Keep (at least) one extra significant figure throughout a calculation to reduce rounding errors; the final result should be consistent with the number of significant figures in the experimental measurements and any subsequent calculations based on them.
5. For repeated trials, calculate a final result for each trial; then calculate an average result for all trials.
6. Error calculations frequently include % error.
7. Error calculations frequently include propagation of uncertainties.
8. Error calculations occasionally include statistical processing such as standard deviations.
9. When repeated calculations are performed on data, a table of results is appropriate for organizing the resulting values.
10. Results tables have the same formatting as Data Tables. Use of proper scientific conventions will be assessed in results tables also, such as title, proper headings, use of units, uncertainties used. (Note, propagation of uncertainties will lead to different uncertainties listed in the heading of Results Tables as opposed to Data Tables.)
11. Graphs must include title, axes labeled with units, appropriate scales, points plotted accurately, "best fit" line or curve, calculation of slope, meaning of slope, and if appropriate, equation for the line of best fit and R^2 value. The independent variable is plotted on the x axis and the dependent variable is plotted on the y axis

Aspect 3: Presenting Processed Data

What is the difference between processing and presenting data? In addition to the task of doing calculations with your data, this section of your lab report is about the idea of communication and evaluation of calculations. Your data will be transformed and used to support a conclusion. Just showing the calculations, however, is not effective communication nor does it convey your understanding of the limitations of your data. This presentation of processed data should be articulate and convincing.

When data is processed, the uncertainties associated with the data must also be considered. If the data is combined and manipulated to determine the value of a physical quantity (for example, specific heat capacity), then the uncertainties in the data must be propagated. **Please note that these uncertainties can be only the uncertainties you attribute to the use of every piece of measuring equipment when you are manipulating few data, or, the uncertainties associated with the range of data when multiple measurements for the same entity are taken. (This mathematical procedure is clarified in a later section of this Guide.) Calculating the percent error (percent difference) between the measured value and the literature value is not sufficient error analysis. You are expected to decide upon your own suitable presentation format. You should provide clear, unambiguous heading for all calculations, tables, and graphs. You should present your processed data such that all stages to the final result can be followed clearly.

The following points should be included in PRESENTING calculations and graphs

1. Present calculations such that the pathway to the final result can be followed.
2. Annotate calculations with a statement about type of calculation or the intent of the calculation.
3. Layout of calculations should be neat and organized.
4. Statistical work also needs to be explained with words to convey understanding of the demonstrated math. There will be short paragraphs of explanations in the DCP section.
5. Use of proper scientific conventions in tables, drawings and graphs.
6. The designations of uncertainties in the column heading of Results Tables will be based on the propagation of error and must, therefore, be different than the uncertainties in the column heading of Data Tables, which are based only on the precision of the measuring device.

Conclusion and Evaluation

Levels	Aspect 1 *Concluding*	Aspect 2 *Evaluating Procedure(s)*	Aspect 3 *Improving the Investigation*
Complete	States a conclusion, with justification, based on a reasonable interpretation of the data.	Evaluates weaknesses and limitations.	Suggests realistic improvements in respect of identified weaknesses and limitations.
Partial	States a conclusion based on a reasonable interpretation of the data.	Identifies some weaknesses and limitations, but the evaluation is weak or missing.	Suggests only superficial improvements.
None	States no conclusion **or** the conclusion is based on an unreasonable interpretation of the data.	Identifies irrelevant weaknesses and limitations.	Suggests unrealistic improvements.

Conclusions will have 3 distinct paragraphs according to the three following aspects to be evaluated. The first paragraph in your conclusion should provide and explain your conclusion. Any % error or statistical analysis is mentioned here to validate your conclusion. Conclusions should be clearly related to the research question and purpose of the experiment. Explain how the conclusion follows from the results. The second paragraph will evaluate the weaknesses and limitations of the procedure, with comments on precision and accuracy. The third paragraph will suggest improvements for future experiments.

Aspect 1: Concluding

Once the data has been processed and presented in a suitable form, the results can be interpreted, conclusions can be drawn and the method evaluated. You are expected to analyze and explain the results of your experiment. A valid conclusion is based on the correct interpretation of your data. This is why data collection and processing is so important. Conclusions should be clearly stated and related to the research question and purpose of the experiment. Justify how the conclusion follows from the results. Quantitatively describe the confidence you have in your conclusion. When measuring an already known and accepted value of a physical quantity, students should draw a conclusion as to their confidence in their result by comparing the experimental value with the textbook or literature value in the form of a percent error. The literature consulted should be fully referenced. Percent error is not an absolute value. The positive or negative direction of the error informs your analysis of error.

Conclusions that are supported by the data are acceptable even if they appear to contradict accepted theories. However, make sure you take into account any systematic or random errors and uncertainties. A percent error should be compared with the overall uncertainty as derived from the propagation of uncertainties. (This mathematical procedure is clarified in a later section of this Guide.)

In justifying your conclusions, you should identify and discuss whether systematic error or further random errors were encountered. Include here uncertainties or errors over which you had no control. You should try to appreciate any systematic errors. Direction and magnitude of systematic error are important to indicate. Analysis may include comparisons of different graphs or descriptions of trends shown in graphs. The explanations should contain observations, trends or patterns revealed by the data.

Aspect 2: Evaluating Procedure

When evaluating your procedure, comment on the design and method of the investigation as well as on the quality of the data. You should specifically look at the processes, use of equipment and management of time. When listing the weaknesses you should also show that you appreciate how significant the weaknesses are. At least 2 reasonable weaknesses or sources of error must be described. Comments about the precision and accuracy of the measurements are relevant here.

Note that it is not insightful to discuss the blunders or personal careless errors that probably occurred. Even though these errors may have been the largest source of error, your experiment should be redone if human error is so great as to prohibit you from making a meaningful conclusion. Error analysis requires deep thinking and is one of the most challenging aspects of writing up a lab report.

Aspect 3: Improving the Investigation

The third paragraph gives suggestions to improve the lab. The suggestions you make should be based on the weaknesses and limitations you have already identified. Modifications to the experimental techniques and the data range can be addressed here. The modifications should address issues of the process, the equipment, management of time, and reproducibility of the results. You should suggest how to reduce random error, remove systematic error, and/or obtain greater control of the variables. These suggested modifications need to go beyond the obvious and arcane, and hopefully be feasible to implement upon repetition of the experiment. Suggestions should be realistic and clearly specified, not involving unavailable equipment or materials. It is not sufficient to generally state that more precise equipment and more pure chemicals should be used. Do not confuse poor management of time with insufficient time to complete an experiment. Our double lab period is a manageable timeframe to complete most labs and is not a substantial limitation to your results! Neither is your lab partner. Finally, evaluation and improving the experiment is not about how much you enjoyed the investigation, although we do anticipate that your lab experience will be beneficial and worthwhile!

Manipulative Skills

Levels	Aspect 1	Aspect 2	Aspect 3
	Following Instructions	*Carrying out Techniques*	*Working Safely*
Complete	Follows instructions accurately, adapting to new circumstances (seeking assistance when required).	Competent and methodical in the use of a range of techniques and equipment.	Pays attentions to safety issues.
Partial	Follows instructions but requires assistance	Usually competent and methodical in the use of a range of techniques and equipment..	Usually pays attention to safety issues.
None	Rarely follows instructions or requires constant supervision.	Rarely competent and methodical in the use of a range of techniques and equipment.	Rarely pays attention to safety issues.

