FROM RELAYS TO MICROCONTROLLERS: THE ADOPTION OF TECHNOLOGY IN OPERANT RESEARCH

DE LOS RELEVADORES A LOS MICROCONTROLADORES: LA ADOPCIÓN DE TECNOLOGÍA EN LA INVESTIGACIÓN OPERANTE

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Abstract

Adoption of exogenous technology for the automated arrangement of contingencies has accompanied and shaped the development of the experimental analysis of behavior. During the early days, motors and electromechanical relays were used for controlling and recording experimental events. As it became available, solid-state equipment began to replace electromechanical relays between the 1960s and 1970s. About the same time, the advent of minicomputers and personal computers, resulted in interfaces, and state-notation programming languages designed for simplifying the daily work of operant researchers. During recent years, new technology involving low-cost microcontroller input-output boards, and a variety of analog and digital sensors has become available worldwide. These boards could help developing new lines of research and disseminating behavior analysis around the world.

Keywords: operant research, relay racks, solid-state equipment, minicomputers, microcomputers, microcontrollers

Resumen

La adopción de tecnología exógena para el arreglo automático de contingencias ha acompañado y moldeado el desarrollo del análisis experimental de la conducta. Durante los inicios se usaron motores y relevadores electromecánicos para controlar y registrar eventos experimentales. El equipo de estado sólido empezó a remplazar a los relevadores electromecánicos a medida en que se hacía disponible entre las décadas de 1960 y 1970. Durante ese periodo, la llegada de las minicomputadoras y las computadoras personales, resultó en interfaces, y lenguajes de programación basados en notación por estados que estaban diseñados para simplificar el trabajo diario de los investigadores en los laboratorios de condicionamiento operante. En años recientes, nueva tecnología que involucra tarjetas de input-output de bajo costo basadas en microcontroladores y una variedad de sensores tanto digitales como analógicos se han vuelto disponibles alrededor del mundo. Estas tarjetas pueden ayudar a desarrollar nuevas líneas de investigación y a diseminar el análisis de la conducta alrededor del mundo.

Palabras clave: investigación operante, racks de relevadores, equipo de estado sólido, minicomputadoras, microcomputadoras, microcontroladores

As in other sciences, the relation between the substantive content of research and the technology that enables it, is a close one (Lattal, 2008b). When describing the development of operant research after 50 years of the *Journal of the Experimental Analysis of Behavior* (JEAB), Lattal noted the numerous cases that exemplify that behavior analysis and technology have evolved together. As part of the analysis of such coevolution, Lattal distinguished between technology from other disciplines (exogenous) and technology created within the discipline (endogenous). Endogenous technology composed of the schedules, procedures, and interventions developed by behavior analysts are an essential component of the body of knowledge of behavior analysis. Such endogenous technology is enabled, and also constrained, by technology developed in other fields. What devices and apparatus from other fields have been adopted and how they were adapted by operant researchers is the topic of this review.

The current landscape of operant laboratories has been shaped by the coevolution of exogenous and endogenous technology. Nowadays it is difficult finding an operant-conditioning laboratory without a computer loaded with Med-PC software, at least one interface and one or several pieces of equipment from Med Associates Inc. The integration between the easy-to-use MedState Notation language and easy-to-connect Med Associates hardware has established a standard in operant research. With this standardized equipment, even inexperienced users can program and run automatically a schedule of reinforcement in hours.

Standardization of the equipment used in operant laboratories is important for replicability of results (Sidman, 1960). Some drawbacks of such standardization, how-

ever, are the high cost of the equipment and that modifying the equipment for presenting events or recording dimensions of behavior, not considered in the initial configuration, are difficult to accomplish. In recent years, new inexpensive technology based on microcontroller boards has become available worldwide. These boards could be useful for recording different dimensions of behavior and presenting a variety of stimuli with accuracy. As noted earlier, adopting exogenous technology for instrumentation in operant research, however, is far from new. Learning about the relation between technology and behavior analysis could help those interested in adopting new technologies, like microcontrollers, to consider the problems that technology could help us solve, and to anticipate problems that might arise from the adoption of these innovative devices. This paper narrates the evolution of instrumentation in behavior analysis from the use of electromechanical equipment to the recent developments using microcontroller boards.

Automation in the Early Days

Automatic control of experimental events and recording of behavior was a concern for Skinner during the early days of the field that was to become the experimental analysis of behavior (Skinner, 1956). Automation was possible thanks to Skinner's adoption, design, and modification of electromechanical devices as he created and improved the operant-conditioning chamber and the cumulative recorder during the 1930s. In *A Case History in Scientific Method,* Skinner (1956) described the evolution of his early devices and the influence that these, and their shortcomings, had on the development of his research agenda (see Lattal, 2008b).

Skinner first mentioned the use of electric devices for automation in 1930 (Skinner, 1930a). He described: "A feeding device permits the animal to obtain uniform pieces of a prepared food… in such a way as to make an electrical contact for each piece taken" (p. 435). In his doctoral dissertation (Skinner, 1930b), he described the apparatus in more detail: "A writing lever was therefore devised which was lifted vertically by the action of a fine thread which could be wound about a carefully turned shaft. The shaft is turned by a ratchet activated by a magnet…" (p. 78). These devices not only facilitated research but also influenced the development of operant research, marking the beginning of the coevolution of behavior analysis and technology (Lattal, 2008b). Weiss (1969) noted, "The ease with which the apparatus could be automated and the clarity of the cumulative record led to the design of equipment that enabled experimenters to record behavior for long periods of time without intervention" (p. 255).

It was after Ferster and Skinner (1957) began the systematic study of behavior under different schedules of reinforcement during the early 1950s that the intricate interconnection of electromechanical relays became common practice in operant research and the standardization of programming equipment commenced. Only a few years later, relay racks populated with spaghetti-like wires became the hallmark of operant-conditioning laboratories (Catania, 2002, Goldiamond & Dyrud, 1968; Gollub,

2002). On these racks, panels equipped with relays, steppers, switches, and timers were interconnected using snap leads.

Electromechanical Relays

Programming experimental events before the advent of integrated circuits (IC) and computers depended mainly on electromechanical relays. Many of the relays used in the first devices in operant research were, as Ferster (1970) noted, "cannibalized" from vending machines, which bear a conspicuous similarity to operant conditioning chambers. An electromechanical relay is a switch operated with an electric current. Each relay is comprised of two sections: the contacts and a magnetic circuit. A contact is a set of conductors that can be separated (open circuit) or touching each other (closed circuit). When an electric current is applied to a coil in the magnetic circuit, it moves the contacts, thus opening or closing the switch. Most relays used in operant research include two contacts: normally open (NO) and normally closed (NC). If the state of the contact is NO, applying a current to the coil forces the contact to touch a common or fixed conductor, thus closing the circuit. If the state of the contact is NC, applying a current forces the contact to separate from the common conductor, thus opening the circuit. The upper left section of Figure 1 shows a diagram of a relay. Most useful relays in operant programming contained four sets of contacts that were moved in the same direction with one magnetic circuit (double-poled relays, see upper right section of Figure 1).

