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Introducing Electronic Circuits and Hydrological Models to Postsecondary Physical Geography and Environmental Science Students: Systems Science, Circuit Theory, Construction and Calibration

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Abstract. A classroom activity involving the construction, calibration and testing of electronic circuits was introduced to an advanced hydrology class at the postsecondary level. Two circuits were constructed by students: (1) a water detection circuit; and (2) a hybrid relative humidity (RH)/air temperature sensor and pyranometer. Along with 3D printing of watersheds, the circuits motivated concepts of systems science, models in hydrology, and calibration. Students used the circuits to collect data useful for providing inputs to mathematical models of hydrological processes. Each student was given the opportunity to create a custom hydrological model within the context of the class. This is an example of constructivist teaching where students engage in the creation of meaningful knowledge and the instructor serves as a facilitator to assist students in the achievement of a goal. Analysis of student-provided feedback showed that the circuit activity motivated, engaged, and facilitated learning. Students also found the activity to be a novel and enjoyable experience. The theory of circuit operation and calibration is provided along with a complete bill of materials (BOM) and design files for replication of this activity in other postsecondary classrooms. Student suggestions for improvement of the circuit activity are presented along with additional applications.

1. Introduction

Geography and environmental science students are often exposed to class activities (Yli-Panula et al., 2019) intended to provide experiential learning opportunities (Healey and Jenkins, 2000; Ives-Dewey, 2009) such as the use of data and computer programs for analysis of spatial phenomena (Bowlick et al., 2017), field trips (Krakowka, 2012; Lai, 1999; Schiappa and Smith, 2019), fieldwork (Elkins and Elkins, 2007; Mol et al., 2019; Ramdas, 2019), case studies (Hofmann and Svobodová, 2017) and guest lectures (Graham et al., 2017; Hovorka and Wolf, 2019). Experiential activities encourage critical thinking related to the environment (Hofreiter et al., 2007); increase an appreciation of landscapes and physical land surface processes (Karvánková et al., 2017); introduce role models that provide examples of career paths available for graduates (Solem et al., 2019); heighten an appreciation of sustainable practices (Robinson, 2019; Yli-Panula et al., 2019); and equip students with skills that improve marketability after graduation (Spronken-Smith, 2019).

Electronic circuits are deployed at field sites to autonomously collect data (Hund et al., 2016; Navarro-Serrano et al., 2019; Wickert et al., 2019) and are used to provide inputs to mathematical models for hydrological prediction and forecasting (Lavers et al., 2020). When visiting geographic locations equipped with electronic instrumentation, students often appreciate the presence of meteorological stations that collect precipitation, solar radiation, heat and energy balance data. These stations can provide data useful for class assignments. The stations may have also been used for the creation of figures in research papers and lectures that the students have read and utilized. Consequently, students are aware of the need for electronic instrumentation to measure hydrological processes.

Plots of actual data collected at field sites are not the same as synthetic curves in textbooks. Data often requires imputation, averaging or filtering prior to providing inputs for hydrological models (Gao et al., 2018) and some hydrology textbooks do not present this in a clear fashion. Students who have worked with actual data appreciate the nuances and challenges of datasets (Lim et al., 2020) and are better prepared for graduate school research and environmental science jobs (Hovorka and Wolf, 2019).

However, despite working with data collected by electronic circuits at field sites, students at the postsecondary level are often not exposed to how these circuits are calibrated or why these circuits work. Calibration is important for circuit operation where an output is corrected for accuracy (Kouider et al., 2003) or related to a physical quantity. A classic example of calibration involves pyranometers to measure solar radiation from the sun: an output voltage is related to a solar radiation flux (Faiman et al., 1992; Kim et al., 2018; Norris, 1973). In addition, hydrological models are often calibrated to select the best model parameters to represent a physical reality (Gupta et al., 1998; Singh and Bárdossy, 2012). Circuit calibration and hydrological calibration can be considered as similar processes since both require the discovery of a transfer function that relates a set of inputs to outputs. Since students will eventually be required to calibrate hydrological models or electronic circuits as environmental science professionals, students should have the opportunity to learn these important skills in the classroom.

When an environmental sensing circuit fails to operate as expected, students should understand that re-calibration is required or that the circuit is not collecting valid data. Moreover, understanding circuit operation may motivate students to eventually develop novel and interesting environmental monitoring circuits, thereby encouraging the development of innovative sensors that help to provide better insight into environmental phenomena.

The open source electronics movement has reduced the cost of monitoring environmental phenomena, democratizing the use of instrumentation and providing non-proprietary methods for data collection that do not require the use of expensive software licenses for data access and programming (Pearce, 2013). Two examples include the use of the Arduino platform to create low-cost dataloggers (Hund et al., 2016; Wickert et al., 2019) and the use of standalone miniature self-contained logging sensors (Lundquist and Lott, 2008; Navarro-Serrano et al., 2019). The introduction of custom electronic circuits in a hydrology class in lieu of commercial devices exposes students to the idea that instrumentation can be developed locally without a high cost of acquisition. Given the opportunity, students can build and test circuits used for environmental measurement. This opportunity can be viewed as empowering and enriches the educational experience by

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introducing threshold concepts that allow students to move beyond the nuanced idea of electronic environmental measurement circuits as black boxes, thereby allowing for a better understanding of how these devices are constructed and calibrated.

This paper describes the circuit theory, construction, calibration and data analysis experiences of the Advanced Hydrology (GEOG 427) class in the Department of Geography and Planning at the University of Saskatchewan. GEOG 427 is a final-year (4^{th} year) undergraduate class that is taken by Environmental Science major, Physical Geography major and Hydrology minor students. Some graduate students will also audit the class as a refresher course on hydrological processes. The goal of the class is to introduce students to instrumentation, mathematical models, and hydrological processes. A secondary goal as discussed in this paper is to introduce systems theory and critical thinking skills.

Before circuits are constructed, the class is initially introduced to actual data from field sites representative of hydrological processes. Prior to circuit construction, circuit theory is explained during class lectures. The students construct circuits in class and are responsible for calibration of these circuits before data collection. For a final class assignment, students are given the option to use these circuits to collect and analyse data to provide inputs for a hydrological model. The assignment is open-ended in that each student is responsible for constructing a simple hydrological model that can be driven by data collected from the circuits that students constructed in class. In this manner, students learn about how the circuit operates and how a hydrological model is assembled from different equations with associated assumptions coupled together to provide a numerical output.

For replication of the circuit activity in other postsecondary classes, this paper describes the educational trajectory of how the class learned about hydrological processes, circuit theory, construction, calibration and data analysis during the Winter Term of 2019 at the University of Saskatchewan. The design files and bill of materials (BOM) used to create the circuits are provided under a permissive open hardware license, allowing for replication of this activity in other classrooms. For pedagogical purposes, hydrological model applications are described that students or instructors can use for facilitating this activity.

Each student in the class is given the opportunity to create electronic circuits and keep the circuits after the class is over. This provides memories of the class and allows for the circuits to be used by the students for other personal self-learning activities outside of the classroom. Written open-ended feedback provided by the students and course feedback collected by the University of Saskatchewan was used to quantify the pedagogical use of circuits in a hydrology classroom.

2 Materials and Methods

2.1 Background

At the beginning of the term, students in the class are initially introduced to the concept of hydrology as a systems science. A systems thinking approach is important in geographic education since this enhances understanding of spatial relationships and interconnections between processes (Cox et al., 2019a, 2019b). At the postsecondary level, systems thinking is a key component of courses designed for sustainable development competencies (Schuler et al., 2018).

A system can be represented as a collection of entities that have attributes and an internal state (Hieronymi, 2013). The boundaries of the system are often demarcated as a type of control volume and visually represented by lines on a diagram (Fig. 1a). A system can have inputs and outputs. Sub-systems can be combined to form a larger system by coupling the outputs from one sub-system to the inputs of another sub-system. Examples of well-known systems with inputs and outputs include a vehicle, plumbing in a building, a computer, a smartphone and the human body. Students tend to understand examples couched in experiential reality (Oliveira and Brown, 2016) and therefore these system concepts have the potential to be more easily understood when presented to the class.

Hydrological processes can also be represented as systems. A watershed is construed as consisting of basins and sub-basins that respectively correspond to systems and sub-systems with inputs and outputs (Zăvoianu, 1985, p.9–25) (Fig. 1b). The sub-systems are coupled together by linkages indicative of water flowpaths associated with processes such as runoff, infiltration, evapotranspiration, sublimation, snowmelt, groundwater flow, and river discharge. Hydrologists have represented sub-systems in hydrological models as Hydrologic Response Units (HRUs) (Fig. 1c); examples include the Cold Regions Hydrological Model (CRHM) (Pomeroy et al., 2007), and the Soil and Water Assessment Tool (SWAT) (Gassman et al., 2007). The summation of inputs and outputs along with an appropriate positive and negative convention is the basic idea associated with the computation of a water balance (Berghuijs et al., 2014).

Students in the Advanced Hydrology class learn about three different types of hydrological simulation models: physical, mathematical and analog (Dingman, 2015, p.597). A physical model is a representation of the world at a different scale; examples include tabletop watersheds, sprinkler plots and hydraulic structures with inputs and outputs of water. Mathematical models have state variables and transfer functions that represent equations coupled together to form inputs and outputs. Analog models nominally use concepts from electrical engineering and circuit theory to represent hydrological phenomena such as groundwater flow and evapotranspiration and also have inputs and outputs. Described in this fashion, the three types of models are considered as systems.

