1

INTRODUCTION

The purpose of this document is to provide detailed descriptions of the Propeller Experiment Controller (PEC). The PEC is free, open-source software for the Parallax Propeller microcontroller (Parallax Inc.; Rocklin, California) that is designed to meet the basic needs of automated behavioral research. First, the PEC *detects* behavioral and environmental variables, such as the lever-pressing behavior of a rat in an operant chamber, or the ambient temperature. Second, it *affects* the environment, in turn often indirectly affecting a subject's behavior. For example, the PEC may control a pellet dispenser, shock grid, stimulus light, or heater. Third, the PEC *saves* detailed data about any event of interest in an experiment (i.e., dependent and independent variables). In addition to producing its own standard data spreadsheet, the PEC also supports MedPC formatted data, a common standard, and user-customized data output. Finally, the PEC implements the above needs (detect, affect, and save) at very precise intervals of *time* while also allowing the user to execute events at specific times and record temporal variables. The PEC also goes beyond the basic needs of behavioral research in that it is both uniquely *portable*, not requiring a connection to a computer, and is very *affordable* compared to commercial alternatives, costing under $100.00 for the basic experiment controller.

We provide detailed information on using hardware related to the Propeller microcontroller as well as the PEC software. This document is designed for those new to microcontrollers. However, it does assume the reader has a basic understanding of electronics concepts such as voltage, current, and resistance, as well as electronics skills, such as soldering circuits and using a solderless breadboard. The reader will also benefit from having prior programming experience. However, this document, and use of the PEC, is also suitable for those new to programming.

In this chapter, we describe the history of automation in behavioral research that led to the development of the PEC. Bolded terms in this and the following chapters also appear in the glossary (Appendix A). The following chapters provide an overview of the PEC, including the basic hardware and software of the Parallax Propeller, the PEC's dedicated behavioral software library, and instructions and examples of common uses of the PEC.

History of Automation: From Relays to Personal Computers

Behavioral scientists have long sought techniques to automate experiments. Automation became especially popular in behavior analysis due to the work of B. F. Skinner. In his studies on operant conditioning, Skinner created automated experimental chambers, often using parts scavenged from other equipment. Developing such equipment allowed Skinner to conduct new types of behavioral experiments. Although Skinner began his initial efforts in automation prior to his doctoral graduation (Skinner, 1930), it was not until after Ferster and Skinner's *Schedules of Reinforcement* (1957) that these types of automated techniques and experiments grew in popularity and became the standard for research in behavior analysis (Escobar, 2014). After this point, the methods in behavior analysis developed along with technology. Techniques developed by behaviorists were later influential in other behavioral fields such as comparative psychology and behavioral neuroscience.

The earliest implementation of automated behavioral techniques, beginning in the 1950s, relied on **electromechanical relays**. Relays can open or close a circuit if the relay itself receives sufficient power from a separate circuit. This relatively simple component can be used to create basic logic circuits, and from there a complex array of counters, adders and other devices can be developed. Behavioral researchers learned to build complex electrical circuits with relay-driven logic to implement their experiments; many such designs were published (e.g., Favell, 1969; Hursh, 1972; Richardson, Ulrich and Wolff, 1964). Some standardization of relay circuits occurred after relays became common in behavior analysis. Many laboratories adopted modular relay racks, where relays and logic circuits could be temporarily connected by snapping wires to input and output terminals (Escobar and Lattal, 2014). Commercial logic, counter, and timer modules were later created so that researchers did not have to rebuild and modify common circuits for each experiment (Escobar, 2014). In the 1960s, **transistors** and solid-state circuitry became popular and began to replace or supplement relays in many logic circuits and other devices (Escobar, 2014). Although transistor and solid-state technology was much smaller and more efficient, the focus remained on constructing dedicated circuits for experiments (Quy, 1976; Saslow and Markowitz, 1964; Smith and Wasson, 1974; Stoddard, 1987).