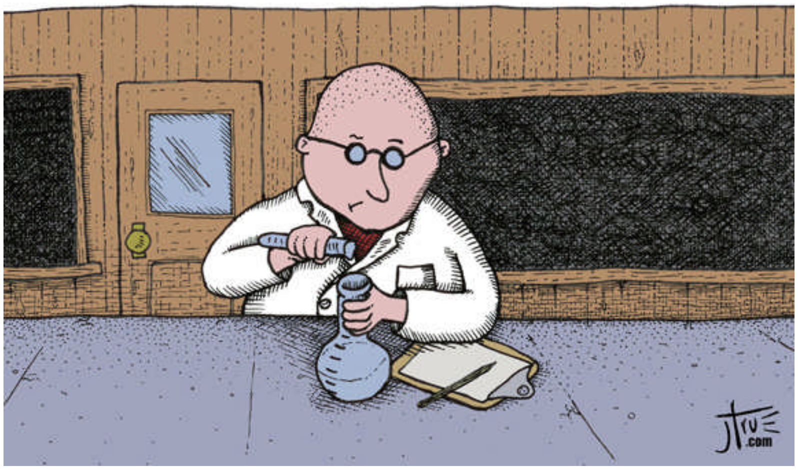
The skills involved are those required to carry out the full range of techniques covered by a thorough laboratory experience. These skills include but are not limited to the following:

- Using volumetric glassware
- Handling flammable, corrosive, and/or toxic chemicals safely
- Performing a titration accurately
- Using a pH meter
- Taking steps to ensure cleanliness and purity appropriate to the experiment

Indications of manipulative ability include the following;

- amount of assistance required in assembling equipment
- ability to follow instructions accurately
- orderliness of carrying out procedures
- yield and purity from preparative exercises
- accuracy of quantitative determinations
- adherence to safe working practices

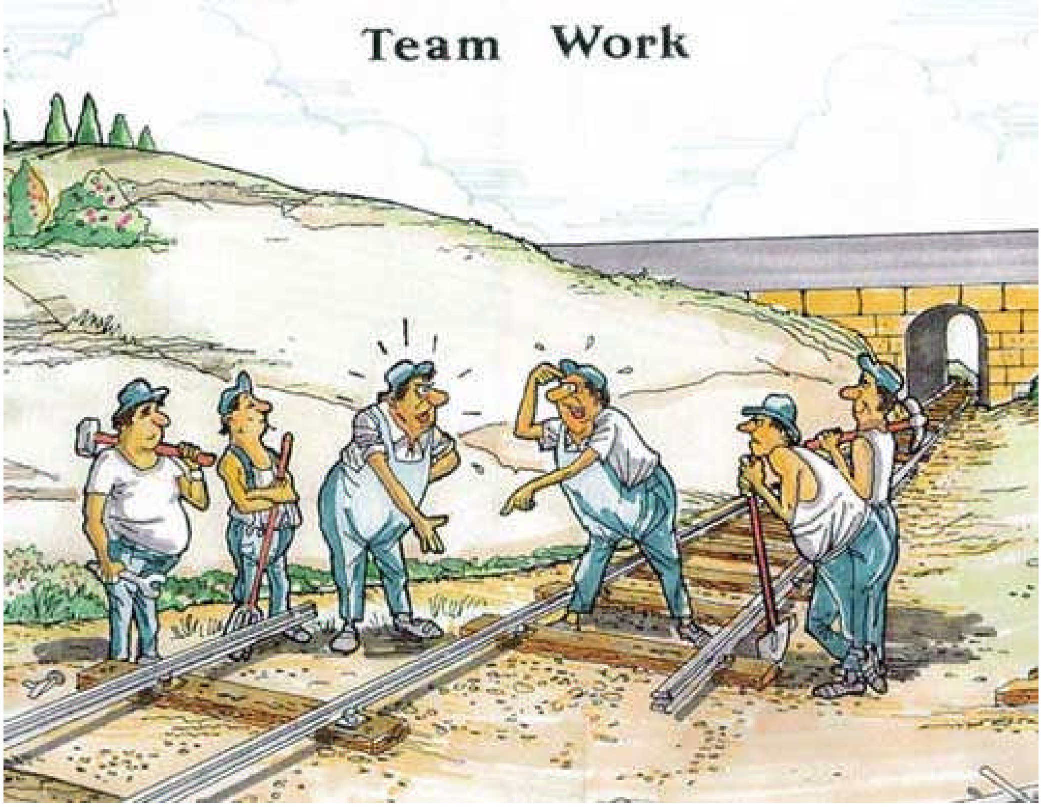
Jerry discovers the element of surprise.....



Personal Skills

Levels	Aspect 1 *Self-Motivation and Perseverance*	Aspect 2 *Working Within a Team*	Aspect 3 *Self-Reflection*
Complete	Approaches the project with self-motivation and follows it through to completion.	Collaborates and communicates in a group situation and integrates the views of others.	Shows a thorough awareness of their own strengths and weaknesses and gives thoughtful consideration to their learning experience.
Partial	Completes the project by some time lacks self-motivation.	Exchanges some views but requires guidance to collaborate with others.	Shows limited awareness of their own strengths and weaknesses and gives some consideration to their learning experience.
None	Lacks perseverance and motivation.	Makes little or no attempt to collaborate in a group situation.	Shows no awareness of their own strengths and weaknesses and gives no consideration to their learning experience.

Working in a team is when two or more students work on a task collaboratively, face to face, with *individual accountability*. Effective teamwork includes recognizing the contributions of others, which begins with each member of the team expecting every other member to contribute. The final product should be seen as something that has been achieved by all members of the team participating in the tasks. Encouraging the contributions of others implies not only recognizing, but also actively seeking contributions from reluctant or less confident members of the team.



IB Laboratory Evaluation Rubric Name________________________________ Date_______

Name of Lab ____

LEGEND FOR ACHIEVEMENT LEVELS:

"**c**" aspect fulfilled completely; "**p**" only partially fulfilled; "**n**" insufficient.

IB Components:

	Assessment Criteria	Aspects with Descriptions of "Complete" Expectations			Level
		Aspect 1	Aspect 2	Aspect 3	
	Design	*Defining the Problem and Selecting Variables* Formulates a focused problem / research question and identifies, with brief explanation, all of the relevant variables.	*Controlling Variables* Designs and presents a method for the effective control of the variables.	*Developing a Method for Collection of Data* Develops a method that allows for the collection of sufficient relevant data.	ccc 6 ccp 5 cpp 4 ppp 3 ppn 2 pnn 1 nnn 0
	Data Collection and Processing	*Recording Raw Data* Records quantitative and qualitative raw data correctly and completely, including units and uncertainties (± values).	*Processing Raw Data* Processes the quantitative raw data correctly and completely.	*Presenting Processed Data* Presents processed data appropriately, using annotations to help interpretation. Includes overall uncertainty where relevant, derived from the propagation of error.	ccc 6 ccp 5 cpp 4 ppp 3 ppn 2 pnn 1 nnn 0
	Conclusion and Evaluation	*Concluding* States a conclusion, with justification, based on a reasonable interpretation of the data. Compares the percent error with overall uncertainty, Considers systematic and random errors in justifying conclusion.	*Evaluating Procedure* Evaluates thoroughly the weaknesses and limitations in the procedure. Includes the relative significance of weaknesses and limitations. Considers precision and accuracy of data.	*Improving the Investigation* Suggests realistic improvements in respect of significant identified weaknesses and limitations, with the aim to eliminate or reduce systematic and/or random error.	ccc 6 ccp 5 cpp 4 ppp 3 ppn 2 pnn 1 nnn 0
✓	**Introduction**	Includes an introduction which discusses theory and nature of the problem and the purpose of the experiment. (2 points)			

For Total;
each "c" = 2 pts, "p" = 1 pts, "n"= 0 pt,

Total ____________

	Manipulative Skills	*Following Instructions* Follows instructions accurately, adapting to new circumstances when required. Seeks assistance from instructor when required, but only after self-direction and peer assistance is pursued.	*Carrying Out Techniques* Competent and methodical in the use of a range of techniques and equipment.	*Working Safely* Pays attention to safety issues.	ccc 6 ccp 5 cpp 4 ppp 3 ppn 2 pnn 1 nnn 0
	Personal Skills	*Self-motivation and perseverance* Approaches the investigation with self-motivation and follows it through to completion.	*Working within a team* Collaborates and communicates in a group situation. Expects and actively seeks the views of others team members, exchanging ideas and integrating them into the task.	*Self-reflection* Shows a thorough awareness of their own strengths and weaknesses and gives thoughtful consideration to their learning experience.	ccc 6 ccp 5 cpp 4 ppp 3 ppn 2 pnn 1 nnn 0

For Total (Manipulative and Personal Skills only);
each “c” = 2 pts, “p” = 1 pt, “n”= 0 pt

Other assessment criteria to be occasionally requested;

Hypothesis; Relates the hypothesis or prediction directly to the research question and explains the hypothesis.

