



## **The C Programmer's Guide to the QVGA Controller**

***The C Programmer's Guide to the QVGA Controller***

by Mosaic Industries, Inc.

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## How To Use This Book

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Welcome, and thanks for purchasing the QVGA Controller™. This manual provides instructions for using your new embedded computer. The QVGA Controller is a state-of-the-art embedded microcontroller with an advanced operator interface. It's an ideal "brain" for instruments that need a highly visible graphical user interface (GUI), touchscreen control, computational power, I/O, and serial communications – all in one compact package.

Commanded remotely from a PC, or used stand-alone, it provides real-time control of dozens of analog and digital I/O lines. Use it for scientific instruments, machine or process control, or as an advanced operator interface for existing products. Its real-time multitasking operating system facilitates concurrent functioning of its user interface, I/O, and application software. You may use this compact, integrated device as the core hardware, software and user interface for your new products – wherever you need an I/O-rich computer and an advanced user interface.

The QVGA Starter Kit includes everything you need to develop a prototype instrument with an advanced GUI: the QVGA Controller with a monochrome or EL display, battery back-up for 128K RAM memory, a full documentation package, power supply and all cables. For a sleek look you can add a black anodized aluminum bezel. The QVGA Controller can be either flush mounted using the bezel or directly mounted to a panel with a cutout.

### ***Prerequisite Knowledge***

The QVGA Controller is intended for use by experienced programmers or any technically minded person up to the challenge of real-time programming. We assume that if you're designing a product requiring an embedded computer, you have experience in the design of the hardware and software needed to customize the QVGA Controller to your product, and an understanding of the basics of writing, compiling and debugging software programs. You should be comfortable programming in either the C or Forth programming languages; you can program the QVGA Controller in either. This manual is geared to the C programmer. If you would rather program in Forth, give us a call and we'll send you the Forth programmers manual. We recommend the following references for novice programmers:

- *The C Programming Language*, by Kernighan and Ritchie
- *C: A Reference Manual*, by Harbison and Steel

Motorola's *M68HC11 Reference Manual* and *MC68HC11F1 Technical Data Manual* are included with this documentation package as Adobe Acrobat Portable Document Format (\*.pdf) files.

## **How to Use this Documentation**

This manual is laid out in several parts, in an order we hope you find most useful. We have invested a lot of effort to make this documentation instructive and helpful. The available software and hardware functions are all described in detail, and many coded examples are presented. For those who are designing "turnkeyed" instruments, we have included a complete turnkeyed application program. This well documented program illustrates how to use dozens of features, including the graphical user interface, interrupts, floating point math, formatted display of calculated results, multitasking, and automatic program startup. The source code is included on your CD-ROM. This sample program can serve as a useful template for a wide variety of applications. This manual contains the following parts:

**Part 1, *Getting Started: A Quick Tour of the QVGA Controller***, will familiarize you with the QVGA Controller (Chapter 1) and its programming environment, and get you writing your first program (Chapter 2). These first two chapters guide you through the QVGA Controller's hardware, explain how to establish communications with it, tell you how to install your compiler, and show you how to compile and run your first program.

After working through the examples of Chapter 2 you will have exercised some of the key hardware and software features of your controller. You might then leaf through the categorized list at the beginning of the C Function Glossary in an Appendix to get a feel for the wealth of precoded library functions available for you to use.

**Part 2, *Programming the QVGA Controller***, provides everything you need to know to master real-time programming on the QVGA Controller.

**Part 3, *Communications, Measurement and Control***, focuses on the QVGA's hardware resources – A/D, D/A, serial communications, timer-controlled I/O, real-time clock and others – and provides examples for using each.

**Part 4, *Putting It All Together***, introduces a real-time interactive application, and provides code you can use as a template for your application. It also discusses the nuts and bolts of product integration, mounting, noise considerations and power requirements.

**Part 5, *Reference Data***, contains detailed specifications, schematics, dimensions, data sheets and glossaries of C functions available for your use.

## **Conventions Used in This Book**

The following conventions are used throughout this manual:

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## Abbreviations

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A/D	Analog to Digital Converter
COP	Computer Operating Properly timer
D/A or DAC	Digital to Analog Converter
EEPROM	Electrically Erasable Programmable Read-Only Memory, nonvolatile
EL	Electroluminescent Display
FLASH	Flash Programmable Read-Only Memory, nonvolatile and on-the-fly reprogrammable
GUI	Graphical User Interface, also called an MMI (Man Machine Interface) or OI (Operator Interface)
I/O	Inputs and Outputs
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
PIA	Peripheral Interface Adapter (a chip that provides 24 digital I/O signals)
PROM	Programmable Read-Only Memory, nonvolatile one-time programmable
QED	Quod Erat Demonstrandum, or Quick Easy Design, whichever you prefer
QED-Forth	The name of the QVGA Controller's onboard operating system and interactive resident language.
RAM	Random Access Memory, volatile
RTC	Real-Time Clock
RTOS	Real Time Operating System
SPI	Serial Peripheral Interface, a fast bidirectional synchronous serial interface
SRAM	Static Random Access Memory, volatile
UART	Universal Asynchronous Receiver Transmitter

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Throughout this manual the names of code functions and extended code segments are distinguished by their typeface. The following font styles are used:

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## Typefaces

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English Text	Plain text uses a Times New Roman Font
C function names appearing within text	<b>void InstallMultitasker(void)</b>
Forth function names appearing within text	<b>BUILD.STANDARD.TASK</b>
C code in listings	<b>#define FULL_SCALE_COUNTS 256</b>
Forth code in listings	<b>256 CONSTANT FULL_SCALE_COUNTS</b>
Commands typed to the QVGA Controller through a terminal	<b>CFA.FOR main PRIORITY.AUTOSTART↵</b>
QVGA Controller responses to a terminal program	<b>ok</b>

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Code function names and listings use a fixed space font. C code uses a font with serifs, QED-Forth code is sans serif. Terminal commands are indented and followed by a back-arrow symbol representing the enter key on the keyboard, and the QVGA Controller's responses are underlined with a dotted line. Both are indented in the text. Listings of more extensive code examples are set off by indenting and captioning.

Integer numbers are not accompanied by a decimal point; the presence of a decimal point indicates that the number is a floating-point format number. Decimal base numbers are written in standard form while binary numbers are written in hexadecimal (base sixteen, using 0-9 and A-F) and preceded with "0x", for example, the 16-bit integer equivalent of decimal 15,604 is represented as **0x3CF4**

### ***Obtaining Code Examples and Example Applications***

Please check our website periodically at [www.mosaic-industries.com](http://www.mosaic-industries.com), where we'll be posting code examples and example applications, and providing software updates and enhancements.

### ***For Technical Help (or just to chat) Contact Us***

We have tested and verified the sample code in this user's guide to the best of our ability, but you may find that some features have changed, or even that we have made a mistake or two. If you find an error, please call us and we'll fix it pronto.

If you are facing a challenging software hurdle, or a hardware problem in interfacing to our products, please don't hesitate to email or call us. We can often help you over the hurdle and save you a lot of time. So contact us by phone or email:

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[support@mosaic-industries.com](mailto:support@mosaic-industries.com)

We provide free technical help to all registered, licensed users.

# *Part 1*

## *Getting Started*



# Chapter 1

## Chapter 1: Getting to Know Your QVGA Controller

*Congratulations on your choice of the QVGA Controller™. This Chapter introduces the various hardware and software features of the QVGA Controller: the graphical user interface (GUI), touchscreen, processor, memory, I/O, serial communications, RTOS and operating system functions.*

*In this chapter you'll learn:*

- ⇒ *All about the operating system and software features of the QVGA Controller;*
- ⇒ *How to connect to your controller; and,*
- ⇒ *How to configure various options on your controller.*

## Introducing the QVGA Controller

To serve the needs of real-time control, modern embedded computers must have a set of complementary features including operating system software, device drivers, user interface, and I/O. You'll find the QVGA Controller has a set of hardware and software that work together to simplify your product development cycle while bringing new capability to your products. The following subsections discuss the interdependent hardware and software aspects of your controller.

### Real-Time Operating System and Built-In Function Library

You wouldn't want to have to load an operating system into your desktop computer each time you turn it on, and the same holds true for embedded computers. Importantly, all of Mosaic's controllers incorporate a full-time, on-board operating system called *QED-Forth*. QED-Forth is an interactive programmable macro language encompassing a real-time operating system (RTOS), object oriented graphical user interface (GUI) toolkit, debugging environment, and a comprehensive set of pre-coded device drivers.

These built-in functions make it easy for you to get the most out of your board's computational and I/O capabilities. You can fully program the QVGA Controller using only the QED-Forth programming language, or you can program it using only the C language – all of the operating system's functions are accessible using either language.

*This manual describes how to program your QVGA Controller using the Control-C programming language, and how to use the built-in functions. Another manual is available if you*

prefer to program in the QED-Forth programming language. Function glossaries provide an in-depth description of every routine. The QVGA Controller's extensive embedded firmware reduces your time time-to-market – we've precoded hundreds of useful routines so you won't have to.

The RTOS in onboard Flash memory also manages all required hardware initializations and automatically initializes and starts your application code. It provides warning of power failures so you can implement an orderly shutdown, and provides the run-time security feature of a watchdog (COP - computer operating properly) timer.

Programming is a snap using the interactive debugger and multitasking executive. The multitasker allows conceptually different functions of your application run independently in different tasks while all accomplishing their duties in a timely fashion.

## Choice of Programming Languages

You can program the QVGA Controller using either the ANSI-standard C language or Mosaic's QED-Forth language. In either language, you can supplement your high-level code with assembly code. Using either language, you have full access to all firmware functions.

### ***The Control-C Programming Environment***

Our Control-CTM cross-compiler was written by Fabius Software Systems and customized by Mosaic Industries to facilitate programming the QVGA Controller in C. It is a full ANSI C compiler and macro pre-processor; it supports floating point math, structures and unions, and allows you to program in familiar C syntax. Extensive pre-coded library functions provide easy command of the controller's digital I/O, A/D, D/A, keypad, display, high current drivers, serial ports, memory manager, multitasker, and much more.

Using the WindowsTM environment on your PC, you can edit your C program in the supplied TextPadTM editor, and with a single mouse click you automatically compile, assemble and link your program, and generate an ASCII hex file ready for downloading. Clicking in the "Terminal" window and sending the download file to the controller completes the process: you can then type **main** from your terminal to execute your program. The interactive development environment also lets you examine and modify variables and array elements, and call individual functions in your program one at a time with arguments of your own choosing. This interactive environment greatly speeds the debugging process!

### ***QED-Forth High Level Language***

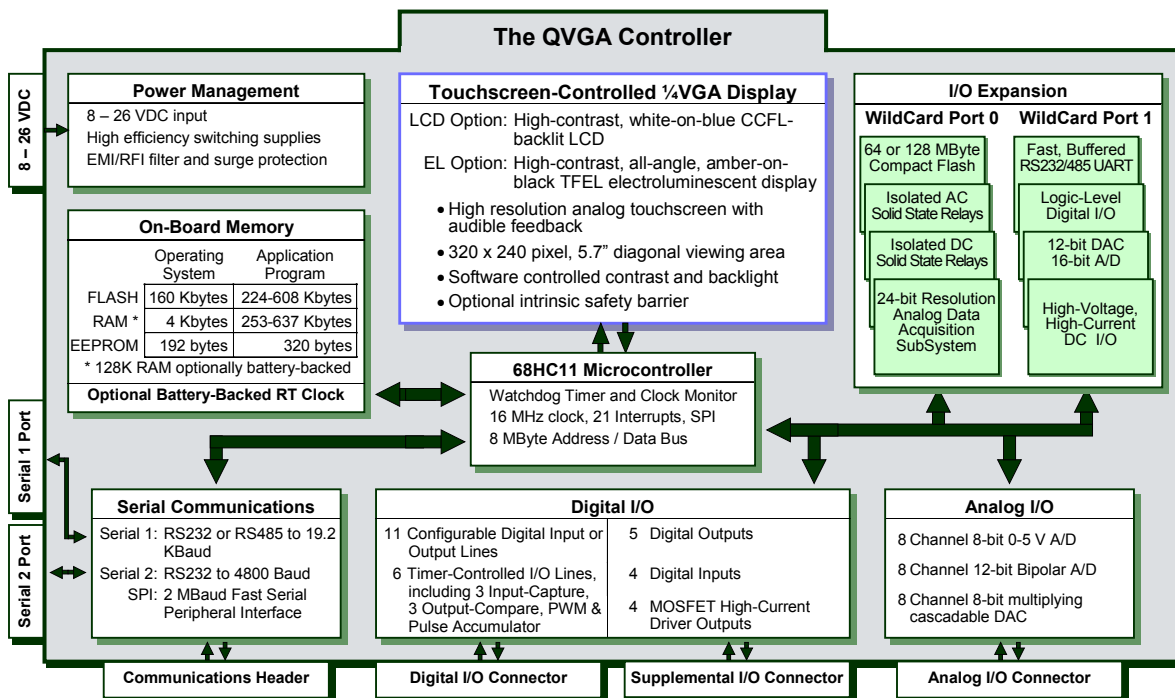
For those who prefer to program in FORTH, no external compiler is needed. You interact with the QED-Forth operating system (an RTOS, interpreter and compiler, all rolled into one) using your PC as a terminal. When programming in Forth you can use the TextPad text editor supplied as part of the Mosaic IDE (or you can use any other editor you prefer) to write your code and download the source code directly to the controller where it is compiled as it downloads. As we will see, even C programmers benefit greatly by the presence of the QED-Forth operating system, as the built-in Forth language provides a quick and easy way to interactively "talk to" your QED Board while debugging your C programs.

## 68HC11 Assembly Code

Both Control-C and QED-Forth include complete in-line assemblers that let you freely mix high level and assembly code. This is sometimes useful when creating specialized time-critical functions such as interrupt handlers.

## Extensive Hardware Functionality

The block diagram of Figure 1-1 provides a cogent summary of the hardware capabilities of the QVGA Controller. Each of the hardware modules shown is described in the following sections.



**Figure 1-1 The QVGA Controller showing up to eight optional Wildcards installed.**

## Power Conditioning and Regulation

The QVGA Controller includes a high-efficiency switching regulator and extensive power line filtering for EMI/RFI isolation. It may be powered by applying any unregulated DC input voltage between 8 and 26 Volts (15-26 V if an EL display is used). If you include the QVGA Controller in a system that already has its own supplies, you may power the QVGA Controller using regulated +5 and +12 V supplies.

If you power the board with an unregulated DC supply, the onboard circuitry is protected by a built-in surge protector and electromagnetic interference (EMI) suppression circuitry. This improves the reliability of the electronics in harsh industrial environments.

## A 68HC11 Processor

The central block in Figure 1-1 represents the 68HC11F1 microcontroller. This chip integrates a central processing unit (CPU), communications, analog and digital I/O, timing capabilities, and memory. It provides the core capabilities of the QED Board. In this document we will refer to the microcontroller chip as the 68HC11F1, or the 68HC11, or simply the HC11.

The processor includes:

- An 8 bit timer-controlled digital I/O port called PORTA. The timer functions include “input captures” that facilitate accurate measurement of pulse widths, “output compares” that make it easy to generate pulse trains and pulse-width modulated waveforms, and a pulse accumulator. These functions are backed up by interrupts that simplify real-time response to external events.
- An 8 channel input port (called PORTE) on the processor that can be configured to read either analog or digital inputs. Analog inputs are converted to an 8 bit digital number by a built-in analog to digital (A/D) converter.
- A built-in serial communications interface (SCI). The SCI is an asynchronous interface, meaning that there is no clock transmitted with the data. Using the SCI, the QVGA Controller can transmit and receive data at standard baud rates to 19200 baud, and at non-standard rates as high as 250 Kbaud.
- A serial peripheral interface (SPI) capable of data transfer rates up to 2 megabits per second. Many useful devices communicate via such a synchronous (clocked) serial interface. Multiple peripheral devices can communicate on this interface as long as each device has a unique chip select signal. As we’ll see, two optional onboard analog devices exchange data with the 68HC11 via the SPI.
- A watchdog timer that can be configured to reset the processor if the application program fails to execute properly.
- A clock monitor available to reset the processor if the clock fails.
- External interrupt request pins and a variety of interrupt functions for quick response to real-time events.
- 512 bytes of electrically erasable PROM (EEPROM). 192 bytes of this nonvolatile memory are used by the operating system and 320 bytes are available for your application. EEPROM provides a convenient way to store calibration constants and other information that must be periodically updated.
- A 16 bit address bus and an 8 bit data bus. While the 68HC11’s native address space is 64 Kilobytes (equal to 65,536 bytes, and often written as 64K), the QVGA Controller expands the addressable memory space to 8 Megabytes by effectively adding 8 “page” bits to the address bus.

## **Learning More about the 68HC11**

The QVGA Controller uses a new version of the 68HC11 microcontroller, called the 68HC11F1. Motorola's *M68HC11 Reference Manual* and *MC68HC11F1 Technical Data Manual* are included with this documentation package as Adobe Acrobat Portable Document Format (\*.pdf) files.

The *M68HC11 Reference Manual* thoroughly describes how to use microcontrollers of the 68HC11 variety, but it does not describe some of the enhanced features that appear in the F1 version. The *MC68HC11F1 Technical Data Manual* provides details of the operation of the F1.

## **Graphical User Interface and GUI Toolkit**

The QVGA Controller features a touchscreen controlled graphical user interface. Combining a high-contrast 5.7" diagonal ¼VGA display and high resolution analog touchscreen, it comes complete with object-oriented menuing software that makes it easy to control your application using buttons, menus, graphs, and bitmapped images.

You can display your own custom graphics on a bright white-on-blue cold-cathode fluorescent (CCFL) backlit LCD. Display screens and graphic objects are quickly developed with most Windows paint programs, such as PC Paintbrush, allowing you to create sophisticated displays including your company logo, system diagrams, and icon-based control panels. Real-time data plotting routines are precoded for you, so the user can see what your instrument is doing. Your application's startup screen executes automatically on power-up.

You can use as many screens as you need, each with software configurable buttons and menus. A precoded menu manager simplifies menu-driven control, making it easy to define buttons, menus, icons, and their associated actions. With the touch or release of a button, the menu manager responds, sending an appropriate command to your application program. Onboard software draws the screen graphics and responds to button presses for you, so you can focus on your application rather than display maintenance.

## **Memory and Mass Memory**

384K Flash and 257K RAM are standard on the QVGA Controller. Of the QVGA Controller's 384K of Flash memory, 224K is available for your application program and data storage. Of the 257K of RAM, 253K is available for application program use. Up to 128K of the RAM can be optionally battery backed. 320 bytes of on-chip nonvolatile EEPROM is also available.

Custom controllers with 768K Flash and 641K SRAM are also available. For those really extensive applications that require lots of memory or removable data storage, the QVGA Controller hosts compact flash cards from 64 Megabytes and up in size.

Like PROM, Flash memory is nonvolatile. Thus it retains its contents even when power is removed, and provides an excellent location for storing program code. Simple write cycles to the device do not modify the memory contents, so the program code is safe even if the processor "gets lost". But Flash memory is also re-programmable, and the Flash programming functions are present right in the QVGA Controller's onboard software library.

Of the Flash memory, 256K resides on the QED Board (see Figure 1-4 ), in its first socket (S1). This 256K includes the 128K operating system, multitasking executive, and device driver routines. The middle socket on the QED Board accommodates a 128K static RAM. A third socket accommodates an optional battery-backed real-time clock. The QVGA Controller's remaining memory is mounted on the QVGA Board.

## Measurement and Control

The QVGA Controller provides a total of 57 I/O channels, distributed among digital, analog and serial communications functions as shown in Table 1-1.

**Table 1-1 I/O available on the QVGA Controller**

I/O	Type
Digital	8 General purpose digital lines configurable either as all inputs or outputs
	3 General purpose digital lines configurable either as all inputs or outputs
	4 Open-drain high-current outputs with onboard snubbers to drive 150 mA continuously or 1 amp intermittently
	5 General purpose digital outputs
	4 General purpose digital inputs
	6 Timer-controlled inputs or outputs including 3 input-capture, 3 output-compare, and a pulse accumulator
Analog	8 8-bit 0-5 V analog inputs at up to 100kHz sampling rate
	8 12-bit analog inputs, 8 channels single-ended or 4 channels differential at up to 30kHz sampling rate with unipolar (0 to +5V) or bipolar (-5 to +5V) input
	8 8-bit multiplying, cascadable DAC outputs, with 0 to +3 V outputs
Serial	1 Serial 1: RS232/485 hardware UART at up to 19.2 KBaud
	1 Serial 2: RS232 software UART at up to 4800 Baud
	1 Synchronous Serial Peripheral Interface at 2 MBaud
<b>57</b>	<b>Total I/O channels</b>

You can control dozens of analog and digital I/O lines in real time. The 30 digital I/O lines are distributed among dedicated inputs and outputs, high-current outputs, and configurable lines, including timer-controlled lines. The analog I/O lines are distributed among 8-bit and 12-bit resolution A/Ds and an 8-bit resolution digital to analog converter (DAC). The 8-channel (or 4-channel differential) A/D with 12 bits of resolution facilitates accurate measurement of analog inputs, and the 8-channel DAC allows the QVGA Controller to generate analog outputs, or to multiply an analog signal by a digitally specified gain factor (to implement volume control, for example). Both of these devices communicate with the processor via the high speed serial peripheral interface (SPI).

For each of these I/O lines, pre-coded I/O drivers make it easy to do data acquisition, pulse width modulation, motor control, frequency measurement, data analysis, analog control, PID control, and communications.

## Communications

Two serial ports and a fast synchronous serial peripheral interface (SPI) provide plenty of communications capability. A hardware UART drives RS232 or RS485 protocols at up to 19.2 Kbaud, and a software UART provides RS232 at up to 4800 baud. Onboard serial interface chips generate the logic levels necessary to implement either the RS232 or RS485 protocol. Two serial ports allow you to program through one while your instrument can still communicate with a third party through the other. If you need greater speed or more ports, UART Wildcards plug directly into the QVGA's Wildcard module bus, each providing two more full-duplex RS232/485 buffered serial communication ports at up to 56 Kbaud.

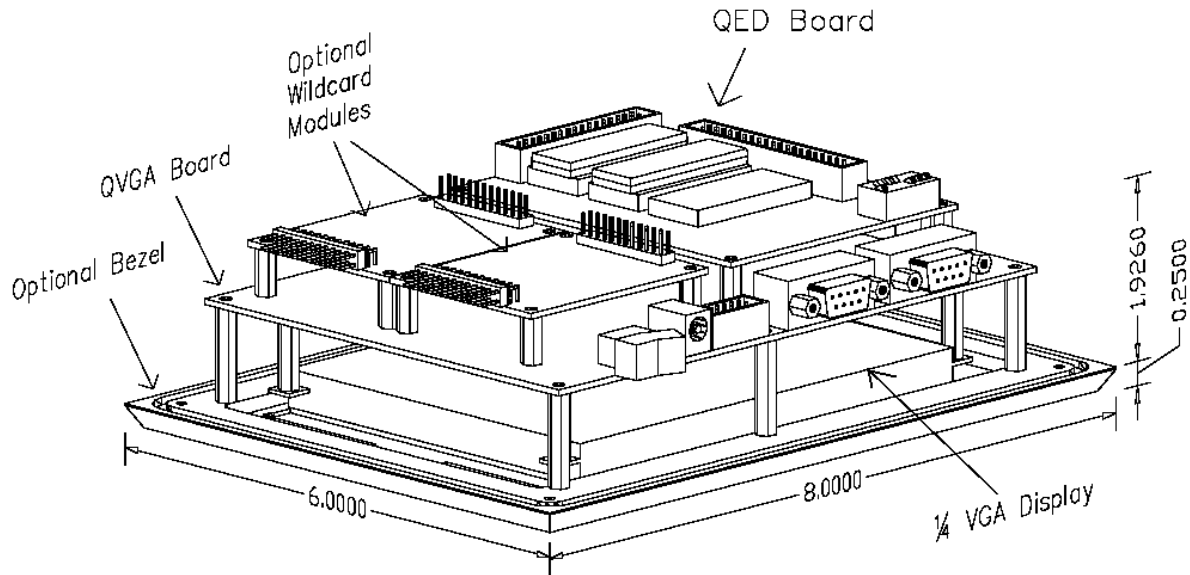
## Extensible I/O

Need even more I/O? The QVGA Controller hosts Mosaic's Wildcards™, small I/O modules for sophisticated and dedicated I/O. Up to eight Wildcards can be stacked on the controller for:

- 16- or 24-bit resolution programmable gain A/D;
- 12-bit D/A;
- Compact flash mass memory;
- Optically isolated AC or DC solid state relays;
- Configurable general-purpose digital I/O;
- Fast, buffered RS232, RS422 or RS485 communications interfaces; or,
- High-voltage, high-current DC inputs and outputs.