To provide an example of hydrological systems science, students in the Advanced Hydrology class were given an assignment to create watersheds from a raster digital elevation model (DEM) by applying watershed delineation algorithms in a geographic information system (GIS). For this class, the Free and Open Source (FOSS) software QGIS (https://qgis.org/) was used since it is freely available for all students without the need to pay for a software license. The digital elevation model (DEM) datasets corresponding to each student watershed were subjected to an algorithm (Modi et al., 2015) consisting of a series of calculations used to produce a stereolithography file (Fig. 1d shows a computer graphics rendering). The stereolithography file was then sent to a 3D printer for creation of a plastic version of the watershed (Fig. 1e). Students were able to view the 3D printer operating during a lab tour. Each student could take home a 3D printed watershed by the end of the term. The assignment demonstrates the use of mathematical models used to convert a DEM file into a physical model that is a representation of the watershed land surface at a different scale. The watershed is printed using a 3D printer that is also a system comprised of sub-systems. The required processing algorithms consist of mathematical models as sub-systems combined to together to produce an output from the DEM raster input data. The watershed delineation algorithms track water flow paths over a landscape and there are inflows and outflows representative of water flow between raster cells in a domain (Haag et al., 2018).

Analog models are often implemented as mathematical models with equations evaluated using a computer program in lieu of building actual circuits (Ménard et al., 2014) (Fig. 2a). Actual circuits were constructed in the past consisting of elements such as resistors and capacitors (Sander, 1976; Shen, 1965; Skibitzke, 1960) (Fig. 2b,c) since computation resources were more limited in the 20th century and building of a circuit allowed for current or voltage to be measured and easily related to the magnitude of a hydrological process.

By conceptualizing hydrological models as systems with inputs and outputs, students can learn how to construct a mathematical model by combining equations along with assumptions in a similar fashion to a circuit, where circuit elements are combined to provide a set of outputs given inputs (Kang, 2016). The practice of assembling a circuit provides students with an experiential example of how sub-systems are combined to form a system.

A similar process also occurs when combining equations to compose a hydrological model. If equations are conceptualized as sub-systems with assumptions, students may find it easier to select equations, combine equations together, and understand how the inputs affect the outputs. This process is useful to learn since it is often performed by graduate students and hydrology research professionals who model hydrological phenomena using mathematics and associated computer programs to produce predictions and forecasts related to phenomena such as drought (Mishra and Singh, 2011), flooding (Teng et al., 2017), geotechnical slope stability (Fawaz, 2014) and avalanche activity (Morin et al., 2020).

Students are given the opportunity to propose their own mathematical models for use with electronic circuits in lieu of everyone in the class being obligated to complete the same assignment. This is in line with the concept of constructivist teaching and learning, where students engage in meaningful and creative activities and the instructor acts in an interactive fashion to help students with the creation of knowledge (Klein and Merritt, 1994). Students thereby assume an active role in the learning process and do not passively receive knowledge from the instructor, textbooks, and lecture notes. Moreover, allowing students to be creative can enhance geographic learning (Yli-Panula et al., 2019). Applied to an environmental science classroom, this instructional method can increase class exam scores and student satisfaction ratings (Lord, 1999).

2.2 Electronic Circuit Theory and Construction

Students in the Advanced Hydrology class were given the opportunity to assemble (Fig. 3) and take home two circuits: a water detection circuit (Fig. 4) and a circuit with a relative humidity (RH)/air temperature sensor as well as a photodiode with a diffuser that is calibrated as a pyranometer to measure shortwave radiation (Fig. 5).

The water detection sensor as the first project provides students with an opportunity to learn some basic circuit theory and construction skills. This first project is deliberately kept simple. This is because students learn best in a formal

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teaching environment where skills and concepts are presented in a fashion progressing from simpler to more complicated formulations (Davis, 2009, p.280–281).

The second circuit (Fig. 5) can also be constructed in three configurations using either or both RH/air and pyranometer sensors. This allows the students to choose which configuration would be most useful for collection of data for an assignment that asks students to formulate their own hydrological models. A microcontroller is used as a control system.

The temperature, relative humidity and calibrated solar flux is displayed on an LCD display driven by the microcontroller. To acknowledge the ancestors of the land on which the University of Saskatchewan is built and to contribute to Indigenous reconciliation in Canada (Castleden et al., 2017), the LCD display shows "Welcome" and "tawāw": words in English and Cree indicating that the device is ready for operation. The Cree word tawāw can be literally translated as "come in, you're welcome; there's room" (Wolvengrey, 2001, p.218) and allows students to view words other than English that are normally displayed on most LCD displays. The letter ā with a macron (overbar) had to be uploaded to the LCD display memory since the default LCD character set did not support this special character used for the Cree Roman Orthography.

Circuit components are provided to the students individually bagged and labelled for the water detection sensor and the RH/air temperature and pyranometer sensors. There are three bags for the RH/air temperature sensor; all students constructing this circuit need to populate the "base" kit, whereas a choice can be made concerning which of the other kits to populate. Toolboxes are provided with solder, battery operated soldering irons and various hand tools for construction (Fig. 6a). The kits and additional components were placed in containers on a cart for transportation to the classroom (Fig. 6b). A dedicated lab was not required for this activity since the instructor provided all required materials.

Students bend, insert and solder components into holes on printed circuit boards (PCBs). Each individual bag is marked with a PCB designator corresponding to a component (or components) on the circuit board. The designator is also marked on the circuit board. This allows students to expeditiously populate components on the PCB without the use of an associated placement diagram. PCBs are designed using layout software (Fig. 7) and further details are given in the Supplement.

Since the Advanced Hydrology class is not an engineering course, students do not design circuits since there is not enough time to learn basic concepts of electrical theory and printed circuit board layout. The creativity aspect of the course in line with constructivist and experiential learning is associated with the use of the circuits to collect data utilized as inputs to student-proposed mathematical models. Circuit theory is described to provide learning context and relevance, so the circuits are not merely considered as black-box systems with inputs and outputs. Relevance is important to motivate learning (Kember et al., 2008) and students are provided with basic circuit theory that can be used for electronics associated with dataloggers and measurement devices.

To provide background circuit theory for the instructor and interested students, a few reference books can be recommended. Horowitz and Hill (2015) serves as an excellent starting point for learning electronic circuit design. Holdsworth and Woods (2002) is a good reference for logic gates. Williams (2014) provides an overview on how to

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program an Atmel AVR microcontroller. Similar books are also available for other microcontroller architectures. De Vinck (2017) offers a complete course on how to solder electronic circuits. These books are selected to provide reference texts for the student activity described in this paper.

The schematics, circuit board design files and bill-of-materials (BOM) are available as an electronic download associated with this paper. All design files are licensed under the CERN Open Hardware Licence (OHL).

Technical details related to circuit operation and calibration are explained in the Supplement. These details are provided for context and to provide students and instructors with background information so that the circuits are not perceived as black box systems with inputs and outputs. Context related to calibration is also important to guide students and instructors in the implementation of this activity.

2.3 Classroom Application

Verbal feedback from students during the circuit activity can be used to assess some common advantages and disadvantages associated with classroom application. The observations listed in this section might not be universally applicable to all groups of students but have been derived from the personal experiences of the instructor of the Advanced Hydrology class.

Everyone in the classroom working on circuits had to wear safety glasses. This prevented eye damage from flying debris when component leads were trimmed after soldering and prevented injury from particulate matter during the soldering process. No soldering injuries associated with burns or scratches occurred during this activity.

Working together, the students were able to help each other construct the circuits and formulate novel methods for circuit calibration and application. Students were also encouraged to work together on the associated calibration and modelling assignment, although each student was responsible for submitting an individual assignment. This is a form of cooperative learning that is known to enhance retention and engage students (Slavin, 1980).

Construction of the water detection sensor took approximately 1.5 hours as the maximum class time and one Advanced Hydrology class was allocated for this activity. Construction of the RH/air temperature circuit took approximately 4 classes for a total time of 6 hours. Out of this total time, three classes (4.5 hours) had to be allocated for construction, and one class (1.5 hours) for debugging of soldering errors associated with construction.

Before the activity started, students were provided with PowerPoint slides and a lecture on circuit construction. Students were told that this activity would count towards a 4% overall participation grade in the class. This participation grade was also assessed throughout the term based on attendance and class participation and was not primarily associated with the circuit activity. The circuit construction activity was introduced as a type of “game” or “puzzle” comprised of matching components to designators on the circuit board and soldering the components in a correct place. This is a form of “gamified learning” that positively improves the enjoyment of an educational activity (Subhash and Cudney, 2018).

Students who had soldered in the past found the circuits easier to construct than students who had not worked with soldering tools and techniques. Students who had previous experience were thereby paired with students who had less experience. This practice reduces tension and prevents students from feeling excluded. Indeed, three students verbally indicated to the instructor that they liked the idea of circuit construction, but they did not feel competent to successfully construct the circuits. The instructor alleviated the concerns of these students by assisting all students in the classroom over the duration of the activity. The idea of an instructor as a facilitator is in line with the philosophy of constructivist teaching (Klein and Merritt, 1994; Lord, 1999).

Five kits of battery-operated soldering irons, pliers, scissors, tape, screwdrivers and IC pin straightener tools were provided to a maximum of 18 students allowing for approximately three to four students per group. The number of kits were limited due to cost and not all the 18 students showed up for the circuit construction activity. However, the finite number of kits allowed students to work together. While one student soldered a component, the other students in the group were able to observe the soldering process and learn from each other. Students were able to help other students with part placement and orientation. This process emphasizes the importance of using battery-operated soldering irons since students can quickly exchange and share irons without the disadvantage of having to deal with cords and power cables. The disadvantage is that a number of additional AA batteries had to be kept in the classroom for facilitating this activity since the batteries in each soldering iron lasted for approximately 45 minutes and had to be changed to allow the students to continue working on the circuit.

Students were able to match designators on the PCB to designators written on a label affixed to the outside of each individually bagged component in the kit. Kits with individually bagged components thereby helped to expedite the class activity.

A container with additional electronics parts and an extra soldering iron was useful. The additional parts accommodated students who had lost a part. Moreover, the additional soldering iron could be used by the instructor to demonstrate soldering or by a student who wanted to work more quickly.

