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Traditional and alternative delivery methods of general chemistry labs: environmental, monetary, and pedagogical comparisons

Sarah Steely
Western Washington University

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TRADITIONAL AND ALTERNATIVE DELIVERY METHODS OF GENERAL CHEMISTRY LABS: ENVIRONMENTAL, MONETARY, AND PEDAGOGICAL COMPARISONS

Accepted in Partial Completion
Of the Requirements for the Degree
Master of Science

Kathleen L. Kitto, Dean of the Graduate School

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MASTER’S THESIS

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Sarah Steely
November 17, 2012
TRADITIONAL AND ALTERNATIVE DELIVERY METHODS OF GENERAL CHEMISTRY LABS: ENVIRONMENTAL, MONETARY, AND PEDAGOGICAL COMPARISONS

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Sarah Steely
November 2012
ABSTRACT

The main objective of my study was to investigate and compare a traditional and alternative mode of general chemistry laboratory delivery using environmental, monetary, and curriculum comparisons. I conducted an environmental carbon footprint analysis of traditional laboratory experiments versus laboratory kit counterparts. A dollar cost assessment of the delivery modes was also calculated. Both the environmental and dollar costs were determined on a per student basis for each experiment evaluated. The results demonstrate that traditional experiments had higher carbon emissions than the kit experiments, and the kit experiments were more expensive per student than the traditional experiments when I accounted for both faculty and graduate teaching assistant instruction. My analyses were strongly influenced by the boundary conditions and assumptions used in the carbon emission and cost calculations, so the results are only valid for the specific conditions described within this thesis.

A review of the literature and a content analysis of the traditional and alternative laboratory delivery methods revealed that there was no clear evidence that one form of delivery was better at delivering a laboratory experience than the other in terms of student performance on exams or course grades. Both methods were also similar in the cognitive skills required of students. While the kits did not appear to be more appropriate at delivering a laboratory experience than traditional laboratories, they may offer an alternative for students who are unable to complete chemistry requirements in a more traditional setting. The literature review also revealed that there is a critical need for peer-reviewed studies with good experimental design to compare the effectiveness of a laboratory kit experience to a traditional laboratory experience.
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GLOSSARY OF TERMS

ALTERNATIVE DELIVERY METHODS: Other ways of delivering a chemistry laboratory experience outside of the traditional teaching laboratory setting (e.g. using laboratory kits).

BLOOM’S HEIRARCHY OF COGNITIVE SKILLS: The six major categories of skills in the cognitive domain. These are, in increasing order: knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom et al., 1956). Lower order cognitive skills comprise the former three, higher order the latter three.

CARBON FOOTPRINT: The amount of carbon dioxide (or carbon dioxide equivalents) emitted by an individual, organization, or activity.

CARBON DIOXIDE EQUIVALENTS (CO2-e): Emissions from other greenhouse gases (e.g. methane, nitrous oxide, ozone) that are based on their global warming potential in reference to carbon dioxide (USEPA, accessed Aug 14, 2012).

CLASSFINDER: Western Washington University’s online course database that contains information on all courses taught at WWU going back to Fall 2003.

COOKBOOK LABORATORY: A laboratory experiment in which students follow a procedure to arrive at a predetermined result.

CONTENT ANALYSIS: Please refer to Illustrative Verbs Analysis.

CONSTRUCTIVIST LEARNING THEORY: An individual will create new knowledge and understanding based off of their pre-existing understanding (Bransford et al., 2000).

CURRICULUM STUDY: In this thesis, a curriculum study is the comparison of the written materials (laboratory manuals) that are used to deliver the laboratory experiments. These manuals are evaluated and compared for cognitive skill use by students during the experiment.

DELIVERY METHOD: The way a laboratory is delivered to the student (e.g. traditional wet chemistry laboratory).

HYBRID LABORATORY: A blend of online course content and face-to-face laboratories.

ILLUSTRATIVE VERBS: A list of verbs compiled by Gronlund (1985) that are useful for stating specific learning outcomes in the six cognitive skill categories described by Bloom’s Hierarchy of Cognitive Skills.

ILLUSTRATIVE VERBS ANALYSIS: A method of evaluating what kinds of higher-order cognitive skills are targeted in a laboratory experiment by analyzing the wording of a
document (Domin, 1999). The document used here was the laboratory manual in context of what skills are targeted in laboratory experiments.

INQUIRY BASED LABORATORY ACTIVITIES: An active learning method that targets building observational, experimental and analytical skills by exploring a question or problem on their own, without following a predetermined procedure.

LABORATORY KIT: A kit that can contain materials and reagents used to conduct laboratories.

LABPAQ CK-S: The specific type of laboratory kit that was used in this thesis. It is manufactured by Hands-On Labs, Inc. (Englewood, CO) and contains 20 experiments that are analogous to first semester college general chemistry laboratories.

PEDAGOGY: The methods and practice of teaching, or the strategies and styles of teaching.

REMOTE LABORATORY: Laboratories where students connect to and manipulate actual analytical instrumentation via the Web.

SIMULATION LABORATORY: Graphic virtual representations (computer simulations) of laboratory experiments.

TECHNICAL AND MECHANICAL COMPLEXITY: The protocols, techniques, experimental procedures and calculations that are commonly used in the field of chemistry at both the instructional academic level and in chemistry careers (e.g. industry, academia, advanced research, etc.).

TRADITIONAL DELIVERY METHOD: The most common method of general chemistry laboratory delivery, which occurs in a laboratory on-campus at a set time(s) every week.

VIRTUAL LABORATORY: graphic representations of laboratory experiments with added levels of interactivity in which students actually “perform” an exercise or experiment.
1.0 INTRODUCTION
The main objective of my thesis was to compare traditional general chemistry laboratory experiments conducted at Western Washington University (WWU) to experiments in a commercially available general chemistry laboratory kit. Laboratory kits are an alternative method of delivering a laboratory experience for a general chemistry course. I calculated and compared the carbon emissions and the monetary cost per experiment (normalized on a per student basis) for select experiments from each delivery method. The curriculum materials of both laboratory delivery methods was also evaluated to determine if there was a difference in cognitive skill use by students performing the experiments. I used an illustrative verb analysis, which evaluates the laboratory manual content and identifies the specific categories of cognitive skills (as defined by Bloom et al., 1956) targeted by the laboratory activity. I also conducted a literature review to ascertain if laboratory kits have been successfully used as alternatives to traditional general chemistry laboratories.

The introduction to my thesis starts out with background information on general chemistry and the purpose of the laboratory in science learning. I will then introduce traditional and alternative general chemistry laboratory delivery methods, followed by a discussion of emissions regulations in the United States and carbon footprints of academic institutions. Finally, the importance of conducting a cost assessment of the laboratory delivery methods will be presented, and my research approach summarized.

1.1 General Chemistry Laboratory Courses
At most universities, the general chemistry series are introductory classes that cover a broad range of concepts. Unlike more advanced chemistry courses, students are introduced to a
wide array of foundation topics including atomic structure, stoichiometry, states of matter, thermodynamics, nuclear chemistry, electrochemistry, chemical kinetics and equilibria, and molecular structure and bonding. Typically, the introductory chemistry series includes laboratory sections that are separate from the class lectures (National Research Council, 2005).

The American Chemical Society believes that a general chemistry course curriculum should include knowledge of basic chemical concepts; strength in quantitative problem solving; adequate preparation for higher-level course work; maturation of students’ knowledge of chemistry; and application of mathematical skills (American Chemical Society, 2009). What concepts to present and how to do so in an effective order have been debated for decades (Cooper, 2010; Havighurst, 1929; Lloyd and Spencer, 1994).

The general consensus within the science and education community is that laboratories are an important component of science learning (Hofstein and Lunetta, 1982; 2004). The official position of the National Science Teachers Association (NSTA) is that “for science to be taught properly and effectively, laboratories must be an integral part of the science curriculum” (NSTA, accessed May 14, 2012). While the NSTA generally refer to laboratories in the context of a traditional laboratory environment, they do support virtual laboratories, which are one form of alternative laboratory delivery (NSTA, accessed May 14, 2012). The NSTA does not address other alternative laboratory delivery methods in their position statements.

The National Research Council (2005) states “laboratory experiences provide opportunities for students to interact directly with the material world (or with data drawn from the material world), using the tools, data collection techniques, models, and theories of
science.” The National Research Council also clearly defines the overall learning objectives for a laboratory experience as:

- enhancing mastery of subject matter
- developing scientific reasoning
- understanding the complexity and ambiguity of empirical work
- developing practical skills
- understanding the nature of science
- cultivating interest in science and interest in learning science
- developing teamwork abilities

They acknowledge that no single laboratory experience will address all of the objectives, but different experiences can be designed to address multiple learning objectives (National Research Council, 2005).

Many educators agree that students can benefit from engaging in laboratory activities (e.g., Hofstein and Lunetta, 1982). But what is the purpose of science laboratory experience itself? Does it serve to draw students into the exciting world of chemistry and to promote general science literacy? Is it hands-on experience with common techniques and protocols used by professionals in their fields? Is it to gain deeper conceptual understanding of the theories and ideas presented in the course? Is it a combination of those ideas: to teach the “tools of the trade” while also enhancing and supplementing the deeper conceptual understanding that the students should be getting out of the coursework? Does the science education community even have a consensus about the main objectives of a laboratory experience in undergraduate general chemistry courses?

The American Chemical Society states that “to learn chemistry, students must directly manipulate chemicals, study their properties and reactions, and use laboratory equipment and modern laboratory instruments” (American Chemical Society, 2009). Common outcomes from the general chemistry laboratory component should include competence in basic
laboratory skills such as laboratory safety, keeping a laboratory notebook, using electronic balances and volumetric glassware, preparing solutions, chemical measurements using pH electrodes and spectrophotometers, data analysis and report writing. More specifically, throughout the general chemistry laboratory series students should be:

- Anticipating, recognizing, and responding properly to potential hazards in laboratory procedures
- Keeping accurate and complete experimental records
- Performing accurate quantitative measurements
- Interpreting experimental results and drawing reasonable conclusions
- Analyzing data statistically, assessing the reliability of experimental results, and discussing the sources of systematic and random error in experiments
- Communicating effectively through written and oral reports
- Planning and executing experiments through the use of appropriate chemical literature and electronic resources
- Synthesizing and characterizing inorganic and organic compounds

These goals are more process and mechanical task oriented, and do not focus on the deeper conceptual learning that could also be occurring. Aspden (1973), as cited in Scanlon et al. (2002), and Toothacker (1983) have asserted manipulative and mechanical skills are the only skills specifically acquired through laboratory work.

The National Science Teachers Association (2007) states:

“...at the college level, all students should have opportunities to experience inquiry-based science laboratory investigations...All introductory courses should include labs as an integral part of the science curriculum. Laboratory experiences should help students learn to work independently and collaboratively, incorporate and critique the published work of others in their communications, use scientific reasoning and appropriate laboratory techniques to define and solve problems, and draw and evaluate conclusions based on quantitative evidence. Labs should correlate closely with lectures and not be separate activities. Exposure to rigorous, inquiry-based labs at the college level also is important because most teachers develop their laboratory teaching techniques based on their own college coursework laboratory experiences.”
Many of us are familiar with the overall format for chemistry laboratories in which students come to laboratory for a set time and perform “cookbook” style experiments. Once the experiment is finished (i.e. the student reaches a predetermined endpoint), the students analyze their data and answer questions in the manual or post-laboratory assignment. For some experiments, students go home and write up a laboratory report in which they describe their methods, results, and conclusions. This format for general chemistry laboratories exposes the student to many of the goals listed by the American Chemical Society, but it is not always clear whether this approach is an effective way to meet those goals.

In 1982, Hofstein and Lunetta conducted a literature review on the purpose of the laboratory in science education and found that the objectives for laboratories were basically the same as objectives for general science learning. They also found that there was a lack of information regarding the effect of laboratory instruction on student learning compared to other types of instruction (Hoffstein and Lunetta, 1982). While our knowledge of how people learn, and the importance of inquiry-based activities has increased (Bransford et al., 2000), there has not been systematic research showing that participating in laboratories provides a better method of learning than a classroom experience (Hofstein and Lunetta, 2004; Hofstein and Mamlok-Naaman, 2007; Tobin, 1990; Toothacker, 1983).

The National Research Council (2005) evaluated the research on high school laboratory experiences and concluded that there were slight improvements in student development of scientific reasoning and cultivation of interest after students participated in a laboratory experience. They also found that laboratories were no more or less effective than other forms of science instruction (e.g. readings, lectures, and discussions) with regards to student mastery of the content. Research on traditional laboratory experiences is
“methodologically weak and fragmented” which makes it difficult to draw clear conclusions (National Research Council, 2005).

The purpose and effectiveness of the laboratory in learning science is certainly a vast and contentious topic. The general consensus, both spoken and published, is that laboratories are important to the process of learning science, but they are only one of the many tools that can help students in their pursuit of scientific knowledge and understanding. The method of laboratory delivery is a tool that can be used to provide laboratory experiences in a variety of traditional and non-traditional learning environments.

1.2 Traditional General Chemistry Laboratory Delivery

General chemistry courses are conducted at all types of post-secondary institutions. Four-year colleges and universities, two-year institutions, and various online programs all offer some form of general chemistry. General chemistry laboratories conducted at two- and four-year institutions are similar in intent, design, and execution, and will be treated the same in my thesis.

I will use WWU in my study as an example of a four-year college and university general chemistry program. Western Washington University is a state funded, four-year university located in Bellingham, Washington. The Chemistry Department at WWU offers American Chemical Society approved chemistry and biochemistry majors (WWU Chemistry Department, accessed June 16, 2010), as well as coursework for students majoring in the life and physical sciences. The department emphasizes the importance of hands-on learning, and incorporates that into coursework. The Department’s mission statement is:
“To provide exceptional opportunities for students to learn chemistry and biochemistry through classroom, laboratory, and research experiences. Students participating in our program will master content, develop critical thinking and communication skills that will prepare them for professional careers as scientists, educators, health professionals, and scientifically literate citizens (WWU Chemistry Department, accessed June 16, 2010).”

This mission statement starts out by discussing the importance of learning in the classroom, laboratory, and through research. But many WWU students only take one class or the three-course general chemistry series. Chemistry is a foundation topic in biological and physical sciences. Students enroll in general chemistry for a variety of reasons. For some it is useful for their personal interest or academic pursuits. Others take it because it is required as part of their academic major or career choice (for example future scientists, health professionals, and educators).

Whatever the reason, large numbers of students take general chemistry each year while only a fraction move on to more advanced chemistry courses (Tables 1.2.1-1.2.2). For example, during the 2008-2009 academic year at WWU, 888 students enrolled in Chemistry 121 (the first course in the three course introductory series), whereas only 61 students took Analytical Chemistry (Chemistry 333), the first of the more advanced chemistry courses at WWU (Table 1.2.1). Similar patterns were apparent in the 2009-2010 academic year (Table 1.2.2).

At WWU the general chemistry series for science majors consists of three quarters of general chemistry (Chemistry 121: General Chemistry I, Chemistry 122: General Chemistry II, and Chemistry 123: General Chemistry III). General chemistry for non-science majors consists of one class, Chemistry 101: Chemical Concepts. There is a separate, required
laboratory component for each of the above courses (WWU Classfinder, accessed Aug 31, 2010). My thesis will focus specifically on the laboratory sections of the chemistry courses.

The general chemistry laboratories at WWU are delivered in the traditional way. Students meet once a week for three hours and conduct a “cookbook” laboratory experiment. In a “cookbook” approach, students are asked to follow directions and perform a procedure, obtain a correct, predetermined result (e.g. titration end point color change) and analyze their data by applying equations and following data analysis steps outlined in the laboratory or lecture. These laboratories are in high demand due to academic requirements for students, and therefore see a high throughput of students, particularly in Chem 121 (Table 1.2.1). In theory, this high demand for Chem 121 could be addressed by an alternative method of laboratory delivery.
Table 1.2.1: Student enrollment* for five chemistry courses** offered at Western Washington University during the 2008-2009 academic year.

<table>
<thead>
<tr>
<th>Quarter</th>
<th>CHEM 101</th>
<th>CHEM 121</th>
<th>CHEM 122</th>
<th>CHEM 123</th>
<th>CHEM 333</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2008</td>
<td>91</td>
<td>536</td>
<td>not offered</td>
<td>143</td>
<td>30</td>
</tr>
<tr>
<td>Winter 2009</td>
<td>88</td>
<td>259</td>
<td>341</td>
<td>not offered</td>
<td>31</td>
</tr>
<tr>
<td>Spring 2009</td>
<td>79</td>
<td>93</td>
<td>151</td>
<td>286</td>
<td>not offered</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>258</td>
<td>888</td>
<td>492</td>
<td>429</td>
<td>61</td>
</tr>
</tbody>
</table>

*Student enrollment data is from WWU’s Classfinder course database (WWU Classfinder, accessed Aug 31, 2010).
Table 1.2.2: Student enrollment* for five chemistry courses** offered at Western Washington University during the 2009-2010 academic year.

<table>
<thead>
<tr>
<th>Quarter</th>
<th>CHEM 101</th>
<th>CHEM 121</th>
<th>CHEM 122</th>
<th>CHEM 123</th>
<th>CHEM 333</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2009</td>
<td>not offered</td>
<td>641</td>
<td>45</td>
<td>173</td>
<td>29</td>
</tr>
<tr>
<td>Winter 2010</td>
<td>81</td>
<td>260</td>
<td>386</td>
<td>57</td>
<td>30</td>
</tr>
<tr>
<td>Spring 2010</td>
<td>60</td>
<td>190</td>
<td>134</td>
<td>337</td>
<td>not offered</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td>141</td>
<td>1091</td>
<td>565</td>
<td>567</td>
<td>59</td>
</tr>
</tbody>
</table>

*Student enrollment data is from WWU's Classfinder course database (WWU Classfinder, accessed Aug 31, 2010).

1.3 Alternative Laboratory Delivery Methods

I will use the term “alternative delivery method” to refer to alternative ways of delivering a chemistry laboratory experience outside of the traditional teaching laboratory setting.

Alternative laboratory delivery can occur in conjunction with a traditional face-to-face lecture component, or as part of an online course. Alternative laboratory delivery settings may include a traditional chemistry laboratory, a student’s home, or a classroom or laboratory that lacks the materials, funding, or infrastructure to conduct traditional general chemistry laboratories.

There are different ways the alternative laboratory experience can be delivered: through hybrid courses, computer simulations and virtual chemistry experiments, remote laboratories via Web-enabled technology, or the use of “homemade” or commercially available laboratory kits. Publications describing the methods and practices of bringing laboratory online are available for instructors who want to increase laboratory science accessibility (Cancilla and Albon, 2010; Jeschofnig and Jeschofnig, 2011), but these alternative delivery methods can also be used in a traditional laboratory setting or in conjunction with a traditional on-campus lecture. This section briefly explains the types of alternative delivery, and provides examples of the various alternative delivery methods.

1.3.1 Hybrid Courses

Hybrid chemistry courses are a blend of online course content (for the lecture) and face-to-face laboratories that are conducted on-campus. These laboratory components are often intensive weekend sessions that are packed full of experiments and other laboratory experiences (Kennepohl, 1996; 2007).
1.3.2 Computer Simulations and Virtual Chemistry Experiments

Computer simulations and virtual experiments are both computer-based methods of laboratory delivery. Simulations are generally graphic virtual representations, whereas virtual laboratories have added levels of interactivity in which students actually “perform” an exercise or experiment (Jeschofnig and Jeschofnig, 2011). Students conduct experiments virtually either in a web browser or through other software. For example, students at Whitman College (Walla Walla, WA) and elsewhere can conduct a virtual fetal pig dissection through Whitman’s Biology Department. Cartwright and Valentine (2002) describe a computer-based chemistry laboratory for conducting virtual titrations, while Georgiou et al. (2008) describe a web-based learning environment for simulated chemistry experiments.

