Build Your Own MC68HC11 Computer Trainer

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1 Introduction

The electronic computer has been called the most complex machine built by man, and anyone fascinated by technology recognizes the computer as the ultimate machine. Infinitely configurable through programming, the computer is a machine that is malleable as clay is to a skilled sculptor. If you love computers, you probably want to become a skilled computer sculptor. Becoming a skilled programmer provides half of the skills you need. Completing your skills means understanding computer hardware, at the heart of which is the *microprocessor*. If learning about computer hardware is your goal, then read on. This paper is going to show you how to build your own practical, working computer from scratch.

This document will show you how to build your own computer trainer based on the Motorola MC68HC11 microprocessor. The design used here is similar to many of the commercially available MC68HC11 single board computers, particularly the Motorola M68HC11 Evaluation Board (EVB). You will learn a great deal by building this project and, in the end, you will have a working EVB of your very own that you can program and customize.

This document contains six sections:

The instructions in the rest of this document assume that you have had little or no exposure to microprocessor electronics. You should, though, have some computer programming experience, particularly with assembly language. Also, you should have some experience with digital electronics as well as some experience with basic electronic assembly. Barring no problems, you can construct this project in about one full week. Good luck, you are on your way to building your first, but probably not your last, computer.

2 The Structure of a Small Computer System

The purpose of a computer is to act out a series of directions given by a person, ultimately performing some physical action. This goal starts with numbers. Numbers, as it turns out, can represent any type of information. Since computers manipulate numbers, computers also manipulate representations of information. The form of numbers that electronic computers use are groups of binary digits or *bits*. Bits are simply numerical digits which only have two states, 0 and 1. This is just like a digit in our decimal system which has ten states, 0 through 9, one state for each finger on our two hands. So you might say that by using the binary system, a computer probably has only one finger on each of its hands! A consequence of bits having fewer states than decimal digits is that you need more binary digits to represent the same number in the decimal system. Nonetheless, both number systems can each represent every possible number. Ultimately, electronic computers use binary digits because by only having two states it has a minimal chance of confusing one state with the other and that provides a maximum level of reliability.

A computer uses its electronic versions of numbers to perform its purpose; acting out a series of directions given by a person. Since numbers can represent anything, we can use numbers to represent the instructions that we want the computer to follow as well as raw information and even some physical actions like turning on an indicator light, sending messages to a teletype or making a sound.

The microprocessor chip contains all of the electronics needed to perform a majority if not all of the actions of a computer system. Usually though, a certain amount of the resources of a computer are too expensive or impractical to squeeze onto one integrated circuit chip. The most notable of these resources is memory. Memory is the single most expensive element of a computer system. Memory gives the computer a place to store numbers. The more memory a computer has, the more numbers it can store. Computer memory typically stores raw data and programs.

If a microprocessor is going to work with external memory it needs external signals to control the memory. These signals can be broken into three parts: an address bus, a data bus and a control bus.

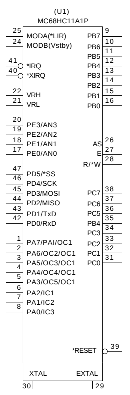
The address bus is a series of digital signal lines which can send out a binary number which in turn represents a single location in the computer’s memory space. Since the address bus can only represent a finite amount of unique numbers, there can only be a finite number of memory locations in a computer system.

Once you have a place to store numbers, you need a way access them. That’s where the data bus comes in. Just like the address bus, the data bus is a series of digital signal lines which can send and receive numbers. In this case, the numbers represents raw data, physical actions or a program.

Finally, the control bus uses its digital signals to keep the address and data busses of the microprocessor synchronized with the external components.

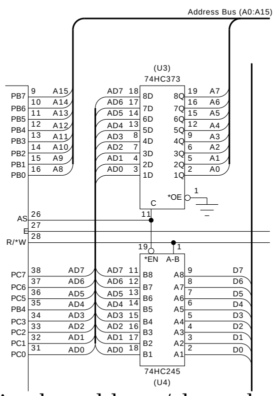
2.1 The Design

The computer we are about to build will have the Motorola MC68HC11 microprocessor at its core. Motorola designed the MC68HC11 so that it requires a minimum of support circuitry in order to build a working design with it. This will suit our purposes nicely since it will allow us to learn how to build a computer without sinking in excessive complexity.

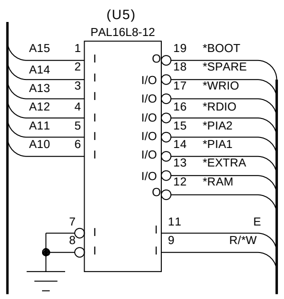


The MC68HC11 has many useful circuits already built into it. For example, it has built-in digital I/O ports, a sophisticated timing system, an asynchronous serial port for RS-232 communications, a synchronous serial port, an analog-to-digital converter and a built-in crystal oscillator circuit. It also has built-in memory such as 256 bytes of Random Access Read/Write Memory (RAM), 512 bytes of Electrically Erasable Programmable Read Only Memory (EEPROM) and in some versions, 8 kB of Read Only Memory (ROM). Having all these resources on one chip allows the MC68HC11 to be used as a single-chip microcontroller requiring no extra support chips. For this project though, we will treat the MC68HC11 as a conventional microprocessor by adding various external resources to it.

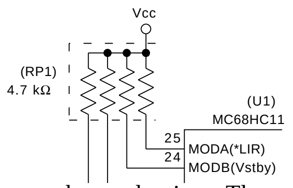
Following is a block-by-block description of the computer's design using sections taken from the main schematic diagram. The complete schematic diagram can be found in Appendix 3.



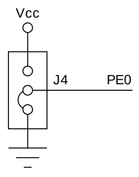
1. This is the address/data demultiplexer circuit. It separates the one address/data bus into distinct address and data busses. Multiplexing the address and data bus saves 8 pins which can be dedicated to other resources at the expense of requiring an external demultiplexing circuit.



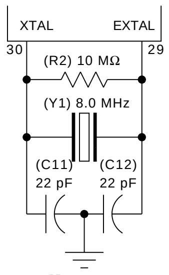
2. This is the Chip Select PAL. Its job is to decode the address space and select the appropriate memory chip. Its inputs are the address lines as well as the E and R/*W lines. Its outputs are the various chip select signals.



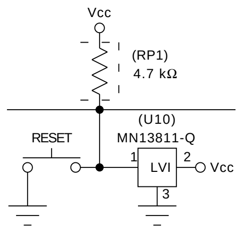
3. These are the mode pins. These two pins allow you to configure the MC68HC11 to run in one of four modes. Pulling both pins high, as in this case, puts the microprocessor in Expanded Mode.



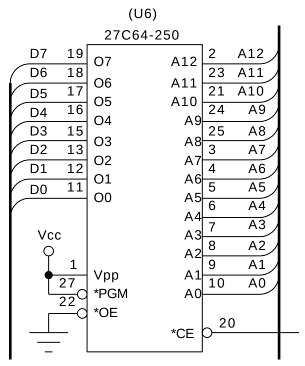
4. This is the “J4” jumper. The BUFFALO monitor program uses this jumper to determine whether or not to jump to the internal EEPROM or run the BUFFALO monitor at startup.



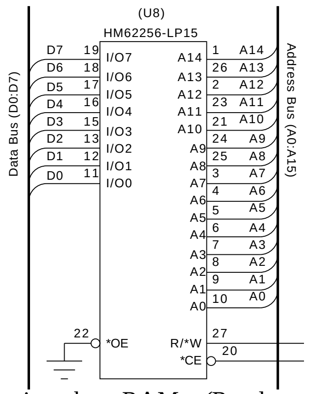
5. This is the oscillator circuit. It provides the “heartbeat” for the microprocessor. The oscillator generates an 8 MHz square wave which is divided internally by a factor of four to supply a 2 MHz clock pulse to the microprocessor.



6. This is the reset circuit. Pressing the Reset button will cause the computer to stop what it is doing and start from scratch. The LVI (Low Voltage Interrupt) chip can also assert the Reset line if the power supply voltage drops below 4 V. This prevents the microprocessor from running before the power reaches a meaningful level.

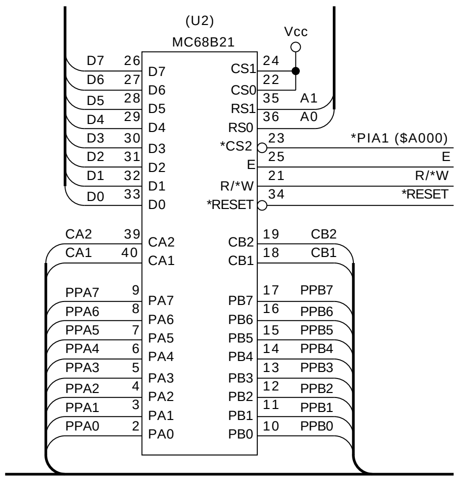


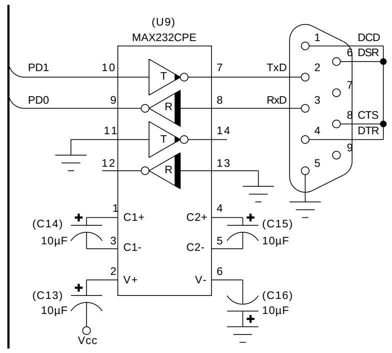
7. This is one of the two EPROMs (Erasable Programmable Read Only Memory). The computer uses this memory chip to store programs and data semi-permanently. In other words, the information stored here can only be erased by shining an ultraviolet light into the glass window on the chip.



8. This is the RAM (Random Access Memory) chip. While the MC68HC11 has 256 bytes of RAM internally, this usually is not enough for software development. The HM62256 provides the computer with an additional 32 kB of R/W memory.

Notice that the EPROM and the RAM chip have similar pin outs. This is due to the JEDEC standard which specifies the pin outs of byte-wide (8-bit) memory devices. The JEDEC standard allows memory of different sizes and from different manufacturers to be used in the same sockets, with little or no modifications.





9. This is the PIA (Peripheral Interface Adapter) chip. Since we are using the MC68HC11 in expanded mode, I/O ports B and C are unavailable for our use. The MC6821 will give us two bi-directional 8-bit I/O ports to work with.

10. This is the RS-232 circuit. The MAX232 provides the interface between the serial port on the MC68HC11 and the DB-9 connector. This buffer chip is required because RS-232 requires relatively high voltages (about ±12 V). Additionally, the MAX232 has a charge pump circuit which uses four capacitors to generate ±10 VDC from the 5V supply. This way the whole computer can run from a single 5V supply.

Additionally, the computer requires a +5 VDC @ 0.3 A power supply. For this project, you can either purchase one or build a simple one from scratch.

Keep in mind that this design isn't inscribed in stone. Feel free to modify the computer in any way you see fit. You can learn a great deal by customizing the computer.

3 Building the Computer

Before you start ordering the parts and constructing the computer, skim through this whole document to get an idea of what to expect. While this document is presented in chronological order, you can avoid many pitfalls as you're building the computer if you know where you're heading.

To build this computer you will need some common pieces of electronic tools and test equipment. The major tools you will need access to are an EPROM programmer and a 15 W soldering iron with a small tip. The test equipment you will need are a +5 VDC power supply, a voltmeter, a personal computer with an RS-232 serial port, a terminal emulation program and possibly an oscilloscope. Additionally, it would help to have access to the World Wide Web.

The following timeline depicts a minimum-time schedule required to complete this project. If all goes well, you can probably finish this project in a week or two. Keep in mind though that this estimate does not include the time required to overcome learning how to build a computer or the time required to debug the computer which can be two large variables in this schedule. Of course, overcoming these obstacles embodies the whole purpose of this project.

