

CTFP Final Report

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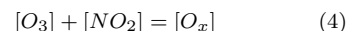
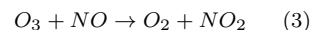
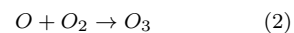
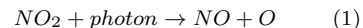
Introduction

Whether we like it or not, we are living in an increasingly data centric world, and the field of chemistry is no exception. An oft overlooked aspect of this is how exactly data (measurements, signals, etc) is transformed into information (trends, correlation) and finally into knowledge. Moreover, the explicit teaching of these concepts is often neglected resulting in increasing student frustration.[Schlotter, 2013] Motivated by this, and the need to transfer to a virtual laboratory environment as a result of Covid-19, we sought to develop a new, remote learning compatible, experiment for *CHM 135: Physical Principles*.

Experiment 1: The Chemistry of Air Quality is the results of our efforts. In this new experiment first-year students are introduced to fundamental data analysis concepts as they explore some of the chemistry of airborne pollutants.

Chemistry background

Since 1975 Environment and Climate Change Canada (ECCC) has been monitoring several airborne pollutants through the National Airborne Pollutant Surveillance (NAPS) program. Two of the key pollutants monitored are ozone (O_3) and nitrogen dioxide (NO_2), and whose interdependent diurnal cycles are expressed through equations 1 to 3, right. The relationship between O_3 and NO_2 is so intimate, atmospheric chemist have developed the term “odd oxygen”, O_x , as the sum of these two components (equation 4).[Kley et al., 1994] Lastly, the correlation between O_3 and NO_2 varies with environmental influences such as increased temperature and concentration of volatile organic compounds encountered during summer months. Trends and relationships between these chemical pollutants are captured in hourly NAPS data, and visualized by students.



Experiment workflow

Operationally, after an introductory pre-lab prepared by Dr. D'eon (with accompanying explanatory video and gas phase chemistry questions), each student analyzes one randomly assigned winter and summer data set from a pool upload and distributed through Quercus. Each data set comprises a 7-day snapshot of hourly O_3 and NO_2 con-

centrations as measured by a downtown Toronto monitoring station from the NAPS program.¹ The experiment instructions, and a supporting *Tip Sheet* on operations in Excel necessary for Experiment 1, guide students through the data analysis workflow made popular by Wickham and Grolemund.[Wickham and Grolemund, 2017]

¹ A more technical explanation of how NAPS data was subsetting for students can be found on page 6.

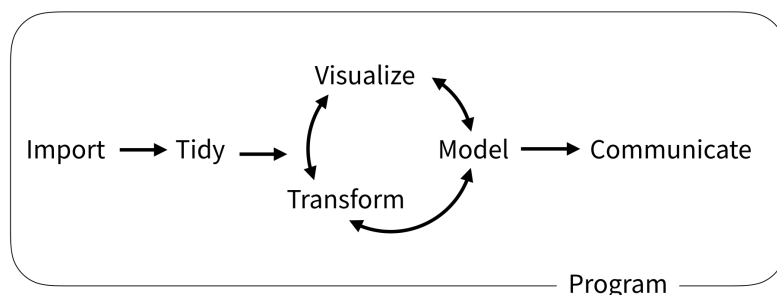


Figure 1: Data exploration/analysis workflow; figure from *R for Data Science* (2017)

Briefly, the experiment proceeds with students:

1. *Importing* their assigned comma separate values (.csv) data sets into Excel.
2. *Tidying* their data and setting up their worksheets. This step consist of formatting cells to properly display values and handling missing data.²
3. *Visualizing* their quantitative information through a time-series plot of time vs. concentration of pollutant.
4. *Transforming* their data using mathematical operators in Excel to calculate total oxidant and adding it to their time-series plot as well as calculating 8 hr moving averages.
5. *Modelling* a linear relationship between O₃ and NO₂ to qualitatively assess the negative relationship between these two contaminants.³
6. *Communicating* and exploring their results through a series of accompanying questions written by Dr. J. D'eon.

² Specifically, NAPS stores missing values as -999, but this value is literally interpreted by Excel, requiring removal before further data visualization/analysis.

³ This is accomplished using the “add trend line” function in Excel, although previous versions of the lab utilized the “linear regression” function of the *Analysis Toolpak*.

Expected student outcomes

Beyond the introduction to gas-phase and atmospheric chemistry, students are expected to learn the basics of data analysis and operations in Microsoft Excel through the Experiment and supporting *Tip Sheet*. Topics covered include: cell referencing, mathematical operators, *find and replace* functions, cell formatting, plotting, and summary statistics. While only touching the surface of data analysis, we believe

this list hits upon the most frequently used operations in Excel, and provides a solid base from which students can improve their understanding and skills on their own or in future laboratory classes.

