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Teaching the Principles of Modern Electricity Metering*

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Energy has become one of the most important topics in recent years. Knowing how much electricity we use and consequently finding ways to save energy are very important in everyday life. Electricity meters have traditionally been mechanical devices, incorporating rotating discs and having geared dials. Recently there has been a lot of interest in metering, and modern microcontroller based electricity meters with LCD outputs have been developed and manufactured. This paper describes the development of a microcontroller based electricity meter with LCD output. The meter described here has been developed for teaching the principles of modern electricity metering techniques to undergraduate engineering students studying Electrical Engineering at the Near East University.

Keywords: energy meter; electricity meter; power meter; teaching electricity metering

INTRODUCTION

AN ELECTRICITY METER, also called an energy meter, measures and registers the amount of electrical energy consumed by electricity users. The first known patent for an electricity meter was in 1870 by Samuel Gardiner [1]; it was in the form of a clock with an electromagnet that started and stopped the mechanism. Early electricity meters used in households and in commercial establishments were mechanical devices, first invented by Elihu Thomson in 1888 [2, 3]. These meters were also known as induction-type electricity meters and they are still in use, due to their simplicity and low costs (see Fig. 1). The mechanical meter has a stator consisting of a voltage coil and a current coil [4]. These coils are connected to the incoming mains line and they react electromagnetically as the line voltage and current changes. Both coils act together to turn a rotor with a disk and the rotational speed is proportional to the product of the voltage and the current, i.e. the power dissipated. Some meters use a gear train to drive the dials, while some more modern meters use non-contact methods such as optical or Hall effect sensors.

Some newer electricity meters are based on semiconductor technology where the load voltage and current are sensed and then multiplied to obtain the load power. The output of these semiconductor devices are in the form of pulse trains where the pulse frequency is directly proportional to the power consumed by the load. For example, it is very common to have meters with 100 imp/kWh (impulses per kWh) where 100 pulses are required to register one kWh of energy usage. Stepping motors are then activated with these pulses to display the energy used.

With the demand for greater precision and complexity of electricity tariffs, electronic electricity meters are now in common use [5]. These devices use state-of-the–art microcontroller technology usually with LCD outputs and they can be programmed for various options, such as different tariffs at different times of the day. Consumers can also purchase plug-in portable electronic meters (see Fig. 2) to monitor their electricity usage. These devices have LCD displays and they can show the power consumption, energy usage, and the total cost of energy used. In addition, some devices can also store and show the mains voltage, load current, line frequency, and the power factor.

An evaluation board is available from Microchip Inc that can be used to learn the principles of modern electricity metering. This evaluation board provides output pulses with a frequency directly proportional to the power dissipated by the load. An LED is available at the output that flashes at a rate proportional to the load power. Thus, by observing the LED, one can have an approximate idea about the load power. Alternatively, a frequency meter or an oscilloscope can be connected to the evaluation board to determine the relationship between the load power and the frequency of output pulses.

A literature survey carried out by the author indicated that there are very few references on the design of modern electricity meters. Most of the references in this field consist of manufacturers' data sheets and application notes. The author therefore felt that it was necessary to carry out research in this field and design a device that will teach engineering students the basic principles of modern electricity meters. In this paper, an electricity meter evaluation board has been connected

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Fig. 1. Electromechanical electricity meter.

to a microcontroller system and the load power and energy consumed are calculated and displayed on an LCD.

ELECTRICAL POWER MEASUREMENT

Expressed mathematically, let the instantaneous voltage be $v(t) = V_m \sin \omega t$ and instantaneous current be $i(t) = I_m \sin(\omega t - \theta)$. Then the instantaneous power $p(t)$ is given by [6]:

$$p(t) = v(t)\, i(t) = V_m I_m \sin(\omega t)\ \sin(\omega t - \theta) \qquad (1)$$