Monday	Order Parts. Download Software. Order Data Sheets.
Tuesday	Buy parts from Radio Shack.
Wednesday	Receive Mail Order Parts.
Thursday	Program PAL and EPROM. Lay out the board.
Friday	Wire the computer.
Saturday	Wire the computer.
Sunday	Test the computer.

3.1 Ordering the Parts

Mail-order is the best way to obtain electronic parts. While it's tempting to run down to the local electronics store and buy the parts off the shelf, you will usually have trouble getting exactly what you need and wind up paying a lot extra. With mail-order, you can almost always get exactly what you want at a good price. All you need is a credit card and a telephone. Begin signing up on the mailing lists of mail-order houses which sell electronic parts. This is easy to do since every major mail-order house has a toll-free number as well as a World Wide Web (WWW) site.

There are three parts listings given for this project, one for each parts supplier. Generally, the fewer orders you make, the less overall shipping charges you have to pay. It turns out that JDR Microdevices, Digi-Key and Radio Shack have all of the parts that we'll need. JDR Microdevices and Digi-Key are mail-order houses, while Radio Shack is usually just a car ride away.

Keep in mind that the parts list, and the whole design for that matter, isn't etched in stone. If you find a better supplier, come up with better parts, or just want to save money, many of these parts can be substituted or even left out entirely. Look over the part list carefully and check the items with the mail-order catalogs. Try to understand what you're buying.

If you find that a particular part isn't in stock, it would be best to substitute the part for another or order it somewhere else, as opposed to backordering the part. Backorders can mean waiting weeks or possibly not getting the part at all, not to mention extra shipping charges. Be sure to keep the mail-order catalog handy when you place your order in case you need to make a quick substitution. Backorders shouldn't be a problem for this project since most of the parts are pretty commonplace.

If you choose, you can order all of the mail-order parts over the Internet. Simply go to the respective WWW site and follow the ordering procedure. One advantage to ordering parts over the Internet is that you can instantaneously check the stock for each item as you go along. Also, you won't feel rushed in case you need to change your mind while ordering.

If you place your order early in the day, the parts suppliers will usually ship the order the same day. As a result, the shipping method you choose will determine the amount of time it will take to get the parts. Second-day air-mail is usually a good buy. With second-day air-mail, the parts will arrive within two business days of when they are shipped.

The prices and part numbers which are listed below reflect what was available at the time of printing. As time progresses, the prices, availability and part numbers will change. If you can't find a part in the recent catalogs, find substitutes using the master parts list in Appendix 1.

The parts marked (*) are ones you might already have in your parts box. If you don't have them, go ahead and order them since you're getting a pretty good deal from the mail-order houses. The parts marked (†) are optional and can be substituted for something less exotic.

Digi-Key, 1-800-344-4539 (http://www.digikey.com)

#	Part No.		Part Description	Unit Price	Total Price
1	AE1020-ND	*	Male-Female DB-9 Cable (2m)	5.35	5.35
1	ED1609-ND	*	2 Position Terminal Block	0.37	0.37
1	ED4648-ND		48-Pin DIP WW Socket 3-Level	5.49	5.49
1	MN13811-Q-ND		3.8V O.D. Low Voltage Detector	0.85	0.85
1	EG1403-ND	*	SPST Momentary Square Yellow Pushbutton	0.98	0.98
1	923252-ND	†	6.5" Solderless Breadboard w/Power Busses	19.25	19.25
1	923292-ND	†	54 Point Terminal Strip with Solder Tails	9.65	9.65
1	L20165-ND	*	PC Board Mount Green LED With Holder	0.67	0.67
			Sub Total		$42.61

JDR Microdevices, 1-800-538-5000 (http://www.jdr.com)

#	Part No.		Part Description	Unit Price	Total Price
			Integrated Circuits		
1	74HC245		Octal Tri-State Transceiver	0.39	0.39
1	74HC373		Octal Tri-State D Type Latch	0.45	0.45
1	MAX232CPE		+5V Powered Dual RS-232 Trans./Rcvr.	1.39	1.39
1	68HC11A1P		8-bit HCMOS MCU	11.99	11.99
1	68B21	2	PIA 2 MHz	2.89	2.89
2	27C64A-200		8kx8 250ns EPROM	2.89	5.78
1	HM62256LP-10		32kx8 100ns Static RAM	1.99	1.99
1	16L8B		PAL 16L8B 15ns	1.49	1.49
			Discrete Components		
1	8.0MHZ		8.0 MHz Crystal	1.39	1.39
1	RPS7-4.7K	†	4.7 kΩ SIP 7 Resistor Network	0.19	0.19
10	R10.0M	*	10 MΩ 1/4 W Resistor	0.05	0.50
10	R330	*	330 Ω 1/4 W Resistor	0.05	0.50
1	100R16	*	100 µF 16V Radial Electrolytic Capacitor	0.14	0.14
4	10R63	*	10 µF 63V Radial Electrolytic Capacitor	0.10	0.40
2	22PF	*	22 pF Ceramic Capacitor	0.05	0.10
9	T.1-35	*	0.1 µF Tantalum Capacitor	0.15	1.35
			Connectors		
1	DB09SRS		Right Angle PC Mount Female DB-9 Connector	0.59	0.59
			IC Sockets		
1	16 PIN WW		16-Pin DIP WW Socket 3-Level	0.79	0.79
3	20 PIN WW		20-Pin DIP WW Socket 3-Level	1.09	3.27
3	28 PIN WW		28-Pin DIP WW Socket 3-Level	1.49	4.47
1	40 PIN WW		40-Pin DIP WW Socket 3-Level	1.69	1.69
			Headers		
10	JUMPER-KT-10	†	Shorting Jumper Block	0.99	0.99
1	HDR-40R	†	1x40 Snappable Header with Right Angle Pins	0.89	0.89
			Sub Total		$43.63

Radio Shack (http://www.radioshack.com)

#	Part No.		Part Description	Unit Price	Total Price
1	278-503		50' 30-Gauge Blue Wrapping Wire	2.79	2.79
1	276-1396		6"x8" IC-Spacing Perfboard	3.49	3.49
1	276-1570	*	Wire-Wrapping Tool	7.49	7.49
			Sub Total		$13.77

3.2 Downloading the Software

While you are waiting for the parts to arrive, you can download the software required for the computer from the Internet. Motorola has an FTP site which has lots of free software that can be used for developing computers based on Motorola microprocessors. For this project, the one important piece of software required is the BUFFALO monitor program. BUFFALO is a stand alone program written for operating a simple MC68HC11 computer through a dumb terminal. We will put the BUFFALO program in an 8 kB boot EPROM so that the computer will be ready for work at power up.

Additionally, there are two other pieces of software that would be useful for this project. The AS11 program is a freeware cross-assembler provided by Motorola. It's invaluable for writing software for the MC68HC11. Also, the FTP site has a copy of BASIC11, a stand alone BASIC interpreter for the MC68HC11. The interpreter is fairly complete and fits inside of an 8 kB ROM.

The Motorola FTP site is located at:

http://www.mot.com/pub/SPS/MCU/

Alternatively, the University of Alberta Motorola Archive is a mirror site:

ftp://nyquist.ee.ualberta.ca/pub/motorola/

Download the BUFFALO Monitor - You only need the ".s19" file, but if you want an up-to-date source listing for BUFFALO, then download the ".zip" file.

Path	Size	Date	Comments
/mon/buf34.s19	19182	03/30/1994	BUFFALO 3.4 monitor for the HC11.
/mon/buf34.zip	116221	03/02/1995	BUFFALO 3.4 monitor for the HC11 with source code.

Download a cross-assembler - AS11 is a freeware cross-assembler for the MC68HC11. It has been ported to many platforms since Motorola has distributed the C source code for the assembler.

Path	Size	Date	Comments
/ibm/as11.exe	18870	03/30/1994	Cross assembler for the MC68HC11.
/ibm/as11new.exe	19584	03/30/1994	Improved version of as11.
/mac/XASMHC11.MAC	49024	03/30/1994	This is as11 ported to the Macintosh by Georgia Tech. Use MacBinary to download this application.

While you're downloading software you might want to get a copy of PALASM. PALASM is a freeware program from American Micro Devices (AMD) which you can use to compile the program for the Chip Select PAL.

The AMD WWW site is located at:

http://www.vantis.com/software/software.html

Download PALASM - When you reach the web site, follow the registration procedure for downloading PALASM.

3.3 Ordering the Data Sheets

Component manufacturers publish data books and data sheets for all of their components. Usually the literature and the phone call are free. Additionally, most major manufacturers have World Wide Web sites which have the literature in electronic form.

For this project, it would be a good idea to get the data sheets for some of the components. Particularly, the data sheets for the MC68HC11 and the MC6821 are indispensable.

You have two options for ordering the literature. You can either call up Motorola literature group or you can access their WWW site. I would recommend using the WWW site since it is as simple as filling out a form. If you choose to go to Motorola's web site, be sure to browse around to see the other services they provide.

Here is the phone number for the Motorola Literature Distribution:

1-800-441-2447

While here is their WWW address:

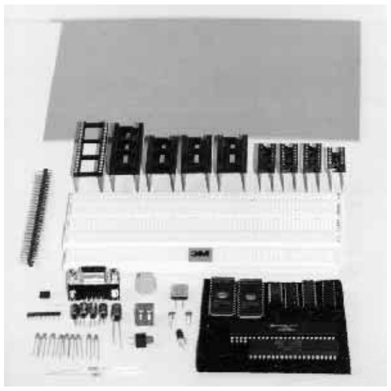
http://mot2.mot-sps.com/home/lit_ord.html

Here are the part numbers for the data books to order:

MC68HC11A8/D	*MC68HC11A8 Technical Data Book*
MC6821/D	*MC6821 Peripheral Interface Adapter Data Sheet*
M68HC11EVB/D1	*M68HC11EVB Evaluation Board User's Manual*

3.4 Construction

Now that the parts have arrived, it is time to assemble your computer. We will start by programming the boot EPROM and the chip select PAL. Following will be a tutorial on wire-wrapping. Finally, we will lay out the components on the board and do the actual wiring.



3.4.1 Programming the EPROMs

The boot ROM will give our computer a program to run every time the computer is powered up. This is possible since the boot ROM provides non-volatile storage (it doesn’t lose its memory when the power is turned off).

This step will require the use of an EPROM programmer. This might be troublesome if you don’t have access to one. Since an EPROM programmer can be an expensive item, you might want to get help from someone who owns one. The Electrical Engineering department at your local university would have one as well as your local electronics trade school. It is also possible that your local electronics repair shop would have one that you can use. If these options aren’t available to you or if you think you will be building more computers in the future, you might want to invest in your own personal EPROM programmer. Most electronics supply stores carry them. For this project, be sure that the programmer you use is able to program both EPROMs and PALs.

You can erase an EPROM by using an EPROM eraser which contains an ultraviolet lamp. The ultraviolet light is shined through the window on the chip. Never look directly at an ultraviolet lamp as it can cause serious eye damage.

Programming the Buffalo EPROM

1. Load the “buf34.s19” file into the EPROM programmer. You might have to tell it that the file is in Motorola Hex format. Specify a base address of $E000.