## Getting to Know Your Hardware

Your QVGA Controller comprises a touchscreen controlled graphical display and two double sided surface mount boards that integrate the many hardware and software functions in a compact package.



**Figure 1-2 The QVGA Controller, display facing down.**

Referring to Figure 1-2, which shows the QVGA Controller oriented with the display facing down, from top to bottom you can see the QVGA Controller has several layers:

- A QED Board (Part No. QED-4-QVGA) sits on top. This double sided, surface mount board is the heart of the QVGA Controller, and uses Motorola's 16 MHz 68HC11F11 microcontroller, reconfigured for an 8 MB address space. The 68HC11 supports 21 interrupts and includes several I/O subsystems including timer-controlled counters, input-capture and output-compare lines, a fast SPI and an 8-channel, 8-bit A/D. The QED Board hosts 128K SRAM (optionally battery-backed) and 256K Flash, and enhances the I/O by providing four high current digital drivers, two serial ports, 12-bit A/D and 8-bit D/A converters.
- The QVGA Board hosts hardware controllers for graphical displays and a touchscreen, contains high efficiency switching regulators to provide regulated, filtered power to other components, and contains additional memory (128K expandable to 512K Flash, and 128K expandable to 512K SRAM).
- The QVGA Board also provides module ports for accommodating up to 8 WildCard I/O expansion modules for just about any kind of I/O you might need. Two modules are shown on the diagram, but you can have any combination of:
  - 16-bit or 24-bit resolution A/D;
  - 12-bit D/A;
  - Isolated AC or DC solid state relays;
  - Compact Flash Cards, 64 Mbyte and up;
  - Logic level, high voltage, and high current digital I/O; or,
  - Additional RS232, RS422 or RS485.

- The ¼ VGA display may be either a bright, amber-on-black, high contrast, all-angle view TFEL electro-luminescent display or a high contrast CCFL white-on-blue monochrome LCD display with software controlled backlight and contrast. For either option the display is 5.7” on a diagonal (3.5” x 4.6”) and shows 320 x 240 pixels.
- A high resolution transparent analog touchscreen is mounted on the front surface of the display. A software controlled beeper on the QVGA Board provides audible feedback for finger touches.
- An optional bezel simplifies mounting the QVGA Controller on instrument front panels.

### ***QVGA Developer Package***

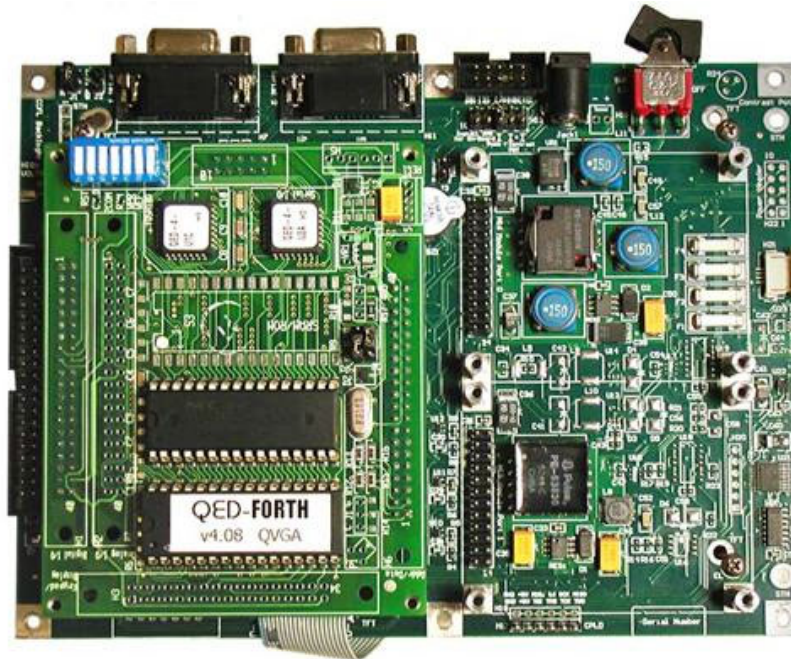
If you purchased a QVGA Controller Developer Package, you should have received the following:

1. A QVGA Controller (Part No. QVGA-Mono or QVGA-EL);
2. A 9-pin PC Serial Cable (Part No. PCC9-232);
3. A 16-24 volt Power Supply (Part No. PS-QVGA);
4. A CD-ROM containing:
  - The Mosaic IDE including a TextPad source code editor and the Mosaic Terminal program;
  - The Control-C Compiler, integrated within the Mosaic IDE;
  - Program examples; and,
  - Motorola M68HC11 Reference Manual and MC68HC11F1 Technical Data Manual (Part No. MAN-HC11);
  - A users guide, “The C Programmer’s Guide to The QVGA Controller”, and associated glossaries and appendixes.

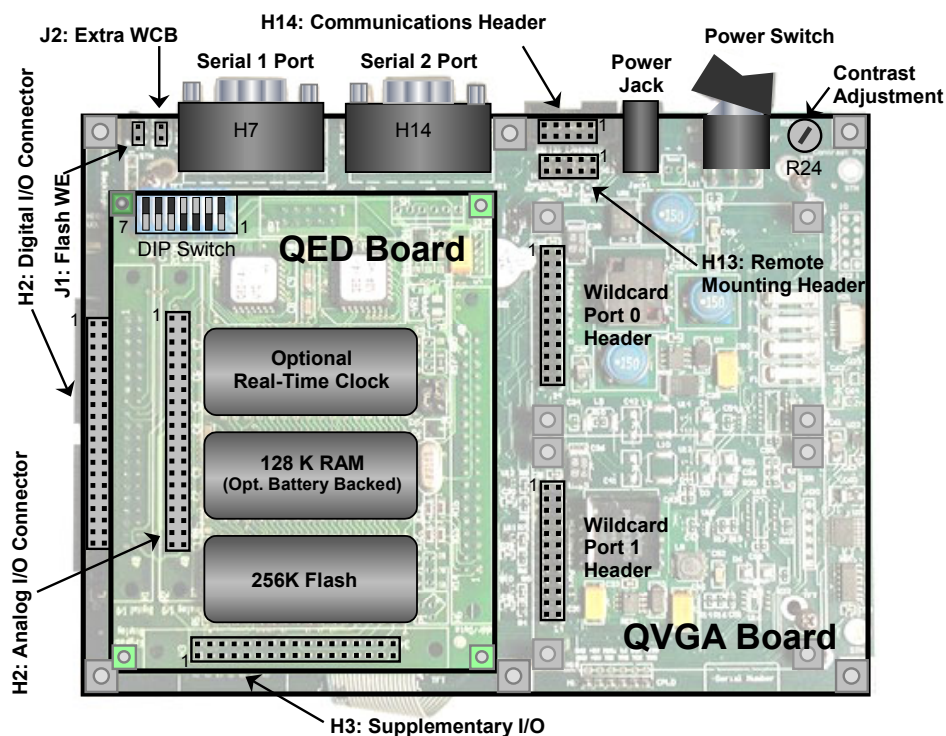
If you are missing any of these items, please contact us immediately.

## **A Tour of Connectors and Switches**

Figure 1-3 shows a photo of the back of the QVGA Controller, and Figure 1-4 diagrams the positions of important connectors.



**Figure 1-3** The QVGA Controller showing the QED Board mounted on the QVGA Board.



**Figure 1-4** Connectors and Switches on the QVGA Controller. In addition to the memory shown on the QED Board, the QVGA Board contains 128 (expandable to 512K) Flash and 128 (expandable to 512K) RAM.

### ***Power Jack and Power Switch***

The power jack is located between the communications header and the power switch. The QVGA Controller can be powered by any power supply that can deliver 8 to 26 volts at 5 watts for the QVGA-Mono or 16 to 26 volts at 20 watts for the QVGA-EL. A switch, located between the power jack and the contrast potentiometer, controls power to the QVGA Controller. The switch is in the “off” position when it is depressed away from the power jack as shown in Figure 1-3 and Figure 1-4.

### ***QED Board Sockets***

The QED Board contains a 256K Flash in socket S1 and 128K of optionally battery-backed RAM in socket S2. An optional battery-backed Real-Time Clock (RTC, also known as the “smartwatch”) can be plugged into socket S3. The RTC is made by Dallas Semiconductor and contains a clock chip, crystal and battery.

### ***Primary and Secondary Serial Ports, Communications Header***

The primary serial port can be configured for RS-232 communication at standard rates up to 19,200 baud and nonstandard rates to 250,000 baud. Its 9-pin connector is located between the Flash Write Enable Jumper and the secondary serial port. The secondary serial port, which can be used for peripheral devices such as a printer or a barcode reader, has a maximum baud rate of 4800 baud. Its 9-pin connector is located between the primary serial port and the Communications Header. To enable the secondary serial port, turn dip switch 5 on the QED Board ON. Otherwise, dip switch 5 should be OFF so that it frees bit 3 of PORTA for use as general-purpose I/O.

### ***Analog I/O Connector***

Header H2 on the QED Board provides 24 analog I/O lines, including access to 8 channels of 8-bit A/D, 8 channels of 12-bit A/D, 8 channels of 8-bit D/A and their associated reference voltages.

### ***Digital I/O Connector***

Header H2 on the QVGA Board provides 26 uncommitted digital I/O lines: PORTA and PORTD from the 68HC11, and PPA and upper PPC from the PIA. It also brings out useful control signals including processor clocks, read/write control signals, reset and power-fail warning signals, and external interrupt request lines. Analog and digital power supplies and their respective grounds as well as an unregulated DC voltage are also available on this bus. This connector can interface directly to external digital I/O signals such as switches, control outputs, and isolated inputs and outputs.

### ***Supplemental I/O Connector***

This connector provides access to four MOSFET high current drivers named HC0-HC3 and their onboard snubber diodes, V+ raw power, and ground. The connector is located on the QED Board and also contains 5 digital outputs and 4 digital inputs.

### ***Piezoelectric Buzzer***

A piezoelectric buzzer mounted on the QVGA Board allows audio feedback for software events such as button presses or alarms.

### ***Contrast Pot***

The contrast potentiometer (pot) adjusts the contrast of the monochrome LCD display and is located next to the power switch. The contrast of the display is properly set before each unit is shipped. If further adjustment is required, simply turn the pot with a small screwdriver. If the contrast pot needs to be mounted in a different location (on an external panel, for example) you can move it and connect it to the Remote Mounting Header (H13) shown in Figure 1-4.

### ***Wildcard I/O Expansion Interfaces***

Wildcard Port Headers 0 and 1 each accommodate up to four stacked Wildcards I/O expansion modules.

## **Configuring QVGA Options**

### **Setting the QED DIP Switches**

The QED Board has a 7-position DIP switch located prominently on the top of the board. The purpose and default positions of each switch are as follows:

#	Legend	Default State	Effect of Switch in the ON State
1	TOSHIBA	OFF	If the QED board is used as a stand-alone controller this switch configures the display interface for direct connection to a Toshiba graphics display. For proper operation of the QVGA Controller it should always be set to the OFF position.
2	WEF	ON	This switch write-enables the entire Flash memory device in the S1 socket. This switch is useful when using the flash memory for code storage when there is no need to modify its contents during normal operation. When OFF, code is protected against modification, and prevents “flash lockout” crashes. When ON, writes to the Flash are enabled, and the Flash device locks out all memory accesses for 10 milliseconds after an “errant” write to the flash – a write without the required “unlocking sequence”. If an application program inadvertently executes a write cycle while the flash is being addressed, the controller will “crash” for at least 10 msec because the program code cannot be read by the processor. This would result in a silent crash that does not return a “QED-Forth V4.x” prompt. Setting Switch 2 OFF prevents this consequence of inadvertent writes. Of course, all application programs should be thoroughly debugged so that there are no “inadvertent writes” to the flash memory. If storing code in Flash, turn this switch ON during development, and OFF once your code is debugged.
3	WPR	ON	Switches 3 and 4 together enable Flash in memory socket 1 and RAM in socket 2. Both switches should always be ON.
4	ROM	ON	Switches 3 and 4 together enable Flash in memory socket 1 and RAM in socket 2. Both switches should always be ON.

#	Legend	Default State	Effect of Switch in the ON State
5	2COM	OFF	Enables serial port 2 communications hardware for use as a second RS232 port. (The OFF state configures bit 3 of PORTA for use as general-purpose I/O.) Turn ON if you require use of the second RS232 port, OFF if you need bit 3 of PORTA.
6	COLD	OFF	Puts the QVGA Controller into “special cleanup mode” on the next power-up or reset. To return the QVGA Controller to its pristine, right-from-the-factory condition, turn this switch ON, toggle switch 7, then turn this switch back OFF.
7	RST	OFF	Resets the QED Board; return switch to OFF position to resume normal operation.

The legend on the QED Board suggests the function of each switch. Please note that:

- ☒ Switches 3 and 4 should always be ON;
- ☒ Switch 2 should be ON when you’re developing and writing to the Flash memory, OFF otherwise; and,
- ☒ Switches 6 and 7 together perform a special cleanup, toggling switch 7 alone resets the board.

## Setting the QED Board Jumpers

A three-post jumper located between the third socket and H6 configures the primary serial port for RS-232 or RS-485 operation. If a jumper shunt is install across the two pins closest to the crystal (the default configuration), the QVGA Controller will communicate using RS-232 over serial 1. If a jumper shunt is install across the two pins closest to the J3 silk screen, the QVGA Controller will communicate using RS-485 over serial 1.

## Setting the QVGA Board Jumpers

### *Jumpers J1, J2, and J3 on the QVGA Board*

The actions of the configurable jumpers on the QVGA board are summarized in Table 1-2.

**Table 1-2 QVGA Controller Jumper Summary.**

Jumper	Label	Description
J1	Flash WE	An installed jumper write enables the flash memory on the QVGA Board. This jumper is installed by default.
J2	Extra WCB	An installed jumper allows you to mount a Wildcard Carrier Board onto the QED Board. This jumper maps the modules on Module Port 0 and 1 of the QVGA Board to pages 8 to 15, rather than addressing them at pages 0 to 7. This jumper and its header pins are not installed by default.
J3	Buzzer Test	If installed a jumper actuates the piezoelectric buzzer. The header pins for this jumper are not installed by default.

## The Remote Mounting Header

Header H13, whose location is shown in Figure 1-4, allows you to remotely mount the power switch, buzzer, and contrast potentiometer. This allows you to move these controls from the back of the controller to a front panel for easy access and increased audibility. The default positions of the jumpers are as follows:

For a QVGA Controller with a monochrome display, jumper shunts are installed across pin pairs 1-2 and 3-4 to enable the on-board contrast potentiometer, and 5-6 to enable the piezoelectric buzzer. For a QVGA Controller with an EL display, a jumper shunt is still installed across pins 5-6 to enable the on-board buzzer, but does not have a contrast pot so pins 1-4 on the Remote Mounting Header are not connected and jumper shunts across these pins do nothing.

### ***Remotely Mounting the Buzzer***

You can mount a buzzer to your front panel for increased audibility. To remotely mount a buzzer, remove the jumper shunt across pins 5 and 6 and connect your buzzer across +5V on pin 7 and the /Beeper\_ON signal on pin 5.

### ***Remotely Mounting the Contrast Adjustment Potentiometer***

If you have a monochrome display, its contrast will vary depending on the ambient temperature. Although we allow you to adjust the contrast in software, if the display is completely washed out, the contrast may have to be adjusted using the contrast adjustment potentiometer. To remotely mount a contrast potentiometer, first remove the jumper shunts across pins 1 and 2 and 3 and 4. Then, connect one side of your potentiometer to Ext\_Pot\_A on pin 1, the other side to Ext\_Pot\_B on pin 3, and the wiper to Ext\_Pot\_A on pin 1.

### ***Remotely Mounting the Power Switch***

You can also mount the power switch to your front panel. To remotely mount a power switch, use a toggle switch and mount one side to *PWR.in* on pin 9 and the other side to *Switched.PWR* on pin 10.

# Chapter 2

## Chapter 2: Your First Program

*This Chapter will get you started using the Control-C language to program your QVGA Controller. It will guide you through the installation of the Mosaic IDE, an integrated editor, compiler, and terminal, and you'll start up and talk with your controller. You'll also:*

- ⇒ *Compile and download your first program using an example multitasking program that performs calculations using floating point math, stores data in arrays in the QVGA Controller's extended memory space, and prints the results to the terminal;*
- ⇒ *Selectively execute any program function using the QVGA Controller's on-board debugging environment (QED-Forth);*
- ⇒ *Use the QVGA Controller's built-in operating system to access extended memory;*
- ⇒ *Use the terminal to interact with a running multitasking application; and,*
- ⇒ *See how easy it is to set up a multitasking application.*

## Installing the Mosaic IDE and Control-C Compiler

The Mosaic IDE, which includes the Control-C Compiler, a full-featured editor and communications terminal, is provided on an installation CD-ROM. To install it onto your PC, first insert the Installation CD-ROM into your CD Drive. If the installer does not launch automatically, browse to your computer's CD drive using the 'My Computer' icon and double click on 'Setup.exe' to manually launch the installer.

We recommend that you use the default installation directory ("C:\Mosaic\") and choose 'Typical Setup' when asked. If you wish to install into a different directory, you may type in any pathname provided that it does not contain any spaces. The 'Custom' setup option can be used if another version of either *TextPad* (the editor used within the Mosaic IDE), the *Mosaic Terminal* (previously called *QED-Term*), or an earlier version of the Mosaic IDE has already been installed. However, the Mosaic IDE requires all of its components to work properly. Please call us at (510) 790-8222 if you have any questions.

When the installation is complete, you will need to restart your computer unless you are installing onto a Windows 2000 machine. Be sure to choose 'Yes' when asked to restart – if you don't, the installation may not complete properly. If you choose 'No' and restart later we recommend that to

assure a full restart you fully shutdown your computer and restart it; lesser restarts don't always restart fully.

You are now ready to talk with your QVGA Controller!

## Turning on Your QVGA Controller

Familiarize yourself with the locations of the power and serial connectors as shown in Chapter 1. After finding them follow these steps to turn on your system and establish communications with it:

1. Examine the settings of the 7 onboard switches. Dip switches 1, 5, 6, and 7 should be turned OFF by depressing the side of the switch towards the edge of the board. Dip switches 2, 3, and 4 should be turned ON. The function of each Dip switch is described in Chapter 1.
2. Connect the female end of the 9-Pin serial communications cable to your computer terminal's serial communications port and the male end to the primary serial port on the QVGA Controller. You can use any of your PC's COM ports. COM2 is usually available, but some PCs only have COM1 available.
3. Power up your PC computer or terminal.
4. You should check the configuration of your Windows communications drivers:
  1. On your PC go to the device manager dialog box by double clicking "System" in the "Control Panel", clicking the "Hardware" tab, and clicking the "Device Manager" button.
  2. In the list of devices open up the list of "Ports" and double click on "Communications Port (COM2)". (If COM2 is tied up with another service, such as a fax/modem, you may want to use COM1 instead.)
  3. You'll now have a dialog box called "Communications Port (COM2) Properties". Click the general tab and make sure you have these settings:

Property	Value
Baud Rate	9600
Data Bits	8
Parity	None
Stop Bits	1
Flow Control	Xon/Xoff

5. We recommend that you use *Mosaic Terminal*, the terminal program that comes with the Mosaic IDE. You can start the terminal by double clicking the TextPad editor (the primary application of the Mosaic IDE) and choosing the terminal toolbar button which looks like this:



(The appearance of this and other toolbar icons may change in subsequent versions of the Mosaic IDE.) You can also start the terminal by double clicking the application "MosaicTerminal.exe".

The terminal starts with using COM2 by default at a speed of 9600 baud, no parity, and 1 stop bit. Xon/Xoff flow control is enabled, and the file transfer options are set so that the terminal waits for a linefeed (^J) character before sending each line (this is very important). You can use any other terminal program, but it must be configured with these same settings. If you use another terminal program, you must specify that it use the linefeed character as its *prompt character*. It might be denoted as LF, ^J, ascii decimal 10, or ascii hex A.

If your PC is set up to use a COM port other than COM2 the Mosaic Terminal will respond with a warning box saying “Invalid port number”. If so, just go to the Mosaic Terminal menu item “Settings→Comm→Port” and choose the COM port you chose when configuring Windows in step 4. above.

6. Plug the QVGA Controller’s power supply into a 110 VAC outlet. European users will need a power transformer for changing European 220 VAC to 110 VAC. Insert the power supply output plug into the power jack on the QVGA Controller and turn the power switch ON by depressing the side of the switch towards the outer edge of the QVGA Board. After a short pause two things should happen:

1. A demonstration program should appear on the screen; and,
2. If you hit the enter key while the cursor is in your terminal window you should see the QVGA Controller respond with,  
     ok.

The demo program, and the serial communications response indicate that your QVGA Controller is now working!

The working software demo that is included in each QVGA Controller automatically starts when power is first applied and the power switch is turned ON. The demo shows three screens, accessible by touching *file tabs* at the top of the screen. The first screen shows a typical numeric keypad entry screen, the second provides examples of font sizes, and the third shows random numbers being plotted into a plot window. Touching the file tabs transfers focus from one screen to another.

While the demo is running as one task, another task on the controller responds to commands from the terminal, and responds with the ‘ok’ prompt to an enter key.

You can play with the demo to see how it works. Observing this demo program run is a good way to verify that all of the hardware is functioning properly and also demonstrates some basic capabilities of the menu control software.

### ***If Something Doesn’t Work***

If your demo is not running, check that power is being properly applied to the controller. The demo should always run on a new QVGA Controller when power is initially applied. If you see only a blank screen and no message appears on your terminal there’s something wrong, so:

1. Verify that power is being properly applied to the controller.
2. Verify that the serial cable is properly connected.

3. Check the terminal configurations of the Mosaic Terminal (using the menu item “Settings → Comm”), and recheck the communications properties of the Windows communications port.
4. Email or call us if you are still having trouble.

## Removing and Reinstalling the Demo Program

### ***Disabling the Demo Program***

When you tire of the demo you can disable it, but don’t do that too quickly because once the demo is disabled you can’t restart it without sending special commands to the controller. So, feel free to play with the demo for awhile, to see how it uses buttons and menus.

Eventually, you will want to disable the demo. You can disable it by doing a *special cleanup* that places the QVGA Controller in a pristine state with no application program running.

#### ***Doing a “Special Cleanup”***

If you ever need to return your QVGA Controller to its factory-new condition, just do a *Special Cleanup*: Turn ON dip switch 6, toggle dip switch 7 ON and then back OFF again, and finally turn OFF dip switch 6. This procedure will remove any application programs and reinitialize all operating system parameters to their factory-new condition.

After you do disable the demo your display should be blank. You can verify that serial communications are working properly by hitting the enter key while your insertion point is in the terminal window,

←

Whenever you hit the ‘Enter’ key, as represented by the ← symbol in the line above, you should see an ‘ok’ prompt.

Now, whenever the QVGA Controller is powered up with your terminal communicating with it, this message,

```
QED:Forth.V4.xx
ok
```

where “V4.xx” represents the current software version number of your QVGA Controller, should appear, and the ‘ok’ prompt should repeat each time you press the carriage return. This message indicates that the onboard operating system is ready to receive commands.

Although the demo now no longer automatically starts when the QVGA Controller is turned on, it still resides in Flash memory. The special cleanup has merely erased an *autostart vector* – a special location that tells the controller the starting address of the program to run when it starts up. You can still start the demo program by typing the following into your terminal window,

```
RESTORE ←
main ←
```

in which the ← symbol represents hitting the ‘Enter’ key on your keyboard. The demo program should now be running. The first command you typed, **RESTORE**, restored pointers to the operating

system's list of names of programs. The pointers had been saved in EEPROM by a **SAVE** command. The second line is the name of the program. When you type the name of a program the operating system responds by executing that program.

The GUI demo (**main**) program will continue operating until the board is reset or the power turned off. If you'd like to restore the demo so that it automatically starts whenever the controller is turned on, simply type the following two lines:

```
RESTORE ←
CFA.FOR main PRIORITY.AUTOSTART ←
```

Note that you must type the lines with the spaces between the words just as in the lines above. The case of the characters isn't important.