One reason for the importance of relays in programming experimental events was that they could be used to control logic operations (e.g., AND, OR, XOR, NAND, and NOR gates) in switching circuits (see lower section of Figure 1). These circuits were commonly used in telephone network programming (e.g., Huffman, 1954). Additionally, relays could be used to generate several outputs (e.g., activate a cumulative recorder, a feeder, and lights with one input (e.g., a lever press), isolating the electric circuit in each device. Catania (2002) recalled that students at Skinner's laboratory learn about switching circuits under Gollub's supervision. Catania noted that programming logic with relays was useful later in their careers because the same logic was incorporated in assembly and high-level programming languages in computers several years later.

Generating schedules of reinforcement using electromechanical relays required ingenious arrangements of devices and logic operations. Timers constructed from rotating motors (e.g., Dinsmoor, 1990) were important for generating fixed-interval schedules or periodic schedules, as they were also called (Skinner, 1938). The motor was started with an electric current and when a metal section attached to the shaft of the motor touched a contact, an electric current activated a relay. If the speed of the motor remained constant, the duration of the period elapsed was fixed. As commercial timers became readily available, these new timers were added to the programming equipment of operant researchers. Figure 2 shows a commercial timer used for programming fixed-interval schedules of reinforcement. In these schedules, a logic
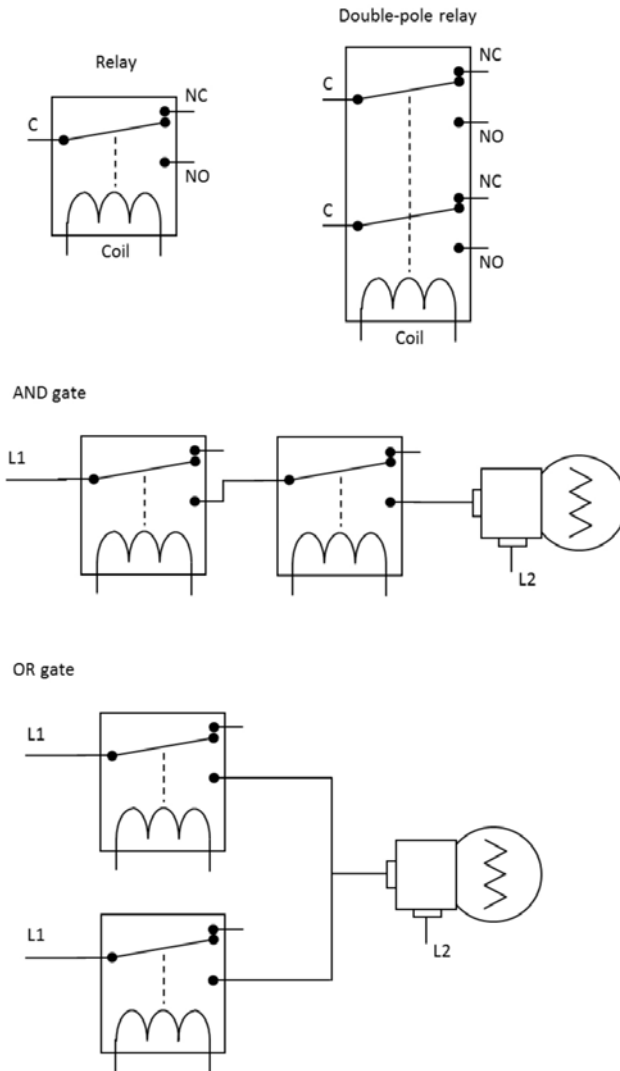
Figure 1. Schematic representation of electromagnetic relays and two logic gates. The upper left section shows a one-pole relay. Only when the coil is activated with an electric current the common (C) wiper changes its position making contact with the NO terminal. The upper right diagram shows a double-pole relay with two sets of contacts. The middle section shows an AND gate. Only when the coil of the two relays is activated, an electric current flows from L1 to L2, turning on the bulb on the right. The lower diagram shows an OR gate. The bulb is on when one or both relay coils are activated.

Figure 2. A Bakelite panel with a GraLab timer. The state of the contacts in an electromagnetic relay in the back of the panel changed when the timer was activated and deactivated. The coil in the relay and the motor of the timer worked with 110-120 V AC. Below the dial, a series of snap studs connected to the contacts of the relay, were used for connecting other devices using snap leads. The connectors in the upper and lower sections of the panel (marked + and -) were used for connection with rods in the relay rack.

AND gate receiving a pulse from the timer and a response device was useful for producing reinforcement delivery.

Variable or aperiodic schedules of reinforcement (Skinner, 1938), before probability generators, required the use of preset mechanical devices. Ferster (1970) and Dinsmoor (1990) described a device designed by Skinner that used a 16-inch phonographic record. Small holes at measured intervals were cut on a non-conductive surface on top of the record. These holes revealed a small section of a metal conductive surface. When a metal stylus fell in one of the holes it closed a circuit that could activate a relay and "wait" for a response to be reinforced. According to Ferster, he adapted a similar device for generating variable-ratio schedules. Although, he did not describe the mechanism, it can be deduced that instead of rotating the motor constantly, it rotated slightly only when a response was recorded. Another device for generating variable schedules used pre-punched tape (generally film). A motor-driven sprocket wheel advanced the tape at a constant speed. Whenever a hole in the tape contacted the mechanism (i.e., a small lever fell inside the hole) a relay was activated. Different distributions of holes in the tape generated intervals of different durations.

A special type of relay, the stepper, contained several contacts. The position of the common conductor was moved one step at a time whenever the stepper was activated. If a device, like a feeder, was connected to one of the contacts, it was activated every time the stepper closed that contact, and whenever it completed a full cycle after a fixed number of activations. It can be inferred the importance of this arrangement for generating fixed-ratio schedules. Another important stepper used by operant researchers was the alternating stepper. In this modified stepper, the common conductor rested indefinitely in one of two positions even when the current was not applied. Therefore, alternating steppers maintained the position even after power outages. Steppers could be used as counting devices using the binary system. Another use was controlling two-state conditions, for example, stimuli presentations in multiple schedules of reinforcement.