2. Program and verify the BUFFALO EPROM.

Programming the Test EPROM

1. Store the test program in Listing 1 into a text file.

Listing 1: The test program listing.

```
****  test.as  ****
RegBase  equ  $1000
PORTA    equu $00
TCTL1    equ  $20
TFLG2    equ  $25
PACTL    equ  $26
PIA_PRA  equ  $A000
PIA_CRA  equ  $A001
PIA_PRB  equ  $A002
PIA_CRB  equ  $A003

         org    $E000
start    ldx    #RegBase
         clr    PIA_CRA          Initialize PIA.
         clr    PIA_CRB
         ldaa   #$FF
         staa   PIA_PRA
         staa   PIA_PRB
         ldaa   #$04
         staa   PIA_CRA
         staa   PIA_CRB
         ldaa   #$80
         staa   PACTL,x
         clr    TCTL1,x
         ldab   #$38             Initialize test pattern.
         clc

delay    ldy    #7               Wait 0.23 seconds by counting seven timer overflows.
loop     brclr  TFLG2,x $80 loop Wait for timer overflow.
         ldaa   #$80
         staa   TFLG2,x          Clear timer overflow flag.
         dey
         bne    loop
         rolb                    Rotate test pattern.
         stab   PORTA,x          Write test pattern.
         stab   PIA_PRA
         stab   PIA_PRB
         bra    delay

         org    $FFFE
         fdb    start
```

2. Assemble the program using the AS11 assembler.

3. Load the resulting .s19 file into the EPROM programmer as before specifying a base address of $E000.

4. Program and verify the test EPROM.

3.4.2 Programming the Chip Select PAL

The Chip Select PAL (Programmable Array Logic) chip is used to perform the logic which “glues” the computer together. By using a PAL, we reduce the number of components by eliminating many discrete logic gates. The PAL can provide much more complex designs than normally would be attempted with discrete logic. Also, if the logic needs to change, a new chip can be programmed replacing the old design.

Since all of the memory and I/O chips share the same data and address busses, they need a way to know when they are being addressed. The PAL will do this job by decoding the current value on the address bus and selecting the appropriate chip. Additionally, the PAL gates the RAM and ROM chip select signals with the E clock signal since the data bus isn't ready until E is high. Also, the ROM chip selects are gated with the R/*W line so that the ROM is only selected during a read cycle.

Programming the PAL

1. Using a text editor, type in the program shown in Listing 2 and save it in a text file.

Listing 2: The program listing for the Chip Select PAL.

```
;----------------------------------- Declaration Segment ------------
TITLE    EVB Address Decoder
PATTERN
REVISION
AUTHOR   G. Yerem
COMPANY  UTK
DATE     06/19/97
CHIP  _CSPAL  PAL16L8

;----------------------------------- PIN Declarations --------------
PIN  1         A15                                COMBINATORIAL ; INPUT
PIN  2         A14                                COMBINATORIAL ; INPUT
PIN  3         A13                                COMBINATORIAL ; INPUT
PIN  4         A12                                COMBINATORIAL ; INPUT
PIN  5         A11                                COMBINATORIAL ; INPUT
PIN  6         A10                                COMBINATORIAL ; INPUT
PIN  7         RW_EN                              COMBINATORIAL ; INPUT
PIN  8         IO_EN                              COMBINATORIAL ; INPUT
PIN  9         RW                                 COMBINATORIAL ; INPUT
PIN  10        GND                                              ; GND
PIN  11        E                                  COMBINATORIAL ; INPUT
PIN  12        /RAM_SEL                           COMBINATORIAL ; OUTPUT
PIN  13        /EXTRA_SEL                         COMBINATORIAL ; OUTPUT
PIN  14        /PIA1_SEL                          COMBINATORIAL ; OUTPUT
PIN  15        /PIA2_SEL                          COMBINATORIAL ; OUTPUT
PIN  16        /RDIO_SEL                          COMBINATORIAL ; OUTPUT
PIN  17        /WRIO_SEL                          COMBINATORIAL ; OUTPUT
PIN  18        /SPARE_SEL                         COMBINATORIAL ; OUTPUT
PIN  19        /BOOT_SEL                          COMBINATORIAL ; OUTPUT
PIN  20        VCC                                              ; VCC

;-----  Boolean Equation Segment.  ----
EQUATIONS
RAM_SEL   = (/A15)*E                                             ; $0000 - $7FFF
EXTRA_SEL = ( A15*/A14*/A13)*E*RW                                ; $8000 - $9FFF
PIA1_SEL  = ( A15*/A14* A13*/A12*/A11*/A10)                      ; $A000 - $A3FF
PIA2_SEL  = ( A15*/A14* A13*/A12*/A11* A10)                      ; $A400 - $A7FF
RDIO_SEL  = ( A15*/A14* A13*/A12* A11*/A10 + IO_EN)*(E* RW + RW_EN)  ; $A800 - $ABFF
WRIO_SEL  = ( A15*/A14* A13*/A12* A11* A10 + IO_EN)*(E*/RW + RW_EN)  ; $AC00 - $AFFF
SPARE_SEL = ( A15* A14*/A13)*E*RW                                ; $C000 - $DFFF
BOOT_SEL  = ( A15* A14* A13)*E*RW                                ; $E000 - $FFFF
```

2. Using PALASM or a similar program, compile the PAL program to generate a JEDEC file. (PALASM is a freeware program from AMD which runs under DOS.)

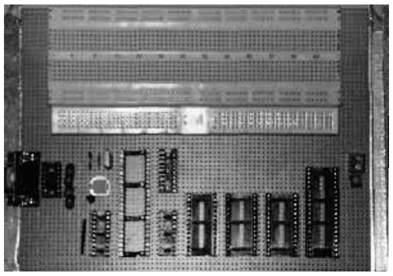
3. Using an EPROM programmer, program the PAL using the JEDEC file.

You can test your PAL by placing it in a solderless breadboard and examining the outputs for different input combinations.

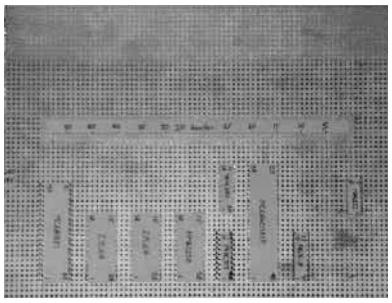
3.4.3 Board Layout

The next step is to lay out the components on the board.

First place the sockets and discrete components on the perfboard. The scale drawing in Appendix 2 offers a suggested layout. Keep in mind that the DIP wire-wrap sockets have an indentation which marks pin 1 of the chip. The indentation on the socket corresponds to the indentation on the chip itself.



Next label the underside of the board. This will prevent errors when you are wiring the board. It can be very frustrating to finish wiring a project, only to find out that you've wired the chips backwards. White adhesive correction tape, which can be found at office supply stores, works good for this purpose. Also, you can buy preprinted labels for wire-wrapping if you don't want to make the labels yourself. For this project, Appendix 4 has some pre-printed labels that you can cut out and glue to the board.



Now remove the discrete components and carefully turn the board over. Cut out the labels in Appendix 4 and glue them underneath the appropriate sockets. A knife and tweezers are helpful for placing the labels. Also, double check to make sure you have the orientations correct.

3.4.4 How to Wire Wrap

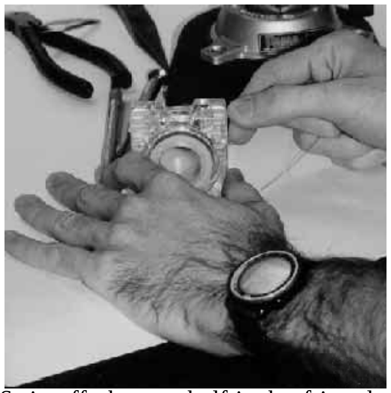
Wire wrapping involves spinning 30-gauge wire onto special sockets with rectangular posts in order to make point-to-point electrical connections. Does that sound simple? Well, actually it is. Wire wrap connections are very reliable and well suited for digital signals.

Some tools you might find useful for wire-wrapping are: tweezers, a wire-wrapping tool, an X-Acto knife, diagonal cutters, needle nose pliers, and a wrapping wire dispenser.

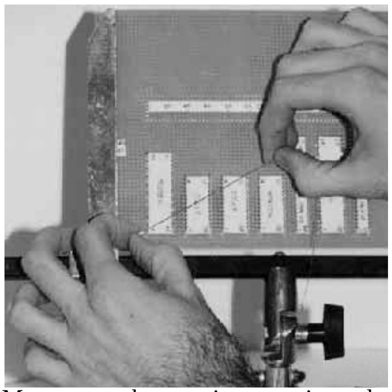
Here is a close-up picture of the wire-wrapping tool that Radio Shack sells. It's a manual tool which is very reliable. Also, hidden in the handle you will find a handy wire stripper.

If you shop around you will find that there are many varieties of wire-wrapping tools available. Some tools will dispense, strip and cut the wire automatically for you and some are also motorized to spin the wire for you. I personally use a manual tool because it is inexpensive and yields very reliable results.

Here is a step-by-step description of wire-wrapping:



1. Strip off about a half-inch of insulation from the end of the spool of wire.

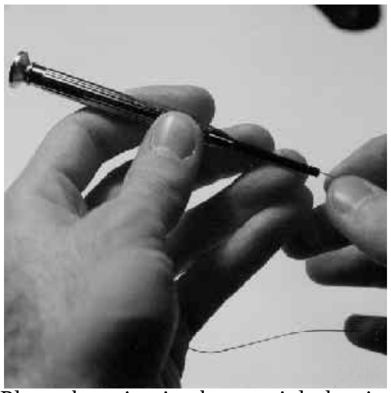


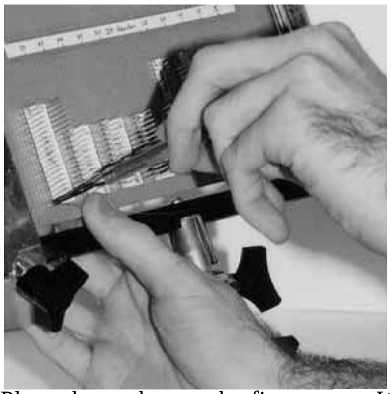
2. Measure the point-to-point length needed, keeping in mind an extra half-inch plus some slop.

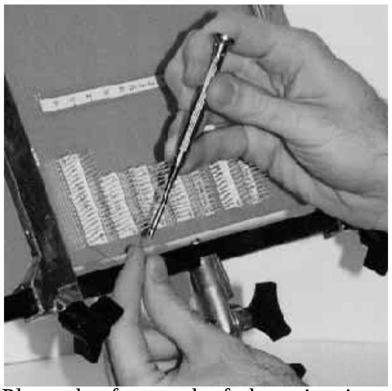
3. Mark the length with your fingernail.

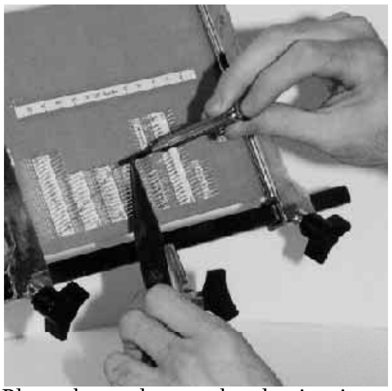
4. Cut the wire.

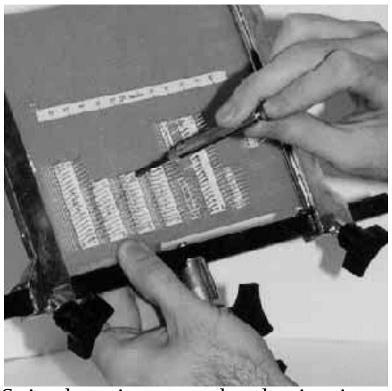
5. Strip off a half-inch of insulation from the other end using some needle nose pliers.