During the circuit construction process, students were asked to identify concepts of systems and sub-systems associated with collections of components on the circuit board; this practice reiterated concepts taught in class. The idea of an analog model associated with resistors and capacitors was also addressed to enhance student comprehension associated with modelling evapotranspiration and water flow processes.

Verbal feedback was provided by students during and after the activity. One student indicated that the circuits should have datalogging capabilities. As a response, the instructor replied that these capabilities will be added in an updated version of the circuit. Students also remarked that the plastic jumpers used to set calibration coefficients were challenging to insert and remove. This is a disadvantage associated with the budgetary cost of each circuit.

One student recommended via written feedback that the PCB should have feet. Conventional plastic feet elevate the PCB above a surface and provide a convenient platform to situate the circuit while it is being operated. To engage students, the instructor used a 3D printer to create a class set of "feet" with toes that can be glued on the bottom of the PCB

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(Fig. 8a). Figure 8b is an example of a student standing next to a PCB with "feet." Injecting humour into a classroom situation is known to increase retention while engaging students by heightening interest and attentiveness (Korobkin, 1988).

Students were given handheld temperature, RH, and solar radiation flux meters to serve as calibration references. These handheld devices are commercially available and are listed in the downloadable BOM associated with this paper. Calibration proceeded based on the types of sensor populated by each student on the PCB (temperature/RH or pyranometer).

For meters that reported light outputs in lumens or lux, students used an appropriate conversion factor to obtain a solar radiation flux in units of $\mathrm{W\,m^{-2}}$. Some students took the PCB and hand-held light meters outside to measure solar radiation flux from the sun as an outdoor calibration procedure (Fig. 9a), whereas others used an indoor calibration procedure utilizing smartphone LED flashlights (Fig. 9b). This was a novel development not anticipated by the instructor. Alternately, some students used radiation flux data from a meteorological station for sensor calibration.

Figure 9b and Fig. 9c show students engaged in the smartphone LED flashlight calibration procedure. The light intensity of the LED flashlight was measured using the handheld light meter. The voltage output of the pyranometer circuit was then determined using the LED flashlight. An associated calibration coefficient was subsequently obtained using the techniques identified in the Supplement. The coefficient was refined using further experiments conducted at an outdoor location.

The students found that pyranometer calibration did not work well at an indoor location such as in the atrium of the Agriculture Building at the University of Saskatchewan. Despite the presence of many windows in this location, sunlight that enters the building interior is directional and strongly diffused by metal and glass reflecting surfaces and is therefore not an accurate representation of solar radiation associated with a hemispherical sky. Pyranometers calibrated in this indoor environment did not provide an approximate representation of radiation flux at an outdoor location.

Due to the inexpensive cost of the photodiode used for the pyranometer, the students found that calibration coefficients did not approximately coincide between PCBs due to manufacturing tolerances. Calibration coefficients could exhibit order of magnitude differences. Students realized that all photodiodes were not alike, and that calibration is important for this application.

The students found that temperature and RH as reported by the circuit (Fig. 5b) agreed to within ± 1 ℃ and $\pm 3\%$ RH. This is approximately the same as the accuracy reported by the AM2320 datasheet and includes differences due to temperature gradients and boundary layer effects near the PCB. For the pyranometer (Fig 5c), students found that the average error ranged between approximately 3% to 35% compared to handheld light/radiation meters. The error was dependent on calibration and the position of the PCB relative to the sun. For more accurate measurements, the pyranometer sensor had to be positioned level to the ground to allow for an approximation of a hemispherical measurement of radiation.

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2.4 Example Applications for Electronic Circuits

Students identified novel applications that were not discussed by the instructor. One student expressed an interest to use the water detection circuit to determine if seasonal water levels exceeded a certain height in wetlands; this indicated whether water could be exchanged between two nearby ponds. Another student suggested that the RH/air temperature circuit and pyranometer could be used in lieu of more expensive micrometeorological handheld instruments to collect measurements at a field site during fieldwork.

The wetness detection sensor can be used as a groundwater dipper (Fulford and Clayton, 2015) to determine the level of the water surface in a groundwater well. The sensor would be waterproofed and fastened on the end of a wire for lowering down an observation well. The piezoelectric buzzer provides audible feedback when the water sensor reaches the position of the water surface. The distance to the water surface is read from a series of graduated markings on the wire.

2.5 Modelling with Electronic Circuit Data

This section briefly summarizes possible models for classroom application. Students can use some of these models for a class assignment. Examples listed in this section were utilized, identified, or considered by students in the Advanced Hydrology class, but other example applications might also be suitable based on regional geography if this activity is to be replicated at another location.

Students are graded on how assumptions are provided in the assignment, since each equation coupled together to form a hydrological model is implicitly associated with assumptions. The students are also graded on how they interpret the model outputs. Students justify if the outputs are physically reasonable based on a literature search or on theoretical calculations providing insight into the magnitude or frequency of hydrological processes.

The RH/air temperature circuit can be used to obtain daily mean air temperature. The mean temperature is related to snowpack temperature or snowmelt using an empirical degree-day or similar relationship for cold regions where snow is prevalent (Fontaine et al., 2002). Relative humidity and air temperature can also be related to transpiration processes (Clum, 1926; Mahajan et al., 2008).

If the pyranometer circuit is used to measure incoming shortwave radiation from the sun, outgoing shortwave radiation can be estimated using an assumed albedo (Oke, 1992, p.86). The longwave radiation can be obtained from a semi-empirical (Sicart et al., 2006) or physical model (Viúdez-Mora et al., 2015). If sensible and latent heat fluxes are modelled or measured along with appropriate assumptions (Essery, 1997; Marks et al., 2008), the energy required for snowmelt and the resulting change in Snow Water Equivalent (SWE) can be calculated (Pomeroy and Brun, 2001, p.92).

2.6 Design, Analysis and Collection of Written Feedback

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The conceptual framework used for the design of written student feedback related to this class activity is outlined by Narciss (2013) as the interactive tutoring feedback model (ITF-model). The ITF-model incorporates ideas of systems theory and constructivist teaching. These two ideas are also utilized within the context of the student activity described in this paper.

Narciss (2013) considers both the learner and the instructor as control systems within three feedback loops. One feedback loop is internalized by the learner and is related to student satisfaction, knowledge creation and retention, whereas another feedback loop is used by the instructor to adjust the class activities to achieve external competency standards and maximize learning associated with instructor and department-specified goals. The third feedback loop links the instructor and student systems together.

The purpose of each conceptual feedback loop is to establish equilibrium in each system with respect to a setpoint that represents a goal or a level of competency. In this paper, the three feedback loops are identified as learner (L), instructor (I), and learner-instructor (L-I) to identify the system domains where these feedback loops operate.

Quantification of learning is to understand how these feedback loops are operating. To quantify each of the three feedback loops identified by Narciss (2013), the Hattie and Timperley (2007) model is used to construct questions. According to Hattie and Timperley (2007), feedback questions are associated with four levels. These four levels are associated with each of the feedback loops in the list below. Although all feedback loops are interrelated, each of the levels have been matched to the feedback loop that is mostly indicative of the level:

1. Task Level, associated with how well the task is performed in relation to an external standard (L-I and I).
2. Process Level, related to how learners perceive the tools and techniques of a task (L, L-I, and I).
3. Self-Regulation Level, indicating a self-assessment of how well a student performs the task (L).
4. Self Level, related to the change in self-worth of a student engaging in the task (L).

Open-ended feedback allows for all the task levels and functioning of the conceptual feedback loops to be assessed. This is because open-ended feedback solicits responses without imposing a more rigid structure associated with specific task-based questions (Ballou, 2008).

Students in the class were voluntarily asked to provide open-ended written feedback on the circuit activity for assessing quality of classroom instruction (Davis, 2009, p.461–463). An open-ended feedback sheet was handed out in class. Eleven students returned the open-ended feedback sheet. The question asked at the top of this sheet was “Using the space below, please provide your thoughts and feedback on the circuit activity.” The students signed a permission consent to indicate acceptance associated with using the feedback in a published paper.

Class feedback in a more structured format involving rating questions and written feedback was also solicited by the College of Arts and Science at the University of Saskatchewan as the Student Learning Experience Questionnaire (SLEQ). Data from the end-of-term SLEQ was collected using the *blue* experience management feedback system (provided by *explorance*, https://explorance.com/products/blue/) in accordance with policies established by the University of Saskatchewan. This automated feedback system aggregates and anonymizes responses. All responses from students are voluntary and eleven students in the class completed this online survey. The SLEQ questionnaire allowed for all four task levels to be assessed.

It is not possible to determine whether the same students also completed the in-class open-ended written feedback sheet. Responses could not be matched to individual students. The SLEQ data is also provided as an associated download for this paper.

The class instructor personalized some of the questions asked by the SLEQ survey. Along with standardized closed-ended questions asked by the Department of Geography and Planning and the College of Arts and Science at the University of Saskatchewan, these personalized open-ended questions helped to address the efficacity of teaching and learning associated with this circuit activity. The questions below are classified to indicate the targeted task level. The questions cover all four task levels to assess the three conceptual feedback loops.

1. What are your thoughts about the building, construction, and calibration of electronic circuits in this class? (Process, Self-Regulation)
2. Do you think that calibration of circuits and understanding how circuits work are important learning experiences for environmental scientists? Why or why not? (Task, Process, Self-Regulation, Self)
3. After taking this class, how do you perceive systems theory as being important in environmental science? (Task, Process)
4. What did you learn about critical thinking in the class related to the use of electronic circuits, models and hydrological processes? (Task, Process, Self-Regulation)

To identify trends and similarities in the feedback, the Voyant web-based tool (https://voyant-tools.org/) was used for quantitative text analysis (Rockwell and Sinclair, 2016). Student feedback responses are provided as a download associated with this paper. The responses were transcribed and anonymized without modification of grammar or sentence structure since this maintains context and intent.