One drawback of using old relays was that responses, especially key pecking in pigeons, were occasionally too fast to activate the relay coil. A solution was using pulse generators that transformed every response, independently of its duration, into a 30 or 40 ms input. The function of pulse formers was that of an analog to digital converter. The variation in response duration was eliminated and transformed into a pulse of a constant duration that activated consistently the coil of electromechanical relays.

Bakelite Panels and Snap Leads

After Ferster (1970) arrived at Skinner's laboratory in Harvard in 1951, the association with Ralph Gerbrands in the mechanical workshop, and Rufus Grason in the electronic workshop, resulted in the design of Bakelite panels in which the components were mounted. These panels, equipped with stud connectors, were interconnected

using snap leads and were laid out on horizontal boards. According to Gollub (2002) it was after 1956 that most horizontal racks were replaced with the more efficient vertical racks. Catania (2002) mentioned that some remaining horizontal racks were used to teach new students in the laboratory. Both horizontal and vertical racks were populated with the ever present snap leads that were assembled with one Nu-Way snap connector at each end of an insulated wire. These connectors were "snapped" onto Nu-Way snap studs screwed to the panels. Snap leads with Nu-Way snap connectors and studs, that could be easily connected, disconnected, and stacked for multiple connections, had an impact on the development of operant research, which inspired by the inductive method required flexibility (see Escobar & Lattal, 2014).

Frick, Schoenfeld, and Keller (1948) described that at Columbia University they placed the electromechanical components in small boxes. This layout was appropriate for their course on the experimental analysis of behavior. Banana plugs were inserted into connectors to use power supplies, levers, feeders, and cumulative recorders. This solution was probably more elegant than the relay racks used at Harvard but it also lacked the flexibility achieved with the relay panels and snap leads. Dinsmoor (1990) noted that he had to completely design and hard wire the programming equipment that he used for his doctoral dissertation.

During the early days of relay programming, most electromechanical devices, including relay coils, operated on 120 V AC (see e.g., relay in timer shown in Figure 2). Because of this feature, any modification of the programs without turning off the equipment was dangerous. Gollub and Catania remember (see Escobar & Lattal, 2014) that students in the laboratory at Harvard learned to avoid any contact with the snap connectors in the panels carrying 110-120 V AC. Any mistake was immediately followed by severe punishment! Gradually, relays operated with 24-28 V DC replaced the old ones operated with 110-120 V AC relays. Although the coil of the relays operated with 24-28 V DC, these relays could be used to control devices working on 120 V AC. At that point, the snap studs attached to Bakelite panels were safer. Working on the back of the panels, however, was still dangerous until all 110-120 V AC devices were replaced with the common 24-28 V DC devices that are still used today. Another important aspect in the standardization of relay racks was that each panel was equipped with clips that were attached to two horizontal power rods carrying 24-28 V DC and ground.

Sodeco Electromechanical Counters

Another small piece of equipment that had an impact on the development of behavior analysis during the mid-1950s was the Sodeco electromechanical counter (see Figure 3). According to Morse (see Lattal, 2004) it was Ferster who brought these Swiss-made counters to Skinner´s laboratory. Although other counters were also available, these Sodeco counters kept track accurately of the fast responses emitted by pigeons. Under variable ratio schedules, pigeons can emit up to 6 responses per sec-
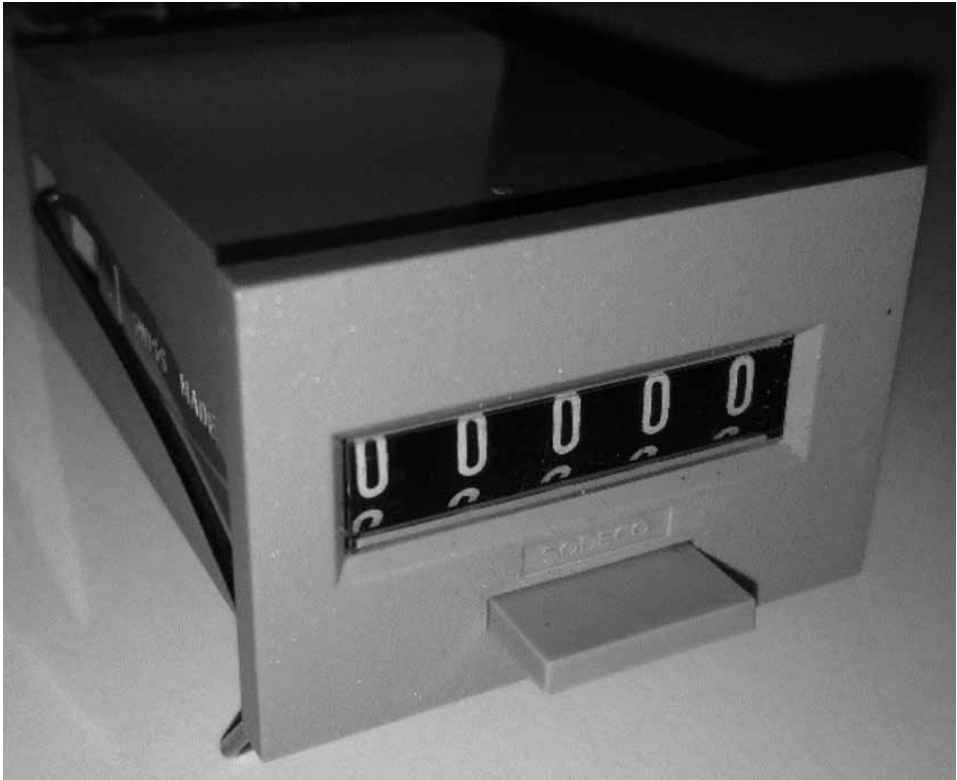
Figure 3. A 5-digit electromechanical Sodeco counter. Although this counter is gray, most of them were black. The legend SWISS MADE was carved on the side. The button on the front is a manual reset. Electromechanical counters were first mentioned in JEAB in a research paper by Conrad, Sidman, and Herrnstein (1958).
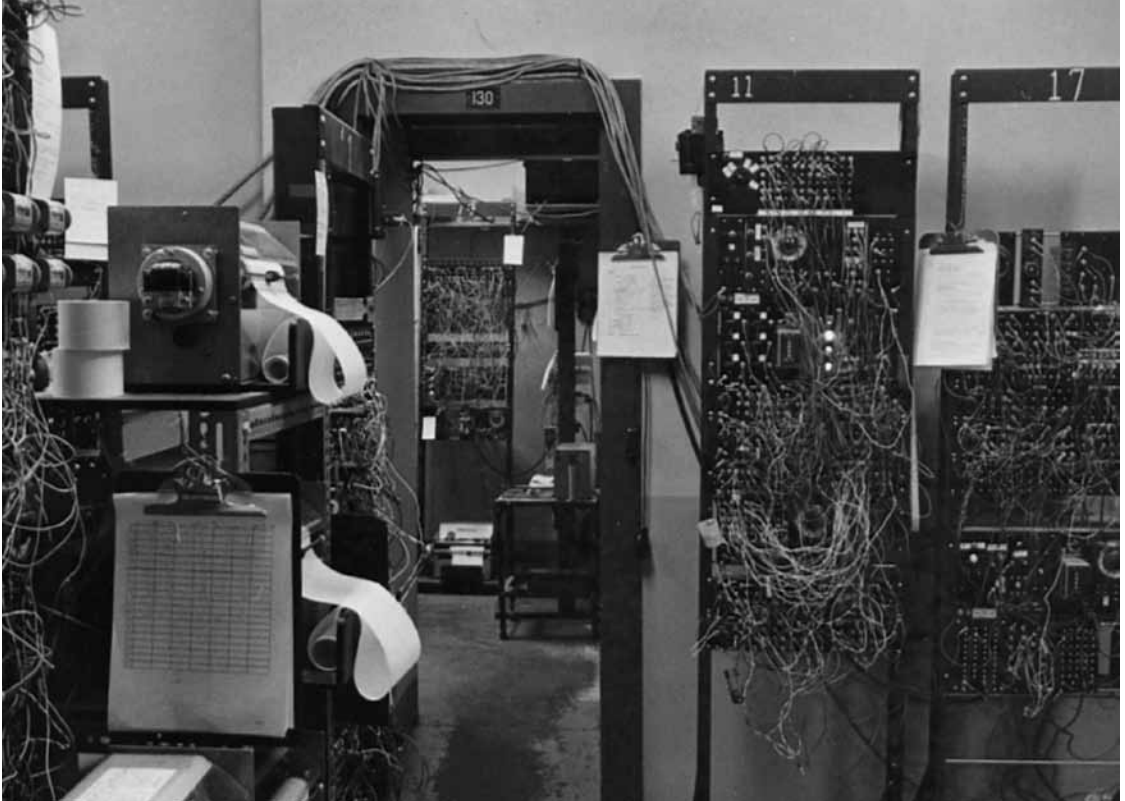
Figure 4. Relay racks in Room 129 in Harvard's pigeon laboratory (from Catania, 2002) (Photograph reprinted with permission from Wiley).

