UMaine General Chemistry Lab Program

Grading Guide

UMaine General Chemistry Lab Program: Grading Guide

Prepared for general chemistry students & instructors

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How to use this guide

- This guide is divided into Three Sections. **Section One** is a quick startup guide, followed by **Section Two** on pre-lab, lab, and post-lab activities. Finally **Section Three** has more details about lab reports.

- For students, this guide presents information about how lab work is assessed and graded. This covers: the type of feedback you can expect and what to do with it, how to use the grading rubric, an example outline for a lab report, illustrative examples from actual student lab reports, and how scientific work falls under the same guidelines that are used in the general chemistry lab program.

- For instructors, this guide represents a summary of the guidelines recommended for use across the general chemistry lab program. All lab instructors take a graduate level course that covers these guidelines and integrates a range of activities into their professional practice including how lab work should be conceptualized, giving students feedback, and different ways that learning outcomes can be assessed.

Section 1: Quick Startup Guide

Useful Stuff

- If you need to make up a lab, you should consult the FAQ (frequently asked questions) list on the general chemistry website: http://umaine.edu/general-chemistry/faq/
- The address for InterChemNet is http://icn2.umeche.maine.edu/newnav/NewNavigator/LoginForm.cfm

Quick Startup Guide

- Lab experiments are selected online using your InterChemNet account where you will be able to download the lab procedures.

- You can find the InterChemNet login page by doing a Google search on "InterChemNet" or by going to http://icn2.umeche.maine.edu/newnav/NewNavigator/LoginForm.cfm.

- In order to log into InterChemNet, you need to have an access packet containing a code number which is purchased at the University of Maine bookstore (this is the only place to purchase these and the code number is found in the packet and can be used for one lab course).

- There is an accompanying general chemistry website (http://umaine.edu/general-chemistry/) which contains both lecture and lab information including answers to many common questions (http://www.umaine.edu/general-chemistry/faq/).

Lab Grades for Each Experiment

- Lab grades are assigned for each experiment considering these factors:

    1. 10%: pre-lab assignment and pre-lab discussion.
    2. 10%: safe behavior in lab.
    3. 10%: laboratory work including taking notes.
    4. 10%: post-lab discussion.
    5. 60%: Laboratory Report.

- Lab reports are graded on a 0-60 pt scale and will be posted on your InterChemNet page. Pre-lab assignments are graded and returned. The remaining points (safety, lab work, post-lab) are presumed, and a lab instructor will inform students only if they do not earn full credit. Deducted points are communicated by the time lab reports are returned. Typically students lose points when they do not attend pre- or post-lab discussions, do something unsafe in lab, or do not use their lab notebooks properly.

Lab Report Rubric*

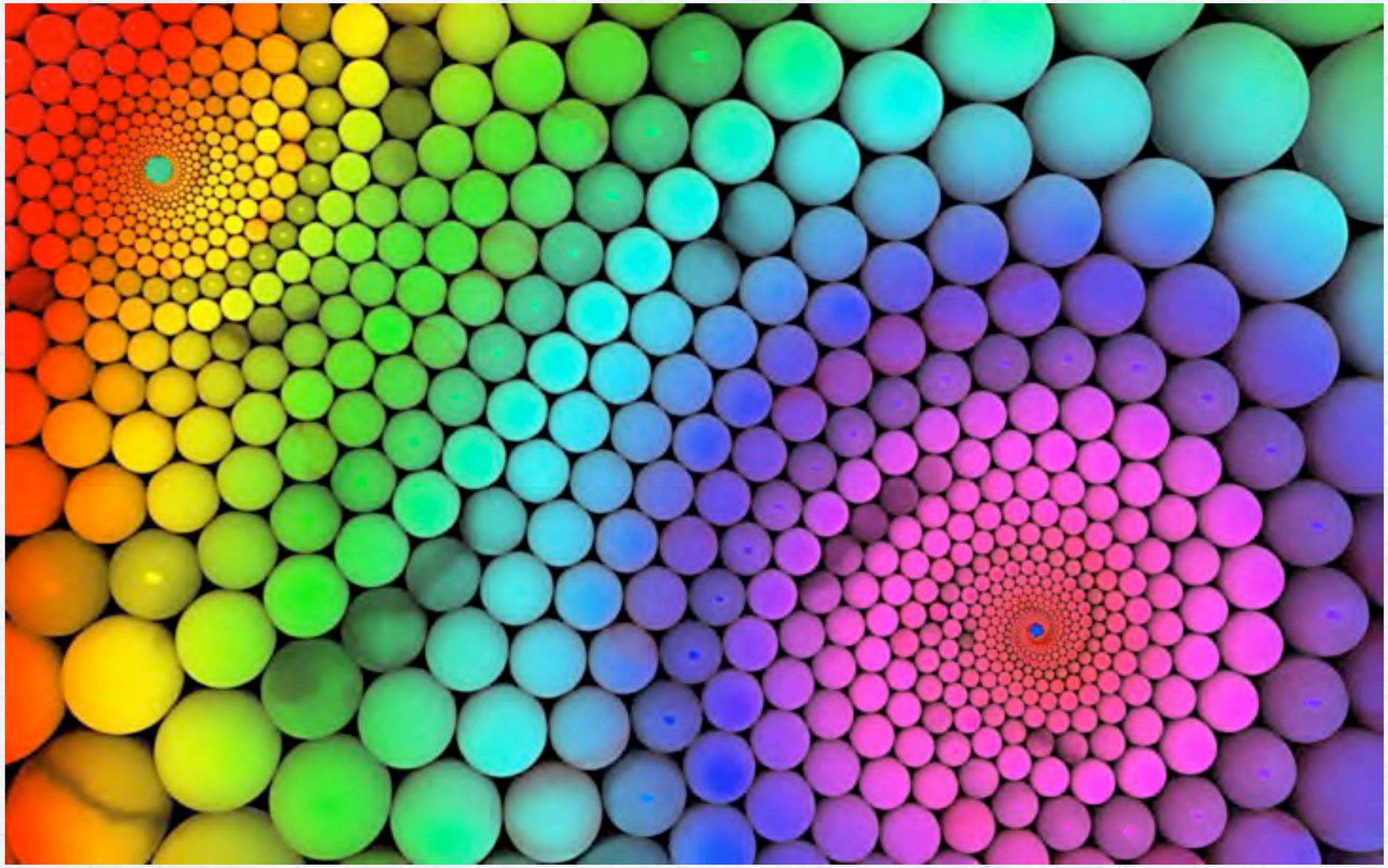
The lab report rubric is a conceptual framework to identify the required components in each lab report. For each component, the rubric describes the type of work that would fall into level 0 (poor), 1 (average), and 2 (excellent) work. Section three illustrates the application of the rubric in more detail.

