JOURNAL OF CHEMICAL EDUCATION

Communication

pubs.acs.org/jchemeduc

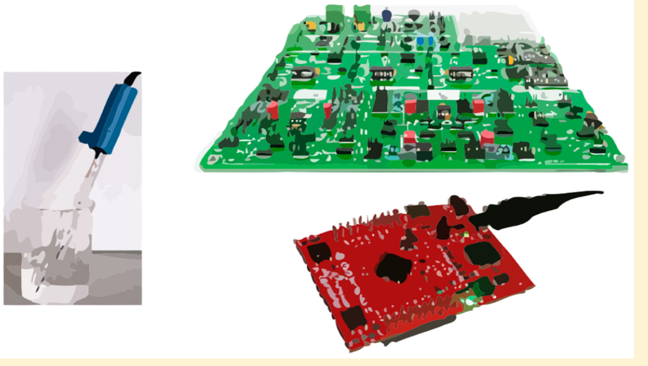
A Chemical Instrumentation Course on Microcontrollers and Op Amps. Construction of a pH Meter

Nikos J. Papadopoulos* and Andreas Jannakoudakis

Department of Chemistry, School of Sciences, Aristotle University, Thessaloniki 54124, Greece

S *Supporting Information*

ABSTRACT: In a chemical instrumentation course, usually analog signal conditioning, data acquisition, and digital signal processing are taught. Analog boards for easy interconnection of operational amplifiers are now available that make an introduction to analog signal processing easier. The digitization process can be demonstrated with microcontrollers. The cost of microcontroller development boards has decreased, and now they represent a cost-efficient platform to clarify the process of data acquisition. In this paper, we show the construction of a pH meter, and, as the development progresses, the characteristics of operational amplifiers and microcontrollers are exposed in the hope of making the internal operation of modern instrumentation more transparent.



KEYWORDS: *Upper-Division Undergraduate, Analytical Chemistry, Computer-Based Learning, Physical Chemistry, pH*

INTRODUCTION

Modern instruments equipped with microcontrollers are effective in making measurements and collecting data. This type of instrumentation gives students the belief that the only thing they have to learn in science is to press the correct button; the instrument will do the work, and when another button is pressed, the instrument will print the results.[1] It is obvious that modern technology has made the internal structure of the world obscure. One way to make the internal operation of instruments more transparent is to explain details of the functions of a microcontroller in an instrumentation course. During the past few years very powerful low-cost digital microcontrollers have appeared that can be used to upgrade lab instruments or construct homemade instruments with good educational characteristics.[2−6]

A microcontroller can be used for data acquisition from various sensors, or any other analog source, after the necessary analog signal conditioning.[7] Operational amplifier circuits can easily offer buffering, amplification, filtering, and range matching to make a sensor output suitable for digitization.[8] The analog boards with easy interconnection of operational amplifiers now available make an introduction to analog signal processing easier. The data acquired by a microcontroller can be preprocessed locally and then transferred to a personal computer with a serial protocol. The low price of development boards makes them attractive for use in an instrumentation course to teach the various capabilities offered by peripherals of a microcontroller and thus make the internal operation of modern instrumentation more transparent. The development boards equipped with a microcontroller utilizing an operating system are easier to program;[9−11] however, development boards lacking an operating system allow one to program the functions of the peripherals directly and consequently give better control and regulation of their operation. In this paper, we demonstrate how to develop a pH meter and during this process clarify the operations in the CPU, the GPIO, ADC, and UART peripherals.

DEVELOPMENT OF THE APPLICATION

Software Development

To start working with a microcontroller, one needs a development board, a debug adapter, and software tools to program the device, which, until recently, were all expensive. Now many microcontroller manufacturers offer universities all the necessary materials (as a donation) for the opportunity to introduce students to the world of microcontrollers.[12] These simple, low-cost development boards are suitable for projects on a tight budget. These boards have a built-in debug adapter, and they can be connected directly to a host computer via a USB port. The microprocessor can be programmed in an integrated development environment (IDE) that is provided by the manufacturer of the microcontroller at no cost. The IDE collects all the software tools in one environment that permits one to develop, debug, and generate code that is suitable for execution on the microcontroller. In this work we have examined the capabilities offered by development boards with the Tiva microcontrollers from Texas instruments.[13,14] The