If T is the period of the voltage or current, the average (or real) power P is given by:

$$P = \frac{1}{T}\int_0^T p(t) = \frac{1}{2} V_m I_m \cos\theta \qquad (2)$$

Letting the RMS values of voltage and current be V_{RMS} and I_{RMS} respectively,

$$V_m = \sqrt{2} V_{RMS} \quad \text{and} \quad I_m = \sqrt{2} I_{RMS} \qquad (3)$$

then the average power is given by:

$$P = V_{RMS} I_{RMS} \cos\theta \qquad (4)$$

The power given by equation (4) is also known as the *real power*, or the *active power* and it has the units of watts (or W). In addition to the real power, we also have the terms *apparent power* (in voltampere, or VA) and *reactive power* (in voltampere reactive), where:

$$\text{apparent power} = V_{RMS} I_{RMS} \qquad (5)$$

and

$$\text{reactive power} = V_{RMS} I_{RMS} \sin\theta \qquad (6)$$

Although the real and apparent powers are always positive, the reactive power can have either sign. For example, if the mains voltage has a peak value of 339 V (RMS value of 240 V) and the current through the load has a peak value of 14.4 A (RMS value of 10 A). Multiplying the two RMS values gives the average (real) power in the load as 2400 W. When there is a phase difference between the voltage and current, the real power is lowered and is not simply the multiplication of the two RMS values. As shown in Equation (4), the cosine of the phase difference must also be multiplied to get the real power. The $\cos\theta$ term is also known as the Power Factor (PF) and is very important in AC circuits. For example, if the current lags the voltage by 45°, then $\cos 45 = 0.7071$ and the real average power dissipated by the load will be 2400 × 0.7071 = 1697 W. It is very important to make sure that the PF is as close to unity as possible in AC power circuits such as in large electric motor circuits.

Fig. 2. Portable plug-in type electricity meter.

There are several special ICs available in the market for modern electricity metering applications. Analog Devices ADE775x series [7] is low-cost single chip devices, manufactured for single-phase electricity metering applications. Clarke [8] describes the design of a portable microcontroller based electricity meter using the ADE7756 chip. Songsee *et al.* [9] present the design and development of an LCD based centralized electrical energy meter using the ADE7755 energy metering IC. Another microcontroller based single-phase electrical energy meter design is presented by Jantaporn [10]. Microchip Inc is another manufacturer of electricity metering ICs. MCP3905/6 devices [11] are manufactured for single-phase applications. More complex chips, such as the MCP3909, are manufactured for multi-phase electricity metering applications. A development board is also available from Microchip, for evaluating and learning purposes. The details of this board are given in the next section.

ENERGY METER EVALUATION BOARD

The electricity meter evaluation board [12, 13] used in this project is based on the MCP3905 energy metering chip. This chip receives the load voltage and load current and then multiplies the two to calculate the power dissipated by the load. The load voltage is directly read by the chip. The load current on the other hand is passed through a 'shunt resistor' and the voltage developed across this resistor is used as a measure of the load current. The MCP3905 evaluation board provides the ideal environment for engineering students as a starting point in learning the basic principles of modern energy metering. As shown in Fig. 3, the evaluation board consists of:

- mains connector;
- load connector;
- current interface circuit;
- voltage interface circuit;
- MCP3905 energy metering IC;
- opto-isolator output;
- various jumpers to configure the board.

In addition, two small prototype areas are provided on the board to add external circuits if required. Students can use the evaluation board stand-alone with no external circuitry. All that is required is to configure the board with jumpers and connect it to a mains supply. The load should then be connected to the input current and voltage interface circuits. When power is applied to the load, a pulse train signal is obtained at the outputs of the board. The board can be configured such that an on-board LED can be connected to one of the outputs of MCP3905, enabling students to observe the LED flashing in proportion to the amount of power drawn by the load. Alternatively, a frequency counter device, or an oscilloscope, can be connected to the appropriate output of the board and the relationship between the load power and output frequency can be determined.

Although the evaluation board can be used as a teaching tool it has several drawbacks:

- There is no direct display of the load power or the energy used by the load. Students can observe the load power on a flashing LED, or the frequency of the output signal can be measured and hence the load power can be determined. This is not an elegant solution and it would be much better if a microcontroller system is used to display the load power and the energy used e.g. on an LCD.
- The evaluation board is not programmable and thus there is very little the students can try on the board.