Please note: there are essential features that are expected (and assumed) for every lab report. Essential features include: Title of Experiment, Name, Introduction, and Explanation of lab procedures. Points will be deducted when these features are missing; typical deductions: missing title: -5 pts; missing name -5 pts; missing introduction: -5 pts; missing procedures section: -5 pts.

Lab Report Rubric	**Level of attainment**		
Required Components	**Level 0 (0-20 points)**	**Level 1 (21-40 points)**	**Level 2 (41-60 points)**
Claim(s): Is a statement(s), derived from evidence, using scientific reasoning. **The claim should be underlined on the first page following the introduction.**	Does not make a claim, or makes an inaccurate claim.	Makes an accurate but incomplete claim.	Makes an accurate and complete claim.
Evidence: Scientific data that supports the claim. The data needs to be appropriate and sufficient to support the claim.	Does not provide evidence, or only provides inappropriate evidence (Evidence that does not support claim).	Provides appropriate, but insufficient evidence to support claim. May include some inappropriate evidence. Evidence from other published sources may be mentioned.	Provides appropriate and sufficient evidence to support claim. Communicates and describes evidence from other published sources that adds significance to gathered evidence.
Reasoning: Scientific arguments that use evidence and appropriate scientific principles to make claims.	Does not provide reasoning, or only provides reasoning that does not link evidence to claim.	Provides reasoning that links the claim and evidence. Repeats the evidence and/or includes some scientific principles, but is not sufficient. May identify and/or mention outside sources or studies.	Provides reasoning that links evidence to claim. Includes appropriate and sufficient scientific principles. Appropriately identifies and discusses outside sources or studies.

*Rubric inspired by the work of Dr. Joseph Krajcik, et al.

Section 2: pre-lab, lab, and post-lab activities



Pre-lab, Lab, and Post-lab activities

- 40% of the lab grade is assigned for activities that happen before and during lab:

    1. 10%: prelab assignment and prelab discussion.
    2. 10%: safe behavior in lab.
    3. 10%: laboratory work including taking notes.
    4. 10%: post lab discussion.

Pre-lab Assignment and Prelab Discussion (10%)

- The pre-lab assignment is handed in at the beginning of the lab period. The pre-lab assignment contains questions about the upcoming lab including a section on safety. The pre-lab assignment is graded and worth 5%. Without it, you can not begin lab.

- Participation in the pre-lab discussion is required. Your presence will earn you 5%. During the pre-lab discussion, the lab instructor will relate important lab information, review the pre-lab assignment, discuss the upcoming lab, and give you an opportunity to ask questions. If you arrive late, the 5% cannot be recovered.

Safe behavior in lab (10%)

- No work can take place in lab without understanding how to conduct the experiments safely.
- You are required to attend a safety presentation at the beginning of the semester and successfully pass a safety quiz in order to continue in the lab course.
- Safety is everyone's concern. If you ever see anything unsafe going on in lab please report this to your lab instructor. If you are unsure if you are doing something safely, please do not proceed without consulting your lab instructor.
- The pre lab will include safety information. If you haven't completed the safety section, you will not be allowed to start lab.
- Safe behavior is presumed and 10% is earned for each lab. If a student exhibits unsafe behavior, the lab instructor has the responsibility to ask students to correct the behavior and even to leave lab. If this occurs, before being allowed to reenter lab, the incident will need to be reviewed by the general chemistry coordinator and laboratory manager.

Laboratory work including taking notes (10%).

- To a large extent, you control what you do in lab. Successful lab work takes active planning and thinking.

- What you do in lab is a reflection of the care and attention given to your laboratory work.

- Sometimes there is room for creative and critical thinking in lab work. For example, the lab procedures are, by design, sometimes incomplete. You may be asked to design an experiment to test a hypothesis. You may be able to design the experiment in more than one equally valid way. Scientists sometimes follow different methods to accomplish the same task and this has led to important scientific discoveries.

- You should use the lab notebook to describe how you approach tasks, answer questions posed in the lab procedure, make observations, and to record important information like the mass of a chemical. Trying to save pages in a lab notebook for next semester is a “penny wise - pound foolish” way of using your lab notebook.

- Lab instructors assign 10% of your grade from lab work. It is rather easy to earn the 10%. It is not so easy, however, to use your time in lab carefully and thoughtfully.

Post-Lab Discussion (10%)

- By the end of lab, you will have gathered evidence. The post-lab discussion is about the process of thinking about this evidence and how it can be analyzed, through reasoning, to make valid scientific claims.

- Not all of the evidence you will gather will be easy to interpret. For example, sometimes mistakes in lab will make conclusions very difficult. However, there is no requirement to get a certain outcome in your lab work. What is required is that you work with the evidence you have generated (unless told by a lab instructor to do otherwise). The post-lab discussion can make writing up your results easier.

- Timing of the post lab discussion varies. Your lab instructor will appreciate your help in forming a group of 4-8 students to have a post lab discussion. Students can have this discussion without the lab instructor but touching base with the lab instructor should always occur before leaving lab.

- <u>To document the post-lab discussion, you should write 5-6 summarizing sentences in your lab notebook, under the heading, Post-lab Discussion.</u>

- The post-lab discussion carries 10 pts for participation. If your lab instructor notices that you do not participate in the lab discussion and that you do not write the summary, these points will not be awarded.

Section 3: lab reports

Lab Report Basics

- During the first few weeks of the semester, your lab report will receive a Tentative Grade from the instructor, which can be improved if resubmitted, taking into account lab report deficiencies. Please see section A on Lab Report Tentative Grade and Regrades as well as section B on: What Can I Expect and What Do I Do with Lab Instructor Feedback?

- Sections C-E look at each of the three components in the rubric separately that were first presented in the Quick Startup Guide (Section 1).

- A suggested outline for a lab report is shown in section F, illustrating each of the components of the rubric.

- Sections G, H, and I contain lab report details including information from actual student lab reports.

- Finally, in section J, a recent scientific publication is shown - illustrating how claim, evidence, and reasoning are used in a scientific paper.

Section A: Lab Report Tentative Grade and Regrades

- During the first few weeks of the semester, your lab report will receive a tentative grade from the instructor. This grade can be improved if resubmitted, taking into account lab report deficiencies. This applies to the first two lab reports.

- In these first two lab report regrades, you can earn all of the points back.

- After that, your TA may ask you to revise a lab report. If this occurs, the maximum score you can achieve on the regrade will be one half of the difference between the maximum and the grade you received.

In the first two lab reports, you can earn all of your points back on a regrade.

Section B: What Can I Expect and What Do I Do with Lab Instructor Feedback?

- This section is part of a "living" document that will be continually added to over time. Our initial examples are shown on this page.