Safety; Includes important safety precautions observed in this lab

Professional Presentation; Presents information clearly, allowing for easy interpretation. Neatly and clearly presents all parts of the lab report.

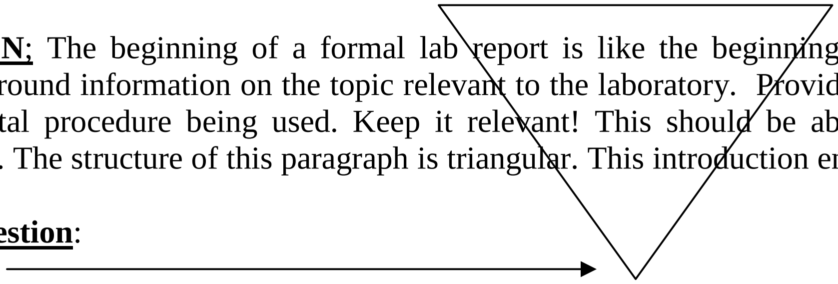
Materials; Lists all necessary equipment and supplies, noting quantity, size, concentration (of solutions), and scale (on thermometers),

Requested Diagrams or Visuals; Presents requested diagrams to aid interpretation of results.
interpretation of results

Formal Laboratory Report Format

Please use the following headings and format when writing a formal laboratory report. All lab reports must be word processed except for the data processing, i.e., calculations.

1. **INTRODUCTION;** The beginning of a formal lab report is like the beginning of a research paper. Begin with background information on the topic relevant to the laboratory. Provide the theoretical basis of the experimental procedure being used. Keep it relevant! This should be about ½ page of typed chemistry content. The structure of this paragraph is triangular. This introduction ends with the following headings;



   Research Question:
   Hypothesis:
   Variables:
      Independent variable: (list and briefly describe variable)
      Dependent variable: (list and briefly describe variable)
      Controlled variables: (list and briefly describe each variable)

2. **MATERIALS AND EQUIPMENT**: List the major equipment and material used.

3. **SAFETY NOTES**:   Consider the safety notes for lab.

4. **PROCEDURE**: Numerically list the steps to perform during the experiment. Do not give directions in paragraph form. Demonstrate your insight into your chosen design by addressing anticipated problems with purposeful strategies. Diagram of lab set-up is recommended.

5. **DATA TABLE**: Design your data table to accommodate both quantitative and qualitative data.

6. **DATA PROCESSING**: Data processing is distinct from data collection. For any calculation, first annotate for the reader the intent of your calculation. Show the equation used in symbolic form, then substitute in numbers with units. These calculations, as with the rest of your lab report, must be typed. Explain any eliminated data or special treatment of the raw data made. Organize repeated calculations into a Results Table. Include any graphs in this section. Some calculations or graphs may need an additional typed paragraph or two of explanation.

7. **CONCLUSION AND EVALUATION**: This section will have three distinct paragraphs. In the first paragraph, state and explain your conclusion, including numerical values for support, if appropriate. Include % error and assessment of direction and types of errors. In the second paragraph the procedure is evaluated. You will assess the precision and/or accuracy of your work. In the third paragraph, evaluate the limitations in the design and execution of the experiment, and suggest realistic ways to improve the experiment for future duplication of findings.

Types of Experimental Errors

INTRODUCTION

Most of the laboratory exercises you complete will require that you calculate an unknown quantity by first measuring various physical quantities, such as mass, volume, temperature, or % transmittance data. In order to obtain acceptable results, you must master the appropriate laboratory techniques associated with these physical measurements and recognize any possible errors you may have introduced during the lab exercise. You must also be able to evaluate the quality of your lab data and present your findings in a meaningful manner. The importance of knowing how to treat this numerical data and estimate the overall uncertainty of your results is an integral part of any lab report.

Every measurement involves some measurement error (or measurement uncertainty). Because all generalizations or laws of science are based on experimental observations involving quantitative measurements, it is important for a scientist to take into account any limitations in the reliability of the data from which conclusions are drawn. In the following section we will discuss different kinds of error; personal, systematic, and random.

TYPES OF ERRORS

There are three types of errors that may occur in data collection during your laboratory exercise.

1. Personal Careless Errors or Blunders: These errors are due to carelessness and obvious mistakes in your laboratory techniques. Examples include such things as spilling or splashing a portion of your sample, misreading a volume measurement, reading the balance or listing the masses incorrectly, misinterpreting the directions, use of dirty glassware, overshooting the endpoint in a titration, not calibrating or zeroing an instrument, et cetera, and so forth, and on and on and on. The list is long and students have experienced all of them. When you know that you have made these errors, STOP! Do not go on with the lab. You should not include these results in your calculations. If time permits, you should repeat these measurements, eliminating the personal careless errors. Blunders should not be discussed in your conclusion in error analysis. Rather, blunders should be avoided and/or corrected when noticed.

2. Systematic (determinate) errors: A systematic error causes an error to be in the same direction in each measurement and diminishes accuracy although the precision of the measurement may remain good. A metal ruler's susceptibility to temperature fluctuations or a miscalibrated scale on a ruler are examples of systematic errors. Systematic errors are not eliminated if you repeat the experiment but may be located and corrected with additional calculations. An example would be using a solution labeled 0.010 M NaOH, but the concentration is actually 0.012 M NaOH. If this error is uncovered, it can be corrected in the data processing.

3. Random(Indeterminate) Errors: If a measurement is made a large number of times, you will obtain a range of values caused by the random errors inherent in any measurement. These errors result from the difficulty in exactly repeating the procedures in spite of your best lab practices. The result of repeated measurements with inherent random error will be a distribution of values. Even though with skill, practice, and repetition of procedures you may reduce random errors, it is not possible to eliminate them completely. For random errors, small errors are more probable than larger errors, and negative deviations are as likely as positive ones. In some cases random errors occur for reasons beyond your control as in fluctuations in voltage affecting your instrument (Spec 20 or pH meter) or variations in external conditions such as changes in temperature, barometric pressure and humidity.

Error Analysis: Some Key Ideas

1. No measurement is infinitely accurate; there is always some error associated with it. Use of significant figures implies the last digit of any measurement is the uncertain digit.

2. There are three types of error that may occur in data collection; personal careless errors, systematic errors, and random errors.

3. Personal careless errors are due to inattentiveness and obvious mistakes in your lab techniques.

4. Systematic errors exemplify bias, tending to skew our data in a particular direction from the accepted value. Systematic errors occur because something is wrong with the way we are taking the measurements (be it human or mechanical error). These errors will taint our results in reproducible, yet misleading, ways. Systematic errors “skew” data and impact accuracy.

5. Random errors occur for many reasons and are usually unbiased. That is, they will spread our results in all directions evenly from the accepted value. Random errors “scatter” data and impact precision. Differences in agreement about the uncertain digit in a measurement are typically random errors (some people will guess too high and others, too low).