In this project the output of the evaluation board is connected to a PIC18F series high performance microcontroller. This setup enables students to develop programs on the microcontroller and then display parameters of interest such as the load power, energy usage, cost of energy etc. The output can either be displayed on an LCD or an interface can be added to the circuit and data can be sent to a PC for storage or further analysis, e.g.,

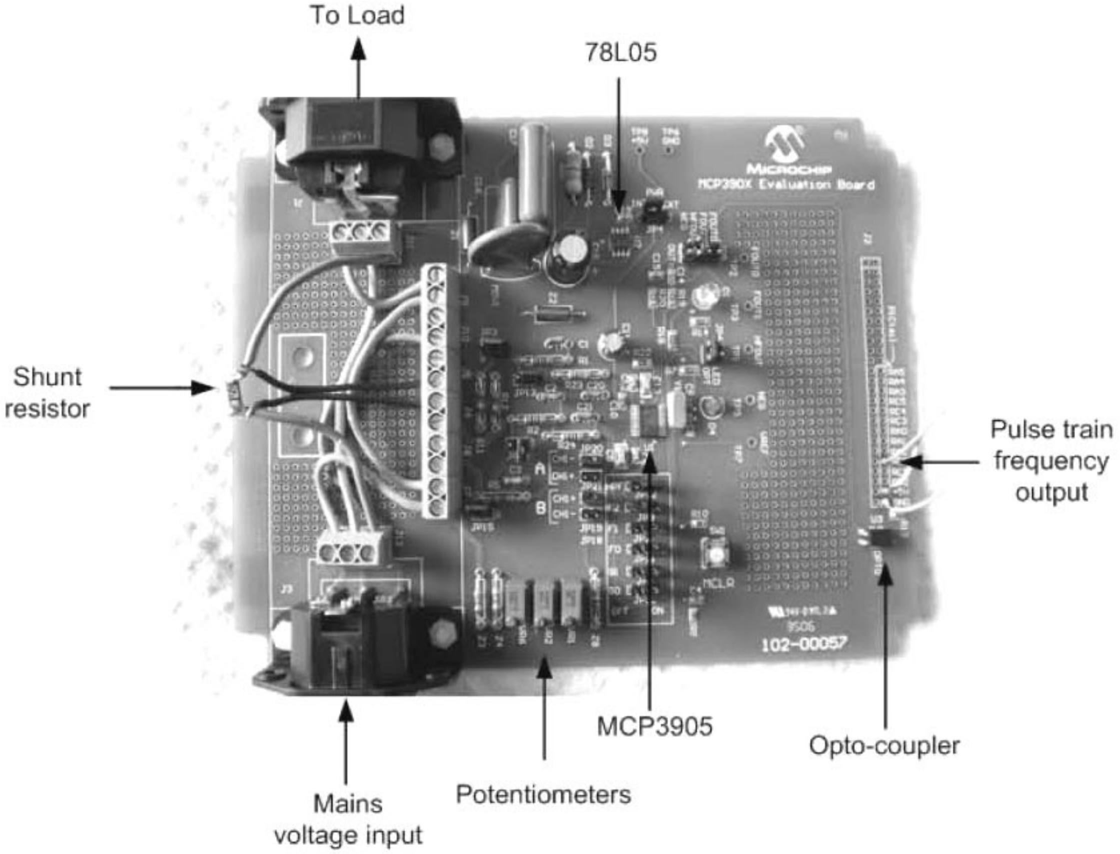


Fig. 3. Electricity meter evaluation board.

by using an FTDI chip [14] to provide USB output.

The relationship between the output pulse train frequency and the power dissipated by the load are given by the following equation [12]:

$$F_{OUT} = \frac{8.06 \times V_0 \times V_1 \times G \times F_C}{(V_{REF})^2} \quad (7)$$

where

F_{OUT} = output pulse train frequency
V_0 = the RMS differential voltage on channel CH0
V_1 = the RMS differential voltage on channel CH1
G = constant Programmable Gain Amplifier (PGA) gain on channel CH0
F_C = clock dependent frequency constant
V_{REF} = constant voltage reference (2.4V).

Equation (7) shows that the output frequency is directly proportional to the product of the voltages on channels CH0 and CH1. The voltage on CH0 is derived from the current through the shunt resistance, which is equal to the load current. The voltage on CH1 is proportional to the load voltage. The relationship between the frequency and power is actually obtained through calibration. i.e. the shunt resistance influences the relationship between power and output frequency. In practice, the meter is calibrated either by using a commercial meter with a load, or by using a load with known dissipation. In both cases, a frequency counter or an oscilloscope is used to measure the pulse frequency and then a constant multiplier is found that relates the pulse frequency to the power dissipated by the load. This constant multiplier is then used in the software to convert the frequency pulses to real power.