We determined the calorimeter's heat capacity to be 1.88. unit?	The units are missing. There are two important aspects about correcting this in a lab report. First, you need to make the correction. Second, you need to carefully review the lab report for all such occurrences.	Units are part of evidence, which in total is worth 20 points. A single occurrence of a missing unit may be marked down "-1" with multiple occurrences up to "-6" points!
Show work!	A result was shown without any information about how the result was arrived at. This is common for a result based on a calculation. The lab report should document this process.	Showing work could be part of the evidence or reasoning. Not showing an important calculation could be a 5 pt deduction.
What was your unknown Concentration? How did you determine this?	A major item was missing from the lab report. This would result in a major mark down. The remedy is to supply this information. Be careful to show work.	Omitting a major section results in a large deduction.
Missing: Your spectra! -10 Graph Abs vs. concentration for Nickel -5 Use graph to find conc. of unknown -3 Sketch of instrument -2	The lab instructor has identified a list of items (longer than shown). This student did not understand what was required for a complete lab report.	This student earned a failing grade on the lab report. Each item should have been supplied.

Section C: Lab Report Evidence

Lab Report Rubric	Level of attainment		
Component	**Level 0 (0-20 points)**	**Level 1 (21-40 points)**	**Level 2 (41-60 points)**
Evidence: Scientific data that supports the claim. The data needs to be appropriate and sufficient to support the claim.	**Does not provide evidence, or only provides inappropriate evidence (Evidence that does not support claim).**	**Provides appropriate, but insufficient evidence to support claim. May include some inappropriate evidence. Evidence from other published sources may be mentioned.**	**Provides appropriate and sufficient evidence to support claim. Communicates and describes evidence from other published sources that adds significance to gathered evidence.**

- The scientific evidence you gather in lab are facts and information that helps support claims.

- For example, if you measured the boiling point of water with a thermometer, and you found that water boiled at 99.8 °C, 100.1 °C, and 99.9 °C, you might use that to indicate that the water in your experiment boiled at an average temperature of 99.9 °C. The three measurements are evidence. But you also add to your evidence observations that gas bubbles were generated at the boiling point.

- You can also cite a reference source (e.g. textbook), that water boils at 100 °C at 1 atm. pressure and approximately 95 °C in Denver, CO where the air pressure is lower.

Section D: Lab Report Reasoning

Lab Report	Level of attainment		
Component	**Level 0 (0-20 points)**	**Level 1 (21-40 points)**	**Level 2 (41-60 points)**
Reasoning: A justification that links the claim and evidence. It shows why the data counts as evidence by using appropriate and sufficient scientific principles.	**Does not provide reasoning, or only provides reasoning that does not link evidence to claim.**	**Provides reasoning that links the claim and evidence. Repeats the evidence and/or includes some scientific principles, but is not sufficient. May identify and/or mention outside sources or studies.**	**Provides reasoning that links evidence to claim. Includes appropriate and sufficient scientific principles. Appropriately identifies and discusses outside sources or studies.**

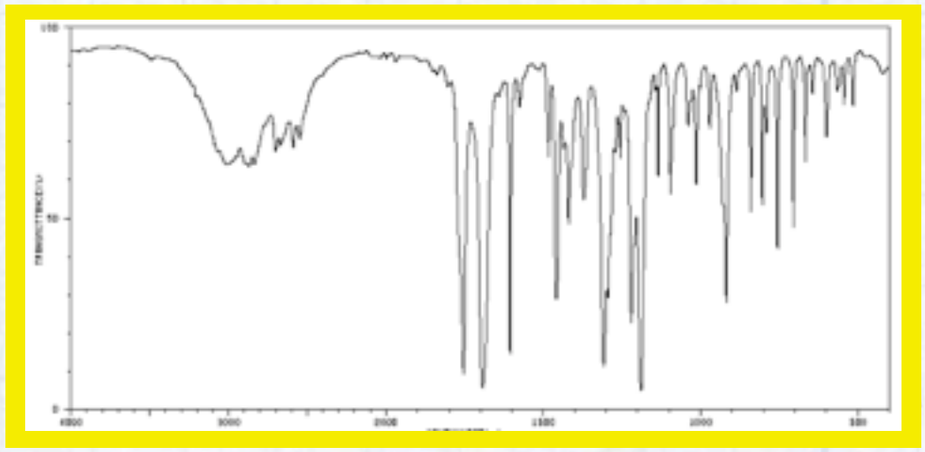
- Scientific reasoning connects evidence and claims.
- If you measured the volume of a gas as a function of pressure and temperature, the evidence you generate can be tabulated and graphed. However, it is the interpretation of the evidence, that allows you to make claims.
- For example, let's say that your evidence indicates that as temperature increases, the volume of the gas increases for a constant number of moles of gas and constant pressure. This evidence is turned into a claim by reasoning that there is a proportionality constant (k) between volume (V) and temperature (T) that can be written as $V = k\,T$ (at constant number of moles of gas and constant pressure).
- An outside source might be brought into the reasoning such as referencing the ideal gas law, $PV = nRT$. Recognizing that for a constant number of moles of gas and constant pressure, the equation can be re-written as $V = (nR/P)\,T$, suggesting that the proportionality constant (k) is equal to nR/P.
- Reasoning enriches the scientific discussions and by bringing in outside sources or studies, allows a much stronger connection to be established between evidence and claim.

Section E: Example Claims

- You are given three bottles: two unknown white powders and one labeled "aspirin". Each is white. To evaluate the substances, you measure the melting point and find: "aspirin": mp=137 °C; unknown A: mp = 138 °C; unknown B: mp = 137 °C. You make the claim that all three substances are consistent with aspirin because melting point is a characteristic property of substances. However, you note that you consider your claim tentative and suggest it is weak because many compounds are white with the same melting points.

- To strengthen your claim, you determine the mass and volume each substance and calculate the densities: "aspirin", d = 1.4 g/mL; unknown A, d = 1.41 g/mL; unknown B, d = 1.39 g/mL. This new evidence supports your initial claim (within the error of your measurements); you have strengthened your original claim but the claim is still not strong since there may be different compounds having the same mp and d.

- Finally, you take an infrared (IR) spectrum of each sample: they all have similar patterns of infrared peaks. You now consider your claim much stronger and state that the substances are very likely all samples of "aspirin".



Section F: Example Lab Report Outline

I. **Title of Experiment**, **Name** (partner names if applicable), **date the experiment was conducted**, **lab section, and lab instructor.**

II. **Introduction:** (typically 1-3 paragraphs, sometimes with equations and a figure). An introduction explains the lab, summarizing your results and states why the experiment was important.

YOUR CLAIM(S) SHOULD BE CLEARLY PRESENTED AND UNDERLINED FOLLOWING YOUR INTRODUCTION

III. **Results**: this section describes the evidence you have gathered during the experiment. This may include data (e.g. "the mass of a compound was ..."), observations (e.g. the solution turned blue after adding HCl"), calculations, graphs, and tables.

IV. **Discussion**: contains your reasoning for how you can build a scientific case connecting your results (evidence) to claims. In supporting your case you may build upon other sources of information, including textbooks and scientific papers.