3. Results

3.1 Manufacturing Defects

Some of the PCBs constructed by the students had manufacturing defects. Table 1 shows the estimated number of defects that had to be repaired before student PCBs worked successfully. Soldering joint defects were the most prevalent. Another common defect was related to some components not placed with the right orientation. Since PCB repair and re-work tools were not available in the classroom, the instructor repaired the PCBs outside of class time.

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3.2 Choice of Configuration

Although most students constructed a hybrid RH/temperature/pyranometer circuit, no students chose to only construct a pyranometer (Table 2). Two students constructed a PCB with only a RH/air temperature sensor and did not populate the pyranometer components. For the RH/air temperature and pyranometer circuit, students had four classes to construct the circuit and students that did not attend the class on one day could attend on another day to work on circuit construction. The students that did not construct a PCB were either absent from class during circuit construction or auditing the class. All students who constructed a water detection circuit were also present for the construction of the hybrid RH/temperature/pyranometer circuit.

3.3 Open-Ended Feedback

Out of the 15 students who completed the in-class circuit activities, 11 students submitted an open-ended feedback sheet, indicating that four students completing the activity chose to not provide in-class feedback or were absent from class. Feedback was mostly positive and indicated that students found the learning experience to be an enjoyable, informative, beneficial, and novel opportunity. Three students indicated changes should be made to the activity: (1) more soldering irons required per group and the calibration process should be explained in a more in-depth fashion; (2) feet should be provided so that the PCB can be situated on a table; and (3) the activity took too long.

The trends plot (Fig. 10a) shows that there are five re-occurring words in the open-ended student feedback: circuit, activity, building, fun and class. This demonstrates that students recognized the experiential aspects of the circuit building activity that occurred in class and that the activity was fun.

Fig. 10b shows that most links in the student feedback are associated with the following words: building, activity, and circuit. Although the word “fun” is linked with “circuit” and “activity” the figure demonstrates that most feedback was focused on the circuit construction. The linkages between the rest of the words indicate that the kits allowed for the incorporation of a unique activity into the class that gave an opportunity for students to experience the building of a circuit. This interpretation is further supported by the associated mandala plot (Fig. 10c) that shows most students found the circuit activity to be “great” and “fun” although “experience” and “opportunity” are also a part of the responses. The word “learning” only shows up in the responses of two students indicating that this was not explicitly identified by most students as a goal of the activity; however, the learning process is implicitly demonstrated by the responses.

3.4 SLEQ Feedback

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The SLEQ feedback closed-ended questions allowed for a quantitative analysis of student responses submitted directly to the university. The feedback was not submitted to the instructor and was processed using a third-party web survey service in accordance with university policies.

Using "A great deal" or "mostly" as rankings, the respondents indicated that the Advanced Hydrology class provided a "deeper understanding of the subject matter" and in this regard, the class responses associated with number of students per ranking scored slightly higher than other classes offered by the department and college at the same 4th year level. Also, in the same fashion, the respondents found the class to be "intellectually stimulating" and once again the scores are slightly higher compared to other classes.

Most respondents indicated that the instructor "created an environment that contributed to my learning" and that the class projects and assignments improved understanding and provided opportunities to "demonstrate an understanding of the course material." The quality of learning in the class was rated as "Excellent" or "Very good" by all respondents.

Although the class did not have a separate lab section, the SLEQ feedback form also asked the students questions related to the quality of experiential learning in the context of a lab that includes the circuit activities. Once again using "A great deal" or "mostly" rankings, students found that the instructor created a conducive learning environment. Similar rankings were also given by most respondents for the question regarding an improvement of understanding related to the course objectives, but one student gave a response to this question as slightly lower with a "Moderately" ranking. Although most respondents indicated that the course lab circuit activity provided transferable skills for other courses with a "A great deal" or "mostly" rankings, two students provided a lower ranking at the "Moderately" level. The quality of learning experience in the lab component associated with the circuit construction was ranked "Excellent" or "Very good" by most respondents, although one respondent indicated that the experience was "Good." For these questions, the rankings either coincided with or exceeded the rankings associated with other classes at the department and college level.

The cirrus representation of words (Fig. 11a) from the SLEQ responses shows that words occurring with a greater frequency are larger and positioned near the centre of the figure. The words "good", "learning", "circuit", "class", and "building" occurred at a higher frequency in the responses. Words that occurred at a slightly lower frequency but still predominant in the responses include "models", "use", "different", "helpful", "systems" and "thought." Words that appeared with lower frequency included "assumptions" and "calibration."

The links plot (Fig. 11b) shows that in the student SLEQ responses, the words "building", "great" and "class" had the most linkages to other words. Words with the least linkages include "good", "electronic", "different" and "mathematical."

The written feedback indicates that students perceived the instructor as accessible, willing to help facilitate the circuit activity and to assist students with learning. Students also indicated that the circuit construction class experience was novel and unique, but some respondents indicated that it took longer than expected. The student feedback indicates the novelty of the activity. In the words of one student, "I never thought I would be building a circuit within my university journey, but I am happy to have experienced it."

All respondents agreed that calibration and learning about how circuits work is an important educational experience for environmental scientists. Most respondents indicated that they found systems theory to be important, although one student indicated "…still confused by it, I think it is good knowledge to know." Most respondents also indicated that they enjoyed the activity and one student indicated that "I would recommend continuing the activity in upcoming classes, as it is something unlike any other class."

Some students also commented on the exploratory nature of the course and the emphasis on not having a right or wrong answer when students had to develop their own mathematical models. In the words of one student, "I had to develop more critical thinking skills as the assignments didn't really have any exact right answer" whereas another student commented that "circuit building, 'story telling' with mathematical equations, building and organizing models, systems and sub-systems" were skills developed in the context of the course.

4. Discussion

The discussion of this activity identifies the feedback loops and the Hattie and Timperley (2007) levels associated with the feedback. This demonstrates the efficacy of the research question design to guide the discussion.

I Feedback Loop: Soldering joint defects were observed by the instructor as most prevalent during PCB construction since many students in the class had not previously used soldering irons to construct electronic circuits. Component orientation was another common mistake since most students were not familiar with polarity and pin indicator marks used in electronics assembly. These mistakes and others in Table 1 could have been mitigated by having the students watch a video demonstrating circuit assembly from a first-person perspective (Fiorella et al., 2017). Although the instructor walked around the classroom and demonstrated soldering and assembly skills during the circuit construction activity, students learned skills from a third-person perspective. These instructor demonstrations may have been less effective than if a first-person perspective video was used in a pedagogical fashion. The act of the instructor repairing the PCBs outside of class time agrees with the philosophy of constructivist teaching where the teacher acts as a facilitator of learning.

Before beginning the activity, the instructor had a preconceived notion that most students in the class would construct a RH/temperature circuit and that only a small number of students would choose to also populate the parts for a RH/temperature/pyranometer circuit. This unfounded thought was based on the idea that most students will choose a simpler project to reduce required effort and maximize gain. But as identified by Inzlicht (2018) as the "Paradox of Effort," more effort expended when completing a task can serve to increase the perceived cognitive value of the task, despite physical activity being costly in terms of physiological energy use.

L Feedback Loop, Self and Self-Regulation Levels: Psychological studies of student motivation in higher education show that students are willing to attempt tasks based on an intrinsic motivation that varies between individuals and a classroom environment cultivated by the instructor where students feel a sense of belonging and interest in performing the activity (Nupke, 2012). Other common factors for motivation that may have played a role include novelty of the activity as

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per self-determination theory (González-Cutre et al., 2016); a participation grade to serve as an incentive for class participation (Czekanski and Wolf, 2013); the possible usefulness of the circuit in a class assignment as necessary for completion of the course; and a possible perception that participating less in the activity would not provide an experience justifying the monetary cost of taking the class, particularly since the circuit was a tangible item as a type of "self-gift" taken home after construction. A "self-gift" may boost self-esteem and encourage an individual to recognize "specialness" (Mick and Demoss, 1990). Moreover, the construction of the circuit is an achievement and taking home a tangible and functioning PCB can be construed as a type of badge or acknowledgement. Badges function as awards, increasing social self-worth, and thereby serve as incentives for behaviour (Ling et al., 2005).

L and L-I Feedback Loops, Process and Self-Regulation Levels: Similar wording was used by the respondents who completed the instructor-provided and open-ended sections of the SLEQ evaluations, indicating that both feedback forms served as reasonable assessments of the class and circuit activity. However, since the open-ended feedback form was given directly to the instructor, students used this form to provide more implementation-based suggestions for improving the circuit activity than the SLEQ evaluation that served to provide a final assessment of class feedback at the end of the term. The SLEQ evaluation was also the most anonymous. These anonymous types of feedback forms make it more likely that the students will provide a less-biased assessment of the class (Stone et al., 1977), although complete anonymity may not always be reliable nor accurate due to lessened accountability (Lelkes et al., 2012). Therefore, both the instructor-provided feedback and SLEQ evaluation can be used together to obtain a more comprehensive understanding of how the students assessed the circuit activity.

L Feedback Loop, Process and Self Levels: The open-ended feedback shows that the students provided responses indicating that the circuit construction activity was grounded in experiential reality; to the students, this was a "hands-on" activity that was also fun. Most student respondents did not use the word "learning" in the open-ended feedback solicited by the instructor, although this word appears in the SLEQ evaluation responses, suggesting that students identified the activities are more enjoyable than classic lecture-based forms of learning and that the learning process was implicit in the circuit building activities.

L Feedback Loop and Self Level: Class activities involving unique experiential opportunities engages students, increases comprehension and facilitates learning (Gavillet, 2018). An element of enjoyment as "fun" for adult learners also heightens appreciation of the class and the associated subject material, increases retention of concepts, and leaves students with a positive and enjoyable experience of the learning process (Lucardie, 2014). The results thereby show that the use of circuits served to bring these elements into the context of the Advanced Hydrology class.