Late Nite Labs offers virtual laboratory simulators for chemistry and biology (REACTOR™ and RADIANCE™, respectively). These are online simulations for high school, colleges and universities, and distance education. Examples of institutions that have used the software include University of Pennsylvania, California State University-Sacramento, Drexel University, Western Piedmont Community College, Eastern Oregon University, University of Wyoming, Western Carolina University, Oregon State University, and the University of Oklahoma (Late Nite Labs, accessed Sept 16, 2010).

OnlineLabs, LLC, is a company founded in 2009 by three chemistry professors at Oregon State University (OnlineLabs, LLC, accessed April 27, 2012). It provides online chemistry laboratories through their OnlineChemLabs software.

Woodfield et al. (2004) at Brigham Young University have successfully implemented virtual inorganic chemistry experiments (called Virtual ChemLab) that reportedly provide a realistic experience. They stress that the point of the Virtual ChemLab is not to teach a
technique; rather, the point is to focus on the process. They also argue that the technique itself should be experienced in a laboratory situation, but that the laboratory setting is not necessary to connect theory with practice or to teach critical thinking skills. But the authors state that if effectively used, the Virtual ChemLab provides practical experience and a realistic learning environment, teaches student the cognitive processes necessary in laboratory sciences, and reduces costs and environmental and safety considerations.

While there are many proponents for the use of virtual experiments, it is generally accepted that they are better as teaching tools incorporated into a more diverse curriculum. The American Chemical Society does not recognize computer simulations as equivalent replacements for laboratory experiments; however, they state that simulations “have the potential to be useful supplements” (American Chemical Society, 2009).

1.3.3 Remote Laboratories

Remote laboratories are when students connect to and manipulate actual analytical instrumentation via the Web. They can do this from home, classroom, or laboratory. Scanlon et al. (2004) describe the remote use of a spectrometer to analyze unknown chemicals. Albon and Hubball (2004) incorporated a remote gas chromatograph-mass spectrometer (GC-MS) laboratory into a newly re-designed pharmaceutical analysis class at the University of British Columbia.

The North American Network of Science Labs Online (NANSLO) is an example of a consortium that provides remote laboratories using robotic manipulation of samples. Students can perform laboratory experiments in biology, physics, geology and chemistry and interact
with technicians in the laboratory while manipulating the instruments. They can also interact with other student logged in on the same experiment (NANSLO, accessed Oct 25, 2012).

The PEARL project is a European Union funded project that developed a system of remote experiments and instrumentation for students in science and engineering (Colwell et al., 2002). The experiments and software interfaces were designed to be accessible and usable by people with disabilities.

Fischer et al. (2007) conducted a remote laboratory case study assessing inquiry learning with the use of the Massachusetts Institute of Technology’s Microelectronics WebLab. This remote laboratory allows students to control instrumentation to characterize microelectronic devices. Students perform experiments in real-time through the Internet. The authors used quantitative surveys and qualitative interviews and found that WebLab allowed students flexibility to learn at their own pace and time, making this approach an effective “instrument of learning.” Massachusetts Institute of Technology also has the iLab project where students can remotely conduct experiments in microelectronics, chemical engineering, polymer crystallization, structural engineering, and signal processing (MIT, accessed Oct 25, 2012).

Western Washington University’s Integrated Laboratory Network (ILN), operated by Scientific Technical Services (SciTech), is an example of a virtual laboratory that makes advanced analytical instrumentation available in the classroom and laboratory. The ILN instruments can be accessed and operated via the Internet from many locations including the classroom, a computer lab, at home, and from locations around the world. Web cameras allow the student to look around the laboratory and see the instrument in action, while the
SciTech technicians can be available to interact and give demonstrations via open-source video conferencing programs (ILN, accessed Nov 16, 2012).

Albon et al. (2006) published a case study that incorporated a remote access laboratory in a pharmaceutical analysis course using a GC-MS through the ILN. They evaluated learning through student surveys, faculty interviews, and examination scores. They did not find a difference in mean final examination scores between the class types, but there was an overall positive response, with 70% of students and 100% the faculty members reporting that the ILN improved student learning about the GC-MS.

1.3.4 Laboratory Kits

Laboratory kits come in a variety of types: kitchen chemistry laboratory kits, institution or instructor assembled laboratory kits, and commercial laboratory kits. With kitchen laboratory kits, students are provided with a laboratory manual and a list of materials to obtain (e.g. vinegar, baking soda). They may then conduct the laboratory experiments from home using the common household or consumer materials (Casanova et al., 2006).

Some laboratory kits are assembled by the instructors and checked out to students. Oliver and Haim (2009) describe an at-home digital design laboratory in an engineering course that used a hardware kit assembled by the instructors. Hoole and Sithambaresan (2003) created an analytical chemistry laboratory kit for teaching their Analytical Chemistry I and II courses via distance education through the Open University of Sri Lanka.

Kennepohl (1996) reported on one of the first home-study laboratories using a laboratory kit in North America. Students in the distance education first semester general chemistry at Athabasca University picked up their laboratory kit on the first day of the
laboratory session. They signed a safety pledge and took the kit home to do the laboratories on their own time. This method was used until 2007, at which point the laboratory kit was mailed to students cost-free (the university also covered return shipping) and without a deposit (Kennepohl, 2007). Students kept the laboratory kit for the duration of the laboratory and their grades were withheld until the kit was returned (99% of kits were returned). The kits were then restocked with consumables and reused for the next course of online students. The kit cost about $800 Canadian (or $680 U.S. in 2007 dollars) and contained all of the equipment and essential chemicals for the experiments, although some household ingredients and materials needed to be provided by the student.

Finally, laboratory kits can be purchased from commercial laboratory kit manufacturers such as Science Kit and Boreal Laboratories, eScience Labs, Quality Science Labs, and Hands-On Labs, Inc. These companies all target marketing towards institutions with increasing online course content, a shortage of laboratory space in the traditional setting, and those institutions facing budget cuts.

Science Kit and Boreal Laboratories (accessed April 2, 2012) provides custom laboratory kits with a K-12 target audience, while eScience Labs, Inc. (accessed April 2, 2012), has made high school and college level laboratory kits since 2008. Standard or custom made laboratory kits from eScience Labs are available for allied health, anatomy and physiology, biology, chemistry, environmental science, forensics, microbiology, physical science, and physics.

Quality Science Labs, LLC (accessed April 2, 2012) produces laboratory kits for college preparatory high school courses. For example, they market an Advanced MicroChem (microchemistry) kit for AP students and first year college chemistry, as well as a regular
college prep high school microchemistry kit that can either be for a classroom or individual. They also offer kits in physics, biology, physical science, earth science, and life science.

Hands-on Labs, Inc., (accessed April 2, 2012) manufactures laboratory kits under the brand name LabPaq. These laboratory kits cover a wide range of disciplines such as allied health, anatomy and physiology, biology, chemistry, earth science, environmental science, forensics, geology, microbiology, and physics. Hands-On Labs, Inc., also offers custom made kits that can be tailored for the particular needs of a course, and been producing college level general chemistry kits for almost 20 years. My thesis uses the LabPaq CK-S laboratory kit as the example of a typical laboratory kit that can be used in both traditional and non-traditional laboratory environments such as a student’s home.

1.4 Environmental Assessment

Measuring environmental impacts related to operational activities is becoming an important factor to consider in chemistry education. Carbon footprint analyses are a way of quantifying that environmental impact in terms of carbon dioxide emissions. These analyses are growing in importance and are useful tools for estimating the emissions associated with an individual or an organization. One aspect of my thesis is to investigate the carbon footprint associated with the traditional and alternative delivery of general chemistry laboratory experiments in an effort to quantify the environmental impact of these laboratory activities.

Calculating a carbon footprint is a common method of estimating an individual or organization’s greenhouse gas emissions. There are many carbon footprint calculators available on the Internet. Some well-known online calculators are Clean Air-Cool Planet, USEPA Household Emissions Calculator, USEPA Office Carbon Footprint Tool, The
Climate Registry, and The California Climate Action Registry. This section provides background on current emissions reporting guidelines in the United States and carbon footprinting at academic institutions.

1.4.1 Emissions Regulation in the United States

On Dec 7, 2009 the U.S. Environmental Protection Agency (USEPA) declared that greenhouse gases, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆), are a threat to public health and welfare now and in the future. Specifically, they determined that greenhouse gases can remain in the atmosphere for hundreds of years; the 38% increase of atmospheric CO₂ from pre-industrial levels to 2009 is anthropogenic in origin; and CO₂ is the most prevalent gas, mostly as a result of the combustion of fossil fuels (USEPA, 2009).

On October 30, 2009 the USEPA published a rule (40 CFR part 98) for the mandatory reporting of greenhouse gas emissions from large greenhouse gas emissions sources in the US (USEPA, 2011). Under this rule, direct greenhouse gas emitters, fossil fuel suppliers and industrial gas suppliers who emit 25,000 metric tons or more of carbon dioxide equivalent (CO₂-e) per year are required to report their emissions to the USEPA. While most small business fall below the reporting threshold, approximately 10,000 facilities (an estimated 85-90 percent of total US greenhouse gas emissions) will be required to submit annual emissions reports.

While current emissions reporting rules exist only for industrial and vehicle emissions (USEPA 2010a, 2010b, 2010c, 2011), academic institutions may one day be required to report carbon or other greenhouse gas emissions as federal regulations addressing climate
change are passed. It may be useful for new initiatives and existing programs to evaluate their environmental impact, particularly since economic and environmental costs can be directly related through energy consumption and natural resource use.

1.4.2 Carbon Footprint of Academic Institutions

The American College and University Presidents’ Climate Commitment (ACUPCC) is a group of colleges and universities that have made a commitment to eliminate net greenhouse gas emissions from designated campus operations. The ACUPCC functions “to promote the research and educational efforts of higher education to equip society to re-stabilize the earth's climate” (ACUPCC, accessed Sept 12, 2010). Its mission is to encourage the global move towards climate neutrality and sustainability by educating students and leading by example for the rest of society. Signatories to the ACUPCC agree to complete an emissions inventory of their institution, set a date by which they will be climate neutral, and immediately begin integrating sustainability into the daily actions of the institution (ACUPCC, accessed Sept 12, 2010).

Western Washington University signed the ACUPCC in 2007, and in 2010 WWU issued its Climate Action Plan. Western Washington University has committed to reducing its net greenhouse gas emissions (both direct and some indirect) to 36% below 2005 levels by 2020 and to achieve climate neutrality by 2050 (WWU, 2010). As part of the ACUPCC, WWU also had to complete an emissions inventory within two years of signing. This inventory was completed in 2007 (WWU, 2010), and showed that total greenhouse gas emissions from WWU were 41,136 metric tonnes of CO₂-e, or approximately 16 lb CO₂-e
per person per day for a campus population of 15,272 (WWU, 2010). Approximately three-quarters (76%) of the total emissions were from the steam plant and electricity purchases.

Like WWU, many other academic institutions have assessed their carbon footprint in conjunction with the ACUPCC. Over 1,600 greenhouse gas inventories have been submitted to the ACUPCC as of November 2012 (ACUPCC, accessed Nov 13, 2012). Carbon footprints on a smaller scale within an institution (e.g. for a department, a course, or a learning activity) are more difficult to find. As of May 2012, I found only one example of a carbon footprint for an academic department (Michigan State University’s Department of Mechanical Engineering, Douglass 2008). I could not find any examples of carbon footprints for chemistry courses or laboratory experiments.

Calculating the carbon footprint for chemistry laboratory experiments is timely and pertinent to WWU’s goal of reducing greenhouse gas emissions and becoming climate neutral. It is also a novel way of beginning to investigate exactly “how bad for the environment” chemistry laboratories actually are from a carbon footprint perspective.

1.5 Cost Assessment

Dollar costs will be used in my study as another mode of comparison between traditional and alternative laboratory delivery methods. The end goal is to determine the dollar cost per student of a traditional experiment versus one delivered via a laboratory kit.

A cost assessment can provide valuable information about the amount of money spent to deliver a general chemistry laboratory. This information can be used to establish a baseline dollar cost per student to run general chemistry laboratories. It can also help to determine
areas of potential cost savings, whether it is to the traditional laboratory delivery or by implementing an alternative delivery.

Public institutions in Washington State saw reductions in state funding as the 2011-2013 state budget proposed a further $630.7 million dollars in cuts to higher education (Gregoire, 2010). Departments and programs faced serious budget reductions or potential elimination, while vacant positions and other jobs were suspended or eliminated in an attempt to meet the budget shortfall. Public higher education institutions responded to these state funding cuts by decreasing operating budgets while increasing tuition.

Since a portion of the budget cuts have been passed on to students in Washington State in the form of tuition increases, and in light of dwindling state-funded resources, it may be beneficial to incorporate a laboratory kit component into the general chemistry laboratories if it would reduce costs without affecting the quality of education. The volume of students enrolled in introductory courses such as Chemistry 121 highlights the fact that there is great demand for these courses, regardless of the economic outlook. A cost assessment can help determine whether one mode of delivery is more cost effective than another. Cost is often a pivotal consideration when implementing a new teaching technique or restructuring the way a laboratory is conducted. If the laboratory kit is comparable in educational content and lower in overall cost, then it would be a reasonable alternative to the traditional laboratory class.

1.6 Research Summary

The purpose of my thesis is to investigate and compare a traditional method to an alternative method of teaching general chemistry laboratories. I will compare the laboratory delivery
methods by calculating their environmental impact and dollar cost. Both the environmental
and dollar costs will be determined on a per student basis for each experiment scrutinized.
Environmental impact of laboratory courses is often thought about but rarely determined
aside from focusing on chemical waste disposal. My project will quantify the environmental
impact of traditional and alternative laboratory experiments using a carbon footprint analysis.
My project is unique in that it is the first to quantify carbon emissions stemming from
laboratory experiments on a per student basis.

An illustrative verb analysis will be used to compare the laboratory manual content of
select experiments from each delivery method. This technique evaluates what types of
cognitive skills are targeted in the laboratory experiment by analyzing the usage of specific
verbs associated with the six different categories of skills in the cognitive domain as defined
by Bloom et al. (1956). The comparison of curriculum materials will ascertain if there is a
difference between delivery methods in the cognitive skills demanded of students during the
experiments. Finally, I will conduct a literature review to ascertain if there is published
research demonstrating that laboratory kits are suitable alternatives to the traditional general
chemistry laboratory experience.
2.0 METHODOLOGY

The primary goal of my project was to compare two methods of general chemistry laboratory delivery using a carbon footprint, cost comparisons, a literature review, and a curriculum study. In the traditional scenario, a student (Student A) is taking a traditional wet chemistry laboratory as part of their on-campus chemistry course. In the alternative scenario, Student B is using a laboratory kit to conduct laboratory experiments at home. The four main questions I asked were:

- What is the difference in carbon emissions per student between the delivery methods?
- What is the difference in cost per student between the delivery methods?
- Is there a difference in laboratory manual content, in terms of cognitive skills required of the student, between delivery methods?
- Have laboratory kits been successfully implemented as alternatives to the traditional laboratory experience?

Cost (either carbon or monetary) was calculated for each experiment and normalized per student with adjustments for when students were working in pairs or alone. This means these comparisons between delivery methods are on a per student per experiment basis. The laboratory manual content was compared using an illustrative verb analysis (Domin, 1999) to assess the types of cognitive skills utilized by the student during the laboratory. I also conducted a literature review to ascertain if laboratory kits have been successfully used as alternatives to traditional laboratories.

Part of my thesis is loosely based on a re-interpretation of raw data collected by two undergraduate researchers, Douglas Naftz and Andrea Thomas, during Summer 2009. Their project investigated the feasibility and potential of improving laboratory learning by using laboratory kits in conjunction with remote laboratory instrumentation at WWU’s Integrated
Laboratory Network (ILN). They investigated three different scenarios in which the use of laboratory kits and remote laboratories replaced traditional wet laboratories and compared them to the traditional wet laboratory in terms of cost and carbon footprint. These scenarios involved students working with laboratory kits and remote instrumentation in either a classroom, their dorm room, or in off-campus housing. Environmental and monetary costs were ascertained for experiments in the various scenarios. They reported their findings in a final report entitled “Investigating Alternative Methods to Traditional Laboratory-Based Science Education; Use of Lab Kits and Remote Instrumentation via the Integrated Laboratory Network Project (ILN).” I had access to this report as well as all of their raw data, Excel spreadsheets, and other documentation. Their carbon footprint and cost analysis results were presented as yearly totals for the various scenarios they investigated.

I took a different approach to the project by focusing on alternative delivery with a laboratory kit in only one alternative scenario, an off-campus kitchen. Naftz and Thomas (2009) investigated the feasibility of implementing remote laboratories conducted using the ILN in conjunction with prepackaged laboratory kits in a classroom, a dorm room, and a kitchen. I assumed that the student is taking a lecture course on-campus and the laboratory off-campus using a laboratory kit; in the traditional scenario both lecture and laboratory are conducted on-campus with WWU’s general chemistry curriculum as an example. A list of all of the assumptions made for this project can be found in Appendices A and B.

Unless otherwise stated, I used the raw data that Naftz and Thomas collected. This includes (but is not limited to) information such as WWU’s yearly steam production and use, the number of lights in the chemistry laboratories, the power drawn by various electronics in the laboratory, average kitchen size. I also used the values they obtained for costs and
emissions per unit for natural gas and electricity, as well as the custom value for emissions stemming from WWU’s steam plant operation. Information they collected from personal interviews with individuals such as F. Scott Wilkinson and Gary Carlton, chemistry department employees, was also incorporated into my project; this information is mostly in the form of Excel spreadsheets that breakdown the costs and supplies needed to prepare the general chemistry laboratories. I also used laboratory manuals and preparer guides that were collected by Naftz and Thomas from the Chemistry Department in digital format, as well as the same laboratory kit and manual that they investigated.
2.1 Laboratory Kit Selection

The LabPaq CK-S laboratory kit was used in this project as a laboratory kit representative of commercially available kits commonly used in conjunction with general chemistry courses. It is manufactured by Hands-On Labs, Inc., in Englewood, CO (Hands-On Labs, Inc., accessed Sept 21, 2010). The CK-S laboratory kit was chosen from a variety of in-home chemistry kits that were available at Scientific Technical Services at WWU. Table 2.1.1 provides a summary of those chemistry kits.

The LabPaq CK-S was used by Naftz and Thomas (2009) in their original assessment, which was part of a larger project associated with the ILN at WWU. The ILN was created as part of a proof-of-concept project that was funded by a grant from the National Science Foundation Division of Undergraduate Education’s Course, Curriculum and Laboratory Improvement program (NSF-DUE-CCLI). A business model was evaluated as part of this grant. The business model included the creation of products such as laboratory kits that would be used in conjunction with the analytical instrumentation of the ILN, or with ILN support, to conduct remote laboratory experiments.

In 2009, the ILN was used to investigate various types of laboratory kits that are commercially available to gather information to possibly develop an ILN-based laboratory kit in partnership with Hands-On Labs, Inc. Naftz and Thomas (2009) used the LabPaq CK-S in their assessment because it was a college level general chemistry kit that was commercially manufactured by Hands-On Labs, Inc., and was available at SciTech.

According to the laboratory manual, the LabPaq CK-S is a series of “micro- and small-scale experiments designed to augment any first semester college or advanced high school level chemistry course” (Jeschofnig, 2008). The LabPaq CK-S is designed to provide
general chemistry laboratories to learners who do not have access to a formal laboratory setting (i.e. online students or students in learning centers without laboratories). It contains 20 experiments covering a variety of concepts. The kit includes an electronic laboratory manual on a CD, equipment including a digital scale, and over 120 individually packaged chemicals. It was designed to be conducted in a non-laboratory setting in conjunction with an introductory chemistry course. The preface for the laboratory manual encourages students to visit the nearest formal laboratory to get a general facilities tour and safety instruction to relate better to the experiments they will perform with the laboratory kit (Jeschofnig, 2008).
Table 2.1.1: A summary of the various laboratory kits ordered by STS-ILN in 2009. Prices include shipping and tax, if applicable.

