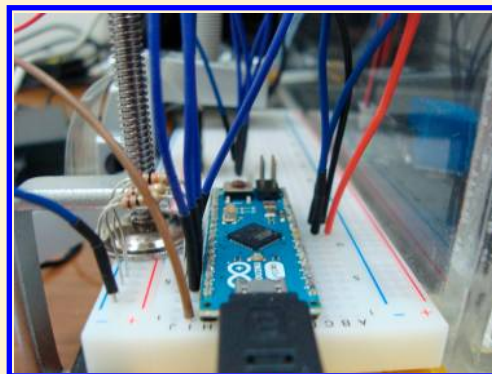# Open-Source Electronics As a Technological Aid in Chemical Education

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Ⓢ *Supporting Information*

**ABSTRACT:** This technology report discusses the possibility of using open-source electronic platforms to enhance technology-oriented training of chemistry students at the undergraduate and graduate level. It is anticipated that the increasing availability of open-source microcontrollers and programming tools can be helpful while teaching students the principles of instrumental techniques. The implementation of such technology in training students can further assist the development of a range of complementary skills, which can readily be combined with chemistry-specific skills.

**KEYWORDS:** *Graduate Education/Research, Upper-Division Undergraduate, Laboratory Equipment/Apparatus, Analytical Chemistry, Chemoinformatics, Demonstrations, Interdisciplinary/Multidisciplinary, Computer-Based Learning, Laboratory Computing/Interfacing*

## ■ INTRODUCTION

It is hard to overlook the growing presence of electronic and information technology in chemistry. However, high-end electronic platforms are often too expensive to be included in chemical education. This obstacle can currently be eliminated by taking advantage of the open-source electronic hardware as well as the associated software. Such devices are inexpensive, and they have already made their way to applications in chemistry and material science.[1,2]

## ■ ARDUINO PLATFORM

One of the most popular open-source electronic platforms is Arduino.[3] According to the official Web site:[3]

> Arduino can sense the environment by receiving input from a variety of sensors and can affect its surroundings by controlling lights, motors, and other actuators.

The basic Arduino microcontroller (version "Uno") comprises an ATmega chip, and it contains 14 digital inputs/outputs and 6 analogue inputs. It can be powered from battery, mains adaptor, or computer (via USB port). The scripts (also referred to as "sketches") can be written in a language derived from C using free integrated development environment (IDE) software, and uploaded to the Arduino printed circuit board (PCB) via the USB port. Arduino microcontrollers are currently used by hobbyists and professionals all over the world to automate daily life operations. However, the platform has already found applications in analytical chemistry, to operate digital microfluidic devices,[4] to construct a portable

capillary electrophoresis apparatus,[5] or an automated micro-extraction system.[6]

## ■ EXAMPLES OF PROJECTS

The range of projects that can be realized by undergraduate or graduate students using the open-source electronic platforms includes building a simple colorimeter, a pH meter, an automated titrator, a data logger, nanoliter-volume dispensing system, and a generic control device for automated assays. The open-source PCBs can be interfaced with sensors (e.g., photoresistors, photodiodes, thermistors, electrodes), relays, and indirectly (with the aid of auxiliary shields) with motors, solenoid actuators, valves, and many other electronic and electromechanical parts commonly used in chemistry laboratories. In fact, numerous low-cost shields are available that enable coupling of various components, such as sensors, to the Arduino PCBs.

Possibilities are endless when it comes to the use of the open-source electronics in chemistry. For example, the graduate students supervised by me combine open-source electronic devices with their experimental setups, which comprise commercial analytical instruments. These students also build their own detection systems, and write scripts to operate them. This way, they learn programming and building simple electronic circuits—skills that are increasingly important for chemists in the 21st century. Building a colorimetric detector using the Arduino platform is a task for half a day for a capable

first-year MS student. It may take several days to develop a complex system controlling various laboratory devices, such as a mass spectrometer, an automated extraction system, or a gas chromatograph, and integrating several sensors and actuators. The beauty of the Arduino platform is that a person who has very little knowledge of electronics or programming can incrementally expand his or her knowledge as the project develops. There is a substantial amount of supporting information on the applications of open-source tools available on the Internet from which students can draw ideas and solutions to particular tasks.

Data acquisition is an important step in instrumental analysis.[7] In the case of Arduino PCBs, reading the values from analogue inputs can be achieved with the analogueRead() command. (See the Supporting Information for an explanatory note, Table S1 and Figure S1.) The acquired values can be displayed directly on the screen of the computer connected via USB port using the serial monitor function of the Arduino IDE. In this case, the values will appear in the "serial monitor" window as they are transmitted to the computer. Sampling rate can be adjusted within certain limits. The raw values can be converted into meaningful analytical data (e.g., absorbance, concentration, potential) by inputting calibration equations with appropriate empirical coefficients into the C sketch in the IDE software. Various Internet forum sites, such as the Stack Overflow,[8] contain a plethora of information on solving specific problems in programming open-source electronic devices. For example, guidance on reading signals from multiple analogue inputs can be found there.[8] Schemes of the electronic circuits can readily be drawn in the open-source software called Fritzing[9] and exchanged between the instructor and the students.

## OTHER PLATFORMS

More complex microcontrollers and microcomputers are also available at low cost (see the Supporting Information, Table S2). For example, the Arduino Mega PCB provides users with 54 digital input/outputs that are helpful for more complex projects. Experienced students can also test their abilities with other platforms, such as Raspberry Pi,[10] or BeagleBone.[11] Both are microcomputers operating in a Linux-related environment. This provides a greater flexibility in terms of programming and application development, although it also requires more patience of the students with less-developed IT skills. Numerous derivatives of the above platforms exist, which are customized for specific tasks. For example, IntelGalileo is a newly introduced microcomputer "designed to be hardware and software pin-compatible with Arduino shields designed for the Uno R3".[12] Such upgraded electronic devices may give the opportunity of expanding the scripts written at the start of project (e.g., for Arduino Uno) when the computational requirements increase and the skills of the students develop.

## CONCLUSIONS

It is suggested that the open-source and other universal electronic devices are used in undergraduate and graduate projects to augment awareness among trainees of the links between modern chemistry, electronics, and computer science, and to foster creativity of aspiring scientists. One may also consider implementing the open-source hardware and programming in practical classes in instrumental chemical analysis. It is anticipated that such a combination of training in

electronics, computer science, and chemistry will help students understand the principles of operation of many commercial devices that they encounter in chemistry laboratories, and to develop technical skills that may be valuable for their future careers in industry and academia.

## ASSOCIATED CONTENT

### Supporting Information

Explanatory note; additional tables and figure. This material is available via the Internet at http://pubs.acs.org.

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### Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

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