motion (not the velocity). In Fig. 2(a), each pendulum lags behind the preceding one by 90°, yielding a standing wave loop repeating after four pendula; in Fig. 2(b) the phase difference is 120°; and in Fig. 2(c) adjacent pendula are out of phase.

Each pendulum can be adjusted in length by rotating a thumbscrew, which pulls the pendulum string up through a small hole in the top frame, as shown in Fig. 1. A nut on the thumbscrew is then tightened to lock the thumbscrew in position. It is necessary to adjust carefully the lengths of the pendula as described above to obtain the correct sequence of periods. The frame was constructed using clear anodized aluminum. The bobs are $\frac{1}{2}$-in.-diam brass balls, with a small screw in one side. The string that supports the bob connects by entering the bob through a hole in the center of the screw, and is then tied in a knot inside the ball. For the present case we arbitrarily chose about 60 oscillations in a time of about 54 s.

II. COMPUTER SIMULATION

For pendulum n in a series of N pendula, the motion is described by the equation

$$x_n = \cos[1 + (n-1)/L]\omega t,$$

where the angular frequency of the longest pendulum is ω, and it executes L oscillations during the time T after the system is started.

We have written a computer program to simulate the motion of the array of pendula so that the interested reader can see what the device will do before actually building one. Needless to say, the real thing is far more impressive, and receives vastly greater response, so this program is only for the purpose of introduction, and not presented as a substitute. A complete cycle of the motion for the actual pendulum waves demonstration which takes about 1 min is stretched into several minutes in the calculation, depending on the computer.

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A to D conversion with the IBM PS/2 for under $5

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This note describes a very inexpensive means for making analog voltage measurements using the parallel port of the IBM PS/2 and a single chip external circuit. This method avoids the expense of specialized analog to digital (A/D) conversion boards and can be set up for under $5. Using this approach we are able to implement several introductory level physics experiments requiring voltage measurements including a simple real-time oscilloscope.

As we have described in an earlier article,[1] using the parallel port to make timing measurements is remarkably simple. Extending this method to include analog data acquisition using the PS/2 is only slightly more complex. The complete ingredients beyond the PS/2 are a single chip A/D converter, a cable to connect the computer to the chip, and a little software. Details of each are described below.

I. A/D CONVERTER

The converter we used was the National Semiconductor ADC 0804. It is very well matched to the constraints of this application, providing eight bits of digital data corresponding to a differential analog voltage input at a rated conversion time of 100 μs. Converter control signals map directly to the computer parallel interface with inputs and buffered outputs at TTL voltage levels to simplify interfacing. This particular converter interacts with the computer in much the same fashion as a printer, using an Acknowledge (signaling end of conversion) and Strobe (signaling start of conversion) for handshaking. Further simplifying the use

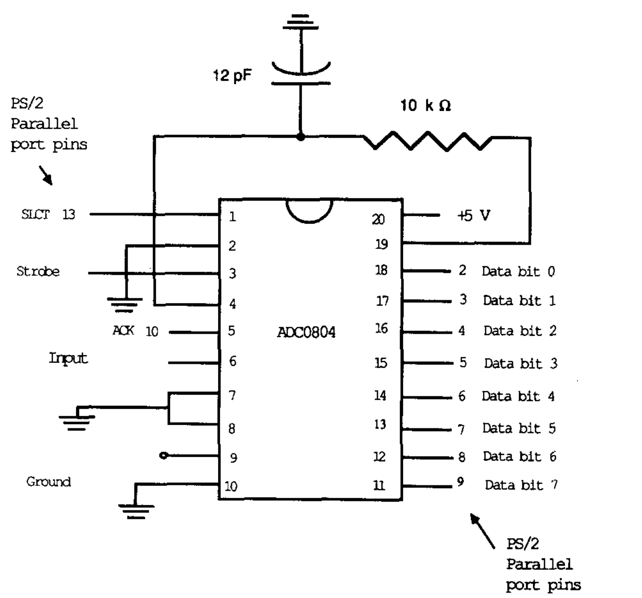

Fig. 1. Circuit for converting an analog voltage in the 0- to 5-V range to a digital signal suitable for the PS/2 parallel port.

of this device is an on-chip clock. Figure 1 shows a circuit for converting an analog signal of 0–5 V to a digital signal constructed using this chip, one resistor, and one capacitor. Other voltage ranges are possible, and any A/D chip with similar characteristics will work equally well in this application.

II. THE CABLE

The cable connects the A/D converter on a breadboard to the parallel port on the PS/2. We recommend using a 26-wire ribbon cable of less than 2 m length and clamp-on connectors, with the converter end having an IC-type plug for easy mating to the breadboard. Using the ADC 0804, the pin to pin mapping is as follows:

ADC 0804		PS/2 Parallel port	
Pin	Signal name	Signal name	Pin
1	CS (Chip Select)	SLCT (Select)	13
2	RD (Read)	Ground	18–25
3	WR (Write)	STROBE	1
5	INTR (Interupt)	ACK (Acknowledge)	10
10	D GND (Ground)	Ground	18–25
11–19	DP7–DB0	Data Bit 0–7	2–9

III. SOFTWARE

Two features of the PS/2 that differ from earlier IBM personal computers are the use of a bidirectional parallel port and the Programmable Option Select (POS). The bidirectional nature of the parallel port is critical for its use in A/D conversion and provides either output to devices such as a printer or input from devices such as the A/D converter used here. The POS allows hardware system board switches to be replaced with programmable registers so that certain characteristics of the system hardware can be controlled by software. The combination of these two features allow the parallel port of the PS/2 to be easily configured by software as an input port for use with the A/D converter.

The key software functions are as follows: (1) program the POS to act as a bidirection parallel port; (2) program the parallel port for data direction as input; (3) request the start of an A/D conversion; (4) wait for acknowledgment of the end of A/D conversion; (5) read and scale the eight-bit digital value to the corresponding analog voltage. The voltage, assuming a 0- to 5-V input range, is scaled by: voltage = (digital input*5 V)/256. It is necessary to scale other voltage ranges to the 0- to + 5-V range in order to use this setup. Coding for functions (1) and (2) above is available by writing to the authors.

The method of A/D conversion described here is very flexible and costs less than $5 to set up. This is quite a savings over the expense of most commercially available A/D boards. We have used this arrangement to collect voltages for a falling magnet Faraday's law experiment[2] and a physical pendulum experiment[3] and as a simple oscilloscope. Software written in *Object Oriented Turbo Pascal* for both voltage collection and the oscilloscope program is available from the authors upon request.

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