V. **Summary/Conclusion** are optional but very useful in providing a condensed version of the lab report. Evidence can be highlighted, the discussion can be summarized, and the claims restated.

Section E: Lab Report Claims

Lab Report	Level of attainment		
Required Component	**Level 0 (0-20 points)**	**Level 1 (21-40 points)**	**Level 2 (41-60 points)**
Claim(s): Is a statement(s), derived from evidence, using scientific reasoning. **The claim should be underlined on the first page following the introduction.**	**Does not make a claim, or makes an inaccurate claim.**	**Makes an accurate but incomplete claim.**	**Makes an accurate and complete claim.**

- A scientific claim builds a case based on evidence using sound reasoning. In contrast, a claim that lacks evidence is scientifically worthless and misleading.

- A claim is not proof in the sense that it has to be 100% correct to be useful or scientific. A claim is supported by the evidence and the reasoning constructs arguments to understand both the strengths and weaknesses of a claim.

- Your claim has to be placed prominently in the lab report so it can be identified as a claim and a person who is reading the lab report can see how the evidence and reasoning supports the claim.

- A discussion of claims is described on the next page.

- Remember that the claim should be included in the beginning of your lab report along with the introduction, safety information, and procedures.

Section G: A detailed look at the beginning of a lab report including where to make your claims (based on actual student work).

- At the beginning of the lab report, you are expected to include certain essential features such as Title of Experiment, Name, Introduction, Underlined claim on first page of lab report, and procedures. Points will be deducted ONLY when these features are missing.
- **Where to make your Claim**. Scientific papers typically convey claims in the **Title** and **Abstract**, placed at the very beginning of a paper. To evaluate the strength of claims, scientists look at the evidence and reasoning used to support the claim. Therefore, we should recognize that while the claims go at the beginning of your lab report, all of your claims should be based on the evidence and reasoning presented in other parts of the lab report. It makes sense then, that you would finalize your claims only after the other sections were written. Modern word processing programs make this easy to do!
- Looking over the grading rubric, you will see three major components: Claims, Evidence, and Reasoning. **Twenty points (out of 60 pts) are earned for the quality of your claim. The lab instructor will look over the evidence (present in other parts of your lab) as well as your reasoning, and will judge if your claim is based on these other components. You are not judged on a result - but rather if your claim is logical and reasonable based on the data from lab as well as how you interpreted it (i.e. reasoning).**
- In the red box below, is the beginning part of a lab report (Title omitted) including: Introduction, Claim, and Procedure sections. This is based on an actual student lab report from fall, 2011. Based on the evidence and reasoning (present in the other sections of the lab report), **this lab report earned 20 pts. for the claim.**

Introduction

This lab is an introduction to the use of a UV-vis spectrometer. Stated by the lab manual on InterChemNet: "A UV-vis spectrometer is an instrument used to measure the amount of ultraviolet and visible absorbed by a solution". Solutions of different metal ions have different characteristic patterns of absorbance bands. The absorbance bands of a series of known metals ions were recorded using a UV-vis spectrometer and then compared to an unknown solution.

Claim

Our claim is that our assigned unknown sample was cobalt. This was based on a comparison of the UV-vis spectrum of our unknown sample to that of the UV-vis spectra of known metal ions.

Safety Precautions!!!

Copper (II) Nitrate, Nickel(II) Nitrate, Cobalt (II) Nitrate, and Iron (III) Nitrate are all string oxidizers. In their pure form they may cause fires when in contact with other materials. Although in this lab they are in solution, that doesn't mean that they should be taken less likely.

Procedures

The procedures were taken from the InterChemNet website, "Qualitative and Quantitative Use of the UV-vis Spectrometer", accessed November 8, 2011. The following changes were made to the procedures during the experiment:

....

....

....

Notes:

(1) The Introduction is short but conveys a clear and focused description of the lab experiment.

(2) The claim is underlined at the beginning of the lab report. This makes it easy for the lab instructor to see what claim(s) was made in the report. In this example, the claim is followed by a description of the way that evidence is used to make the claim. The lab instructor who graded this lab found this very useful!

(3) The safety information was summarized in an easy to understand format.

(4) The lab procedure was referenced, the date that the lab was downloaded was noted, and only the changes made that differed from what was written in the lab procedure were noted. These were explicitly and clearly described and taken directly from the lab notebook.

Section H: A detailed look at evidence presented in lab reports.

- Looking over the grading rubric, you will see three major components: Claims, Evidence, and Reasoning. **Twenty points (out of 60 pts) are earned for the presentation of evidence gathered in lab.**
- **There are many different forms of evidence that can be included.**

Data Tables are useful in presenting information. This example was taken from an actual lab report from fall, 2010. (Please note that 2 pts were deducted because the units for temperature were missing).

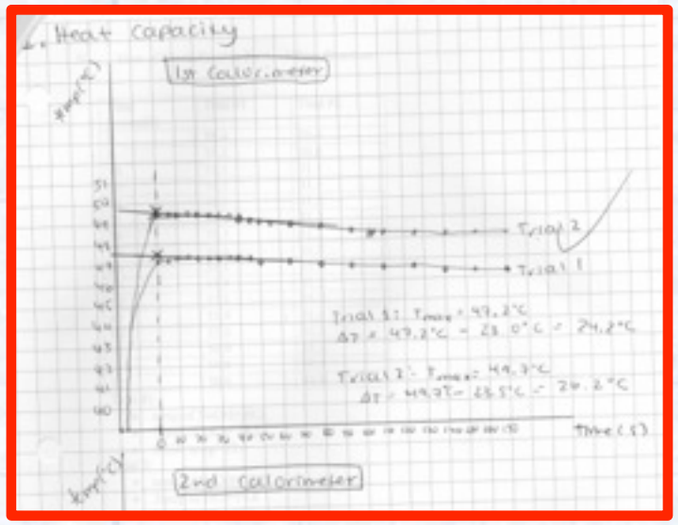
II. Heat of Neutralization for Acid/Base Reaction

Time (seconds)	Trial #1	Trial #2
0	25.4	22.3
5	31.1	30.8
10	31.1	31.1
15	31.1	31.1
20	31.1	31.2
25	31.1	31.2
30	31.1	31.2
35	31.1	31.2
40	31.1	31.2
45	31.1	31.2
50	31.1	31.2.
65	31.0	31.1
80	31.0	31.1
95	30.9	31.1
110	30.8	31.1
125	30.6	31.0