These commands store the starting address of the **main** routine in the autostart vector. The two words, **CFA.FOR main**, find the *code field address* of the routine **main** and send it to the routine **PRIORITY.AUTOSTART** which stores it in the autostart vector. Now, the demo should automatically start up whenever the controller is turned on.

If you download other programs to the QVGA Controller you will overwrite the demo program, which is stored in Flash memory. Also, any execution of the **SAVE** command will overwrite the saved pointers. In either case, to revive the demo you will need to reload it. That is done by using the Mosaic Terminal to reload the compiled demo file to the controller's Flash memory. For instructions for doing that please see the comments in the folder, "C:\Mosaic\GUI Toolkit\Demo".

## Using the Mosaic IDE

### Using the Editor and Compiler

The Mosaic IDE has two main components, the TextPad editor, which includes the Control-C compiler, and the Mosaic Terminal program, both of which you'll find in the default directory "C:\Mosaic\":

- *TextPad* is a fully featured and highly configurable text and program editor. You'll use it to write and compile your code. All of the functions of the C compiler tools are available through the controls in TextPad. You can launch TextPad from the 'Mosaic IDE' group in the 'Programs' section of your Windows 'Start' menu. For convenience, you may want to place a shortcut to it on your desktop or on your Windows Taskbar.
- The *Mosaic Terminal* is a serial communications terminal that allows you to interactively control your controller over its RS-232 interface. You'll also use it to download your compiled C programs into the memory of the QVGA Controller. *Mosaic Terminal* may be launched from the 'Mosaic IDE' group within 'Start→Programs', but it is also available from within TextPad, either from the 'Tools' dropdown menu or by clicking the terminal icon on TextPad's toolbar.


You can type characters directly into the terminal window, and they will be accepted by the QVGA Controller's line editor and interpreter. This mode of interaction is convenient when debugging or typing short code fragments. If you are sending source code to the QVGA Con-

troller, it is best to create a file first. The file can be saved to disk to provide a record of your work, and the terminal program can be used to download the file to the QVGA Controller. You can also use the terminal to record your debugging sessions and save them as a file on disk


### **The TextPad Tool Bar**

Along with the standard tools you expect in a text editor you'll find four custom tools available in the toolbar that you'll use to compile and download your programs. Each of these tools is also accessible in the 'Tools' dropdown menu of TextPad. For C programmers the Debug (magnifying glass) icon calls the C compiler and assembler only, the Single-Page C icon performs a standard build of your program, and the Multi-Page C icon performs a multi-page memory model build of your program. Forth programmers won't need to use these tools. Both C and Forth programmers will find the Image Converter and Terminal icons useful. The Image Converter facilitates converting bitmap images to a form the QVGA Controller can use, and the terminal icon launches the *Mosaic Terminal* program. Each of these tools is described in more detail below.

### **The 'Compile Tool' Finds Syntax Errors in C Programs**


 The Compile Tool, designated by the "Debug" or "Magnifying Glass" icon, invokes the compiler and assembler only – it does not produce downloadable code. Use it to quickly check the syntax of a program and find compilation errors without performing the full build which would be needed to download the program into the microcontroller.

### **The 'Single-Page Make Tool' Compiles and Makes a Downloadable Single-Page C Program**

 The Single-Page Make Tool, designated by the "Make" or "Single-Page C" icon, performs a standard, single-page memory model build of your program. If you are compiling a program whose compiled size does not exceed 32 Kbytes of memory you should use this mode for fastest execution. Although this program size is sufficient for many applications, you may need to use the multi-page build if your application grows beyond 32 K. If you see the following warning printed in the compiler output, then you must switch to the multi-page memory model build (Multi-page C icon):

```
WARNING:...Input section ".doubleword" from 'progname.o11' is not used..!
```

### **The 'Multi-Page Make Tool' Compiles and Makes a Downloadable Long C Program**

 The Multi-Page Make Tool, designated by the "Multi-Page C" icon, invokes the C compiler's multi-page build mode. Programs compiled in this mode may be many pages in length limited only by the amount of FLASH installed in the QVGA Controller. It is always a good programming practice to break large projects into multiple smaller source code files for organization, and the multi-page build also uses this organization for distributing the compiled program across multiple 32 Kbyte pages. Thus, no source code file may contain more than 32 Kbytes worth of compiled source code or the above warning will be issued and the program will not run. A more detailed description of this behavior is available in Chapter 3.

You may wonder why there are both “Multi-Page” and “Single Page” compile modes. The reason is that C function calls between pages take just a little longer to execute (calls to functions on a different page take 49 microseconds while those on the same page or to common memory take only 11.5 or 13.75 microseconds, respectively). Because most function calls are to functions on the same page or to common memory page changes are rare; the average execution speed of multi-page C applications is still quite fast.

### **The ‘Mosaic Terminal’ Communicates with Your Product**



The Terminal icon launches the communications program, *Mosaic Terminal*. When you launch *Mosaic Terminal* for the first time, check the communications settings (Settings→Comm) to verify that the serial port is set correctly for your computer. Even if your QVGA Controller is running a demo program it will still respond to the terminal if the communications settings are correct.

## **Your First C Program**

Now that we’ve learned about the QVGA Controller's hardware, established serial communications, and installed the Mosaic IDE on the PC, it’s time to compile, download and execute a C program. We’ll also explore the QVGA Controller’s on-board operating system and use it to interactively debug a program.

### **Compiling a Program**

In this section we’ll be running a simple program that does some computation and communicates its results on the serial port. The program is one of several examples for use with the Control-C IDE in the “\Mosaic\C\_Examples” directory. Let’s compile, download, and run it.

Start TextPad, and open the source-code file “getstart.c” from the C\_Examples directory. You should see the source code in an open window – browse through it to get a feel for it. You’ll see that the final routine in the file is called **main()**; it’s the top-level, executable program. The first routine within **main()** that is called when the program starts is **InitVars()**. Note that in the run-from-place applications of embedded systems it’s important to initialize all variables with a run-time procedure when the program starts. Variables that are initialized when the program is compiled are not automatically initialized when the program runs; you should have a runtime routine in your code that does that.

Clicking on the Single-Page C icon will compile and produce a downloadable form of the program, named “getstart.txt”. A new window named ‘Command Results’ will appear so that you can watch the compilation process. When compilation has finished, you can scroll the Command Results window up and look for warnings, which don’t prevent creating a valid download file, and errors, which do. You should see two warnings near the beginning:

```
GETSTART.C(126): Warning: Expression is always TRUE.!\nGETSTART.C(197): Warning: Symbol 'unused_variable' is never used in function 'main'.
```

We deliberately inserted into ‘main’ a variable named **unused\_variable** that is never used in the function. If you double click on an error or warning line in the command results, TextPad will jump

to the corresponding line in the affected source file. Despite the warnings, the program should have compiled successfully; the command results will end with:

```
Qcc-> Creating QED Download File: getstart.txt
Tool Completed Successfully
```

You can quickly switch between the Command Results window and your source code file either by hitting Ctrl-Tab, or by clicking on the file tabs at the bottom of the TextPad window.

The file named “getstart.txt” is ready to be downloaded to the microcontroller using the Mosaic Terminal program.

## Downloading and Running the Program

If it is not already open, launch Mosaic Terminal either from the ‘Start’ menu or using the TextPad toolbar or dropdown menu. It’s most convenient to use the Terminal icon on the TextPad toolbar. If the factory demo is still running on your QVGA Controller, use the *special cleanup* procedure as outlined above. A special cleanup is performed by simply turning dip switch number 6 on, power cycling the QVGA or resetting it by toggling switch 7, and turning dip switch number 6 back off. This procedure causes the microcontroller to disable the automatic start up, but does not delete the GUI Toolkit demo program from FLASH. Now, you should be able to hit enter at the Mosaic Terminal prompt and see the ‘ok’ response with the microcontroller plugged in and turned on. If this is not the case, check your communications settings and cabling.

Now, select ‘File → Send File’ from the Mosaic Terminal menu and enter the “\c\_examples” directory, or wherever you compiled the program. Set the file type to “Text Files (\*.txt)” and select “getstart.txt”. You will see various commands and hex data scrolling on the screen as the file is downloaded to the microcontroller. When the download is complete, the text will turn from gray to green to indicate that it is finished. Now, it’s time to run your program.

To execute the top level function of your code, simply type ‘main’ and press enter,

```
main←
```

The getstart program will respond with:

```
Starting condition:
The radius is.....0; the circular area is.....0.
..ok
```

While on its face that doesn’t seem a very impressive response, you’re running your first program! This particular example program uses multitasking. The program runs a background task called **CalculationTask** continuously, incrementing a radius variable and using it to compute a new area. The program is running in its own task, leaving the communications task free so you can continue to interact with the controller.

You will notice that you can hit enter, and use the interactive debugging capabilities discussed in Getting Started with the Control-C Programming Language even though the program is still running. For example, try executing the following function interactively from the terminal:

```
Announce( )←
```

Note that you must type the space after the `(` character. Each time you execute this function you'll notice that the output is different, as the radius is being continuously incremented by the background task. Now try executing,

```
Nap( )←
```

which puts the background CalculationTask **ASLEEP**. If you again execute

```
Announce( )←
```

several times, you will notice that the radius and area are no longer being updated by the **CalculationTask**. To wake up the **CalculationTask** again, type

```
Wakeup( )←
```

and notice that the calculation is again being performed by the task.

You may want to stop the program; in particular you'll need to stop it before attempting any new downloads. This can be done most easily by simply entering **'warm'** at the microcontroller's prompt. The warm restart causes a soft reset to occur, terminating any background tasks that may be running.

After having run this program, you may want to play with the other example programs in the `"C_Examples"` directory. We strongly recommend that you compile these programs and work through the examples as suggested in the text of this manual. This will provide you with a thorough "hands-on" introduction to the Control-C programming environment.

## Interactively Debugging Your Program

We have seen how to interactively call the **main()** function from the terminal to execute our entire program; most C development environments let you do this. But the QVGA Controller's operating system makes it easy to interactively execute any designated function in your program. By simply preceding a function definition or prototype with the **\_Q** keyword (we chose **"\_Q"** as a unique keyword that suggests *QED*), you can ensure that the function will be interactively callable from your terminal.

### *An example: **Announce( )** Displays an Area and Radius*

For example, to display a summary of the current values of the radius and calculated circular area variables, we would like to call the function **Announce( )**.

Using the editor, look near the top of the **GETSTART.C** file and you'll see that its definition is:

```
_Q void Announce(void)
{ printf("\nThe radius is %6u; the circular area is %5.4g.\n",radius,area);
}
```

The **void** keywords indicate that the **Announce( )** function does not return a value, and does not expect any input parameters to be passed to it.

The **\_Q** declarator instructs the Make Tool that we want to be able to interactively call this function using the on-board QED-Forth interpreter. The names and execution addresses of all functions

defined with the `_Q` designator are placed in the `.TXT` download file so that QED-Forth will recognize them and will be able to interactively execute them.

The `printf()` function invoked in `Announce()` prints the specified string to the serial1 port. The parameters of the `printf()` function are well defined by the ANSI standard, and are described in many excellent texts. Briefly, the `\n` is an escape sequence that instructs `printf` to insert a newline at the designated places in the string. The `%` characters are formatting symbols that tell the compiler to substitute the listed arguments (in this case, the radius and area) for the `%` sequences at runtime. The `%6u` sequence tells the compiler to display the radius as an unsigned decimal number with a minimum field width of 6. The `%5.4g` sequence tells the compiler to display the area using either decimal or exponential notation with a precision of 4 decimal places to the right of the decimal point, and a minimum field width of 5.

The `printf()` function in Control-C differs from the ANSI standard in one respect: the maximum length of a printed string is limited to 80 characters instead of the standard 255 characters. This limitation also applies to the related functions named `sprintf()` (which writes a string to a buffer) and `scanf()` (which inputs a string). Of course, you can handle strings longer than 80 characters by using multiple calls to these functions.

### ***Interactively Calling Announce()***

To interactively call this function, simply type at your terminal

```
Announce( )←
```

followed by a carriage return (indicated by the arrow above). Spaces are important to the QED-Forth interpreter which processes this command; make sure that there is no space between the function name `Announce` and the opening parenthesis `(`, and there must be at least one space after the opening parenthesis. If QED-Forth does not recognize your command, it will repeat what you typed followed by a “?” character and wait for another command, so you can try again. The case of the letters does not matter: you can use all uppercase, all lowercase, or any combination when typing commands for the QED-Forth interpreter.

After calling `Announce()`, you should now see the message

```
The radius is.....0; the circular area is.....0.
```

on your screen, except that the printed values of the radius and area will correspond to the values they had when you executed the “WARM” command to stop the calculations. Then you will see an additional line of text starting with “Rtn:” that summarizes the return value of the function in several formats, followed by the “ok” prompt. Because the `Announce()` function has no return value, the return value summary is not relevant. The “ok” prompt indicates that QED-Forth has successfully called the function and is now ready to execute another command.

If you make a mistake while typing a command, just type “backspace” or “delete” to erase as many characters as necessary on the current line. Once you’ve typed a carriage return, though, QED-Forth executes your command. You can’t edit a command that was entered on a previous line. If you type an incorrect command and then type a carriage return, you may receive the “?” error message which means that QED-Forth does not understand the command you typed. If this happens, you can usually just re-type the command line and continue.

## Area Calculation

The next function defined in `GETSTART.C` is called `IncrementRadius()`. This simple function increments the radius variable, and resets it to 0 when it exceeds the `MAX_RADIUS` constant. As described below, `IncrementRadius()` is called from the infinite loop in `CalcForever()`; this results in the radius taking on all integer values between 0 and 1000.

The next function defined in the `GETSTART.C` file calculates the area of a circle; its definition is:

```
_Q float CalcArea(uint radius)
{ return PI * radius * radius;
}
```

As described above, the `_Q` designator flags this function as one that can be called interactively. The “float” keyword declares that the function returns a floating point value, and the parameter list tells us that the function expects a single unsigned integer (`uint`) as its input. (Note: `uint` and other useful type abbreviations and declarations are defined in the `TYPES.H` header file in the `\FABIUS\INCLUDE\MOSAIC` directory.)

To interactively test this function with an input radius of 5, type at your terminal

```
CalcArea( int 5)←
```

followed by a carriage return. QED-Forth uses spaces as delimiters; consequently, you must type at least one space after the `(` character and after the “`int`” keyword. You should see something like the following response at your terminal:

```
Rtn:..17053..5242..=0x429D147A=fp:..78..54
```

This line summarizes the returned value in several formats, including decimal or hexadecimal 16-bit values, 32-bit hexadecimal, and floating point. Because the `CalcArea()` function returns a floating point (`fp`) value, the final number on the line, labeled

```
=fp:..78..54
```

is the relevant return value. Indeed, 78.54 is the area of a circle that has the specified radius of 5. You can execute the function with any integer input as the radius, and verify that it returns the correct circular area. This capability enables interactive testing of the function over its allowed range of input values. Such thorough function-by-function testing of a program facilitates rapid development of reliable programs.

In the next chapter the interactive debugging process will be explored in more detail. You will learn how to examine the values of static variables and Forth arrays, pass parameters by value or by reference, generate hexadecimal and ascii dumps of memory contents, and modify the contents stored in variables and Forth arrays.

## Restrictions on the Use of `_Q`

Nearly every function in the many sample programs in the `\FABIUS\QEDCODE` directory is declared with the `_Q` keyword to facilitate easy debugging. There are, however, two restrictions associated with the use of the `_Q` declarator.

First, a function defined using the `_Q` keyword cannot use

...

(ellipsis) in its parameter list; rather, the number of input parameters must be specified when the function is defined. (If you try to define the `_Q` function with an ellipsis as an input parameter, the compiler will issue a warning and remove the `_Q` specifier, so you will not be able to interactively call the function during debugging.)

The second restriction is that the `_Q` function cannot be called via a function pointer if the function accepts input parameters. In other words, do not use the `_Q` declarator if:

- a. You need to call the function using a function pointer; and,
- b. The function accepts input parameters.

To see an example in which the `_Q` keyword cannot be used, open the sample program named **GRPHEXT.C** in the `\FABIUS\QEDCODE` directory and search for the function named **SetTheBits**.

This restriction does not affect many functions. Any function declared using `_Q` can always be called in the standard way (that is, by invoking the function name followed by parentheses that contain any input parameters). Moreover, any `_Q` function can be called indirectly via a function pointer (by passing its name without any parentheses) if the function's input parameter list is `"void"`.

## An Introduction to Extended Memory

The QVGA Controller's onboard operating system, called QED-Forth, provides numerous run-time services, including providing a heap memory manager. Using this memory manager we can access the controller's extended memory.

### **8 Megabyte Addressable Memory Space**

The standard 68HC11 processor can address 64 kilobytes of memory using 16-bit addressing. The QVGA Controller expands the address space to 8 Megabytes, addressing the lower 32 Kbytes of the processor's memory space by means of an 8-bit "Page Latch" that selects one of 256 pages. The 256 pages times 32 Kbytes per page yields 8 Megabytes of addressable memory. The upper 32 Kbytes of the 68HC11's address space is called the "common memory". This address space is always accessible, regardless of the contents of the Page Latch.

### **Available Common RAM**

The ANSI C compiler supports the standard 16-bit addressing scheme via its *small memory model*. It also supports a *medium memory model* that allows functions to be called on any specified page using a 24-bit address (16-bit standard address plus an 8-bit page). All C variables and C arrays, however, must be accessible using a simple 16-bit address. For practical purposes, this means that variables and C arrays must reside in the QVGA Controller's available 8 kilobytes of available common RAM located at addresses 0x8E00 to 0xADFF. In multitasking applications, this RAM is also used for task areas; each task requires 1 Kbyte of common RAM area.

You are of course free to use ANSI-standard C arrays located in the variable area in common RAM. These arrays allow you to use standard C pointer arithmetic, and their use is explained in all of the C textbooks. However, if you need to store *a lot* of data, the available 8K of common RAM may not be sufficient. But don't worry – you can still use all the memory.

### ***Built-in Array Library Routines Manage Access to Paged Memory***

The **FORTH\_ARRAY** routines that reside in ROM on the QVGA Controller provide an efficient means of accessing the large paged address space for storage of data. The pre-defined **DIM()** macro makes it easy to dimension a 2-dimensional array to hold signed or unsigned characters, integers, longs, or floating point values. Other pre-defined library functions handle storing, fetching, and copying data to and from the arrays. These QED-Forth functions are callable from C, and provide access to a large contiguous memory space that is very useful for real-time data storage and analysis.

Each array is referred to using a named 16-bit pointer to a “parameter field” structure in common RAM. Once the array has been “dimensioned”, this structure holds the number of rows and columns, data size, and a pointer to the QED-Forth heap where the array is allocated. The ROM-resident heap manager allocates and deletes the arrays in real time under the control of the C program, thereby maximizing the effective use of available paged RAM.

This section introduces the use of the arrays, and as we'll see in a late Chapter they are very useful for storing data from the QVGA Controller's A/D convertors. The header file named **ARRAY.H** in the **\FABIUS\INCLUDE\MOSAIC** directory contains all of the function and macro definitions that are used to access Forth arrays, including the **DIM()**, **FARRAYFETCH()** and **FARRAYSTORE()** macros that are mentioned in this section.

### ***Declaring and Dimensioning a FORTH ARRAY***

Let's look at the example code in the **GETSTART.C** file. Approximately 1/3 of the way into the file, you'll find a section called “Array Dimensioning, Storing and Fetching”. The first command in this section is:

```
FORTH_ARRAY    circle_parameters;
```

which declares a new **FORTH\_ARRAY** named `circle_parameters` and allocates storage for the structure in the variable area in common RAM. **FORTH\_ARRAY** is a **struct typedef** (see the **ARRAY.H** file) that specifies how the dimensioning information for the array is to be stored. Whenever we want to call a function to operate on this array, we will pass the pointer

```
&circle_parameters
```

as an argument to the function.

After using **#define** directives to define some dimensioning constants, we encounter the following function definition:

```
_Q void DimAndInitFPArray(float value,int rows,int cols,FORTH_ARRAY* array_ptr)
{  int r,c;
   DIM(float, rows, cols, array_ptr);           // dimension; allocate in heap
   for(c = 0; c < cols; c++)                     // for each column
       for(r=0; r< rows; r++)                     // for each row
           FARRAYSTORE(value,r,c,array_ptr);     // store in array
```

```
}
```

The function dimensions a **FORTH\_ARRAY** and initializes all elements of the array to have a specified floating point value. The inputs are the floating point value, the number of rows and columns, and a pointer to the **FORTH\_ARRAY** structure in common memory. After declaring the automatic variables **r** and **c**, the **DIM()** macro is invoked to emplace the dimensioning information in the **FORTH\_ARRAY** structure, and allocate memory for the array in the heap.

The first parameter expected by **DIM()** is a type specifier; type definitions and abbreviations are defined in the **TYPES.H** file in the **\FABIUS\INCLUDE\MOSAIC** directory. Valid type arguments for **DIM()** include the following:

```
char  unsigned char  uchar
int   unsigned int   uint
long  unsigned long  ulong
float xaddr
```

The next two input parameters expected by **DIM()** are the number of rows and columns, and the final input parameter is a pointer to the **FORTH\_ARRAY** structure. The nested **for()** statements cycle through each row and column element in the array, calling the macro **FARRAYSTORE()** to store the specified value into the array element. **FARRAYSTORE()** expects a floating point value, row and column indices, and a pointer to the **FORTH\_ARRAY** as its inputs.

The starting “**F**” in the name **FARRAYSTORE()** means “floating point”; a parallel macro named **ARRAYSTORE()** is used for arrays that contain signed or unsigned **char**, **int**, or long data.

The **SaveCircleParameters()** function in the **GETSTART.C** file calls the macro **FARRAYSTORE()** to store the radius and area as floating point values in their respective columns of the **circle\_parameters** array. Then it increments the **row\_index** variable, handling overflow by resetting the **row\_index** to zero to implement a circular storage buffer.

The next function in **GETSTART.C** is called **PrintFPArray()** which prints an array of floating point values to the terminal. Its definition is as follows:

```
_Q void PrintFPArray(FORTH_ARRAY* array_ptr)
{  int r, c;
   putchar('\n');
   for (r = 0; r < NUMROWS(array_ptr); r++)          // for each row
   {   for (c = 0; c < NUMCOLUMNS(array_ptr); c++)    // for each col
       printf("%9.4g ", FARRAYFETCH(float,r,c,array_ptr));
       // min field width=9;precision=4;g=exp or decimal notation
       putchar('\n');    // newline after each row is printed
       PauseOnKey();    // implement xon/xoff output flow control
   }
}
```

As usual, the **\_Q declarator** allows this function to be called interactively from the terminal. **PrintFPArray()** expects a pointer to a **FORTH\_ARRAY** as its input parameter, and uses 2 nested **for()** statements to print the contents of the array one row at a time.

The **printf()** statement invokes the Forth library macro **FARRAYFETCH()** to fetch the contents of the array at the specified row and column. **FARRAYFETCH()** returns the value stored in the array; it expects a type specifier (used to cast the return value to the required type), row and column indices, and a pointer to the **FORTH\_ARRAY** as its inputs.

The **%9.4g** argument to **printf()** specifies that the number should be printed using either decimal or exponential formatting (whichever displays better precision), with 4 digits to the right of the decimal point and a minimum field width of 9 characters. The **putchar('\n')** statement inserts a newline character after each row is printed. The **PauseOnKey()** function is a handy library routine that serves 2 purposes:

- It implements XON/XOFF output flow control to avoid “inundating” the terminal with characters faster than the terminal can process them, and
- It allows the user to abort the printout by typing a carriage return from the terminal.

For further details, please consult the definition of **PauseOnKey()** in the Control-C Glossary.

To see how the **DimAndInitFPArray()** function is called, scroll down to the function named **CalcForever()** in the **GETSTART.C** file. The first statement in the function is:

```
DimAndInitFPArray(0.0,CIRCLE_ROWS,CIRCLE_COLUMNS,&circle_parameters);
```

where 0.0 is the floating point value to be stored in each element, the constants **CIRCLE\_ROWS** and **CIRCLE\_COLUMNS** specify the number of rows and columns in the array, and **&circle\_parameters** is a pointer to the **FORTH\_ARRAY**.

### ***Interactively Dimension, Initialize and Print the Array***

It is easy to interactively call the functions that we’ve examined. The syntax that we’ll type at the terminal looks similar to an ANSI C function prototype, with one of the following type declarators being used before input parameters that are passed by value:

```
char      int      long      float
char*     int*     long*     float*
```

When passing the address of a variable or a structure, use only the name of the variable or structure, without any additional declarators or **&** operators. All of this is explained in detail in a later Chapter; for now, the goal is see how easy it is to use the interactive function calling tools.