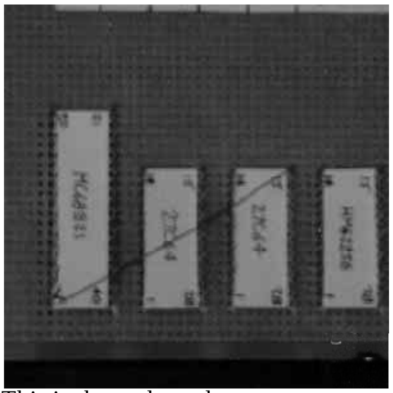

6. Place the wire in the special slot in the tool with about an eighth-inch of insulation inside of the tool. Bend the wire at a right angle at the tip of the tool.


7. Place the tool over the first post. With the forefinger of your free hand, hold the socket to the board and with your thumb, hold the wire taught. Turn the tool in one direction until all of the bare wire is spun onto the post.
Now, while holding the socket, give the turns a push with the tool. This will eliminate the gap between the turns and the board, mechanically holding the socket firmly to the board.


8. Place the free end of the wire into the tool the same way as before, with about an eighth-inch of insulation inside of the tool.


9. Place the tool over the destination post and pull the wire taught with some pliers. Be careful not to break the wire.


10. Spin the wire onto the destination post and give it a press when your done.



11. This is the end result.

To correct a mistake, you can spin the tool in the opposite direction which removes the wire. Be careful though not to inadvertently unwrap any wires underneath.

Here are some handy tips to follow when wire-wrapping:

- There should be about 1 turn of insulation and about 4 turns of bare wire wrapped around a post.
- While spinning wires onto a post, be sure not to oppose the direction of wires already tied there.
- Try not to tie too many wires to a single post. Four connections to a single post is about the limit while two connections is the average.
- A nice straight connection usually works best. It may take a few trys to thread the wire to its destination. Tweezers help for doing this.
- Try not to force the tool when you are spinning it because the wire may break and you will have to start over. With a little practice, you will find that a light touch works best.
- When wiring the discrete components, cut the leads to about 1/2 inch long.
- Be careful not to twist and break the leads of a discrete component.
- Do **not** solder the chip connections! Soldered wire-wrap connections are impossible to remove if a mistake has to be corrected or if a repair is needed. The wire-wrap connection alone is strong enough to last 10-20 years.
- Do **not** cut the wire wrapping pins if you can help it. Again, corrections and modifications are easier to make if you leave the posts intact.

- Do solder the discrete component connections. Discrete component connections usually require some soldering since the leads are rounded, unlike the rectangular wire-wrapping posts. As a result, there are no edges for a wire to grip on to. A 15 watt soldering iron with a small tip does a good job in this case.
- Don't ruin your eyes. Use a magnifying glass and good lighting when you work

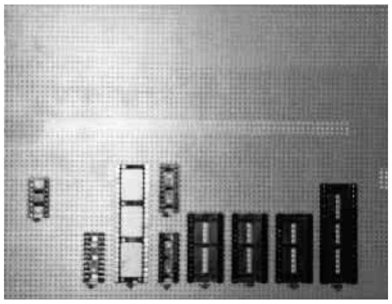
Wire-wrapping can be a juggling act at times, but you will get used to it and come across many tricks and shortcuts as you progress.

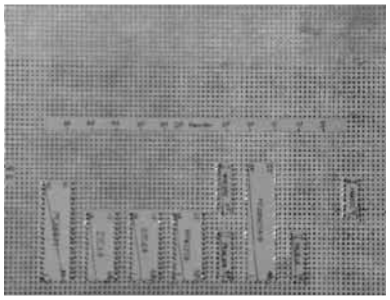
3.4.5 Wiring the Board

Now it's time to do some wiring. While you are wiring the computer, you will have to refer to the schematic diagram in Appendix 3. The schematic diagram depicts all of the connections that must be made. It will be helpful to mark the connections on the schematic with a red pencil as you wire them.

Before wiring, cut the leads of the discrete components to be 1/2 inch long.

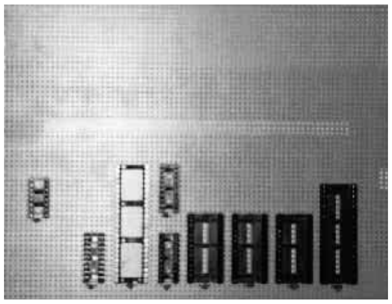
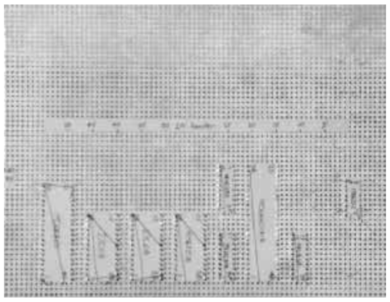
Here is a step-by-step description of the wiring:



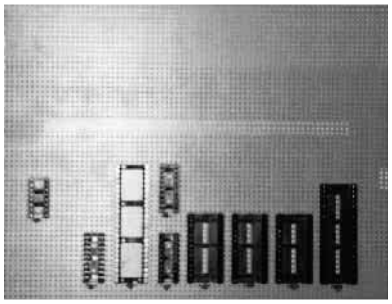
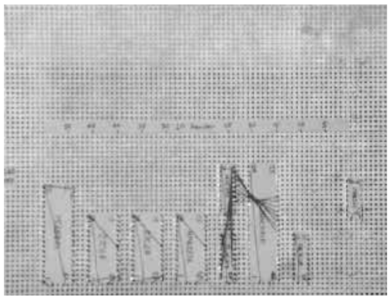


1. **Wire the Bypass Capacitors -** Wire a 0.1µF tantalum bypass capacitor to the power connections of all nine chips. The power connections for each chip are listed in the table on the schematic diagram. The bypass capacitors will help filter switching transients from the power lines. Since the tantalum capacitors are polarized, be sure to wire the plus lead to the Vcc connection and the other lead to ground.

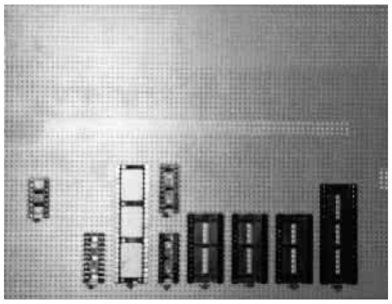
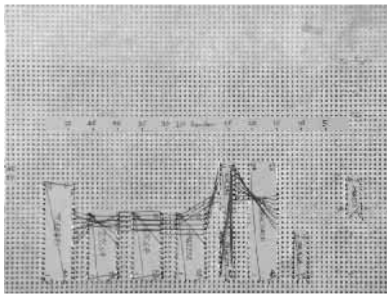
   When you spin the wire around each lead, be extra careful not to twist and break the lead off. Also, the connection to the capacitor won't be as good as the connection to the chip since the leads on the capacitor are round with no edges for the wire to grip on to. When we're done with the whole computer and see it working, we can solder the capacitor connections for extra reliability. For now though, don't solder anything just in case you need to make corrections.

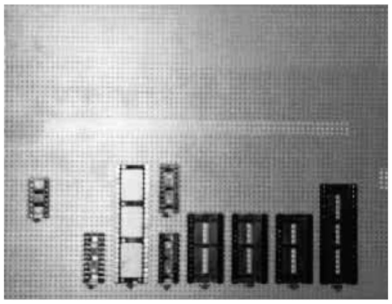
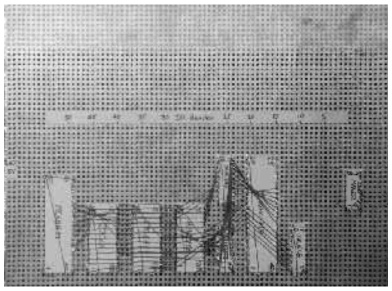
2. **Wire the Internal Connections -** The internal connections in this case are the leads which are grounded or pulled high. The 74HC373, the PAL16L8, the 27C64s, the HM62256 and the MAX232 all have internal connections.

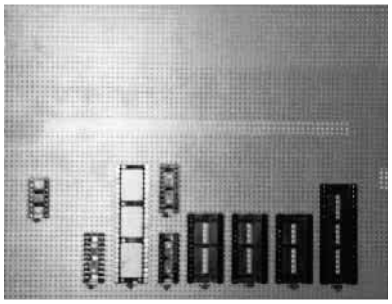
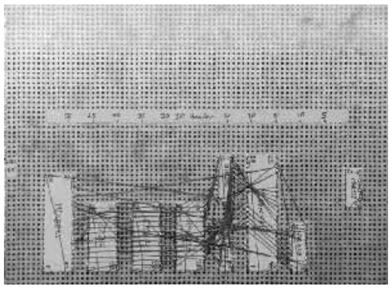
3. **Wire the Multiplexed Address/Data Bus -** These are the lines labeled AD0 through AD7 which connect the MC68HC11 to the 74HC245 and 74HC373.

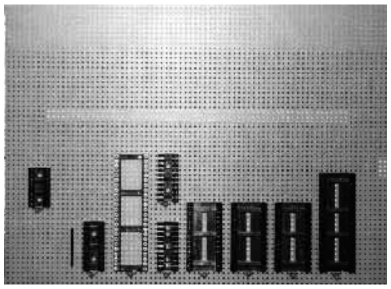
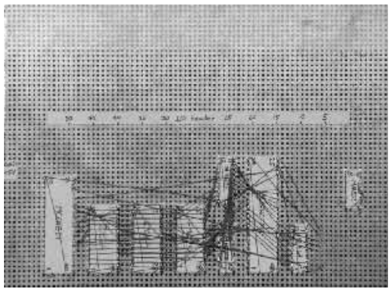
4. **Wire the Data Bus -** These are the lines labeled D0 through D7. The Data Bus connects the 74HC373 to the 27C64s the HM62256 and the MC68B21.

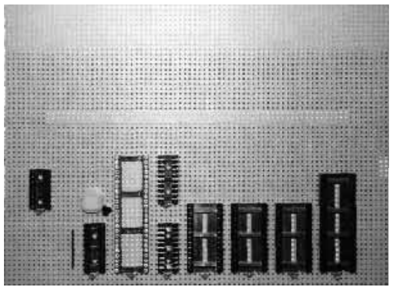
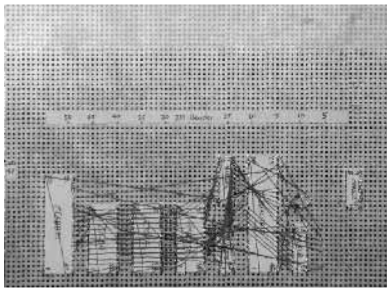
5. **Wire the Address Bus -** These are the lines labeled A0 through A15. The lines A0 through A7 originate with the 74HC373 and go to the 27C64s the HM62256 and the MC68B21, while the lines A8 through A15 originate with the MC68HC11 and go to the 27C64s the HM62256 and the PAL16L8.

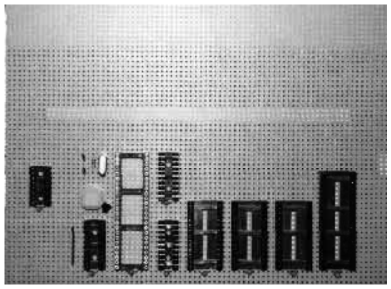
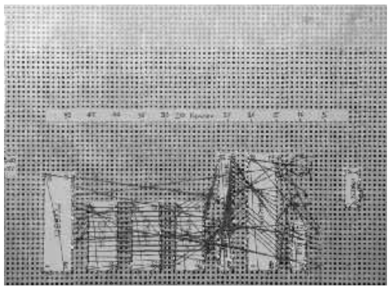
6. **Wire the Control Bus -** The signals in the control bus include *RESET, AS, E, R/*W, *BOOT, *SPARE, *RAM and *PIA1.

