

Laser Writer

Final Project Report

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Engineering 155, Micro Processor design

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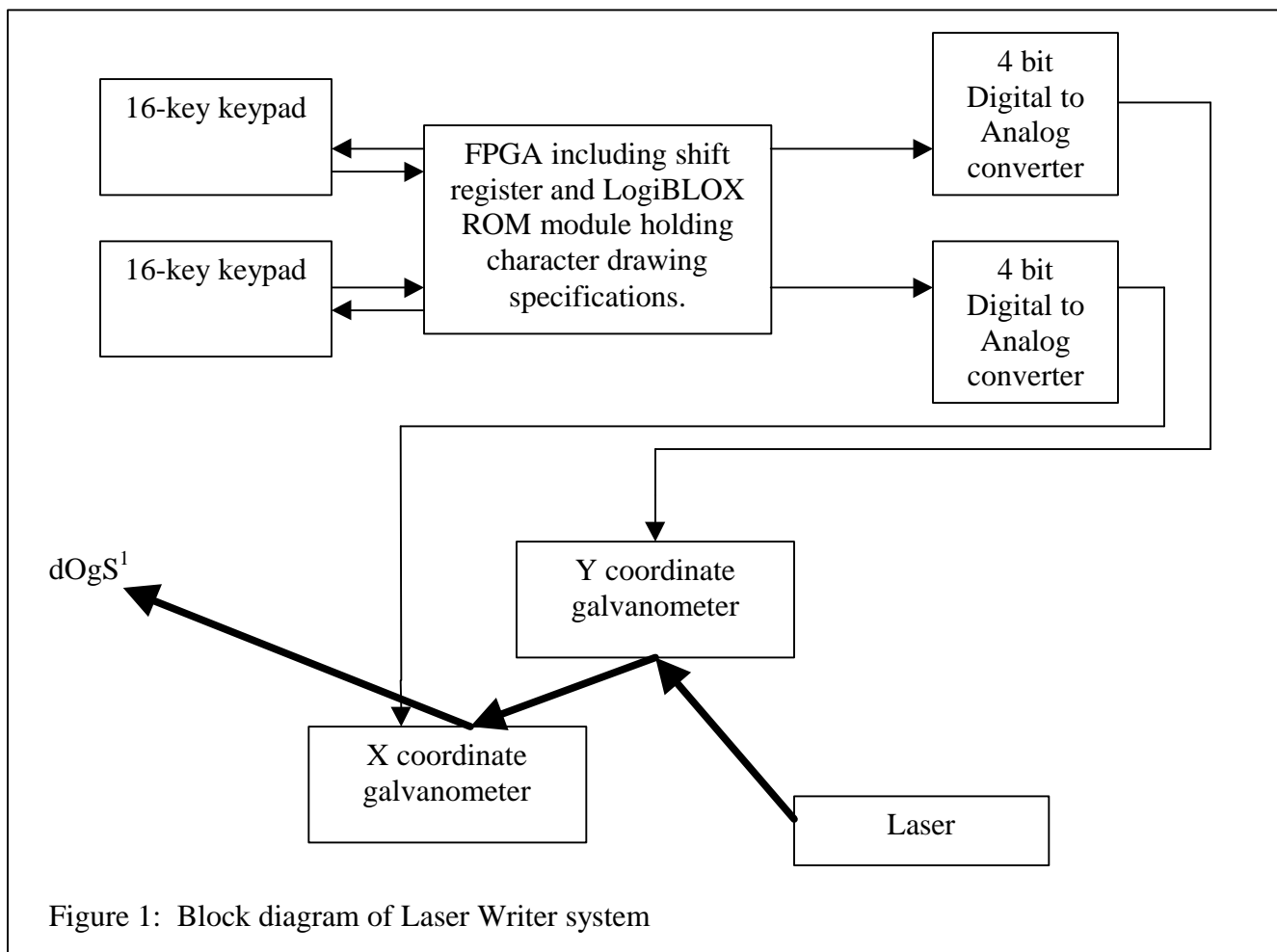
Abstract:

The Laser Writer system uses a single laser beam to project letters onto a flat, smooth surface across a room. Persistence of vision permits a sufficiently fast moving laser to trace through a series of discrete points and yield a vector graphic image. The laser beam is deflected using galvanometers controlled by the FPGA. ROM in the FPGA stores the discrete points used to construct letters and a shift register stores the last four letters typed into a set of keypads. Four letters are currently displayed although this does not utilize the full capabilities of the system. The system as currently implemented displays small but readable four-letter words.

Introduction

This project was driven by the wish to have an amusing toy that could become a portable physical system. The idea for the project came from recalling a similar device built by one of our suitemates from our freshman year. He had built a laser display system controllable with audio signals or by computer. We wished to have a similar device that was low budget and portable. Also, we were more interested in the drawing capability than the audio signal display. We knew that to move a laser beam, we either needed to move the laser itself or deflect the beam with mirrors or opto-electric crystals. We chose to implement the mirror design.

Our system is controlled solely by the FPGA board with a minimal amount of external components. The mirror deflection hardware was created with two galvanometers, a magnetic field, a laser and some mounting brackets. The HC11 board was not used in order allow the system to be computer independent and thus more portable. A block diagram of the system is given below.



1. The Laser Writer does not actually display curved letters or the “Times New Roman” font.

New Hardware

In order to accomplish beam positioning, we needed to find a method to deflect the laser beam fast enough for a refresh rate that would allow persistence of vision. After doing some research we found many different components that would allow us to do this. One such method that we didn't use due to high cost was opto-electric crystals. These crystals change their index of refraction with a supplied current. They are very precise and very fast. The downsides to this method are that it is very expensive, difficult to acquire components for, and it requires a high current to be passed through the crystals. Another option was to use small motors to move mirrors. Three different types of these motors include stepper motors, actuators, and servos. All of these allow precise control but stepper motors would limit the maximum possible resolution because they are not continuous in their motion. Good actuators and servos also tend to be rather expensive. A third option that we found utilized galvanometers.

Galvanometers are typically used to measure an electrical signal by deflecting a light beam in proportion to the current applied. They consist of a coil attached to a small mirror that resides within a magnetic field. Current applied to this coil produces a force and causes the coil (and mirror) to rotate.