ond, and up to 15 under differential reinforcement of high rates. This rates were no problem for the reliable Sodeco counters that recorded up to 35 responses per second. In addition, these counters were available with 4 or 5 digits and included a manual reset. Sodeco counters allowed changing the emphasis of the analysis of behavior from patterns of responding observed in cumulative records to changes in number of responses per unit of time or response rate. Although rates and number of responses could be extracted from cumulative records, the precision achieved with these small counters undoubtedly favored the growth of quantitative analysis of behavior (see Lattal, 2008b).

Aside from Sodeco counters, a variety of slower electromechanical counters were available. The Behavioral Apparatus Virtual Museum (Lattal, 2008a) shows some these counters: a Veeder-Root counter, and those commercialized by Foringer and Lehigh Valley (http://aubreydaniels.com/institute/museum/observation-measurement/indirect-observation-measurement/digital-accumulating-counting-device). Lattal noted that some of these counters were adequate for recording rats, monkeys or primate lever or key presses but not for pigeons' key pecking. Electromechanical counters were later incorporated into predetermined counters that could be set to activate a pulse after a fixed number of operations was completed. These counters substituted stepper relays with multiple contacts, which were used for programming, for example, fixed-ratio schedules of reinforcement.

With the addition of the electromechanical counter, relay racks equipped with Bakelite panel, and interconnected with snap leads, acquired their final form that allowed precise presentations of events but with enough flexibility for modifying experiments with relative ease. Figure 4 shows a photograph of the relay racks used in Harvard's pigeon laboratory. As Bakelite panels were distributed by different manufactures, standardization of the equipment arose and relay racks extended from Harvard to other laboratories. In regards to the importance of relay racks, Killeen (1985) noted:

> The relay rack provides control along another dimension as well, time. It permits stimulus sequencing accurate to fractions of a second, with the ability to repeat, with modification, those sequences indefinitely. It symbolizes the step from a folksy type of natural history to a science that takes accuracy and replicability seriously. (p. 177)

Solid-State Equipment

As transistors became smaller and cheaper, circuits based on relays were gradually replaced with solid-state digital equipment. The name solid state referred to the lack of moving parts in the components. The component in these new equipment were transistors, resistors, diodes, capacitors, and ICs. As solid-state equipment was adopted in operant conditioning laboratories, two noticeable changes took place: the increased precision of recording and event presentation, and the reduction of noise in the laboratories.
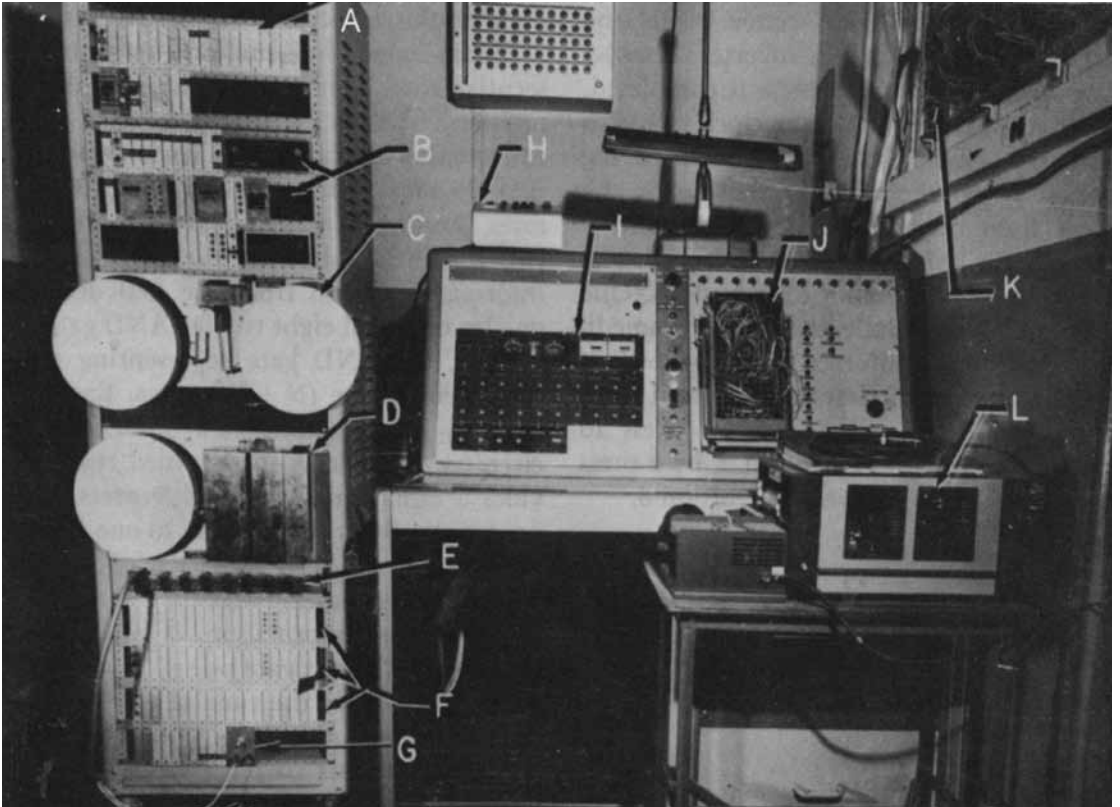
Figure 5. Integrated solid-state system for programming and for recording and analyzing data. These equipment was in Herrick's laboratory in the U. S. Naval Air Development Center in Johnsville, PA. Logic modules are marked A, B, F, and G. The plugboard connected to the programming modules is marked J. Storage tape is marked C (from Herrick and Denelsbeck, 1963) (Photograph reprinted with permission from Wiley).