Early computers, called **minicomputers**, were also used by behavioral laboratories in the 1960s. Although large, around the size of a household refrigerator, minicomputers were much smaller than the massive room-sized mainframes of the 1950s. Minicomputers were also comparatively affordable, from $25,000.00 to $30,000.00 (Sidowski, 1972). As behaviorists adopted the use of programmable laboratory computers, researchers and technicians shifted away from building specialized circuits, and instead focused on developing programs for the minicomputers (Barenstien and Lockard, 1973; Millenson, Kehoe, Tait, and Gormezano, 1973). Fortunately, many of the skills used to create logic circuits also were useful in early programing (Catania, 2002). Several minicomputers, such as the PDP-8 (Digital Equipment Corporation; Maynard, Massachusetts), and the NOVA (Data General; Westborough, Massachusetts), became common in behavioral laboratories (Sidowski, 1972), leading to some standardization of programming practices. Several state notation languages for the minicomputers, such as SCAT (Polson, 1973), and SKED (Snapper, 1973), were developed based on Mechner's (1959) notation for operant conditioning.

As technology became smaller, faster, and more affordable, the minicomputers gave rise to the **microcomputers** of the 1980s. Several microcomputers were popular for behavioral research, including the Apple II (Apple Inc.; Cupertino, California; Poltrock and Gregory, 1982; Thompson, 1979), Commodore 64 Amiga and PET microcomputers (Commodore International; West Chester, Pennsylvania; Coney, 1989; Goldstein, Blekkenhorst, and Mayes, 1982; Kallman, 1986; O'Dell and Jackson, 1986), Timex Sinclair (Timex Corporation; Middlebury, Connecticut; Nicholls and Potter, 1982; Trelease, 1982), and the TRS-80 (Tandy Corporation; Fort Worth, Texas; Perera, 1981). Researchers shared software to control experiments as well as methods to connect microcomputers to experimental equipment. The state notation languages of the minicomputers also evolved. Med Associates Inc. (Fairfax, Vermont) developed a new version of the state notation language called MedState notation (Tatham and Zurn, 1989) for the increasingly popular DOS family of operating systems. As microcomputers evolved into modern **personal computers**, the popularity of MedState notation and associated Med-PC equipment caused Med-PC to become the norm in behavioral laboratories. Even today, it is difficult to find an operant conditioning laboratory without Med-PC software and equipment (Escobar, 2014).

The Walter/Palya Experiment Controller

Although microcomputers and today's personal computers are much more affordable than the minicomputers of the 1960s, automated behavior research laboratories can still be expensive. As commercial research companies such as Med Associates Inc., Lafayette Instrument Neuroscience (Lafayette, Indiana), and Harvard Apparatus (Holliston, Massachusetts), grew and took on the role of apparatus and software development previously held by researchers, the price of equipment increased. Presently, the cost of relatively simple operant conditioning equipment can range from $2,000.00 to $20,000.00 (Devarakonda, Nguyen and Kravitz, 2016; Hoffman, Song, and Tuttle, 2007; Pineño, 2014).

As an alternative to commercial equipment, Donald Walter and William Palya developed one of the first dedicated experiment controllers (Palya and Walter, 1993; Walter and Palya, 1984). The Walter/Palya experiment controller is responsible for interfacing with apparatus hardware, executing experimental events, and recording behavior. The system hardware was designed to be connected to a variety of devices, both custom designed and commercial, enabling the Walter/Palya experiment controller to be used with many species and research methods. It only required a connection to a computer during the initial launch of an experiment program, and for receiving data logs after an experimental session ended. The reduced requirements for a laboratory computer during an experimental session meant that the computer could be used for other tasks, and it also allowed a single host computer to interface with a network of experiment controllers. The Walter/Palya experiment controller's software was a dedicated library of techniques useful for behavioral experiments, with two programing languages designed specifically for the system, the user-friendly ECBASIC, and the much faster ECL. This software allowed many of the common needs of behavioral experiments, such as counting responses and keeping track of time, to be conducted in the background. In addition to the programing languages, several sample programs were available for use in experiments. Despite these benefits, the Walter/Palya controller was also very affordable at $150.00 on release (Walter and Palya, 1984), and around $575.00 at the end of its sale (B. Palya, personal communications, January 24, 2011; March 10, 2018). Although the technology is now outdated, the Walter/Palya experiment controller was highly successful with a variety of species including pigeons (Minervini and Branch, 2013), rats (Ranaldi, Ferguson, and Beninger, 1994), bees (Dinges et al., 2013), and rattlesnakes (Place, Varnon, Craig, and Abramson, 2017), and is still in use today by several laboratories.