Trial #1:
- temp of NaOH=20.2
- Temp of HCl= 19.5
- Initial temp=25.4

Trial 2:
- temp of NaOH=19.7
- Temp of HCl=19.8
- Initial temp = 22.3

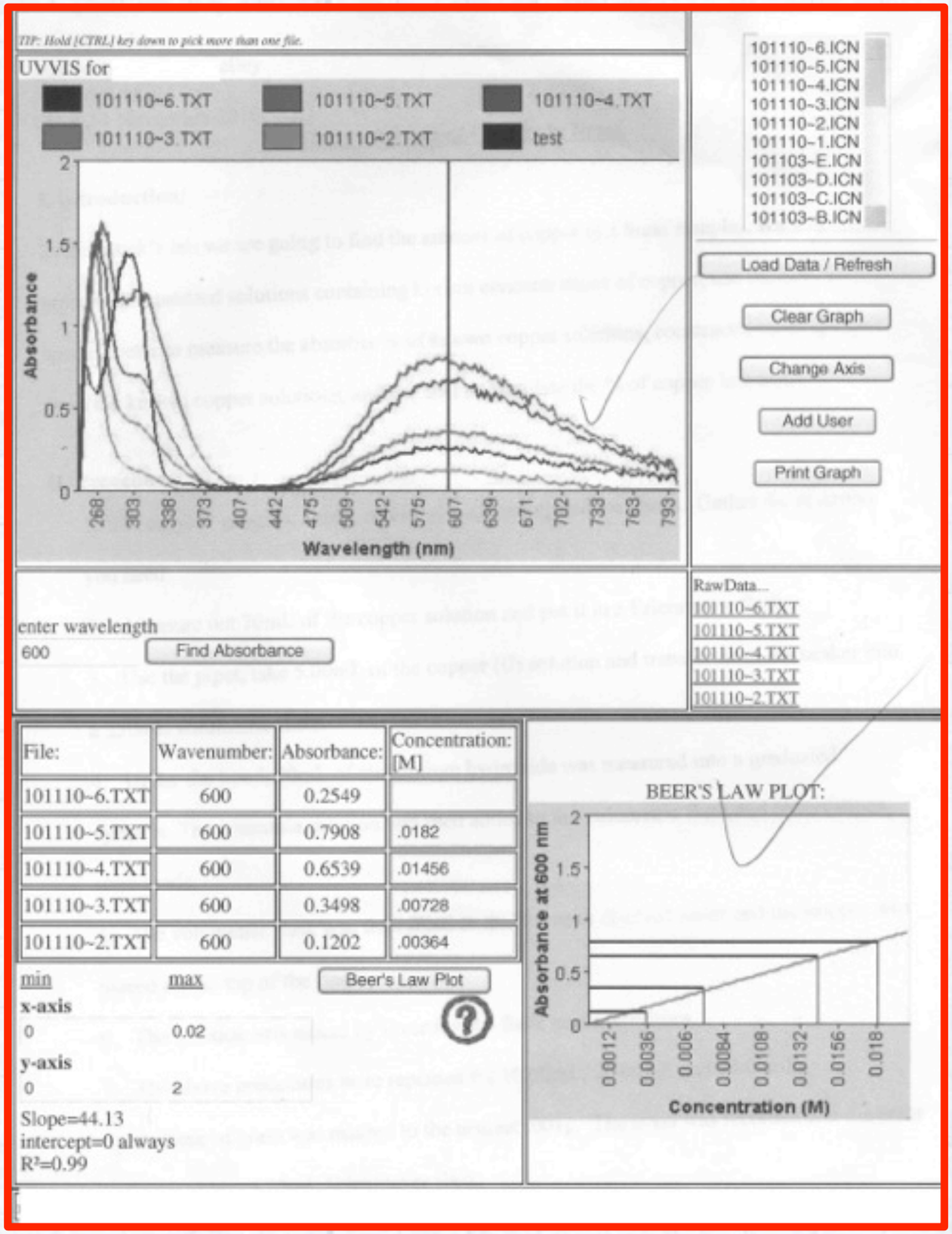
Figures are often required as part of the lab report. This example was taken from an actual lab report from fall, 2010. Here a student reproduced a drawing made from his/her lab notebook. This is perfectly acceptable, if the figure meets all of the requirements. Note that this figure includes units for the X (second) and Y (temp, °C) axes.



Section H (cont.): A detailed look at evidence presented in lab reports.

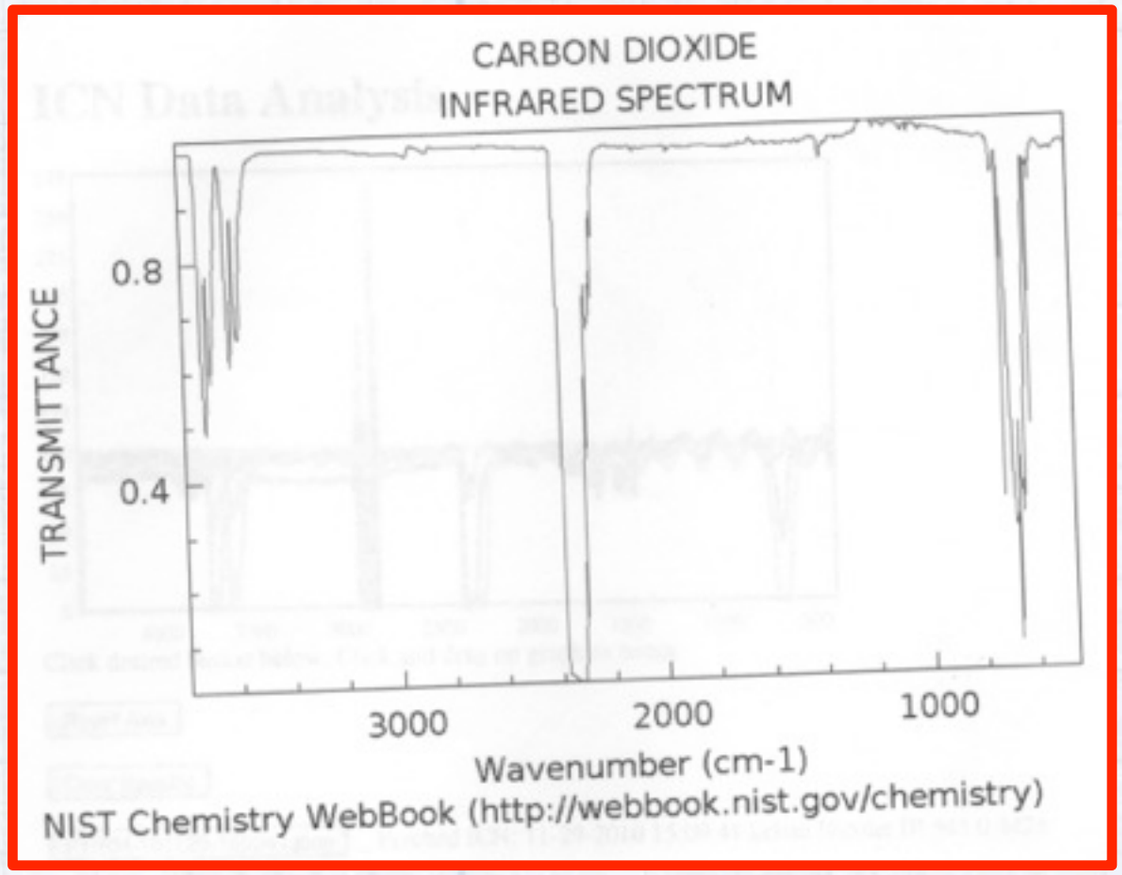
InterChemNet provides a UV-vis Beer's Law subroutine for analyzing UV-vis data. The data taken from a fall, 2010 lab report shows student evidence including UV-vis spectra, a Table of absorbance (600 nm) and concentrations, and a plot of absorbance vs. concentration. A linear line (correlation coefficient = 0.99) is also determined which can be used as a standard calibration curve.