For example, to interactively dimension and initialize the **circle\_parameters** array to have 10 rows, 2 columns, with each element initialized to a value of 34.56, type the following line at your terminal:

```
DimAndInitFPArray( float 34.56,int 10,int 2,circle_parameters)←
```

Remember to type at least one space after the **(** character, and after the **float** and **int** keywords. QED-Forth will respond to your command with a line of text that summarizes the return value of the function, followed by the “**ok**” prompt. We can ignore the return value summary, because this function does not return a value.

Now to verify that the initialization was performed correctly, we can type at the terminal:

```
PrintFPArray( circle_parameters)←
```

and, as always, we make sure that there is a space after the **(** character. Note that we do not use the **&** (address-of) operator before the **circle\_parameters** argument; it turns out that

**circle\_parameters** has already been defined in QED-Forth as the base address of the **FORTH\_ARRAY** structure.

QED-Forth calls the function which prints the contents of the **circle\_parameters** array, and then summarizes the return information (which we can ignore in this case). You can verify that the value of each array element is the same one that you specified when you called the **DimAndInitFPArray()** function. (Slight differences in the values are due to rounding errors in the floating point conversion and printing routines.) Using this interactive method, you can test each function with a variety of dimensioning and initialization information.

## An Introduction to Multitasking

Many instrumentation and automation applications can be logically conceived of in terms of a set of distinct “tasks” that cooperate to solve the problem at hand. For example, a program that manages a hand-held sensing instrument might have one task that acquires sensory data, another that performs calculations to process the data, and a third task that displays the results on a liquid crystal display.

Using the QVGA Controller’s built-in multitasking executive confers significant advantages when designing real-time systems. Breaking up a complex program into easily understood modular tasks speeds debugging, improves maintainability, and prevents source code modifications of one task from adversely affecting the required real-time performance of another task.

### The Task Activation Routine

In a multitasking environment, a “task” is an environment capable of running a program. After declaring (naming) a new task (which also allocates a 1 Kbyte task area), its environment is “built” by initializing its required stacks, buffers and pointers in the 1 Kbyte task area. Then the task is “activated” by associating it with an “activation routine” that performs a specified set of actions.

A typical task activation routine is the **CalcForever()** function in the **GETSTART.C** file. Its definition is straightforward:

```
_Q void CalcForever(void)
// this infinite loop function can be used as a task activation routine
{ DimAndInitFPArray(0.0,CIRCLE_ROWS,CIRCLE_COLUMNS,&circle_parameters);
  while(1)                                // infinite loop
  { IncrementRadius();                     // updates radius variable
    area = CalcArea(radius);               // updates area variable
    if(radius%10 == 0)                     // on even multiples of 10...
      SaveCircleParameters();              // save data in FORTH_ARRAY
    Pause();                               // give other tasks a chance to run
  }
}
```

The first thing that this function does is to dimension and initialize the **circle\_parameters** array. Then it enters an infinite loop that increments the radius variable, calculates the corresponding circular area and stores it in the area variable, and saves the radius and area in the **circle\_parameters** array if the radius is an even multiple of 10. The function calls **Pause()** on every pass through the loop. **Pause()** is a multitasking function that instructs the multitasking executive to change to the next task (if any) in the round-robin task list. This enables “cooperative multitasking”, in which a task willingly lets other tasks run by executing **Pause()**. The other type

of multitasking, also supported by the QVGA Controller, is “pre-emptive multitasking”, in which an interrupt-driven timeslice clock forces a task switch on a periodic basis.

In summary, the **CalcForever()** function is an infinite loop that manages the calculation and storage of the radius and circular area. This function can be the “activation routine” for a stand-alone task running in a multitasking environment.

### ***Declare, Build and Activate a Task***

The short section titled “Multitasking” in the **GETSTART.C** file demonstrates how easy it is to set up a task using the pre-defined macros. First we declare the new task as:

```
TASK CalculationTask;
```

The **TASK** typedef allocates a 1 Kbyte task structure named **CalculationTask** in the common RAM.

The function **SetupTask()** builds and activates the new task; its definition is:

```
void SetupTask()
{ NEXT_TASK = TASKBASE;                // empty task loop before building
  BUILD_C_TASK(HEAP_START,HEAP_END,&CalculationTask); // private heap
  ACTIVATE(CalcForever, &CalculationTask);    // define task's activity
}
```

The first statement empties the round-robin task loop by setting the **NEXT\_TASK** pointer in the task's user area to point to the task's own **TASKBASE**. The next statement invokes the **BUILD\_C\_TASK()** macro which expects starting and ending addresses for the task's heap, and the address at which the task is located. We have defined the constants **HEAP\_START** and **HEAP\_END** to specify a task-private heap occupying a full 32 Kbytes on page 7. The task base address is simply **&CalculationTask**. **BUILD\_C\_TASK()** sets up all of the stacks, buffers and pointers required by the task.

The final statement in **SetupTask()** invokes the **ACTIVATE()** macro which expects a pointer to the activation function (which is **CalcForever**) and the **TASKBASE** address (which is **&CalculationTask**).

Multiple tasks can be declared, built and activated in the same way.

### ***Putting a Task Asleep***

A “sleeping” task remains in the round-robin task loop, but is not entered by the multitasking executive. The status of a task can be changed from **AWAKE** to **ASLEEP** and back again by simply storing the appropriate constant in the **user\_status** variable in the task's **USER\_AREA**. The **USER\_AREA** is a task-private structure initialized by **BUILD\_C\_TASK()** that contains the pointers that a task needs to operate; it is defined in the **USER.H** file in the **\FABIUS\INCLUDE\MOSAIC** directory. The **USER\_AREA** structure is the first element in the **TASK** structure.

The **Nap()** function in **GETSTART.C** is a simple function that puts the **CalculationTask** asleep:

```
_Q void Nap(void)    // put calculation task asleep
{ CalculationTask.USER_AREA.user_status = ASLEEP;
}
```

This function simply stores the **ASLEEP** constant into the **user\_status** variable in the **CalculationTask**'s **USER\_AREA** structure. A similar function named **Wakeup()** stores the **AWAKE** constant into **user\_status** to wake up the task. We'll see how to use these functions in the next section.

### ***The main Function Gets Us Going***

The **main()** function is the highest level routine in the program. Its definition is:

```
void main(void)
// Print starting area and radius, build and activate CalculationTask.
{ int unused_variable; // an example of how warnings are handled!
  InitVars();
  printf("\nStarting condition:");
  Announce();           // print starting values of radius and area
  SetupTask();          // build and activate the CalculationTask
}
```

As you recall, the declaration of the **unused\_variable** was inserted to demonstrate how the Control-C IDE highlights the source code line associated with compiler errors and warnings.

**InitVars()** performs a runtime initialization of the variables used by the program; this is very important, because compile-time initializations won't ensure that variables are properly initialized after the program has run once, or after the processor is restarted.

After initializing the variables, **main()** announces the starting values of radius and area and then calls **SetupTask()** to build and activate the **CalculationTask**. To execute the program, simply type at your terminal:

```
main←
```

You'll see the following message:

```
Starting condition:
The radius is .....0; the circular area is .....0.
ok
```

The "ok" prompt lets you know that QED-Forth is ready to accept more commands. We have set up a two-task application: the default startup task (named the **FORTH\_TASK**) is still running the QED-Forth interpreter, and the **CalculationTask** that we built is running the **CalcForever()** activation routine. At any time we can monitor the current values of radius and area by interactively calling the function:

```
Announce( )←
```

Remember to type a space after the ( character, and you may have to type slowly so that the multi-tasking program does not miss any of the incoming characters from the terminal. To view the contents of the circular buffer array named **circle\_parameters**, type the command:

```
PrintFPArray( circle_parameters)←
```

To suspend the operation of the **CalculationTask**, type:

```
Nap( )←
```

Now notice that successive invocations of:

```
Announce( )←
```

all show the same values of the radius and area; this is because the **CalculationTask** is no longer updating them. To re-awaken the **CalculationTask**, simply type:

```
Wakeup( ) ←
```

To abort the multitasking program altogether and return to a single task running the QED-Forth monitor, you can perform a “**warm**” restart by typing:

```
WARM ←
```

The QED-Forth startup message will be displayed.

Of course, if you want to run the program again, you can type **main** or any of the interactively callable function names at any time. Remember to type

```
WARM ←
```

or

```
COLD ←
```

before trying to download another program file; the QVGA Controller can’t run multiple tasks and accept a download file at the same time. (Both **WARM** and **COLD** re-initialize the system, but **COLD** performs a more thorough initialization and causes QED-Forth to immediately “forget” the definitions of the C functions that were sent over in the **.TXT** download file).

## Summary

Now you’ve worked through the **GETSTART.C** program in detail. You know how to compile, download and execute programs, perform simple floating point calculations, print formatted strings and numbers to the terminal, dimension and access **FORTH\_ARRAYS** in paged memory, and define a multitasking application with an interactive terminal interface. That’s pretty good considering that this is your first C program on the QVGA Controller!



# *Part 2*

## *Programming the QVGA Controller*



# Chapter 3

## Chapter 3: The IDE: Writing, Compiling, Downloading and Debugging Programs





*In this Chapter we'll explore the QVGA Controller's tools for writing, editing, downloading and debugging your application program. You'll learn:*

- ⇒ *How to efficiently use the editor and compiler to write and compile both short and long programs;*
- ⇒ *Coding and file-naming conventions;*
- ⇒ *How to access the QVGA Controller's onboard functions; and,*
- ⇒ *How to interactively debug your programs.*

## Writing Programs

### Using the Editor/Compiler

In the prior Chapter we introduced the Mosaic IDE and the tools you can use to edit, compile, and download your program. Briefly, the text pad toolbar provides the following buttons:

-  The *Debug or Compile Tool* invokes the compiler and assembler only – it does not produce downloadable code. Use it to quickly check the syntax of a program and find compile errors.
-  The *Single-Page Make Tool* performs a standard, single-page memory model build of your program for programs that do not exceed 32 Kbytes of memory. If you see the following warning printed in the compiler output, then you must switch to the multi-page memory model build (Multi-Page Make icon):  
**WARNING:...Input section "...doubleword" from 'progname.o11' is not used..!**
-  The *Multi-Page Make Tool* invokes the C compiler's multi-page build mode for long programs. Still, each source code file should be less than 32 Kbytes worth of compiled source code or the above warning will be issued and the program will not run.
-  The Terminal icon launches the communications program, Mosaic Terminal which is used to download your compiled program to the QVGA Controller.

## Sylistic Conventions

### Code Comments

At the top of the `GETSTART.C` source code file are some comments that tell what the program does. Single- or multi-line comments can be enclosed in the standard

```
/*    */
```

delimiters. The double-slash

```
//
```

token means that the remainder of the line is a comment. Note that the editor colors all comments differently to make it easy to distinguish comments from source code. C keywords are also colored differently than user-defined routines. You can change the default colors if you like.

### Style Conventions

The example programs on your CD-ROM follow several stylistic conventions. Here is a brief summary:

- Macros and constants are spelled with **CAPITAL\_LETTERS**.
- Variable names are spelled with **small\_letters**.
- Function names use both capital and small letters, with capital letters indicating the start of a new *subword* within the function name. For example:

```
void SaveCircleParameters(void)
```

To minimize the need to skip from one file to another, we have decided not to group all **#define** statements in a header file that is separate from the program being compiled. Rather, the **#define** statements are defined close to where they are used in the program file that is being compiled.

### File Naming Conventions

For backward compatibility with DOS and Windows 3.1, all filenames have 8 or fewer characters. C source code files have the `.C` extension, and header files have the `.H` extension. When you use the Make Tool utility to compile a source code file with the filename,

```
NAME.C
```

several files with the extensions shown in Table 3-1 are created:

**Table 3-1** Enter your Table Caption here.

FILENAME.ext	Description
NAME.C	Source code text file created by you, the programmer
NAME.A11	Assembled output text file created by C11 compiler
NAME.O11	Object code binary file created by ASM11 assembler

FILENAME.ext	Description
<b>NAME.LCF</b>	Linker command text file created by CC or CCM batch file
<b>NAME.S</b>	S-record (raw download ascii file) created by linker
<b>NAME.DLF</b>	Final download file created by CC or CCM batch file; includes S records and definitions for QED-Forth
<b>NAME.MAP</b>	Map file listing created by linker
<b>NAME.MEM</b>	Symbols map file
<b>NAME.USE</b>	Memory usage summary
<b>NAME.BAK</b>	Backup file sometimes created by the editor

While this list may seem overwhelming, you won't have to worry about most of these files. You'll create your **NAME.C** and **.H** source code and header files in a directory of your choice, run the automated Make Tool by clicking on the Make icon, and send the resulting **NAME.DLF** download file to the QVGA Controller using the Terminal program. In fact, unless you tell it otherwise, the editor's "File" menu will typically show you only files with the **.C** and **.H** extensions ("Source Files"); you won't have to wade through the files with the other extensions. Similarly, the Mosaic Terminal typically lists only files with the **.DLF** extension, so it will be easy to select the download file to send to the QVGA Controller.

## Using Function Prototypes

This stylistic convention deserves its own section. We strongly urge that you define or prototype each function before it is called. If the compiler generates a warning that a function has been called without a prototype, we recommend that you check your source code and insert the required function prototype, or move the definition of the function so that it is defined before it is called.

A prototype is a declaration that specifies the function name and the types of its return value and input parameters. For example, the following is a valid function prototype:

```
_Q float CalcArea( unsigned int radius);
```

This declaration specifies that **CalcArea()** is a function that expects one unsigned integer input and returns a floating point value. As discussed below, the **\_Q** tags the function as one that is interactively callable during debugging. The **CalcArea()** function can then be defined later in the source code file. If a function is prototyped in one file and defined in another, add the **extern** specifier before the prototype.

You can preface any function prototype with the **\_Q** tag if you want to interactively call the function from the terminal. The QVGA Controller's onboard operating system maintains a list, called the *dictionary*, of the names of functions tagged with the **\_Q** so that it can recognize them when you send a command line from your terminal.

***Prototype and Declare the Parameter Types of Every Function***

Defining or prototyping a function before it is called allows the compiler to help find parameter passing errors, and it also prevents unnecessary *promotion* of parameters that can render the code slower and defeat the QVGA Controller's interactive function-calling capability. To avoid unwanted promotion and runtime errors, each and every parameter in the function prototype or function definition must be preceded with a type specifier. For example, leaving out the **unsigned int** keywords in the prototype for **CalcArea()** above would lead to promotion of the input parameter, possibly resulting in a *runtime error* message from the compiler or linker.

Using function prototypes and definitions that explicitly specify the type of each and every input and output parameter results in more readable and reliable code.

**Accessing the Standard (Kernel) Library Functions**

The command

```
#include < \mosaic\allqed.h >
```

near the top of the **GETSTART.C** file is a preprocessor directive that includes all of the relevant header files for the QVGA Controller, and all of the standard C header files (such as **stdio.h**, **math.h**, **float.h**, **string.h**, etc.) We strongly recommend that this statement be placed at the top of each C program file that you write. It gives you access to all of the pre-coded library routines that reside on the QVGA Controller. These routines let you control the A/D and D/A converters, digital I/O, serial ports, keypad, display, elapsed-time clock, real-time clock/calendar, and many other useful functions. The **ALLQED.H** file also gives you access to the QVGA Controller's multi-tasking and paged memory capabilities, as well as the standard ANSI C library functions including printing and string conversion routines such as **printf()** and **sprintf()**. Including these files is very efficient; it generates almost no additional runtime code while giving you access to very powerful capabilities.

You can call any of these functions from within your C code. There is one limitation however:

**Do not nest functions of the type `_forth`.**

Many functions that are callable from C are actually of the **\_forth** type. This includes functions that are in the kernel on the QVGA Controller, or are part of software distributions such as the Graphical User Interface (GUI) Toolkit or the ATA Flash Card Software Package. A call to one of these **\_forth** functions may not be made from within the parameter list of a call to another **\_forth** function.

There is always a straightforward way of avoiding such nesting of function calls: simply use a variable to hold the required intermediate return value/parameter. For example, if you need to use the **\_forth** function **FetchChar()** to fetch the first character from the extended address returned by the **\_forth** function **DisplayBuffer()** in paged memory, you could execute the following statements:

```
static xaddr buffer_xaddress = DisplayBuffer( );
FetchChar( buffer_xaddress);
```

This code is correct, while nesting the call to `DisplayBuffer()` inside the parameter list of `FetchChar()` would be incorrect.

## Initializing Variables

### Caution:

#### RAM-Resident Variables & Arrays Must Be Initialized Within Functions

A common mistake made when creating application programs for embedded systems is the use of *compile-time initialization* for RAM-based quantities such as variables and arrays. While this approach of initializing quantities outside of function definitions may work during program development, it fails when the device goes into production because the variables and arrays are not properly initialized when power is cycled.

Only *run-time initialization*, i.e., initializations that are performed within functions (which are in turn called by the autostart program), will occur reliably in an embedded application.

Even users with battery-backed RAM in their systems should always perform initializations within functions. This approach will avoid hard-to-diagnose field failures that result from corrupted data in a battery-backed RAM that is never re-initialized to valid values.

Feel free to call Mosaic Industries for help with this or other programming issues.

## Compiling Programs

### Compiling Multiple Source Code Files

When writing large programs it is often useful to break up the program into multiple source code files. The Make Tool allows you to accomplish this in one of two ways.

1. First, you can designate one of your source code files as the primary file, and insert into this file statements of the form,

```
#include "\\path\\filename"
```

to include the other source code functions, where `\path` is the standard DOS path specification that allows the file to be located. The primary file **must have a .C extension**.

2. Second, you can split your source code into several files that start with the same sequence of characters, such as:

```
CODE.C      // this is the primary file that you compile
CODE1.C     // CODE1.C and CODE2.C are subsidiary files that are automatically
CODE2.C     // compiled and linked when CODE.C is compiled
```

All of these files must have the `.c` extension. Then, when you compile `CODE.c` using the Make Tool (by clicking on the Make icon), all of the files with a `.c` extension whose name starts with `CODE` (namely, `CODE.c`, `CODE1.c` and `CODE2.c`) will be compiled and linked together. Note that the Make Tool cannot handle filenames that start with a numeral; thus a source code file named `1CODE.c` cannot be compiled.

Finally, note that one and only one of the program files must include a function named `main()`.

## Using the Interactive Debugger

In the prior chapter, you gained experience using the debugging environment that lets you interactively execute any designated function with input arguments of your own choosing. Now we'll look more closely at the operation of the debugging environment, and explain how to use it to examine and manipulate the values of static variables, Forth Array elements, and memory locations.

The interactive debugging environment conveys several advantages. First, you can test each function of a program individually without changing the `main()` function and recompiling. This saves compilation and download time. Second, the environment makes it easy to test each function with a wide range of input parameters, allowing you to isolate bugs that might otherwise be missed until later in the program development cycle. Such thorough function-by-function testing of a program facilitates more rapid development of reliable programs.

We'll start by learning how to use the interactive environment to examine the values of static variables. The explanation of how this works involves taking a brief high-level look at the interactive QED-Forth language that is built into the QVGA Controller. Understanding how QED-Forth operates will empower you to take full advantage of the debugging capabilities of the QVGA Controller.

## Overview of the Forth Language and Programming Environment

The QED-Forth interactive environment makes it easy to examine the contents of static variables. A brief overview of how the Forth language works will help clarify the procedure.

### ***The Forth Data Stack***

Forth is a stack-oriented high level language that combines the interactive benefits of an interpreter with the speed of a compiler. Unlike C, FORTH is implemented as a two-stack language. In addition to the return stack that most languages use to keep track of function calls and returns, FORTH has a *data stack* that is used to pass parameters. All arithmetic, logical, I/O, and decision operations remove any required arguments from the data stack and leave the results on the data stack. This leads to *postfix* notation: the operation is stated after the data or operands are placed on the stack. This is the same notation used by Hewlett Packard's RPN (*reverse polish notation*) calculators.

Unlike C, Forth uses spaces as delimiters to distinguish different keywords and tokens. For example, a C compiler can easily parse the addition expression:

5+4

as three distinct tokens: 5, +, and 4. But because the above expression was typed without any spaces, Forth would interpret the expression as a single token, assume it's the name of a function, and would try to find it in its dictionary. In Forth the expression must be entered as:

```
5 4 +
```

which includes the required spaces and uses postfix notation to add the numbers and leave the result on the data stack.

To see how this works, we'll talk to the interactive QED-Forth interpreter on the QVGA Controller. To start, enter the terminal now: if the terminal program is already active, click on its window or hold down the "Alt" key and press "Tab" until the terminal announcement appears on your screen. If you haven't started the terminal program yet during this session, double-click on the Mosaic Terminal icon to start it up. Connect and power up your QVGA Controller; pressing the Return key should cause QED-Forth's **ok** prompt to appear in the terminal window.

To start, we'll ensure that the current number base is decimal by typing the command,

```
DECIMAL←
```

from the terminal. With each character you type QED-Forth echoes the character in your terminal window. The back arrow in the line above indicates that you pressed the Enter key which sends a carriage return character; but you won't see it as an echoed character on your screen. QED-Forth executes this command when the terminating carriage return is received. Also recall that QED-Forth is case-insensitive, so you can freely mix upper and lower case letters. Now we can put some numbers on the QED-Forth data stack by typing :

```
5 7←
```

followed by a carriage return. QED-Forth responds:

```
ok.....( 2 )\..5\..7
```

We have underlined QED-Forth's response for clarity. QED-Forth is showing a picture of its data stack. The **( 2 )** means that there are two items on the stack. Each of the items is listed, and items are separated by a \ character, which can be read as *under*. So we could describe the stack right now as 5 under 7; the 7 is on top of the stack, and the 5 is under it. If there are more than 5 items on the stack, the stack print displays the number of stack items and the values of the top 5 items.

The stack print that shows what's on the data stack is a feature of the debugging environment. To disable the stack print, you could execute (that is, type at your terminal) the **DEBUG OFF** command. It is not recommended that you do this, though; it's very helpful to keep track of the items on the data stack while developing your program.

To multiply the numbers that are now on the stack, type the multiply operator which is a **\*** character:

```
*←
```

and QED-Forth responds:

```
ok.....( 1 )\..35
```

The QED-Forth **\*** operator removes the two operands 5 and 7 from the stack, multiplies them, and puts the result of the multiplication on the stack. To subtract 5 from the number on the stack, type:

```
5 - ←
```

which produces the response:

```
ok.....\.\.30
```

The QED-Forth `-` (minus) operator takes the 35 and the 5 from the stack, subtracts, and puts the result on the data stack.

To print the result to the terminal, we could simply type the printing word:

```
. ←
```

(that's right, the command is simply a *dot*, the period on your keyboard) which prints the response:

```
30.....ok
```

The printing word `.` removes the 30 from the stack and prints it. The stack is now empty, so QED-Forth does not print a stack picture after the ok.

Notice that throughout this exercise QED-Forth has been interpreting and executing commands immediately. This is because the Forth language is *interactive*. The results of executing commands can be immediately determined. If they are incorrect, the command can be changed to correct the problem. This leads to a rapid iterative debugging process that speeds program development. This interactive function execution has been harnessed to speed development of C programs for the QVGA Controller.

### ***QED-Forth Numeric Printing Functions***

There are a variety of QED-Forth printing functions, and some related functions that set the current number base and clean up the data stack. Here is a short list of useful functions that can be executed interactively:

Function	Description
<code>.</code>	Prints a 16 bit signed integer in the current number base
<code>U.</code>	Prints a 16 bit unsigned integer in the current number base
<code>D.</code>	Prints a 32-bit signed long in the current number base
<code>PrintFP</code>	Prints an ANSI-C floating point number
<code>HEX</code>	Sets the number base to hexadecimal
<code>DECIMAL</code>	Sets the number base to decimal
<code>SP!</code>	Clears all items off the stack without printing anything

Each of the printing routines removes a number from the data stack and prints it to the terminal. Because characters are promoted to unsigned `int` in Forth, the `.` (dot) function is also used to print 8-bit character data. The `PrintFP` function was specifically written to display floating point numeric output from C programs, as internally QED-Forth uses a non-ANSI floating point representation for its own floating point numbers.

The default QED-Forth number base after a **COLD** restart is **DECIMAL**. The number base can be changed to hexadecimal by executing **HEX**. All non-floating-point numbers typed at the terminal or

printed by QED-Forth are converted using the current number base (corresponding to the most recent execution of **DECIMAL** or **HEX**). Floating point numbers are always converted using the decimal number base.