Modern Automation

The Walter/Palya experiment controller was based on a **microprocessor**, originally the Motorola 6809 microprocessor (Motorola; Schaumburg, Illinois; Walter and Palya, 1984), and later the Intel 80C188EB microprocessor (Intel Corporation; Santa Clara, California; Palya and Walter, 1993). Microprocessors are small, programmable computer processors. Along with other components, microprocessors can be used to build general purpose computer systems or specialized devices like the Walter/Palya experiment controller. When the Walter/

Palya experiment controller was designed, building a specialized system around a microprocessor was an elegant solution to many automation problems. Now, however, modern **microcontrollers** provide a number of new opportunities. Microcontrollers, like microprocessors, are small programmable computers. The distinction between microcontrollers and microprocessors is that microcontrollers contain an entire system on a single chip and are often specialized at interfacing with other hardware devices. The ability of a single microcontroller to be programed to control other equipment makes microcontrollers perfect for acting as a dedicated experiment controller.

Surprisingly, despite the need for low-cost, adaptable research equipment, relatively few experiment controllers are based on modern technology (see Varnon, Lang and Abramson, 2018 for a detailed review). Of these recent controllers, few compare to the Walter/Palya experiment controller. Only the Walter/Palya experiment controller offers a dedicated software system to conduct behavioral research. The modern devices are generally specialized by species, experimental paradigm, or both. Many also cannot be used untethered to a personal computer, limiting the potential of low-cost research, field work, or use of experiment controllers in teaching laboratories.

The Propeller Experiment Controller

We developed the Propeller Experiment Controller (PEC; Varnon and Abramson, 2013), free software for the **Parallax Propeller** microcontroller, to provide a low-cost solution to the experiment control problem faced by many behavioral scientists. In many senses, we designed the PEC to be a true successor to the Walter/Palya experiment controller. Like the Walter/Palya experiment controller, the PEC is an adaptable system, not restricted to species or method. Both offer a dedicated library of software and instruction sets that are useful for behavioral research, and both execute the most common requirements of behavioral research in the background without oversight from the user. The PEC also goes beyond the Walter/Palya experiment controller: it is completely portable, even with the potential to be battery powered; it automatically provides a user-friendly data output spreadsheet that can be used by programs such as Microsoft Excel (Microsoft Corporation; Redmond, Washington); it can interface with modern, complex devices to detect behavior and affect the environment; and it has eight independent processors allowing for true multi-tasking in experiment programs. The PEC is also very affordable, at around $85.00 for the basic Propeller board and required accessories (not including apparatus costs).

The PEC has been used in a variety of contexts, both for teaching and research. We first used the PEC to develop a low-cost learning laboratory course (Varnon and Abramson, 2013). In experimental research, the PEC has been used with a variety of species including honey bees (Dinges, Varnon, Cota, Slykerman, and

Abramson, 2017), horses (Craig, Varnon, Pollock, and Abramson, 2015), human infants (Colaizzi, 2016), pigeons (Varnon, 2013), and wild squirrels (Phelps and Varnon, 2015).

The adaptable design of the PEC provides behavioral scientists with an inexpensive yet powerful automation system that can be used in many behavioral fields such as comparative psychology, behavior analysis, behavioral ecology, and behavioral neuroscience. The PEC is designed to remove reliance on expensive commercial equipment and return control of research to those who conduct it, and this is uniquely positioned to encourage new research in the study of behavior. Although using the PEC does require some technical skills, the following chapters, in addition to the Propeller Datasheet (Parallax Semiconductor, 2012) and Propeller Manual (Martin, 2011), can be used as an instructional resource.