The selection of data, how many UV-vis spectra, input of the concentrations (found by using other data from the lab) are all key parts of the evidence presented in this page of a lab report. This student earned full marks for the evidence presented in this lab report (some of which is not shown here).



Section H (cont.): other evidence presented in lab reports.

One aspect of evidence that is highly valued is evidence from other published sources that adds significance to gathered evidence (see grading rubric). The example here is from a student lab report called, FTIR Analysis of Greenhouse Gases (fall 2010) showing the FTIR spectrum of carbon dioxide. Note that the source of the figure was identified (a website). Please note that you should include an access date for any evidence taken from the Internet.



Section I: A Detailed Look at the Reasoning Section

- Looking over the grading rubric, you will see three major components: Claims, Evidence, and Reasoning. **Twenty points (out of 60 pts) are earned for the presentation of reasoning gathered in lab.**
- **Reasoning involves constructing scientific arguments that use evidence and appropriate scientific principles to make claims.**
- **Experimental data presents a number of challenges. To name a few: error, inappropriate procedures for the concept under investigation, missing data, and unclear logic used in reasoning. Applying reasoning to data can be tricky and requires very careful thinking. The reasoning is also often tied to the goals for a particular lab. If experiments are conducted using student designs, the goals of the experiments are also important to define and reason through in the lab report.**
- **The reasoning section of a lab report is therefore, the hardest to define as well as illustrate. The example to the right is from a student lab report called "Identifying Metal Ions by Chromatography" from Fall, 2011. Some general discussion points are outlined below.**

In the chromatography lab, four known metal ions were used to spot a strip of paper, and the ends placed in a solvent. By capillary action, the solvent moves up the paper, bringing with it to different extents, the metal ions. The distance the solvent moves (solvent front) as well as the distance each of the metal ions travels is measured and tabulated (i.e. evidence). The ratio is found to be characteristic of the metal ion (i.e. R_f value). Reasoning suggests that given similar conditions, an unknown metal ion will travel up the paper in such a way that the R_f can be used to identify the unknown metal ion solution. The student's unknown can be run at the same time along side several known metal ions. The known metal ions are run in order to make sure that the conditions under which the unknown is run is similar to that when the known metal ions were previously run (and the R_f values calculated). The identity of the unknown is made based on the R_f value for known metal ions. The claim that the unknown was (e.g. cobalt) was then made. The colors of the solutions (qualitative data) can also be used as important indicators.

One of the lab's purposes was to discover the components of an unknown solution. The unknown solution was made up of Cu^{2+}, Ni^{2+}, and Co^{2+}. I know this, because I performed the procedure known as Paper Chromatography, and the results showed that these solutions were in it. The unknown solution's spots had the R_f values of .157, .363, and .294. Each of those closely compare to Ni's .169, Cu's .367 and Co's .331. Not only is that not all the evidence, but the dots with those corresponding R_f's had the same colors throughout the different stages of this procedure, which is why in the end of the chromatographic process, the colors were brown, red, and yellow, which correspond with Ni, Cu, and Co.

Although this lab could be considered a success, it doesn't change the fact that there was change

... sample 2 than in sample 1.

Table for Step 3

Sample Name	Distance from Line to Leading Edge of Spot	Distance from Line to Solvent Front	R_f value	Color of the observable spots during and after each step in the procedure
Cu	13.6cm	5cm	.368	During:Blue After: Brown
Co	14.2cm	4.7cm	.331	During:Nothing After: Yellow
Ni	13.6cm	2.3cm	.164	During: Nothing After: Red
Fe	14.2cm	10.3cm	.7253	During: Yellow
Unknown#1 First mark	10.2cm	2.2cm	.157	After: Red Corresponds with Ni
Second Mark	10.2cm	3.7cm	.363	After: Brown Corresponds with Cu
Third Mark	10.2cm	3cm	.294	After: Yellow Corresponds with Co

Notes:

1. This was a student designed experiment. The student's major reasoning was based on a comparison of the data from the unknown to data from known metal ions.

2. The data could have been strengthened if one or more known metal ions were run at the same time that the unknown was run. The use of too many significant digits for the data was noted and points were deducted.

3. The student's reasoning used the solution colors to help in the identification.

Section J: An example from the scientific literature: Claim, Evidence, and Reasoning

The claim is stated right in the title.

The evidence that was used in the analysis (i.e. reasoning) is stated in the first sentence of the abstract.

Ravishankara et al. Science, 326, 123-125, 2009. Cited over 150 times in other papers since publication.

The full article can be downloaded from Folger library.

Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century

A. R. Ravishankara,* John S. Daniel, Robert W. Portmann

By comparing the ozone depletion potential–weighted anthropogenic emissions of N_2O with those of other ozone-depleting substances, we show that N_2O emission currently is the single most important ozone-depleting emission and is expected to remain the largest throughout the 21st century. N_2O is unregulated by the Montreal Protocol. Limiting future N_2O emissions would enhance the recovery of the ozone layer from its depleted state and would also reduce the anthropogenic forcing of the climate system, representing a win-win for both ozone and climate.

The depletion of the stratospheric ozone layer by human-made chemicals, referred to as ozone-depleting substances (ODSs), was one of the major environmental issues of the 20th century. The Montreal Protocol on Substances That Deplete the Ozone Layer (*1*), MP, emerged from the Vienna Convention for the Protection of the Ozone Layer (*2*). The MP has been highly successful in reducing the emissions, growth rates, and concentrations of chlorine- and bromine-containing halocarbons, the historically dominant ODSs (*3*), and has limited ozone depletion and initiated the recovery of the ozone layer.

The relative contributions of various ODSs to ozone layer depletion are often quantified by the ozone depletion potential (ODP) (*4*). An ODP relates the amount of stratospheric ozone destroyed by the release of a unit mass of a chemical at Earth's surface to the amount destroyed by the release of a unit mass of chlorofluorocarbon 11, CFC-11 ($CFCl_3$). ODPs are widely used for policy formulation because of their simplicity in quantifying the relative ozone-destroying capabilities of compounds.