## Displaying the Values of Static Variables

Now that we understand how the Forth data stack works, the procedure for examining variables will make sense. The examples presented here use code from the **GETSTART.C** program that we've already discussed in detail. If you have already downloaded the program, you are ready to go. If your board is presently running a multitasking application and you want to download a new file, type

```
WARM←
```

to stop the program so that a new download file can be accepted.

If you have not yet compiled the **GETSTART.C** program and you want to do the exercises here, first compile it by opening **\MOSAIC\DEMOS\_AND\_DRIVERS\MISC\C EXAMPLES\GETSTART.C** in the TextPad editor, click on the Make Tool, and after the compilation, enter the Mosaic Terminal and use the "Send Text File" menu item to send **GETSTART.DLF** to the QVGA Controller. To run the program, type

```
main←
```

at your terminal – this initializes all the pointers and variables. After typing **main**, let's type

```
Nap( )←
```

to put the calculation task asleep; remember to type at least one space after the **(**. This stops the variables from being updated in the background.

Let's start by initializing the contents of the radius variable to 5 by interactively executing (typing) from the terminal:

```
SetRadiusAndArea( int 5)←
```

Remember to type at least one space after the **(** character and after **int**. This function is defined in **GETSTART.C** as:

```
_Q SetRadiusAndArea( uint r)
{  radius = r;
  area = CalcArea( r);
}
```

It assigns the specified input parameter to the unsigned integer **radius** variable, and assigns the corresponding circular area to the floating point area variable.

Now we can check the value of **radius**. The following interactive command places the contents of the integer variable named **radius** on the Forth data stack:

```
int radius←
```

QED-Forth responds with:

```
ok....(..1...)..5
```

Because `radius` is defined as an unsigned integer, we use the unsigned integer printing routine named `U.` (U-dot) to remove the value from the Forth data stack and print it. Type

```
U.←
```

to print the radius as an unsigned integer. QED-Forth responds with:

```
5..ok
```

To speed things up, we can type the entire command sequence on one line so that QED-Forth immediately prints the result. Type:

```
int radius U.←
```

and QED-Forth responds with:

```
5..ok
```

To interactively examine the contents of the floating point area variable, type the command sequence:

```
float area PrintFP←
```

and QED-Forth responds:

```
78.54...ok
```

which is indeed the area of a circle whose radius equals 5.

### ***Extracting the Value Referenced by a Pointer***

Sometimes C programs add an additional layer of indirection, referencing a value by means of a pointer. An example of this technique appears in the `GETSTART.C` program in the form of the static variables `radius_ptr` and `area_ptr`; they are defined as:

```
static uint* radius_ptr;  
static float* area_ptr;
```

In the `InitVars()` function near the end of the program, these pointers are initialized as follows:

```
radius_ptr = &radius;  
area_ptr = &area;
```

In other words, `radius_ptr` holds the address of a variable that represents the radius, and `area_ptr` holds the address of a variable that represents the area. Given the `radius_ptr` and `area_ptr`, we want to be able to extract the value of radius and area. The following keywords can be executed interactively to accomplish this:

```
char*      int*      long*      float*
```

Note that there cannot be any spaces before the `*` in each keyword, and there must be at least one space after the `*` and before any subsequent number or variable name.

For example, to print the radius you can type:

```
int* radius_ptr U.←
```

The `int*` keyword fetches the 16-bit address from `radius_ptr` and from that location fetches the integer contents. `U.` then prints the answer to the terminal. Similarly, to print the area you can type:

```
float* area_ptr PrintFP←
```

The **float\*** keyword fetches the 16-bit address from **area\_ptr** and from the resulting location fetches the floating point contents. **PrintFP** then prints the result.

### ***Signed versus Unsigned Numbers***

Note that the type specifier used above does not specify signed versus unsigned numbers; rather, the printing function determines whether the number is interpreted as signed or unsigned. For example, type the following two command lines from the terminal and see how QED-Forth responds:

```
65535 U.←
65535 .←
```

In the first instance, QED-Forth prints 65535, while in the second instance, QED-Forth prints -1 (we're assuming that you have not changed the number base to **HEX**). The same binary pattern (in this case, all 16 bits of the number are set) can represent either 65535 or -1 depending on how the number is interpreted and printed. Thus by choosing the printing function, you can control whether a number is displayed as a signed or unsigned quantity.

### ***Summary***

In summary, to display the contents of a simple static variable, type a command of the form:

```
type variable_name print_function_name
```

where type is one of the following keywords:

```
char    int    long    float
```

To display the contents of a static variable that is pointed to by a pointer, type a command of the form:

```
type    pointer_name    print_function_name
```

where type is one of the following keywords:

```
char*   int*   long*   float*
```

## **Use Type Keywords To Interactively Call C Functions**

The same family of familiar C type-declaration keywords that we used to fetch the contents of variables is also used to facilitate interactive calling of C functions. Recall that these keywords are:

```
char    int    long    float
char*   int*   long*   float*
```

We have seen that these keywords are used in two different contexts while debugging. In the prior chapter we used them to declare the type of an input parameter while interactively calling a function. For example, we can interactively type from the terminal:

```
CalcArea( int 5)←
```

where the **int** keyword is used with the same syntax as an ANSI-C function prototype to declare the input arguments to the called function.

Second, we used the type keywords in this chapter to extract the value from a variable, as in the interactive QED-Forth command

```
int radius U.←
```

which prints the contents of the radius variable as an unsigned integer.

These two contexts for the use of the **int** keyword are related. For example, to calculate the area corresponding to the current value of the radius variable, we can interactively execute:

```
CalcArea( int radius)←
```

and QED-Forth prints the resulting floating point area in its summary of the return value. The **int** keyword serves two complementary purposes here: it tells QED-Forth that the input parameter is a 16-bit integer, and it extracts the value of the radius variable so the variable is *passed by value*.

When interactively calling a function, all parameters that are passed by value should be preceded by the appropriate type keyword. However, when passing the address of a variable or a structure, simply state the variable or structure name without any type specifiers or **&** (address-of) operators.

For example, the function prototype for the **DimAndInitFPArray()** function in **GETSTART.C** is:

```
Q void DimAndInitFPArray(float val,int rows,int cols,FORTH_ARRAY* array_ptr)
```

and the program includes the array declaration:

```
FORTH_ARRAY circle_parameters;
```

which declares **circle\_parameters** as a **FORTH\_ARRAY** structure in memory. As we shall see, executing (typing) the name **circle\_parameters** in QED-Forth leaves the address of the array structure on the stack, so there is no need for additional type declarators or **&** operators. Thus to interactively dimension the array to have 10 rows, 2 columns and a initialization value of 12.34, we type from the terminal:

```
DimAndInitFPArray( float 12.34,int 10,int 2,circle_parameters)←
```

To verify that this worked, you can execute:

```
PrintFPArray( circle_parameters)←
```

which displays the contents of the newly initialized **circle\_parameters** matrix.

## Displaying the Values of **FORTH\_ARRAY** Elements

The same type specifier keywords that let you examine static variables can also be used to examine any specified element in a two-dimensional **FORTH\_ARRAY**. The syntax is parallel to what we have already used; the difference is that we now append the row and column indices in square brackets after the array name to specify which element should be fetched.

For example, recall that `circle_parameters` is a **FORTH\_ARRAY** that is dimensioned to hold 10 rows and 2 columns of floating point data. To print the contents of the first element in the array at [row=0, col=0], we type:

```
float circle_parameters[ 0, 0] PrintFP←
```

and QED-Forth prints the result. While this array notation is not exactly like the standard C syntax, it is straightforward. To print the element whose row index is 5 and whose column index is 1, type:

```
float circle_parameters[ 5, 1] PrintFP←
```

As you might expect, there must not be a space before the `[` character, and there must be at least one space after the `[` character. This is because

```
circle_parameters[
```

is defined as a space-delimited QED-Forth function in the `GETSTART.DLF` file, as explained later in this chapter.

All of the keywords that we learned about above can be used to fetch the contents of appropriately dimensioned arrays. Arrays that are dimensioned to hold character, integer, long, or float data are accessed using the **char**, **int**, **long** and **float** keywords, respectively, in front of the array name. If for some reason you use a **FORTH\_ARRAY** to hold 16-bit pointers, the **char\***, **int\***, **long\*** and **float\*** keywords can be used in a manner exactly analogous to the description in the earlier section of this chapter.

## Assigning Values to Static Variables and FORTH\_ARRAY Elements

You can interactively change the contents of any static variable or **FORTH\_ARRAY** element using the following assignment keywords:

```
=char    =int    =long    =float
```

Each of these keywords expects to be preceded by the address of a variable or **FORTH\_ARRAY** element, and expects to be followed by a valid number, variable name, or **FORTH\_ARRAY** element specifier. As expected, the value of the right hand side is assigned to the variable or array element on the left hand side of the assignment expression.

For example, to change the current value of radius to 22, simply type:

```
radius =int 22←
```

This syntax was designed to be similar to a C statement that assigns the value 22 to the radius variable. As you might guess, **=int** is a single keyword defined in QED-Forth, so there cannot be any spaces between **=** and **int**. Similarly, the other tokens in the expression must be separated by spaces; thus there is at least one space after **radius** and at least one space before **22**.

To set the current value of the floating point area variable to 1520, type:

```
area =float 1520.←
```

To assign the current value of the area variable to element [ 0, 1] in the **FORTH\_ARRAY** `circle_parameters`, you can execute:

```
circle_parameters[ 0,1] =float area←
```

To check that these operations actually worked, we can execute the following commands to examine the contents of the affected variables and array elements:

```
int radius U.←
float area PrintFP←
float circle_parameters[ 0,1] PrintFP←
```

## Under the Hood of the QED-Forth Interactive Debugger

This section is for the curious among you; you need not read or understand this section to use the QED-Forth interactive debugger. However, it will give you additional insight into the debugging environment.

### Variable Declarations

In the example above, **radius** is defined in the **GETSTART.DLF** download file as a QED-Forth constant whose value is the address of the radius variable. To see for yourself, use your editor to open the **GETSTART.DLF** file. Select “Open” from the editor’s “file” menu, set the “List Files of Type” option to either “Text Files” or “All Files”, and double click on **GETSTART.DLF** in the **\MOSAIC\DEMOS\_AND\_DRIVERS\MISC\C EXAMPLES** directory. The top portion of the file is the hexadecimal dump of the compiled C code in the Motorola S2 record format. Near the bottom of the file you’ll see some **CONSTANT** declarations. Among them is the declaration:

```
008E03 CONSTANT radius
```

which defines **radius** as a QED-Forth constant that places the hexadecimal value **8E03** on the stack. You can verify this by clicking on the Terminal window and typing:

```
HEX radius U.←
DECIMAL←
```

from the terminal. This command sequence instructs QED-Forth to print the hexadecimal address of the **radius** variable, and then return to decimal base. Note that if you want to pass the address of the **radius** variable as a parameter to a function (also known as *passing a pointer* or *passing by reference*), you leave out the **int** keyword before **radius** in the parameter list.

The keyword **int** is actually a QED-Forth function that examines the next token in the input stream; if it is already a number such as 5 or 3.2, **int** simply converts it to the nearest integer. If the next token is a variable address (such as **radius**), **int** extracts the 16-bit contents stored at the address. To see this behavior for yourself, try the following commands at your terminal:

```
int 5 U.←
int 5.45 U.←
int radius U.←
```

These three statements all yield identical results if the value of **radius** is still 5.

### Function Declarations

Returning to the **GETSTART.DLF** file that you opened in the editor, scroll to the area just above the list of **CONSTANT** definitions and you will see a set of lines starting with the **:** (colon) character. In Forth, the **:** character marks the start of a new definition (function or subroutine), and the **;** (semi-

colon) marks the end of the definition. These are the *function definitions* that tell QED-Forth the names and execution addresses of each function in **GETSTART.C** that was preceded by the **\_Q** declarator. Among these functions you will find some familiar ones including:

```
SetRadiusAndArea(
CalcArea(
DimAndInitFPArray(
PrintFPArray(
```

The body of each of these Forth definitions defines the compilation address and invokes the routine **CALL.CFN** (meaning *call-C-function*). **CALL.CFN** accepts an optional list of comma-delimited parameters terminated by a closing **)** and then sets up the stack frame and calls the function.

So when you type the interactive command

```
CalcArea( int radius)←
```

with a terminal enter key, here's what happens:

1. When QED-Forth accepts the carriage return, it starts interpreting the command line that has been entered. It looks for the first space-delimited token, and it finds the token:  
**CalcArea(**
2. It looks in its dictionary, and sure enough, it finds that this token has been defined; the definition was compiled when the **GETSTART.DLF** download file was sent to the QVGA Controller.
3. When QED-Forth executes the **CalcArea(** token, it executes the **CALL.CFN** routine which starts looking for a terminating **)** character, and processes any tokens that are present.
4. The next space-delimited token found is **int**, which looks for the next token (in this case, **radius**). Because **radius** is not a number, **int** assumes that it is a variable and extracts the 16-bit contents from the address that is left on the Forth data stack by **radius**. The contents are left on the Forth data stack.
5. The terminating **)** is found, so the **CALL.CFN** routine pushes the items on the Forth data stack onto the C stack in the proper order to make a legal C stack frame, and then executes the **CalcArea()** function as defined in the C program at the specified execution address.
6. When the **CalcArea()** function returns, QED-Forth traps its return value from the 68HC11's registers and prints the value using integer and floating point formats.

## **FORTH\_ARRAY Declarations**

Near the bottom of the **GETSTART.DLF** file you can find the definition of **circle\_parameters** that facilitates examining and modifying any element of this array. The QED-Forth definition is:

```
: circle_parameters[
  circle_parameters DO[]
;
```

As described above, the **:** character marks the start of a new definition, and the **;** marks the end of the definition. The body of the definition is simple: the constant **circle\_parameters** leaves the base address of the **FORTH\_ARRAY** structure on the stack, and **DO[]** does the rest of the work. **DO[]** is defined in the QED-Forth kernel; it searches for a row index followed by a comma, and a column

index followed by a terminating `]` character. Then it passes the specified row, column, and array parameter field address to the Forth function named `[]` (*brackets*) which places the 32-bit extended address of the array element on the stack. This extended address can be used as the argument to the familiar keywords that we have discussed such as `char`, `int`, `long`, `float`, `=char`, `=int`, `=long`, `=float`, etc. Thus all of the following are legal debugging commands:

```
float circle_parameters[ 3,0] PrintFP←  
circle_parameters[ 2,1] =float area←  
circle_parameters[ 5,0] =float 345.←
```

Some of you may have noticed that `CalculationTask[]` is also declared to QED-Forth as a potential `FORTH_ARRAY` in the `GETSTART.DLF` download file; yet we know that `CalculationTask` is a task identifier, not a `FORTH_ARRAY`. The reason for this is that Make Tool always declares the last variable allocated in the common RAM as a potential `FORTH_ARRAY`; it does this because there it can't determine the allocated size of the last variable. The extra definition of `CalculationTask[]` does no harm (as long as we don't try to use it improperly).

## Summary

The Make Tool calls the `QCC.EXE` executable program to create the QED-Forth debugging declarations that appear at the bottom of the `.DLF` download file. This program has to decide whether each compiler symbol in the `.OUT` file is a callable function, a variable, or a `FORTH_ARRAY`. The Make Tool identifies callable functions by detecting the `_pascal?` tag that the compiler places there in response to the `_Q` specifier, and in response prints the `functionname(` definition into the `.DLF` file. The Make Tool identifies variables by detecting whether the corresponding address lies in the common RAM area, and in response prints a QED-Forth `CONSTANT` declaration into the `.DLF` file. Finally, it tentatively identifies `FORTH_ARRAYS` by checking the size of each variable; if there are exactly 18 bytes allocated to one item in the common RAM, it decides that the associated name should also be declared as a `FORTH_ARRAY` by printing the `name[` definition in the `.DLF` download file. To be safe, the Make Tool always declares the last variable as a `FORTH_ARRAY` because it cannot be sure of its allocated size.

## Other Useful QED-Forth Functions

QED-Forth is a complete language that includes over a thousand pre-defined functions, all of which reside in ROM on the QVGA Controller. Many of these functions are declared in the header files in the `\MOSAIC\FABIUS\INCLUDE\MOSAIC` directory, and so are callable from C. The names and descriptions of these functions are detailed in the *Control C Glossary* in the documentation package. But there are also additional routines described there that are useful while debugging; these allow you to:

- Modify the contents of EEPROM on the 68HC11 processor.
- Dump the contents of a specified region of memory in hex and ascii format using the `DUMP` command.
- Specify a new (faster!) baud rate for the serial port to speed downloads using the `BAUD1.AT.STARTUP` command.

- Configure the QVGA Controller to execute a specified program each time a reset or restart occurs using the **AUTOSTART** command.
- Dump out a replica of the board's program memory space in Intel Hex or Motorola S2 record format to archive your production code.

In sum, the versatile QED-Forth language enhances the power of Control C by providing many operating system functions as well as an interactive debugging environment that speeds program development and testing.



# Chapter 4

## Chapter 4: Making Effective Use of Memory

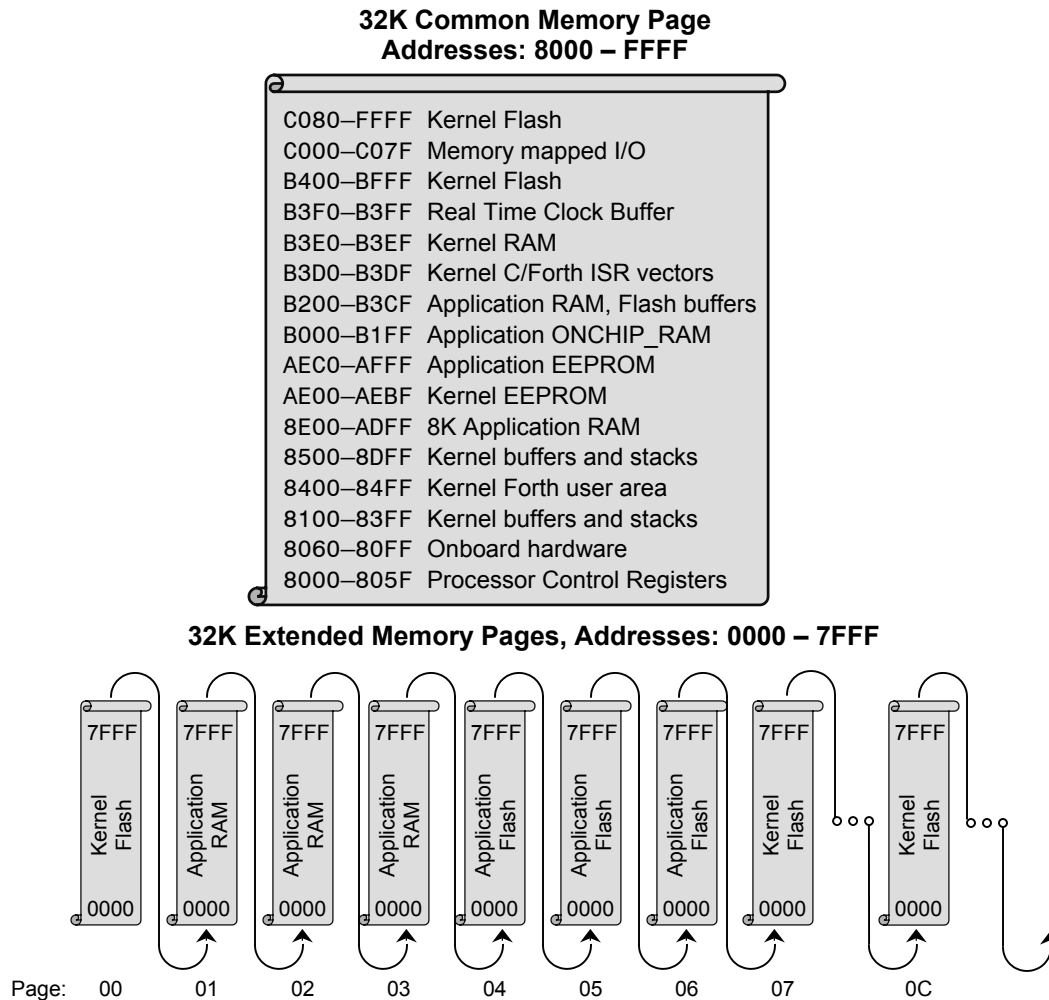
### The QVGA Controller's Memory Map

The QVGA Controller uses a paged memory system to expand the processor's 64Kbyte address space to 8 Megabytes of addressable memory. The top half (32 Kbytes) of the address space (at addresses 0x8000 to 0xFFFF) addresses a common memory page that is always visible (i.e., accessible using standard 16-bit addresses) to any code running, no matter where it resides in the memory space. The bottom half (32 Kbytes) of the address space (at addresses 0x0000 to 0x7FFF) is duplicated many times and addressed through the processor's 16-bit address bus augmented by an 8-bit page address. Together the address and page are held in a 32-bit data type, an *xaddress*.

A subroutine on any page can fetch or store to any address on the same page or in the common memory, or transfer control to another routine there. It "sees" a 64K address space comprising its own page at addresses from 0x0000 to 0x7FFF and the common memory at addresses 0x8000 to 0xFFFF. To address memory on another page, or to call a routine on another page, special memory access routines are used to change the page. The heap memory manager and array routines allow you to think of the paged memory as contiguous memory for data storage. The operating system automatically handles function calls and returns among the pages.

The operating system is designed so that there is very little speed penalty associated with changing pages..

Figure 4-1 illustrates the memory map of the QED Board. Briefly, the upper 32K of the 68HC11's address space, the *common memory*, is always accessible without a page change. In the lower 32K of the processor's address space, the operating system creates 256 pages of memory selected by an 8 bit on-chip port, with each page containing 32 Kbytes. The 32K of common memory at addresses 0x8000 to 0xFFFF (the upper half of the processor's memory space) is always accessible without a page change. Up to 256 pages (32K per page) occupy the paged memory at addresses 0x0000 to 0x7FFF. The first 9 pages of the QVGA Controller's 19 pages of installed memory are shown in the figure.



**Figure 4-1 The paged memory space of the QVGA Controller.**

## Common Memory

The *common memory* is addressed at locations 0x8000 – 0xFFFF. Some of it is used by the 68HC11 processor, some by the Forth kernel, and some is available for your programs to use. The processor's registers are located at 0x8000 – 0x805F, onboard hardware occupies addresses through 0x80FF, and the operating system reserves memory through location 0x8DFF for user areas, buffers, and stacks. For example, the default user area that runs the interactive Forth interpreter occupies 0x8400 – 0x84FF.

The 8 Kbytes at locations 0x8E00 – 0xADFF are available RAM for the user. The Control-C compiler uses this area for static variables, arrays, task areas, etc.

The processor's on-chip EEPROM (Electrically Erasable Programmable Read Only Memory) is located at 0xAE00 – 0xAFFF. Locations 0xAE00 – 0xAEBF are reserved by the operating system for use by the **SAVE** and **RESTORE** utilities, and for interrupt vectors. EEPROM at 0xAEC0 – 0xAFFF is available to your programs.