Solid-state equipment was first announced in JEAB in 1961. In July 1961 a transistorized interval timer was advertised. In October 1961, BRS and Foringer described whole systems using solid-state equipment arranged in modules or units. Only a few years later, several manufacturers had replaced the relays, timers, and steppers in Bakelite panels with innovative integrated logic gates in modules. In some popular models (e.g., BRS), each module was inserted into a slot in tall racks resembling previous relay racks.

Programming was greatly simplified with the integrated gates in individual modules but it was still a complex and tedious task. Figure 5 shows an integrated solid-state system for programming. In this system, connections between the logic modules were done with banana plugs that were inserted in the programming plugboard to the right (J). A consequence of shifting from electromechanical relays to electronic components was that the latter required lower voltages than the 24-28 V DC used in relay racks. A solution was using two voltages: -12 V DC for operating solid-state equipment, and 24 or 28 V DC for controlling the devices in operant-conditioning chambers.

Aside from the integrated AND, and OR gates, some new devices were added to the programming equipment of the operant researcher. Flip-flop modules were the solid-state replacement of alternating relays. When connected in series, flip-flop modules served as binary counters. One-shot modules and multivibrators replaced electromechanical timers. When a one-shot module was triggered with a pulse (positive transition from -12 V DC to 0 V DC), it produced a pulse for a fixed time. A capacitor and a variable resistor were used for varying the length of the pulse. One-shot modules were used, for example, for programming reinforcement delays. Multivibrators, in contrast, emitted pulses equally spaced in time. As with one-shot modules, capacitors and variable resistors were used to vary the time between pulses. Weiner (1963) described how multivibrators attached to binary counters and logical gates were used as clocks in fixed-interval schedules.

Apparently for accelerating the transition from relays to solid state, in November 1966 BRS offered in advertisement in JEAB to exchange electromechanical equipment with solid state equipment. Judging from the available photographs of the laboratories of operant conditioning, Bakelite panels with relays were never fully replaced in laboratories that were already using them but rather complemented with solid-state modules. One notable exception was Mechners' laboratory during the late 1950s. Snapper (1990) described that "Our laboratory had the first on line transistorized digital computer used in behavioral research. In 1958 transistorized computers differed greatly from the mini and microcomputers of the present time" (p. 63). The computer described by Snapper used tape and counters for recording behavior, and was programmed using patch cords that interconnected individual logic modules. Although such machine was prohibitively expensive at 150 000 USD, in terms of functioning, it was closer to solid-state stations and relay racks than to modern computers.

Solid-state equipment was not only used for experimental control but also for data recording. Aside from cumulative records, automatic and permanent records of real-time behavior in an experiment were unavailable. Data displayed by electromechanical counters was recorded by hand. One solution for automatic and precise recording of real-time behavior was using tapes in which holes representing experimental events were punched. Herrick and Denelsbeck (1963) described programming and recording of lever pressing displacement using solid-state equipment. Recording was achieved by using solid-state equipment for programming and a series of relays for punching holes in the tape. These punch tapes were read later with tape readers incorporating photocells. In another paper, Ellen and Wilson (1964) described the use of punched tapes for recording behavior in five operant chambers operating simultaneously (see also Snapper, 1990). These tapes were analyzed using the first computers available that were programmed and read data stored in punched cards. Snapper recalled "we then proceeded to carry these cards to a Burroughs clone of the IBM 650 for further analysis and graphs… this computer could be programmed in Fortran using a paper tape punch. It usually took only four hours per day to run the cards into this computer…" (p. 64).

Minicomputers, Interfaces, and Programming

The reign of solid-state equipment as innovative technology in operant research did not last long. The transition from electromechanically relays to solid-state programming equipment was interrupted by the development of minicomputers during the 1960s. In time, the advent of mini and microcomputers transformed instrumentation in every operant laboratory in the world. During the early 1960s, computers were massive, expensive, and complex devices that were kept behind glass in enormous computer centers. These intimidating machines were used by only a few trained individuals for performing complex calculations and data analysis. Weiss (1962) was probably the first operant researcher that considered seriously using computers for programming events. He recalled:

It seemed to me that even with dozens of electromechanical counters and cumulative records, one could not gain a very good appreciation of what went on inside an operant chamber. As we were not really able to quantify behavior, I began looking into computer technology. (Weiss, 1992, p. 6)

Weiss (1992, 2010) narrated that he tried using two IBM 1401 computers for controlling experimental events and recording behavior. This endeavor, however, did not come to fruition. It took him too long to find a solution even after receiving technical support from one sympathetic IBM engineer. Additionally, at the same time, a project with a different computer, which was undertaken at MIT, came to his attention.

Figure 6. Upper photograph shows Weiss at Cambridge during the summer of 1963 where he assembled and tested his own computer and learned to program it as part of the LINC Evaluation Project. The lower photograph shows two students, a technician, and an engineer using the LINC in Weiss and Laties' laboratory at Rochester in 1966 (Photographs by Bernard Weiss, reprinted with permission).