Received: September 30, 2015
Revised: May 15, 2016
Published: May 31, 2016

DOI: 10.1021/acs.jchemed.5b00743
J. Chem. Educ. 2016, 93, 1323−1325

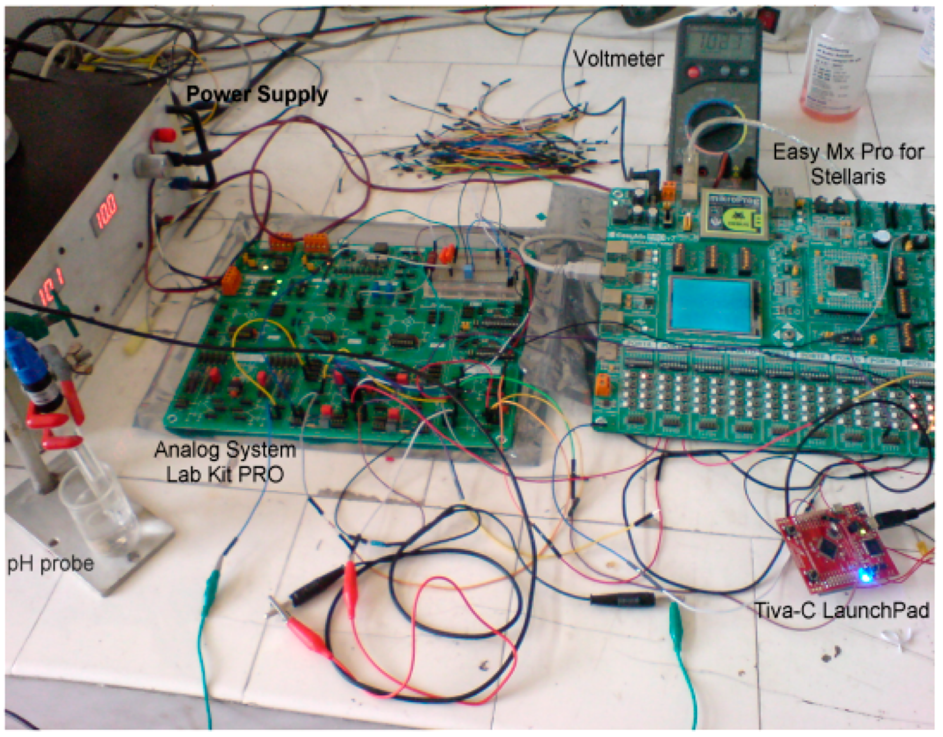


Figure 1. Experimental setup, showing a pH probe, a power supply, the MX analog pro board, and the two development boards equipped with Tiva microcontrollers.

boards have been programmed with Code Composer Studio.[15] More details about these boards are given in the Supporting Information. The pH meter application is developed gradually step by step. The aim of this approach is to progressively familiarize the students with the IDE, the embedded C constructs, and how to use basic peripherals. The goal is, in the limited time that is available, to learn how to use the microcontroller as a tool and not to learn every detail about the microcontroller, or how to program it efficiently. Instead of writing code from scratch we encourage our students to modify existing code. In the Supporting Information we give detailed information about the software that we have developed.

The peripherals are controlled by reading and writing to specific memory locations, with the same instructions that the microprocessor would normally use to access memory. Each peripheral possesses a plethora of registers that first need tuning and coordination for the peripheral to function properly. A number of example programs and drivers from the microcontroller development board manufacturer are available and can serve as a reference for the use and control of the peripherals.[16] A peripheral driver allows one to write software for the control of the peripheral without the need to know the function of each register and its bit fields, as well as the regulation, coordination, and sequence of activation. The drivers perform low-level register writing and reading on the hardware and offer an application program interface (API) enabling access to the functions of the peripherals. Thus, an in-depth understanding of the operation and knowledge of the precise details of the peripherals is not required. It is possible to write an entire application rapidly without direct access to the hardware registers.

A microcontroller can read the signal from a sensor with the analog to digital converter (ADC) peripheral which connects the analog world to the digital environment of the microcontroller. The pH electrode is an extremely high impedance sensor, and the signal coming from a pH sensor needs amplification, filtering, and range matching to meet the range of the ADC.[17] In addition, the signal should be manipulated to compensate for the slope and the rest potential of the electrode.