<table>
<thead>
<tr>
<th>Kit name</th>
<th>Manufacturer*</th>
<th>Price</th>
<th>Number of Students</th>
<th>Purpose</th>
<th>Types or Number of Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intro to Organic Chemistry Microchemistry Kit</td>
<td>Carolina Biological Supply</td>
<td>$69.72</td>
<td>30 students working in pairs (15 groups)</td>
<td>Introduction to organic chemistry</td>
<td>Students study 5 types of organic compounds (alkanes, alkenes, alcohols, aldehydes, and carboxylic acids)</td>
</tr>
<tr>
<td>Synthesis of Aspirin Microchemistry Kit</td>
<td>Carolina Biological Supply</td>
<td>$40.90</td>
<td>30 students working in pairs (15 groups)</td>
<td>Aspirin synthesis and related experiments</td>
<td>Compare properties of acetylsalicylic acid and salicylic acid, extract salicylic acid from willow bark, synthesize aspirin from the extract, compare purity to aspirin tablets brought from home</td>
</tr>
<tr>
<td>The Award-winning MicroChem Kit</td>
<td>Quality Science Labs, LLC</td>
<td>$224.95</td>
<td>Individual (with enough material to do each experiment five times)</td>
<td>Full year of high school chemistry laboratories</td>
<td>17 experiments at the micro-scale level</td>
</tr>
<tr>
<td>CHEM C3000 Chemistry Experiment Kit</td>
<td>Thames &amp; Kosmos, LLC</td>
<td>$121.90</td>
<td>Individual student aged 12 and up</td>
<td>Prepare student for high-school or college level chemistry</td>
<td>387 experiments from over 50 topics</td>
</tr>
<tr>
<td>LabPaq CK-S</td>
<td>Hands-On Labs, Inc.</td>
<td>$289.34</td>
<td>Individual</td>
<td>Perform 20 college level chemistry experiments at home or elsewhere</td>
<td>20 experiments</td>
</tr>
</tbody>
</table>

2.2 Equivalent Laboratory Experiment Selection

I chose laboratory experiments in the LabPaq CK-S and WWU’s general chemistry curriculum that had similar student expectations and learning goals, as well as similarities with experimental setup and levels of technical and mechanical complexity. I defined “technical and mechanical complexity” as the protocols, techniques and experimental procedures and calculations that are commonly used in the field of chemistry at both the instructional academic level and in chemistry careers (e.g. industry, academia, advanced research, etc.). To help determine similarities in student expectations and learning goals, I listed the learning objectives for the experiments and read through the manuals to evaluate the experimental procedure. The LabPaq manual contains a list of pre-defined learning objectives for the experiments (Appendix C). Appendix D lists the learning objectives for the WWU laboratory experiments used in my thesis. Not all of the laboratory experiments from either delivery method’s curriculum were used in this project.

The WWU learning objectives were a combination of objectives defined in the manual and from the teaching practicum for new chemistry graduate teaching assistants, or based on my personal experience teaching the general chemistry labs (Chem 121, 122 and 123) and reviewing the manuals (Chem 101). During the 2010-2011 academic year I taught six sections of Chem 121, two sections of Chem 122, and one Chem 123 section. Some of the laboratory experiments used in the original data collection during the summer of 2009 have since been changed or omitted, so I used the manuals collected by Naftz and Thomas in 2009 for my thesis (with one exception discussed in Section 2.5.2).

The majority of the laboratories I selected for comparison (Table 2.2.1) were also used by Naftz and Thomas. There were differences, however, in that some of their laboratory
choices were not ideal fits for direct comparison due to weak similarities between the learning objectives and the experimental techniques utilized. There are three equivalent laboratories for the introductory non-science major chemistry course (Chem 101), four equivalent laboratories for first quarter general chemistry (Chem 121), and three equivalent laboratories for second quarter general chemistry (Chem 122).

In selecting laboratory courses and experiments to compare, I found that there were no laboratories in Chem 123 that fit with the LabPaq curriculum. The Chem 123 laboratory experiments focus primarily on techniques such as titration, precision and accuracy in measurements, and calculations involving stoichiometry. It is also the most advanced of the general chemistry series because it is the third and final course. Therefore, it is not surprising that the laboratories have a different, more advanced focus than the LabPaq laboratories, especially because the LabPaq CK-S is mostly meant to provide laboratories for a first-semester general chemistry course.
<table>
<thead>
<tr>
<th>WWU Course</th>
<th>Experiment Title</th>
<th>LabPaq Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Determination of fat in chips</td>
<td>#10: Caloric Content of Food</td>
</tr>
<tr>
<td></td>
<td>Measurement and density</td>
<td>#2: Lab Techniques &amp; Measurements</td>
</tr>
<tr>
<td></td>
<td>TLC analysis of analgesic drugs</td>
<td>#15: Chromatography of Food Dyes</td>
</tr>
<tr>
<td>121</td>
<td>Introduction to measurements</td>
<td>#2: Lab Techniques &amp; Measurements</td>
</tr>
<tr>
<td></td>
<td>Solutions and dilutions</td>
<td>#14: Beers Law and Colorimetry</td>
</tr>
<tr>
<td></td>
<td>Analysis of Vinegar</td>
<td>#16: Titration for Acetic Acid in Vinegar</td>
</tr>
<tr>
<td></td>
<td>The nine solution problem</td>
<td>#8: Ionic Reactions</td>
</tr>
<tr>
<td>122</td>
<td>Bleach analysis</td>
<td>#11: Determination of Water Hardness Using a Titrator</td>
</tr>
<tr>
<td></td>
<td>Synthesis of copper sulfate pentahydrate</td>
<td>#9: Stoichiometry of a Precipitation Reaction</td>
</tr>
<tr>
<td></td>
<td>Reaction of crystal violet with NaOH: A kinetic study</td>
<td>#17: Reaction Order and Rate Laws</td>
</tr>
</tbody>
</table>
2.3 Carbon Footprint Comparisons

The purpose of the carbon footprint comparisons between the WWU and LabPaq laboratory experiments was to get an idea of how the delivery methods compare in terms of carbon emissions. The carbon emissions were calculated as either carbon dioxide or carbon dioxide equivalent (CO$_2$-e) emissions per student per experiment. Carbon dioxide equivalents are the emissions from other greenhouse gasses (e.g. methane, nitrous oxide, ozone) and are based on their global warming potential in reference to carbon dioxide (USEPA, accessed Aug 14, 2012).

I initially used the carbon footprint estimation tiers described by Matthews et al. (2008) to determine the boundaries and scope of my carbon footprint assessment (Table 2.3.1). Matthews et al. (2008) estimate that industry emissions from direct operations and energy inputs (Tiers 1 and 2) only account for about 26% of total company emissions. Therefore, to estimate the carbon footprint accurately, supply chain and the product life-cycle emissions (Tiers 3 and 4) also need to be included; otherwise, the carbon footprint is vastly under-reported.

Based on extensive literature searches, it does not appear that there are and published calculations showing the carbon footprint for chemistry laboratory experiments. Because of this, I used the estimation tier guidelines for the production of goods and services, which target business and industrial emissions. While not directly applicable to my objectives, this approach provided a good starting point for considering what types of emissions to include for carbon footprint analysis related to chemistry laboratory experiments. The “service” that this estimation revolves around is a chemistry laboratory experiment conducted in a traditional, on-campus setting (WWU chemistry labs) or in an alternative, at-home setting.
(LabPaq laboratory kit). The “company” is defined as either WWU’s chemistry laboratories or the student’s home.

Clearly defined “boundary conditions” were the first important step in building the carbon footprint. I decided to start from the moment WWU or the student purchases the service or good that goes into the laboratory experience. The carbon footprint would therefore begin with the shipping of chemical reagents and supplies or the laboratory kit to WWU or the student, and end with disposal of the waste generated from the experiment. I then used the estimation tiers to classify the various emissions associated with the laboratory experiments.

It is very complicated to track the entire supply chain and to follow the “service” (the laboratory experiment) from cradle to gate. To account for everything, I should take into account the entire supply chain and life-cycle emissions for all of the chemicals and materials that go into the laboratory experiments. This would include manufacturing emissions. However, this is a vast undertaking and was outside the scope of my project.

I also consulted online carbon footprint calculators and frameworks to get an idea of what is commonly included in carbon footprinting. The California Climate Action Registry (which closed in December 2010) and The Climate Registry (which now covers all of North America) were two of my main sources (California Climate Action Registry, 2009; The Climate Registry, accessed April 28, 2012). The California Climate Action Registry contained an online reporting tool, the Climate Action Registry Online Tool (CARROT), and a reporting protocol manual that outlined the steps needed to complete a full assessment of greenhouse gas emissions (California Climate Action Registry, 2009).
The emissions from the various tiers were calculated in pounds of carbon dioxide equivalents (lb CO$_2$-e) per student per experiment to allow direct comparison across delivery types. The emissions that I considered, with respect to the emission tiers described by Matthews et al. (2008) are shown in Table 2.3.2. The following emissions were not included in either scenario due to limited data availability, complexity of calculations, or negligible emission quantities:

- student and personnel transportation emissions (Tier 1)
- communication, network, and data storage servers (Tier 2)
- supply chain emissions (Tier 3)

The emissions conversion rate of 1.04 lb CO$_2$-e per kWh of electricity (PSE, 2009) was used for both scenarios. My assumptions for the analysis are listed in Appendices A and B.
Table 2.3.1: Carbon footprint estimation tiers as suggested by Matthews et al. (2008).

<table>
<thead>
<tr>
<th>Carbon Footprint Estimation Tiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 1: Emissions directly from company operations</td>
</tr>
<tr>
<td>Tier 2: Emissions from energy inputs to company operations</td>
</tr>
<tr>
<td>Tier 3: Entire supply chain emissions for a good or service (cradle to gate emissions)</td>
</tr>
<tr>
<td>Tier 4: Total life-cycle emissions for production (Tier 3) plus delivery, use, and end-of-life</td>
</tr>
</tbody>
</table>
Table 2.3.2: Carbon footprint estimation tiers as suggested by Matthews et al. (2008) and the emissions included in this thesis.

<table>
<thead>
<tr>
<th>Carbon Footprint Emissions Considered</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tier 1:</strong> Emissions directly from company operations</td>
</tr>
<tr>
<td>• Emissions from paper usage (both scenarios)</td>
</tr>
<tr>
<td>• Personnel and student transportation emissions (not included)</td>
</tr>
<tr>
<td><strong>Tier 2:</strong> Emissions from energy inputs to company operations</td>
</tr>
<tr>
<td>• Laboratory or home infrastructure emissions (lighting, heating, balances, computers, fume hoods, printers, servers)</td>
</tr>
<tr>
<td>• Heat and compressed air (traditional), home heating (alternative)</td>
</tr>
<tr>
<td>• Electricity to power the fume hoods, top-loading and front-loading electronic balances, laboratory lights, computers, computer monitors, and printers in standby mode (traditional)</td>
</tr>
<tr>
<td>• Electricity to power lights, active and standby laptop use, printer in standby mode (alternative)</td>
</tr>
<tr>
<td>• Electricity for printing laboratory manuals (both scenarios)</td>
</tr>
<tr>
<td>• Electricity for communication, network, and data storage servers (not included)</td>
</tr>
<tr>
<td><strong>Tier 3:</strong> Entire supply chain emissions for a good or service (cradle to gate emissions)</td>
</tr>
<tr>
<td>• Shipping emissions of materials (traditional), shipping emissions of laboratory kit (alternative)</td>
</tr>
<tr>
<td>• Supply chain emissions (not included)</td>
</tr>
<tr>
<td><strong>Tier 4:</strong> Total life-cycle emissions for production (Tier 3) plus delivery, use, and end-of-life</td>
</tr>
<tr>
<td>• Hazardous waste disposal (traditional)</td>
</tr>
</tbody>
</table>
2.3.1 Carbon Footprint of Traditional Laboratory Experiments at WWU

Heat, Hot Water and Compressed Air Generation

Western Washington University heats its buildings with an on-site steam plant that burns natural gas to create steam. The steam plant runs around the clock and provides campus buildings with space heat and hot water, compressed air for building control and laboratory space use with an output capacity of 253,000 pounds of steam per hour (WWU Facilities Management, accessed April 23, 2012).

The yearly Chemistry Building emissions per square foot were calculated according to Equation 1. The resulting value was used in Equation 2 to calculate the CO$_2$-e per student per experiment. Total chemistry building natural gas use (in cubic feet) for calendar year 2008 was calculated by adding the monthly consumption from January through December 2008. This information was taken from the Facility Management monitoring data (Bailey, 2009; as cited by Naftz and Thomas, 2009). The pounds of CO$_2$-e per therm was calculated by Dr. Daniel Hagen of WWU’s College of Business and Economics and accounts for specific efficiency factors of WWU’s steam plant (Hagen, 2009; as cited by Naftz and Thomas, 2009).

\[
\text{lb CO}_2 - e\ ft^{-2}\ year^{-1} = \frac{\text{Natural Gas Use (ft}^3\cdot\text{year}^{-1})}{100\ ft^3\cdot\text{therm}^{-1}} \ast 11.5\ \text{lb CO}_2 - e\ \cdot\ \text{therm}^{-1} \ast \frac{\text{Chemistry Building Area (ft}^2)}{\text{Chemistry Building Area (ft}^2)}
\]

\[
\text{lb CO}_2 - e\ student^{-1}\ experiment^{-1} = \frac{\text{lb CO}_2 - e\ \cdot\ ft^{-2}\cdot\ year^{-1} \ast \frac{\text{CB 210 Area (ft}^2)}{8765.8\ \text{hours}\cdot\text{year}^{-1} \ast 3\ \text{hours experiment}^{-1}} \ast \frac{3\ \text{hours experiment}^{-1}}{24\ \text{students}}}{24\ \text{students}}
\]
The building square footage was taken from WWU's Facilities Management Website and the teaching laboratory square footage was estimated from the chemistry building floor plans (WWU Office of Facilities Development & Capital Budget, accessed Sept 11, 2011). The general chemistry teaching laboratories are Chemistry Building (CB) 210 and CB 220. Using these values in Equations 1 and 2 resulted in emissions of 0.167 lb CO₂-e per student per experiment:

\[
0.167 \text{ lb CO}_2 - e \text{ student}^{-1} \text{ experiment}^{-1} =
\]

\[
\frac{4,257,566.56 \text{ ft}^3 \cdot \text{year}^{-1}}{100 \text{ ft}^3 \cdot \text{therm}^{-1}} \cdot \frac{11.5 \text{ lb CO}_2 - e \cdot \text{therm}^{-1}}{72,574 \text{ ft}^2} \cdot \frac{1,734 \text{ ft}^2}{8,765.8 \text{ hours} \cdot \text{year}^{-1}} \cdot \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students}}
\]

**Fume Hoods**

The emissions stemming from fume hood use were calculated using the yearly electrical consumption (in kWh), an emissions conversion factor of 1.04 lb CO₂-e per kWh, and the assumption that there were 24 students in the laboratory and each experiment was three hours long (two hours for Chem 101; Equation 3).

\[
0.877 \text{ lb CO}_2 - e \text{ student}^{-1} \text{ experiment}^{-1} =
\]

\[
59,135 \text{ kWh} \cdot \text{year}^{-1} \cdot \frac{1.04 \text{ lb CO}_2 - e}{\text{kWh}} \cdot \frac{\text{year}}{8,765.8 \text{ hours}} \cdot \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students}}
\]

The yearly fume hood electrical consumption (in kWh) was calculated using the online energy calculator provided by the Lawrence Berkeley National Laboratory (accessed Sept 17, 2010). Naftz and Thomas (2009) collected the input parameter data (e.g. fume hood velocity,
dimensions, number of hoods) in the summer of 2009 and calculated the total yearly
electrical consumption. I could not verify these values for fume hood emissions because
Naftz and Thomas did not include all fume hood parameters in their documentation

Analytical Balances

The emissions per student per experiment from electricity used by the electronic balances
were calculated using Equations 4 and 5. First, the emissions per student were calculated
using the power rating of the balance, the number of balances per 24 students, and the
electricity conversion factor (PSE, 2009).

\[
lb \ CO_2 - e \ student^{-1} = \frac{Wh \ balance}{# \ balances \ 24 \ students} \frac{kWh \ balance}{1000 \ Wh} \frac{1.04 \ lb \ CO_2 - e}{kWh}
\]

Because a power rating of Wh means that for every hour the balance is running it is drawing
1 watt per hour, the emissions must be multiplied by 3 to account for the three-hour
experiment (Equation 5).

\[
lb \ CO_2 - e \ student^{-1} \ experiment^{-1} = lb \ CO_2 - e \ student^{-1} \ hour^{-1} \ \frac{3 \ hours}{experiment}
\]

The top-loading balances drew 10 watts, and the front-loading balances used 9 watts. There
were two top-loading and four front-loading balances per 24 experiments, and each
experiment lasted three hours (two hours for Chem 101). The wattage rating and number of balances was recorded by Naftz and Thomas (2009).

The top-loading balance emissions were $2.6 \times 10^{-3}$ lb CO$_2$-e per student per experiment, and the analytical balance emissions were $4.7 \times 10^{-3}$ lb CO$_2$-e per student per experiment. An example calculation for the top-loading balance is as follows:

$$2.6 \times 10^{-3} \text{ lb CO}_2 - \text{e student}^{-1} \text{ experiment}^{-1} =$$

$$\frac{10 \text{ Wh}}{\text{balance}} \times \frac{2 \text{ balances}}{24 \text{ students} \cdot \text{hour}} \times \frac{kWh}{1000 \text{ Wh}} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{kWh} \times \frac{3 \text{ hours}}{\text{experiment}}$$

**Lighting**

The emissions from laboratory lighting electricity use were calculated using the power rating of the lights in CB 210, the total number of lights, the electricity conversion factor, normalized on a per experiment per student basis (Equation 6). The power rating and number of lights in CB 210 was determined by Naftz and Thomas (2009).

$$0.41 \text{ lb CO}_2 - \text{e student}^{-1} \text{ experiment}^{-1} =$$

$$\frac{32 \text{ Wh} \cdot \text{light}^{-1}}{1000 \text{ Wh} \cdot kWh^{-1}} \times \frac{106 \text{ lights}}{1 \text{ student} \cdot \text{hour}} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{kWh} \times \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students} \cdot \text{hour}}$$

**Computers and Computer Monitors**

The emissions per student per experiment associated with computer use were calculated using Equations 7 (computer) and 8 (monitor). There were 12 Dell Optiplex 755 computer stations in CB210.
\[ \text{lb CO}_2 - \text{e student}^{-1} \text{ experiment}^{-1} = \]

\[ \frac{\text{Wh} \cdot \text{computer}^{-1}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \times \text{number of computers} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students} \cdot \text{hour}} \]

\[ \text{lb CO}_2 - \text{e student}^{-1} \text{ experiment}^{-1} = \]

\[ \frac{\text{Wh} \cdot \text{monitor}^{-1}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \times \text{number of monitors} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students} \cdot \text{hour}} \]

The power usage of the computer was taken from the Dell Environmental Data Sheet (Dell Inc., accessed Sept 25, 2010). The idle mode wattage rating was used (49.79 W versus 72.61 W at maximum use) because laboratory experiment use would not maximize the computing ability of the unit. Using these values in Equation 7:

\[ 0.078 \text{ lb CO}_2 - \text{e student}^{-1} \text{ experiment}^{-1} = \]

\[ \frac{49.79 \text{ Wh} \cdot \text{computer}^{-1}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \times 12 \text{ computers} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students} \cdot \text{hour}} \]

The computer station monitors were Dell 15” Flat Screen LCD Monitors. The typical power usage of this model was 19.6 W (Dell Inc., accessed Sept 17, 2010). There were 12 monitors for 24 students in CB210. Using these values in conjunction with Equation 8:

\[ 0.031 \text{ lb CO}_2 - \text{e student}^{-1} \text{ experiment}^{-1} = \]

\[ \frac{19.6 \text{ Wh} \cdot \text{monitor}^{-1}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \times 12 \text{ monitors} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{1.04 \text{ lb CO}_2 - \text{e}}{\text{kWh}} \times \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students} \cdot \text{hour}} \]
Printers in Standby

I assumed that the laboratory printers remained idle for the duration of the laboratory experiment. Students do print out the post-laboratory assignments on the laboratory printers after they complete their experiment, but I did not include this because I did not include post-laboratory assignments in my comparisons. Therefore the printing emissions were underestimated.