LINC and PDP-8

According to Rosenfeld (1983), while IBM was aiming at increasing the capabilities of their massive computers, Wesley Clark's project at MIT attempted to produce a smaller and cheaper computer that could be used as laboratory equipment, especially for bio-medical research. The result was the first successful minicomputer in 1962. Initially known as Linc, short for Lincoln Laboratory, it was later named LINC (the acronym of Laboratory Instrument Computer) and was distributed by Digital Equipment Corporation (DEC). Testing LINC in biomedical laboratories was a crucial part of the project. In 1963, twelve LINCs were offered to researchers that committed to spend a month at MIT for instruction, and to conduct a project for evaluating the LINC as a laboratory tool. The news reached the laboratories run by Weiss and Laties at John Hopkins, Blough at Brown, and Boneau at Duke. They presented their respective projects and were selected from 72 proposals as part of the LINC Evaluation Program. Three of the twelve LINCs were tested in operant research. After spending the summer of 1963 at Massachusetts assembling and learning to program the LINC, they took the computer to their laboratories and initiated the era of computers in operant research (see Figure 6).

LINC used 12-bit architecture and was equipped with 1 Kb of usable memory. One characteristic of this machine was that instructions and data were stored in a magnetic tape and organized in blocks. A series of instructions could be stored, read or executed from the tape. Commands were entered using a series of buttons and a keyboard in which keys remained pressed until the command was entered. Another important characteristic was that the LINC was equipped with analog to digital, and digital to analog converters that facilitate data recording and experimental control (Weiss, 2010).

As part of the LINC Evaluation Program, Weiss, Blough, and Boneau with colleagues and students presented the results of the applications of the LINC in operant research in a meeting in 1965. The results were published in subsequent papers. For example, Weiss and Laties (1965) used the LINC for generating autoregressive schedules of reinforcement in which the probability of reinforcement depends on the similarity of successive inter-response times. Blough (1966), and later Weiss, Laties, Siegel, and Goldstein (1966) extended the knowledge on the effects of reinforcement on inter-response times. Uber and Weiss (1966) described the use of telephone lines to control an experimental chamber with a remote LINC. Boneau, Holland, and Baker (1965) studied discriminations among various spectral wavelengths. A remarkable aspect of the interaction between operant research and the new computers was that most of the lines of research developed by Weiss and Laties, Blough, and Boneau, were already in progress when they applied for the LINC Evaluation Project. The computer, however, by allowing precise control of experimental events and recording new dimensions of behavior, allowed researchers to expand their areas of study and generate new research questions.

Although the LINC was described as the ideal laboratory computer (Boneau, 1965), it was still a large and expensive computer with a limited market. It sold for

approximately 40, 000 USD (Clayton, 1970). Even before the LINC was designed, computers targeted to wider audiences by focusing on general purposes instead of research, were in development. A series of computers known as PDP (acronym for Programmed Data Processor) were designed between the late 1950s and early 1960s. The first commercially successful minicomputer was the PDP-8 introduced in 1965 and commercialized by DEC for 18, 000 USD. This 12-bit machine was equipped with 4 K memory and was cheap enough to be acquired by laboratories with relatively modest funding. In subsequent versions, for example the PDP-8/S, peripherals like a disk reader were added. Another example was the PDP-8/E in which diverse input-output peripherals could be used. One peripheral commonly used in operant laboratories was a teletype (ASR33), that performed three important functions as a printer, a tape punch and punched tape reader, and as an interface for controlling external devices like feeders (Snapper, 1990). The PDP-8 equipped with peripherals was sold as LAB-8 in 1968.

The first computer advertised in JEAB was the LINC-8 in January 1967. This computer incorporated a LINC and a PDP-8 computer in one package but sold for approximately 39, 000 USD, too expensive for most laboratories. In the following years, as general-purpose computers became cheaper they were gradually adopted by operant researcher. One major problem with these computers was that programming in machine language was a complex and tedious task. According to Blough and Marlowe (1965), Lloyd Marlowe first had the idea of creating a compiler for the LINC that transformed contingencies written in English to computer language. Some months later, Arthur Snapper had the same idea.

State Notation Language

Marlowe, and Snapper presented their developments during the 1967 Digital Equipment Computer Users' Society (DECOS) Biomedical Symposium. Marlowe (1967) was overwhelmed by the task of creating the compiler. He noted, "the effort required… might offset any gain made by using such a programming language" (p. 10). Snapper, Kadden, Knapp, and Kushner (1967) offered a revolutionary solution. They proposed combining the rationale for the notation system used for representing schedules of reinforcement developed by Mechner (1959), and the logic of finite automata or deterministic finite state machines in mathematical theory (see also Michael & Shafer 1995; Stephens & Van Haaren, 1977).

A finite automaton is an abstract machine that can model problems by moving between a finite number of states. There is one starting state and state transitions occur after the conditions are fulfilled in the previous state, thus the model, represented with state diagrams, can be only in one state at a time. The origins of the finite automata can be traced to the work on artificial neural networks by McCulloch and Pitts (1943), and to the application of the model in sequential switching networks. Overcoming previous limitations of Mechner's (1959) notation system, Snapper et al., (1967) dem-

onstrated that operant procedures can be formulated as finite state automata in state diagrams (see also Snapper, Knapp, & Kushner, 1970). Figure 7 shows the state diagram of a fixed-interval schedule. The machine starts in State 1. The occurrence of event T, a fixed time elapses, triggers a transition to State 2. In this state, event R, a response, triggers a transition to State 3 where event SR (reinforcer) is presented. Ending the presentation of SR triggers a transition to the initial State 1.

Following the rationale of Snapper et al. (1967), state notation languages were born. An endogenous technology developed within behavior analysis that was crucial for the integration and standardization of computers in operant research. Diagrams were transformed into a notation organized in states (although some symbols, like arrows, were preserved). Three popular notation languages were ACT (Automated Contingency Translator, Millenson, 1968), SCAT (State Change Algorithm Translator, Polson, 1973), and SKED (Snapper, 1973). In a few years, these notation languages were combined with minicomputers equipped with interfaces. Grason-Stadler first advertised SCAT in JEAB in July 1968 but it was in September 1968 and March, 1969 that the advertisement included a reference to an interface for the PDP-8. A photograph of the ASR33 Teletype was shown. In November 1969 in JEAB, Lehigh Valley Electronics (LVE), advertised INTERACT, which integrated ACT notation language, and an interface based on the ASR33 teletype for the PDP-8. SKED also was distributed in combination with an interface for the PDP-8 by State Systems established in Kalamazoo Michigan. The interface distributed by State Systems in combination with SKED software system was the least expensive (Wood, Sette, & Weiss, 1975).