In searching for any of these devices to use, we ran across two galvanometers, model CEC 7-361, for auction on Ebay. Because the description of the items was somewhat vague, and they are not used in mainstream applications, we were the only bidders and managed to pick them up for \$10 apiece. Later, in talking with one of engineers who helped design the model we were using, we found that the actual retail cost of these galvanometers was \$528. These galvanometers were designed for use in a high-precision oscillograph machine that would include an array of multiple galvanometers. Such a machine would be used with laser beams and photosensitive paper to record signals in a fashion similar to a polygraph machine. The galvanometers included lenses to focus an incoming beam at focal distances of 7 or 11.5 in. Also, we learned that this model of galvanometer was used by the Wright Patterson Air Force Base in a training simulator to display profiles of enemy aircraft. Knowing this, we were confident that they would suit our purpose, however we did not know how to use the devices.

We found a number of specifications on our model of galvanometer. Some of these are included below.

Type	External Damping Resistance Required (Ohms)	Undamped Natural Frequency (Hz)	Flat Frequency Range (Hz)	Terminal Resistance (Ohms +- 10%)	Undamped DC Sensitivity (mA/in.)	Undamped DC Sensitivity (in./mA)
7-361	20-2000	8000	0-5000	57	46.1	0.0217

System Voltage Sensitivity (V/in.)	System Voltage Sensitivity (in./V)	Static Balance (in./g)	Maximum Safe Current (mA)
5.16	0.194	0.005	100

Table 2: Galvanometer CEC 7-361 specifications

The terms in table 2 are as follows:

Damping Resistance – the value of resistance of the driving source required for 0.64 critical damping

Natural Frequency – the frequency of maximum forced amplitude for an un-damped galvanometer.

Flat Frequency Range – galvanometers operating under 64% of critical damping conditions have a flat (within 5 percent) frequency response range in the frequency stated.

Terminal Resistance – the DC resistance of the coil and suspension measured at the terminals.

Un-damped DC Sensitivity – the relationship between the magnitude of the current flowing through the coil and the amplitude of the resulting deflection at an optical arm distance of 11.5 inches.

System Voltage Sensitivity – the magnitude of open-circuit voltage required of the source which has a source resistance equal to the damping resistance required for 0.64 damping to result in one inch of true deflection.

Static Balance – the maximum trace deflection of an 11.5 inch optical arm when the galvanometer is subjected to a 1 g acceleration change in any plane.

Safe Current – the value of current that may be continuously passed through the galvanometer without damage.

Also, we learned that the galvanometers require an external magnetic field to function since they are too small to include a sufficiently large magnet. We purchased two rare-earth magnets from radio-shack and fixed them to either side of the galvanometers. We re-positioned the magnets to get the maximum deflection out of the galvanometers since we had no specifications as to how the magnetic field should be aligned in relation to the galvanometer. Finally, we learned that the galvanometers deflected based on a varying current up to 100mA and that the two input terminals were the two terminals on the top of the galvanometer. A drawing of the galvanometer with key parts labeled is included in Appendix A.

We purchased two galvanometers: One for the x coordinates and one for the y coordinates. We would then send the laser beam into the y galvanometer, it would reflect at some angle into the x galvanometer, reflect off of that mirror and onto the display surface. In order for the beam to stay aligned through multiple mirrors even during deflection, the galvanometers were placed very close together to minimize vertical or horizontal distance while keeping the same angular deflection. The size of the image projected is dependent on the distance to the projection surface. A photograph of the setup is given below in Figure 3.