PROJECT SETUP

Figure 4 shows the block diagram of the project. The opto-coupled output of the evaluation board is connected to a PIC microcontroller system. An LCD is used as the output device. The microcontroller determines the frequency of the signals at its input. The frequency is then converted into the load power, the duration of power usage and thus the energy used by the load are then determined. The load voltage is sensed by the voltage sensing circuit. Similarly, the load current is sensed by measuring the voltage across a small shunt resistor (500 $\mu\Omega$).

The circuit diagram of the project is shown in Fig. 5. A PIC18F452 type microcontroller [15] is used in this project, although most other types of microcontrollers can be used. This is a high performance microcontroller from the PIC18F family, with the following features:

- 32K flash program memory
- 1536 byte RAM data memory
- 256 byte EEPROM memory
- 4 timer modules
- 32 I/O pins
- 8 channel 10-bit A/D converter
- USART and I^2C
- Capture/Compare/PWM module
- DC to 40 MHz clock.

As shown in Fig. 5, the circuit is in two parts: Data Collection (DC), and Data Analysis and Display (DAD). The DC is simply the MCP3905 evaluation board, configured to output pulses from an on-board opto-coupler. Using an opto-coupler provides safety to the project as it isolates the high-power section from the low-power microcontroller. Electrical safety is always very important in engineering experiments. The output of the DC is

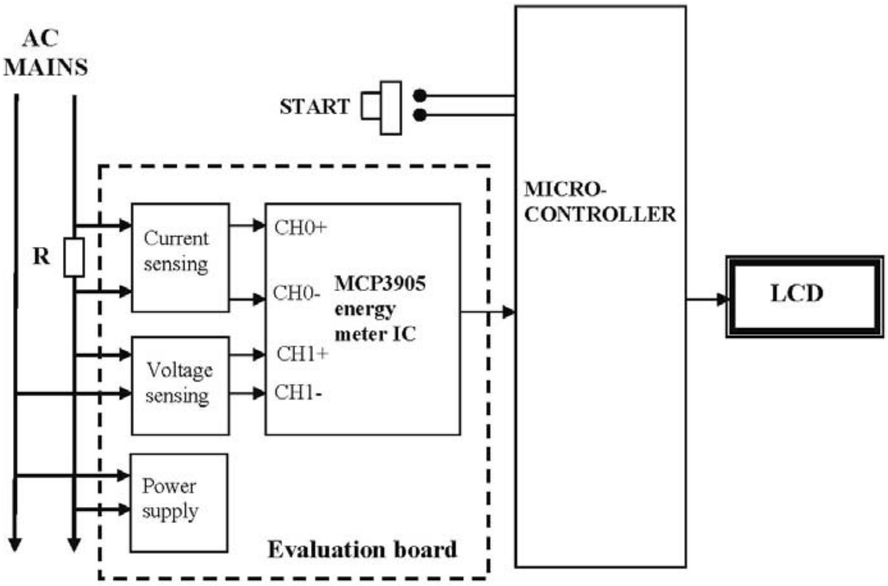
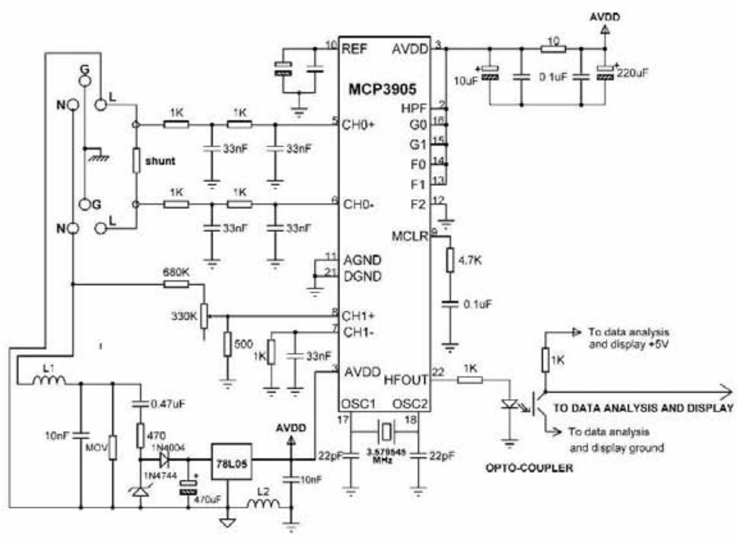
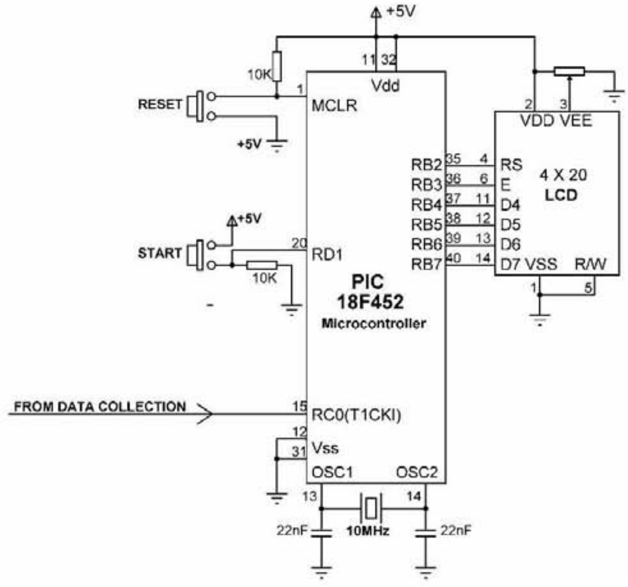


