



*Supplement of*

## **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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## Electronics Background

A PCB (Printed Circuit Board) acts as the substrate for a circuit and can be created from paper, fiberglass, flexible materials, and metal (Robertson, 2004). Although circuit components can be wired together using other construction techniques (i.e. rat's nest wiring, wirewrap and breadboards), the PCB provides an easy way for components to be soldered to create electrical connections (Catsoulis, 2005, p.136–146). Traces on the PCB are produced using photochemical methods and act as copper wires that electrically connect components (Varteresian, 2002). For this student project, a common fiberglass FR-4 laminate is utilized for the PCB since this is inexpensive, sturdy and readily used (Jawitz and Jawitz, 2007).

There are two ways of mounting components on a PCB. Each component has metal pins (or pads/balls for some parts) that are connected to the PCB. Surface-mount components are soldered directly to pads on the PCB and are smaller than through-hole components that are inserted into conductive “plated” holes (De Vinck, 2017). Although many modern PCBs (such as those for smartphones) are manufactured mostly using surface-mount technology (SMT) to reduce space (Abdullah et al., 2012), through-hole components have a higher-reliability mechanical connection to the circuit board (Lau et al., 1990). Through-hole components are easier to solder for students who have never soldered and the components tend to be larger and more easily handled by students in a classroom situation (Ferri et al., 2017). Some surface mount components are so small that microscopes and specialized solder iron tips are required for hand-soldering these components onto a PCB.

PCBs are designed using a computer program “layout software” (Mitzner et al., 2019; Monk et al., 2017) that is analogous to a geographic information system (GIS) where the schematic represents connectivity and the PCB layout shows the position of components and circuit board layers (Fig. 7). Each component is given a designator that uniquely identifies the component on the PCB. In a similar fashion to a map of the London Underground where connectivity is important (Guo and Lu, 2016), the schematic (Fig. 7a) indicates inflows and outflows of electrons but does not indicate the position of components on the printed circuit board (PCB) (Fig. 7b). Some layout software packages can also generate a 3D model of the PCB (Fig. 7c). This is an apt demonstration of systems theory and models.

Vias are conductive holes on the circuit board that provide electrical connectivity of traces between layers. Layers are required to route traces and are also used for ground and power planes to provide electricity to components. The PCB layers are stacked and bonded together with prepreg layers and epoxy to form the PCB. All PCBs used for this project had two layers.

## Water Detection Circuit

The water detection circuit schematic provided as an associated download (<https://doi.org/10.6084/m9.figshare.12410588>) shows electrical connections between components. Lines on the schematic demarcate inputs and outputs. Dots show connections between components indicative of sub-systems that comprise the complete circuit as a system.

The water sensor (with designator J1) is a grid of conductive traces on the PCB referred to as a “comb” (Mims, 1995, p.24). A drop of water provides an electrical connection between traces that are at a potential of ground (GND) and traces that are at a potential of 3 V. Designator R1 is a resistor that provides a weak “pullup” to 3 V. Since the value of the resistor is 1 M $\Omega$ , a small amount of current flows through this circuit element. Although rainwater and tap water are not good electrical conductors, when a water droplet is present enough current flows to bring node N1 to an electrical potential of GND.

Power is provided by two 1.5 V AA batteries connected in series to produce 3 V. A regulator has not been included in the circuit to reduce cost, the number of parts, and complexity associated with an increase in construction time since the circuit was designed to be completed within one class (less than 1.5 hours). Also, the batteries can provide a stable output voltage at a level that exceeds the minimum operating voltage of the U1 inverter.

U1 is a Schmidt-trigger hex inverter semiconductor integrated circuit (IC) comprised of six inverters placed in the same component package. The inverter is a logic gate that reverses a logic level input so that a logic input 0 becomes an output 1 and a logic input 1 becomes output 0 corresponding to associated voltage levels. The Schmidt trigger is a type of logic gate with hysteresis so that if the input is at a voltage level above a maximum threshold the input will be considered as a logic high level. If the input is at a voltage level lower than a minimum threshold the input will be considered as a logic low level. This ensures that the circuit will detect the presence or absence of water without exhibiting high frequency fluctuations between two logic states. Designator C1 is a decoupling capacitor that acts as a charge reservoir to ensure that the IC will continue to operate when drawing current during switching events. The idea of the capacitor serving as a charge reservoir is analogous to the notion of a hydrological reservoir where water is stored.

When the water droplet is not present on comb J1, node N2 is at a low logic level since the input to all Schmidt-trigger inverters is a logic high level present at node N1 due to the pullup resistor. When the water droplet provides an electrical connection over the comb traces, node N1 is logic low at GND and the inverter outputs at node N2 are logic high. All the inverters connected in parallel provide enough current to turn on a light emitting diode (LED) as D1. Resistor R2 limits the current through the LED and thereby ensures that the LED does not fail due to power dissipation. Header P1 is provided for interfacing the circuit to a datalogger to record time series data or to a piezo buzzer to provide an audible alarm related to the presence or absence of water.