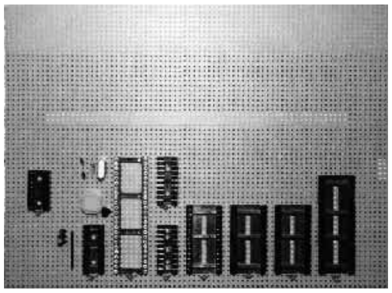
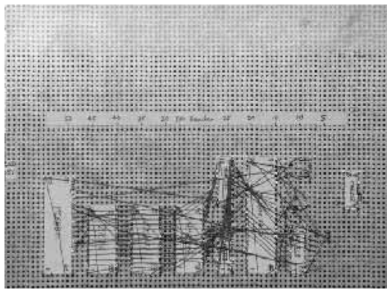
7. **Wire the 4.7kΩ Resistor Pack -** These connections go to the MC68HC11. Be careful, the pins are short and fragile. We'll solder the connections later. The pin with the dot above it is the common which goes to Vcc. You can use tweezers to manually wrap the wires to the resistor pack. Alternately, you can wire the pins first, then thread the wires through the board. In that case, you may need to drill the holes out a little.

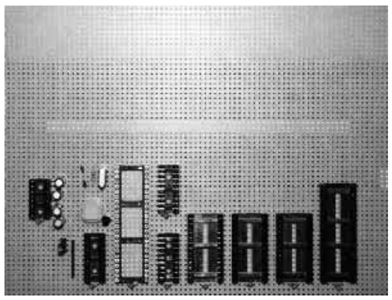
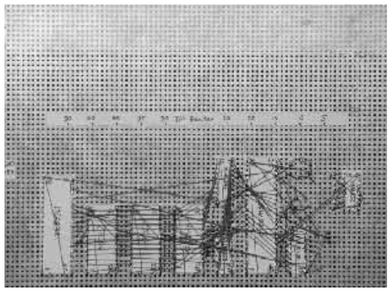
8. **Wire the Reset Circuit -** Use a resistor in the 4.7kΩ resistor pack for the pull-up resistor. A bead of solder on each pin of the push-button will mechanically secure it to the board. Be careful not to burn any of the wires.

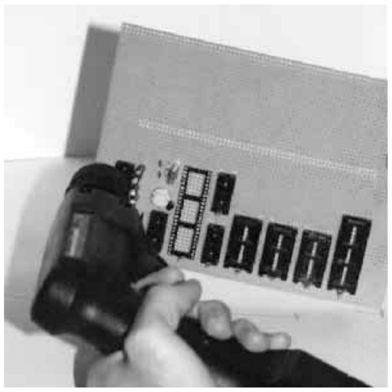
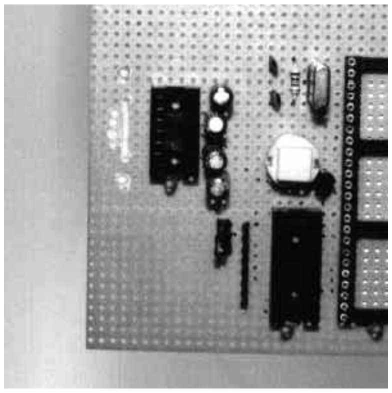
9. **Wire the Crystal Connections -** This includes wiring Y1, R2, C11 and C12 to the MC68HC11.

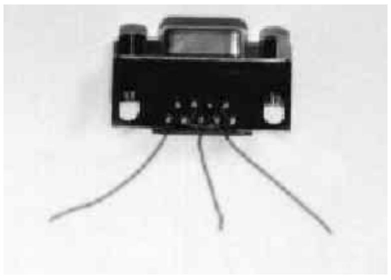
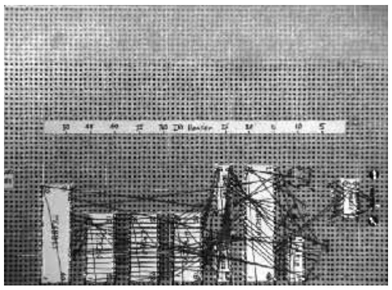
10. **Wire the J4 jumper -** Cut off a 3x1 section of the header connector. Unbend the right-angle pins so that they are straight. This will give us some extra long pins to wire wrap to.

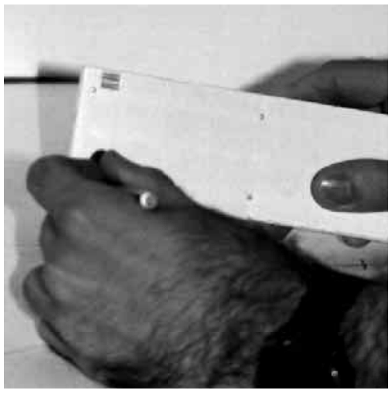
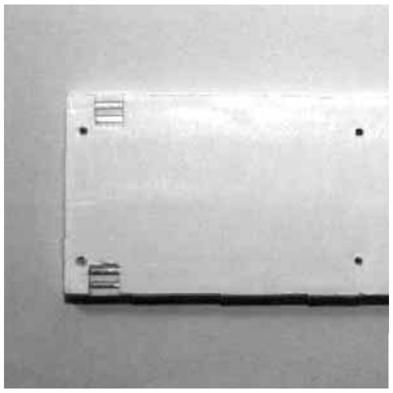
11. **Wire the MAX232 -** Wire the capacitors to the MAX232 and wire the MAX232 to the micro.

12. **Drill and Cut the Holes for the DB-9 Connector -** Since the row of five pins on the connector aren't aligned with the perfboard, we need to cut a slot for them. Also, drill out the two mounting holes.

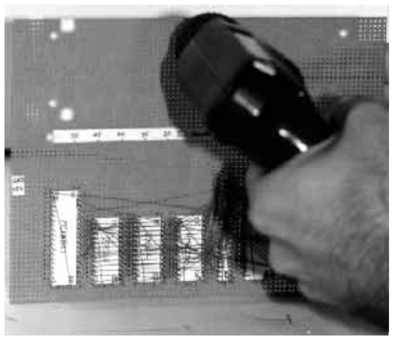
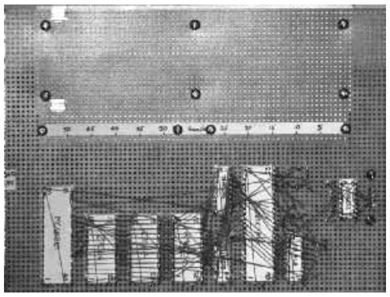



13. **Mount and Wire the DB-9 Connector -** Connect the DCD, DSR, CTS and DTR lines together. Also, prewire the TxD, RxD and GND lines with some wire of an appropriate length. Now thread the three loose wires through the perfboard, screw the DB-9 connector to the perfboard and wire the connector to the MAX232.

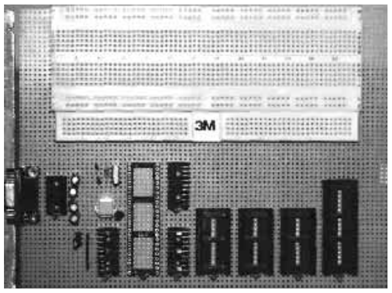
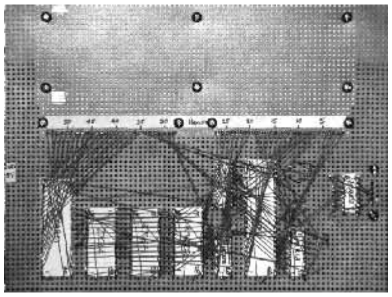



14. **Prepare the Wireless Breadboard -** Cut off two small rectangles of the foam backing of the wireless breadboard behind the top and bottom power strips. Four metal strips should be exposed, two on the top and two on the bottom. We will use these openings to wire power directly to the bread board. The photograph in Step 15 shows the recommended orientation for the holes.

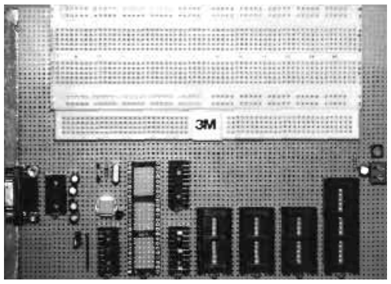
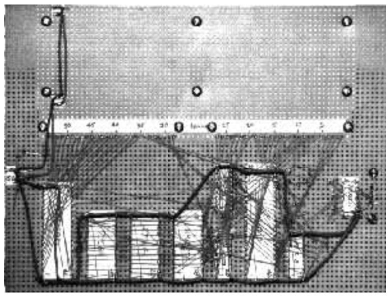
    One thing to keep in mind is that the power strips on the breadboard are actually divided in half. In other words, the strips don't connect all the way across. An easy solution is to put small jumper wires in the top of the board.

15. **Mount the Breadboard and Terminal Strip -** Drill all the mounting holes for the solderless breadboard and the terminal strip. Also, drill and cut the two holes for the power connections to the breadboard. Screw on the breadboard and terminal strip.

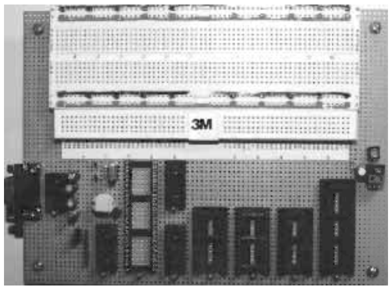
16. **Wire the Terminal Strip -** The connections to the terminal strip are arbitrary. A recommended series of signals to bring out is listed on the label in Appendix 4.

17. **Wire the Power Connections , Power Connector and LED -** Use heavier gauge wire for the power busses. Wire the power busses on the breadboard. You might want to paint the power busses on the breadboard so that you remember the polarity.

The final step in construction is to solder the discrete components. Using a 15W iron with a small tip, place a small bead of solder on the discrete component connections. After soldering the discrete components, you can cut their leads shorter. Again, do **not** cut or solder the chip sockets. It's a good idea that you wait before doing any soldering until after the testing stage when you are sure that the computer is working.

Additionally, it would be a good idea to add some standoffs to the corners of the board. Machine screws work good for this purpose. Alternatively, you can mount it in a box to protect the wiring. You might want to hold off on mounting the computer until after the computer is tested out though.



Wow! That was a lot of work! Now it's time to test the computer out.

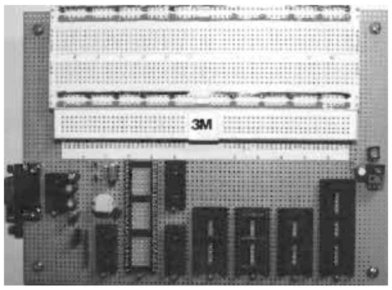
4 Testing the Computer

Now let’s test the computer and see if it works. The testing stage is an opportunity where you can learn the most, so try not to get frustrated if everything doesn’t work the first time. Every problem that you face can be conquered with a little patience and the success will be rewarding and educational. Turn on your detective skills. The process of elimination will illuminate many hidden problems.