Standby printer emissions were calculated using Equation 9. The printer used in the chemistry laboratories was a HP 9050n printer and the power consumption information (200 W in standby) was taken from its specification sheet (HP, accessed Oct 5, 2010).

\[
0.026 \, \text{lb CO}_2 - e \, \text{student}^{-1} \, \text{experiment}^{-1} = \]

\[
\frac{200 \, \text{Wh}}{1000 \, \text{Wh} \cdot \text{kWh}^{-1}} \cdot \frac{1.04 \, \text{lb CO}_2 - e}{\text{kWh}} \cdot \frac{3 \, \text{hours idle} \cdot \text{experiment}^{-1}}{24 \, \text{students} \cdot \text{hour}} \]  

(9)

Printing of the Laboratory Manual

Western Washington University chemistry students are expected to come to laboratory with the manual for the day’s experiment already printed. Because students are printing out the manuals, this is an emission associated with the laboratory. The emissions associated with active printer use were determined using Equation 10:

\[
lb \, \text{CO}_2 - e \, \text{per hour} = \]

\[
\text{Active Power Rating (Wh)} \cdot \frac{\text{kWh}}{1000 \, \text{Wh}} \cdot \frac{1.04 \, \text{lb CO}_2 - e}{\text{kWh}} \]  

(10)
This was an hourly value because a power rating means that for every hour in use the printer will draw that much power. Therefore, the time the printer was in active mode can be determined, and the printing emissions for one student to print out their laboratory manual for the experiment can be calculated using Equation 11.

\[
\text{lb CO}_2 - e \text{ student}^{-1} \text{ experiment}^{-1} = \frac{b \text{ CO}_2 - e \text{ hour}^{-1} \times \text{number of pages}}{\text{printer speed (pages min}^{-1})} \times \frac{\text{hour}}{60 \text{ min}}
\]

Information for the printer speed (50 pages per minute) and power consumption (1000 W in active mode) was taken from the manufacturer information sheets for HP 9050n printers (HP, accessed Oct 5, 2010). The number of pages per manual was counted for each experiment.

**Paper Usage**

Paper emissions per student per experiment were determined by counting the pages printed per laboratory manual experiment and then multiplying by the pounds of CO\textsubscript{2}-e per page of paper (Equation 12). One pound of paper is approximately 110 sheets and has emissions equivalent to 4.3 lb CO\textsubscript{2}-e (BlueSkyModel.org, accessed May 4, 2012), or 0.039 lb CO\textsubscript{2}-e per sheet. The number of pages per manual was counted for each experiment.

\[
\text{lb CO}_2 - e \text{ student}^{-1} \text{ experiment}^{-1} = \frac{\# \text{ pages}}{110 \text{ pages}} \times \frac{4.326 \text{ lb CO}_2}{110 \text{ pages}}
\]
Shipping Emissions

Emissions of CO₂ emanating from the shipment of chemical consumables to WWU for the general chemistry experiments were calculated using Equations 13, 14 and 15. The weight of the solid (Equation 13) and liquid (Equation 14) materials being shipped was converted to pounds and a packaging constant of 1.5 lb was added to obtain the total shipping weight (Naftz and Thomas, 2009). This constant accounted for added mass due to packaging materials such as storage bottles, padding, and boxes.

\[
\text{Total shipping weight for solid chemical (lb)} = 1.5 \text{ lb packaging} + (\text{chemical weight of purchase (g)} \times 2.2 \times 10^{-3} \text{ lb g}^{-1}) \tag{13}
\]

\[
\text{Total shipping weight for liquid chemical (lb)} = 1.5 \text{ lb packaging} + (\text{volume of purchase (mL)} \times \text{density (g} \cdot \text{mL}^{-1}) \times 2.2 \times 10^{-3} \text{ lb g}^{-1}) \tag{14}
\]

Emissions stemming from the ground transportation of materials to WWU were calculated using the average shipping distance and a conversion factor of $2.2 \times 10^{-4}$ lb CO₂ per mile per pound of package weight (Equation 15). This conversion value was created by Naftz and Thomas (2009) using emissions estimates from www.greenshipping.com. The combined average shipping distance (2,117 miles) to WWU from the most common chemical supplier shipping hubs was used in calculating ground transportation mileage (Naftz and Thomas, 2009). The chemistry stockroom manager, Gary Carlton, identified Fisher Scientific and VWR as main chemical suppliers, with shipping hubs in Philadelphia, San Francisco, Houston, and Chicago (Carlton, 2009).
An example of calculations using ethyl acetate in the Chem 101: TLC of Analgesic Drugs laboratory is shown below.

9.4 lb shipping weight =

\[1.5 \text{ lb packaging} + \left(4000 \text{ (mL)} \times 0.897 \left(\frac{g}{mL}\right) \times 2.2 \times 10^{-3} \text{ lb per g}\right)\]

0.027 lb CO₂ − e student⁻¹ experiment⁻¹ =

\[9.4 \text{ lb} \times 2,117 \text{ miles} \times \frac{2.2 \times 10^{-4} \text{ lb CO}_2}{\text{mile} \cdot \text{lb package weight}} \times \frac{33 \text{ mL}}{4000 \text{ mL}} \times \frac{1 \text{ pair}}{2 \text{ students}}\]

Only chemical consumables were used in the shipping emissions calculations. Reusable items like boiling chips, glassware, ring stands, burets, etc., were not considered because they are shared by all of the laboratories in CB210 and CB220 and do not have a high turn-over rate. The amount of chemical used per student pair in each experiment was taken from the chemistry department laboratory coordinator supplies spreadsheet (Wilkinson, 2009; as cited by Naftz and Thomas, 2009). Chemical amounts and prices were determined using information available online from Fisher Scientific (accessed April 22, 2012). Specific gravity/density information (used in weight/volume conversions) was taken from chemical or product MSDS sheets. Some items used in the laboratory experiments were purchased locally (vinegar, bleach, sugar, red food coloring, analgesic drugs, potato chips, and gummy bears).
and therefore not shipped. I did not include them in the emissions estimates because I am not considering transportation emissions.

_Hazardous Waste Incineration_

The carbon dioxide emissions resulting from hazardous waste incineration was based on Reinhardt et al. (2008). They performed a carbon mass balance on a hazardous waste incineration plant in Germany to ascertain the carbon dioxide emissions resulting from hazardous waste incineration. They determined that 196 Kg of CO₂ was emitted for every 1,000 Kg of hazardous waste incinerated (or 0.196 lb CO₂ per lb waste). This value does not include the carbon entering the plant from fossil fuels or additives because they determined these values to be “very small.” These emissions were only for carbon dioxide, so the emissions from the chemistry laboratory waste disposal were likely underestimated.

The emissions were calculated using Equation 16. The volume of waste from each experiment was calculated by adding up the total volume of the reagents used from the laboratory coordinator’s spreadsheets (Wilkinson, 2009; as cited by Naftz and Thomas, 2009). The volume of waste generated per experiment is likely underestimated because many reagents were prepared in bulk and centrally dispensed to the students. Students often take (and use) more of a reagent than the minimum amount that the protocol required. It was assumed that the density of the waste generated was equivalent to the density of water at 25 °C, or 0.997 g/mL. The density was converted into pounds per milliliter (0.00219 lb/mL), and that value was multiplied by the volume of waste in milliliters. The weight of hazardous waste was multiplied by the emissions conversion. Finally, the emissions were normalized on a per student basis, with adjustments made if a student was working in pairs or alone.
As of 2006, servers and data centers consumed approximately 61 billion kWh of electricity nation-wide. This is 1.5% of total electricity consumption in the U.S. (US DOE, 2007). Data centers are buildings that contain networked computer servers and consume large amounts of energy. Data centers primarily house information technology (IT) equipment for data storage (storage equipment), communications (network equipment) and data processing (servers). Universities often “use and operate many data centers for information management and communication functions” (USEPA, 2007).

A data center requires reliable, high quality power and backup power, and environmental controls to regulate temperature and humidity. This requires a lot of electricity; larger data centers can be 40 times more energy intensive than conventional office buildings (Greenberg et al., 2006; as cited in USEPA, 2007).

There are various typical IT equipment and site infrastructure system characteristics for various types of servers/data centers. The space classifications are, in order of increasing square footage, server closet, server room, localized data center, mid-tier data center, and enterprise-class data center. The individual servers housed in the servers/data centers are classed at either volume, mid-range, or high-end. In 2006, a volume class server used an estimated 225 W of power, a mid-range server 675 W, and a high-end server 8,163 W
(USEPA, 2007). Note that these values do not contain estimates for energy use by storage
devices and network equipment.

I could not obtain information on the size of WWU's server and data center, so, for
the purpose of this study I assumed that WWU operated a localized data center (<1000 ft²,
moderate external storage, dozens to hundreds of servers) with a volume server class. Further
assumptions were that WWU operates at the low end of the server range. Volume servers use
an estimated 225 W of power, so 12 servers would use 2,700 W. Server emissions per
student per experiment were calculated using Equation 17.

\[ lb \ CO_2 \ - \ e \ student^{-1} \ experiment^{-1} = \]
\[
\frac{\text{Power Rating (Wh)} \cdot \text{server}^{-1}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \cdot \frac{\text{number of servers}}{3 \text{ hours} \cdot \text{experiment}^{-1}} \cdot \frac{1.04 \ lb \ CO_2 \ - \ e}{\text{kWh}} \cdot \frac{\text{Total Students at Western}}{12}.
\]

I decided not to incorporate emissions or monetary costs from the server into the calculations
because this value was negligible and did not have an impact on the overall carbon footprint
or cost. For example:

\[ 6.1 \times 10^{-4} \ lb \ CO_2 \ - \ e \ student^{-1} \ experiment^{-1} = \]
\[
\frac{225 \ (Wh) \cdot \text{server}^{-1}}{1000 \ (Wh) \cdot \text{kWh}^{-1}} \cdot 12 \text{ servers} \cdot \frac{1.04 \ lb \ CO_2 \ - \ e}{\text{kW} \cdot \text{h}} \cdot \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{13,777 \text{ students in 2008 - 2009}}.
\]

**Transportation Emissions**

Student transportation emissions to and from campus were not included for several reasons.
First, an informal survey of my chemistry laboratory students indicated that the majority of
students taking general chemistry are underclassmen, and therefore more likely to live on campus. Second, I assumed that off-campus students rarely came to campus solely for a general chemistry laboratory, but would instead had other courses they are taking and would use other university facilities in addition to the chemistry laboratory room. This would be true for faculty, staff, and graduate lab instructors as well – most did not come to WWU strictly for the chemistry lab, but rather had additional work to attend to on campus. Finally, the majority of students commuting to and from campus rode the bus or walked. During the 2008-2009 school year, 4,086 students lived on campus (Karen Walker, Personal Communication) out of the 13,777 full and part time students enrolled at WWU (WWU Office of University Communications, accessed April 14, 2011). That meant that approximately 70% of the student body commuted to and from campus. The results of the Spring 2008 Western Student Transportation Survey (Gruen et al., 2009) showed that of the 3,971 students responding, 18% regularly drove to or from campus in cars (this included carpooling and driving alone). The rest walked or took the bus.

2.3.2 Carbon Footprint of Alternative Laboratory Experiments

The emissions included in the carbon footprint were calculated in pounds of carbon dioxide (or carbon dioxide equivalents, if available) per student per experiment.

Home heating

Home heating emissions for a kitchen were calculated using a similar approach as for the general chemistry teaching laboratory space. Specifically, the emissions per square foot was determined from the overall building heating emissions and multiplied by the area of the
kitchen. The home heating emissions per experiment were calculated using Equation 18. The average American home emits 6,400 pounds of CO₂ per year when using natural gas for heat (NPR, 2007; Naftz and Thomas, 2009), the average American home built in 2009 was 2,438 square feet (US Census Bureau Online, accessed April 24, 2012), and the average kitchen is 300 square feet (ABC News, 2005; Naftz and Thomas, 2009).

\[ 0.3 \text{ lb CO}_2 – e \text{ student}^{-1} \text{ experiment}^{-1} = \]
\( \frac{6,400 \text{ lb CO}_2 \cdot \text{ year}^{-1}}{2,438 \text{ ft}^2} \times \frac{\text{ year}}{8765.8 \text{ hours}} \times \frac{3 \text{ hours}}{\text{ student} \cdot \text{ experiment}} \times 300 \text{ ft}^2 \)

**Lighting**

The emissions due to lighting were calculated using Equation 19 and the assumption that there were two fluorescent light bulbs (26 W rating) in the kitchen for the experiment duration.

\[ 0.16 \text{ lb CO}_2 – e \text{ student}^{-1} \text{ experiment}^{-1} = \]
\( \frac{26 \text{ Wh} \cdot \text{ bulb}^{-1}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \times 2 \text{ bulbs} \times \frac{1.04 \text{ lb CO}_2 – e \text{ kWh}^{-1}}{\text{kWh}} \times \frac{3 \text{ hours} \cdot \text{ experiment}^{-1}}{\text{ students} \cdot \text{ hour}} \)

**Active and Standby Laptop Use**

Although I assumed that students print the laboratory manual prior to class, they would still require computer usage. For example, a student may be required to post their experimental results in a group database, or write about their experience in a laboratory forum. The amount of time spent on the computer will vary depending on the individual, so I made the general
assumption that students would spend a half hour with the computer active. The other 2.5
hours of their laboratory experience would be spent with the computer in standby. Emissions
for laptop use were calculated using Equation 20 (active mode) and Equation 21 (standby).
The active mode power rating for a Dell Inspiron 15 laptop is 41.38 W, and the standby
mode power rating is 1.413 W (Dell Inc., accessed May 6, 2012).

\[
0.2 \text{ lb } CO_2 - e \text{ student}^{-1} \text{ experiment}^{-1} = \\
\frac{41.38 \text{ Wh}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \cdot \frac{1.04 \text{ lb } CO_2 - e}{\text{kWh}} \cdot \frac{0.5 \text{ hours active} \cdot \text{ experiment}^{-1}}{\text{student} \cdot \text{hour}}
\]

\[
0.004 \text{ lb } CO_2 - e \text{ student}^{-1} \text{ experiment}^{-1} = \\
\frac{1.413 \text{ Wh}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \cdot \frac{1.04 \text{ lb } CO_2 - e}{\text{kWh}} \cdot \frac{2.5 \text{ hours active} \cdot \text{ experiment}^{-1}}{\text{student} \cdot \text{hour}}
\]

*Printer in Standby*

Emissions from the printer in standby were calculated using Equation 22. As with the student
in the traditional laboratory setting, I assumed that the printer would remain idle for the
duration of the experiment. Specifications for a HP DeskJet 1000 printer were used in the
calculations. The printer used 2.3 W in standby mode (HP, accessed May 3, 2012).

\[
0.0072 \text{ lb } CO_2 - e \text{ student}^{-1} \text{ experiment}^{-1} = \\
\frac{2.3 \text{ Wh}}{1000 \text{ Wh} \cdot \text{kWh}^{-1}} \cdot \frac{1.04 \text{ lb } CO_2 - e}{\text{kWh}} \cdot \frac{3 \text{ hours idle} \cdot \text{ experiment}^{-1}}{\text{student} \cdot \text{hour}}
\]
Printing Laboratory Manual

The LabPaq CK-S was shipped with a digital copy of the laboratory manual; no hard copy was provided. Although some students might read the laboratory protocol on their computer screens, I assumed that most would print the lab protocol before conducting the experiment. The emissions associated with this printing were calculated as described in Section 2.3.1 using Equations 10 and 11. Specifications for a HP DeskJet 1000 printer were used in the calculations. At a printing speed of five pages per minute, the printer used 10 W in active mode (HP, accessed May 3, 2012).

Paper Emissions

Emissions from the use of paper were calculated as described in Section 2.3.1 using Equation 12.

Shipping Emissions of Laboratory Kit

Emissions stemming from the ground transportation of the laboratory kit to the student were calculated using Equation 23. Because the LabPaq was shipped as a unit that contains 20 experiments, I included all 20 units in the calculations even though only 10 of the units were used for direct comparison with WWU labs.

\[ 0.11 \frac{lb \ CO_2}{e \ student^{-1} \ experiment^{-1}} = \frac{4.4 \ lb \ package \ weight}{20 \ experiments \cdot student} \times 2,174 \ miles \times \frac{2.2 \times 10^{-4} lb \ CO_2}{mile \cdot lb \ package \ weight} \]
The conversion factor was created by Naftz and Thomas (2009) using emissions estimates from www.greenshipping.com. The LabPaq CK-S weighed 4.4 pounds, and shipped from one of two cities: Englewood, CO, or Syracuse, NY. The average ground transportation distance (2,174 miles) to Bellingham, WA, was used in the calculations.

Hazardous Waste

While there was waste generated from the LabPaq experiments, there was no hazardous waste that required special disposal. All of the chemicals used in the laboratory kit were in small quantities and were disposed of down the sink with lots of water or in the household waste. While there were emissions associated with waste transport/disposal, they were not considered in this study because the emissions directly related to lab kit waste disposal would be negligible.

Transportation

There were no student transportation emissions associated with the alternative lab because the student performed the experiment in their own home. There also were no emissions associated with instructor transportation because there was no instructor for the alternative lab delivery scenario.

Server

Server emissions were not included for the reasons stated in Section 2.3.1.
2.4 Cost Comparisons

The costs were calculated in dollars per student per experiment to allow direct comparison between WWU and LabPaq laboratory experiments. The costs included for each scenario were:

- natural gas for heat and compressed air (traditional), natural gas for home heating (alternative)
- electricity to power the fume hoods, top-loading and front-loading electronic balances, laboratory lights, computers, computer monitors, and printers in standby mode (traditional)
- electricity to power lights, active and standby laptop use, printer in standby (alternative)
- cost of paper usage (both scenarios)
- purchase of materials (traditional), purchase and shipping of laboratory kit (alternative)
- hazardous waste disposal (traditional)
- electricity for printing laboratory manuals (both scenarios)
- laboratory personnel wages (traditional)
- broken glassware and laboratory upkeep (traditional)

The following emissions were not included due to limited data availability, complexity of calculations, or negligible costs:

- water cost (both scenarios)
- initial stocking of laboratory drawers and shared equipment (traditional)
- building upkeep and overhead (both scenarios)
- communication, network, and data storage servers (both scenarios)

The same prices for energy and natural gas were used for both scenarios. The price per kWh of electricity in 2009 was $0.07 (PSE, 2009), and natural gas was $1.26 per therm (pricing from personal gas bills in 2009). Assumptions made for the analysis are listed in Appendices A and B.
2.4.1 Cost of Traditional Laboratory Experiments at WWU

Heating, Compressed Air, and Hot Water

The cost per student per experiment of heat, hot water, and compressed air was calculated using Equation 24.

\[
\text{\$0.02 student}^{-1} \text{ experiment}^{-1} = \frac{4,257,566.56 \text{ ft}^3 \text{ year}^{-1}}{100 \text{ ft}^3 \text{ therm}^{-1}} \times \frac{\$1.26 \text{ therm}^{-1}}{72,574 \text{ ft}^2} \times \frac{1,734 \text{ ft}^2}{8765.8 \text{ hours} \cdot \text{year}^{-1}} \times \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students}}
\]

The yearly natural gas consumption information was taken from the Facility Management monitoring data (Bailey, 2009; as cited by Naftz and Thomas, 2009). The building area (72,574 ft²) was taken from WWU’s Facilities Management Website and the teaching laboratory square footage (1,734 ft²) was estimated from the chemistry building floor plans (WWU Office of Facilities Development & Capital Budget, accessed Sept 11, 2011). The price per therm ($1.26) reflects the 2009 price of natural gas.