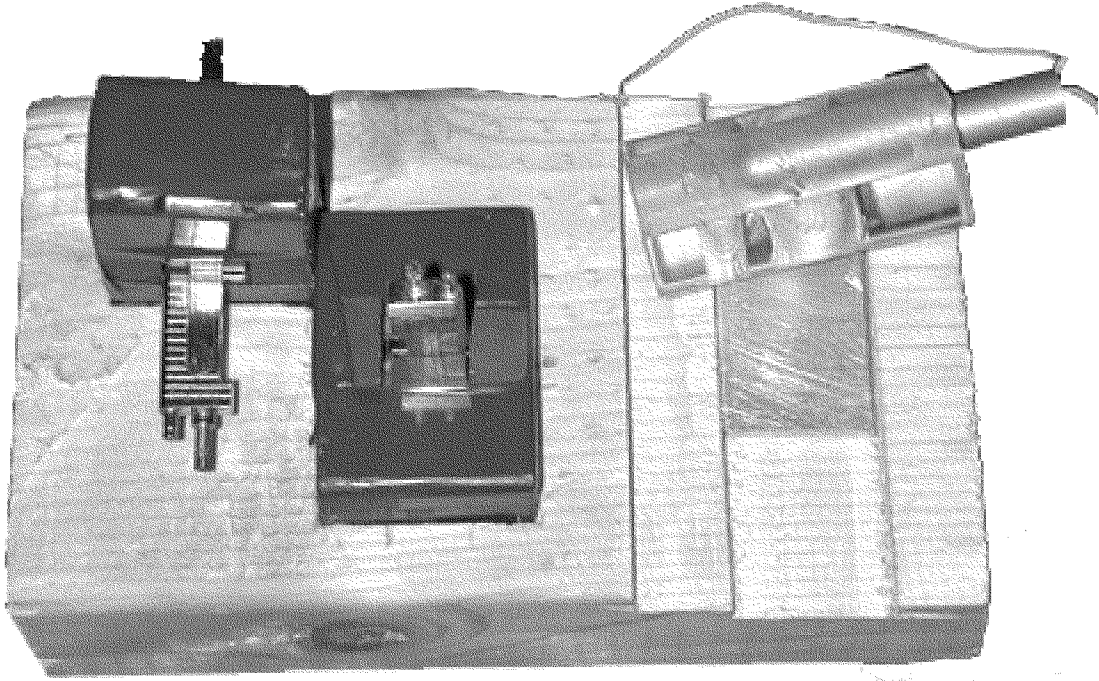
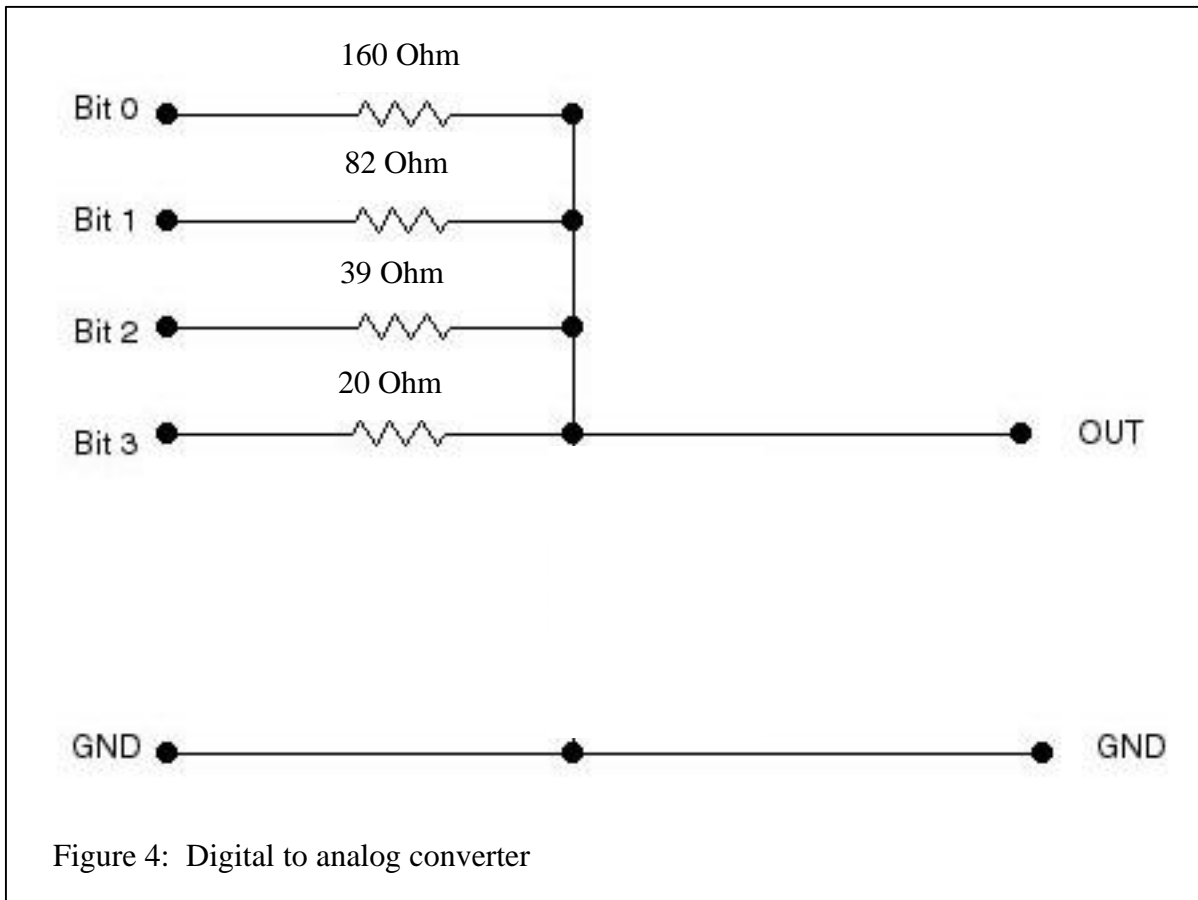


Figure 3: Laser and galvanometers setup

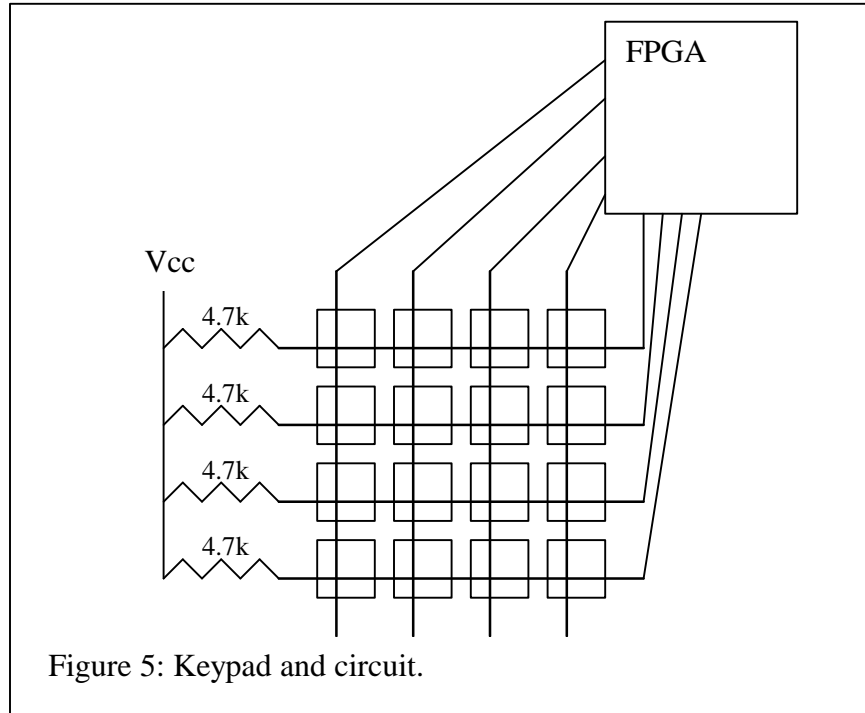
Schematics

The only additional components we used were resistors. We configured one set of resistors to act as a simple digital to analog converter. The converter works on the principal of current addition. By sending 5 volts through different valued resistors, different currents are drawn. Those currents are then tied together such that the output is an analog representation of the original digital signal. The only thing to keep in mind is that the resistor values must all be multiples of 2 of each other to ensure linearity. In our design, we used two 4-bit digital to analog converters for each direction, x and y. This is because out of each pin the FPGA would only supply a small amount of current. By doubling the number of pins, we could supply twice the current. This allowed us to have larger deflection of our galvanometers. A schematic of our digital to analog converter is given below in figure 4.



Resistor values that were smaller than those used would theoretically supply more current but they caused a problem with the FPGA overheating and resistors burning out. Also, some of the resistor values above, namely 20 and 160 ohms, were created using multiple resistors in series or parallel.