## **Relative Humidity (RH)/Air Temperature Circuit**

The relative humidity (RH)/air temperature circuit schematic (available as a download from <https://doi.org/10.6084/m9.figshare.12410588>) consists of a microcontroller (U6) interfaced via a parallel communications bus to a liquid crystal display (LCD, as U1). The LCD contrast can be adjusted using R1 as a variable resistor (potentiometer). The microcontroller communicates with an I2C digital RH/temperature sensor (U10). The I2C bus (Valdez and Becker, 2015) is implemented using digital logic communications hardware incorporated into the microcontroller and consists of clock and data wires used to read internal registers of the RH/temperature sensor.

The RH/temperature sensor has an on-board application specific integrated circuit (ASIC) that utilizes an analog-to-digital converter (ADC) internally interfaced to an on-board air temperature and relative humidity sensor. Power is provided to the circuit by a 9V battery and a linear regulator U13 with an output voltage of 5V. Diode D2 protects the circuit from a reverse polarity supply if the battery holder wires are soldered to the wrong terminals. Theory related to the operation of digital CMOS temperature and relative humidity sensors is respectively found in Bakker and Huijsing (1996) and Gu et al. (2004).

The microcontroller was programmed using the C language. The source code is provided as an associated digital download to this paper and is licensed using the GNU GPL to allow for modification and code sharing.

The raw outputs of the RH/temperature digital sensor U10 are 16-bit integers for temperature and RH. The most significant bit (MSB) of the temperature integer is a sign bit that indicates whether the temperature is positive or negative. According to the sensor datasheet, the AM2320 RH/temperature sensor can detect temperatures ranging between  $-40\text{ }^{\circ}\text{C}$  to  $80\text{ }^{\circ}\text{C}$  with a resolution of  $0.1\text{ }^{\circ}\text{C}$  and an accuracy of  $\pm 0.5\text{ }^{\circ}\text{C}$  over the temperature range. The RH is reported by the ASIC as an integer nominally ranging from 0 to 999 corresponding to a RH percentage of 0% to 99.9% with a resolution of 0.1% and an accuracy of  $\pm 3\%$ .

Both the raw temperature and RH outputs from the AM2320 sensor need to be scaled by the same coefficient to provide a valid output. The AM2320 datasheet provides this coefficient as  $\beta = 10$ , but due to micrometeorological boundary layer effects near the PCB edge, this scaling coefficient may be slightly higher or lower for a certain temperature range of operation. Students are given the following Eq. (S1) and the learning goal is to select a scaling coefficient  $\beta$  given an integer  $\varphi$  as the raw output from the sensor. The output  $\varepsilon$  is the temperature or RH displayed by the microcontroller on the LCD screen (Fig. 5b).

$$\varepsilon = \frac{\varphi}{\beta} \quad (\text{S1})$$

Calibration is an important skill to learn since this is how an output voltage or current from a sensor is converted into a physical quantity used for measurement, monitoring and modelling of hydrological phenomena. This is the basic principle of operation of a wide variety of sensors interfaced to a datalogger.

The calibration coefficient  $\beta$  can be selected by algebraic re-arrangement of Equation (S1) and linear curve-fitting utilizing known  $\varepsilon$  and  $\varphi$  that students collect as a data table. Alternately, known  $\varepsilon$  and  $\varphi$  can be used to compute  $\beta$  directly without curve-fitting. Students obtain  $\varepsilon$  from meteorological station measurements or from hand-held instrumentation provided in-class for experimentation. As part of the assignment, students are asked to identify assumptions associated with the use of online data or hand-held instruments. These assumptions can be used to identify why there might be differences between comparison measurements and outputs produced by the

circuit. These differences can be related to micrometeorology, boundary layers and temperature gradients in a room and at a field site.

U7 is a GPIO expander that reads the logic state of jumpers placed on the header pins of P5. Students find the calibration coefficient  $\beta$  as an integer and then apply jumpers to P5 to represent  $\beta$  as a binary number, where the presence of a jumper indicates a binary 1 and the absence of a jumper indicates a binary 0. Learning about binary numbers allows students to have an appreciation of how numbers are represented in computing (Feaster et al., 2012; Herman et al., 2011) and provides skills that transfer to the programming of dataloggers and computers for data collection and creation of hydrological models. Jumpers are used in lieu of DIP switches to reduce cost, but DIP switches could be used for increased efficiency in entering calibration coefficients.

### **Pyranometer Circuit**

The pyranometer circuit is interfaced with the microcontroller and can co-exist with the RH/air temperature circuit on the PCB. Students have the option of populating the components for the pyranometer circuit or the RH/air temperature circuit. Alternately, if students choose to populate components for both circuits, a slide switch J1 needs to be populated to choose whether to display LCD output from the RH/air temperature sensor or the pyranometer. The circuit schematic is also available for download (<https://doi.org/10.6084/m9.figshare.12410588>).