**Table 4-1 Partition of Flash and RAM among Kernel and Application Functions**

Function	Size	Memory Page	Memory Address	Physical Location
<b>Kernel Flash (160K)</b>				
Kernel	64K	00, 0C	0000 – 7FFF	QED Board S1
Kernel	1K	0E	various	QED Board S1
Kernel	19K	common	B400 – FFFF	QED Board S1
Kernel	12K	0F	0000 – 2FFF	QED Board S1
GUI Toolkit	64K	07, 0D	0000 – 7FFF	QED Board S1
<b>Kernel RAM (4K)</b>				
Kernel	3.5K	common	8000 – 8DFF	QED Board S2
Kernel	0.5K	0E	various	QED Board S2
RTC	48 bytes		B3D0– B3FF	68HC11
<b>Kernel EEPROM (192 bytes)</b>				
Kernel	192 bytes	common	AE00 – AEBF	68HC11
<b>Application Flash (224K to 608K)</b>				
Application code and graphic images	96K	04 – 06 (01– 03)	0000 – 7FFF	QED Board S1
Application code and graphic images	128K	70 – 73 (60 – 63)	0000 – 7FFF	QVGA Board
Application code and graphic images, available with extended memory option	384K	74 – 7F (64 – 6F)	0000 – 7FFF	QVGA Board
<b>Application RAM (253K to 637K)</b>				
C variables	512 bytes	common	B000 – B1FF	68HC11
C variables, available at runtime but used during download as a Flash write buffer	464 bytes	common	B200 – B3CF	68HC11
C Variables and task area, optionally battery-backed	8K	common	8E00 – ADFF	QED Board S2
Arrays and heap memory, optionally battery-backed	20K	0F	3000 – 7FFF	QED Board S2
Arrays and heap memory, optionally battery-backed	96K	01 – 03 (04 – 06)	0000 – 7FFF	QED Board S2
Arrays and heap memory	128K	60 – 63 (70 – 73)	0000 – 7FFF	QVGA Board
Arrays and heap memory, available with extended memory option	384K	64 – 6F (74 – 7F)	0000 – 7FFF	QVGA Board
<b>Application EEPROM</b>				
EEPROM Variables	320 bytes	common	AEC0 – AFFF	68HC11

**Notes:**

1. Pages not enclosed in parentheses indicate the *standard*, or run-time memory map; pages in parentheses indicate the addressing of the memory during program download, i.e., the *download* memory map.
2. The 128K RAM in socket S2 on the QED-Flash Board can be optionally battery-backed.
3. Pages 00, 07, 0C, 0D, 0E and a portion of 0F are reserved to the operating system (the Kernel).
4. Application code is free to reside on pages 01-06, 60-6F, and 70-7F.
5. Addresses from 8000 through FFFF comprise common memory that is visible to code on all pages.

The 68HC11's 1 Kbyte of on-chip RAM is located at 0xB000 – 0xB3FF. Locations 0xB3F0 – 0xB3FF are reserved for the real-time clock buffers. Locations 0xB3D0-0xB3DF are reserved for

support of Forth interrupt service routines called from C-compiled programs. Locations 0xB200 – 0xB3CF are reserved for the flash programming routines. Locations 0xB000 – 0xB1FF are always available to the programmer (this area is named **ONCHIP\_RAM** in the C linker command file; C programmers can locate data in this area using a **#pragma** directive).

Locations 0xB400 – 0xBFFF and 0xC100 – 0xFFFF contain kernel code. A *notch* at 0xC000 – 0xC07F is not decoded by any onboard devices, and provides a convenient place for the user to memory map I/O that must be accessed quickly (that is, without requiring a page change). Of course, an almost limitless amount of I/O can be mapped onto pages in the QVGA Controller's 8 Megabyte address space.

## Paged Memory

Occupying the paged memory space are 384K Flash and 256K RAM. Of the QVGA Controller's 384K of Flash, 224K is available for your application program and data storage. The remainder is used by the QED Forth Kernel for its multitasking operating system, debugger, interactive Forth compiler, assembler, and hundreds of pre-coded device driver functions. Of the 256K of RAM, 253K is available for application program use. Up to 128K of that can be optionally battery backed. An option is available that expands the installed memory to 768K Flash and 640K SRAM.

Table 4-1 illustrates the partitioning of the onboard memory between the operating system (Kernel) and your application functions. Most of the Flash memory is available as two blocks of contiguously addressable memory on pages 4-6 and 70-73. RAM for your application program is also available in the paged memory in two contiguously addressable chunks, filling pages 1-3 and 60-63. There is also 20K available RAM on page 0F, and approximately 9K in the common memory. This 9K is particularly important because it is used to hold C variables and task space for each separate task your application program sets up.

**Table 4-2 Partition of the Common Memory**

Address	Size (bytes)	Type	Function
C100 – FFFF	16128	Flash	Kernel – code
C000 – C0FF	256	I/O	Memory mapped I/O
B400 – BFFF	3072	Flash	Kernel – code
B3F0 – B3FF	16	RAM	Kernel – Real Time Clock Buffer
B3E0 – B3EF	16	RAM	Kernel
B3D0 – B3DF	16	RAM	Kernel – C/Forth ISR vectors
<b>B200 – B3CF</b>	<b>464</b>	<b>RAM</b>	<b>Application – C variables at runtime, Flash write buffer during program download</b>
<b>B000 – B1FF</b>	<b>512</b>	<b>ONCHIP_RAM</b>	<b>Application – C variables</b>
<b>AEC0 – AFFF</b>	<b>320</b>	<b>EEPROM</b>	<b>Application – nonvolatile storage</b>
AE00 – AEBF	192	EEPROM	Kernel
<b>8E00 – ADFF</b>	<b>8192</b>	<b>RAM</b>	<b>Application – C Variables and multitasking task areas, optionally battery-backed</b>
8500 – 8DFF	2304	RAM	Kernel – buffers and stacks
8400 – 84FF	256	RAM	Kernel – Forth user area
8060 – 83FF	928	RAM	Kernel – buffers and stacks
8000 – 805F	96	RAM	Kernel – processor Control Registers

Shaded entries indicate memory available for application programs.

The common memory is also partitioned between the operating system and application program. Table 4-2 shows the addresses used by the operating system, and in boldfaced type those addresses available to the application program.

## Addressing Memory in C

Although 8-bits are sufficient to address the 256 possible pages, the page is padded out to a more standard 16-bit data type so that the full address, lower 16 bits plus 16-bit page, occupies 32 bits. We'll refer to this full address as an *xaddress* (32-bit extended addresses). Three macros are available in the `\mosaic\fabius\include\mosaic\types.h` file to simplify the manipulation of *xaddresses* and their constituent 16-bit addresses and pages. These C macros are:

```
TO_XADDR
XADDR_TO_ADDR
XADDR_TO_PAGE
```

Multi-page C programs rely on a “page change” routine in the common kernel memory to call functions on other pages. Unlike the Forth compiler, the C compiler is not “page smart”, and does not know at compile time whether a page change is needed. In fact, page changes are rarely needed, because most functions call other functions that are located on the same page or in common memory. Calls to functions on the same page or to common memory take only 11.5 or 13.75 microseconds, respectively, while function calls to other pages require just under 49 microseconds. Because page changes are rare, the average execution speed of multi-page C applications is not significantly impacted by the need for page changes.

## Addressing Flash

Flash memory is nonvolatile, like PROM. Thus it retains its contents even when power is removed, and provides an excellent location for storing program code. Simple write cycles to the device do not modify the memory contents, so the program code is fairly safe even if the processor “gets lost”. But flash memory is also re-programmable, and the flash programming functions are present right in the QVGA Controller's onboard software library. These functions invoke a special memory access sequence to program the flash memory contents “on the fly”. This allows you to modify your operating software (for example, to perform system upgrades). You can also store data in the flash device. You can program from 1 byte up to 65,535 bytes with a single function call using the pre-coded flash programming routine. Programming time is approximately 60 milliseconds per kilobyte.

Six special functions facilitate access to Flash memory. Their function names are:

```
DownloadMap()  PageToFlash()  PageToRam()
StandardMap()  ToFlash()      WhichMap()
```

The FLASH programming functions use a buffer in the 68HC11's on-chip RAM starting at hex addresses B200-B3CF. The remaining on-chip RAM at B000 to B1FF is available to you. Also, because FLASH programming is generally not done at run-time, you can still use the Flash buffer for run-time variables.

## Software Development Using Flash Memory

Because code cannot be downloaded or compiled directly into flash memory, the flash memory map implements *page swapping* to provide a mechanism for getting the compiled code into the flash memory. There are two page-swap modes: one is called the Standard Map and the other is called the Download Map. As the names suggest, the Standard Map is used during run-time, and the Download Map is used during downloading C-compiler S-records from the PC to the QED Board. The two maps are very similar; the effect of changing from the Standard to the Download map is to swap the locations of pages between the flash and the RAM.

**Table 4-3 Addressing the Flash and RAM in Standard and Download Memory Maps**

	Flash Pages		RAM Pages	
Standard Address Map	04 – 06	70 – 7F	01 – 03	60 – 6F
Download Address Map	01 – 03	60 – 6F	04 – 06	70 – 7F

In normal operation the Flash memory is addressed on pages 04-06 and 70-7F, and the RAM is addressed on pages 01-03 and 60-6F. During download their addresses are swapped, so that the Flash is addressed at pages 01-03 and 60-6F and the RAM at pages 04-06 and 70-7F.

To see how it works let's consider a hypothetical download. Suppose you have compiled code intended to load into the Flash and run from it at addresses on page 4. Automated commands contained in the download file establish the download map, load the code into RAM, transfer the code to flash, and re-establish the standard map. In this case, the download file would:

1. Swap the addresses of the RAM and Flash (by executing the command **DOWNLOAD.MAP**) so that the RAM is now addressed on page 04;
2. Download the code to its proper addresses on page 04;
3. Copy the code (using the command **PAGE.TO.FLASH**) from page 04 into the Flash addressed on page 01; then,
4. Swap (by executing the command **STANDARD.MAP**) the RAM and Flash addresses back so that the Flash is now addressed on page 04, and the RAM on page 01 is available for run-time use by your program.

The Control-C download file does all this for you so you don't need to worry about the details. But if you're interested, just peruse the download file in the editor where you'll see the commands it uses to manage memory during the download process.

You can now run the program by typing

```
MAIN←
```

or any function name that was preceded with the `_Q` designator. (By the way, the `_Q` does not compromise performance in any way; it simply makes it possible for the PC-resident batch routines to

send out the execution addresses of the designated functions to the QVGA Controller to simplify debugging).

## Locating Nonvolatile Data in EEPROM

The QVGA Controller's built-in EEPROM provides an ideal place to store calibration constants or other data that must be changed from time to time, but that must be retained even when power is removed. The EEPROM (Electrically Erasable Programmable Read-Only Memory) can be modified up to 10,000 times before it loses its ability to retain data. The **ANALOGIO.C** file presents an example of how to locate a static "variable" in EEPROM.

The EEPROM variable should be declared as an un-initialized static variable; these are located by the linker in the "data" section, which normally points to system RAM where normal variables are stored. By following the syntax presented here, you can relocate the data section to point to EEPROM while defining the EEPROM variables, and then restore the data section to its standard RAM location. To define an EEPROM variable, use the following code:

```
#pragma option data=.eeprom // put the following variables in eeprom
static uchar numsamples;
static int  nonvolatile_int;
static float calibration_value;
#pragma option data=.data // restore the data area to RAM
```

The **#pragma** statements are pre-processor directives that are interpreted by the linker. In the code fragment above, we located three nonvolatile variables in EEPROM; note that we did NOT include initializers in the declaration statements. Initializers don't make any sense for EEPROM variables, because special functions must be called to store values into EEPROM, so initialization can't be accomplished by placing initialization data in the download file. These EEPROM variables must be initialized programmatically at run-time.

To store data into the EEPROM variables, use the following functions which are declared in the **XMEM.H** file in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory:

```
void StoreEEChar(char value, char* addr)
void StoreEEInt(int value, int* addr)
void StoreEELong(long value, long* addr)
void StoreEEFloat(float value, float* addr)
```

To learn how to interactively modify the contents of EEPROM variables, read the glossary entries for these functions in the Control-C Glossary.

These EEPROM storage functions are easy to use. For example, to store the value 123 into the character variable **numsamples**, you would place the following statement in your program:

```
StoreEEChar( 123, &numsamples);
```

To avoid wearing out the EEPROM by executing unneeded write cycles, these functions check whether each EEPROM byte already holds its specified contents. If so, the write is not performed. Thus there is no penalty for redundant execution of commands that initialize particular locations in EEPROM.

While EEPROM variables *must* be initialized programmatically at run-time the first time they are used, they don't need to be re-initialized each time the processor starts up because the nonvolatile EEPROM retains the data. Even so, initializations can be performed every time the processor starts up, with no adverse effects on the life span of the EEPROM. For example, initialization code in an autostart routine could execute ATTACH functions to ensure that all needed interrupt vectors are properly initialized each time the processor restarts. If the EEPROM cells have been corrupted for some reason, the ATTACH command installs the correct contents, but if the specified interrupt vector information is already in the EEPROM, the memory cells are not needlessly rewritten.

### ***Interrupts are disabled during writes to EEPROM***

All of the EEPROM storage routines globally disable interrupts while each EEPROM byte is being programmed, and it takes 20 milliseconds to program each byte. Thus you should avoid storing values in EEPROM while time-critical events are being serviced by interrupts.

For experts and the curious: Interrupts are disabled during stores to EEPROM because QED-Forth vectors all interrupts via the EEPROM, and the 68HC11 hardware does not allow any EEPROM cells to be read while a single EEPROM cell is being written to. Thus if an interrupt occurs while one of the EEPROM storage functions is writing to EEPROM, the interrupt will not be able to read the instruction code in the interrupt vector. Disabling interrupts prevents this error, but the interrupt service is delayed until the EEPROM write is finished.

## **Write-Protecting EEPROM**

It is possible to write-protect locations within the EEPROM to ensure the integrity of calibration constants or other vital information. This is done using the EEPROM block protect register named **BPROT** (MC68HC11F1 Technical Data Manual, p.8-2). Four blocks of size 32, 64, 128, and 288 bytes may be individually protected by storing an appropriate configuration value to **BPROT**. The contents of the **BPROT** register may be changed using the C function **InstallRegisterInits**; please consult its glossary entry for details.

To make a turnkeyed application maximally “bullet-proof” and fail-safe, consider using the **BPROT** register to protect the first three blocks in the EEPROM totaling 224 bytes. This protects the on-board kernel's configuration region (the first 32 bytes in EEPROM) plus the interrupt vectors (the next 160 bytes in EEPROM) plus an additional 32 bytes available to the programmer. The remaining 288 bytes of EEPROM then remain available for modification by the application program.

# **Using C Arrays and Forth (Kernel) Arrays**

## **Storing Data Acquisition Results in C Arrays and Forth Arrays**

Programs written in Control-C use space in common memory to store variables. You may store simple variables or arrays of variables there using standard C syntax. However, common memory is limited to approximately 9K. It can get used quickly in multitasking systems because each task requires a task area of about 1K. Consequently, the programmer may require access to additional

RAM. Access is provided through the use of Kernel Arrays, also called Forth Arrays. Using Forth Arrays you may dynamically dimension arrays of virtually any size in the extended address space – and their memory allocation is automatically handled by the kernel's heap memory manager.

The code presented in the sample program **ANALOGIO.C** uses a C array and a **FORTH\_ARRAY** to store the results of multiple A/D conversions. This section uses that code as an example to discuss some interesting features of both C Arrays and **FORTH\_ARRAYS**.

## Declaring a C Array

The use of C arrays is discussed in detail in all standard C texts. In this program, the one-dimensional 16-element character array named **results\_8** is declared and allocated in RAM using the statement:

```
uchar results_8[DEFAULT_NUMSAMPLES];
```

where **DEFAULT\_NUMSAMPLES** is a constant equal to 16. The arrays are easy to use. For example, the following C statement assigns the last element in the array to a static variable named **my\_variable**:

```
my_variable = results_8[15];
```

To see another simple example that demonstrates how C arrays are accessed, look at the **InitAnalog()** function in the **ANALOGIO.C** file. The **results\_8** array is zeroed by executing the following statement:

```
for(i=0; i< DEFAULT_NUMSAMPLES; i++)
    results_8[i] = 0;          // zero the array
```

Note that this array is dimensioned and allocated by the compiler and linker. In contrast, **FORTH\_ARRAYS** are dimensioned and allocated dynamically by the run-time program itself.

## Converting a 16 Bit Address to a 32 Bit xaddress

The **AD8ToCArray()** function that we just used provides an interesting example of type conversion. The definition of the function is:

```
_Q void AD8ToCArray( int channel)
{
    EXTENDED_ADDR buffer;
    buffer.sixteen_bit.addr16 = results_8;
    buffer.sixteen_bit.page16 = 0;
    AD8Multiple(buffer.addr32,0,DEFAULT_NUMSAMPLES,channel);
}
```

The purpose of **AD8ToCArray()** is to properly call **AD8Multiple()** which is defined in the **ANALOG.H** file. **AD8Multiple()** is optimized to use a **FORTH\_ARRAY** buffer, and so expects a 32 bit buffer xaddress instead of a simple 16 bit buffer address. To convert the simple 16 bit address returned by **results\_8** into a 32 bit extended address, we take advantage of the **EXTENDED\_ADDR** union defined in the **TYPES.H** file in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory. The union is defined as:

```
typedef union{    xaddr addr32;
    struct{ uint  page16;
    char*  addr16;
```

```
    } sixteen_bit;  
    } EXTENDED_ADDR;
```

To convert a 16 bit address into a 32 bit xaddress, we use the **EXTENDED\_ADDR** typedef to declare an instance of the union (named “**buffer**” in this example), store the 16 bit address into the **buffer.sixteen\_bit.addr16** element, and store 0 (the default page) into the **buffer.sixteen\_bit.page16** element. Then we reference the corresponding 32 bit xaddress via the **buffer.addr32** element of the union. While it is rare that you will have to convert from 16 bit to 32 bit address types, this example provides a template for how to do it.

## ***A Review of FORTH ARRAYS***

**FORTH\_ARRAYS** have two key advantages. First, they are allocated in paged memory, so they allow your program to access the large 8 Megabyte memory space of the QED Board. In contrast, C arrays must reside in the available common RAM which is limited to approximately 9 kilobytes on the QVGA Controller. Second, they can be dynamically dimensioned, re-dimensioned and de-allocated (deleted) while your program is running; this boosts efficiency by maximizing the use of the available memory.

To define a new Forth Array, simply use the **FORTH\_ARRAY** typedef followed by a name of your choice. For example, in the **ANALOGIO.C** file the following declaration appears:

```
FORTH_ARRAY  results_12;
```

Before the **FORTH\_ARRAY** can be accessed at runtime, it must be dimensioned. This is typically accomplished by calling the **DIM()** macro defined in the **ARRAY.H** header file. For example, to dimension the **results\_12** array to have 10 rows and 1 column of integer data, we would execute:

```
DIM(int, 10, 1, results_12);
```

In the **ANALOGIO.C** file, the pre-defined macro named **DIM\_AD12\_BUFFER()** invokes the **DIM()** routine for us (its definition is in the **ANALOG.H** file in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory).

After the **FORTH\_ARRAY** is dimensioned, it can be accessed by a family of macros and functions that are defined in the **ARRAY.H** header file and are described in the Control-C Glossary. These include functions that fetch from, store to, and calculate the address of individual elements, swap and copy entire arrays, fill an array with a specified character, and delete the array so that it no longer requires memory in the heap. The **PrintForthArray()** and **InitAnalog()** functions in **ANALOGIO.C** provide examples of how to call a few of these functions.

## ***Printing the Contents of a FORTH ARRAY***

The **PrintForthArray()** function presented in **ANALOGIO.C** is a more general version of the **PrintFPArray()** function in **GETSTART.C** as discussed in an earlier chapter. The function is defined as follows:

```
_Q void PrintForthArray(int float_flag, FORTH_ARRAY* array_ptr)  
// works for FORTH_ARRAYS dimensioned using the standard DIM() macro.  
// float_flag is true if array holds float numbers, false otherwise.  
{ int r, c;  
  putchar('\n');
```

---

```

for (r = 0; r < NUMROWS(array_ptr); r++)          // for each row
{   for (c = 0; c < NUMCOLUMNS(array_ptr); c++) // for each column
    if(float_flag)
        printf("%9.4g  ",FARRAYFETCH(float,r,c,array_ptr));
    else
        printf("%9ld  ",ARRAYFETCH(long,r,c,array_ptr));
    putchar('\n');          // newline after each row is printed
    PauseOnKey();          // implement xon/xoff output flow control
}
}

```

After calling **putchar()** to output a newline character, we enter nested **for()** statements that print the contents of each element. Because the compiler treats floating point numbers differently than numbers stored in other formats, we use **FARRAYFETCH()** to access floating point arrays, and **ARRAYFETCH()** to access **char**, **int** or **long** arrays. The **PauseOnKey()** function is called once per row to suspend the QVGA Controller's printed output if the terminal program has sent the **XOFF** handshake character; the printout resumes when the terminal sends the **XON** character. **PauseOnKey()** also gives the user the ability to terminate the printout by typing a carriage return character from the terminal.

This function can be tailored to meet the detailed needs of your application. You can change the **printf()** formatting, or insert extra carriage returns to confine the printout to one screen width.



# Chapter 5

## Chapter 5: Programming the Graphical User Interface

*The Graphical User Interface (GUI) Toolkit is a suite of programming tools that gives you the ability to build an informative and interactive graphical user interface to monitor and control your instrument. This chapter*

- ⇒ *Introduces the structure of the GUI Toolkit;*
- ⇒ *Takes you on a step-by-step guide to building your interactive application; and*
- ⇒ *Provides you with detailed descriptions of each component of the GUI Toolkit.*

### The Structure Of The GUI Toolkit

A graphical user interface is created from building blocks such as bitmapped images and ASCII strings. These building blocks, or data, must be organized in an intuitive way so users can easily run your instrument. Object oriented concepts are the key to organizing this data and make it easy for you to design and implement your user interface. Object oriented programming allows you to organize data hierarchically based on objects and manipulate the data using methods. With the GUI Toolkit, it is simple to create elementary objects such as graphics that contain bitmapped image data and textboxes that contain ASCII string data. You can load those objects into other objects such as screens so that they can be shown on the display. You can create yet another type of object, a control, which can execute functions that acquire data from a user or actuate hardware when a user touches the touchscreen. A button is one kind of a control.

### A Closer Look At Objects

The two concepts of object oriented programming essential to modern programs with user interfaces are “Objects” and “Events”. An object is an association of *properties* and *methods*, and may respond to *events*. An *event* is an external action that prompts an object into action. GUI Toolkit objects that can respond to events are called *controls*.

#### **Properties**

Properties describe an object’s physical attributes like its size, location, or image. Objects contain a data structure that holds its properties. Properties generally don’t do anything by themselves; they are more like read/write variables. However, properties may qualify the object’s behavior when the object does do something or has something done to it.

Some properties may be read only while others may be read/write. GUI Toolkit properties are always 32-bit numbers and are accessed or modified by calling the methods **Get\_Property** or **Set\_Property**. **Set\_Property** requires a reference to an object, its property, and the new value, while **Get\_Property** requires a reference to an object and its property as parameters and returns the property value.

## Methods

Methods are actions the object can do or have done to it. Many methods, like **Load**, are overloaded; that is, they are applicable to several different types of objects. For example, you can *load* buttons, graphics, and textboxes into a screen. Overloaded methods allow you to use a single simple syntax with respect to many different objects.

## Events

Events are external actions that an object responds to by executing a user defined function called an *event procedure*. Objects automatically recognize a predefined set of events, it is up to you to decide if and how they respond to those events. You specify the event procedure called when the event happens (or *fires*) by storing your function into the appropriate property using **Set\_Property**. Event procedures are written, for example, to specify the program actions that occur in response to the press of a button.

## The GUI Toolkit Objects

The following table lists the objects in the GUI Toolkit.

Object	Description
GUI_TOOLKIT	The central object that contains properties relevant to all other objects.
GUI_DISPLAY	The object tied to the physical display.
GUI_SCREEN0 to GUI_SCREEN5	An object that contains a collection of other functionally related objects such as graphics, textboxes, buttons, and plots.
GUI_TOUCHSCREEN	The object tied to the physical touchscreen.
GUI_PEN	A tool object that is used in conjunction with the Draw method to draw lines and geometrical figures onto screens.
GUI_BUZZER	The object tied to the physical buzzer.
GUI_FONT	The 8-pixel wide by 10-pixel tall Courier New font that is used to render strings in textboxes by default for the GUI Toolkit.
GRAPHIC	An object that contains a single image as a property.
FONT	An object that contains a single image of the 95 ASCII characters that is used to render strings in textboxes.
TEXTBOX	An object that uses a font object to render strings onto a screen.
BUTTON	An object with an associated graphic that responds to a user's touch on the touchscreen.
PLOT	An object used to render numerical data into graphical form onto a screen.

Some of these objects are created when you initialize the GUI Toolkit while others are created by functions that you write. All GUI objects reside in their own task with their own heap and some respond to events. In the next section, we'll show you how to create your user interface and then how to write your application using the GUI Toolkit.