6. Precision and accuracy are not the same. High precision involves a series of measurements within a relatively small range. High accuracy occurs when the data comes relatively close to the true value. Since we do not always know the true value, we must agree on a best value.

7. We can never eliminate error in measurements but we can do some things to increase our confidence in our results.
    - We can take the measurement many times and average our results.
    - We can have others try to match our results.
    - We can make predictions based on our results and test those predictions.

8. Increasing the number of measurements will statistically improve data affected by random error, but not systematic error. Systematic errors are dangerous because one can achieve precision without achieving accuracy. Averaging results containing a systematic error will not yield accurate results. Systematic error must be hunted down and evaluated in your conclusion.

9. Data that lies far from the statistical average should be studied carefully. In some cases, you may be justified in ignoring this data. Data that seems out of place are called "outliers". It requires some statistical work to determine whether we are justified in discounting a particular piece of data.

10. When graphing, data points are based on two measurements (the x and y measurements), both of which contain error. Any best fit line or curve should pass close to but need not necessarily pass through the point itself (though that would be nice).

11. Error due to uncertainty “propagates” (carries through and grows) with processing of data. If three dimensions of a geometric object are measured, when the volume is calculated the uncertainty in that answer is greater than the uncertainties in any of the individual measurements. This propagated error is called the overall uncertainty of your results and must be indicated in DCP and CE.

Precision and Accuracy in Measurements; A Tale of Four Graduated Cylinders *

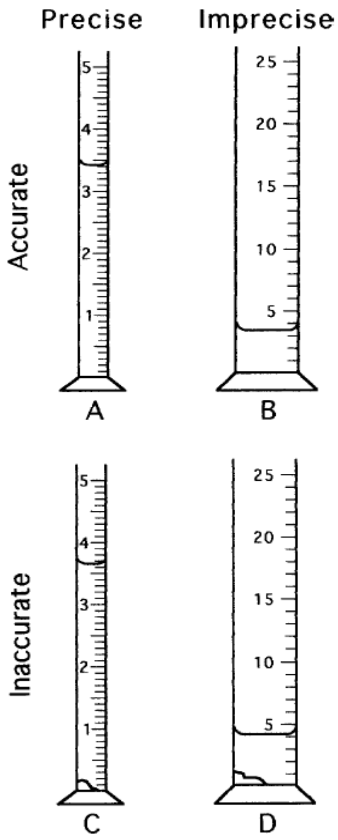


Figure 1. Graduated cylinders of the model experiment

Table 1. Data from Graduated Cylinders Illustrated in Figure 1

Cylinder	Measured Volume / mL **	Mean / mL	Precision		Accuracy	
			Range / mL	Standard Deviation / mL	Error / mL	Percent Error
A	3.42 3.43 3.41 3.44 3.41	3.422	0.03	0.013	0.002	0.06
B	3.5 3.3 3.4 3.3 3.4	3.38	0.2	0.084	– 0.04	−1.2
C	3.67 3.65 3.64 3.68 3.65	3.658	0.04	0.016	0.238	6.96
D	4.2 4.1 4.3 4.3 4.1	4.20	0.2	0.100	0.78	22.8

** Each cylinder contains exactly 3.420 mL

> *"To err is human; to describe the error properly is sublime."*
>
> Cliff Swartz, Physics Today **37** (1999), 388

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* Article in Journal of Chemical Education, Vol • 75 No. 8, August 1998 • JChemEd.chem.wisc.edu

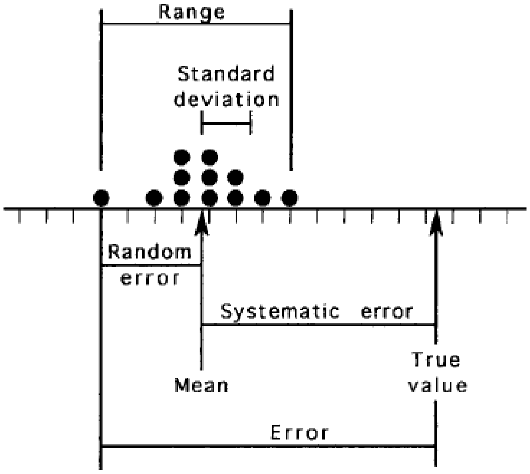


Figure 2. Illustration of terms for expressing presicion, accuracy, and error.

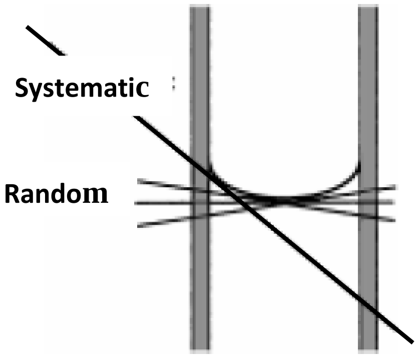


Figure 3. Random and systematic errors caused by parallax.

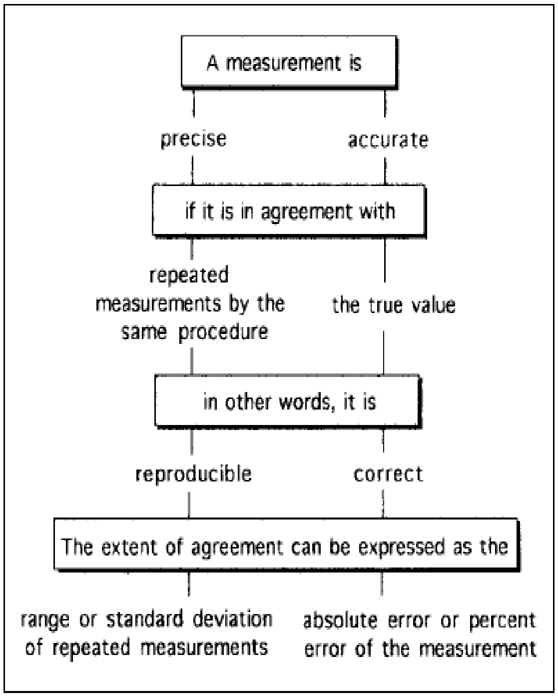


Figure 4. Concept chart for contrasting precise and accurate measurements.

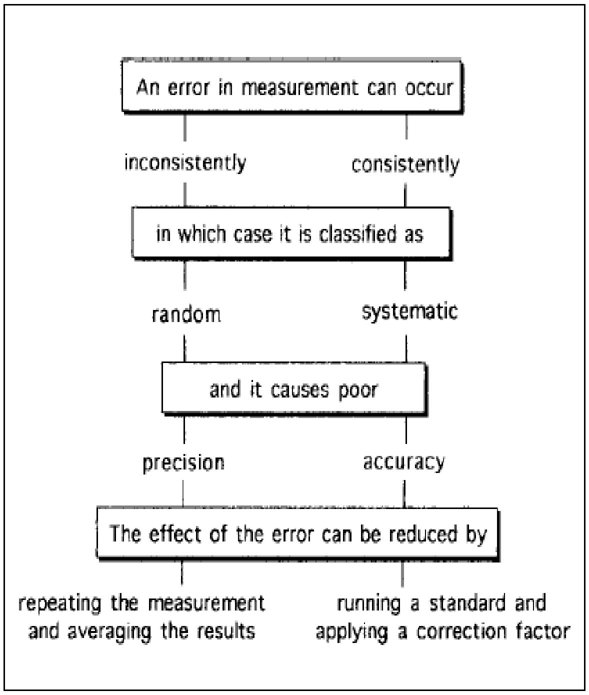


Figure 5 . Concept chart for contrasting random and systematic errors.