Fig. 4. Block diagram of the project.



DC (the Evaluation board)



DAD (Data analysis and display)

Fig. 5. Circuit diagram of the project.

connected to the timer input of the DAD. The DAD calculates the load power and energy and displays on an LCD connected to port B of the microcontroller. The DAD was built on a breadboard so that students can modify it to try new hardware and software ideas.

THE SOFTWARE

The software was developed using the mikroC programming language. mikroC is a popular high-level language for PIC microcontrollers, developed by mikroElektronika [16]. A limited size version of mikroC compiler is available free of charge and this is ideal for developing small projects. The operation of the software is shown in Fig 6 as a simple Program Description Language (PDL), which is a program documentation tool consisting of English-like sentences. The microcontroller basically counts the number of pulses output from the evaluation board every 5 seconds. The frequency of the pulses and thus the power dissipated by the load are then calculated and displayed on the LCD. Timer TMR0 is programmed to generate interrupts every 5 second intervals. Timer TMR1 is operated as a counter and clocked by the pulses received from the evaluation board. The value of TMR1 is used to calculate the power and energy consumed by the load.

Main Program

```
BEGIN
    Initialise program variables
    DO FOREVER
      IF START button pressed
        Load TMR0 for 5 second interrupts
        Clear TMR1
        Enable TMR0 interrupt
      ENDIF
      IF TMR0 interrupt occurred
        Get TMR1 value
        Calculate frequency of pulses
        Calculate and display Power using the
           constant multiplier
        Calculate and display connection time
        Calculate and display Energy used
      ENDIF
    ENDDO
END
```

TMR0 Interrupt Service Routine

```
BEGIN
  Get and save TMR1 value
  IF TMR1 value > 0
    Increment total load connect time
  ENDIF
  Clear TMR1
  Re-load TMR0 for 5 second interrupts
  Re-enable timer interrupt
END
```

Fig. 6. Operation of the software.

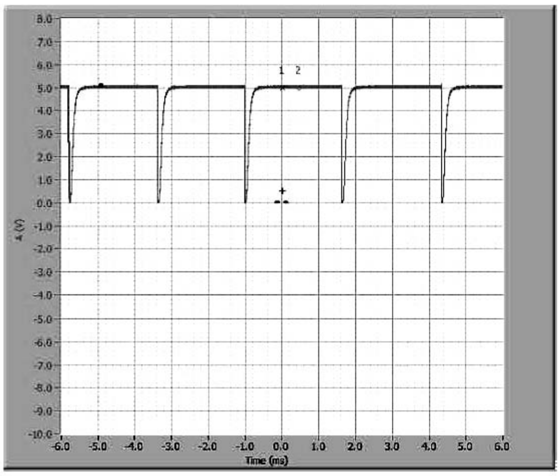


Fig. 7. Output pulse train when a 1 kW load is used.