Fume Hoods

Fume hood dollar costs were calculated using by multiplying the fume hood energy using Equation 25. The yearly fume hood electrical consumption (in kWh) was calculated using the online energy calculator provided by the Lawrence Berkeley National Laboratory (accessed Sept 17, 2010) and the electrical rate was $0.07 per kWh (PSE, 2009).

\[
\text{\$0.06 student}^{-1} \text{ experiment}^{-1} = \frac{59,135 \text{ kWh} \cdot \text{year}^{-1}}{\frac{\$0.07}{\text{kWh}} \frac{\text{year}}{8765.8 \text{ hours}} \frac{3 \text{ hours} \cdot \text{experiment}^{-1}}{24 \text{ students}}}
\]
**Electronic Balances**

The electrical cost for the electronic was calculated as described in Section 2.3.1 using Equations 4 and 5; the cost per kWh of electricity was substituted for the emissions per kWh.

**Laboratory Lighting**

The electrical cost for the laboratory lighting was calculated as described in Section 2.3.1 using Equation 6; the cost per kWh of electricity was substituted for the emissions per kWh.

**Computers and Monitors**

The electrical cost for the computers and monitors electricity was calculated as described in Section 2.3.1 using Equations 7 and 8; the cost per kWh of electricity was substituted for the emissions per kWh.

**Printers in Standby**

The electrical cost for the printer in standby was calculated as described in Section 2.3.1 using Equation 9; the cost per kWh of electricity was substituted for the emissions per kWh.

**Printing the Laboratory Manual**

The electrical cost for the printing the laboratory manual was calculated as described in Section 2.3.1 using Equations 10 and 11; the cost per kWh of electricity was substituted for the emissions per kWh.
**Paper**

The paper usage cost per student was calculated using Equation 26. A ream of paper (500 sheets) costs $4.61, or $0.00922 per sheet (Jack Herring, Personal Communication).

\[
\text{Cost (\$ student}^{-1} \text{ experiment}^{-1} = \frac{\text{\# pages in manual} \times \frac{\$4.61}{500 \text{ pages}}}{\text{\# pages in manual}}
\]

Naftz and Thomas (2009) did not cite the 2009 cost of a ream of paper, so the cost reflects the May 2012 price per ream.

**Material Consumable Purchases**

Only consumables were used in the cost calculations. Reusable items like boiling chips, glassware, ring stands, burets, etc., were not considered because they are shared among all of the laboratories that are held in CB210 and CB220 and do not have a high turnover rate. I used the Chemistry Department’s estimates of chemical costs per student per laboratory experiment. These estimates are $1.49 for Chem 101, $3.02 for Chem 121, and $4.43 for Chem 122 (Brandon Dietrich, Personal Communication).

The cost of gloves and Kimwipes was also included in the consumable cost calculations (Equation 27) based on the data provided by Gary Carlton, the Chemistry Department Stock Room Manager (Personal Communication). For the number of boxes of gloves and Kimwipes that are planned for each course each quarter (Table 2.4.1), these estimates were divided by the number of experiments in a quarter and the number of students taking that course (for example, 288 students for Chem 121).
Cost ($) student\(^{-1}\) experiment\(^{-1}\) =

\[
\frac{boxes \cdot cost \cdot box^{-1}}{number\ of\ experiments\ \cdot\ total\ students\ in\ all\ sections\ of\ course\ in\ CB210}
\]  

(27)

The cost per box of gloves ($18.40) and Kimwipes ($5.23) was taken from Fisher Scientific’s website (accessed Nov 16, 2012) using academic pricing (no shipping and tax charged). An example calculation using gloves for Chem 121 is shown below:

$0.04\ student^{-1}\ experiment^{-1} =

\[
\frac{5\ boxes \cdot $18.40\ box^{-1}}{9\ experiments\ \cdot\ 288\ students}
\]  

One drawback is that these estimates were very conservative (Gary Carlton, Personal Communication). In addition, all of the materials cost estimates were calculated using 2012 dollars and reflect 2012 pricing, which was different from 2009 pricing.
Table 2.4.1: Number of gloves and Kimwipes per laboratory per quarter (Gary Carlton, Personal Communication)

<table>
<thead>
<tr>
<th>Course</th>
<th>Gloves (boxes)</th>
<th>Kimwipes (boxes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>121</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>122</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>
Broken Glassware and Laboratory Upkeep

The cost of broken glassware replacement and laboratory equipment upkeep was calculated (Equation 28) from the laboratory fee that the Chemistry Department charges students. The Chemistry Department factors a broken glassware and laboratory equipment upkeep fee of $20.52 per student per quarter into the overall flat fee charged to students (Sara Young, Personal Communication). This fee was the same for all general chemistry laboratory courses.

\[
$2.28 \text{ student}^{-1} \text{ experiment}^{-1} = \frac{20.52 \text{ student}^{-1} \cdot \text{quarter}^{-1}}{9 \text{ experiments}^{-1} \cdot \text{quarter}^{-1}} \quad (28)
\]

Laboratory Personnel: Laboratory Coordinator

The laboratory coordinator, Brandon Dietrich, estimated that he spends 1 hour per week training laboratory preparers, 0.5 hours on laboratory setup, 0.25 hours on miscellaneous administrative tasks, 1.25 hours on teaching practicum, and 1 hour of laboratory support (Brandon Dietrich, Personal Communication). This added up to a total of 4 hours per week for each laboratory. It should be noted that this was the minimum of time spent on the laboratories as it did not include laboratory make-ups, curriculum development, other administrative work, and other miscellaneous tasks associated with the laboratories.

The hourly salary was estimated using Equation 29 and the yearly salary and staff year information found in the 2011-2012 Operating Budget (WWU University Planning and Budgeting, accessed Oct 19, 2012). The average number of sections per week was calculated
by averaging together the number of sections taught for each course during the 2011-2012 academic year, not including summer quarter (WWU Classfinder, accessed Oct 22, 2012). This worked out to 1 section per week of Chem 101, 19 sections per week of Chem 121, and 12 sections per week for Chem 122.

\[
\text{Cost student}^{-1} \text{ experiment}^{-1} =
\]

\[
\frac{\text{Yearly Salary}}{\text{Staff Year (weeks} \cdot \text{year}^{-1})} \div 40 \text{ hours} \cdot \text{week}^{-1}
\]

\[
\times \left[ \frac{\text{Experiment Prep (hours} \cdot \text{week}^{-1})}{\text{average number of lab sections (week}^{-1})} \times \frac{\text{hourly salary rate}}{\text{number of students in a section}} \right]
\]

An example for Chemistry 121 is:

\[
\$0.17 \text{ student}^{-1} \text{ experiment}^{-1} =
\]

\[
\frac{\$33,336 \text{ year}^{-1}}{43 \text{ weeks} \cdot \text{year}^{-1}} \div 40 \text{ hours} \cdot \text{week}^{-1}
\]

\[
\times \left[ \frac{4 \text{ hours} \cdot \text{week}^{-1}}{19 \text{ sections} \cdot \text{week}^{-1}} \times \frac{1 \text{ section}}{24 \text{ students} \cdot \text{experiment}} \right]
\]

**Laboratory Personnel: Laboratory Preparer**

The Chemistry Department employed undergraduate students to prepare the general chemistry laboratories each week. These students were paid $10 per hour (Sara Young, Personal Communications). Experienced preparers take two to three hours per week to prep, whereas inexperienced students making every solution from scratch took approximately eight hours per week to prep the laboratories (Brandon Dietrich, Personal Communication). Due to the variability in prep times, I used an estimate of four hours per week of prep time in my calculations.
The cost per student per experiment was calculated using Equation 30. An example calculation for Chemistry 121 is:

\[
0.09 \text{ student}^{-1} \text{ experiment}^{-1} = \frac{4 \text{ hours} \cdot \text{week}^{-1}}{19 \text{ sections} \cdot \text{week}^{-1}} \times \frac{\$10 \text{ per hour}}{24 \text{ students} \cdot \text{experiment} \cdot \text{section}^{-1}}
\]

_Laboratory Personnel: Graduate Teaching Assistants (GTAs)_

The cost for GTA laboratory instruction was calculated using Equation 31 using a GTA hourly wage of $17 per hour (Sara Young, Personal Communication). Graduate TAs teach three laboratory sections per week. They also are required to hold office hours for two hours per week (or 0.67 hours per section).

\[
\text{Cost student}^{-1} \text{ experiment}^{-1} = \frac{[\text{hourly wage} \times \frac{\text{number of hours}}{\text{section}} + \text{hourly wage} \times \frac{\text{total office hours}}{3 \text{ sections}}]}{24 \text{ students} \cdot \text{section}}
\]

For example:

\[
2.60 \text{ student}^{-1} \text{ experiment}^{-1} = \frac{[\$17 \cdot \frac{3 \text{ hours}}{\text{section}} + \$17 \cdot \frac{2 \text{ hours}}{3 \text{ sections}}]}{24 \text{ students} \cdot \text{section}} = 2.60
\]

_Laboratory Personnel: Faculty Laboratory Instructors_

The cost per student per laboratory experiment was calculated by determining the portion of faculty salary spent on laboratory instruction and normalizing it per student per experiment. I
assumed that the faculty laboratory instructor was a non-tenure track faculty member and that they taught two sections per week. While tenure track faculty occasionally teach general chemistry lectures, they rarely teach laboratories (Emily Borda, Personal Communication; Classfinder, accessed Nov 16, 2012). I observed that the non-tenure track faculty taught two laboratory sections a quarter when I was a general chemistry teaching assistant in 2010 and 2011; I therefore assumed that the non-tenure track faculty taught two sections of laboratories. Faculty member office hours were not included in the calculations because their laboratory office hours are not separate from lecture office hours.

I used salary data from two non-tenure track faculty members that teach general chemistry laboratories (Sara Young, Personal Communication). The salary information for these two individuals was taken from the State of Washington’s Office of Financial Management 2011 Personnel Detail Report (accessed Nov 16, 2012). The salaries for January through December 2010 were $14,777.77 and $33,966.19. I used WWU Classfinder (accessed Nov 16, 2012) and calculated the total number of credits for each faculty members for the calendar year 2010 (which was 10 and 18 credits, respectively). The salary per credit was calculated using Equation 32:

\[
\text{Cost credit}^{-1} = \frac{\text{2011 salary}}{\text{2010 credit load}} = \text{Cost credit}^{-1}
\]

I averaged the costs per credit for the two faculty members ($1,682.39), and calculated the cost per student per experiment (Equation 33).
Laboratory Personnel: GTA and Faculty Instructors

Because laboratories are taught by a mixture of graduate teaching assistants and faculty members, I also calculated the instructor cost when a quarter of the laboratories are taught by faculty and three-quarters are taught by graduate teaching assistants (Equation 34).

\[
\begin{align*}
\text{\$11.68 student}^{-1} \text{ experiment}^{-1} &= \\
&= \left( \frac{1,682.39 \text{ credit}^{-1} \cdot 3 \text{ credits lab}^{-1}}{9 \text{ experiments lab}^{-1}} \right) \div (2 \text{ sections} \cdot 24 \text{ students} \cdot \text{section}^{-1}) \\
&= \left( \frac{0.75 \cdot \text{\$2.60 student}^{-1} \cdot \text{experiment}^{-1}}{\text{student} \cdot \text{experiment}} \right) + \left( \frac{0.25 \cdot \text{\$11.68 student}^{-1} \cdot \text{experiment}^{-1}}{\text{student} \cdot \text{experiment}} \right)
\end{align*}
\]

Hazardous Waste Disposal

Many of the experiments conducted in general chemistry do not generate hazardous waste; often the waste can be neutralized, logged, and flushed down the drain with a large volume of water. Of the 10 WWU experiments analyzed, only four generated hazardous waste (Table 2.4.2). This information was found in the laboratory preparer handouts provided by the Chemistry Department as well as my personal experience as a laboratory instructor.

The General Hazardous Waste Disposal Price Sheet included in the 2009 contract with Clean Harbors, WWU’s contracted waste disposal entity (State of Washington, 2009)
was used to determine the disposal methods and costs for the EHS waste generated by the chemistry laboratories. The waste generated from TLC Analysis of Analgesic Drugs best fits the Organic Solvent (non-halogenated, <5000 BTU/LB) category. This waste was incinerated and costs $2.85 per gallon. The other disposal option for this experiment was Energy Recovery for Organic Solvent/Aqueous Mix ($1.80 per gallon), but because the waste generated from this laboratory contains analgesics, I chose incineration as the method of disposal. Energy recovery involves the combustion of the waste to generate energy, so, while cheaper, there would still be CO₂ emissions associated with this process.

The three other laboratory experiment wastes were classified as Aqueous Solutions >90% Inorganic (pH 0-14, may contain any/all TCLP metals except mercury) and cost $3.00 per gallon to dispose. Incineration was the method for disposal for that type of hazardous waste.

The waste sent off-campus for disposal must be contained in either a 30- or 55-gallon steel or poly (polyethylene) drum (State of Washington, 2009). Corrosive waste would be stored in the poly drum, whereas organic waste would more likely be stored in the steel drum. Ethyl acetate, ethanol and acetic acid (the main solvents in the TLC of Analgesics experiment) are all chemically compatible with polyethylene for storage. Therefore, I assumed that 55-gallon poly drums were used for the storage and handling of the hazardous waste. A new, tight head 55-gallon poly drum costs $68, or $1.24 per gallon.

The waste generated per student was calculated using Equation 31. The waste costs from the individual chemical calculations was added together to obtain the total cost.
Cost student$^{-1}$ experiment$^{-1}$ =

\[
\left[ \left( \text{waste (gallon)} \times \frac{\text{disposal cost}}{\text{gallon}} \right) + \left( \frac{\text{drum cost}}{\text{gallon}} \times \text{waste (gallon)} \right) \right] \div 2 \text{ students} \cdot \text{experiment}
\]

An example calculation using the TLC laboratory acetic acid-ethyl acetate waste:

$0.007 \text{ student}^{-1} \text{ experiment}^{-1}$ =

\[
\left[ \left( 0.0033 \text{ gallon} \times \frac{\$2.85}{\text{gallon}} \right) + \left( \frac{\$68}{55 \text{ gallon}} \times 0.0033 \text{ gallon} \right) \right] \div 2 \text{ students} \cdot \text{experiment}
\]
**Table 2.4.2:** The Western Washington University laboratory experiments that generate hazardous waste.

<table>
<thead>
<tr>
<th>Course</th>
<th>Laboratory Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>TLC Analysis of Analgesic Drugs</td>
</tr>
<tr>
<td>121</td>
<td>The Nine Solution Problem</td>
</tr>
<tr>
<td>121</td>
<td>Types of Chemical Reactions</td>
</tr>
<tr>
<td>122</td>
<td>Synthesis of Copper Sulfate Pentahydrate</td>
</tr>
</tbody>
</table>
2.4.2 Cost of Alternative Laboratory Experiments

Home Heating

The cost of natural gas to heat a kitchen for the duration of an experiment was calculated by multiplying Equation 18 by a conversion factor of 0.08696 therms per lb CO₂-e, then multiplying by $1.26. The conversion factor was created from the WWU steam plant emissions data. Because 1 therm of natural gas releases 11.5 lb CO₂-e (Hagen, 2009; as cited by Naftz and Thomas, 2009), there are 0.08696 therms per pound of emissions. While not ideal, this approach was used because other reliable data could not be found. The value was likely not representative of actual home energy emissions and costs because the emissions per therm of natural gas were specific to WWU’s steam plant.

Laboratory Kit Purchase and Shipping Costs

In 2009, the LabPaq CK-S was $269 plus $15 shipping. In September 2011, the cost was up to $299 plus shipping. These prices came from the LabPaq website (accessed Sept 11, 2011), and used to include a description of the product. LabPaq no longer makes their current laboratory kit descriptions or costs publicly available on their website. Because the other values in this study used 2009 dollars and data, the 2009 cost of the LabPaq and shipping was used in determining the cost per experiment. The LabPaq CK-2 contains 20 experiments, so the cost per experiment is $14.20 ($284 divided by 20).

Lighting

The cost of electricity for lighting was calculated as described in Section 2.3.2 using Equation 19; the cost per kWh of electricity was substituted for the emissions per kWh.
Active and Standby Laptop Use

The cost for laptop use was calculated as described in Section 2.3.2 using Equations 20 (active) and 21 (standby); the cost per kWh of electricity was substituted for the emissions per kWh.

Standby Printer

The cost for standby printer electricity was calculated as described in Section 2.3.2 using Equation 9; the cost per kWh of electricity was substituted for the emissions per kWh. Specifications for a HP DeskJet 1000 printer were used in the calculations. The printing speed was five pages per minute, and the printer used 10 W in active mode (HP, accessed May 3, 2012).

Printing of the Laboratory Manual

The cost for printing was calculated as described in Section 2.3.1 using Equation 10; the cost per kWh of electricity was substituted for the emissions per kWh. Specifications for a HP DeskJet 1000 printer were used in the calculations. The printing speed was five pages per minute, and the printer used 10 W in active mode (HP, accessed May 3, 2012).

Paper

The cost for paper was calculated as described in Section 2.4.1 using Equation 26 and substituting $9.29 for the cost of paper. A ream of 100% recycled copy paper (500 sheets) from Staples cost $9.29 in May 2012, or $0.0186 per sheet (www.staples.com and Staples in Northampton, MA).
2.5 Literature Review and Curriculum Study

2.5.1 Literature Review

I conducted a review of published studies involving the use of laboratory kits in post-secondary education to investigate if laboratory kits have been successfully used as alternatives to traditional science laboratories. To find papers, I performed searches on various academic databases such as Academic Search Complete, JSTOR, EBSCO, Web of Science, ERIC, and Google Scholar. I also searched within and browsed the Journal of Chemical Education, Journal of Science Education and Technology, Science, Science Education, The Chemical Educator, and the American Journal of Distance Education.

2.5.2 WWU and LabPaq Experiment Laboratory Manual Analysis

I used an illustrative verb content analysis (Domin, 1999) to compare WWU and LabPaq experiments. I also tested and validated the use of the illustrative verb content analysis by including a WWU laboratory that was taught with a different learning approach that should theoretically utilize both lower and higher order cognitive skills. I also analyzed pre-and post-laboratories (as well as manuals) for some of the WWU laboratory experiments selected for curriculum comparison to validate the use of this comparison method.

I selected experiments from the WWU and LabPaq experiment pairs used in the cost analysis and carbon footprint that had strong similarities in learning objectives, concepts, techniques, and experimental setup. I chose the four that were the most similar, with special attention focused on the experimental procedure and learning objectives (Table 2.5.1). Of these four experiment pairs, only one pair had similar methods of data manipulation and analysis. These were the Stoichiometry of a Precipitation Reaction (LabPaq) and Synthesis of
Copper Sulfate Pentahydrate (Chem 122).

I also included the Chem 122: Intermolecular Forces and Physical Properties (IMF) laboratory, which was taught during the 2010-2011 academic year. This laboratory was not part of the 2008-2009 curriculum, but it represents a different way of teaching a traditional general chemistry wet laboratory in that it takes more of a constructivist approach to examining physical phenomena. Constructivist learning is based on the idea that an individual will create new knowledge and understanding based off of their pre-existing understanding (Bransford et al., 2000). In the IMF laboratory, students investigate physical properties such as solubility, evaporation, viscosity and surface tension and are asked to use their existing knowledge coupled with experimental observation to develop explanations for these phenomena. For example, after two activities with the evaporation of various solvents, students are asked to use their experimental evidence in conjunction with their existing knowledge of intermolecular properties and kinetic molecular theory to explain evaporative cooling, and then how sweating affects skin temperature. The student is actively synthesizing new knowledge based off of their existing understanding and experimental observations.