The only other circuit used in the system is given below. It was used to retrieve input from the keypads. The rows of the keypad are tied high with large resistors so that they will remain high until pulled low by contact with a low column line during a keypress. A schematic of the circuit is given below in Figure 4.



FPGA Design

Our design uses eight outputs for the laser control, four outputs for the columns of the two keypads, and eight input lines for reading the rows of the keypads. There are actually 16 outputs for the laser control due to having two sets of outputs for increased current, but in terms of actual signals, there are eight laser control output lines. The general function of the FPGA circuit is to store the past four keypresses in registers, and display the characters for those keys by looking up coordinates from a ROM module. The ROM is a LogiBLOX module with eight bit addressing and 256 eight bit words. The words are divided into sections of eight, for storing eight points per each of 32 characters. A five bit counter is used to step through the sequence of points for the four characters currently in the registers. The top two bits of the counter determine which character is being displayed. Those bits are used in a module called “keysel” that returns the value in the register denoted by the bits. That five bit value is combined with the lower three bits of the counter to determine the current ROM address. The three lower bits of the counter cause the address to step through eight values, which are the individual points in a character. The output of the ROM is the value of the word addressed. There are two four bit portions of each word. The first is the x coordinate in binary, and the second is the y coordinate in binary. The x portion of the output is translated based on the character that the output is part of. The first character is not translated and the other three are translated by a multiple of the register number.

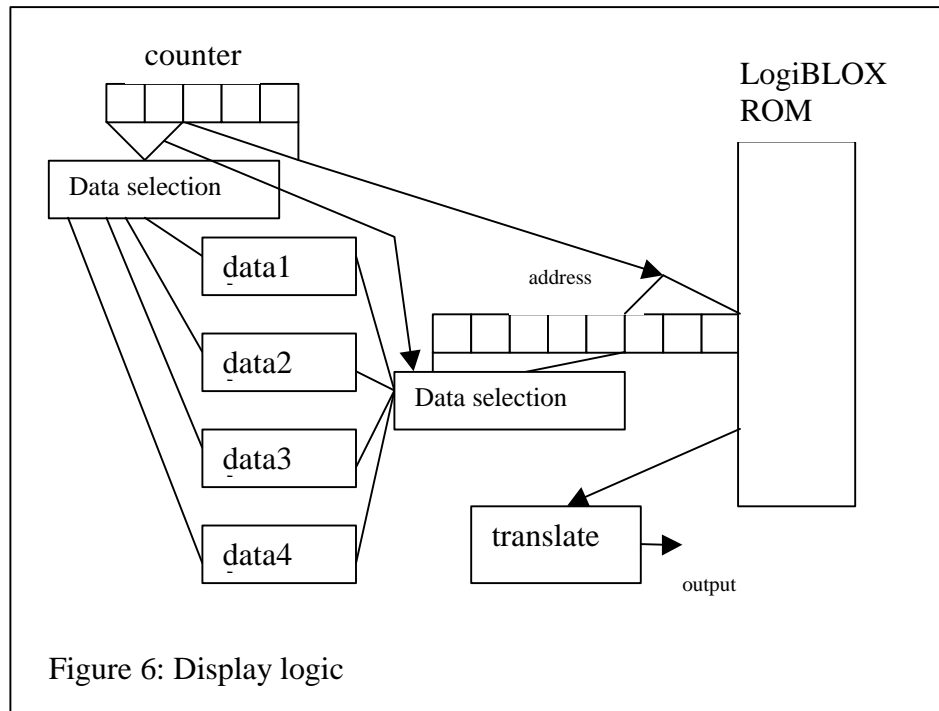


Figure 6: Display logic

The logic for storing keypresses involves sequential logic that when a key is pressed, stores the keypress in the first register, the first register's contents in the second register, etc. The key press detection logic polls the column lines of the keypads, pulling them

low in sequence, and checks to see if any of the row lines are low. If there's a key pressed, the row for that key will go low when the column for that key is being polled. The key press logic determines the key based on which column is low and which row is low. A bit is added to the four bit value for the key to signify which keypad the key was on. That gives five bits per key, enough for 32 keys which is enough to use all of the 32 characters stored in the ROM module.

Results

We accomplished our goal of creating a system to draw simple vector graphics. We were able to specialize and extend the system in order to accept input and display four letters.

There were several challenging aspects of this project. The first that arose was finding devices to do the beam deflection. We were fortunate to find the galvanometers at such a low price, but we had to do some extra work to get them functioning. We had no information about the devices to start out with, and it took a long conversation with one of the designers to learn some of the more obscure specifications. This made the hardware part of the design quite difficult, yet as a result, we were able to use very precise scanning devices.

The second difficulty was in driving the galvanometers. After getting the galvanometer and laser setup built, we didn't have a lot of time left to work with. We tried to find DAC chips and had trouble getting the ones we wanted. We tested one, and could not get it to work. We decided to just build our own DAC circuit, which had its own issues, since it's difficult to find the proper resistor values for this. Finally, we spent some time trying to amplify the current out of the DAC so we could get the full range of motion out of the galvanometers. Had we had more time we would have gotten this to work, but a lack of experience in designing actual amplifying circuits prevented this.

Despite these difficulties, we did create a working design, and the results were satisfactory. There are traces between letters since the system doesn't have a beam blocking system. The letters are visible even at distances of 20 to 30 feet in a dark room. The letters are very small at close distances, since the galvanometers deflect by such a small amount. This is good, since the display will work at larger distances, and also, the system could be extended to display more letters, since they can be drawn so small.

We are especially pleased with the portability of the system. We could convert the system to run off of batteries, and build a custom board for the FPGA and external circuitry and the whole system could be made quite small. The platform with galvanometers and laser currently has a footprint of about four by seven inches. The largest component needed to make the system battery powered would be the batteries themselves.

On the whole, we are satisfied with the results, and excited by the possibilities for this system.