The energy meter was calibrated using the commercially available PM230 electricity meter [17] as a reference. Figure 7 shows the typical output pulse train when a 1 kW load is used. As can be seen from this figure, the output pulse frequency was 384 Hz, corresponding to a constant multiplier of 2.604 Hz/W.

Assuming the minimum of 1 pulse per 5 second measuring period, the lowest measurable frequency is 0.2 Hz, and this corresponds to the lowest measurable power of 0.52 W. The evaluation board is recommended for operation at 230 V, 13 A (it is possible to design a meter to measure much higher electrical powers using the MCP3905 chip), corresponding to the maximum measurable power of about 3 kW. Thus, the useful range of the meter is 0.52 W to 3 kW. Floating-point arithmetic was used in the program to give a display resolution with two digits after the decimal point. The accuracy of the meter depends on how accurately the frequency of the output pulse train can be measured. Since TMR1 is directly clocked by the pulse train, the meter accuracy depends entirely on the frequency accuracy of this pulse train. The MCP3905 chip is reported by the manufacturers to be 0.1% accurate over its full dynamic range.

The performance of the designed electricity meter was compared with the commercially available electricity meter PM230. Various loads were connected to the meter ranging from several watts to kilowatts. The load powers were then measured and noted, and the results were compared with those obtained using the PM230. In all tests the results were within 5% agreement with each other.

USING THE ELECTRICITY METER IN TEACHING

The Near East University [18] is a private international institution in Cyprus, established in 1980. Currently the university has 11 faculties with over 15 000 full-time students from all parts of the world. The faculty of engineering consists of the departments of computer engineering, electrical and electronic engineering, civil engineering, and mechanical engineering. The students in electrical engineering work in the laboratories for 4 hours a week in addition to normal lecture hours. The energy metering device described in this paper will be used as an experiment in '*Electromechanical Energy Conversions*' (EE331/332) undergraduate courses. Students will be expected to learn how to operate the evaluation board, which will give them an insight into the principles of modern energy metering. They will then develop microcontroller based hardware and software systems to measure and display the power and energy usage. Laboratory notes will be prepared, where students will be expected to complete the experiment in a single 4 hour laboratory session.

CONCLUSIONS

This paper has described the design of an educational microcontroller based modern electricity meter device where the power and energy consumed by a load is displayed on an LCD.

The device is based on the PIC18F452 microcontroller and MCP3905 energy meter evaluation board. The electricity meter described in this paper is low-cost and can be used in electrical engineering laboratories to teach the principles of modern electricity metering to students. The device can be used to measure power in the range 0.52 W to 3 kW. The performance of the device was compared with a commercially available electricity meter and very close agreement was obtained in all measurements.

The electricity meter described in this paper also provides a good starting point to encourage students to take energy related projects. Students can test their ideas using the evaluation board or an electricity metering IC and then develop full-scale projects based on the measurement of electrical power or energy. Some possible undergraduate projects in this field are:

- Designing a portable electricity meter with LCD and SD card interface
- Designing an electricity meter with PC interface
- Designing an electricity meter with real-time clock
- Designing a wireless electricity meter
- Home electricity pricing using an electricity meter
- Home energy saving using an electricity meter
- Home energy monitoring using an electricity meter
- Microcontroller based automatic electrical power control.

In addition, the students can use the evaluation board as an electrical power sensor in many microcontroller based projects.

- Although the energy meter described in this paper has high educational value, it can be enhanced in several ways and it can be made into a commercially viable product by the addition of:
- A flash memory card interface (e.g. SD card) can be added to store the power and energy values over long periods of time.
- USB type output can be added to the device (e.g. using an FTDI chip) to send the energy and power measurement values to a PC. The collected data can then easily be analysed on the PC. For example, the data can be imported into Excel and the variation of power or energy usage in a given time interval can be analysed or plotted. Such a graph can provide very useful information when one needs to reduce energy consumption and save energy. Students will be expected to carry out such an analysis and write reports on it.
- A real-time clock chip can be added to the device so that the energy usage can be stored or processed with absolute date and time stamps.

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