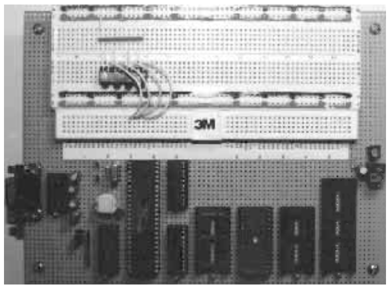
While you are testing, check for obvious errors. For example, go through and double check your connections with a continuity tester. Sometimes a broken or shorted connection is not visible to the naked eye. Remember, a single miswired connection can have bad effects. Here is a common sense checklist to keep in mind during the testing:

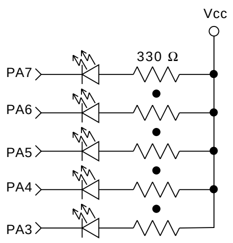
- Is the power on? Check the power light.
- Is the power supply set to +5 VDC? Be careful not to supply a high voltage to the computer because that will damage the chips. On the other hand, if the power supply voltage is too low (<4 V) the LVI chip will activate holding the computer in a Reset state.
- Are any chips loose? Check to make certain that each chip is firmly plugged in.
- Is a pin bent under? Sometimes a chip’s pin can be bent underneath when inserting the chip into its socket causing the pin not to make contact.
- Is a chip plugged in backwards or wired backwards?

Here is a step-by-step procedure for testing the computer:



1. Check for shorts in the power buss with a continuity meter. If you use an ohmmeter to check for continuity, keep in mind that the filter capacitors will charge up giving you a changing reading. Now hook up a +5 VDC power supply to the computer. With no chips installed, power the computer and check each socket for power with a voltmeter. Make certain that you read +5 VDC at the correct polarity.





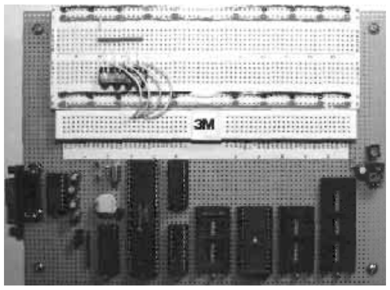
2. Turn off the power and plug in the MC68HC11, the Test ROM, the 74HC373, the 74HC245 and the PAL16L8. The Test ROM should be plugged into the

Boot ROM socket. Also, wire five LEDs to PA3 through PA7 of the MC68HC11.

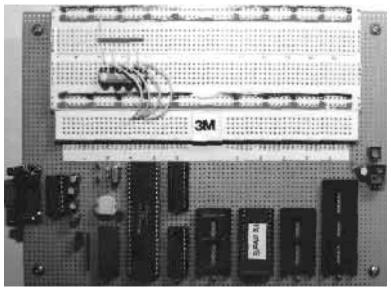
It's time to perform a smoke test. A smoke test is simply a test where you turn on the project and check for smoke. After you turn on the computer, feel each chip to make sure that none are getting hot. This could indicate a backwards power connection. Keep one hand on the power switch and be ready to turn off the power at the first sign of trouble.

Now check the LEDs. Are they blinking? Is the program running? If not, it's time to do some troubleshooting.

- Is the EPROM programmed properly?
- Is the PAL programmed properly?
- Is the crystal oscillator running? Check the E clock signal on an oscilloscope and look for a 2 MHz square wave.
- Is the Reset line high? Try pressing the Reset button and see if the program starts running.



3. Don't disconnect the LEDs yet. Turn off the computer and plug in the MAX232 chip. Power up the computer again and perform another smoke test. Make sure that the MAX232 is not getting hot. Using a voltmeter, check pin 2 of the MAX232, it should be +10 VDC with respect to ground. Now check pin 6, it should be -10 VDC with respect to ground. Also, make certain that the test program is still running.



4. For this step you need a serial terminal program for your personal computer. Turn off the project, remove the Test ROM and plug the BUFFALO ROM in its place (don't plug the ROM in backwards). Also, make certain that the J4 jumper is grounded.

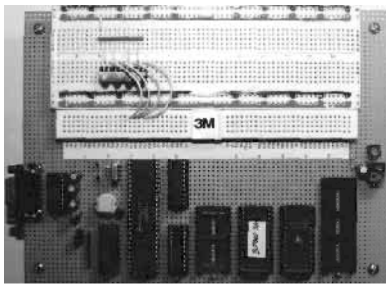
   Hook up the computer to the serial port on your personal computer. Set the serial terminal program to 9600 Baud, 8 Data Bits, No Parity, 1 Stop Bit and No Handshaking.

Now power up the computer and perform another smoke test. Did you get a BUFFALO prompt similar to the one below? Try hitting the Return key on your personal computer.

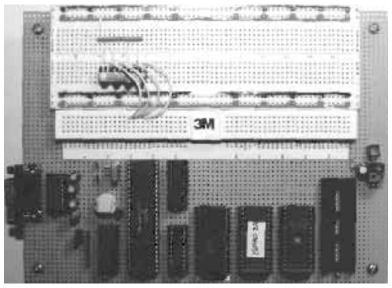
```
BUFFALO 3.4 (ext) - Bit User Fast Friendly Aid to Logical Operation
```

If nothing happened then:

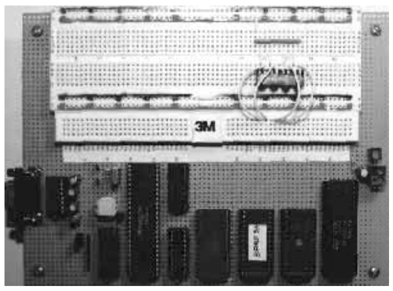
- Is the DB-9 connector wired properly?
- Do you see a data transmission every time you hit the Reset switch? You can check for this by placing an oscilloscope on the transmit pins, 10 and 7 of the MAX232 and pin 43 of the MC68HC11.
- Did you plug in the right ROM (BUFFALO)?
- Are you connected to the correct serial port on your personal computer?
- Do you have a good connection between the two computers?

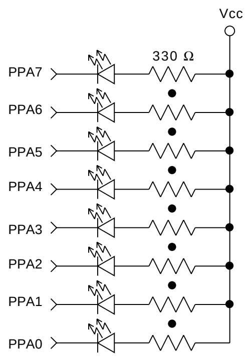


5. Turn off the computer and plug the Test ROM into the Extra ROM socket. Turn the computer back on and perform another smoke test. Now from BUFFALO type: `go C000 [ENTER]`. Are the LEDs blinking? To stop the program press the Reset button. Now, try disassembling the test program. Type: `asm C000 [ENTER]`. Hit `[ENTER]` to advance to the next line. To exit the disassembler type: `[Control-A]`.

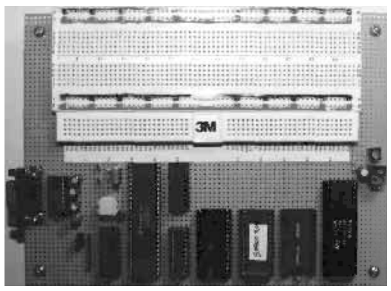


6. Turn off the computer and plug in the HM62256. Turn the computer on and perform the smoke test as usual. Using the BUFFALO Block Fill command, try to write to locations in the RAM. Type: `bf 7000 7100 AA [ENTER]`. Now type: `md 7000 [ENTER]`. Were you successful writing to the RAM? Also, try running the test program. Is it still working?





7. Turn off the computer and plug in the MC68B21. Wire eight LEDs to the PIA. Perform the usual smoke test. Run the test program. Are the LEDs blinking?



Congratulations! You have just built your own working computer from scratch.

5 Using the Computer

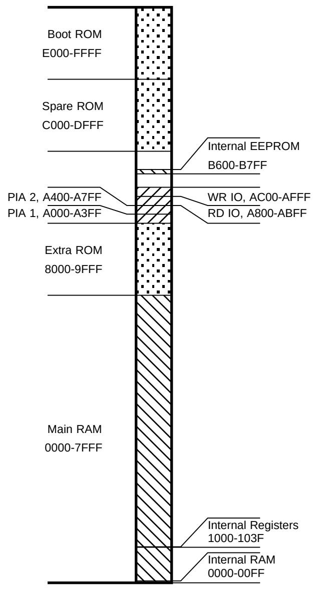
Now that the computer is finished you can start putting it to use. This section will describe what is required to program your new computer.

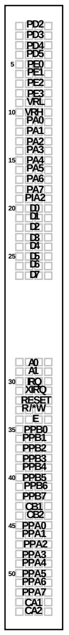
In addition to reading this section, read through the MC68HC11A1 data book, the MC6821 data sheet and the M68HC11EVB Evaluation Board user's manual. These documents cover a lot of information not dealt with here.

Our computer was designed to be similar to the Motorola MC68HC11 Evaluation Board (EVB) which you may be familiar with. Nonetheless, our board has many differences from the EVB, so keep this in mind when you are programming. This section will cover what those differences are.

5.1 Programming

When you are programming your computer, the most important thing to be aware of is the memory map. The Chip Select PAL divides up the 64 kB memory space among the external memory and peripherals while the MC68HC11 handles the addressing of its internal devices. When there is an address space conflict between the internal and external devices, the internal devices have priority. In the memory map drawn below, you can see that the internal RAM and Control Registers overlap the 32 kB of external RAM.





Use this memory map to plan the organization of any hardware and software that you add to the computer.

The MC68HC11 has a large number of on-chip peripherals to take advantage of. The MC68HC11 data book describes how to program the on-chip peripherals.

5.1.1 Using BUFFALO

The BUFFALO monitor program will allow you to do most of your program development. In BUFFALO you can view and modify memory and registers, assemble and disassemble programs, and perform advanced debugging. The most important feature of BUFFALO is its Load command. It allows you to download Motorola Hex (.s19) files to the computer's RAM through the serial port. Here is a procedure for using BUFFALO in your program development:

1. Write the source code.
2. Give the source code a base address somewhere in the RAM's address space between $0000 - $7FFF (watch out for the MC68HC11's Control Registers).
3. Cross-compile your program as an .s19 file.
4. At the BUFFALO prompt, type: `load t [ENTER].` Now BUFFALO will wait to receive a .s19 byte stream over the serial port. Use your terminal emulator program to send the .s19 text file to BUFFALO.
5. If everything goes well, BUFFALO will print the message: `done` and provide the command prompt again.
6. You can now run your program by using the go command.

If you forget a command in BUFFALO, typing: `help [ENTER]` will display the list of commands. The EVB manual has detailed descriptions of the other BUFFALO commands.

5.1.2 Programming Your Own ROMs

You can write your program to fit in a boot ROM. First you have to place the program in the space between $E000 - $FFFF and place a jump vector to your program in the address $FFFE. When your new ROM is programmed you must physically remove the BUFFALO ROM and replace it with your new ROM. Subsequently, your new program will run every time the computer is turned on.

Alternately, you can use the Spare ROM socket for your program. In this case you must place your program within the space $C000 - $DFFF. This time though, you won't be able to modify the Reset jump vector to jump to your program. You can either run your program from the BUFFALO prompt, or pull the J4 jumper high to tell BUFFALO to jump to the first location of the MC68HC11's internal EEPROM at $B600. Then you simply need to put a jump instruction at $B600 to call your new program. Keep in mind that the Spare ROM socket is for your use and can be left empty most of the time.

Most of the time though, you will be loading your program into the computer's RAM and executing the program from there. The advantage of this is that you will be able to rapidly change your program and try it out. The disadvantage is that the program will disappear when the computer is turned off.