Process and Self Levels: The SLEQ feedback standardized questions quantitatively showed that students in the Advanced Hydrology class perceived the educational experiences as leading to a better understanding of the subject area; to the students, these experiences were engaging and perceived to be intellectually beneficial. The instructor of the class was identified as facilitating learning and acting as a consultant for the student learning experience. These results underscore the efficacy of the constructivist teaching philosophy used for the class and emphasizes how this philosophy engages students

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and facilitates learning. Since the standardized question scores for the Advanced Hydrology class tend to exceed the average scores at the college or departmental level, this indicates the usefulness of these techniques for teaching hydrology at the university level.

Despite the emphasis on circuit construction, analysis of written SLEQ feedback from the students in the class also identified that a "different" learning experience was offered in a fashion that is helpful for thinking about models and systems as conceptualizations of hydrological processes. Associated with the use of models were two related ideas of assumptions and calibration. Although these ideas are often used with mathematical models, the student responses did not show a strong association with mathematics (cf. Fig. 11b). This is important since the students learned concepts in class related to identification and analysis of models and systems. The use of mathematics was de-emphasized in favour of concepts, although the students used mathematics to propose hydrological models. De-emphasizing mathematics and focusing class lectures on concepts may have reduced any possible math anxiety present in students at the postsecondary level (Núñez-Peña et al., 2013), thereby allowing students to focus on gaining an understanding of hydrological and environmental processes within the context of the class.

Self Level: The open-ended feedback did not provide any results related to the "gamified learning" aspects of circuit construction. There is a possibility that the idea of circuit construction as a game or puzzle enhanced student enjoyment of class activities, but since no questions were provided on the feedback forms explicitly addressing this concept, it is possible to only conjecture that the idea was beneficial to help facilitate the activity. Further classroom implementation and analysis would be required to quantitatively assess the benefits of gamified learning to teach hydrology. Computer games have been used to teach water resource management (D'Artista and Hellweger, 2007; Seibert and Vis, 2012) indicating the possible benefits of involving hydrology students in gamified learning opportunities.

The constructivist teaching philosophy associated with this course was also demonstrated by the open-ended nature of the assignments where students were given the opportunity to propose models of environmental phenomena. Allowing students to create knowledge helps to prepare students for future graduate and consulting work in hydrology and environmental science where mathematical modelling skills are necessary.

The positive nature of the student feedback suggests that the circuit activity heightened interest in class subject matter and engaged students. Out of the total number of 18 students in the class, only three students did not participate in the circuit construction activities, indicating that 83% of students showed up for class and engaged in the activity.

All Levels: Wilson et al. (2014, p.76) indicate that techniques for motivating student interest in the higher education classroom involves "suspense, novelty, ambiguity, incongruity, or discovery." These terms can be used as a framework to analyse the student circuit activity and associated ideas related to systems and models in hydrology.

The use of circuit construction is suspenseful since in a similar fashion to a puzzle, students assemble the circuit and after a successful assembly, the circuit can be turned on and data displayed on an LCD display. Also associated with this idea is the notion introduced by the instructor as the circuit assembly serving as a type of "game" that is implicitly a puzzle.

The 3D printed watersheds and circuit construction activities are novel additions to the class. This statement is supported by student feedback, where some students indicated that they had not constructed a PCB and electronic circuit in the context of a class at the postsecondary level.

Ambiguity and incongruity are associated with the novelty of the circuit construction activity. Since many students had not constructed a PCB and electronic circuit, mistakes were made with respect to soldering and the placement of components. However, these mistakes can serve as useful learning opportunities where students are better prepared for future situations when an experiment does not work as expected (Glagovich and Swierczynski, 2004).

Discovery was evident in the Advanced Hydrology classroom since the students had the opportunity to formulate novel models of hydrological phenomena and to use a self-constructed circuit to collect data. This engaged students and allowed students to develop creative ways of thinking and learning.

5. Conclusions

A custom electronic circuit was developed specifically for the Advanced Hydrology class. The circuit was used to introduce concepts of systems theory in hydrology and environmental science as well as models in hydrology. The use of Cree and English on the LCD display acknowledged the ancestors of the land on which the class was taught and contributed to the reconciliation and Indigenization efforts of the University of Saskatchewan. The activity also taught students the Cree word tawāw, introducing the students to a word in an Indigenous language.

After circuit construction, students were given the opportunity to use the circuit to collect data useful for application of a hydrological model that was proposed and tested in the context of a student assignment. The assignment was open-ended and allowed for students to creatively examine concepts associated with assumptions and modelling of hydrological processes. These activities engaged students, increased relevance of the subject material, and allowed for the development of important skills related to electronics and modelling that can be useful for graduate work or application in the context of a job related to environmental science and hydrology. Introducing the circuit construction as a type of "game" or "puzzle" may have enhanced enjoyment, but there are no quantitative results in the feedback to support this hypothesis.

Circuit theory and explanation of concepts are provided in this paper for classroom implementation and replication. Student-provided feedback served to assess the efficacity of this activity for teaching hydrology at the postsecondary level. The Voyant software tools provided a means for graphical visualization and analysis of the feedback. The Narciss (2013) and Hattie and Timperley (2007) models provided a conceptual framework for the collection and analysis of feedback associated with this activity. The Wilson et al. (2014, p.76) framework was used to indicate that the circuit activity can motivate student interest.

The circuit construction and modelling activities supported the implementation of constructivist teaching in the Advanced Hydrology classroom, where students are the constructors of knowledge rather than passive consumers of facts

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and material provided by the instructor for rote memorization. The instructor also served in the role of a facilitator to support student learning. This motivated students to attempt the circuit construction task and heightened interest in the activity. Given the engagement of the students in this class, constructivist teaching should be more widely applied at the higher education level to improve the student experience and enhance learning.

For future implementations of this activity, student feedback indicated that some aspects should be modified. As indicated by one student, additional soldering irons should be provided to allow students to work more quickly, but this is dependent on the class budget and number of batteries available. Although battery-operated soldering irons are beneficial for allowing students to work freely without cords and cables, a permanent teaching lab for hydrological circuits would benefit from the use of AC-powered soldering irons to reduce the number of batteries required for this activity. Student feedback also suggests that the calibration process should be clearly explained in the context of systems theory and mathematical modelling, so the instructor should be willing to address this concept in an in-depth fashion by extensive demonstrations, lectures or videos shared with the students to enhance comprehension.

One caveat addressed by student feedback was the time required for this activity. Since the Advanced Hydrology class did not have a lab section, classroom lecture time had to be used for this circuit-building activity, reducing the time for lectures and other activities. We therefore recommend that future circuit construction activities should be conducted in the context of a scheduled lab to allow class time to be effectively utilized for questions, problem-solving activities, and lectures.

Although the circuit activity was primarily intended to teach systems theory in hydrology and to allow students to collect data for use with mathematical models of hydrological phenomena, there is a possibility to further develop this activity. As suggested by verbal feedback from students in the class, the circuits should be modified to log data to flash memory (such as SD cards), thereby enabling automated collection of data. Although increasing the complexity and cost of the circuit construction activity, this would be a worthwhile addition to a circuit used for pedagogical purposes. Moreover, the PCBs should be waterproofed to allow for usage in wet environments such as at a field site location.

Since environmental scientists and hydrologists often utilize electronic circuits in conjunction with dataloggers, circuit design could also be introduced to advanced undergraduates and graduate students in the context of a separate class at the undergraduate level. This class would enable students to propose, design and test their own electronic circuits, thereby encouraging innovation and allowing students to develop important skills useful for the collection of data in the context of graduate work and environmental consulting.

6. Code and Data Availability

The microcontroller code, data, bill-of-materials (BOM) and associated circuit design files for replicating this activity are available as a link from Github (https://github.com/nkinar/Introducing-Electronic-Circuits) or Figshare

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(https://doi.org/10.6084/m9.figshare.12410588). This download also includes figures created by the Voyant software.

7. Author Contribution

Conceptualization, N.K.; methodology, N.K.; software, N.K.; validation, N.K.; formal analysis, N.K.; investigation, N.K.; resources, N.K.; data curation, N.K.; writing—original draft preparation, N.K.; writing—review and editing, N.K.; visualization, N.K.; supervision, N.K.; project administration, N.K.; funding acquisition, N.K.

8. Competing Interests

The author declares that there is no conflict of interest.