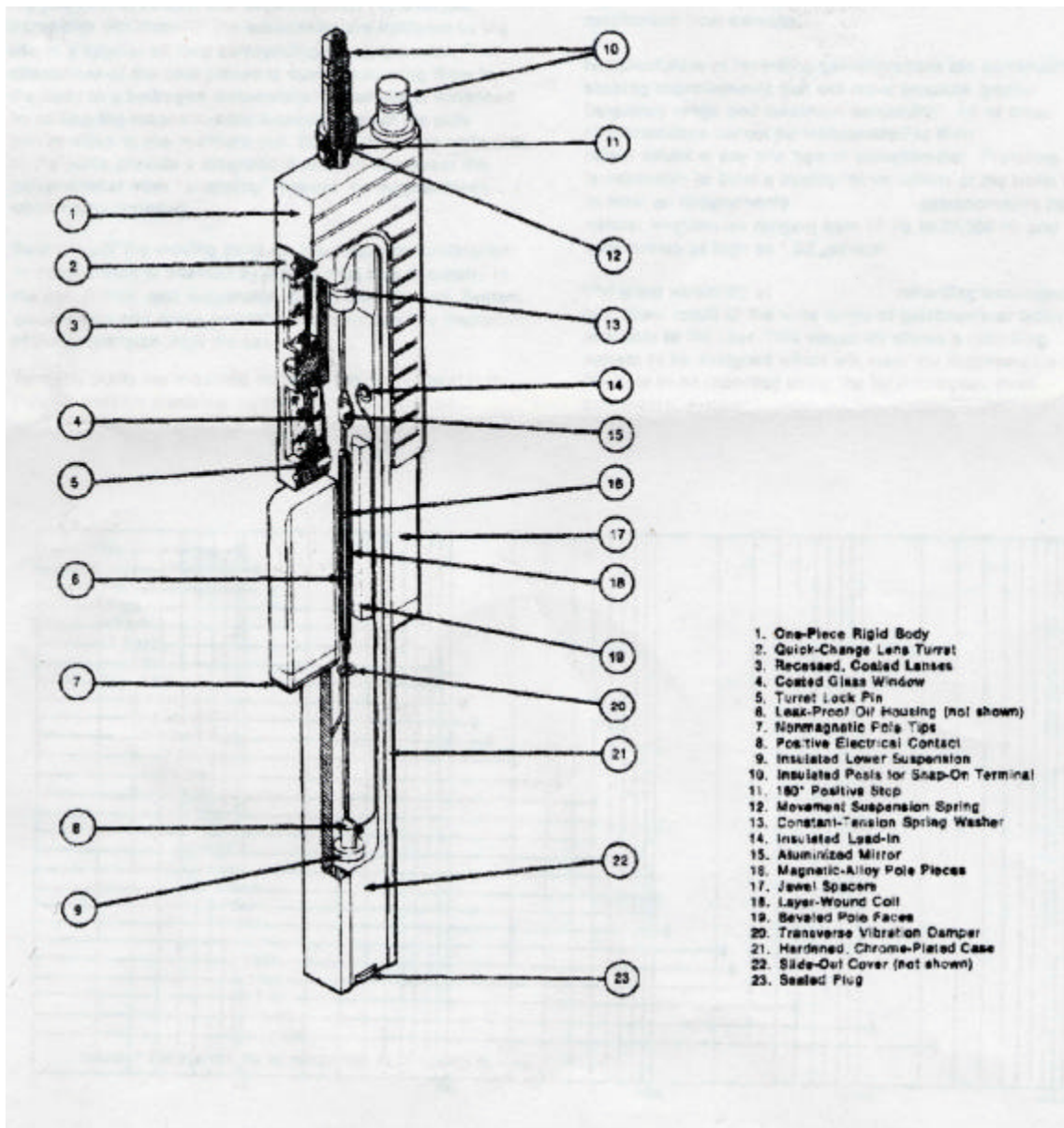
References

Various data and information from James Pace appended in Appendix A.

Parts List

Part	Source	Vendor Part #	Price Paid
Various Resistors	Radio Shack	Varied	\$7.99
2 Galvanometers	Private Ebay auction	CEC 7-361	\$10.00 each (\$558.00 retail)
Laser pointer	Fry's Electronics	Generic 5mW	\$15.00

Appendix A



Series 7-300 Galvanometers are designed for use in the slotted pole-piece magnet blocks of oscillographs.

Construction of these precision miniature instruments is rigidly controlled to insure meeting design goals of ruggedness, accuracy, and dependability. For example, transverse vibrations of the suspension are inhibited by the use of a special oil loop surrounding the suspension. Firm attachment of the pole pieces is made by brazing them to the body in a hydrogen atmosphere. Sensitivity is enhanced by setting the magnetic-alloy tapered faces of the pole pieces close to the multiturn coil. Brass tips on the underside of the poles provide a magnetic insulation to prevent the galvanometer from "snapping" against the magnet block when being installed.

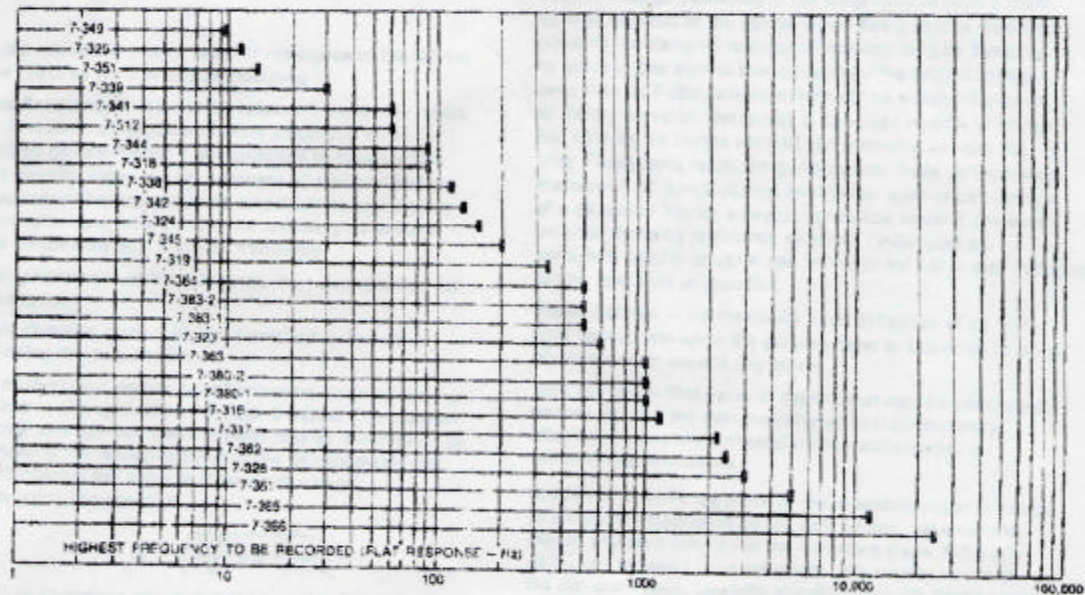
Balancing of the moving parts for low response to vibration or acceleration is attained by maintaining true symmetry in the coil, mirror, and suspension during manufacture. System ground-loop and noise problems are minimized by insulation of the suspension from the case.