The Analog Part

The analog signal processing can be easily realized with the Analog System Lab Kit PRO.[18] The calibration steps are accomplished digitally by the microcontroller. The analog circuit has been designed with Tina from DesignSoft. Tina is a simulation environment for circuit design with a simple and intuitive graphics-based interface that can be used to observe the behavior of electronic components used in chemical instrumentation.[19,20] Simulation environments can familiarize students with the behavior of electrical and electronic circuits.[21] A version of this program can be downloaded without cost and can be used to design a circuit, see the dc voltage and noise at various points of the circuit, and see the settling time and stability of the circuit from Bode plots. The circuit we used is detailed in the Supporting Information. Figure 1 depicts the experimental setup.

Communication and Control of the Microcontroller

The data acquired by the ADC are initially stored in memory and can be either displayed on a screen, if it is available, or transferred to a PC for further data manipulation. For a Windows PC many free RS-232 terminal programs can be downloaded and used to set up the communication between the PC and the microcontroller. We have chosen a terminal program written in C#, which can be modified and extended according to the users' needs.[22] The calibration parameters can be stored in the FLASH memory of the microcontroller and recalled every time the microcontroller is switched on. Code Composer Studio provides a software tool (GUI Composer)

DOI: 10.1021/acs.jchemed.5b00743
J. Chem. Educ. 2016, 93, 1323−1325

that can create a graphical user interface on the computer screen. This software provides a toolbox with prebuilt objects, knobs, buttons, graphs, and displays that can be placed on the computer screen. Variables in the microcontroller program are linked with the graphical controls, and any change in the connected variable is reflected in the value displayed by the graphical control. The pH meter can be used and calibrated with the mouse (Figure 2).

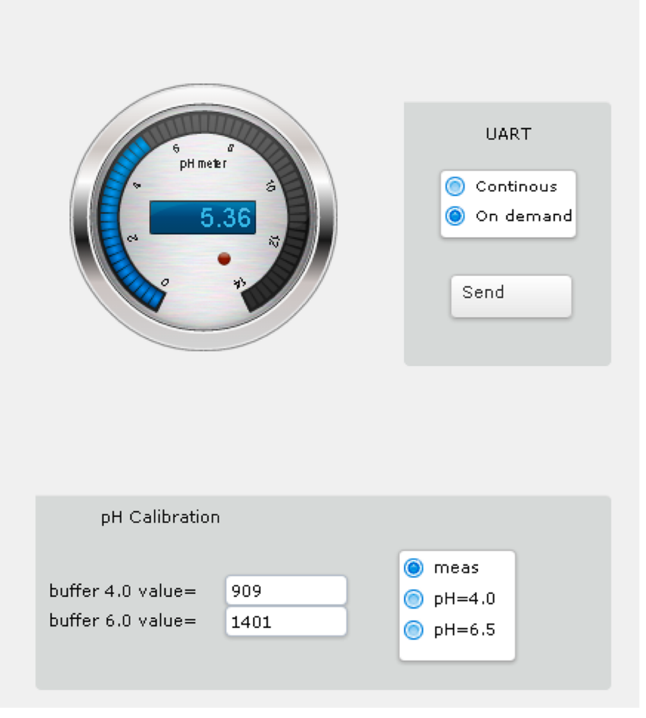


Figure 2. Screenshot of the pH meter control using GUI Composer.

■ ADDITIONAL EDUCATIONAL MATERIAL

In our chemical instrumentation course we do not have the time to teach microcontrollers and analog electronics to the depth that we would desire.[23] Only the essentials can be taught, and the advanced material is left as self-study for students who are more motivated and ready to accept more responsibility for their own learning.[24] Thus, they can broaden their perspectives and enhance their job opportunities. In the Supporting Information we provide some sources of online educational material for the interested students.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00743.

Detailed description of the material used, diagrams from the Tina software, and Web addresses for online educational material (PDF, DOC)

Software for the realization of the pH meter application (ZIP)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: njpapado@chem.auth.gr.

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Bauer, S. H. Scientific Literacy vs. Black Boxes With Reference to the Design of Student Laboratory Experiments. *J. Chem. Educ.* **1990**, *67* (8), 692–693.