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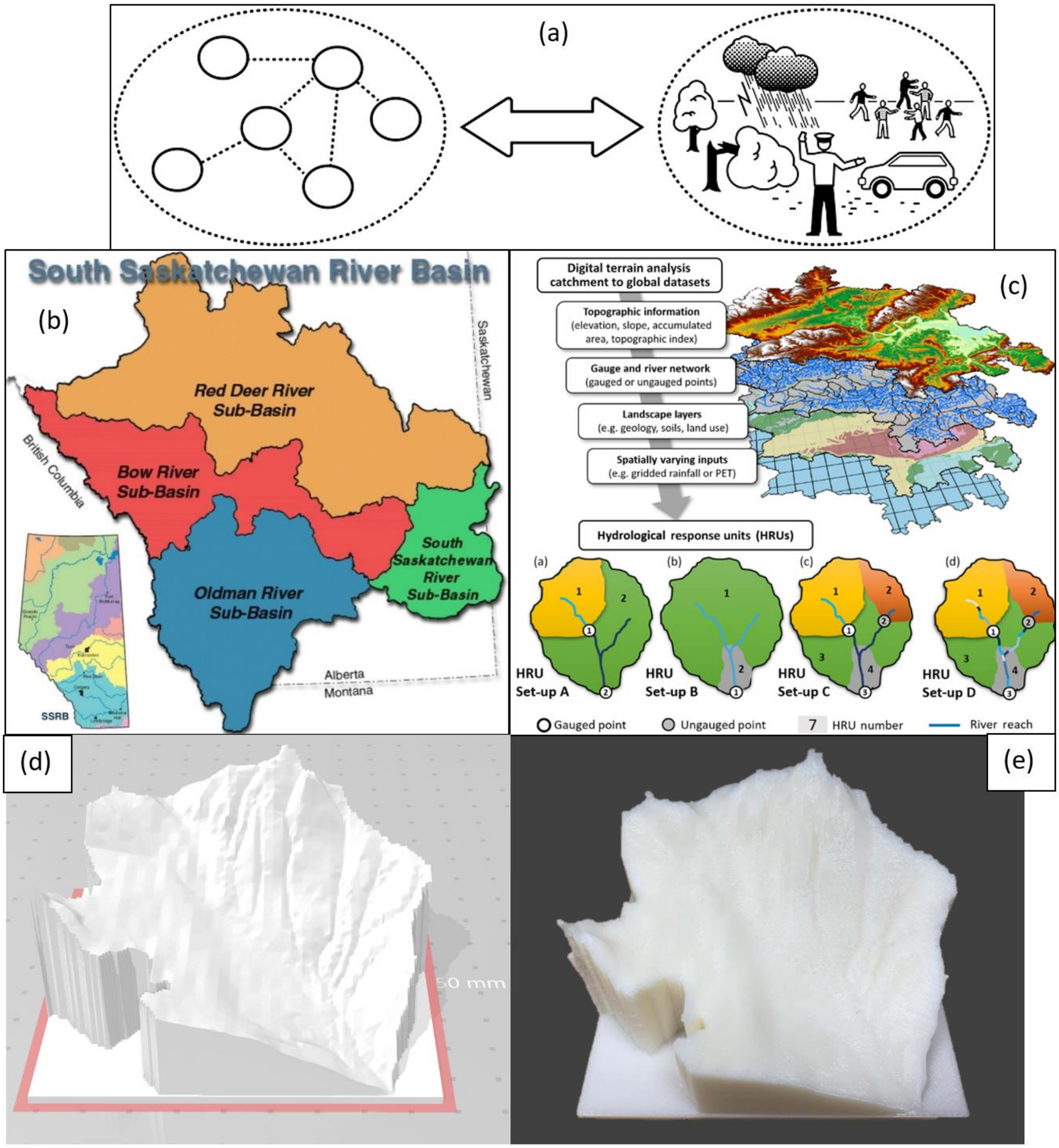

Fig. 1. (a) Demarcation of a system using control volumes and lines (Hieronymi, 2013). (b) Sub-basins used as an in-class example (Sauchyn et al., 2016). (c) Fig. showing connectivity between HRUs (Coxon et al., 2019). (d) Example 3D rendering of a student watershed created from a digital elevation model (DEM). (e) 3D printed version of the same watershed. Figures 1a-c are provided under license by John Wiley and Sons.

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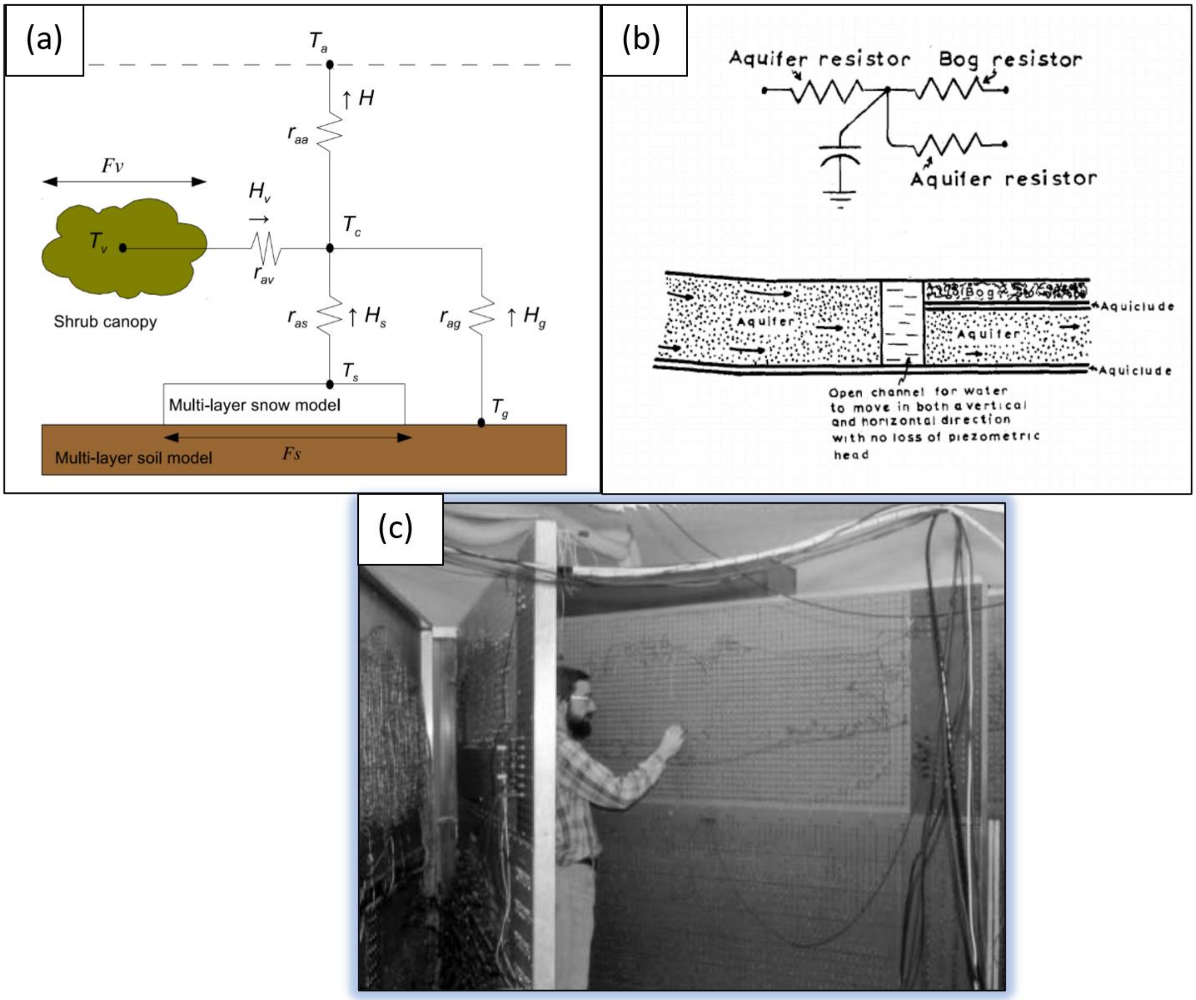

Fig. 2. (a) Example of an analog model used for modelling heat exchange between snow, soil, a shrub canopy and the atmosphere at a sub-Arctic tundra site (Ménard et al., 2014). For a complete explanation of terms, please see Ménard et al. (2014). Visible on this circuit schematic are resistors connected to form a circuit. (b) Analog model used to represent the flow of water in a peat bog (Sander, 1976). Visible on this circuit schematic are resistors and capacitors. (c) Picture showing a large analog circuit in the 1970s used to model groundwater (Reilly, 2004). Figures 2a-c are provided under license by John Wiley and Sons.

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Fig. 3. Example images of circuit assembly in the Advanced Hydrology class. The students are using battery-operated soldering irons to solder components to the PCB.

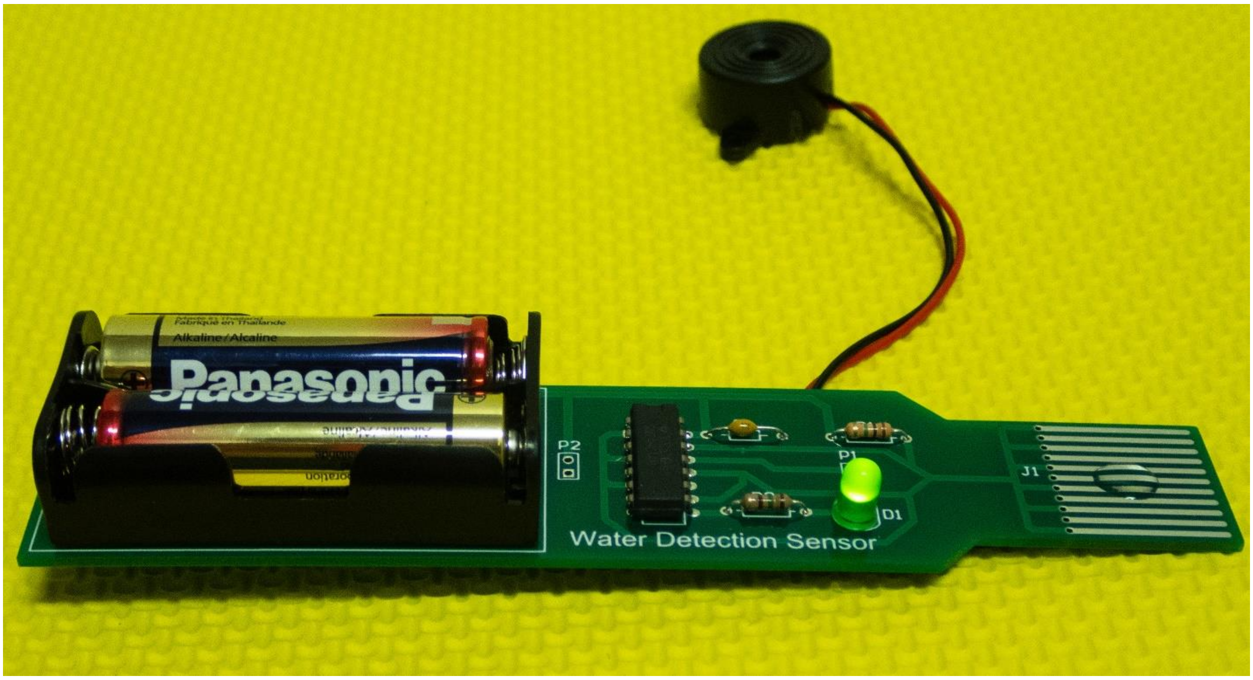

Fig. 4. Water detection PCB. A droplet of water turns on the light-emitting diode (LED) and an attached piezoelectric buzzer to provide visual and audible feedback.