When power is applied to the circuit via slide switch J2, the microcontroller software checks for the presence of the AM2320 sensor U10 and the GPIO expanders U7, U8, and U9. If any of these parts are not soldered, the software will select the appropriate operating state to display RH/air temperature or pyranometer data on the LCD display. This allows for the circuit to continue to operate in some fashion if insufficient soldering or mistakes with part population are present on the PCB. This functionality also allows the students to selectively populate components to choose circuit operation.

Pyranometers can be created with a current-to-voltage converter circuit utilizing a single resistor or a transimpedance amplifier op-amp. The transimpedance amplifier increases cost and complexity but improves linearity and accuracy by operating the photodiode in photovoltaic mode (Zhen, 2013). Therefore, a transimpedance amplifier has been selected for this circuit.

The photodiode D1 is responsive to sunlight and provides a current output that is converted to a corresponding voltage by op-amp U11A configured as a transimpedance amplifier. Resistor R5 sets the output sensitivity and  $910\ \Omega$  was found to be suitable for practical radiation flux measurements. Op-amp U11B is a unity-gain inverter that takes a negative voltage output from the transimpedance amplifier to a positive voltage to serve as an input to a 12-bit ADC incorporated into the microcontroller. The ADC has a nominal voltage resolution of 1.22 mV with a maximum voltage input of 5 V. U12 is a charge pump that develops a voltage of approximately -9 V from the 9 V battery to provide a negative power rail for the op-amps. D4 clamps the op-amp output to a positive voltage to prevent damage to the microcontroller if the op-amp output becomes negative. Both op-amps are incorporated into one IC package to reduce cost and complexity.

The photodiode D1 is covered with a diffuser created from an ABS pipe glued to a Teflon disc. Students use cyanoacrylate glue to fasten the diffuser to the PCB. Analogous to commercial

pyranometers, the purpose of the diffuser is to ensure that photodiode D1 has a cosine response to obtain a measurement of radiation flux integrated over a hemisphere. Further details on the cosine response are given by Martinez et al. (2009).

GPIO expanders U8 and U9 read the logic state of headers P4 and P6 that provide a binary representation of a calibration coefficient  $\beta_f$  as a 32-bit IEEE 754 single-precision floating-point number referred to as a “float” in the C programming language. In a similar fashion to the RH/air temperature circuit calibration, jumpers are applied to headers P4 and P6 to represent the floating-point number in binary. The radiation flux  $F$  in units of  $\text{W m}^{-2}$  is related to the output voltage  $E$  as in Eq. (S2) below. The microcontroller software outputs the radiation flux in  $\text{W m}^{-2}$  to the LCD display (Fig. 5c).

$$F = E\beta_f \quad (\text{S2})$$

Students who build this circuit can find the calibration coefficient  $\beta_f$  using radiation data from a nearby meteorological station, or measurements can be obtained using a hand-held solar radiation flux meter / lightmeter provided by the instructor. For an assignment, students list assumptions associated with this calibration process; the assumptions can be used to identify errors and quantify the accuracy of measurements. An online calculator webpage or a calculator app can be used to represent a real number in binary format. These resources can be easily found by students using a web search. For manual computation of a floating point number and for associated theory, consult Overton (2001).

### **Application Considerations**

To keep costs low and to ensure that all students can complete the activity without a computer, this circuit operates in a standalone fashion without datalogging capabilities. All sensors are sampled by the microcontroller using a timer with a 2 second update rate and processed outputs are displayed on the LCD. The sampling rate can be modified by changing the microcontroller code, but 2 seconds is generally suitable for representing changes in temperature as a student walks across a field site or between campus buildings. This update rate is also suitable for stationary applications.

By manually observing the LCD display, students gain an appreciation of the role of automation. If the circuit is taken to an outdoor location, students are also able to observe how solar radiation levels change over time along with cloud cover and geographic location. A smartphone or camera with a time-lapse intervalometer can be used to automate the observation process.

To accommodate students, instructors should not generally assume that all members of the class have access to a computer outside of university lab resources (Vermaat, 2013, p.34), although this is becoming a necessity for many postsecondary students. If the circuit needs to be interfaced to a computer for logging, P3 on the schematic is a male header that can be populated and connected to a USB-to-RS232 serial port with CMOS logic levels. Consult the downloadable microcontroller source code for a serial command-line interface (CLI) if this functionality is required.

Although the circuit is not waterproofed after initial construction, a conformal coating (Medgyes and Ripka, 2007) can be applied to waterproof and protect most of the circuit board. The circuit can also be placed inside of a waterproof enclosure with holes to protect the AM2320 digital sensor U10. The development of waterproof enclosures is outside of the scope of this classroom activity due to the time and effort required, but an extension of this project is possible utilizing 3D printing technology.

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