Terminal posts are mounted on top of the galvanometer to provide positive electrical connection. The precision

windings of the coil are maintained in uniform suspension under adverse environments by positioning synthetic rubies inside the coil to act as a mandrel. Sharp focus of the trace beam over the deflection range is achieved by the use of a precision ground and coated window and lens assembly. Rigidity of the one-piece body protects the internal mechanism from damage.

Manufacturers of recording galvanometers are continually seeking improvements that will make possible greater frequency range and maximum sensitivity. All of these characteristics cannot be incorporated to their fullest extent in any one type of galvanometer. Therefore it is necessary to build a number of variations of the basic type to meet all requirements. . . . galvanometers have natural frequencies ranging from 10 Hz to 25,000 Hz and sensitivities as high as 1.62 $\mu\text{a}/\text{inch}$.

The great versatility of . . . recording oscillographs is a direct result of the wide range of galvanometer types available to the user. This versatility allows a recording system to be designed which will meet the requirements of the data to be recorded using the least complex, most economical system.



Oscillographs and Galvanometers are working partners in recording analog data with convenience and accuracy. They not only provide the truest data obtainable anywhere, they are also able to record more types of data, making them the most useful and versatile oscillographic recorders in the world.

Types 7-365 and 7-366 galvanometers have extended frequency range capabilities permitting greater use of oscillographs in vibration analysis, quick-look data application, and dynamic analyses involving transient phenomena. Type 7-365 has a useful frequency range of 0 to 15,000 Hz and Type 7-366 has a frequency range of 0 to 25,000 Hz. These units are viscous damped and are ideal for use in severe environments.

Very low frequency range galvanometers are ideal for measuring quasi-static or low frequency data in the presence of higher frequencies. These galvanometers act as low-pass filters for such applications as thermocouple, strain, and acceleration measuring. Natural attenuation of response beyond the frequency range results in a fairly sharp cutoff. Examples of these units are the Type 7-349, having a flat frequency range of 0 to 6 Hz, and the Type 7-351, flat in frequency response from 0 to 12 Hz.

Damping resistance — that value of resistance of the driving source required for 0.64 critical damping

Natural Frequency — Natural (or resonant) frequency refers to the frequency of maximum forced amplitude for an undamped galvanometer. It is impossible to measure this quality directly. However, for purposes of practical testing, the frequency of maximum force amplitude obtained when galvanometers are tested under the following conditions will be considered true resonant frequency:

Damping resistance at least 20 times the value required for 0.64 damping

No fluid damping other than that furnished by the air surrounding the suspension.

In the case of fluid damped galvanometers, the true resonant frequency is changed when the fluid is added. The resonant frequency of a damped galvanometer may be determined by

- a. Plotting the response curve of the galvanometer and comparing the curve to theoretical curves.
- b. By using the equation

$$f_r = \sqrt{\frac{(f_2)^2}{3} - (f_1)^2}$$

where f_1 = frequency where response equals dc response
and f_2 = frequency at which response equals $\frac{1}{4}$ dc response

Both of these methods assume the galvanometer responds as a simple dynamic system. This is not a true assumption since other modes of oscillation will affect the results to some extent. However, the resonant frequency obtained should be close enough for all practical purposes.

The optimum value of damping resistance assures a uniform amplitude versus frequency response out to 60 percent of the natural frequency. Phase response is linear out to the natural frequency for the same value of damping.

Flat Frequency Range — 7-300 galvanometers operating under optimum damping conditions (64 percent of critical) have a flat (within 5 percent) frequency response range from 0 to 60 percent of the natural frequency stated. Galvanometers are frequently used to record alternating current, and it is necessary that the spot deflection be proportional to the instantaneous current over the frequency range of interest.

Galvanometers employ a damping value which is 64 percent critical.

Terminal Resistance — the dc resistance of the coil and suspension measured at the galvanometer terminals. This measurement must be performed with an instrument which will not pass excessive current through the coil. The actual terminal resistance will be within ± 10 percent of the value stated when measured at 75°F

Undamped DC Sensitivity — the relationship between the magnitude of the current flowing through the galvanometer coil and the amplitude of the resulting deflection of the reflected spot of light on the recording paper which is at an optical arm distance of 11.5 inches.

System Voltage Sensitivity — the magnitude of open-circuit voltage required of the source which has a source resistance equal to the damping resistance required for 0.64 damping to result in one inch of true deflection. The system voltage sensitivity of 7-300 galvanometers will be within ± 5 percent of the stated value. Sensitivity is specified in units of inches per millivolt, or inches per volt and millivolts, or volts per inch. These units relate the galvanometer trace deflection on the record (11.5 inch optical arm) to the open-circuit voltage of a generator having a source resistance equal to the stated external damping resistance required. Undamped d-c sensitivity (ma/in or μ a/in and in/ma or in/ μ a) is also indicated, but no tolerance is specified

Static Balance — the maximum trace deflection of an 11.5 inch optical arm when the galvanometer is subjected to a 1 g acceleration change in any plane.

Safe Current — that value of current that may be continuously passed through the galvanometer without permanently affecting its operating characteristics and exceeding specification tolerances.

Deflection — when the plane of the recording paper is normal to the plane established by the light source, galvanometer mirror, and zero position of the recording trace. Full scale deflection is based upon maximum safe current values of the galvanometers. Linearity specifications are based upon rated deflection ± 2 inches at an optical arm of 11.5 inches. For example the 7-324 Galvanometer can be deflected the

full width of the chart and still be well within the maximum safe current limits.