Through the work of Crutzen (*5*) and Johnston (*6*), nitrogen oxides ($NO_x = NO + NO_2$) are also known to catalytically destroy ozone via

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$O + NO_2 \rightarrow NO + O_2$$

$$\text{net: } O + O_3 \rightarrow 2O_2$$

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The primary source of stratospheric NO_x is surface N_2O emissions [(*7*) and references therein]. N_2O has been thought of as primarily a natural atmospheric constituent, but the influence of its changes on long-term changes in ozone concentrations has also been examined (*8–10*).

Nitrous oxide shares many similarities with the CFCs, historically the dominant ODSs. The CFCs and N_2O are very stable in the troposphere, where they are emitted, and are transported to the stratosphere where they release active chemicals that destroy stratospheric ozone through chlorine- or nitrogen oxide–catalyzed processes. They both have substantial anthropogenic sources. Unlike CFCs, N_2O also has natural sources, akin to methyl bromide, which is another important ODS. Assigning an ODP for N_2O and separating out the natural and anthropogenic emissions are therefore no more conceptually difficult than they are for methyl bromide.

In spite of these similarities between N_2O and previously recognized ODSs and in spite of the recognition of the impact of N_2O on stratospheric ozone, N_2O has not been considered to be an ODS in the same sense as chlorine- and bromine-containing source gases. The signatories to the Vienna Convention (*2*) have agreed in Article 2 (General Obligations) to "Adopt appropriate legislative or administrative measures … to control, limit, reduce or prevent human activities under their jurisdiction or control should it be found that these activities have or are likely to have adverse effects resulting from modification or likely modification of the ozone layer." Yet N_2O remains unregulated by the MP (*1*).

Here, we present the ODP of N_2O to be positive and nonzero and show that N_2O is an ozone-depleting substance on the basis of the extent of ozone depletion it causes. Indeed, current anthropogenic ODP-weighted N_2O emissions are the largest of all the ODSs and are projected to remain the largest for the rest of the 21st century.

We have calculated the ODP of N_2O by using the Garcia and Solomon two-dimensional (2D) model [(*11*) and references therein], which is similar to models used previously for such calculations (*12*, *13*). The ODP of N_2O under current atmospheric conditions is computed to be 0.017. This value is comparable to the ODPs of many hydrochlorofluorocarbons (HCFCs) (*3*) such as HCFC-123 (0.02), -124 (0.022), -225ca (0.025), and -225cb (0.033) that are currently being phased out under the MP. We conclude that the value of the ODP of N_2O is robust because (i) our similarly calculated ODPs for CFC-12 (1.03) and HCFC-22 (0.06) agree with the accepted values (*3*); (ii) ozone depletion by NO_x from N_2O dominates the chemical control of ozone in the mid-stratosphere (*13*), a region well represented with 2D models; and (iii) ozone reductions by enhanced N_2O have been reported in other studies (*8*, *10*, *14*), although no published study, to the best of our knowledge, has previously presented an ODP for N_2O.

We examine here a few important factors that influence the ODP of N_2O. At mid-latitudes, chlorine-catalyzed ozone destruction contributes most to depletion in the lowest and upper stratospheres, that is, below and above the ozone maximum. Nitrogen oxides contribute most to ozone depletion just above where ozone concentrations are the largest. This leads to efficient ozone destruction from NO_x (*13*). The ODP of N_2O is lower than that of CFCs primarily because only ~10% of N_2O is converted to NO_x, whereas the CFCs potentially contribute all their chlorine.

There are important interconnections between the roles of nitrogen oxides with chlorine such that the N_2O ODP may be different from the calculated value in the past and future. It is well known that nitrogen oxides dampen the effect of chlorine-catalyzed ozone destruction via the formation of $ClONO_2$, which ties up some of the chlorine in a benign form. However, as shown by Kinnison *et al.* (*9*), other reactions, such as the conversion of ClO to Cl by NO, can offset the damping.

We quantify the dependence of the ODP of N_2O on atmospheric concentrations of chorine by calculating it for 1959 concentrations of strato-

An example from the scientific literature: Claim, Evidence, and Reasoning (cont.)

It is important to note that the ODP alone cannot fully quantify the impact of a chemical that is released into the atmosphere. The entire emission history, and even the potential future emission projections, must be considered by using an extensive quantity like ODP-weighted emission as a metric rather than an intensive quantity such as ODP, which only considers the ozone depletion per unit mass. Figure 1 compares the anthropogenic N_2O emissions with those from the major ODSs (now controlled under the MP) for 1987 and 2008. It is clear that ODP-weighted anthropogenic emissions of N_2O were a substantial fraction of the ODP-weighted emissions of CFC-11, CFC-12, and CFC-113 even in 1987, just before the adoption of the MP. They were likely larger than the sum of the ODP-weighted emission of halons and were much larger than that of methyl bromide.

Even though N_2O's ODP is only 0.017, roughly one-sixtieth of CFC-11s, the large anthropogenic emissions of N_2O more than make up for its small ODP, making anthropogenic N_2O emissions the single most important of the anthropogenic ODS emissions today (Fig. 1). For example, the global anthropogenic emission of N_2O now (produced mainly as a byproduct of fertilization, fossil fuel combustion and industrial processes, biomass and biofuel burning, and a few other processes) is roughly 10 million metric tons per year, a total annual emission during the 1990s of 17.7 TgN, of which 6.7 TgN (10.5 million metric tons of N_2O) were anthropogenic in origin.

that is, the so-called banks. However, much of the banked halocarbons reside in applications that are generally not cost-effective to recover