This is different from a “cookbook” laboratory where student cognitive skill use throughout the laboratory is mostly applicative; that is, the students are expected to apply procedures described in the laboratory manual or instructor introduction to their experimental procedure. The experiment is finished once they arrive at the pre-determined endpoint, and then they apply the concepts and equations learned in lecture or described in the laboratory manual to their data analysis. Students are not often asked to develop their own experimental approach, explain their observations, or synthesize new understanding based off of prior knowledge.
<table>
<thead>
<tr>
<th>Experiment Title</th>
<th>LabPaq Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chem 101: TLC analysis of analgesic drugs</td>
<td>#15: Chromatography of Food Dyes</td>
</tr>
<tr>
<td>Chem 121: Analysis of Vinegar</td>
<td>#16: Titration for Acetic Acid in Vinegar</td>
</tr>
<tr>
<td>Chem 122: Synthesis of copper sulfate pentahydrate</td>
<td>#9: Stoichiometry of a Precipitation Reaction</td>
</tr>
<tr>
<td>Chem 122: Reaction of crystal violet with NaOH: A kinetic study</td>
<td>#17: Reaction Order and Rate Laws</td>
</tr>
</tbody>
</table>
My rationale for including the IMF laboratory in the curriculum study was to determine whether the illustrative verb analysis is an appropriate method of comparing the content of the laboratory manuals. If this method can indeed discern differences between what categories of cognitive skills are being utilized, I would expect that the IMF laboratory would contain more instances of higher order cognitive tasks than the other WWU laboratory experiments.

The illustrative verb analysis evaluated what kinds of higher-order cognitive skills were targeted in the wording of the laboratory manuals. This approach was one way of investigating the pedagogy of the laboratory delivery in the absence of other information such as supplementary curriculum materials, laboratory instructor teaching methods, laboratory observation, and measures of student conceptual understanding of course materials. The verb analysis looked at the way the laboratory experiments were written and identified verbs that illustrated each type of cognitive skill defined in Bloom’s hierarchy of cognitive skills.

According to Bloom et al. (1956), there are six major categories of skills in the cognitive domain. These are, from the lowest order to highest: knowledge, comprehension, application, analysis, synthesis, and evaluation. The first three categories are representative of lower-order cognitive skills, while the latter three are higher-order.

The lower-order skills can be generalized as recognizing, recalling, and applying a learned rule, while higher order is inferring, planning, appraising (Domin, 1999). More specifically, the knowledge domain involves remembering or recalling previously learned information. The comprehension domain covers the ability to understand the information.
Application refers to the capability to use the learned information in new ways, while the analysis domain involves examining and breaking down information into its constituent parts. Synthesis involves putting constituents together in a new way, and evaluation is the ability to judge material or present and defend ideas (Gronlund, 1985).

Gronlund (1985) compiled a list of illustrative verbs that are useful when stating specific learning outcomes in the different cognitive skill categories (Appendix E). For example, a student asked to *manipulate* data using mathematical equations is using skills from the application category, whereas a student who is *justifying* a conclusion drawn from their data analysis is working from the evaluation category.

The verb list, in conjunction with contextual use in the text, can be used to identify what categories of Bloom’s hierarchy are being utilized in the laboratory manual, and therefore the laboratory experiment delivery. This verb list was used by Domin (1999) in his analysis, and was also the verb list that I used in my analysis.

Domin argued that laboratories are not designed for the development of higher-order cognitive skills, and so he analyzed the content of 10 undergraduate chemistry laboratory manuals of experiments working with calorimetry, gas laws and kinetics. Most of the laboratory manuals that Domin (1999) analyzed contained introduction sections that introduce and explain the concepts for the laboratory, step-by-step procedural sections, data tables or fill-in-the-blank sections for data and results, and pre- and post-laboratory questions. This was similar to the organizational style of both the LabPaq manual and the WWU general chemistry manuals.

The laboratory manuals I evaluated did not have any pre-laboratory questions and few
post-laboratory questions were included in the procedures for each experiment. Western
Washington University general chemistry students did complete a set of pre- and post-
laboratory questions before and after each experiment but they were not part of the laboratory
manual document. They were stored and accessed on the same website as the WWU
laboratory manual. The LabPaq laboratory did not contain pre-laboratory assignments, and
only a few of the experiments contained post-laboratory questions that encouraged
comprehension, application or analysis of data. It is reasonable to expect that instructors
conducting an online laboratory using a laboratory kit would post separate pre- and post-
laboratory assignments for students to conduct, just like in the on-campus WWU
laboratories.

I did not have an example of an alternative chemistry course curriculum that utilized
the LabPaq CK-S, so for consistency, I only compared the laboratory manuals. I used WWU
pre-and post-laboratories in conjunction with the IMF laboratory to test and validate the use
of the illustrative verb content analysis. I obtained the pre- and post-laboratories used in
Chem 121 and 122 laboratories during 2008-2009 from the general chemistry Laboratory
Coordinator (Brandon Dietrich, Personal Communication).

To perform the analysis, I read through each manual and highlighted every illustrative
verb that appeared on Gronlund’s list of illustrative verbs. I evaluated the context of each
verb to ensure that I only included verbs that would correspond to student action or
cognition. I also assessed the context because several verbs are indicative of more than one
category of cognitive skill depending on its use. Each illustrative verb found in the laboratory
experiment manual was recorded in its corresponding category of cognitive skill.
3.0 RESULTS

3.1 Carbon Footprint Results

The objective for the carbon footprint analysis was to determine if there was a difference in carbon emissions per student per experiment between the comparable laboratory experiments. Based on my results, there was a difference between the delivery types. The WWU laboratory experiments had higher emissions per student per experiment than the LabPaq laboratories (Table 3.1.1). The average emissions for the WWU experiments was 1.87 ± 0.09 lb CO\textsubscript{2}-e per student per experiment, while the average emissions for the LabPaq experiments was 0.77 ± 0.06 lb CO\textsubscript{2}-e per student per experiment.

The laboratory that had the highest emissions was Chem 101: Measurement and Density (2.08 lb CO\textsubscript{2}-e per student per experiment). This was due to the emissions from printing and paper usage; at 12 pages, it had the longest laboratory manual of any of the experiments evaluated. But the overall difference in emissions between delivery methods was because the infrastructure emissions for the chemistry building were much higher than for an individual’s home. This was expected because the teaching laboratories had a much larger area to heat and illuminate than a home kitchen (1734 ft\textsuperscript{2} versus 300 ft\textsuperscript{2}, respectively) as well as more energy intensive equipment that are always operational (e.g. fume hoods).

It is interesting to note that WWU’s emissions per person per day in 2007 was 16 lb CO\textsubscript{2}-e (WWU, 2010), which means for every three hours, about 2 lb CO\textsubscript{2}-e was emitted. This was similar to the average emissions per student per three-hour experiment on-campus, which was 1.87 lb CO\textsubscript{2}-e. A student spending three hours conducting a chemistry experiment at home would have fewer emissions (0.77 lb CO\textsubscript{2}-e).
3.2 Cost Comparison Results

The LabPaq laboratories were more expensive per student per experiment than the WWU laboratories (Table 3.2.1) when the WWU personnel costs incorporated both graduate TAs and faculty members as laboratory instructors. The average cost per student per experiment for the WWU laboratories was $11.65 ± $0.88, while the average cost per student per experiment for the LabPaq laboratories was $14.32 ± $0.03. However, when compared to the cost of WWU faculty instruction alone ($18.47 ± $0.88; Table 3.2.2), the WWU laboratories were more expensive. The biggest difference in costs occurred if the WWU laboratory sections were taught entirely by graduate TAs ($9.38 ± $0.88; Table 3.2.3).
Table 3.1.1: The carbon emissions per student for the Western Washington University and LabPaq chemistry experiments.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>lb CO₂-e per student</th>
<th>LabPaq Experiment #</th>
<th>Experiment</th>
<th>lb CO₂-e per student</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Determination of fat in chips</td>
<td>1.82</td>
<td>10</td>
<td>Caloric Content of Food</td>
<td>0.73</td>
</tr>
<tr>
<td>101</td>
<td>Measurement and density</td>
<td>2.08</td>
<td>2</td>
<td>Lab Techniques and Measurements</td>
<td>0.81</td>
</tr>
<tr>
<td>101</td>
<td>TLC analysis of analgesic drugs</td>
<td>1.88</td>
<td>15</td>
<td>Chromatography of Food Dyes</td>
<td>0.77</td>
</tr>
<tr>
<td>121</td>
<td>Introduction to measurements</td>
<td>1.91</td>
<td>2</td>
<td>Lab Techniques and Measurements</td>
<td>0.81</td>
</tr>
<tr>
<td>121</td>
<td>Solutions and dilutions</td>
<td>1.75</td>
<td>14</td>
<td>Beers Law and Colorimetry</td>
<td>0.84</td>
</tr>
<tr>
<td>121</td>
<td>Analysis of Vinegar</td>
<td>1.81</td>
<td>16</td>
<td>Titration for Acetic Acid in Vinegar</td>
<td>0.69</td>
</tr>
<tr>
<td>121</td>
<td>The nine solution problem</td>
<td>1.77</td>
<td>8</td>
<td>Ionic Reactions</td>
<td>0.73</td>
</tr>
<tr>
<td>122</td>
<td>Bleach analysis</td>
<td>1.93</td>
<td>11</td>
<td>Determination of Water Hardness</td>
<td>0.73</td>
</tr>
<tr>
<td>122</td>
<td>Synthesis of copper sulfate pentahydrate</td>
<td>1.91</td>
<td>9</td>
<td>Stoichiometry of a Precipitation Reaction</td>
<td>0.73</td>
</tr>
<tr>
<td>122</td>
<td>Reaction of crystal violet with NaOH: A kinetic study</td>
<td>1.87</td>
<td>17</td>
<td>Reaction Order and Rate Laws</td>
<td>0.84</td>
</tr>
</tbody>
</table>
Table 3.1.2 The cost per student for the Western Washington University chemistry experiments and comparable LabPaq experiments.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Cost per student</th>
<th>LabPaq Experiment</th>
<th>Experiment</th>
<th>Cost per student</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Determination of fat in chips</td>
<td>$12.41</td>
<td>10</td>
<td>Caloric Content of Food</td>
<td>$14.31</td>
</tr>
<tr>
<td>101</td>
<td>Measurement and density</td>
<td>$12.47</td>
<td>2</td>
<td>Lab Techniques and Measurements</td>
<td>$14.34</td>
</tr>
<tr>
<td>101</td>
<td>TLC analysis of analgesic drugs</td>
<td>$12.44</td>
<td>15</td>
<td>Chromatography of Food Dyes</td>
<td>$14.32</td>
</tr>
<tr>
<td>121</td>
<td>Introduction to measurements</td>
<td>$10.66</td>
<td>2</td>
<td>Lab Techniques and Measurements</td>
<td>$14.34</td>
</tr>
<tr>
<td>121</td>
<td>Solutions and dilutions</td>
<td>$10.62</td>
<td>14</td>
<td>Beers Law and Colorimetry</td>
<td>$14.36</td>
</tr>
<tr>
<td>121</td>
<td>Analysis of Vinegar</td>
<td>$10.62</td>
<td>16</td>
<td>Titration for Acetic Acid in Vinegar</td>
<td>$14.29</td>
</tr>
<tr>
<td>121</td>
<td>The nine solution problem</td>
<td>$10.64</td>
<td>8</td>
<td>Ionic Reactions</td>
<td>$14.31</td>
</tr>
<tr>
<td>122</td>
<td>Bleach analysis</td>
<td>$12.22</td>
<td>11</td>
<td>Determination of Water Hardness</td>
<td>$14.31</td>
</tr>
<tr>
<td>122</td>
<td>Synthesis of copper sulfate pentahydrate</td>
<td>$12.24</td>
<td>9</td>
<td>Stoichiometry of a Precipitation Reaction</td>
<td>$14.31</td>
</tr>
<tr>
<td>122</td>
<td>Reaction of crystal violet with NaOH:</td>
<td>$12.21</td>
<td>17</td>
<td>Reaction Order and Rate Laws</td>
<td>$14.36</td>
</tr>
<tr>
<td></td>
<td>A kinetic study</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.1.3: The cost per student for the Western Washington University chemistry experiments if taught by faculty.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Cost per student</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Determination of fat in chips</td>
<td>$19.22</td>
</tr>
<tr>
<td>101</td>
<td>Measurement and density</td>
<td>$19.29</td>
</tr>
<tr>
<td>101</td>
<td>TLC analysis of analgesic drugs</td>
<td>$19.26</td>
</tr>
<tr>
<td>121</td>
<td>Introduction to measurements</td>
<td>$17.47</td>
</tr>
<tr>
<td>121</td>
<td>Solutions and dilutions</td>
<td>$17.43</td>
</tr>
<tr>
<td>121</td>
<td>Analysis of Vinegar</td>
<td>$17.43</td>
</tr>
<tr>
<td>121</td>
<td>The nine solution problem</td>
<td>$17.46</td>
</tr>
<tr>
<td>122</td>
<td>Bleach analysis</td>
<td>$19.04</td>
</tr>
<tr>
<td>122</td>
<td>Synthesis of copper sulfate pentahydrate</td>
<td>$19.06</td>
</tr>
<tr>
<td>122</td>
<td>Reaction of crystal violet with NaOH: A kinetic study</td>
<td>$19.03</td>
</tr>
</tbody>
</table>
Table 3.1.4: The cost per student for the Western Washington University chemistry experiments if taught by GTA.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Cost per student</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Determination of fat in chips</td>
<td>$10.14</td>
</tr>
<tr>
<td>101</td>
<td>Measurement and density</td>
<td>$10.20</td>
</tr>
<tr>
<td>101</td>
<td>TLC analysis of analgesic drugs</td>
<td>$10.17</td>
</tr>
<tr>
<td>121</td>
<td>Introduction to measurements</td>
<td>$8.38</td>
</tr>
<tr>
<td>121</td>
<td>Solutions and dilutions</td>
<td>$8.35</td>
</tr>
<tr>
<td>121</td>
<td>Analysis of Vinegar</td>
<td>$8.35</td>
</tr>
<tr>
<td>121</td>
<td>The nine solution problem</td>
<td>$8.37</td>
</tr>
<tr>
<td>122</td>
<td>Bleach analysis</td>
<td>$9.95</td>
</tr>
<tr>
<td>122</td>
<td>Synthesis of copper sulfate pentahydrate</td>
<td>$9.97</td>
</tr>
<tr>
<td>122</td>
<td>Reaction of crystal violet with NaOH: A kinetic study</td>
<td>$9.94</td>
</tr>
</tbody>
</table>
3.3 Literature Review and Curriculum Study Results

3.3.1 Literature Review

The objective of the literature review was to investigate if laboratory kits are a suitable way to deliver a laboratory experience. I found two peer-reviewed laboratory kit studies with statistical comparisons of student performance (Kennepohl, 2007; Reuter, 2009). Three peer-reviewed studies were found that compared either exam or overall course grades between distance and on-campus students in courses with a laboratory kit component (Boschmann, 2003; Casanova et al., 2006; Oliver and Haim, 2009). There were also two studies that reported student survey feedback of first time laboratory kit implementation in distance education chemistry courses (Hoole and Sithambaresan, 2003; Kennepohl, 1996).

Both of the papers with survey feedback reported positive responses from students following the implementation of laboratory kit use. Kennepohl (1996) reported student survey results on one of the first home-study laboratories using a laboratory kit in North America. Kennepohl provided descriptions of the experiments and the materials included in the microlaboratory kit, which contained four experiments and was used with a first semester general chemistry class (CHEM 217) at Athabasca University (Alberta Province, Canada). Students picked up their laboratory kit on day one of laboratory session, signed a safety pledge, and then took the kit home to do the laboratories on their own time. Students were surveyed about the microlaboratory kit at the end of the course (n=85), and overall student response was positive, with greater that 78% favorable responses on whether the lab kit had clear instructions, contained interesting, high quality experiments, reinforced course material,
and encouraged a desire for more home-study labs. The kits were portable, easy to use, inexpensive, safe, and convenient and flexible for the student.

Hoole and Sithambaresan (2003) described their analytical chemistry laboratory kit that tested for implementation while teaching Analytical Chemistry I and II via distance education through the Open University of Sri Lanka. The normal laboratory component included a week of laboratories on-campus, so a limited number of kits were made available as recommended activities for students to test. Over 20 students initially tried the kits; Hoole and Sithambaresan randomly selected five volunteers who had completed the Analytical Chemistry I exam. These five students were asked to respond to an online evaluation to test suitability of the kits as a laboratory component. The survey included questions involving student comfort with the kit, whether supplemental Web material was helpful and user-friendly, and whether the home-laboratories were successful at teaching chemical concepts. Based on the positive feedback from this test group, Hoole and Sithambaresan then incorporated the laboratory kit into an Analytical Chemistry II course with at-home laboratories.

The three studies that compared student grades in courses with laboratory kit components found that distance education student performance was equal to or better than on-campus student performance. Boschmann (2003) described the teaching experience and discussed laboratory kit delivery and the technologies used in Elementary Chemistry 101 for nonmajors at Indiana University-Purdue University Indianapolis. This course has had a distance education option since 1990. Students in the course were issued a laboratory kit with instructions for 12 experiments and necessary equipment for the experiments. The students
used common household items in the experiments. Evaluation included an external review (consisting of reports, student evaluations, and interviews), a campus assessment of satisfaction, and an analysis of student pre- and post-course test performance. The external review found that students liked the flexibility of the distance laboratory and the technology used in delivery (web or television) was not a hindrance. Drawbacks were that it also requires self-discipline and the laboratory experiments took a long time to perform. The campus assessment of satisfaction found that distance and on-campus students were equally satisfied except when communication would break down for the distance education students.

Student performance was assessed by administering a pretest in both the on-campus and distance courses. It contained 25 multiple-choice questions that covered a variety of topics presented in the course. The same test was administered again at the end of the semester. This was done for two semesters in the 1999-2000 academic year. The distance education students performed as well or better than the on-campus students (based on the number of A’s), although they also withdrew from class at a much higher rate than the on-campus students. When one looks at student performance distribution across all of the grades earned and not just the number of A’s, the trends are more obfuscated because there were large differences in sample sizes between the on-campus and distance education students, and the authors did not take this into account when discussing their findings. For example, in Fall 1999, there were 196 students in the daytime on-campus course, but only 24 students in the web-based course; of those 24, almost half (45.8%) of the students withdrew. This was twice that of the on-campus course withdrawals (21.9%). Based on the unequal sample sizes and high rates of withdrawal, it is difficult to draw clear conclusions about student performance.
Casanova et al. (2006) described a hybrid and an online chemistry course in which students at Cape Fear Community College were provided with kitchen chemistry laboratory experiments. The two versions of the distance education course were paired with sections of a conventional course at the University of North Carolina-Wilmington. Qualitative data for the online course was collected via Web-based forums. The at-home laboratory met 9 of the 17 conventional laboratory objectives described for University of North Carolina-Wilmington. Quantitative comparisons of the final exam and laboratory practical were also evaluated. The average exam scores of the distance learning students were higher than the conventional student scores (75.84 for hybrid, 80.11 for online versus the on-campus 61.98 and 65.63, respectively). However, the sample sizes were vastly different. There were 25 students in the hybrid course compared to 117 students in the conventional course. The online course had 30 students, while the conventional course had 318. Casanova et al. (2006) caution that the groups were non-equivalent, so only general conclusions about learning method effectiveness can be drawn. They concluded that the various formats can complement the “personal situations and learning styles of different groups.”