Verification of student learning is assessed through the results of each student's data analysis. For each data set, students are expected to plot a time-series of pollutant concentration and a correlation plot of O_3 and NO_2 with linear regression (Figure 2A and 2B). Additionally they perform the same analysis on both the winter and summer data sets, illustrating the increasing complexity of atmospheric chemistry, visualized as a decrease in correlation in summer months (Figure 2C). Through their visualizations, students must answer a series of accompanying questions wherein they inquire about possible explanations for the differences in their winter and summer results. Any faults in a student's data analysis are readily apparent in their visualizations. For example, an errant '-999' value leftover from the NAPS data set is easily visible to the TA, whereas it may be lost in the summary statistics (i.e. mean) (Figure 2D). Lastly, every student data set that is generated is accompanied by a PDF answer sheet containing a time-series plot, correlation plots, and all summary statistics students are expected to perform. Consequently TAs can simply compare a student's analysis of a given data set against the accompanying answer sheet to quickly verify their work. How the answer sheets are generated is discussed below.

Lab Results

We were unable to introduce a survey to undergraduate students to explicitly explore their experiences and thoughts with Experiment 1. However, discussing Experiment 1 with the four laboratory TAs revealed two promising insights. Firstly, the TAs found that students' questions were largely related to lab content, and not the technical aspects of Excel. Secondly, student questions that did pertain to Excel were readily addressed by directing them to the supporting *Tip sheet* document.

Furthermore, after inspecting more than 300 student submitted figures, none had any critical flaws (either in visualization or data analysis). There were instances of several minor issues common to several student plots (i.e. adding a linear regression to a time-series plot), but these have been addressed in the updated Experiment 1 instructions and supporting *Tip Sheet* for the Fall 2020 session.

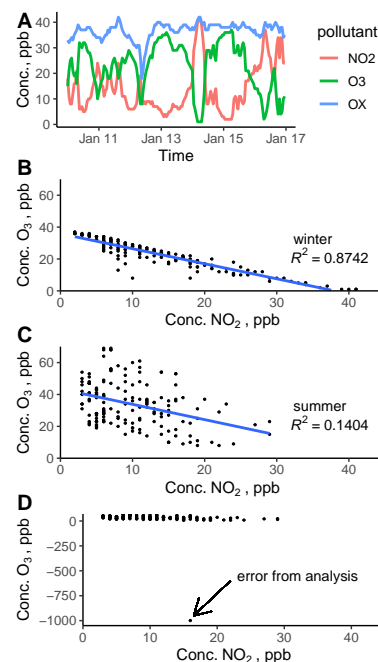


Figure 2: Example of plots students are expected to create. (A) time-series of pollutants across 7 winter days. (B) Correlation plot of O_3 and NO_2 concentrations with linear regression in the winter and (C) summer data sets. (D) Example plot if a '-999' value wasn't removed.

Implementation in the Fall Term

Experiment 1 is slated to be introduced in the upcoming Fall 2020 CHM 135 session, with an estimated >1500 enrolled students. Fortunately, the scope of the NAPS program and the readily scalable coding used to generate student data sets/answer sheets can easily cope with the increase in course participants. As well, a limitation of the summer session was that limitations in the Quercus setup practically limited the entire course to 15 winter and 15 summer data sets. This has been addressed in the upcoming session where each lab section will have its own unique pool of data sets from a unique NAPS monitoring station in Toronto. While we'd ideally like to assign each student with a unique data set, this approach best minimizes overlap in student analysis while remaining logistically practical within the existing Quercus infrastructure.

Future Directions & Personal Speculations

We believe the data analysis, numeracy, and graphicacy⁴ discussed in Experiment 1 will have a role in the CHM 135 laboratory curriculum beyond the Covid19 restrictions on in-person labs. Perhaps this may result in a computational “dry” lab similar to the one conducted in CHM 136, or in shifting the data analysis to student generated data sets (i.e. grouping all experimental results from one lab group together and have students analyze them individually).

Speaking of graphicacy and numeracy, many elements of statistical analysis, interpretation set statistical analysis results, useful Excel functions that did not make it into the lab, and extended discussions on graphicacy were produced for CHM 135. While many of these were removed to streamline the Experiment 1 *tip sheet*, it raises the question of construction an “in-house” reference for undergraduate chemistry students. Such a book can be easily created as a website containing common Excel tutorials in a chemistry specific context. Such a repository would relieve upper year teaching as faculty can simply reference the guidebook rather than individually writing instructions, and students would have a central guide for many of their data analysis questions. This could be fertile grounds for a future CTFP.

⁴ literacy is the ability to read and write; numeracy is the ability to understand and work with numbers; and graphicacy is the ability to understand and present information in the form of charts, graphs and other non-textual formats.