Assessment of Errors and Uncertainties in IB Lab Reports

The consideration and appreciation of the significance of the concepts of errors and uncertainties helps to develop skills of inquiry and thinking that are not only relevant to the experimental sciences. The evaluation of the reliability of the data upon which conclusions can be drawn is at the heart of a wider scientific method that IB students consider in other areas of study, such as history and theory of knowledge. They then may apply this in their subsequent educational, professional and personal lives.

Expectations at standard level and higher level

The expectations with respect to errors and uncertainties in the laboratory are the same for both standard and higher level students. Within the lab assessment students should be able to:

Within Data Collection and Processing: aspect 1

- make a quantitative record of uncertainty range (± value)

Within Data Collection and Processing: aspect 3

- state the results of calculations to the appropriate number of significant figures. The number of significant figures in any answer should reflect the number of significant figures in the given data.
- propagate uncertainties through a calculation by using the absolute and/or percent uncertainties from measurements to determine the overall uncertainty in calculated results. Only a simple treatment is required. For functions such as addition and subtraction, absolute uncertainties can be added. For multiplication, division and powers, percentage uncertainties can be added. **If one uncertainty is much larger than others, the overall uncertainty in the calculated result can be taken as due to that quantity alone.**
- determine physical quantities (with units) from graphs by measuring and interpreting a slope or intercept. When constructing graphs from experimental data, students should make an appropriate choice of axes and scale, and the plotting of points should be clear and accurate. The uncertainty requirement can be satisfied by drawing best-fit curves or straight lines through data points on the graph.

Within Conclusion and Evaluation: aspect 1

- justify a conclusion by discussing whether systematic errors or further random errors were encountered. The direction of any systematic errors should be appreciated. The percent error should be compared with the overall uncertainty as derived from the propagation of error due to uncertainties.

Within Conclusion and Evaluation: aspect 2

- comment about the precision and accuracy of the measurements when evaluating the procedure.

Within Conclusion and Evaluation: aspect 3

- suggest how the effects of random uncertainties may be reduced and systematic errors be eliminated. Students should be aware that random, but not systematic, errors are reduced by repeating readings.

Explaining Terms and Concepts in Error Analysis

(a) Random and systematic error

Systematic errors arise from a problem in the experimental set-up that results in the measured values always deviating from the "true" value in the same direction, that is, always higher or always lower. Examples of causes of systematic error are miscalibration of a measuring device or poor insulation in calorimetry experiments.

Random errors arise from the imprecision of measurements and can lead to readings being above or below the "true" value. Random errors can be reduced with the use of more precise measuring equipment or its effect minimized through repeat measurements so that the random errors cancel out.

(b) Accuracy and precision

Accuracy is how close a measured value is to the correct value, whereas **precision** indicates how many significant figures there are in a measurement. For example, a mercury thermometer could measure the normal boiling temperature of water as 99.5° C (±0.5° C) whereas a data probe recorded it as 98.15° C (±0.05° C). In this case the mercury thermometer is more accurate whereas the data probe is more precise. Students should appreciate the difference between the two concepts.

(c) Uncertainties in raw data

When numerical data is collected, values cannot be determined exactly, regardless of the nature of the scale or the instrument. If the mass of an object is determined with a digital balance reading to 0.1 g, the actual value lies in a range above and below the reading. This range is the uncertainty of the measurement. If the same object is measured on a balance reading to 0.001 g, the uncertainty is reduced, but it can never be completely eliminated. When recording raw data, estimated uncertainties should be indicated for all measurements.

There are different conventions for recording **uncertainties in raw data**. Our convention will be to reasonably subdivide the smallest increment on a measuring device and indicate that value as the ± uncertainty in the measurement.

(d) Propagating errors

Random errors (uncertainties) in raw data feed through a calculation to give an estimation of the overall uncertainty (or error) in the final calculated result. There is a range of protocols for **propagating errors**. A simple protocol is as follows:

1. When **adding or subtracting** quantities, then the **absolute uncertainties are added**.

For example, if the initial and final burette readings in a titration each have an uncertainty of ±0.05 cm^3 then the propagated uncertainty for the total volume is (±0.05 cm^3) + (±0.05 cm^3) = (±0.10 cm^3).

2. When **multiplying or dividing quantities**, then the **percent uncertainties are added**.

Example;

Imagine having a large cube of plastic. This particular plastic has a determined density of 1.15 g/cm^3 ±0.05 g/cm^3. The edge of the cube has a length of 0.87m ± 0.01m. What is the mass (in kg) of this cube of plastic with the overall uncertainty expressed both as overall absolute uncertainty and overall percent uncertainty?

		Absolute Uncertainty	**Percent Uncertainty**
Density	**1.15 g/cm^3**	±0.05 g/cm^3	$\frac{0.05\ \text{g/cm}^3}{1.15\ \text{g/cm}^3} \times 100 = \mathbf{4\%}$
Edge length	0.87m	±0.01m	$\frac{0.01\text{m}}{0.87\text{ m}} \times 100 = 1\%$
V = l x w x h **Volume = (edge length)^3**	V = l x w x h V = (0.87m)^3 = **0.66m^3**	Calculation not needed for this problem.	Find uncertainty in this volume calculation. Rule for multiplying; Add percent uncertainties = 1% + 1% + 1% = **3%**

$$\text{Density} = \frac{\text{mass}}{\text{volume}} \qquad \text{therefore; mass} = \text{Density} \times \text{volume}$$

$$\text{Mass} = \frac{1.15\text{ g}}{1\text{ cm}^3} \times \frac{1 \times 10^6\text{ cm}^3}{1\text{ m}^3} \times \frac{0.66\text{ m}^3}{1} \times \frac{1\text{ kg}}{1000\text{ g}} = 760\text{ kg}$$

Density has an uncertainty of 4%

Volume has an uncertainty of 3%

Mass has a an overall uncertainty of 7%

Answer to Problem	**Overall Percent Uncertainty**	**Overall Absolute Uncertainty**
Mass = 760 kg	Rule for multiplying; Add percent uncertainties; 4% + 3% = ±7%	(0.07) (760kg) = ±50 kg

$$\boxed{710\text{ kg}} \; \underbrace{\xleftarrow{\hspace{3cm}}}_{-7\% \;=\; -50\text{ kg}} \; \boxed{760\text{ kg}} \; \underbrace{\xrightarrow{\hspace{3cm}}}_{+7\% \;=\; +50\text{ kg}} \; \boxed{810\text{ kg}}$$

The mass of the plastic cube = **760 kg ± 7%** **or** **760 kg ± 50kg**

(e) Averaging repeated measurements

Repeated measurements can lead to an average value for a calculated quantity. The averaged value should be stated to the propagated error of the component values in the average.

For example, ΔH_{mean} = 106 kJ mol^{-1} (±10%)

ΔH_{mean} = [+100. kJ mol^{-1} (±10%) + 110. kJ mol^{-1} (±10%) + 108 kJ mol^{-1} (±10%)] / 3

This is more appropriate than adding the percent errors to generate 30%, since that would be completely contrary to the purpose of repeating measurements.

A more rigorous method for treating repeated measurements is to calculate standard deviations and relative standard deviations. These statistical techniques are more appropriate to large-scale studies with many calculated results to average.

(f) Overall uncertainty in calculated results

This is the uncertainty associated with your calculated results based on the propagation of error due to uncertainties. The percent error of your results, calculated from literature values, should be compared to the overall uncertainty of the results to justify your conclusion.