## Building Your Application

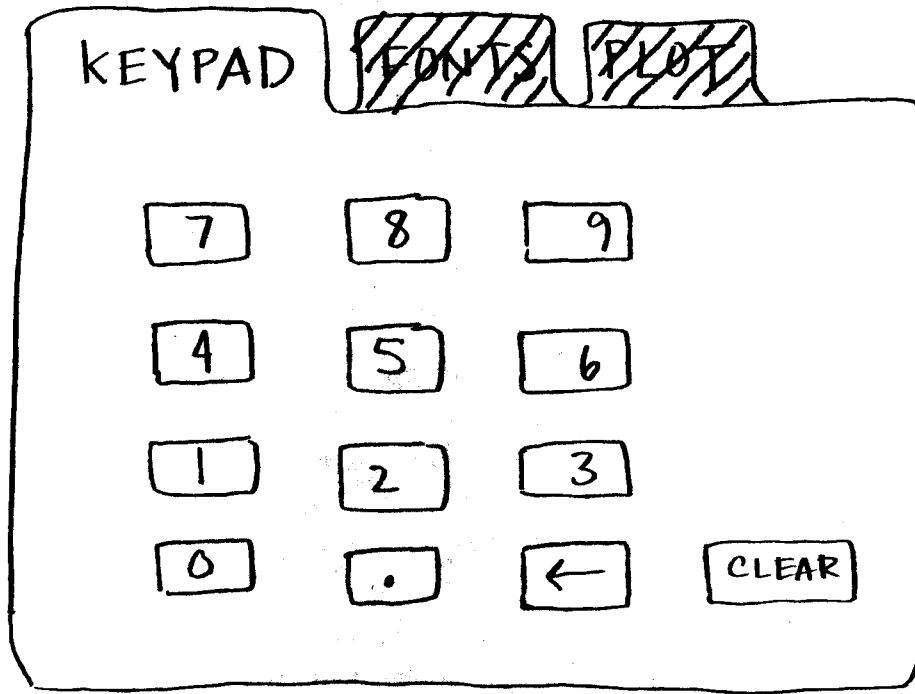
In this section, we'll explore the GUI Toolkit in the order in which you would typically build your application. We'll show you how to:

- Design and create your user interface on a PC;
- Transfer the images that you created for your user interface from the PC to the QVGA Controller;
- Write your application using the demo program as a reference guide;
- Handle errors; and,
- Expand the capabilities of the GUI Toolkit.

The demo program shows you how to build a multitasking application with three simple screens. The first screen is a numeric keypad that allows you to enter up to 20 digits and render them in a textbox. The second screen displays three different size Courier New fonts ranging from the default font of 8 pixels wide by 10 pixels tall to a large font that is 32 pixels wide by 40 pixels tall. The third screen plots an 8-bit A/D input every 10 seconds. As we describe each part of the GUI Toolkit, we'll use the numeric keypad screen of the demo to illustrate the important concepts.

## Designing Your User Interface

Before you start coding your application, it's a good idea to sketch out how you want your user interface to look. Figure 5-1 shows a rough sketch of the first screen of the demo program. Sketching out your user interface before you start programming will help you to think about how you want your application to be organized and how you want to present information to your user.



**Figure 5-1** The sketch of the first screen of the demo program.

### ***Drawing Your Screens***

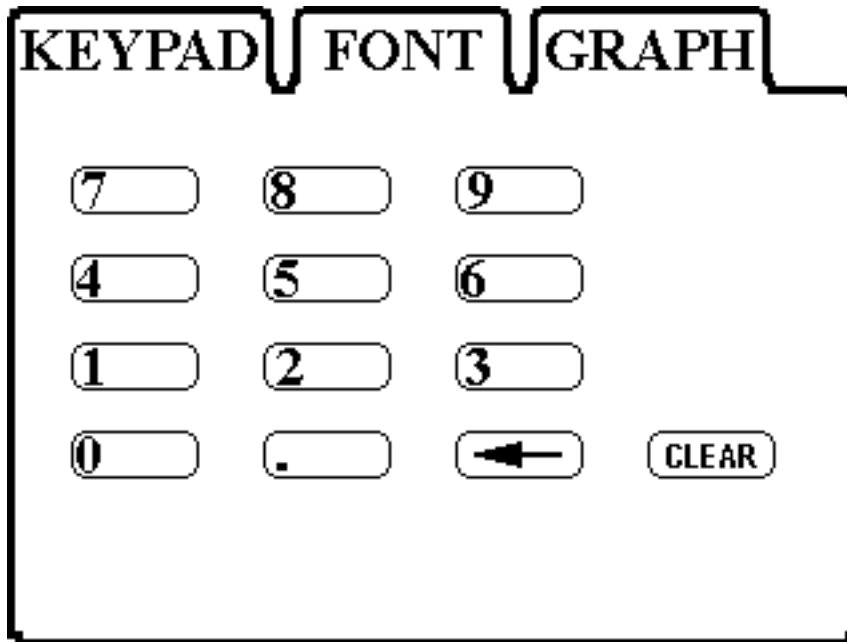
Once you've sketched out and designed your user interface, you need to create bitmapped images of your interface using an image-editing program. Images may be created using Microsoft Paint, which is included with all versions of Windows. You can also use other image-editing programs such as Corel Draw, Photoshop, and Paint Shop Pro. In this section and throughout this chapter, we provide step-by-step instructions for creating and manipulating images using Photoshop. However, all of the image-editing programs have similar tools and functionality. For example, the pencil tool in Photoshop is simply called the pencil in Paint and the line tool in Photoshop is called the line in Paint. Thus, the steps listed in the examples, although specific to Photoshop, apply to all image-editing programs.

To create an image of a screen from your sketch using Photoshop:

1. Create a new file with a width of 320 pixels and a height of 240 pixels, a resolution of 72 pixels per inch, and using the bitmap image mode. 320x240 is the size of the display and the size of a screen. The resolution is not important because it refers to the number of pixels per inch for the monitor. However, the image mode is important and must be set to bitmap if you are using a monochrome or EL display. This configures the image to have one bit per pixel.
2. Draw all lines using the pencil tool with a brush size of one pixel. The line tool, paint brush tool, and airbrush tool are also useful in drawing shapes and patterns.
3. Draw text using the type tool.

4. Save the image as a windows bitmap. A dialog box may appear informing you that some image data, such as printer settings, cannot be saved with this format. This does not effect the image so you can just click on OK.

The image that we created based on the sketch in Figure 5-1 is shown in Figure 5-2 .



**Figure 5-2** The bitmap image of the first screen of the demo program that was created using Adobe Photoshop.

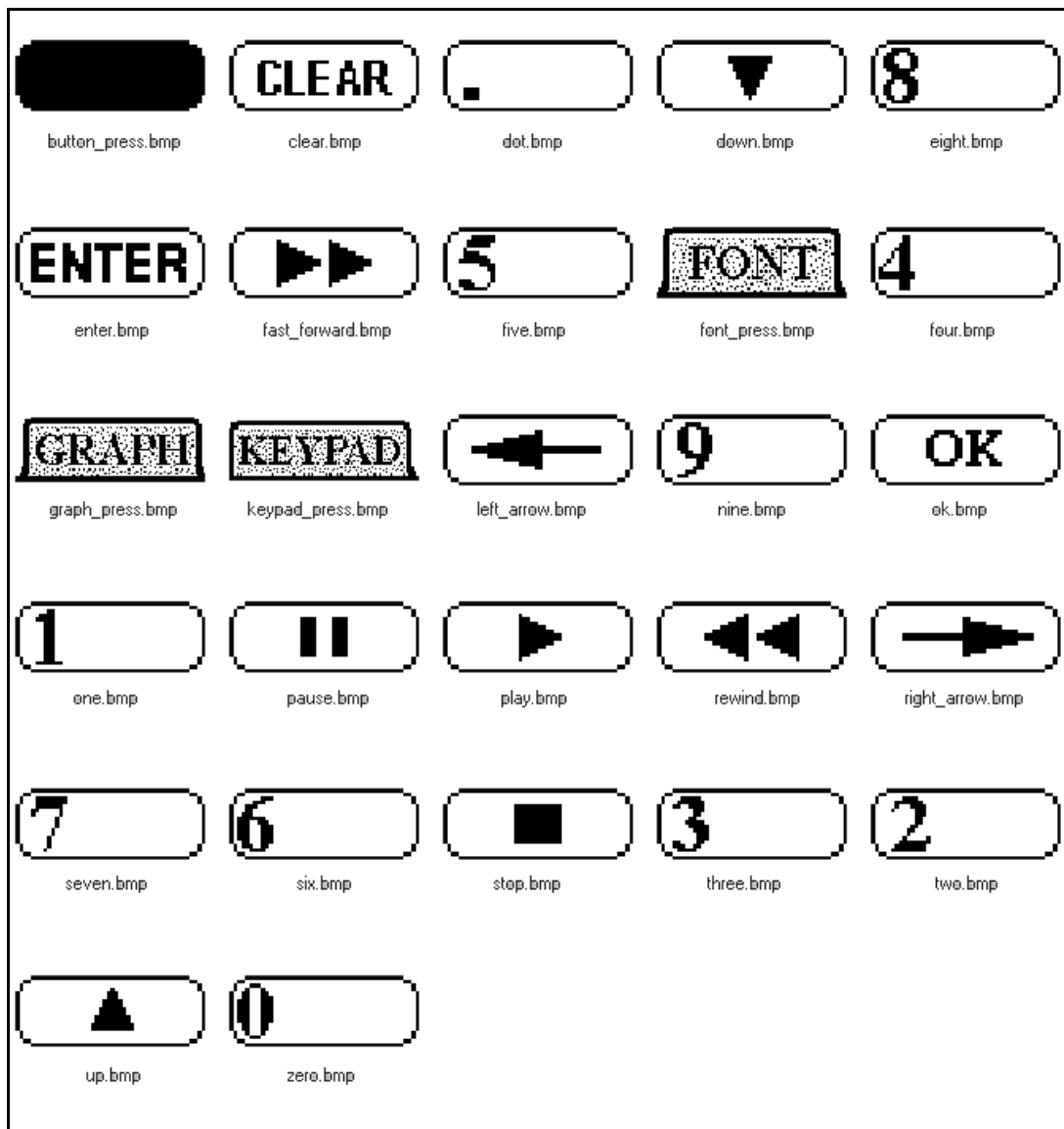
### ***Creating Your Images***

Once you have created the screens for your user interface, you need to ungroup them. Ungrouping the screens into smaller images will allow you to save space in Flash memory since you don't want to store images with a lot of white space. It will also allow you to associate the images with individual buttons. To ungroup an image using Photoshop:

1. Select the marquee tool;
2. Left click on the upper left corner of an image you want to ungroup and drag the mouse pointer to the lower right corner of the image. This will create a box with a moving dashed line around the image;
3. Note the location of the upper left corner of the image; this location will be needed when you want to load a graphic containing the image onto a screen;
4. Under the Edit Menu, select the cut option to move the image to the clipboard. The image will disappear from the screen;
5. Under the File Menu, select the create new file option;

6. Name the file, based on the image. The height and width will automatically be set to the height and width of the image that is in the clipboard;
7. Under the Edit Menu; select paste; and,
8. Save the ungrouped image in the Windows bitmap format.

The width of an image must be a multiple of 8 pixels and the image must be positioned on an 8 pixel horizontal grid in a screen. Finer horizontal pixel placement and image widths would require bit shifting of each byte of the image every time it is drawn, significantly slowing performance of the GUI Toolkit. There are no limitations on the height of an image or the placement of an image in the vertical direction.



**Figure 5-3** The images included with the demo program that you can use in your application.

The demo program also provides a set of images that you can use with your application. The images are shown in Figure 5-3 .

## Transferring Your Images to the QVGA Controller

Once you have ungrouped all the images for your user interface, assemble them into a single directory. Images must be processed before you can use them with the GUI Toolkit; Mosaic's Image Conversion Program concatenates images into a single text file called an *Image Data File*. The Image Data File is stored in the same directory as your images and when it is transferred to the QVGA Controller, it stores your image data in RAM and then copies it into Flash. You must transfer the Image Data File using QEDTerm, Mosaic's Terminal Program, to the QVGA Controller before you transfer your application code. For more information on the Image Conversion Program, see the section on the Image Conversion Program .

### The Image Header File

An *Image Header File* is also created with the Image Conversion Program and stored in the same directory as your images. The Image Header File associates the names of your images with the location of their image data in Flash. The Image Header File must be included in your application in order for you to create graphic objects.

The following shows the first few lines of the Image Header File used by the demo. The Image Header File defines a few constants, named after the image files `down.bmp`, `button_press.bmp`, and `one.bmp` shown in Figure 5-3 . The constants contain the addresses of the image data in Flash memory on the QVGA Controller. For more information on the memory map of the QVGA Controller see *Chapter 4: Making Effective Use of Memory*.

**Listing 5-1** The first few lines of the Image Header File.

```
#define BOTTOM_EDGE_BMP 0x700000
#define BUTTON_PRESS_BMP 0x700110
.
.
.
#define ONE_BMP 0x705806
```

## Coding Your Application

Once you have designed and built the user interface for your application and you have transferred the images to the QVGA Controller, you can start writing the code to animate your instrument. All GUI applications need the following components:

- ☒ The pre-loaded GUI Toolkit driver software;
- ☒ The Image Data and Image Header Files from the Image Conversion Program;
- ☒ An initialization routine that initializes the GUI Toolkit and sets up a task to run your application's user interface.
- ☒ Routines that create and configure objects;

- ☑ Event procedures that animate controls; and,
- ☑ Routines that load objects onto screens.

Each of these components are described in the following sections.

### ***The GUI Toolkit Driver Software***

The GUI Toolkit driver software is pre-installed on your QVGA Controller. However, you will need to copy the library files (which define constants, structures, and headers for the GUI Toolkit methods) to the same directory as your source code as described below. To reload the driver software, please see section XX.

The GUI Toolkit driver software is provided as a pre-coded modular runtime library, known as a “kernel extension” because it enhances the on-board kernel's capabilities. The library functions are accessible from C and Forth.

The kernel extension for the GUI Toolkit is available from Mosaic Industries on the Demo and Drivers media (diskette or CD). Look in the Drivers directory, in the subdirectory corresponding to your hardware, in the GUI Toolkit folder.

The kernel extension is shipped as a “zipped” file named “packages.zip”. Unzipping it (using, for example, winzip or pkzip) extracts the following files:

- ☐ readme.txt - Provides summary documentation about the library.
- ☐ install.txt - The installation file, to be loaded to COLD-started QED Board.
- ☐ library.4th - Forth name headers and utilities; prepend to Forth programs.
- ☐ library.c - C callers for all functions in library; #include in C code.
- ☐ library.h - C prototypes for all functions; #include in extra C files.

Library.c and library.h are only needed if you are programming in C. Library.4th is only needed if you are programming in Forth. The uses of all of these files are explained below.

We recommend that you move the relevant files to the same directory that contains your application source code; the references to the library files in the demo assume the library files are in the same directory as the source code.

#### Using the Driver Code with C

Move the library.c and library.h files into the same directory as your other C source code files and use the following directive in your source code file:

```
#include "library.c"
```

This file contains calling primitives that implement the functions in the kernel extension package. The library.c file automatically includes the library.h header file. If you have a project with multiple source code files, you should only include library.c once, but use the directive

```
#include "library.h"
```

in every additional source file that references the GUI Toolkit functions.

Note that all of the functions in the kernel extension are of the `_forth` type. While they are fully callable from C, there are two important restrictions. First, `_forth` functions may not be called as part of a parameter list of another `_forth` function. Second, `_forth` functions may not be called from within an interrupt service routine unless the instructions found in the file named

`\fabius\qedcode\forthirq.c`

are followed.

**NOTE: If your compiler was purchased before June 2002, you must update the files, `qlink.bat` and `qmlink.bat` in your `/fabius/bin` directory on your installation before using the kernel extension. You can download a zip file of new versions from [http://www.mosaic-industries.com/Download/new\\_qlink.zip](http://www.mosaic-industries.com/Download/new_qlink.zip)**

**The two new files should be placed in `c:\Fabius\bin`. This upgrade only has to be done once for a given installation of the C compiler.**

### ***Using the Image Data and Image Header Files***

Before writing your application code, be sure to transfer the Image Data File, created with the Image Conversion Program, to the QVGA Controller. Then, be sure to include the Image Header File in your application as shown below:

***Listing 5-2 The first few lines of the demo program.***

```
#include <\mosaic\allqed.h> // Include all of the Mosaic utilities.
#include "library.c"        // Include the headers for the GUI Toolkit's methods.
#include "image_header.h"   // Include constants that define location of your images
```

### ***Writing Your Application's Initialization Routine***

The initialization routine of your application needs to initialize the GUI Toolkit and setup a task to control the GUI Toolkit before any GUI Methods are called.

**`Initialize_GUI` must be called before any other GUI method!**

To initialize the GUI Toolkit, call `Initialize_GUI`, passing it a heap start address and a heap end address as shown in the demo.

***Listing 5-3 Initializing the GUI Toolkit***

```
#define GUI_HEAP_START 0x0F3000L
#define GUI_HEAP_END   0x0F6FFFFL
.
.
void main( void )
{
    Initialize_GUI ( GUI_HEAP_START, GUI_HEAP_END );
    .
    .
}
```

**Initialize\_GUI** performs three actions: it sets up a heap memory structure for the GUI Toolkit; it sets up and activates a task for the GUI Toolkit; and it configures several critical objects, called the GUI Toolkit's *pre-instantiated* objects.

All GUI objects and their associated properties are stored in a heap accessed only by the GUI Toolkit. This GUI Heap can be located in any contiguous block of RAM (i.e. it may span consecutive pages of RAM) but it is typically placed on page 0x0F from 0x3000 to 0x6FFF as shown in the example above. The size of the heap that is needed by the GUI Toolkit depends on your application. As a benchmark, the demo program uses approximately 4k of heap space. Because all objects are stored in the GUI Heap, it is easy to add, modify, or resize objects without worrying about the specifics of their memory allocation.

The GUI Toolkit runs in a stand-alone task called the GUI Task. The GUI Task executes an endless loop that:

- continuously checks to see if new objects need to be created or existing objects need to be modified;
- polls the touchscreen looking for events;
- services events when they occur; and,
- calls **Pause**.

When a touchscreen event occurs, the GUI Task sends a message indicating that the event procedure of the responsible control should be executed. **Service\_GUI\_Events** listens for messages from the GUI Task and executes the appropriate event procedure when commanded.

**Service\_GUI\_Events** must be included in the infinite loop of a task that you create (separate from the GUI Toolkit's Task) as shown in the following example. This task should also be in charge of creating and initializing the objects for your application.

#### Listing 5-4 Servicing GUI Events

```
TASK taskbase;
.
.
void GUI_Monitor ( void )
{
    .
    .
    while(1)
    {
        .
        .
        Service_GUI_Events();
        Pause();
    }
}
void main( void )
{
    Initialize_GUI ( GUI_HEAP_START, GUI_HEAP_END);
    .
    .
    Init_Keypad();                // create & init objects for keypad
    .
    .
    BUILD_C_TASK(0, 0, &taskbase); // build task
```

```

    ACTIVATE( GUI_Monitor,&taskbase); // activate task
    StartTimeslicer();                // starts elapse time clock, enables interrupts
    Pause();                          // start next task immediately
}

```

The GUI Toolkit is a resource whose access must be controlled. Only the GUI Toolkit (running in the GUI Task) polls the touchscreen, writes to the display, creates objects, or modifies objects. We recommend that you use only one task to run the your application's user interface so that only one task interacts with the GUI Toolkit. However, if multiple tasks in your application need to use the GUI Toolkit, you must use the resource variable **gui\_resource** to assure that only one task accesses the GUI Toolkit at a time. See section XX for more information on using resource variables or the glossary entry for **gui\_resource**.

The GUI Task should have an opportunity to run approximately once every 15 milliseconds. Calling the GUI Task more frequently will not improve performance because the GUI Task polls the processor's free running counter, TCNT, to assure it is not called more than once every 10 milliseconds. Calling the GUI Task less frequently will not cause any errors but may result in sluggish performance. The GUI Task takes approximately one millisecond to execute if no events occur, no new object needs to be created, and no existing object needs to be modified. When an event fires, the time the GUI Task takes to execute is proportional to the number of items that are loaded onto the visible screen. For a screen with 15 objects, it will take approximately 5 milliseconds to pass the event to the responsible control. Additional time is required if the responsible control has an image that has to be redrawn.

### ***The GUI Toolkit's Pre-Instantiated Objects***

The GUI Toolkit has a set of special objects that are created and configured only when you initialize the GUI Toolkit. These special objects are called the pre-instantiated objects because they are *instantiated* or created before the GUI Toolkit starts its task. These objects include the GUI Toolkit itself, the display, six predefined screens, the touchscreen, the pen, the buzzer, and the default font. You can not create additional instances of these objects because they are tied to a specific piece of hardware or unique function of the GUI Toolkit.

The GUI Toolkit is itself an object with properties that influence the operation of the GUI Task and all other objects. The GUI Toolkit Object is called the **GUI TOOLKIT** and has properties that determine how objects such as graphics and controls are loaded into screens, whether touchscreen events are serviced, and the behavior of the GUI Task when an error occurs.

The Display Object is called the **GUI\_DISPLAY**, and is tied to the physical display. Properties of the **GUI\_DISPLAY** control the behavior of the display such as blanking and inverting. The **GUI\_DISPLAY** contains six pre-instantiated screens called **GUI\_SCREEN0** to **GUI\_SCREEN5**. A property of GUI Screens is their Visibility property. Only one of the GUI Screens may be made visible at a time. When it is made visible, the other GUI Screens are automatically made not visible and the display suddenly shows the visible screen's objects. GUI Screens are the only objects that are shown on the physical display. To show an object like a graphic on the display, the object must be loaded into the visible GUI Screen. The visible screen after **Initialize\_GUI** is called is **GUI\_SCREEN0**.

The Touchscreen Object is also known as the **GUI\_TOUCHSCREEN** and corresponds to the physical touchscreen. The **GUI\_TOUCHSCREEN** generates events when a user places a finger on the physical touchscreen (press event), while the user continues pressing the physical touchscreen (held event), and when the user removes their finger (release event). Properties of the **GUI\_TOUCHSCREEN** contain the identity and pixel coordinates of the last event.

The Pen Object is called the **GUI\_PEN**. This useful tool generates geometric shapes and line drawings on a screen. The **GUI\_PEN** has properties that control how the points and lines are drawn so you don't have to pass all the optional parameters to the drawing method each time it is called.

The Buzzer Object is called the **GUI\_BUZZER** and it is associated with the piezo electric beeper. Properties of the **GUI\_BUZZER** control the length of time of a beep and turn the buzzer on and off.

The Default Font Object is called the **GUI\_FONT** and is associated with the 8-pixel wide by 10-pixel tall Courier New font that renders string data in a textbox onto a screen.

### ***Creating New Objects***

The GUI Toolkit also has other objects, like graphics and buttons, that you can create using the **New\_Object** method. **New\_Object** requires one input parameter that specifies the type of object you want to create; **GRAPHIC**, **FONT**, **TEXTBOX**, **BUTTON**, and **PLOT** are all valid object types. **New\_Object** returns an integer that you store into a variable. This variable (which we call an object reference because it contains a reference to the object) is used to set properties of the object and perform actions on the object like loading the object onto a screen.

The following code from the demo, creates a new graphic object and stores its object reference into a variable named **graphicOne**. Later, we'll set the image of the graphic and then configure the "one" button of the keypad to use this graphic as its **DRAW\_GRAPHIC**.

#### ***Listing 5-5 Creating a New Graphic.***

```
int graphicOne;
.
.
.
void Init_Keypad_Images ( void )
{
    graphicOne = New_Object ( GRAPHIC );
    .
    .
}
```

Objects can be created but not destroyed. Because objects are stored in the heap, you can only create a finite number of them. Different objects use different amounts of heap space. For example, graphics and fonts only use a few bytes of heap space while plots use hundreds of bytes depending on the size of its buffer.

### ***Setting the Property of Objects***

All objects have their properties set to default values when they are created so that you need to set as few properties as possible to have a fully functional object. However, certain objects like graphics require you to set its image before the graphic can be loaded onto a screen or into a button.

In the demo, **Init\_Keypad\_Images** creates a graphic and then sets its image property using a constant defined in the Image Header File.