Stuff left on the cutting room floor

A surprisingly difficult aspect of creating Experiment 1 was deciding what *not to* include in the course. While we're largely satisfied with the present course, some of the elements could prove useful for

future iterations or upper year classes. These ideas can be readily re-integrated into the existing experimental framework if needed. Some of these ideas are briefly described below. We hope that they inspire readers for future versions of this lab.

- SO₂ is the main pollutant responsible for acid rain, and was regulated nationally in 1985 and provincially in 2007. Consequently, we wanted students to investigate if SO₂ levels have significantly decreased as a result of these regulations. NAPS data of SO₂ emissions cover more than 50 stations in Ontario and coverage extends as far back as 1975. While a great opportunity to discuss statistical significance, and readily executable in Excel, we struggled with exploring the larger chemistry of this phenomenon in a context appropriate to the CHM 135 course.
- The current lab utilizes the “add trend line” option in Excel. We had originally envisioned using the *Analysis Toolpak* which extends the linear regression beyond a line of best fit and R² to significance of the coefficients (slope) and ANOVA analysis. While the greater exploration of linear regression was promising, the statistical discussion is considered to be beyond first-year chemistry students.
- Building off of the last point, we had integrated historical ECCC weather data⁵ into the analysis. We envisioned students comparing the correlation of O₃ with NO₂ and with temperature (or other weather phenomena). This was abandoned for the present winter vs. summer approach.
 - There exists an opportunity to expand this component to multiple linear regression utilizing pollutant concentration and various weather readings, although this is more appropriate for an upper year environmental chemistry course.
- Since O₃ and NO₂ levels are largely affected by anthropogenic activity, we wanted to analyze the effects of the Covid-19 related “anthropause” on downtown Toronto levels.⁶ Unfortunately the NAPS data sets have a one year lag time to publication, and the live feed from the Ontario Ministry of the Environment⁷ requires either significant data collection from students or web-scraping. The former is unreasonable as the entire course could be derailed if the website goes down, and the latter is beyond the skills/contract hours of this humble TA.
 - This may be worth revisiting in upcoming years when the 2020 NAPS data set is released.

⁵ Hourly weather data downloadable here: <https://Toronto.weatherstats.ca/download.html>

⁶ See *Blue skies turn grey* in the Sep. 5, 2020 issue of *The Economist*, <https://econ.st/3bHD4Qv>

⁷ MOE real time air quality data can be found here: <http://www.airqualityontario.com/history/summary.php>

- The NAPS program spans the entirety of Canada. We explored comparisons between rural and urban NAPS measurements but found the discussion around regional variation in air quality quickly escalated beyond a CHM 135 appropriate discussion.

Source code and instructions for generating data sets

Generation of all of the data sets and their accompanying answer sheets are executed in R with prodigious use of the *tidyverse* and *Rmarkdown*. As it stands we can easily generate a unique pairing of summer/winter data sets for every student in the Fall 2020 session. The source code and example ECCC data, student data sets, and TA answer reports can all be found on GitHub.⁸

A more detailed description of the process is described in the Git Hub repo, but briefly:

1. ECCC hourly data for NO₂ or O₃ is subset based on a given reporting station; in the present iteration all measurements are from downtown Toronto in 2018.
2. Bilingual headers, ancillary columns, etc. are removed from the ECCC data set, dates are converted to Excel format, and the remaining data is transformed from the ‘wide’ matrix style to the ‘long’ columnar format for easier manipulation in Excel, see table 1.
3. A specified number of student data sets are generated from a 7-day moving window of the year-long data. I.e. data set 1 is January 1st to 7th, data set 2 is January 2nd to January 8th. A complimentary summer data set is taken starting from July 1st.
4. A “-999” error is inserted randomly into each student data set, ensuring each student encounters it.
5. Data sets are saved in a new folder as .csv files.
6. For each data set generated, an Rmarkdown script generates a PDF with the analysis results. TAs can compare the answer sheet to student submissions.

Again, all of this code is explained on the Git Hub repo. For the unawares, Git Hub provides hosting for software development, distribution version control, and source code management and is readily integrated into the RStudio environment. In practice, this means that the code used to automatically generate student data sets and answer keys is preserved online, and can be safely passed along from year to year thanks to version control. The Git Hub environment is ideal for introducing new components and removing old ones from the code thanks to version control, and provides an effective framework to ensure Experiment 1 can be readily changed in its future iterations.

⁸ Git hub repository with source code:
https://github.com/DavidRossHall/CHM135_Exp1Data

Table 1: Structure of student data sets

Date	NO2	O3
43110.00	18	15
43110.04	11	21
43110.08	8	-999
⋮	⋮	⋮
43117.00	12	20

Acknowledgements

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References

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