Sidowski (1972) identified over a hundred minicomputers. In behavior analysis the common choice were the minicomputers manufactured by DEC (e.g., PDP-8) with SKED, INTERACT and SCAT systems. These systems, however, were not cost effective for most operant laboratories. As noted by Sidowski, the more applications required by the computer, the more expensive it became because of the requirements of added memory and peripherals. Some temporary solutions for reducing the cost included eliminating the computers and building an integrated system running SKED (e.g, SKED Microprocesor system). Another solution was to build rather complex low-cost interfaces. For example, Rosenberg, Woodruff, and Isaacson (1975) used logical gates, and solenoids drivers connected to electromechanical relays. It was only when a new generation of computers were designed, the microcomputers, that computers became cost effective in operant laboratories.

Compared to previous minicomputers, microcomputers (e.g., Apple II and TRS-80 launched in 1977) were markedly cheaper. As they became available, the problems of operant researchers concentrated on finding a suitable interface and programming language. One inexpensive solution was using the popular TRS-80 (a 4K RAM, 1.77 MHz system with monitor, keyboard, and cassette-tape deck) connected to operant chambers using electromechanical relays and programming using BASIC language. This arrangement however, permitted running only one experiment at a time. During the early 1980s some manufacturers advertised interfaces for the popular TRS-80 and Apple II
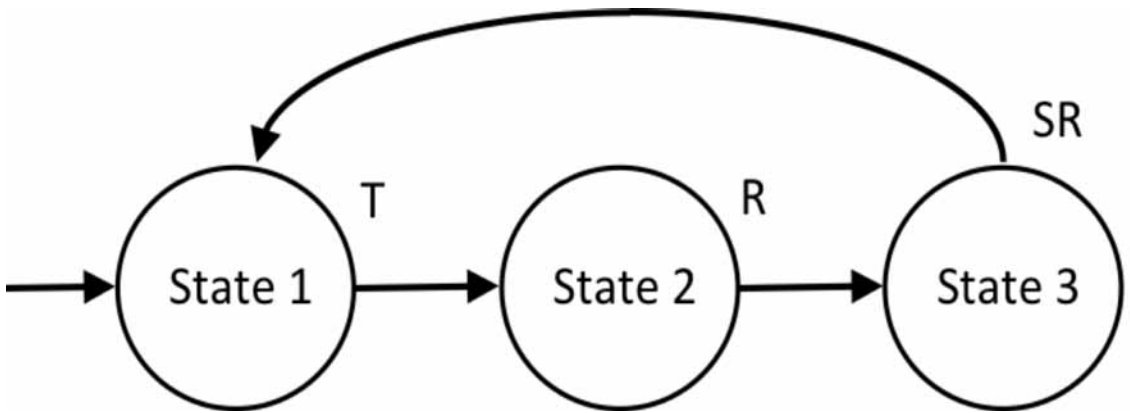
Figure 7. State diagram of a fixed-interval schedule. States are represent ed with circles and transitions with arrows. The event triggering a transition is placed above the arrow. Event T is the elapsed time, event R is a response, and event SR is a reinforcer (Drawing based on Snapper et al. 1970).

(e.g., Micro Interfacers Inc, Alpha, LVB, Med Associates). For example, in May 1982 Med Associates advertised an interface for the TRS-80 and the Apple II. This interface however, was programmed with BASIC that is considerably more difficult to learn for operant researchers than previous notation languages like SKED. State Systems were still distributing SKED as a part of their system known as SuperSKED but it was compatible with the operating system OS/8 used in the PDPs, which were becoming obsolete.

The last piece of the puzzle fell into place when Med Associates incorporated a state notation language. The language was known as MedSKED but the name had to be changed to Medstate Notation (see advertisement in March 1988 in JEAB) after a lawsuit from State Systems[1]. Med Associates described that Medstate notation was implemented within Med-PC software (Tatham & Zurn, 1989) used in their interface for the new IBM-Personal Computer (PC). In time, the functionality and reliability of Med Associates products put them into almost every operant laboratory in the world.

Standardization of laboratory equipment has simplified enormously the work of operant researchers. This simplification, however, comes at a cost. The environment created in operant laboratories is so specific and involves so many events occurring behind the curtain, that the repertoire involved in connecting operant chambers, which are part of integrated control systems, and arranging contingencies using state-notation programming, does not necessarily generalize to other environments. A consequence of the lack of generalization could be an overdependence on integrated commercial equipment for conducting operant research and refusal to using new developments in technology that could help the advancement of behavior analysis.

Controllers, Parallel Ports, and Microcontrollers

Standardized equipment for operant research is distributed by several companies (e.g., Med Associates, Lafayette, Coulbourn). As companies have improved the designs, tested, and manufactured integrated and reliable systems for operant laboratories, prices of the relatively simple equipment have reached several thousand dollars. Obtaining such equipment without funding is, to say the least, problematic. In the last decades, researchers have designed systems that meet the requirements of precision and accuracy for operant research use and could be assembled for a fraction of the price of commercial equipment.

One notable example was Palya and Walter (1993) experiment controller. The controller consisted of a board equipped with an Intel 80188 processor (a second generation processor after the 8088 used in the first IBM PC). This main board functioned as a dedicated computer and controlled, by means of a custom-made interface card, up to 16 relay cards, each connected to an operant-conditioning chamber. Experimental events were scheduled using ECBASIC® programming. The design of the controller that operated as a network was remarkable, events were recorded with

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[1] State Systems II, Inc. v. Med Associates, Inc,. E.D. PA, No. 88-0064, filed Jan. 6, 1988.

1-ms resolution. As would be expected, this controller was used in various studies in operant conditioning. The relatively inexpensive Palya-Walter controller, however, required numerous specialized components and meticulous assembly. Another problem was that users were required to learn ECBASIC® programming.

Other authors (e.g., Escobar & Lattal, 2010; Gollub, 1991) suggested using a computer´s parallel port for controlling experimental chambers. Pins in the parallel port can be used as digital inputs or outputs and can be controlled with a few instructions using BASIC programming or object-oriented programming like Visual Basic®. Escobar and Lattal described how the parallel port can be connected to an operant-conditioning chamber using an array of relays, which can be assembled for less than 30 dollars, and described a series of applications like connecting buttons for experiments with human participants or inexpensive photocells. Furthermore, they described how the freely distributed Visual Basic Express Edition® can be used for programming schedules of reinforcement. Visual Basic was selected as programming language because it has been used previously in operant research (see e.g, Dixon & McLin, 2003). Hayes (2003) noted: "Of the many modern programming languages available, none is more popular than Visual Basic" (p. vii). Although the combination of a parallel port with Visual Basic programming is inexpensive, this port is outdated and difficult to find in modern computers. Another problem is that most computers equipped with parallel ports include only one of these ports, thus only 17 input/output pins are available per computer.