Exceptions to this rated deflection are:

Type 7-326 $\pm 1\frac{1}{2}$ inch peak deflection

Type 7-361 ± 1 inch peak deflection

Type 7-365 1 inch peak to peak deflection

Type 7-366 0.8 inch p. to p.

Nonlinearity — maximum nonlinearity of 7-300 galvanometers is less than ± 0.5 percent of the rated deflection, except for the following types which have a tolerance of ± 1 percent:

Type 7-325

7-339

7-349

7-351

7-353

Insulation resistance — the resistance between either terminal and the galvanometer case exceeds 1000 megohms at 45 volts d-c. The insulation breakdown voltage is 800

volts dc minimum for fluid damped units and 400 volts dc minimum for magnetically damped units.

Environmental Specifications

Operating temperature — all operating specifications are derived with the galvanometer mounted in a magnet block maintained at a temperature of $\pm 100^\circ\text{F}$.

Storage

Each galvanometer is originally shipped in a reusable plastic scabbard. This scabbard makes an ideal storage container.

Storage environment should not exceed:

32° to 150°F temperatures

95 percent relative humidity

Atmospheric pressures corresponding to altitudes between -10,000 and +70,000 feet

± 10 g accelerations for magnetically damped types

± 25 g accelerations for fluid damped types.

If extremely long storage periods are anticipated, fluid damped units should be stored in an upright position.

Type	External Damping Resistance Required Ohms	Undamped Natural Frequency Hz	Flat Frequency Range Hz	Terminal Resistance Ohms ($\pm 10\%$)	Undamped dc Sensitivity		System Voltage Sensitivity		Static Balance In./g	Maximum Safe Current ma
					(--- Magnetically Damped ---)	(--- Fluid Damped ---)	mv/in.	in./mv		
7-348	350	10	0-5	130	1.62	0.617	0.778	1.284	0.032	15
7-351	350	20	0-12	33	2.68	0.375	1.02	0.982	0.016	15
7-339	350	50	0-36	30	4.61	0.217	1.75	0.572	0.032	15
7-341	350	100	0-50	47	5.12	0.193	2.43	0.411	0.012	10
7-325	350	18.5	0-11	18	7.84	0.125	2.92	0.343	0.050	15
7-344	180	150	0-80	45	9.75	0.103	2.20	0.453	0.008	15
7-342	350	225	0-135	66	10.7	0.0935	4.67	0.214	0.008	15
7-346	180	335	0-200	84	23.9	0.0418	6.29	0.158	0.008	15
7-312	350	107	0-60	40	29.9	0.0334	11.7	0.0858	0.016	25
7-318	180	150	0-90	26	30.6	0.0327	6.29	0.156	0.012	25
7-338	120	210	0-125	25	57.6	0.0173	8.40	0.119	0.012	50
7-324	83	290	0-180	43	265.0	0.00377	33.3	0.030	0.012	50
7-319	25	585	0-360	25	426.0	0.00235	21.7	0.046	0.012	50
(--- Fluid Damped ---)										
7-364	200	835	0-500	68	0.38	2.50	0.107	9.37	0.008	50
7-363	20-2000 (200)	1670	0-1000	69	1.96	0.50	0.533	1.878	0.005	100
7-323	75-2000 (1000)	1000	0-600	26	2.50	0.400	2.56	0.390	0.008	100
**7-363-2(LM)	20	1600	0-500	76	4.7	0.213	0.44	2.270	0.015	75
**7-363-1(LM)	20	1600	0-500	76	5.9	0.170	0.56	1.785	0.015	75
7-316	20-2000 (200)	2000	0-1300	25	9.17	0.108	2.05	0.487	0.005	100
7-362	20-2000 (200)	4150	0-2500	69	12.0	0.0833	3.23	0.31	0.005	100
**7-360-2(LM)	20	5000	0-1500	75	15.8	0.063	1.80	0.566	0.010	75
**7-360-1(LM)	20	5000	0-1000	75	19.0	0.053	1.92	0.521	0.010	75
7-326	20-2000 (55)	6000	0-3000	53	31.8	0.0314	3.44	0.291	0.005	100
7-317	20-2000 (25)	3709	0-2200	25	40.8	0.0248	2.16	0.484	0.005	100
7-340	20-2000 (55)	6000	0-5000	57	46.1	0.0217	5.16	0.194	0.005	100
7-340	150	13000	0-13000	112	86.0	0.0145	18.18	0.055	0.005	80
*7-366	150	25000	0-25000	97	133.4	0.0075	33.33	0.030	n/l	55

*Maximum deflection 1.0" p-p

**Sensitivity is for 9.0" optical arm

(LM) Large mirror galvanometers

For use with Tungsten light source

Appendix B

toplevel.v

```
module letters(A, DO);
input [7:0] A;
output [7:0] DO;
endmodule

module topLevel(clk, reset, out, out2, rows, cols, rows2);

input clk, reset;

input [3:0] rows;
input [3:0] rows2;
output [3:0] cols;

output [7:0] out;
output [7:0] out2;

reg [4:0] counter;
reg [4:0] data1, data2, data3, data4;

wire [7:0] uninout;
wire slowclk;

wire [4:0] sel;
wire [4:0] sel2;

                                // translate letters based on position
assign out[7:4] = uninout[7:4] + {counter[4:3], 2'b00};

assign out[3:0] = uninout[3:0];

assign out2 = out;                                // duplicate output

clkdiv slower(clk, reset, slowclk);                // slows the clock

dualkeypad keyp(slowclk, reset, rows, cols, rows2, data1, data2, data3, data4);

                                // look up a register
keysel keys(slowclk, reset, counter[4:3], sel, data1, data2, data3, data4);

letters readdata( .A({sel, counter[2:0]}), .DO(uninout));

always @(posedge slowclk or posedge reset)
    if (reset) counter <= 5'b00000;
    else counter <= counter + 1;

endmodule
```

clkdiv.v

```
module clkdiv(clk, reset, slowclk);
input clk;
input reset;
output slowclk;

reg [11:0] count;

always @(posedge clk or posedge reset)
    if (reset) count <= 0;
    else count <= count + 1;

    assign slowclk = count[5];
endmodule
```