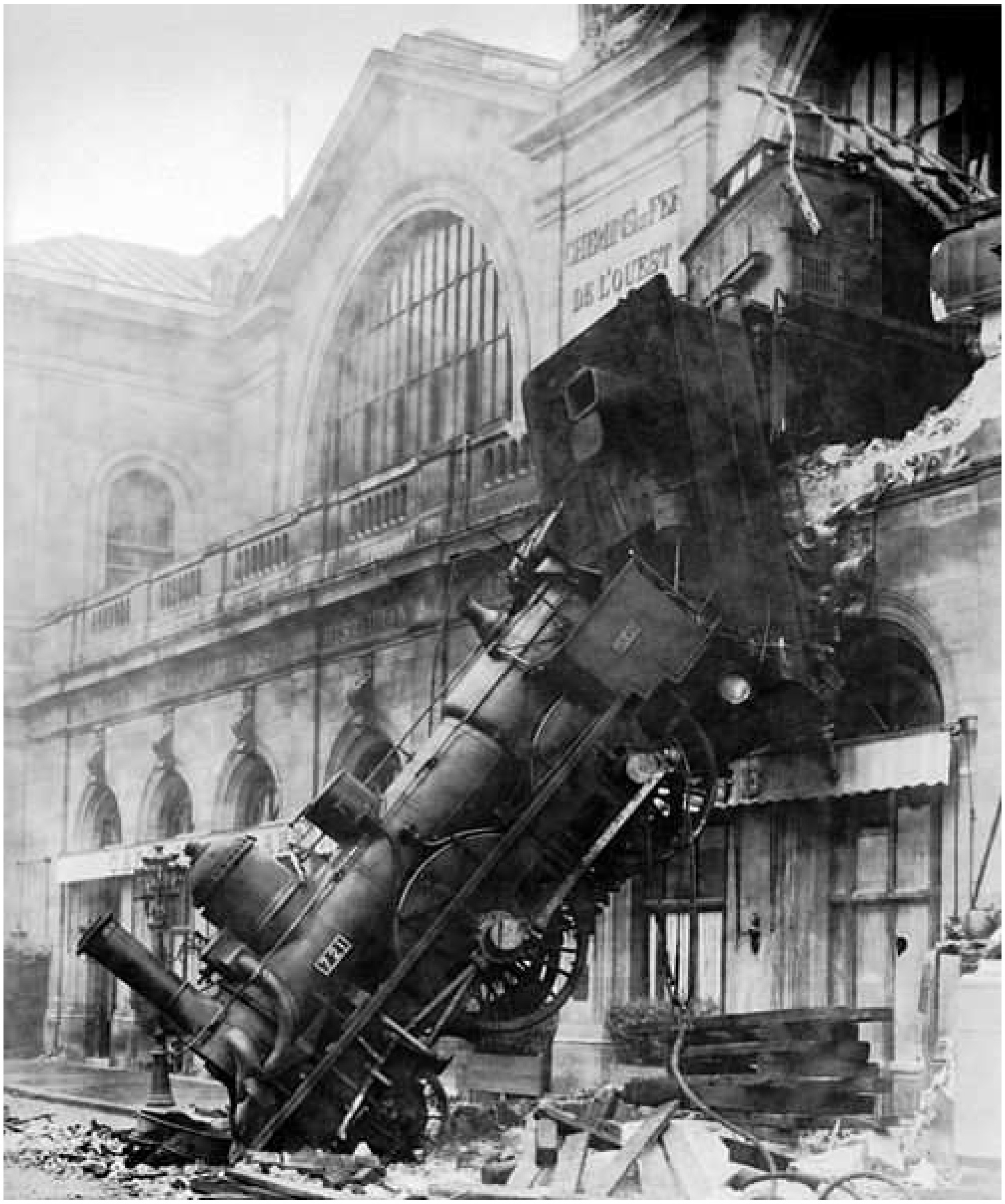
For example, when attempting to measure an already known and accepted value of a physical quantity, such as the value of the ideal gas constant, students can make two types of comments in CE for Aspect 1:

1. **The error in the experimental results can be expressed by comparing the experimental value with the textbook or literature value**.
   Perhaps a student determined the density of a metal to be 7.32 g/cm^3, and the accepted value is 7.14 g/cm^3. The percent error (a measure of accuracy, not precision) is 2.5%. This sounds good, but if, in fact, the overall uncertainty due to propagated error is only 2%, random errors alone cannot explain the difference, and some systematic error(s) must be present.

2. **The experimental results fail to meet the accepted value** (a more relevant comment).
   The experimental range of overall estimated random error does not include the accepted value. The experimental value has an overall uncertainty of only 2%. A critical student would appreciate that they must have missed something here. There must be more uncertainty and/or errors than acknowledged. This is discussed in the conclusion of the lab report.

In addition to the above two types of comment, students may also comment on errors in the assumptions of the theory being tested, and errors in the method and equipment being used.

Note: A common protocol is that the final overall percent uncertainty should be cited to no more than one significant figure if it is greater than or equal to 2% and to no more than two significant figures if it is less than 2%.



Example of Error in Calculations

Train wreck at Montparnasse Station, Paris, France, 1895.

Mathematics of Evaluating Accuracy and Precision

In a number of your laboratory experiments you will be asked to evaluate your data for accuracy and/or precision. The following discussion and examples will be helpful in understanding the mathematical treatment of errors.

Evaluating Accuracy:

If the True (accepted) value for an experimental quantity is known, then you will be expected to calculate the percent error for your lab report.

$$\text{Percent Error} = \frac{(\text{experimental value} - \text{acccepted value})}{\text{accepted value}} \times 100$$

Note that your experimental value may be the arithmetic average of a set of experimental data, or may be a single value. Also, the sign of the percent error can be positive or negative. This *direction* of error is as valuable to assess as the magnitude of the error.

Evaluating Precision:

In most real laboratory experiments, the True value of the result is not known. In this type of experiment the most probable value is obtained by assuming that positive and negative errors occur with equal frequency and tend to cancel each other out. Thus the most probable value is given by the arithmetic mean (average) of the measured values.

The mean value (X) or arithmetic average may be calculated as follows;

$$\overline{X} = \frac{X_1 + X_2 + X_3 + \ldots X_n}{n}$$

where: $\overline{X}$ = the mean value (average)
$X_1, X_2, \ldots X_n$ = individual data points
n = total number of data points

Once you have obtained the mean value you will need to determine the precision of your data to communicate to others the reliability of your measurements and results. The precision of your results is usually stated in terms of the sample standard deviation (S). When the precision of the data is good, the standard deviation is small. To determine S you must first calculate the deviation (d_i). Deviation (d_i) is the difference between the measured value and the calculated mean ($\overline{X}$).

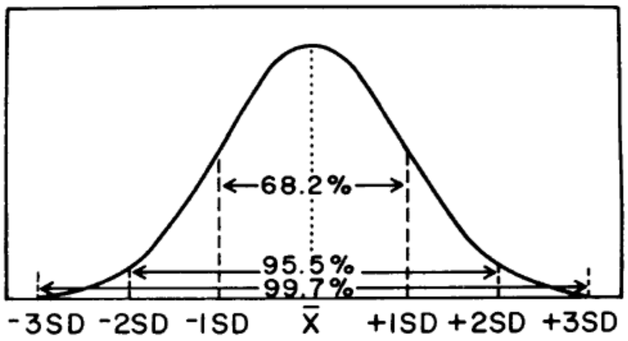
$$d_i = X_i - \overline{X}$$

When the total number of experimental (N) measurements is small the standard deviation is designated by S, and is determined by:

$$S = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + \ldots . d_n^2}{(N-1)}} = \left(\frac{\sum (X_i - \overline{X})^2}{N-1} \right)^{\frac{1}{2}} = \left(\frac{\Sigma\, d^2}{\text{N-1}} \right)^{½}$$

This formula says: Sum the squares of the deviations, divide by N – 1, and take the square root of the result. This formula actually gives only an estimate of the standard deviation unless the number of measurements is large (>50). We must recognize that when we repeat a measurement only two or three times, we are not obtaining a very large sample of measurements, and the confidence we can place in the mean value of a small number of measurements is correspondingly reduced.