Another alternative to commercial equipment was offered by Hoffman, Song, and Tuttle (2007). These authors described a system named Electronic Operant Testing Apparatus (ELOPTA) composed of an inexpensive operant-conditioning chamber for pigeons controlled with a custom built input/output board. The board contained a PIC® microcontroller (PIC16F877A). A microcontroller is programmed to execute a specific function and it resembles a small computer in a single unit (IC). Therefore, they are generally used for embedded applications. Microcontrollers are composed of a processor, RAM, flash memory, input/output channels, and they can be programmed in a language similar to C. In the case of PIC® microcontrollers, programs are uploaded to the microcontroller using a specialized programmer and debugger device. Hoffman et al. provided diagrams for building an input/output board with the PIC® microcontroller. The board is necessary for accessing the functions of the micro-controller and for communicating with the input/output pins. Their design consisted in using MPLab® software on a PC to program the microcontroller using C language. The program was uploaded to the microcontroller using an ICD 2 programmer device connected to a PC using a USB port. Afterwards, the microcontroller executed the program saving data in the microcontroller non-volatile internal memory (EEPROM). These data in ASCII format were transferred to a PC using Microsoft® HyperTerminal®, a program used for serial communications that presented text on the screen. Although Hoffman et al. noted that their system was 3% the cost of commercial equipment, the system required knowledge of C language and extensive assembly.

In recent years, inexpensive and compact input /output boards equipped with microcontrollers, have become readily available. These boards have gained popularity because they do not require assembly and are ready to be connected to a variety of sensors for detecting changes in the environment and to actuators like solenoids or motors. Integrated microcontroller boards include Arduino®, equipped with ATmega® microcontrollers, and Parallax® boards based on Propeller® microcontrollers. Although these boards are used mainly in robotics, they also could be used in operant research.

Escobar and Pérez-Herrera (in press) described that an Arduino board in combination with Visual Basic® programming can be used for controlling operant-conditioning chambers. Two free distribution programs are required. One is a single multi-purpose program in Arduino language (similar to C), that is loaded to the microcontroller using a USB port of a PC. The second was written in Visual Basic and is used for sending and receiving data from the Arduino board. An array of electromechanical (or solid state) relays and an external power supply are used to control the 28 V DC devices in operant chambers with 5 V DC supplied by Arduino boards. Controlling multiple operant conditioning chambers with one computer requires one Arduino board per chamber. This arrangement is inexpensive and accurate enough for research in operant laboratories. Initial tests suggest that the system allows recording accurately up to 125 responses per second. Escobar and Pérez-Herrera described that the cost of a basic version of the system including an Arduino Uno card and two electromechanical relays is approximately 50 dollars per experimental chamber (excluding the external 28 V DC power supply), which is only a fraction of the cost of commercial control equipment.

Pérez-Herrera and Escobar (2014) described another application suitable for laboratory courses and demonstrations. They noted that an Android device could be used for controlling experimental chambers in laboratory courses. After installing an application (downloadable for free) in a smartphone or a tablet loaded with Android operating system, a Bluetooth connection can be established with an Arduino Uno board. The Arduino board is connected to an experimental chamber. Real-time data of the experiment are stored in the Android device for subsequent analysis. The application, however, in its current version is only useful for presenting basic schedules of reinforcement (see also Escobar, 2013).

Varnon and Abrahmson (2013) described that the Parallax QuickStart could be used in laboratory courses for demonstrations of habituation, classical, and operant conditioning. They described ingenious procedures in which different motors and could be used for presenting stimuli using subjects of different species. For example, a relay controlled aquarium pump can be used for presenting puffs of air in planarians and elicit body contractions and extensions. Also, a vibrating motor could be used to elicit body movements in earthworms. A potentiometer could be used for regulating the intensity of the stimuli presented. The application in the classroom, however, required responses to be recorded by the students with a pushbutton.

Microcontroller boards can be used as a low cost alternative to commercial equipment in operant laboratories. This alternative could be especially useful where resources are limited. While it is unlike that such technology will replace the standard Med Associates equipment in the near future, it could help expanding the breadth of operant research by helping the development of current projects and eventually suggesting new lines of research. As new and easy-to-learn programming languages are becoming available (e.g., Livecode, see Potter, Roy, & Bianchi, 2014 in this issue), new combinations of hardware and software could arise helping those interested in taking advantage of new technology to expand behavior analysis. Furthermore, numerous sensors of force, proximity, sound, temperature, accelerometers, GPS, which are easy to connect and read with microcontroller boards, could suggest new and exciting ways of studying behavior.

Conclusions

Adoption of exogenous technology has unquestionably helped the development of operant research by enabling automation of operant procedures and allowing progressively more complex and precise analysis of behavior. Electromechanical relays, transistorized solid-state equipment, and computers, marked three stages of evolution in operant laboratories. The adoption of technology in each stage followed a similar course: initial use, improvement with endogenous technology, and standardization. A remarkable aspect is that successful use of exogenous technology began by applying new devices for revising unsettled research questions. After technology helped researchers with ongoing research, it stimulated new research questions. At that point, a mixture between exogenous and endogenous technology commenced. Such mixture modified exogenous technology by making it adequate and easy to use for operant researchers. Finally, standardization began with commercial distribution and, by survival of the fittest, the standards in operant laboratories were determined by commercial success.

Adopting exogenous technology also has risks. Lattal (2008b) noted that one risk arises when adoption of technology replaces the object of study. He skillfully noted "The experimental analysis of behavior is best served when technology is neither prison nor prisoner" (p. 134). Adoption of technology for the sake of it, cannot replace the questions aiming at improving our understanding of behavior. Another risk is stagnation by technology. Taking an analogy from evolutionary biology, adoption of technology is akin to saltation. After the initial adoption of technology, it reaches a stable phase with minimum or no changes for years. Reaching the point of technological stability could be attributed to the fruitful generation of behavioral data: "if it is not broken do not fix it" but could also lead to stagnation by a process that resembles behavioral momentum: "it has always been done this way." Whether operant laboratories have reached the point where technology is limiting the evolution of our discipline is an open and vital question. Looking at the history of our discipline could be a starting point in finding an answer.

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