dualkeyp.v

```
module dualkeypad(slowclk, reset, rows, cols, rows2, data1, data2, data3, data4);
    input slowclk;
    input reset;
    input [3:0] rows;
    output [3:0] cols;
    input [3:0] rows2;

    output [4:0] data1, data2, data3, data4;
    reg [4:0] data1, data2, data3, data4;

    reg state;
    reg [3:0] cols;
    reg [3:0] key;
    reg [3:0] key2;

    always @(posedge slowclk or posedge reset)
        if (reset) begin
            state <= 0;
            cols <= 4'b0111;
            data1 <= 5'b000000;
            data2 <= 5'b000000;
            data3 <= 5'b000000;
            data4 <= 5'b000000;
        end else if (&rows & &rows2) begin // poll the columns
            state <= 0;
            cols <= {cols[0], cols[3:1]};
        end else if (~state) begin
            state <= 1;
            if (&rows) begin // shift in new data
                data1 <= data2;
                data2 <= data3;
                data3 <= data4;
                data4 <= {1, key2}; // second keypad
            end else if (&rows2) begin // a bit of rows is low
                data1 <= data2;
                data2 <= data3;
                data3 <= data4;
                data4 <= {0, key}; // first keypad
            end
        end

    always @(rows or cols)
        case ({rows, cols})
            8'b0111_0111: key <= 'hC; // map a row and column to
            8'b1011_0111: key <= 'hD; // a key value
            8'b1101_0111: key <= 'hE;
            8'b1110_0111: key <= 'hF;

            8'b0111_1011: key <= 'h3;
            8'b1011_1011: key <= 'h6;
            8'b1101_1011: key <= 'h9;
            8'b1110_1011: key <= 'hB;

            8'b0111_1101: key <= 'h2;
            8'b1011_1101: key <= 'h5;
            8'b1101_1101: key <= 'h8;
            8'b1110_1101: key <= 'h0;

            8'b0111_1110: key <= 'h1;
            8'b1011_1110: key <= 'h4;
            8'b1101_1110: key <= 'h7;
            8'b1110_1110: key <= 'hA;
            default: key <= 'h0;
        endcase

    always @(rows2 or cols)
        case ({rows2, cols})
            8'b0111_0111: key2 <= 'hC;
```

```

        8'b1011_0111: key2 <= 'hD;
        8'b1101_0111: key2 <= 'hE;
        8'b1110_0111: key2 <= 'hF;

        8'b0111_1011: key2 <= 'h3;
        8'b1011_1011: key2 <= 'h6;
        8'b1101_1011: key2 <= 'h9;
        8'b1110_1011: key2 <= 'hB;

        8'b0111_1101: key2 <= 'h2;
        8'b1011_1101: key2 <= 'h5;
        8'b1101_1101: key2 <= 'h8;
        8'b1110_1101: key2 <= 'h0;

        8'b0111_1110: key2 <= 'h1;
        8'b1011_1110: key2 <= 'h4;
        8'b1101_1110: key2 <= 'h7;
        8'b1110_1110: key2 <= 'hA;
        default: key2 <= 'h0;
    endcase
endmodule

```

keysel.v

```

module keysel(clk, reset, sel, d, data1, data2, data3, data4);
    input clk, reset;
    input [1:0] sel;
    output [4:0] d;
    input [4:0] data1, data2, data3, data4;
    reg [4:0] d;

    always @(sel) // use a binary number to select the register or character
        case(sel)
            0: d <= data1;
            1: d <= data2;
            2: d <= data3;
            3: d <= data4;
        endcase
endmodule

```

Appendix C

```
;
; memfile mem.mem for LogiBLOX symbol letters
; Created on Monday, November 20, 2000 01:57:59
;
; Header Section
RADIX 10
DEPTH 256
WIDTH 8
DEFAULT 0
;
; Data Section
; Specifies data to be stored in different addresses
; e.g., DATA 0:A, 1:0
RADIX 16
; now store only 8 points per symbol, instead of 16
DATA 00, 04, 24, 20, 22, 02, 22, 20, ;A
00, 04, 00, 20, 22, 02, 22, 20, ;b
00, 04, 24, 04, 00, 20, 00, 20, ;c
00, 20, 22, 24, 22, 02, 00, 20, ;d
00, 02, 22, 21, 01, 00, 20, 20, ;e
00, 04, 24, 04, 02, 22, 02, 00, ;F
00, 20, 24, 04, 02, 22, 40, 40, ;g
00, 02, 04, 02, 22, 24, 22, 20, ;H
00, 10, 14, 04, 24, 14, 10, 20, ;I
00, 10, 14, 04, 24, 14, 10, 10, ;J
00, 02, 04, 02, 24, 02, 20, 20, ;K
00, 01, 02, 03, 04, 00, 10, 20, ;L
00, 02, 04, 22, 44, 42, 40, 40, ;M
00, 02, 04, 12, 20, 22, 24, 20, ;N
00, 04, 24, 20, 00, 04, 24, 20, ;O
00, 02, 04, 24, 22, 02, 04, 00, ;P
20, 22, 24, 04, 02, 22, 20, 30, ;q
00, 02, 04, 24, 22, 02, 20, 20, ;R
00, 20, 22, 02, 04, 24, 04, 02, ;S
10, 12, 14, 04, 24, 14, 12, 10, ;T
00, 04, 02, 00, 20, 24, 22, 20, ;U
10, 04, 10, 24, 10, 04, 10, 24, ;V
00, 04, 02, 00, 22, 40, 44, 40, ;W
00, 12, 24, 12, 04, 12, 20, 20, ;X
10, 12, 04, 12, 24, 12, 10, 10, ;Y
00, 12, 24, 04, 24, 12, 00, 20, ;Z
00, 00, 00, 00, 10, 10, 10, 10, ;width 1 space
00, 00, 00, 00, 20, 20, 20, 20, ;width 2 space
00, 04, 24, 20, 04, 24, 00, 20, ;square with x in it
00, 04, 24, 20, 04, 24, 00, 20, ;square with x in it
00, 88, 08, 80, 88, 00, 08, 00, ;medium square with x
00, FF, 0F, F0, FF, 00, 0F, 00, ;big square with x
; end of LogiBLOX memfile
```