Although the formula may look forbiddingly complex, the steps are very simple. First calculate the arithmetic mean, or average value, $\overline{X}$, of the measurements. Then subtract the mean value, $\overline{X}$ from each one of the individual values, X_i, to obtain the deviation. Square each deviation, and add all of the squares. Divide the total by N-1 where N is the total number of measurements. Finally take the square root of the result to obtain the estimate of the standard deviation.



This is the Gaussian distribution of data around the mean ($\overline{X}$), showing the probability of finding a value within 1, 2, or 3 standard deviations.

± # of S.D.	0	0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.5	3.0	3.5	4.0
Prob (%)	0	20	38	55	68	79	87	92	95.4	98.8	99.7	99.95	99.99

This table represents the probability of finding a value within ± fraction of a standard deviation from the mean.

The standard deviation expressions are *absolute*, that is, they are expressed in the same units as the measurements themselves. *Relative* values for these are sometimes more meaningful since they are based on the magnitude of the quantity being measured. A small Relative Standard Deviation indicated a higher degree of precision. For beginning Chemistry students an acceptable value, on most labs, is an RSD of less than 3.0%.

$$\text{Relative Standard Deviation (RSD)} = \frac{S}{\overline{X}} \times 100$$

Where S = sample standard deviation
$\overline{X}$ = mean (average)

Try this example calculation:
Four different mixtures were analyzed in the lab to yield the following results:

Sample #	**1**	**2**	**3**	**4**
% $KClO_3$	16.37	16.29	16.39	16.35
d				
d^2				

Determine the mean (average) value:
Calculate the deviation and the deviation squared for each value:
Calculate the standard deviation (actually the estimate of the standard deviation):
Calculate the Relative Standard Deviation:

Rejection of Data

The beginning student in Chemistry frequently is faced with the situation where one result in a set of measurements does not agree well with the other results. The student must decide how large the difference between the suspect result and the other data must be before discarding the result. This problem may be addressed by several methods. Using information based on the standard deviation or the method commonly called the Q test, outlying data may be discarded.

Procedure:

1. Look very carefully for Personal Careless Errors made in your measurements. If a definite error is found, reject the reading. Be sure to enter an appropriate explanation in the lab report in the section labeled Discussion of errors. The errant data should still remain in your data table, but not used in subsequent calculations.

2. No datum should be rejected unless at least four data have been obtained. You should not discard more than one piece of data.

3. If no Personal Careless Errors are found, apply the following reliability test. If the test indicates rejection, the result may be discarded with a high percentage of confidence.

<u>TWO STANDARD DEVIATION TEST</u>

a) Calculate the mean value ($\overline{X}$) or arithmetic average for your data.

b) Calculate the standard deviation (S) for your data.

c) Any data value equal to or greater than two standard deviations (2S) from the mean value may be rejected with a high percentage of confidence.

Try this sample calculation;
A student obtained the following molarities during standardization of a basic solution:

0.1012, 0.1014, 0.1012, 0.1021, 0.1016

Should the result 0.1021 be discarded?

Try the TWO STANDARD DEVIATION TEST

More Examples of Propagating Error due to Uncertainties

If all measurements have an associated uncertainty due at least to the measuring instrument, then so also the calculated results have an associated uncertainty that must be larger than any one measurement used in the calculation. This is called *the propagation of error*.

• Overall Uncertainty • (or Overall Estimated Random Error or Propagated Error due to Uncertainties)

This is the uncertainty associated with your calculated results based on the propagation of error due to uncertainties. The percent error of your results should be compared to the overall uncertainty of your results to justify your conclusion.

In assessing uncertainty of your measurements, recall that at least two things must be kept in mind --- human sensory limitations and instrument sensitivity limitations. While you usually estimate to tenths of the smallest calibrated division, if the instrument is not sensitive enough to warrant reading with this precision, then instrument sensitivity is the limiting factor. In this case, instrument sensitivity determines the probable error that is recorded. Sometimes a human's use of an instrument is less sensitive than the instrument itself, as with a stopwatch that has a precision of 0.001s. You will always have to use your good judgment to assess the uncertainties that you will propagate through your calculations.

• Absolute Uncertainty •

This is the uncertainty in the measurement due to the instrument (although this could be due to the human use of the instrument). When a measurement is recorded as 28.00 cm ±0.05 cm, it is meant that the true value probably is within five hundredths centimeter of 28.00 cm.

Absolute uncertainty = ± 0.05cm

• Percent Uncertainty •

This is the absolute uncertainty divided by the measurement then multiplied by 100. Hence, for the example above:

$$\text{Percent uncertainty} = \pm \frac{0.05\text{cm}}{28.00\text{ cm}} = \times 100 = \pm 0.2\%$$

You have learned how to estimate the uncertainty in a single measurement and how to calculate the precision of multiple measurements by using the standard deviation. But experimental results often require calculations involving several measurements. It is necessary to learn to estimate the overall uncertainty (or total random error) due to uncertainty in the result when several measurements, each containing its own uncertainty, are combined in mathematical operations. This is called "Propagation of Error due to Uncertainties by Mathematical Operations". Let's look at the basic rules.

Addition and Subtraction

RULE 1: *When two or more measurements are added or subtracted, the* ***absolute uncertainties*** *of each measurement are added.*

Example: What is the perimeter of a rectangle that is 3.00 cm ± 0.05 cm long and 2.00 cm ± 0.05 cm wide? The values are expressed and added as follows:

$$\begin{array}{rl} & 3.00 \pm 0.05\ \text{cm} \\ & 3.00 \pm 0.05 \\ & 2.00 \pm 0.05 \\ & \underline{2.00 \pm 0.05} \\ P = & 10.00\ \text{cm} \pm 0.20\ \text{cm} \end{array}$$

The overall uncertainty (or error) in the perimeter can be converted to a percent uncertainty:

$$\frac{\pm 0.20\ \text{cm}}{10.0\ \text{cm}} \times 100 = \pm 2\%$$

Remember: A common protocol is that the overall percent uncertainty should be cited to no more than one significant figure if it is greater than or equal to 2% and to no more than two significant figures if it is less than 2%.

Example: If the reading of the level of liquid in a buret was 19.80 ml ± 0.02 ml before titration and after titration the liquid remaining in the buret was 44.80 ml ± 0.02 ml, what volume of liquid was titrated? The values are expressed and subtracted as follows:

$$\begin{array}{rr} & 44.80\ \text{ml} \pm 0.02\ \text{ml} \\ & \underline{-19.80\ \text{ml} \pm 0.02\ \text{ml}} \\ \text{volume} = & 25.00\ \text{ml} \pm 0.04\ \text{ml} \end{array}$$

If we wish, we can convert the absolute uncertainty in the volume to percent uncertainty:

$$\frac{\pm 0.04\ \text{ml}}{25.00\ \text{ml}} \times 100 = \pm 0.16\% = \pm 0.2\%$$

You can express your overall uncertainty either using absolute uncertainty; 25.00 mL ± 0.04 ml or using percent uncertainty; 25.00 mL ± 0.2%

Multiplication and Division

RULE 2: *When two or more measurements are multiplied or divided, the* ***percent uncertainties*** *of each measurement are added.*

Example: Suppose we have obtained the following values for the mass and length of a cylinder and wish to compute its density.

		absolute uncertainty		percent uncertainty
Mass	=	165.9 g ± 0.5 g	or	165.9 g ± 0.3%
Height	=	4.27 cm ± 0.05 cm	or	4.27 cm ± 1.2%
Diameter	=	2.64 cm ± 0.05 cm	or	2.64 cm ± 1.9%

The density of the cylinder is;

$$\text{Density} = \frac{m}{\Pi r^2 h}$$

We are now ready to find the overall uncertainty in the computed density. But first it should be noted that the error associated with the radius must be added twice, since r^2 means r x r.

percent uncertainty in mass = ± 0.3%
percent uncertainty in height = ± 1.2%
2 x percent uncertainty in radius = ± 3.8%
overall percent uncertainty in density = ± 5.3%

It should be noted that no error was associated with the use of Π, for we may choose a value for Π that has any number of significant figures that our purposes require. Hence, error for Π can be reduced to where it is negligible. In the above example, the choice of 3.1416 for Π would give one significant figure more than that in any of the other data.