Oliver and Haim (2009) described an at-home digital design laboratory that used a hardware kit for an engineering course. Traditional digital design laboratories consist of on-campus design practice sessions, which require infrastructure, resources, and time. Possible alternatives are the same as for chemistry laboratories, and have similar drawbacks. These include simulations (which lack design process), remote laboratories (logistical issues with remote configurable hardware), or at-home laboratories.
The authors designed and gave students hardware kits that contained a board, power source, design software, and a user manual. The kits were used in conjunction with three topics: combinational circuits, sequential circuits, and hardware description language. More than 65 students in four courses had to analyze a given problem, design a solution, and test the circuit using the hardware kit. Effectiveness was evaluated using an analysis of laboratory learning objectives and final course grade comparisons before and after the implementation (the laboratory was not graded prior to implementation so they could not compare). Course grades were reported as the percentage of students with grades higher than 50% in a bar graph for 2000 through 2007. After throwing out one set of results from 2004 because they were “exceptional,” Oliver and Haim reported that before the 2004 implementation of the laboratory kits, just over half of the students (52%) had final course grades higher than 50%. This increased to an average of 64% following implementation. The learning objective analysis involved describing how the new laboratory kits meet the ABET/Sloan Colloquy laboratory objectives of instrumentation, models, experiment, data analysis, design, learn from failure, creativity, psychomotor, safety, communication, teamwork, ethics in the laboratory, and sensory awareness.

Two other studies also used statistical analyses to evaluate student performance in courses involving laboratory kit experiments. Kennepohl (2007) reviewed the transition from traditional laboratories to home-study laboratory kits over 15 years in Athabasca University’s distance education Chemical Principles I (CHEM 217) course. Kennepohl examined the student experience and actual performance and found that student grades remained essentially unchanged over time. The laboratory component began as face-to-face instruction
on campus or in regional centers, and then became a kitchen chemistry laboratory experience, and finally a full home-study laboratory kit was incorporated into the laboratory curricula. Student performance in laboratory, assignments and exams were tracked throughout different versions of the course (six in total), and a t-test was used to assess performance as the course changed. The only significant difference in scores was the midterm and final examinations and laboratories scores when the initial transition was made to the full home-study laboratory component. Student feedback through surveys and qualitative ratings were positive.

Reuter (2009) had the best study with regards to experimental set-up and statistical analysis. Reuter compared the on-line and on-campus version of a soils course offered through Oregon State University Ecampus and OSU-Cascades Campus/Central Oregon Community College to see if there was a significant difference between on-campus or online laboratory-based science courses. Students enrolled in Soils: Sustainable Ecosystems were informed of the study and given the option of participating or not. The course lecture material, exams, and quizzes were identical for both delivery types. The laboratories covered similar content, and several of the on-campus field experiments used the same methods that the online students would use for a particular experiment. The online students conducted the laboratory component using a laboratory kit that they supplemented with household materials. The study lasted for two terms. Students took standardized pre- and post-term assessments designed to test knowledge and skills from both the laboratory and lecture components. A statistical evaluation was done on the pre- and post-term assessments, overall course grade, and laboratory grade. Reuter found no significant difference between overall
grade or laboratory grade between course type. Reuter also compared student demographics and found that mean age was significantly different, with the online students averaging 34 years of age and the on-campus students 25 years.

### 3.3.2 WWU and LabPaq Experiment Laboratory Manual Analysis

The purpose of the laboratory manual analysis was to compare the traditional and alternative laboratory deliveries to see if there was a difference in laboratory manual content in terms of cognitive skill use. The verb content analysis did not reveal a strong difference between delivery styles, although the WWU laboratories tended to draw from more skill categories than the LabPaq laboratories (Table 3.3.1). The analysis did reveal that the IMF laboratory required students to utilize cognitive skills from all six categories, and that there were more instances of illustrative verbs compared to the other experiments. This illustrates that the verb content analysis is robust enough to pick out the differences in delivery styles within the WWU general chemistry curriculum (a constructivist versus a “cookbook” approach).

All of the experiments I analyzed required the use of at least one type of cognitive skill. All but one of the laboratory experiment manuals demanded lower order cognitive skills (those in the Knowledge, Comprehension, or Application categories). The most common category was Application; all but one of the laboratories had students use cognitive skills from this category. The most frequently found verbs were show and use (Appendices F and G).

The higher order cognitive skill categories (Analysis, Synthesis, and Evaluation) were present in six of the laboratory manuals. Three of these were WWU laboratories and three
were LabPaq laboratories. Another item to note is that although two of the LabPaq laboratories utilized the Synthesis skills, I considered the manner in which they were incorporated more appropriately classified in the Application category (although I left them labeled as Synthesis). Synthesis is a higher-order skill that involves the ability to put bits of information together to form a new whole; while these two LabPaq laboratories ask the student to write new chemical reactions or rate laws, they are walked through the process in minute detail in the introductory material. The student is technically putting bits of information gathered from the laboratory experiment together to form a new whole, but in the most basic way possible as they are merely following step-by-step instructions rather than figuring it out on their own.

There are no real trends or differences between the LabPaq and the WWU laboratory experiments. The average number of verb instances for the LabPaq laboratories was $4 \pm 1.7$ compared to $6 \pm 2.7$ for WWU. There was a large difference between the IMF laboratory and all of the other laboratories. This laboratory required students to utilize all six types of cognitive skills and was the only one that included all lower and higher order cognitive skills. Additionally, its total verb count was 32 which is four times greater than the next highest (8 verbs, Chem 122: Synthesis of Copper Sulfate Pentahydrate).

The analysis of pre-, post-laboratories and manuals of the WWU laboratories further illustrates this difference (Table 3.3.2). While the inclusion of the pre- and post-laboratories increased the instances of verbs, the IMF laboratory still had the highest verb count (40). About half (53%) of the illustrative verbs in the IMF laboratory were from the higher
cognitive skill categories, compared to only 43% in the laboratory with the next highest overall verb count (Chem 122: Reaction of Crystal Violet with NaOH, 28 verbs total).
Table 3.3.1: The number of instances and percentage of illustrative verbs in each category of Bloom's taxonomy. Laboratory manuals only.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Knowledge</th>
<th>Comprehension</th>
<th>Application</th>
<th>Analysis</th>
<th>Synthesis</th>
<th>Evaluation</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEM 122</td>
<td>Intermolecular Forces &amp; Physical Properties</td>
<td>1 (3.1%)</td>
<td>2 (6.3%)</td>
<td>12 (37.5%)</td>
<td>3 (9.4%)</td>
<td>7 (21.9%)</td>
<td>7 (21.9%)</td>
<td>32 (100%)</td>
</tr>
<tr>
<td>CHEM 101</td>
<td>TLC Analysis of Analgesic Drugs Chromatography of Food Dyes</td>
<td>2 (28.6%)</td>
<td>1 (14.3%)</td>
<td>2 (28.6%)</td>
<td>2 (28.6%)</td>
<td></td>
<td></td>
<td>7 (100%)</td>
</tr>
<tr>
<td>LP 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 (100%)</td>
</tr>
<tr>
<td>CHEM 121</td>
<td>Analysis of Vinegar</td>
<td>2 (100%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 (100%)</td>
</tr>
<tr>
<td>LP 16</td>
<td>Titration for Acetic Acid in Vinegar</td>
<td>4 (66.7%)</td>
<td></td>
<td></td>
<td>2 (33.3%)</td>
<td></td>
<td></td>
<td>6 (100%)</td>
</tr>
<tr>
<td>CHEM 122</td>
<td>Synthesis of CuSO₄•5H₂O</td>
<td>1 (12.5%)</td>
<td></td>
<td>6 (75%)</td>
<td>1 (12.5%)</td>
<td></td>
<td></td>
<td>8 (100%)</td>
</tr>
<tr>
<td>LP 9</td>
<td>Stoichiometry of a Precipitation Reaction</td>
<td>3 (60%)</td>
<td></td>
<td>2 (40%)</td>
<td></td>
<td></td>
<td></td>
<td>5 (100%)</td>
</tr>
<tr>
<td>CHEM 122</td>
<td>Reaction of Crystal Violet and NaOH</td>
<td>7 (100%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7 (100%)</td>
</tr>
<tr>
<td>LP 17</td>
<td>Reaction Order and Rate Laws</td>
<td>3 (75%)</td>
<td></td>
<td>1 (25%)</td>
<td></td>
<td></td>
<td></td>
<td>4 (100%)</td>
</tr>
</tbody>
</table>
Table 3.3.2: Laboratory manuals and pre- and post-laboratories for select chemistry laboratories, number of instances and percentage of illustrative verbs in each category.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Knowledge</th>
<th>Comprehension</th>
<th>Application</th>
<th>Analysis</th>
<th>Synthesis</th>
<th>Evaluation</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEM 122</td>
<td>Intermolecular Forces &amp; Physical Properties</td>
<td>1 (2.5%)</td>
<td>3 (7.5%)</td>
<td>15 (37.5%)</td>
<td>7 (17.5%)</td>
<td>7 (17.5%)</td>
<td>7 (17.5%)</td>
<td>40 (100%)</td>
</tr>
<tr>
<td>CHEM 122</td>
<td>Reaction of Crystal Violet and NaOH</td>
<td>1 (3.6%)</td>
<td>2 (7.1%)</td>
<td>13 (46.4%)</td>
<td>1 (3.6%)</td>
<td>8 (28.6%)</td>
<td>3 (10.7%)</td>
<td>28 (100%)</td>
</tr>
<tr>
<td>CHEM 122</td>
<td>Synthesis of CuSO₄•5H₂O</td>
<td>1 (9.1%)</td>
<td>1 (9.1%)</td>
<td>8 (72.7%)</td>
<td></td>
<td>1 (9.1%)</td>
<td></td>
<td>11 (100%)</td>
</tr>
<tr>
<td>CHEM 121</td>
<td>Analysis of Vinegar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.0 DISCUSSION

4.1 Carbon Footprint

At-home laboratories had a smaller carbon footprint than traditional laboratories. Additionally, the use of large quantities of toxic substances that required special disposal as hazardous waste was avoided when students conducted an experiment using a laboratory kit. It would be possible for on-campus laboratories to be redesigned with more eco-friendly reactions by applying principles of green or microscale chemistry in the laboratory (Haack et al., 2005).

Changing the laboratory curriculum to be more eco-friendly does not address the carbon emissions associated with the infrastructure (e.g. fume hoods, heating, equipment standby electricity) because most of those infrastructure emissions would occur regardless of what class was meeting in the teaching laboratories. Those emissions would occur even if an institution such as WWU were to implement the use of at home laboratory kits.

It could be environmentally beneficial if an institution such as WWU were to offer laboratory kit laboratory components in addition to their traditional on-campus curriculum, particularly when the large numbers of students enrolled in just one quarter of general chemistry are taken into account. The resulting environmental impact from increasing student enrollment would be smaller than if the department decided to increase the number of on-campus laboratory offerings to accommodate more students.

One limitation in my calculations was my assumption that the entire building (whether the Chemistry Building or student’s home) was being heated equally. The heating emissions per square foot were calculated from overall data, and the laboratory space
emissions determined from that value. This is unlikely as different rooms or hallways within each building would use different amounts of heat. Another limitation to this analysis is the assumption that the student with the laboratory kit is conducting their laboratory experiment in an off-campus home and not in another location such as a dorm room, a learning commons, an empty classroom, at another person’s home.

The largest limitation to the carbon footprint analysis was not including comprehensive Tier 3 emissions. These are complete supply chain emissions from the moment each product is created to its end-of-life. The majority of the carbon footprint is omitted when the emissions of refining, manufacturing, and assembling the individual experiments in the laboratory kit. The supply chain emissions for all of the chemical reagents and materials used in the traditional chemistry laboratories were also not included, and thus the WWU chemistry laboratory emissions are also under represented.

4.2 Cost

The objective for the cost analysis was to determine if there was a difference in cost per students between the comparable laboratory experiments. This thesis showed that the LabPaq experiments were more expensive than the WWU experiments. However, this difference changes depending on the assumption of who is teaching the WWU labs because faculty wages are more expensive than graduate teaching assistants. Another item that was underestimated was the purchase and shipping cost of the laboratory kit. I assumed that the student who purchased the laboratory kit would conduct all 20 experiments, but I only used 9 experiments in the comparisons. If I had divided the laboratory kit cost by 9 rather than 20, the cost would be greater ($31.56 for 9 experiments versus $14.20 for 20). However, WWU
students do nine experiments a quarter, and of those I only evaluated three for Chem 101, four for Chem 121, and three for Chem 122. I also underestimated the combined cost of the entire curriculum per student per course (i.e. Chem 121). If you consider that a laboratory kit is a full semester of chemistry laboratories, I evaluated 45% of the laboratories compared to 33% for Chem 101, 44% for Chem 121, and 33% for Chem 122. Although these costs were underestimated, they were consistently underestimated for both delivery scenarios.

The sensitivity of my study to the assumptions in place when calculating costs is its biggest limitation. For example, I assumed that non-tenure track faculty teach two laboratory sections per week, for a cost of $11.68 per student per experiment. If I had assumed that the non-tenure track faculty member taught one laboratory per week instead of two, the cost per student per experiment would be $23.37. Because the cost (and carbon emissions) calculations are strongly influenced by the boundary conditions and assumptions I used, my results are only valid for the specific scenarios I described.

Many of the other variables for the WWU and LabPaq costs may have been underestimated. For example, the number of gloves and Kimwipes used by the general chemistry laboratories was a very conservative estimate (Gary Carlton, Personal Communication). Another variable that I encountered when teaching the general chemistry laboratories was the volumes of hazardous waste generated by students; although the Chemistry Department incorporates some amount of excess into the estimated waste generation, far more is actually generated.

The manner in which the costs were structured means that for the LabPaq laboratory experiments the only variable that had a large impact on cost (and carbon footprint) was the
number of laboratory manual pages being printed. However, including a different number of laboratories in calculating the cost of materials in the laboratory kit would drastically change the overall cost, as illustrated above. Finally, tuition and laboratory fees for both delivery scenarios should also be incorporated into the calculations as well to assess who is bearing more of the financial burden of running the laboratories—the students or the academic institution.

4.3 Literature Review and Curriculum Study

The objectives for the pedagogical literature review and the comparisons between equivalent laboratory manuals was investigate if the alternative delivery method has been successfully implemented and to see if there were differences between the manual content. Overall, my findings indicated that laboratory kits were acceptable ways to deliver a chemistry laboratory, but that there was not enough research to conclude that one form of delivery is better than another. Each had its advantages and disadvantages, and each delivery method was susceptible to the same problems of “cookbook” style laboratory experiences that did not readily foster the use of higher cognitive skills.

The main conclusions I can draw from the literature review is that students have positive views of the use of laboratory kits. In addition, the studies I found indicated that there was no difference in student performance between delivery methods. Although some studies indicated that the online students using laboratory kits performed better than the traditional on-campus students, these studies have very uneven sample sizes, have had high dropout rates, and resulted from uneven demographics (Casanova et al., 2006; Reuter, 2009).
I also discovered that there were very few published, peer-reviewed studies that measured outcomes of student learning with laboratory kits, particularly well-designed studies evaluating the effectiveness of laboratory kits in distance and online education. This is clearly something that needs to be addressed because online education has increased in popularity in the last decade.

I am not alone in having difficulties in finding studies evaluating the use of laboratory kits as an alternative form of general chemistry laboratory delivery. Even research on traditional laboratory experiences, which one would at first glance think would be easy to find, is “methodologically weak and fragmented” (National Research Council, 2005). This makes it difficult to draw accurate conclusions about the effectiveness of traditional laboratory delivery, which is somewhat surprising considering the science teaching laboratory has been in use since the early 1800s (Pickering, 1993).

It is no wonder that published, peer-reviewed studies that discuss postsecondary laboratory delivery methods and analyze effectiveness are "widely scattered" in the literature (Kennepohl, 2009). Kennepohl suggested that the reason is because many of the educators view themselves as academic research scientists who happen to teach, and not as science educators. While there are many instructors teaching laboratory sciences, few are publishing how they teach labs, particularly with regard to format of delivering the laboratory. Meyer (2003) said that there are few studies that use solid experimental design to assess multiple variables in evaluating online versus traditional education.

It is important to note that many researchers evaluate student performance using exam or final course grades when measuring effectiveness of the laboratory kit. This process of
assessing performance does not necessarily reflect student comprehension or permanent learning of important course concepts. Many courses, especially in the sciences, are taught in ways that encourage short-term memorization over deeper understanding. Students often come into courses with prior misconceptions regarding scientific phenomena that, unless they are recognized and addressed, will persist long after the student has taken their final exam (Bransford et al., 2000). Effective comparisons of alternative and traditional delivery methods should not be solely based on grades. It should include a variety of measured outcomes, especially regarding student conceptual understanding and what kinds of cognitive skills students are using.

So what are the potential benefits and drawbacks to the use of laboratory kits? Laboratory kits are a hands-on way of conducting chemistry experiments at home or outside of the traditional laboratory environment. The use of laboratory kits could enable more institutions to offer online chemistry courses with laboratory components, thereby increasing student access to courses that are in high demand. Laboratory kit experiments performed at home can also allow greater flexibility with scheduling because students can spend as much time as they need on laboratory experiments. This makes it easier for students to learn at their own pace without being rushed. There is also the added benefit that children of non-traditional students could watch their parents perform experiments. Carrigan (2012) relays that some older children have considered this to be “very cool.”

Home laboratory kits can show students the real world applicability of chemistry because they can witness chemistry in action when conducting experiments using household items. And as this thesis demonstrated, the laboratory kits were also more environmentally
friendly because they use small or no amounts of hazardous chemicals and also had fewer carbon emissions associated with them.

The laboratory kits can be cheaper for the home institution because much of the costs for conducting a laboratory course are shifted onto the student. While this could be a major drawback for students, Carrigan (2012) observed that despite the high price tag of commercial laboratory kits, using LabPaq chemistry kits actually saved her students at Portland Community College money on gas, child care, parking costs, and lodging. Students may also save money on the purchase of expensive textbooks, tuition, and laboratory fees. Students may be more likely to be actively involved in their learning if they invest hundreds of dollars into a laboratory kit.

A major drawback of laboratory kits is that students do not have real-time interaction with instructors, and cannot get immediate feedback if they have questions or problems with the procedure or with conceptual understanding. Additionally, a laboratory kit at home means that the students do not get the chance to work in an actual wet chemistry laboratory.

The laboratory kit laboratories also can be just as “cookbook” as traditional laboratories, and possibly even more so because there is no instructor present to assess real-time conceptual understanding and misconception formation. There is also the added difficulty of how the instructor can effectively assess student performance and understanding if they are not able to interact face-to-face. Video-conferencing and discussion boards are potential workarounds to this, but there are physical and temporal limitations to what an instructor and see and do via the Internet. Instructors are not always efficient at gauging student progress in a traditional laboratory setting, particularly when they have large
laboratory sections. Each delivery type has its strengths and weaknesses, and each type may appeal to students with a variety of learning styles.

In conclusion, there is no clear evidence that one form of delivery is more effective than the other. This is mostly due to the fact that well designed comparisons are practically non-existent. The larger, unanswered question is whether both forms of delivery are effective in their most common applications. Both laboratory kits and traditional laboratory effectiveness should be subjected to rigorous investigations utilizing strong experimental design and measures of actual student conceptual learning rather than student performance on exams and final grades.
5.0 CONCLUSION

I found that laboratory kit experiments were associated with fewer carbon emissions and higher monetary costs than traditional laboratory experiments. The laboratory kit and traditional laboratory experiments had similar content with regards to the types of cognitive tasks expected of the student. I also found that the published data on laboratory kits and student performance was either survey-based or based on outcomes of student satisfaction or course grades. There is a need for peer-reviewed studies with good experimental design that compare student performance with a laboratory kit experience to a face-to-face laboratory experience. There is also a need for more studies assessing the effectiveness of traditional face-to-face laboratories, particularly well-designed studies that measure learning outcomes in a teaching environment that encourages student learning and not rote memorization of materials and procedures.

The flexibility of an at-home laboratory kit laboratory component can increase accessibility for non-traditional or overburdened students. Because many students take only first quarter general chemistry there is a lot of competition for course times that accommodate a student's busy schedule. The use of laboratory kits could decrease the possibility of course conflicts for students, particularly those who are not planning on continuing on in a laboratory science. The drawback is that the student loses out on the laboratory experience, and that is a big failure if part of the goal of general chemistry is to give students exposure to working in a laboratory.