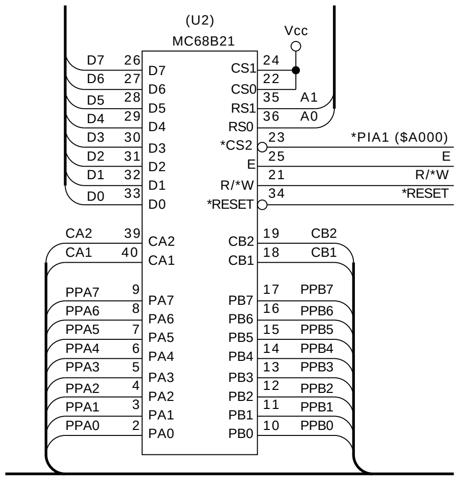
5.2 Interfacing

In order to keep the design practical certain built-in resources of the MC68HC11 aren't available on our computer. For example, in this design the pins PD0 and PD1 are used for the serial port and as a result aren't readily available for use as digital I/O. Also, since the BUFFALO monitor program uses PE0 as an input for the J4 jumper, PE0 shouldn't be used for other purposes. Additionally, lines PE4 through PE7 of Port E aren't pinned out on the MC68HC11A1P version used in this design. This is because the DIP (Dual Inline Package) version of the MC68HC11A1 used here doesn't have enough pins to accommodate all of Port E. The pins PE4 through PE7 are only available on the PLCC (Plastic Leaded Chip Carrier) version. The PLCC version wasn't used for this project because it would have been harder to wire by hand. Finally, Port B, Port C, STRA and STRB are unavailable because we are operating the MC68HC11 in expanded mode as opposed to single chip mode. Expanded mode is what allows us to connect external memory like the HM62256 RAM chip and the 27C64 EPROM chip to the microprocessor.

Despite these limitations, expanded mode allows us to add as much I/O to the computer as we require, albeit with a few extra chips required. In this design, the MC68B21 chip augments the available digital I/O. The following sections will describe how to use the MC68B21 and how add even more digital I/O to the design.

5.2.1 How to use the MC6821

The MC6821 Peripheral Interface Adapter (PIA) chip provides bi-directional digital I/O for the 6800 family of microprocessors with a minimum of fuss. The MC6821 has two bi-directional 8-bit data ports along with two handshaking control lines for each port. The handshaking lines allow each port to be used as parallel communication ports.



Internally, the MC6821 has six registers for operating the chip, three registers for Port A and three registers for Port B. When RS1=0 the Port A register set is selected and when RS1=1 the Port B registers are selected. When RS0=1 the Control Register for the given port is selected. When RS0=0 the register that is accessed depends on bit 2, the DDR Access Bit, of the Control Register. If the DDR Access Bit is 0, the Data Direction Register is selected. If the DDR Access Bit is 1, the Peripheral I/O Register is selected.

The MC6821 Control Register

b7	b6	b5	b4	b3	b2	b1	b0
IRQ A(B) 1 Flag	IRQ A(B) 2 Flag	CA2 (CB2) Control			DDR Access	CA1 (CB1) Control	

The Data Direction Register for each port allows any of the lines on a port to be configured as inputs or outputs. A zero bit will configure a line as an input while a one bit will configure the line as an output. Similarly, the Peripheral I/O Register allows you to read from and write to the I/O ports.

A simple procedure for programming a port on the MC6821 is to:

1. Set the DDR Access Bit in the Control Register to 0.
2. Program the Data Direction Register.
3. Set the DDR Access Bit in the Control Register to 1.
4. Access the Peripheral I/O Register to read and write the I/O port.

This procedure applies for both Port A and Port B. Once you have programmed the Data Direction Register, you probably will want to leave the DDR Access Bit set to 1 for the rest of the program.

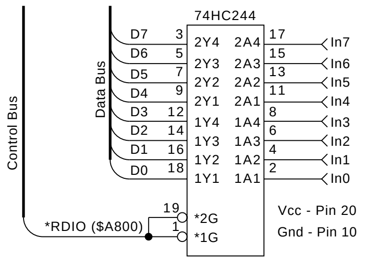
Here is a code snippet which demonstrates how to program the MC6821:

```
clr  $A001   Set the DDRA Access Bit to 0.
clr  $A003   Set the DDRB Access Bit to 0.
ldaa #FF
staa $A000   Set all bits on Port A to output.
ldaa #0F
staa $A002   Set upper bits of Port B to input and lower bits to output.
ldaa #04
staa $A001   Set the DDRA Access Bit to 1.
staa $A003   Set the DDRB Access Bit to 1.
ldaa #FF
staa $A000   Turn on all of the bits on Port A.
ldaa $A002   Read Port B.
```

Check the MC6821 data sheet to find out how to use its more advanced features.

5.2.2 Adding a Basic Input Port

If you need digital inputs, the following one chip circuit will do the job,



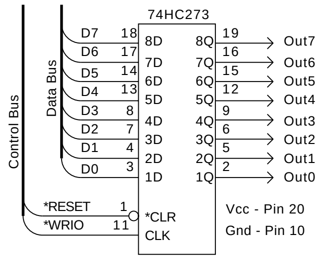
To read the current state of the input lines simply perform a read from the address $A800. The following line of assembly language will read the values of the eight input lines into the A register:

```
ldaa $A800
```

This circuit can apply to other type of digital input that you would want to connect to the computer, such as an analog-to-digital converter.

5.2.3 Adding a Basic Output Port

Here is a circuit similar to the previous one which provides eight digital outputs to the computer,



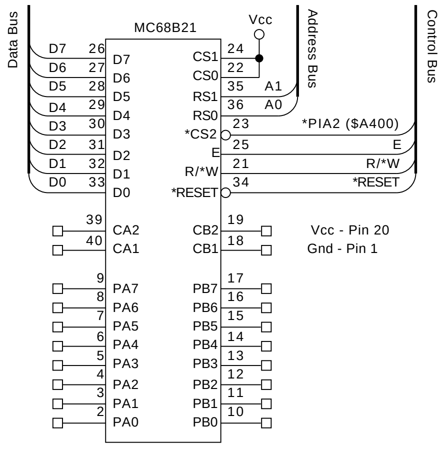
A simple write to the address $AC00 will change the states of the outputs. The following two lines of assembly language show how to do this:

```
ldaa #AA
staa $AC00
```

You can of course use this circuit as an example for connecting other types of output devices to the computer.

5.2.4 Adding More PIAs

If you require more sophisticated I/O, you can add more PIAs to the computer. Simply plug the new PIA into the breadboard and wire it directly to the data bus through the terminal strip. The only difference between the second PIA and the original one is that the *CS2 pin of the new PIA is connected to the *PIA2 signal. This means that the base address of the new PIA begins at $A400 instead of $A000.



Now you have two extra bi-directional ports to work with. Similarly, you can add as many PIAs to the computer as you need, keeping in mind that there are only a finite number of unused address locations available.

6 Conclusion

I hope this was a great learning experience for you. When I built my first computer it was pretty frustrating. Part of the frustration was due to the complexity of the computer and part was due to errors in the instructions. I hope that I've at least eliminated those two variables for you. Nonetheless, after a lot of struggling I was able to get the computer working and learned a lot in the process.

I'm sure you will get much use out of your new computer and I know there will be more home-built computers in your future. Just think, ten years from now you will look back fondly to this experience.

References

[1] Ciarcia, Steve and Burt Brown. “Using the Motorola MC68HC11.” *Circuit Cellar INK* 18 (1990): 36-48.

[2] Farmer, Brian. “Planting Geraniums by Robot / Build an MC68HC11-based 2-D Sensor.” *Circuit Cellar INK* 29 (1992): 12-21.

[3] Greenfield, Joseph D. *The 68HC11 Microcontroller*. Orlando, FL: Saunders College Publishing, 1992.

[4] Motorola Inc. *MC68HC11A8 Technical Data Book* (Lit. No. MC68HC11A8 / D). Phoenix, AZ: Motorola Inc., 1991.

[5] Motorola Inc. *MC6821 Peripheral Interface Adapter Data Sheet* (Lit. No. MC6821 / D). Phoenix, AZ: Motorola Inc., 1985.

[6] Motorola Inc. *M68HC11EVB Evaluation Board User’s Manual* (Lit. No. M68HC11EVB / D1). Phoenix, AZ: Motorola Inc., 1986.

[7] Olney, Bruce L. “Inexpensive 68HC11 Cross-development.” *Circuit Cellar INK* 44 (1994): 22-29.

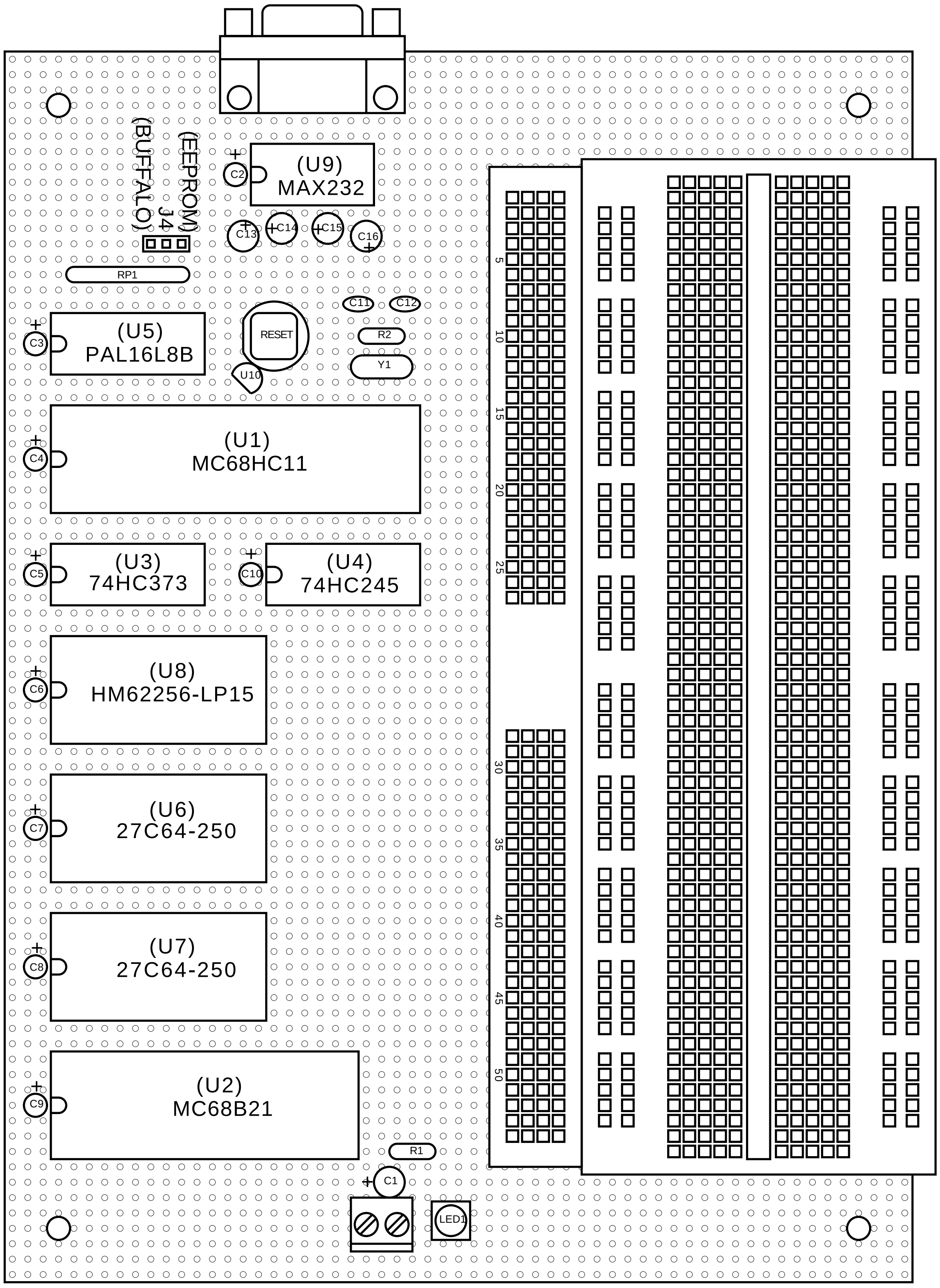
[8] Swiger, Frank and Joe Glover. “The FS-100 MC68HC11-Based Single-Board Computer.” *Circuit Cellar INK* 24 (1991): 52-59.