Returning to the example,

$$\text{Density} = \frac{m}{\Pi r^2 h} = \frac{165.9\text{ g}}{3.1416 \times 1.32\text{ cm} \times 1.32\text{ cm} \times 4.27\text{ cm}} = 7.10\text{ g/cm}^3 \pm 5.3\%$$

Our result can be expressed as overall absolute uncertainty. Since 5.3% of 7.10 = 0.38, we can write:

$$\text{Density} = 7.10\text{ g/cm}^3 \pm 0.38\text{ g/cm}^3$$

which can be visualized as the overall uncertainty range of

$$6.72\text{g/cm}^3 \text{——} \boxed{7.10\text{g/cm}^3} \text{——} 7.48\text{g/cm}^3$$

Typical Instrumental Uncertainties

It is always advisable to find the manufacturers' designated uncertainties or ascertain your own uncertainties in using a particular instrument

Instrument	**Typical Uncertainty (±)**
Platform balance	±0.50 g
Triple-beam (centigram) balance	±0.01 g
Top-loading electronic balance	±0.01 g
Analytical balance	±0.0001 g
100-mL graduated cylinder	±0.2 mL or ±0.5 mL
25 mL graduated cylinder	±0.3)
10-mL graduated cylinder	±0.1 mL
50-mL buret	±0.02 mL or ±0.05 mL
25-mL pipet	±0.02 mL
10-mL pipet	±0.01 mL
1 mL pipet	±0.006 mL
100 mL volumetric flask	0.08 mL
250 mL volumetric flask	±0.12 mL
Thermometer (10^{o}C to 110^{o}C, graduated to 1^{o}C)	±0.2 ^{o}C
Barometer (mercury)	±0.5 mmHg

The above chart is comprised of typical uncertainties associated with common instruments used in the chemistry laboratory. This list is not meant to be rigorous. Rather, you need to use your best judgment as to whether you can read the finest subdivision of a given scale to the 0.5, 0.2, 0.1 or whole unit. This is a reasoned decision you make each time you use a measuring device.

More Confucius quotes;

"By three methods we may learn wisdom: First, by reflection, which is noblest; second, by imitation, which is easiest; and third by experience, which is the bitterest."

"Everything has beauty, but not everyone sees it."

"Choose a job you love, and you will never have to work a day in your life."

"A journey of a thousand miles begins with a single step."

Checklist for Writing IB Lab Reports

General Considerations

1. Lab reports must be word-processed.
2. Keep your lab report organized by using headings and sub-headings, following the formatting suggestions for Formal Lab Reports found on page 16.
3. Express yourself clearly and succinctly.
4. Hand your work in on time. Grades are reduced if handed in late.
5. Learn from your mistakes. In the early part of the course do not expect to get everything correct the first time you do it. Find out why you lost points and improve your next presentation.
6. File all your laboratory reports. At the end of the course some of them may be requested by IB.

Design

1. Does your introduction demonstrate that you recognize the nature of the proposed problem?
2. Is current theory used to provide background to the problem?
3. Is your description of the problem being studied specific, clear, concise, and appropriate?
4. Is your hypothesis in the format if…then….because….?
5. After you listed your variables, did you briefly describe each one?
6. Are your controlled variables well thought out, and not trivial or routine?
7. As you plan the methods to be used in an experiment, there are always difficulties that you anticipate and precautions that your take to avoid these difficulties. Does your method demonstrate that you have purposefully chosen certain techniques to accomplish your goals? Is this able to be evaluated based on what you have written?
8. Do you list all materials and equipment needed, including quantities, sizes, chemicals, and conc.?
9. Did you include safety considerations?
10. Do you have a complete procedure, with numbered steps, such that another student could duplicate your experiment?
11. Do you have the provision for multiple trials?
12. Are the levels of your independent variable large enough to collect of sufficient data?
13. Is it clear how your dependent variable is to be specifically measured?
14. Did you use appropriate terminology and equipment names?
15. Is a diagram beneficial to your procedure? Did you label or footnote the diagram?
16. *Did you proofread, edit, and revise this part of your lab report*?

Data Collection and Presentation

1. Did you plan ahead and leave room in your data table for your qualitative data?
2. Do you have your original raw data? Do you have both qualitative and quantitative data?
3. Is your RAW data neat and organized?
4. Is your qualitative data reasonable or trivial? Did you include in your qualitative data any color, solubility, or heat changes? Record all observations.
5. Does your data table have a descriptive title? Sometimes the title provides useful information such as specific conditions under which the data was collected
6. Do you have headings in the columns of your table, "/ units", and uncertainty in parentheses?
7. Is the data recorded to appropriate significant figures?
8. Are your calculations annotated to provide clarity and thoroughness?
9. If you have a graph, do you know whether your "line" should go through the origin?
10. Did you check the scale used in the axes of your graph for appropriateness?

11. Did you include a trendline, the equation, and the R^2 value?
12. Did you rewrite the equation in appropriate sig figs and explain the significance of the equation?
13. Did you refer to the R^2 value and explain its meaning?
14. Does your graph have any perceived trend articulated in a paragraph in DCP?
15. Did you include a sample calculation of every type of calculation?
16. Does your sample calculation include the equation with variables, substituted data for variables, and calculated answer, all with units and appropriate sig figs?
17. Do you have % error with cited reference?
18. Did you organize the results of multiple calculations into a Results Table? Do you have headings in the columns of your table, "/ units", and uncertainty in parentheses?
19. If data is manipulated in Excel, did you list and describe all the calculations?
20. Is statistical analysis appropriate?
21. Did you propagate error due to uncertainties and calculate the overall uncertainty in your results?
22. *Did you proofread, edit, and revise this part of your lab report?*

Conclusion and Evaluation

1. Is your first sentence a clear and thorough statement of the conclusion of your experiment?
2. Does your conclusion include numerical values that support the conclusion?
3. Is your conclusion as powerful as your data can support? Don't understate or overstate.
4. After you state your conclusion did you compare your results to literature or "actual" results? Comparisons can also be made to other class results.
5. Did you justify your results?
6. Did you comment on random and systematic errors or question any assumptions?
7. Did you assess the types of errors giving specific examples and indicating the direction of error?
8. Did you evaluate the procedure with care and insight?
9. Did you comment on the limitations of the procedure by identifying any weaknesses?
10. Did you show an awareness of how significant the weaknesses are?
11. Did you suggest how the method chosen could be realistically and specifically improved? Do your suggestions for improving the lab compensate for the weaknesses you identified in the design, procedure, equipment, or analysis of the lab?
12. Are your suggestions feasible for our situation?
13. *Did you proofread, edit, and revise this part of your lab report?*

Manipulative skills (MS)

- You follow instructions carefully and show initiative when necessary.
- You ask (first a peer) when you are uncertain.
- You show proficiency and competence in a wide range of different chemical techniques.
- You are enthusiastic in your approach.
- You show a high regard for safety in the laboratory.

Personal skills (PS)

- You show that you are highly motivated and involved.
- You persevere throughout the whole lab experience.
- You collaborate well with others by listening to their views and incorporating them into your work as well as making your own suggestions.
- You show an awareness of your own strengths and weaknesses.
- You show that you have reflected well on the whole lab and learned from the experience.