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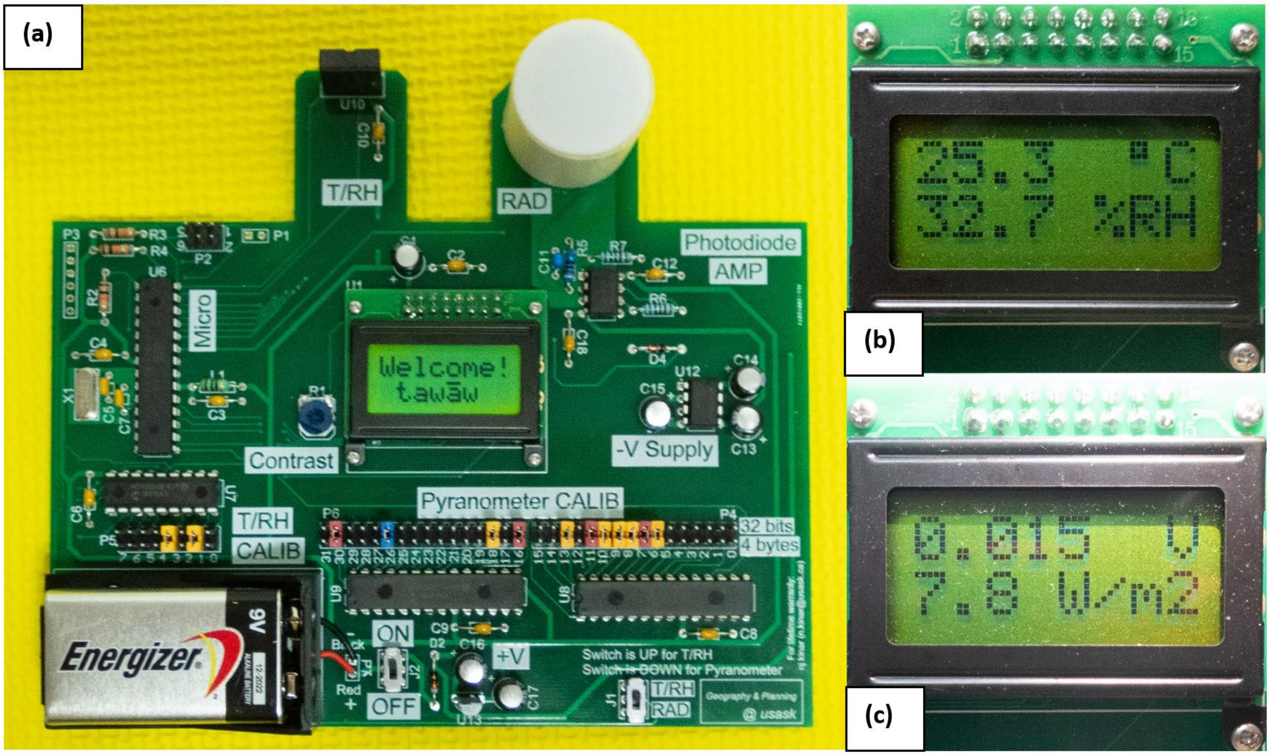

Fig. 5. (a) Hybrid temperature, relative humidity (RH) and solar radiation sensor. (b) LCD display showing calibrated temperature and relative humidity (RH) readout. (c) LCD display showing calibrated voltage output and radiation flux in $\mathrm{W\,m^{-2}}$. Calibration coefficients are set using removable plastic jumpers and the position of each calibration header is indicated by "CALIB" marked on the PCB silkscreen. The "T/RH" marking indicates the position of the temperature and RH sensor, whereas the "RAD" marking indicates the position of the pyranometer sensor comprised of a photodiode and an op-amp. The photodiode is covered with a piece of plastic pipe and a circular Teflon diffuser. This ensures that the photodiode has a cosine response to obtain a hemispherical measurement. Other markings indicate the positions of various PCB sub-systems, including a switch for setting the mode of circuit operation and a contrast adjustment potentiometer.

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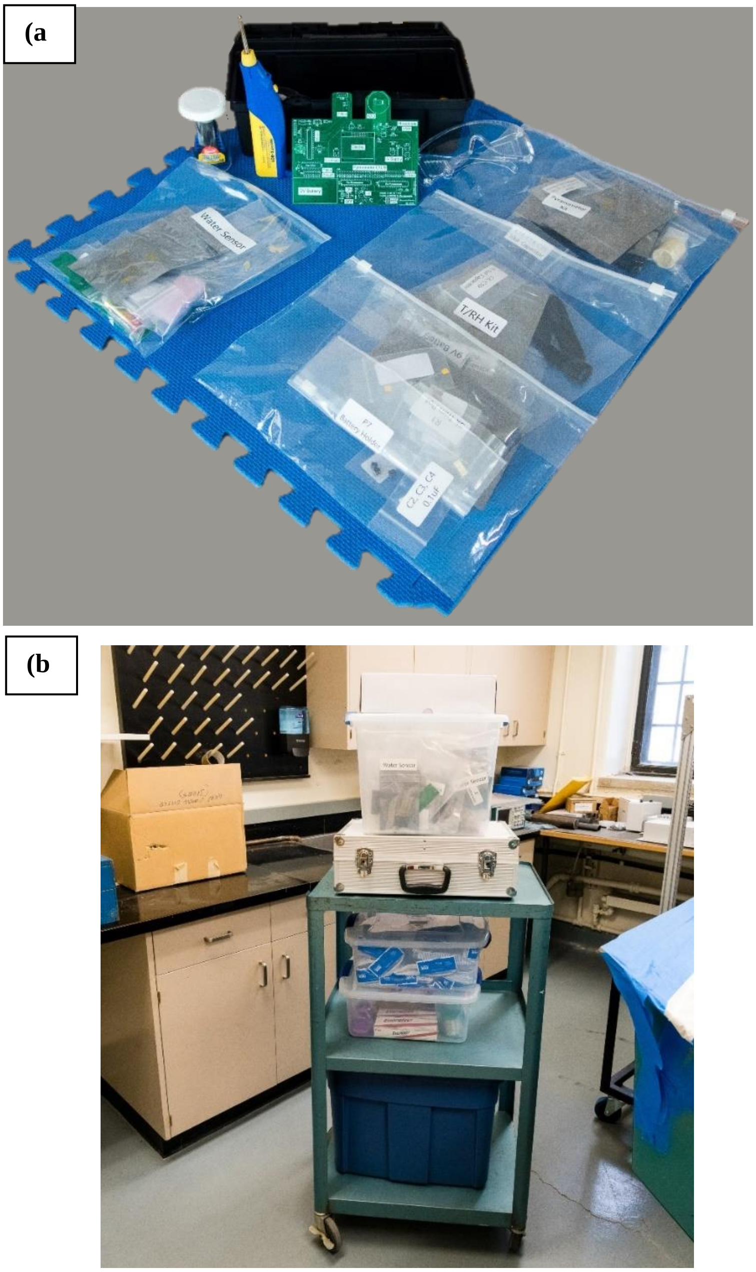

Fig. 6. (a) The circuit components were individually bagged and labelled for student assembly. Also visible in this image is the battery-operated soldering iron used by students for soldering, a toolbox containing hand tools for assembly and a glue bottle used to glue on the diffuser to the circuit board to cover the photodiode to create a pyranometer. (b) Image showing containers used to transport the kits to a classroom.

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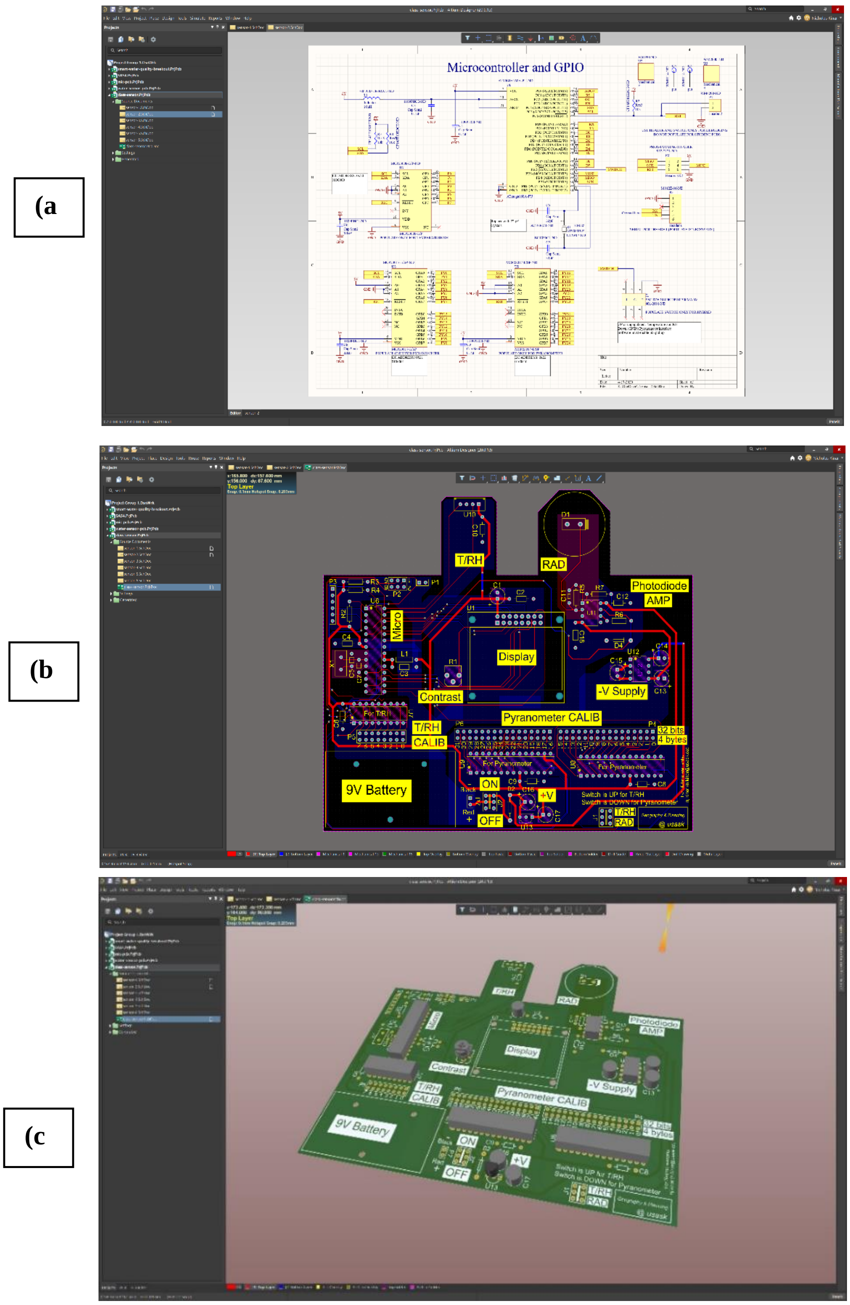