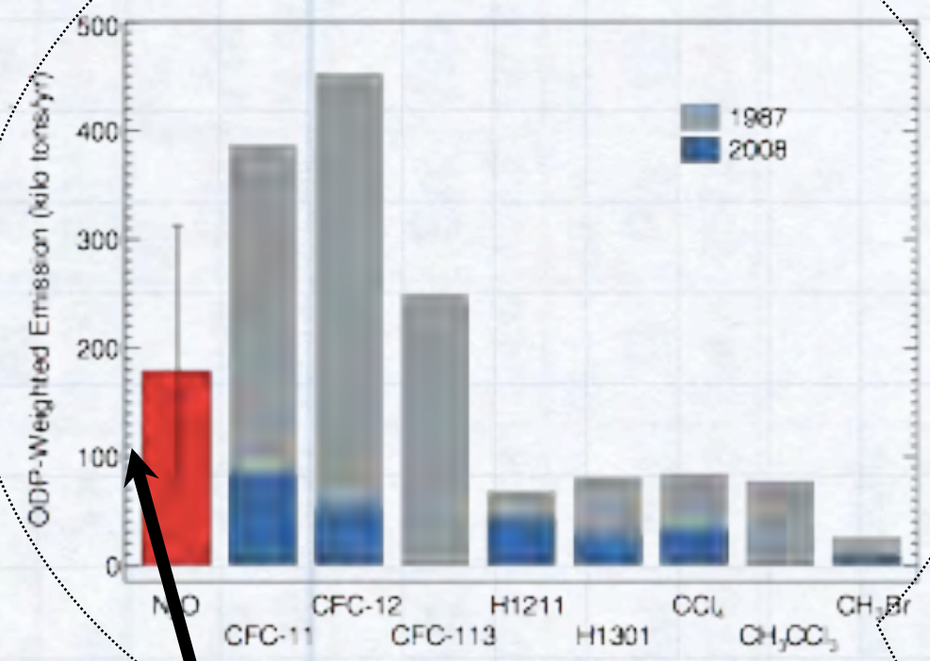

Fig. 1. Comparison of annual N_2O ODP-weighted emissions from the 1990s [IPCC, 2007 (*18*, *23*)] with emissions of other ozone-depleting substances in 1987, when the emissions of chlorine- and bromine-containing ODSs were near their highest amount, and for 2008. Emissions during 2008 were inferred from observations taken by the Global Monitoring Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration for CFC-11, CFC-12, Halon 1211 (H1211), Halon 1301 (H1301), and CH_3Br; all other emissions are taken from WMO (*3*). ODPs for all, except N_2O, are assumed to be the semi-empirical ODPs from WMO (*3*). Even at the height of ODS emissions in the 1980s, annual anthropogenic N_2O emissions were the fourth most important. Currently, anthropogenic N_2O emissions represent the largest contribution to ozone-depleting gas emissions. HCFC-22, the most important CFC replacement, would fall below the 1987 amount of CH_3Br for both time periods if included in the figure. The N_2O error bar represents a bottom-up uncertainty range. The lower end of the range is calculated by summing the lowest emissions estimates, and the higher end by summing the highest estimates, of the various individual sources provided by the IPCC (*18*).

The reasoning that leads to the author's conclusion is clearly presented.

An error bar is shown in the figure to estimate the uncertainty in measurement.

The evidence is presented in a figure and analyzed in the text.

An example from the scientific literature: Claim, Evidence, and Reasoning (cont.)

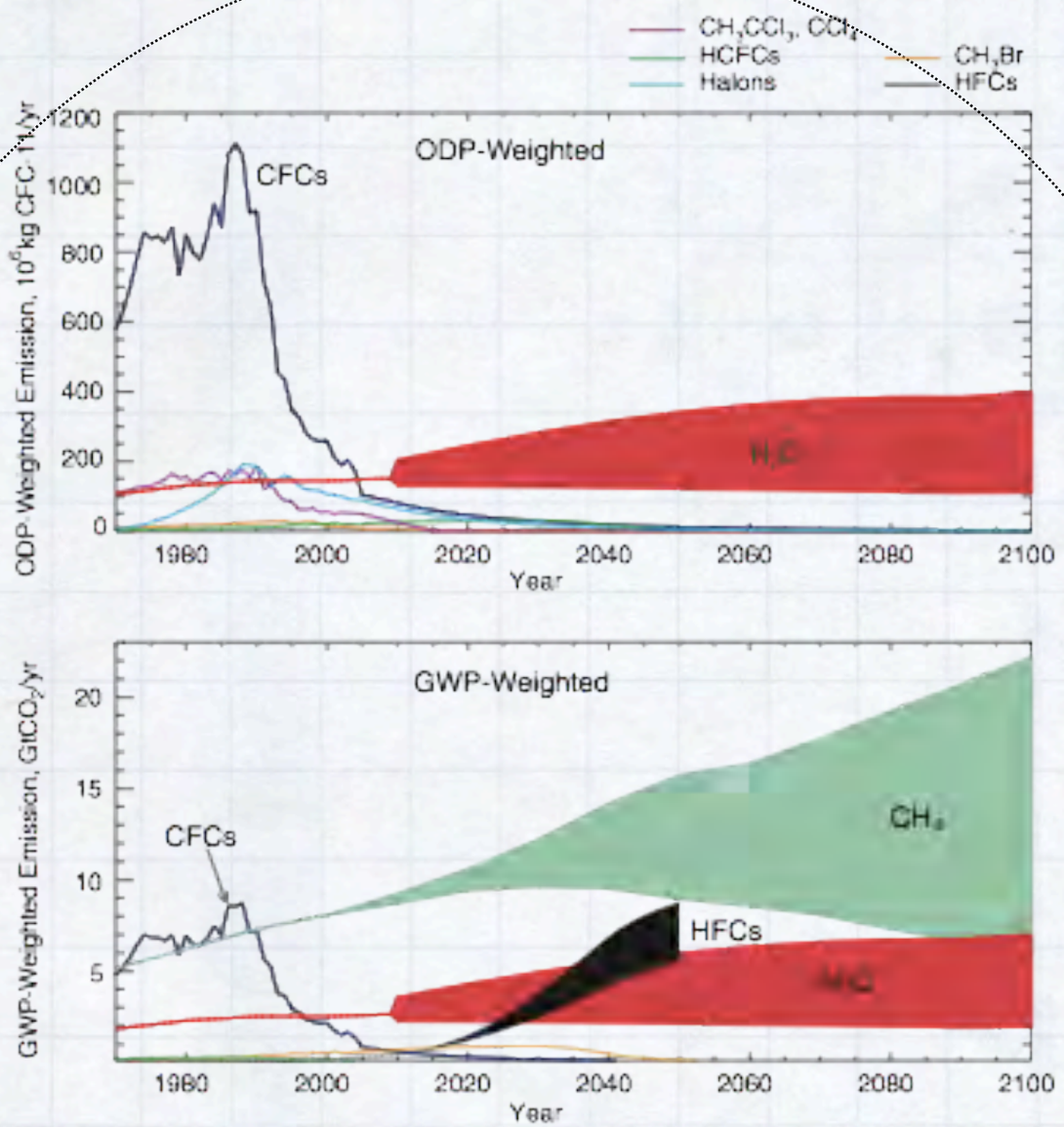

Fig. 2. Historical and projected ODP- and GWP-weighted emissions of the most important ODSs and non-CO_2 greenhouse gases. Non-N_2O ODS emissions are taken from WMO (*3*). Hydrofluorocarbon (HFC) projections are taken from Velders *et al.* (*24*), do not include HFC-23, and are estimated assuming unmitigated growth. The HFC band thus represents a likely upper limit for the contribution of HFCs to GWP-weighted emissions. CH_4 emissions represent the range of the Special Report on Emissions Scenarios (SRES) A1B, A1T, A1FI, A2, and B1 scenarios (*23*). The range of anthropogenic N_2O emissions is inferred from the mixing ratios of these same SRES scenarios [see (*13*) for details of calculation].

Evidence from other studies is used in graphic form to put this study into a scientific context.