Laboratory kits are also a way of delivering a laboratory in non-traditional learning settings, such as online, and can be used in conjunction with an online chemistry course.
Students can and do take online chemistry courses. Many of those students are non-traditional students who work full time and have families or other responsibilities that put them at a disadvantage compared to traditional students who can dedicate all of their time to their studies if they so desire. Therefore, if educators continue to place an emphasis on the importance of the laboratory to learning chemistry (even though the literature does not support this), it would make sense that an institution with online chemistry offerings should try to provide a high quality laboratory experience that results in similar learning outcomes and student performance in comparison to their on-campus offerings.

A chemistry course offering in any learning setting should have a laboratory component and laboratory kits are tools that could help develop analytical thinking and other cognitive skills that we would desire from a scientifically literate, well-informed public. It is important to remember, though, that laboratory experiments, whether on-campus or in the kitchen, are still just one of many tools that can be used to educate students in chemistry.
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APPENDIX A: The overall assumptions for my thesis. These assumptions are for both traditional and alternative delivery methods unless otherwise stated.

Overall Assumptions

1) The traditional laboratories were conducted at Western Washington University.

2) The student using the laboratory kit took an on-campus lecture but performed laboratories at home.

3) Initial costs and emissions associated with the traditional laboratory were not considered; only those related to the existing curriculum were considered.

4) Traditional laboratory manuals used were from 2008-2009 except for the Chem 122 Intermolecular Forces & Physical Properties laboratory which was from 2011.

5) Chem 101 laboratories were two hours long; Chem 121, 122, and the laboratory kit laboratories were three hours.

6) Calculations assumed a full traditional laboratory section, or 24 students in CB 210.

7) Traditional wet laboratories were taught in the Chemistry Building (CB) general chemistry teaching laboratories CB 210 (or CB 220, which has identical square footage and design layout to CB 210). Laboratories are usually running simultaneously in both laboratories.

8) I determined values unless Naftz and Thomas (2009) are cited.

9) Laboratory kit experiments were conducted in the kitchen of an average American home. The average kitchen size was 300 ft^2 (ABC News, 2005; Naftz and Thomas, 2009) and the average American home was 2,438 ft^2 (US Census Bureau Online, accessed April 24, 2012).

10) The laboratory kit scenario kitchen was lit by two 26 W fluorescent light bulbs.

11) CB 210 computers and monitors were in idle mode for the duration of the experiment (only idle and maximum processing mode power ratings were available).

12) Alternative scenario students spent 0.5 hour with an active laptop and 2.5 hours with the laptop in standby per laboratory experiment.

13) Printers were in standby for duration of experiment for each scenario.
APPENDIX A, continued

14) The traditional laboratory contained twelve Dell Optiplex 755 computers, twelve Dell 15” Flat Screen LCD monitors, and an HP 9050n printer.

15) The alternative scenario student had an HP DeskJet 1000 printer and a Dell Inspiron 15 laptop.

16) Students in either scenario printed their laboratory manual to perform the experiment.

17) Laboratories took place during normal academic year (September to June) for both scenarios.

18) Natural gas was used for heating in the laboratory kit scenario, and the average American home emitted 6,400 lb CO₂ for heating (Naftz and Thomas, 2009; NPR, 2007)

19) Both scenarios used Puget Sound Energy as the electric service provider, and both scenarios had the same energy source profile.

20) The student who used the laboratory kit lives in Bellingham, WA and attends Western Washington University.

21) No hazardous waste was generated for laboratory kit scenario.
APPENDIX B: Specific assumptions for the carbon footprint, cost, and curriculum comparisons. Unless specified otherwise, the assumptions are for both traditional and alternative delivery methods.

**Carbon Footprint Assumptions**

1) Emissions were calculated in pounds of carbon dioxide (or carbon dioxide equivalents, if available) per student per experiment.

2) Electricity was purchased from Puget Sound Energy and 1 kWh produced 1.04 lb CO₂-e (PSE 2009).

3) Western Washington University’s steam plant produced 11.5 lb CO₂-e per therm (Hagen, 2009; as cited by Naftz and Thomas, 2009).

4) Products and supplies were shipped to Bellingham, WA.

5) Average packaging weight of shipments for traditional delivery method was 1.5 lbs, average laboratory kit weight was 4.4 lbs, and ground transportation emitted 2.2 x 10⁻⁴ lb CO₂ per mile per pound package weight (Naftz and Thomas, 2009).

6) Average ground shipping distance was 2,117 miles for chemical suppliers (originating in Philadelphia, San Francisco, Houston or Chicago) and 2,174 miles for LabPaq (originating in Englewood, CO or Syracuse, NY). These values were calculated by Naftz and Thomas (2009).

7) Density of hazardous waste was equal to density of water at 25°C (1 g/mL).

8) Hazardous waste incineration released 0.196 lb CO₂ per pound of waste (Reinhardt et al., 2008).

9) One pound of paper is 110 sheets and had emissions equivalent to 4.3 lb CO2-e or 0.039 lb CO₂-e per sheet ((BlueSkyModel.org, accessed May 4, 2012).

10) For both scenarios I assumed that the entire building and not just the laboratory space (either kitchen or traditional laboratory) was being heated. The heating emissions per square foot were calculated, and the laboratory space emissions determined from that value.

**Cost Comparison Assumptions**

1) Natural gas was purchased from Cascade Natural Gas at the 2009 rate of $1.26 per therm (pricing was from personal gas bills in 2009).
APPENDIX B, continued

2) Electricity was purchased from Puget Sound Energy (2009) at the 2009 rate of $0.07 per kWh.

3) Faculty laboratory instruction was provided by non-tenure track faculty who taught two traditional laboratory sections per week.

4) Faculty office hours (both scenarios) and laboratory instructor salary (alternative) were not included.

5) Graduate teaching assistants taught three laboratory sections and conduct two hours of office hours per week. Tuition wavers were not included in the cost.

6) The laboratory coordinator spent four hours per laboratory course per week (Brandon Dietrich, Personal Communication).

7) Only chemical consumables were considered; re-usable materials were not included.

8) Academic pricing from Fisher Scientific using 2012 rates was used, but not tax or shipping costs.

9) I assumed a 55-gallon poly drum was used to store and dispose of the hazardous waste, and that the waste and poly drum were incinerated.

10) Paper was purchased from either Western Washington University’s Central Stores (traditional) or Staples (alternative) at a cost of $4.61 or $9.29 per ream, respectively. All paper purchased was 100% recycled.

11) Laboratory preparers spent four hours per week preparing the laboratories (traditional).

**Curriculum Comparison Assumptions**

1) Only laboratory manuals were included for comparisons between traditional and alternative methods of delivery.

2) Pre- and post-laboratories as well as laboratory manuals for select Chem 121 and 122 laboratories were used to validate the illustrative verb analysis.
### APPENDIX C: LabPaq CK-S laboratory experiment learning objectives (from Jeschofnig, 2008)

<table>
<thead>
<tr>
<th>Lab</th>
<th>Title</th>
<th>Objectives</th>
</tr>
</thead>
</table>
| 1   | Observations of Chemical Changes     | Observe some properties of chemical reactions  
|     |                                      | Associate chemical properties with household products                                                                                 |
| 2   | Laboratory Techniques and Measurements | Become familiar with several important laboratory techniques  
|     |                                      | Gain proficiency with some of the common measuring devices used in a chemistry laboratory  
|     |                                      | Determine the volume and density of objects                                                                                              |
| 3   | Separation of a Mixture of Solids    | Become familiar with the separation of mixtures of solids                                                                               |
| 4   | Properties of Gases                  | Investigate some physical and chemical properties of gases  
|     |                                      | Use these properties to identify these gases when they are encountered                                                                   |
| 5   | Liquids and Solids                   | Determine the boiling point of a liquid  
|     |                                      | Determine the melting point of a solid                                                                                                  |
| 6   | Physical and Chemical Properties     | Investigate the chemical properties of pure chemical substances  
|     |                                      | Investigate the physical properties of pure chemical substances                                                                            |
| 7   | Identification of Metallic Ions      | Perform and observe the flame tests of some alkali and alkaline earth metal ions                                                          |
| 8   | Ionic Reactions                      | Study the nature of ionic reactions  
|     |                                      | Write balanced equations  
|     |                                      | Write net ionic equations for precipitation reactions                                                                                     |
| 9   | Stoichiometry of a Precipitation Reaction | Predict the amount of product in a precipitation reaction using stoichiometry  
|     |                                      | Accurately measure the reactants and products of the reaction  
|     |                                      | Determine the actual yield vs. the theoretical yield  
|     |                                      | Calculate the percent yield                                                                                                               |
## APPENDIX C, continued

<table>
<thead>
<tr>
<th>Lab</th>
<th>Title</th>
<th>Objectives</th>
</tr>
</thead>
</table>
| 10  | Caloric Content of Food                    | Measure the energy content of various food items  
Became familiar with energy units like calories and joules                               |
| 11  | Determination of Water Hardness using a Titrator | Develop familiarity with the concept of hardness of water  
Practice a titration technique using a Titrator  
Determine the hardness of your local water supply                                          |
| 12  | Colligative Properties and Osmotic Pressure | Compare the freezing point of a pure solvent to that of the solvent in solution with a nonvolatile solute  
Observe the phenomenon of osmosis and gain a fundamental understanding of the principle on which dialysis is based |
| 13  | Le Chaterlier's Principle                  | Determine the effect of a change on a system at equilibrium  
Correlate the observed responses with Le Chaterlier's principle                                                                         |
| 14  | Beer's Law and Colorimetry                | Construct a Beer's Law plot  
Determine the concentration of an unknown using the Beer's Law plot  
Determine the concentration of FD and C Blue #1 dye in a commercial drink using Colorimetry                                         |
| 15  | Chromatography of Food Dyes                | Learn how mixtures of compounds can be separated  
Learn what food dyes are found in certain foods                                                                                         |
| 16  | Titration for Acetic Acid in Vinegar       | Develop familiarity with the concepts and techniques of titration  
Determine the concentration of an acetic acid solution                                                                              |
<table>
<thead>
<tr>
<th>Lab</th>
<th>Title</th>
<th>Objectives</th>
</tr>
</thead>
</table>
| 17   | Reaction Order and Rate Laws               | Study the effect of reactant concentration on the rate of the reaction between sodium thiosulfate and hydrochloric acid  
Determine the order of each reactant and the rate law for the reaction  |
| 18   | Oxidation-Reduction/Activity Series        | Allow students to observe oxidation-reduction reactions  
Introduce students to the activity series  
Allow students to assign Unknown X a place in the activity series  |
| 19   | Electrochemical Cells and Cell Potentials  | Study a redox reaction involving copper and zinc species  
Construct a variety of electrochemical cells  
Learn to use a digital multimeter to measure electrochemical cell potentials and be able to use the appropriate sign conventions to calculate standard reduction potentials from cell potentials  |
| 20   | Qualitative Cation Tests                   | Identify some commonly occurring cations  
Study some of the reactions used for their identification  |
# APPENDIX D: Western Washington University laboratory experiment learning objectives

<table>
<thead>
<tr>
<th>Course</th>
<th>Lab Title</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Determination of fat in chips</td>
<td>Extract fat from chips and calculate % fat and calories based on mass of fat present                                                    Exposure to extraction procedure</td>
</tr>
<tr>
<td></td>
<td>Investigating a Chemical Reaction</td>
<td>Use observations to figure out a reaction took place (heat Mg turnings, turn into MgO)                                                                 Propose a chemical reaction, calculations using mass, moles How does observational evidence support proposed reaction? How would changing experimental conditions affect the reaction?</td>
</tr>
<tr>
<td></td>
<td>Ionic and covalent compounds-electrical</td>
<td>Investigate conductance of various ionic and covalent compounds                                                                 ionic versus covalent compounds (bonds) Writing chemical equations, strong versus weak versus no conductance</td>
</tr>
<tr>
<td></td>
<td>conductance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Measurement and Density</td>
<td>Introduction to lab, measurements and density                                                                                             Mass versus volume, how to measure and calculate mass, volume and density</td>
</tr>
<tr>
<td></td>
<td>TLC analysis of analgesic drugs</td>
<td>Concept and application of chromatography                                                                                                 Introduction to common procedure in organic chem Calculation of $R_f$, identify analgesics in pills</td>
</tr>
</tbody>
</table>
## APPENDIX D, continued

<table>
<thead>
<tr>
<th>Course</th>
<th>Lab Title</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>121</td>
<td>Introduction to</td>
<td>Familiarize students with laboratory</td>
</tr>
<tr>
<td></td>
<td>Measurements</td>
<td>Introduce laboratory equipment and glassware, familiarize students with proper techniques Demonstrate precision and accuracy with taking measurements</td>
</tr>
<tr>
<td></td>
<td>Solutions and Dilutions</td>
<td>Use volumetric glassware to prepare dilutions from stock solution; emphasis is on dilution techniques, not the colorimetry Work on pipetting technique Demonstrate use of instrument technique (colorimeter) as chemistry laboratory tool; learn how to use it Collect absorbance data, generate linear regression plot using modified beer’s law</td>
</tr>
<tr>
<td></td>
<td>Types of Chemical</td>
<td>Introduce/demonstrate combination, decomposition, single replacement, double replacement Carry out several reaction types, make observations and use variety of laboratory techniques Write balance chemical equations (w/ phase labels), learn to identify what kind of reactions took place</td>
</tr>
<tr>
<td></td>
<td>Reactions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analysis of Vinegar</td>
<td>Determine amount acetic acid in vinegar by titrating with standard NaOH Titration techniques and related calculations (stoichiometry)</td>
</tr>
<tr>
<td></td>
<td>The nine solution</td>
<td>Use solubility rules and problem-solving skills to correctly identify nine unknown solutions Write net ionic equations, write down observations</td>
</tr>
</tbody>
</table>
### APPENDIX D, continued

<table>
<thead>
<tr>
<th>Course</th>
<th>Lab Title</th>
<th>Objective</th>
</tr>
</thead>
</table>
| 122    | Identification of an unknown metal | Identify unknown metal through reaction with HCl  
Measure volume of hydrogen gas generated, carry out gas law calculations  
Present data and calculations in neat and organized manner, attention to significant figures and units |
|        | Bleach analysis                    | Practice titration techniques and calculations  
Make and standardize titrant (sodium thiosulfate)  
Titrate dilute bleach with standardized titrant to determine % available chlorine and mass % sodium hypochlorite in commercial bleach  
Practice proper pipetting and titration techniques, calculations significant figures and units |
|        | Synthesis of cupper sulfate pentahydrate | Convert metallic copper to crystalline solid copper (II) sulfate pentahydrate  
Gain experience handling chemicals and using laboratory techniques for isolating pure chemical compounds (decanting, filtering, washing, drying)  
Calculations involving chemical equations, stoichiometry, limiting reactant, theoretical, actual and percent yield |
|        | Reaction of crystal violet with NaOH | Study reaction rate using colorimetry  
Determine reaction order w/respect to each reactants  
Calculate room temp rate constant for the reaction  
Apply kinetic rate laws and beer's law, working carefully, calculations, significant figures, units |
APPENDIX E: The six major categories of skills in the cognitive domain and associated illustrative verbs (Bloom et al., 1956; Gronlund, 1985).

<table>
<thead>
<tr>
<th>Rank</th>
<th>Cognitive Domain</th>
<th>What is it?</th>
<th>Illustrative Verbs for Stating Specific Learning Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Knowledge</td>
<td>remembering or recalling previously learned information</td>
<td>defines, describes, identifies, labels, lists, matches, names, outlines, reproduces, selects, states</td>
</tr>
<tr>
<td>2</td>
<td>Comprehension</td>
<td>the ability to understand the information</td>
<td>converts, defends, distinguishes, estimates, explains, extends, generalizes, gives examples, infers, paraphrases, predicts, rewrites, summarizes</td>
</tr>
<tr>
<td>3</td>
<td>Application</td>
<td>capability to use learned information in new ways</td>
<td>changes, computes, demonstrates, discovers, manipulates, modifies, operates, predicts, prepares, produces, relates, shows, solves, uses</td>
</tr>
<tr>
<td>4</td>
<td>Analysis</td>
<td>examining and breaking down of information into constituent parts</td>
<td>breaks down, diagrams, differentiates, discriminates, distinguishes, identifies, illustrates, infers, outlines, points out, relates, selects, separates, subdivides</td>
</tr>
<tr>
<td>5</td>
<td>Synthesis</td>
<td>putting constituents together in a new way</td>
<td>categories, combines, compiles, composes, creates, devises, designs, explains, generates, modifies, organizes, plans, rearranges, reconstructs, relates, reorganizes, revises, rewrites, summarizes, tells, writes</td>
</tr>
<tr>
<td>6</td>
<td>Evaluation</td>
<td>judge material or present and defend ideas</td>
<td>appraises, compares, concludes, contrasts, criticizes, describes, discriminates, explains, justifies, interprets, relates, summarizes, supports</td>
</tr>
</tbody>
</table>
APPENDIX F: The illustrative verbs (and number of instances for repeats) found within the Western Washington University and LabPaq laboratory manuals.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Knowledge</th>
<th>Comprehension</th>
<th>Application</th>
<th>Analysis</th>
<th>Synthesis</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEM 122</td>
<td>Intermolecular Forces &amp; Physical Properties</td>
<td>defines</td>
<td>distinguishes (2)</td>
<td>predicts (3)</td>
<td>distinguishes</td>
<td>combines</td>
<td>concludes (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>shows (3)</td>
<td>identifies (2)</td>
<td>explains (4)</td>
<td>justifies (3)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>uses (6)</td>
<td></td>
<td>relates</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>writes</td>
<td></td>
</tr>
<tr>
<td>CHEM 122</td>
<td>Synthesis of CuSO4•5H2O</td>
<td>labels</td>
<td></td>
<td>shows</td>
<td></td>
<td></td>
<td>organizes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>uses (5)</td>
<td></td>
<td></td>
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<tr>
<td>LP 9</td>
<td>Stoichiometry of a Precipitation Reaction</td>
<td>converts (3)</td>
<td></td>
<td>shows</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>uses</td>
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<tr>
<td>CHEM 101</td>
<td>TLC Analysis of Analgesic Drugs</td>
<td>labels</td>
<td></td>
<td>summarizes</td>
<td></td>
<td></td>
<td>identifies (2)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>uses</td>
<td></td>
<td></td>
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<tr>
<td>LP 15</td>
<td>Chromatography of Food Dyes</td>
<td>lists</td>
<td></td>
<td>identifies</td>
<td></td>
<td></td>
<td>compares</td>
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<tr>
<td>CHEM 121</td>
<td>Analysis of Vinegar</td>
<td></td>
<td></td>
<td>uses (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP 16</td>
<td>Titration for Acetic Acid in Vinegar</td>
<td></td>
<td></td>
<td>uses (4)</td>
<td></td>
<td></td>
<td>writes</td>
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<tr>
<td>CHEM 122</td>
<td>Reaction of Crystal Violet and NaOH</td>
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<td>manipulates</td>
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<td></td>
<td>modifies</td>
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<td>solves</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>uses (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP 17</td>
<td>Reaction Order and Rate Laws</td>
<td></td>
<td></td>
<td>uses (3)</td>
<td></td>
<td></td>
<td>writes</td>
</tr>
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</tr>
</tbody>
</table>
APPENDIX G: The illustrative verbs (and number of instances for repeats) found within the pre-laboratories, manuals, and post-laboratories for select Western Washington University chemistry laboratories.

<table>
<thead>
<tr>
<th>Course</th>
<th>Experiment</th>
<th>Knowledge</th>
<th>Comprehension</th>
<th>Application</th>
<th>Analysis</th>
<th>Synthesis</th>
<th>Evaluation</th>
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<td>Intermolecular Forces &amp; Physical Properties</td>
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