Fig. 7. (a) Layout software showing a schematic page of the hybrid temperature, relative humidity, and solar radiation sensor. (b) Associated circuit board with layers stacked in a similar fashion to a geographic information system (GIS). (c) 3D model of the circuit board generated using the layout software.

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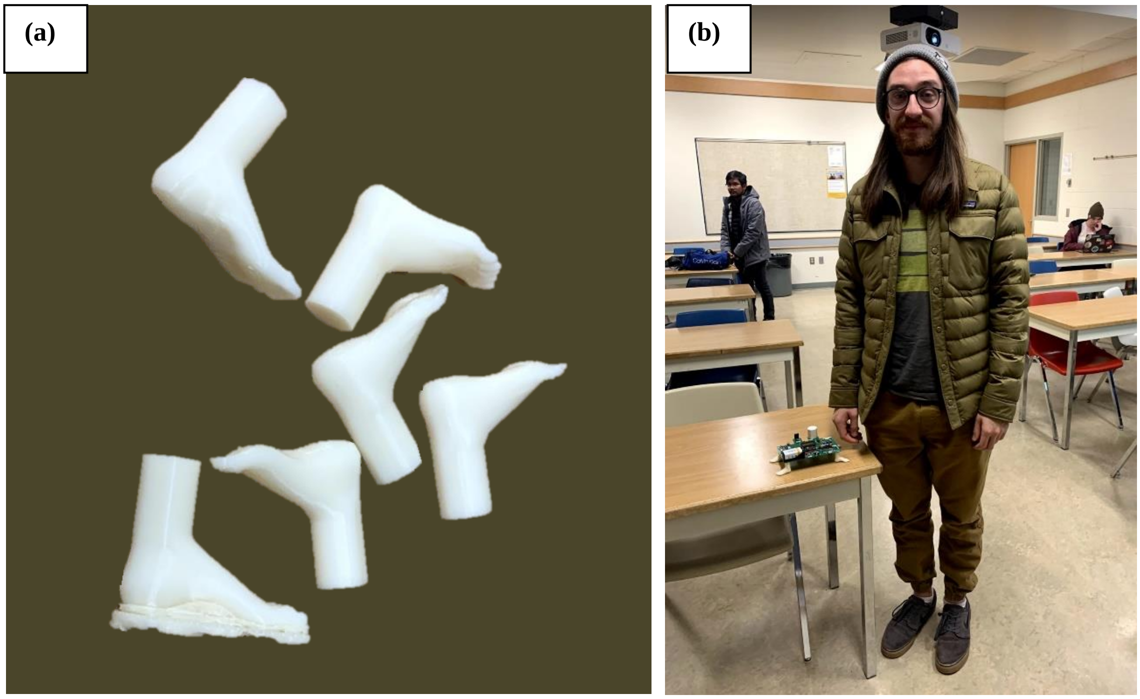

Fig. 8. (a) Example of 3D printed "feet" to be glued on the bottom of a PCB. The 3D printed "foot" nearest the bottom of the image has a 3D printed "raft" that has not been removed. The "raft" is placed on the 3D printer build platform to ensure that the deposited plastic sticks to a substrate. (b) Student next to a PCB exhibiting "feet" glued on the bottom.

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Fig. 9. Students engaged in calibration activities. (a) Outdoor calibration of temperature, RH and pyranometer devices using hand-held commercial sensors. Indoor calibration (b, c) with a smartphone flashlight and a hand-held solar radiation meter used as a standard for comparison.

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Fig. 10. Text analysis for the open-ended class feedback using the Voyant software. (a) Trends plot showing words that occur most often with respect to student responses. The "Corpus" in the Voyant software refers to the student responses. (b) Links plot showing relationships between words over all responses. (c) Mandala plot indicating relationships between student responses and words.

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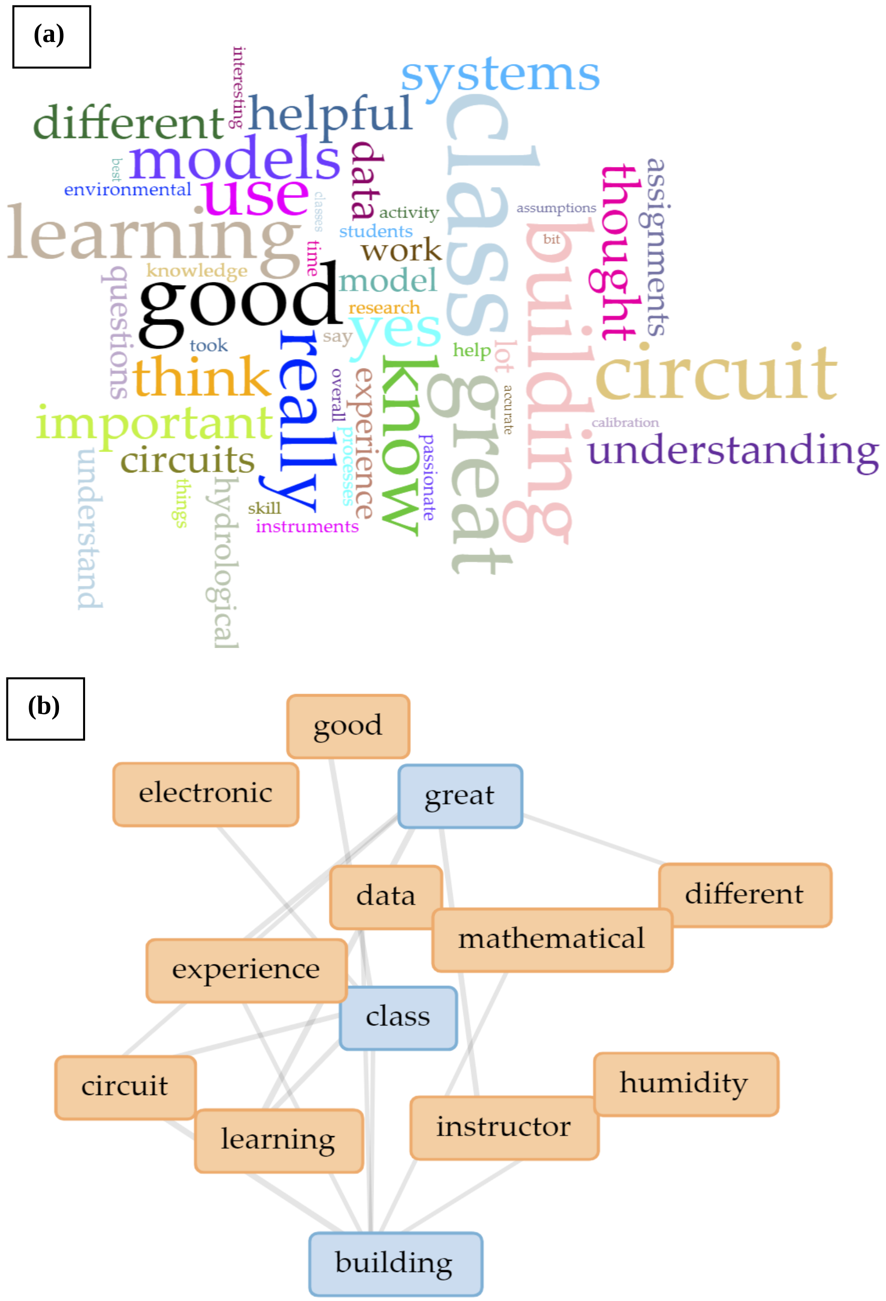

Fig. 11. Text analysis for the SLEQ class feedback. (a) Cirrus plot showing words with higher frequencies as larger and closer to the center of the Fig.. (b) Links plot showing relationships between words over all responses.

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Manufacturing Defect	Number of PCBs Affected
Soldering joints	9
Components placed with wrong orientation	5
Battery connections	3
Glue dripping on photodiode from diffuser	4
Battery holder breaking	3
Damaged PCB pads	1

Table 1. Estimated list of defects associated with PCBs created by the students.

PCB Configuration	Number of Students
Water detection circuit	12
Relative humidity (RH)/air temperature	15
Pyranometer	0
RH/Temperature/Pyranometer	13
Total Students in Class	18

Table 2. Number of students with completed circuit configurations.