(2) McClain, R. L. Construction of a Photometer as an Instructional Tool for Electronics and Instrumentation. *J. Chem. Educ.* **2014**, *91* (5), 747–750.

(3) Mabbott, G. A. Teaching Electronics and Laboratory Automation Using Microcontroller Boards. *J. Chem. Educ.* **2014**, *91* (9), 1458–1463.

(4) Urban, P. L. Open-Source Electronics As a Technological Aid in Chemical Education. *J. Chem. Educ.* **2014**, *91* (5), 751–752.

(5) Kubínová, Š.; Šlégr, J. ChemDuino: Adapting Arduino for Low-Cost Chemical Measurements in Lecture and laboratory. *J. Chem. Educ.* **2015**, *92* (10), 1751–1753.

(6) Famularo, N.; Kholod, Y.; Kosenkov, D. Integrating Chemistry Laboratory Instrumentation into the Industrial Internet: Building, Programming, and Experimenting with an Automatic Titrator. *J. Chem. Educ.* **2016**, *93* (1), 175–181.

(7) Antler, M.; Salin, E.; Wilczek-Vera, G. Teaching Data Acquisition. An Undergraduate Experiment in the Advanced Analytical Chemistry Laboratory. *J. Chem. Educ.* **2005**, *82* (3), 425–427.

(8) Braun, R. D. Operational Amplifier Experiments for the Chemistry Laboratory. *J. Chem. Educ.* **1996**, *73* (9), 858–861.

(9) Raspberry Pi 2 Model B+. https://www.raspberrypi.org/products/model-b-plus/ (accessed May 2016).

(10) BeagleBone. http://beagleboard.org/bone (accessed May 2016).

(11) Intel Galileo Gen 2 Development Board. http://www.intel.com/content/www/us/en/embedded/products/galileo/galileo-overview.html (accessed May 2016).

(12) ARM Embedded Systems Education Kit, Course/Lab Material for Teaching Embedded Systems/MCUs. http://www.arm.com/support/university/educators/embedded/ (accessed May 2016).

(13) Getting Started with the TIVA C Series TM4C123G LaunchPad. http://processors.wiki.ti.com/index.php/Getting_Started_with_the_TIVA%E2%84%A2_C_Series_TM4C123G_LaunchPad (accessed May 2016).

(14) EasyMxPRO. http://processors.wiki.ti.com/index.php/EasyMxPRO (accessed May 2016).

(15) Code Composer Studio (CCS) Integrated Development Environment (IDE). http://www.ti.com/tool/ccstudio (accessed May 2016).

(16) TivaWare Peripheral Driver Library. http://www.ti.com/tool/sw-tm4c (accessed May 2016).

(17) LF444 Quad Low Power JFET Input Operational Amplifier pH Probe Amplifier/Temperature Compensator. http://www.ti.com/lit/ds/symlink/lf444.pdf (accessed May 2016).

(18) ASLKPRO University Kit. http://www.ti.com/tool/aslkpro (accessed May 2016).

(19) Getting Started with TINA-TI. http://www.ti.com/lit/ug/sbou052a/sbou052a.pdf (accessed May 2016).

(20) TINA-TI SPICE-Based Analog Simulation Program. http://www.ti.com/tool/tina-ti (accessed May 2016).

(21) Sadik, O. A.; Cheung, M. C. Computer Simulation of Electronic Circuits Used in Chemical Instrumentation. *J. Chem. Educ.* **2001**, *78* (5), 658–662.

(22) Termie: A Simple RS-232 Terminal. http://www.codeproject.com/Articles/23656/Termie-A-Simple-RS-Terminal (accessed May 2016).

(23) Zielinski, T. J.; Brooks, D. W.; Crippen, K. J.; March, J. L. Time and Teaching. *J. Chem. Educ.* **2001**, *78* (6), 714–715.

(24) Developing Independent Learners in Chemistry. Report from ECTN Working group. http://ectn-assoc.cpe.fr/network/wg_pres/ECTN30n_DevIndepLearnChem.htm (accessed May 2016).

DOI: 10.1021/acs.jchemed.5b00743
J. Chem. Educ. 2016, 93, 1323–1325