Appendix 1 - Master Parts List

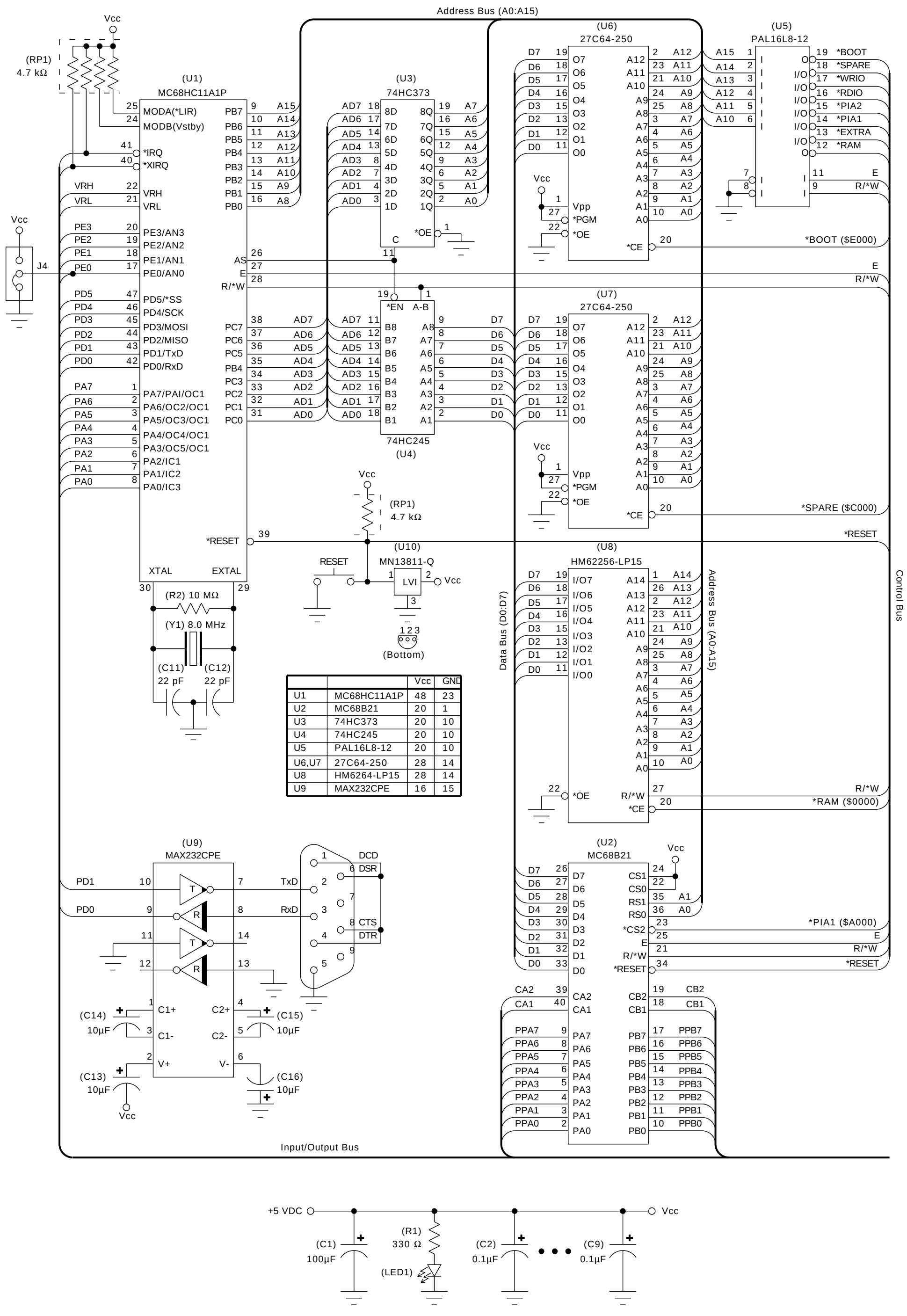
This is the master parts list for the prototype computer that was built. The quantity, manufacturer, manufacturer part number and general description is shown. Specific manufacturers aren't listed for easy to find generic parts.

#		Part Description	Part No.	Manufacturer
1	U1	8-bit HCMOS MCU	MC68HC11A1P	Motorola
1	U2	PIA 2 MHz	MC68B21	Motorola
1	U3	Octal Tri-State D Type Latch	74HC373	
1	U4	Octal Tri-State Transceiver	74HC245	
1	U5	PAL 16L8B 15ns	16L8B	
2	U6, U7	8kx8 ≤250ns EPROM	27C64-250	
1	U8	32kx8 ≤250ns Static RAM	HM62256LP-10	
1	U9	+5V Powered Dual RS-232 Trans./Rcvr.	MAX232CPE	Maxim
1	U10	3.8V O.D. Low Voltage Detector	MN13811-Q	Panasonic
1	Y1	8.0 MHz Crystal		
1	RP1	4.7 kΩ SIP 7 Resistor Network		
1	R1	330 Ω 1/4 W Resistor		
1	R2	10 MΩ 1/4 W Resistor		
1	C1	100 µF Radial Electrolytic Capacitor		
4	C13-C16	10 µF Radial Electrolytic Capacitor		
2	C11, C12	22 pF Ceramic Capacitor		
9	C2-C9	0.1 µF Tantalum Capacitor		
1		Right Angle PC Mount Female DB-9 Connector		
1	J4	Shorting Jumper Block		
1	J4	1x3 WW Header Pins		
1		16-Pin DIP WW Socket 3-Level		
3		20-Pin DIP WW Socket 3-Level		
3		28-Pin DIP WW Socket 3-Level		
1		40-Pin DIP WW Socket 3-Level		
1		48-Pin DIP WW Socket 3-Level	123-93-648-41-001	Mill-Max
1	LED1	PC Board Mount Green LED With Holder	5381H5	Industrial Devices, Inc.
1		SPST Momentary Square Yellow Pushbutton	520-01-2	E-Switch
1		2 Position Terminal Block	ED1609	On-Shore Technology, Inc.
1		6"x8" IC-Spacing Perfboard	276-1396	Radio Shack
1		6.5" Solderless Breadboard w/Power Busses	923252	3M
1		54 Point Terminal Strip with Solder Tails	923292	3M
1		Male-Female DB-9 Cable (2m)	AK131-2	Assmann
1		Wrapping Wire, 50' Spool		

Appendix 2 - Suggested Board Layout

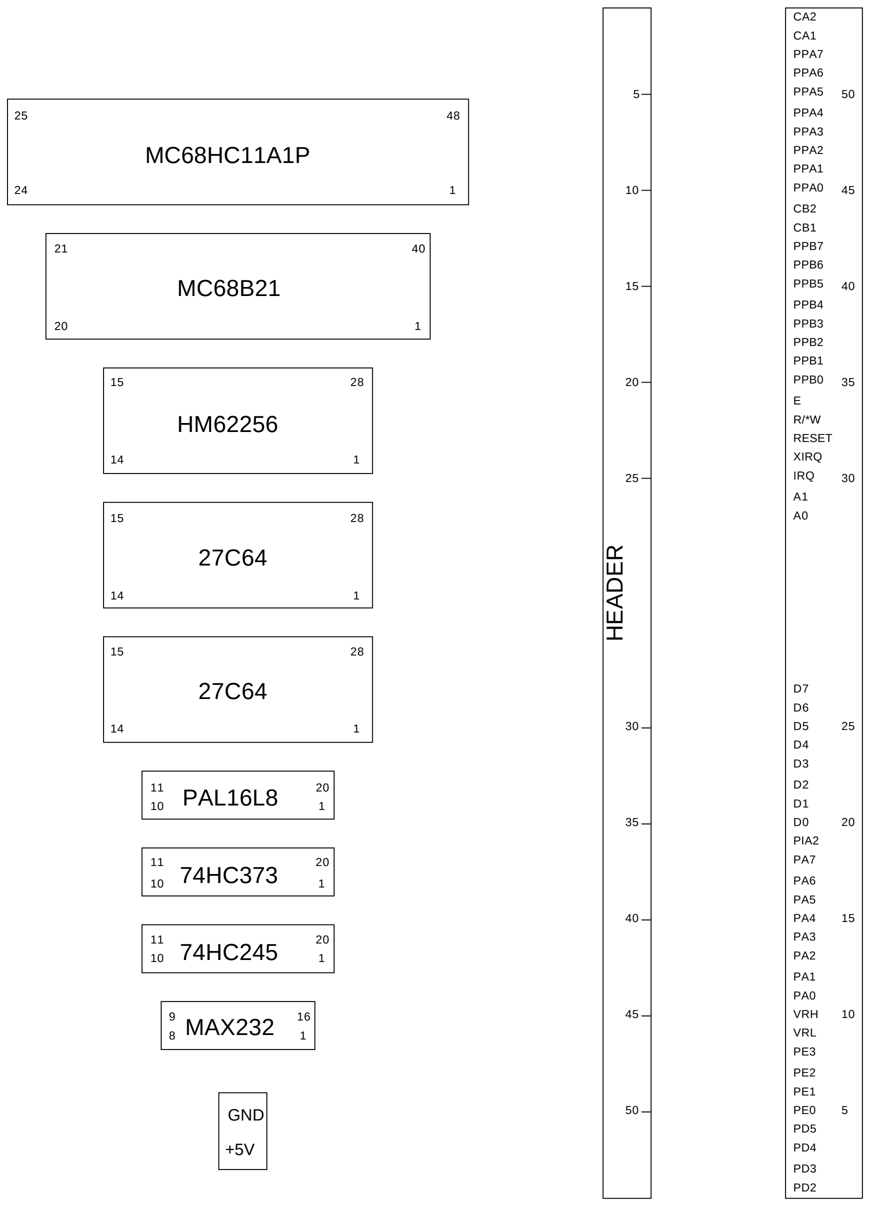


Appendix 3 - Schematic Diagram



		Vcc	GND
U1	MC68HC11A1P	48	23
U2	MC68B21	20	1
U3	74HC373	20	10
U4	74HC245	20	10
U5	PAL16L8-12	20	10
U6,U7	27C64-250	28	14
U8	HM6264-LP15	28	14
U9	MAX232CPE	16	15

Appendix 4 - Wire Wrapping Labels


25
48
MC68HC11A1P
24
1
21
40
MC68B21
20
1
15
28
HM62256
14
1
15
28
27C64
14
1
15
28
27C64
14
1
11
10
PAL16L8
20
1
11
10
74HC373
20
1
11
10
74HC245
20
1
9
8
MAX232
16
1
GND
+5V
HEADER
5
10
15
20
25
30
35
40
45
50
CA2
CA1
PPA7
PPA6
PPA5
PPA4
PPA3
PPA2
PPA1
PPA0
CB2
CB1
PPB7
PPB6
PPB5
PPB4
PPB3
PPB2
PPB1
PPB0
E
R/*W
RESET
XIRQ
IRQ
A1
A0
D7
D6
D5
D4
D3
D2
D1
D0
PIA2
PA7
PA6
PA5
PA4
PA3
PA2
PA1
PA0
VRH
VRL
PE3
PE2
PE1
PE0
PD5
PD4
PD3
PD2
50
45
40
35
30
25
20
15
10
5