**Listing 5-6** *Setting the Property of a Graphic.*

```
int graphicOne;
.
.
.
void Init_Keypad_Images ( void )
{
    graphicOne = New_Object ( GRAPHIC );
    Set_Property ( graphicOne, IMAGE, ONE_BMP );
    .
    .
    .
}
```

## Creating and Initializing Controls

Now that you're familiar with creating graphic objects, we'll show you how to create a button. To create a button:

1. Use the **New\_Object** method to create a button and store the object reference to the button into a variable. By default, the button will beep when it receives a press event. You can change this behavior by setting the **BEEP\_ON\_PRESS** property to **GUI\_FALSE**.
2. Create and define a graphic for the **DRAW\_GRAPHIC** property of the button. A button needs at least one graphic to define its size and active area.
3. Create and define a graphic for the **PRESS\_GRAPHIC** property of the button. By defining a **PRESS\_GRAPHIC** that is different from the **DRAW\_GRAPHIC**, you will provide the user with visual feedback for press events, thus enhancing your user interface.
4. Define the **PRESS\_EVENT\_PROCEDURE** for the button. Writing event procedures is covered in the next section.
5. Initialize the **DRAW\_GRAPHIC**, **PRESS\_GRAPHIC**, **RELEASE\_GRAPHIC**, and **PRESS\_EVENT\_PROCEDURE** properties of the button using **Set\_Property**. Typically, the **RELEASE\_GRAPHIC** is set to the **DRAW\_GRAPHIC** to provide visual feedback for release events.

The following code shows the **Init\_Keypad\_Buttons** function from the demo that illustrates how to create a button that, when pressed, will beep, show a filled-in image of button on the display, and execute an event procedure. When the button is released, the filled-in image of the button is replaced with the **DRAW\_GRAPHIC**.

**Listing 5-7** *Creating and Initializing a Control.*

```
int buttonOne;
.
.
.
void Init_Keypad_Buttons ( void )
// Init_Keypad_Images() must be called before this routine
{
    buttonOne = New_Object( BUTTON );
    Set_Property(buttonOne, DRAW_GRAPHIC,          (long) graphicOne);
    Set_Property(buttonOne, PRESS_GRAPHIC,          (long) graphicButton_Press);
}
```

```

    Set_Property(buttonOne, RELEASE_GRAPHIC, (long) graphicOne);
    Set_Property(buttonOne, PRESS_EVENT_PROCEDURE, (long) one_event_procedure_ptr);
    .
    .
    .
}

```

Remember that all properties are 32-bits in size so when setting any of the graphic properties of the button, the graphic object reference must be cast into a 32-bit number.

## Writing Event Procedures

Event procedures are functions that you write to animate your controls. Event procedures cannot take any parameters or return any values, but they can set variables and call other GUI methods like **Clear** and **Refresh**. In the demo, the event procedure for the one button of the keypad must write the number one into the textbox of the keypad at the correct position and then refresh the keypad screen so the new number will appear. The following shows the code for the one button's event procedure.

### *Listing 5-8 Writing the Event Procedure.*

```

// Define a constant to represent the maximum number of numbers we can enter
// using the keypad.
#define BUFFER_LENGTH 20
// Declare a variable that contains the next position we're writing to the textbox
int buffer_pos;
.
.
.
void One_Event_Procedure ( void )
{
    if(buffer_pos < BUFFER_LENGTH-1)
    {
        String_To_Textbox(textboxBuffer, " 1", 0, buffer_pos);
        buffer_pos++;
        Refresh(GUI_SCREEN0);
    }
}
// We need to store the address of the event procedure into a function pointer which
// will be used in Set_Property.
#include "begin_event_procedure_pointers.h"
.
.
.
xaddr (*one_event_procedure_ptr)(void) = One_Event_Procedure;
.
.
.
#include "end_event_procedure_pointers.h"

```

## Loading Objects into Screens

The final step in creating a GUI application is loading the objects onto the screen. To load an object onto a screen, use the **Load** method. The following code initializes the graphics, buttons, and textbox for the keypad and then loads them onto the first visible screen, **GUI\_SCREEN0**.

### *Listing 5-9 Loading a Control into a Screen.*

```

void Init_Keypad ( void )
{
    Init_Keypad_Images();
}

```

```

Init_Keypad_Buttons();
Init_Keypad_Textbox();
buffer_pos = 0; // Init pointer to the current position within the keypad textbox.
Load ( GUI_SCREEN0, buttonOne, 24, 126 );
.
.
.
}

```

We've now shown you how to design and build your user interface, initialize the GUI Toolkit, create and initialize objects, write event procedures, and load objects onto screens. This final section covers how to handle errors that may occur during your application.

## Handling Errors

The GUI Toolkit has extensive error handling and reporting abilities. When an error occurs, an error code is logged and an attempt is made to recover from the error. For example, if you try to load a graphic that contains an image which is 24 pixels wide to the coordinates (304,0), 8 pixels of the image will hang off the edge of the screen (since the width of a screen is 320 pixels). This will generate an **X\_OUT\_OF\_RANGE** error, and the graphic will instead be loaded to the right-most position on the screen at (296,0). You can read the error code by using the **Read\_Error** method of the GUI Toolkit object. Because only the last error is recorded, you must call **Clear\_Error** after you read the error to prevent servicing the same error more than once. The following code shows how to create a custom error handling and reporting routine:

### *Listing 5-10 Handling Errors.*

```

void Print_Error ( void )
{
    switch (Read_Error())
    {
        case HEAP_FULL: printf("Can't create any more new objects.\n"); break;
        case X_OUT_OF_RANGE: printf("X coordinate is out of range.\n"); break;
        // You would put other error codes and error messages here.
    }
    Clear_Error(); // Be sure to clear the error after we read it;
                  // we don't want to respond to the same error more than once.
}

```

Multiple errors can occur for each GUI Toolkit method but only one can occur at a time. It is up to you to decide if and when you should check for errors.

A useful debugging tool that comes with the GUI Toolkit is the property **ABORT\_ON\_ERROR**. If true, an error causes the controller to disable interrupts, stop multitasking, and send a descriptive error message to the primary serial port, Serial 1. The error message identifies the calling method and parameters that triggered the error. **ABORT\_ON\_ERROR** helps you to quickly identify the source of the error; this is especially useful when developing a complex application. This property should be set to **GUI\_FALSE** for the production version of your application.

## Expanding the GUI Toolkit's Objects and Methods

We understand that each GUI application you write has unique requirements. Although it is possible for you to implement many things like custom plotting routines or drawing geometrical shapes by writing high level code, there maybe a significant performance advantage in our providing pre-

packaged objects to you that perform the desired function. Please contact Mosaic Industries about adding additional objects, properties, and methods to the GUI Toolkit. We are planning to add many features to the toolkit to enhance its capabilities; the features you are looking for may already exist.

## GUI Objects in Detail

There are many kinds of GUI objects. Some are tied tightly to particular hardware (the **GUI\_TOUCHSCREEN** and **GUI\_DISPLAY**), some collect other objects together (GUI Screens), some respond to events (buttons), some are tools (the **GUI\_PEN**), and some simply contain data for display (graphics and textboxes). Several of the GUI objects are created and configured when **Initialize\_GUI** is called. These objects include the **GUI\_DISPLAY**, **GUI\_TOUCHSCREEN**, **GUI\_BUZZER**, **GUI\_FONT**, GUI Screens, and **GUI\_PEN**. You can not create more of these object types. For other object such as graphics, textboxes, buttons, and plots, you can create as many as you like. All of the GUI Toolkit objects, their 32-bit properties, associated methods, and possible errors are described below.

## GUI\_TOOLKIT

The GUI Toolkit is itself an object that contains properties that effect all other objects. The GUI Toolkit Object is called **GUI\_TOOLKIT**. These are its properties, methods, and possible errors:

### Properties

**Table 5-1** Properties of the **GUI\_TOOLKIT**.

Property	Values	Meaning
<b>HORIZONTAL_SNAP_TO_GRID</b>	<b>GUI_TRUE</b>	Read only. Causes all objects loaded onto a screen to be located on the nearest 8-pixel horizontal boundary. This property is always true for speed.
<b>VERICAL_SNAP_TO_GRID</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If true, causes all objects loaded on to a screen to be located on the nearest 8-pixel vertical boundary.
<b>SERVICE_EVENTS</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If false, events are not serviced. All events generated by the touchscreen are ignored.
<b>STANDARD_FONT</b>	<b>GUI_FONT</b> or custom font object	Contains the reference to the font object used to render ASCII string data in textboxes. At initialization, <b>STANDARD_FONT</b> is set to <b>GUI_FONT</b> which is Courier New with a width of 8 pixels and a height of 10 pixels. You can set this property to your own custom font, if desired.
<b>ABORT_ON_ERROR</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If true, disables interrupts, stops multitasking, and sends a detailed message to serial 1 when an error occurs.
<b>AVAILABLE_HEAP_SPACE</b>	Long	Read only. Contains the number of bytes remaining in the GUI Heap.

## Methods

**Table 5-2** Methods of the `GUI_TOOLKIT`.

Method	Parameters	Return Value	Action
<code>Initialize_GUI</code>	start of the GUI Heap, end of the GUI Heap	none	Initializes the <code>GUI_TOOLKIT</code> , <code>GUI_DISPLAY</code> , <code>GUI_TOUCHSCREEN</code> , <code>GUI_PEN</code> , <code>GUI_FONT</code> , <code>GUI_BUZZER</code> , and GUI Screens. Sets up and activates a task in common memory. Calling any other GUI Toolkit method before calling <code>Initialize_GUI</code> will crash the controller.
<code>Service_GUI_Events</code>	none	none	Executes the event procedures of controls. This method must be included in a task as part of the infinite loop to service events generated from the GUI Task.
<code>Read_Error</code>	none	error code	Reads the last reported error.
<code>Clear_Error</code>	none	none	Clears the last reported error.
<code>New_Object</code>	object type	object reference	Create a new object and return an object reference which is stored in an object variable for later use.
<code>Set_Property</code>	object reference, property, value	none	Set an object's property as a 32-bit value.
<code>Get_Property</code>	object reference, property	value	Get an object's property as a 32-bit value.

## Errors

**Table 5-3** Errors of the `GUI_TOOLKIT`.

Error	Associated Method	Meaning
<code>HEAP_FULL</code>	<code>Initialize_GUI</code> , <code>New_Object</code>	Heap is full. There is no room to create the GUI Toolkit, create new objects, or resize existing objects.
<code>GUI_EXISTS</code>	<code>Initialize_GUI</code>	The GUI Task has already been activated. Do not call <code>Initialize_GUI</code> more than once!
<code>DISPLAY_INITIALIZATION_FAILURE</code>	<code>Initialize_GUI</code>	There was a problem initializing the display. This error occurs if there was a hardware communications problem talking to the display controller. If the problem persists, contact Mosaic Industries.
<code>INVALID_OBJECT</code>	<code>New_Object</code> , <code>Set_Property</code> , <code>Get_Property</code>	The object reference is not valid.
<code>INVALID_PROPERTY</code>	<code>Get_Property</code> , <code>Set_Property</code>	The property is not valid.

Error	Associated Method	Meaning
INVALID_IMAGE	Set_Property	There is no valid image at the specified address. This error is returned after attempting to set the <b>IMAGE</b> property of a graphic or a font.
INVALID_GRAPHIC	Set_Property	The object reference is not a graphic, setting the <b>DRAW_GRAPHIC</b> , <b>PRESS_GRAPHIC</b> , or <b>RELEASE_GRAPHIC</b> property of a button.
INVALID_FONT	Set_Property	The object reference is not a font, setting the <b>STANDARD_FONT</b> property of the GUI Toolkit or setting the <b>TEXTBOX_FONT</b> property of a textbox.
BUFFER_SIZE_OUT_OF_RANGE	Set_Property	The size of the plot object buffer must be greater than or equal to the width of the plot in pixels
COLUMN_OUT_OF_RANGE	Set_Property	The number of columns will create a textbox that is wider than the width of the screen.
ROW_OUT_OF_RANGE	Set_Property	The number of rows will create a textbox that is taller than the height of the screen.
WIDTH_OUT_OF_RANGE	Set_Property	The width will create a plot that is wider than the width of the screen.
HEIGHT_OUT_OF_RANGE	Set_Property	The height will create a plot that is taller than the height of the screen.

## GUI\_DISPLAY

The **GUI\_DISPLAY** corresponds to the physical display. Properties of the **GUI\_DISPLAY** and all other GUI objects are accessed or modified using the **GUI\_TOOLKIT** methods **Set\_Property** and **Get\_Property**.

### Properties

**Table 5-4** Properties of the **GUI\_DISPLAY**.

Property	Values	Meaning
WIDTH_IN_PIXELS	320 pixels	Read only. Contains the width of the display in pixels.
HEIGHT_IN_PIXELS	240 pixels	Read only. Contains the height of the display in pixels.
CONTRAST	0 to 31	Changes the contrast voltage of the monochrome display. Saturates at 0 or 31. Initialized to 16.
BACKLIGHT_ON	GUI_TRUE, GUI_FALSE	If true, turns the backlight on for monochrome displays.
BLANK_DISPLAY	GUI_TRUE, GUI_FALSE	If true, blanks the display.
INVERT_DISPLAY	GUI_TRUE, GUI_FALSE	If true, inverts all pixels on the display.

## GUI Screens

A screen is a collection of functionally related objects, including textboxes, plots, buttons and graphics that are presented together on the display. Screens are fixed in size to 320 pixels wide by 240 pixels tall. For speed, objects loaded into screens are aligned on 8 pixel horizontal grid. A property of the GUI Toolkit, called **VERTICAL\_SNAP\_TO\_GRID**, allows you to align objects vertically as well. The coordinate system for specifying the location of objects and drawing to a screen is in pixels and the origin is the upper left corner of a screen. The x coordinate represents a displacement from the origin in the horizontal direction and the y coordinate represents a displacement from the origin in the vertical direction. An increase in x moves the coordinate to the right and an increase in y moves the coordinate down.

Screens whose object images are stored in the display's memory are called GUI Screens. GUI screens have a visible property that when set, causes the selected screen to be shown on the display and makes all other GUI Screens invisible. Only one GUI Screen can be made visible at a time. GUI Screens are the only objects that are shown on the physical display; to show an object like a graphic on the display, the object must first be loaded into a GUI Screen. The visible screen after **Initialize\_GUI** is called is **GUI\_SCREEN0**.

### Properties

**Table 5-5 Properties of GUI Screens.**

Property	Values	Meaning
<b>WIDTH_IN_PIXELS</b>	320 pixels	Read only. Contains the width of the screen in pixels.
<b>HEIGHT_IN_PIXELS</b>	240 pixels	Read only. Contains the height of the screen in pixels.
<b>VISIBLE</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If true, makes the screen visible and sets the last visible screen's property to false.
<b>NUM_OBJECTS</b>	Long	Read only. Contains the number of objects contained in the screen.
<b>IN_DISPLAY</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	Read only. TRUE if the screen is in the display memory, FALSE otherwise. All GUI screens have this property set to <b>GUI_TRUE</b> .
<b>SCREEN_ADDRESS</b>	Extended Address	Read only. Contains the address of the screen.

### Methods

**Table 5-6 Methods of GUI Screens.**

Method	Parameters	Return Value	Meaning
<b>Load</b>	screen reference, object reference, x coordinate, y coordinate	none	Load an object into a screen at the specified x and y coordinates.
<b>Un_Load</b>	screen reference, object reference, x coordinate, y coordinate	none	Unload an object from a screen at the specified x and y coordinates.
<b>Clear</b>	screen reference	none	Unloads all objects from the screen and erases the screen.

Method	Parameters	Return Value	Meaning
<b>Refresh</b>	screen reference	none	Re-renders textboxes and plots in the screen that have their refresh flags set to true. Sets the refresh flags to false once the objects have been refreshed.
<b>Redraw</b>	screen reference	none	Re-draws all objects contained in the screen.

## Errors

**Table 5-7** Errors of GUI Screens.

Error	Associated Method	Meaning
<b>HEAP_FULL</b>	<b>Load</b>	Heap is full. There is no room to load an object into a GUI Screen.
<b>INVALID_OBJECT</b>	<b>Load, Un_Load</b>	The object reference cannot be loaded into a GUI Screen.
<b>INVALID_SCREEN</b>	<b>Load, Un_Load, Clear, Redraw, Refresh</b>	The object reference is not a GUI Screen.
<b>X_OUT_OF_RANGE</b>	<b>Load, Un_Load</b>	The x coordinate plus the width of the object is greater than the width of the GUI Screen.
<b>Y_OUT_OF_RANGE</b>	<b>Load, Un_Load</b>	The y coordinate plus the height of the object is greater than the height of the GUI Screen.

## GUI\_TOUCHSCREEN

The **GUI\_TOUCHSCREEN** corresponds to the physical touchscreen and serves as a container for all the properties of the touchscreen.

## Properties

**Table 5-8** Properties of the **GUI\_TOUCHSCREEN**.

Property	Values	Meaning
<b>LAST_EVENT</b>	<b>NO_EVENT, PRESS_EVENT, HELD_EVENT, RELEASE_EVENT</b>	Read only. Contains the last touchscreen event that occurred.
<b>CAL_COORDS</b>	Long	Read only. Contains the calibrated touchscreen coordinates of the last touchscreen event. The y coordinate is located in the 16 most significant bits and the x coordinate is located in the 16 least significant bits.
<b>RAW_COORDS</b>	Long	Read only. Contains the uncalibrated touchscreen readings of the last touchscreen event. The y reading is located in the 16 most significant bits and the x coordinate is located in the 16 least significant bits.

## Methods

**Table 5-9** Methods of the `GUI_TOUCHSCREEN`.

Method	Inputs	Outputs	Meaning
<b>Calibrate</b>	point1, point2, point3	none	Calibrates the analog touchscreen. See the section on Touchscreen Calibration for more information. Each point is a 32-bit number with the uncalibrated y reading in the 16 most significant bits and the uncalibrated x reading in the 16 least significant bits. The calibration coefficients are stored in Flash memory with the GUI Toolkit.

## Errors

**Table 5-10** Errors of the `GUI_TOUCHSCREEN`.

Error	Associated Method	Meaning
<b>FLASH_NOT_PROGRAMABLE</b>	<b>Calibrate</b>	Can't store the calibration coefficients into Flash memory. Make sure the Flash memory is not write protected.

## Touchscreen Calibration

The analog touchscreen is tested and then calibrated after each QVGA Controller is assembled and before it is shipped from Mosaic Industries. If the touchscreen calibration changes (i.e. you push a button and nothing happens or another button registers the press event), you will have to recalibrate the touchscreen. To calibrate the touchscreen it is recommended that you acquire the uncalibrated touchscreen readings from three points. The points are chosen to avoid non-linearities (points that are not too close to the edge), minimize scaling errors (points that are not too close to each other), and yield non-redundant simultaneous equations. The recommended calibration points are (34,19), (290,123), and (162,219). Once you obtain the three points, simply call the **Calibrate** method to calculate and store the new calibration coefficients for the touchscreen into Flash memory for later use. The calibration coefficients will then be applied to the uncalibrated touchscreen readings each time someone touches the touchscreen.

The following example code shows how to calibrate the touchscreen. In the example code, there are two routines. The first routine, called **Get\_Raw\_Coords**, waits until there is a press event before beeping the buzzer and reading the raw coordinates of the press event. **Get\_Raw\_Coords** then waits until the user has removed their finger before returning. The second routine, called **Calibrate\_Touchscreen** clears `GUI_SCREEN0`, makes `GUI_SCREEN0` the visible screen, prompts the user to press three locations on the touchscreen, captures the user's touches using the **Get\_Raw\_Coords** routine, and finally calls the **Calibrate** method.

**Listing 5-11** Example Calibration Routine.

```
// Declare an object variable for the textbox used to hold the calibration messages.
int textboxCalibration;
long Get_Raw_Coords ( void )
```

```

{
    long coordinates;
    while(Get_Property(GUI_TOUCHSCREEN, LAST_EVENT) == HELD_EVENT )
    { // Wait until the user touches the touchscreen before continuing...
        Pause();
    }
    Buzz(); // Provide audio feedback for the press.
    coordinates = Get_Property(GUI_TOUCHSCREEN, RAW_COORDS);
    while(Get_Property(GUI_TOUCHSCREEN, LAST_EVENT) != HELD_EVENT)
    { // Wait until the user removes their finger before continuing...
        Pause();
    }
    return coordinates;
}

void Calibrate_Touchscreen( void )
{
    // Calibrates analog touchscreen by asking user to press three points on display.
    // Initializae_GUI must be called before calling this routine.
    Clear(GUI_SCREEN0); // Clear GUI_SCREEN0
    Set_Property(GUI_SCREEN0, VISIBLE, GUI_TRUE); // Make sure screen is visible.

    // Write a message to user, informing them that we need to calibrate touchscreen.
    textboxCalibration = New_Object( TEXTBOX );
    Set_Property(textboxCalibration, ROWS, (ulong) 4);
    Set_Property(textboxCalibration, COLUMNS, (ulong) 26);
    String_To_Textbox(textboxCalibration, "Entering Calibration Mode.", 0, 0);
    String_To_Textbox(textboxCalibration, "Please remove finger from", 0, 0);
    String_To_Textbox(textboxCalibration, "touchscreen and touch the", 0, 0);
    String_To_Textbox(textboxCalibration, "following points:", 0, 0);
    Load(GUI_SCREEN0, textboxCalibration, 0, 100);

    // Resize the textbox to hold the labels for the labels for the points.
    Set_Property(textboxCalibration, ROWS, (ulong) 1);
    Set_Property(textboxCalibration, COLUMNS, (ulong) 7);

    // The GUI_PEN, on start up, is configured to draw pixels. Properties of
    // the GUI_PEN allow you to also erase pixels, draw lines, and erase lines.
    long raw_coords1, raw_coords2, raw_coords3;
    Draw(35,19); Draw(33,19); Draw(34,18); Draw(34,20); // Draw point 1.
    String_To_Textbox(textboxCalibration,"POINT 1", 0, 0);
    Load(GUI_SCREEN0, textboxCalibration, 40, 15); // Label point 1.
    raw_coords1 = Get_Raw_Coords(); // Get point 1.

    Draw(291,123); Draw(289,123); Draw(290,124); Draw(290,122); // Draw point 2.
    String_To_Textbox(textboxCalibration,"POINT 2", 0, 0);
    Load(GUI_SCREEN0, textboxCalibration, 224, 120); // Label point 2.
    raw_coords2 = Get_Raw_Coords(); // Get point 2.

    Draw(163,219); Draw(161,219); Draw(162,218); Draw(162,220); // Draw point 3.
    String_To_Textbox(textboxCalibration,"POINT 3", 0, 0);
    Load(GUI_SCREEN0, textboxCalibration, 168, 215); // Label point 3.
    raw_coords3 = Get_Raw_Coords(); // Get point 3.
    Calibrate(raw_coords1, raw_coords2, raw_coords3);
}

```

## GUI\_PEN

The **GUI\_PEN** is a tool used to draw points, lines, and shapes on a screen. You use its **Draw** method to draw to the screen, and its properties control how points or lines are rendered so you don't have to pass all the optional parameters to the **Draw** method.

## Properties

**Table 5-11** Properties of the `GUI_PEN`.

Property	Values	Meaning
<code>PEN_TYPE</code>	<code>SET</code> , <code>UNSET</code>	Determines whether the pen draws or erases from the screen.
<code>SHAPE</code>	<code>POINT</code> , <code>LINE</code>	Determines the shape that is drawn or erased from the screen.
<code>TARGET_SCREEN</code>	Screen Reference	Contains the screen the pen is rendering to.
<code>LAST_COORDS</code>	Long	Contains the last coordinates passed to the <code>Draw</code> method. The y coordinate is located in the 16 most significant bits and the x coordinate is located in the 16 least significant bits.

## Methods

**Table 5-12** Methods of the `GUI_PEN`.

Method	Inputs	Outputs	Meaning
<code>Draw</code>	x coordinate, y coordinate	none	Draw or erase a point or a line onto a screen. If drawing a line, draws from the last coordinate to the coordinates passed to <code>Draw</code> . To draw a line from an arbitrary point rather than the last coordinate, place the new coordinate into <code>LAST_COORDS</code> .

## Errors

**Table 5-13** Errors of the `GUI_PEN`.

Error	Associated Method	Meaning
<code>X_OUT_OF_RANGE</code>	<code>Draw</code>	The x coordinate is greater than the width of the screen.
<code>Y_OUT_OF_RANGE</code>	<code>Draw</code>	The y coordinate is greater than the height of the screen.

## GUI\_BUZZER

The `GUI_BUZZER` corresponds to the piezo electric beeper and controls the length of the beep when a button is pressed. The buzzer is located on the QVGA Controller PCB. An external buzzer can be attached for increased audibility. Please see Section XX for more information.

## Properties

**Table 5-14** Properties of the `GUI_BUZZER`.

Property	Values	Meaning
<code>BEEP_TIME</code>	Long	Controls the length of time the piezo electric buzzer is on during a call to the <code>Buzz</code> method and when a button receives a press event. Only the 16 least significant bits are used. The units of <code>BEEP_TIME</code> are in TCNTs or 2 microsecond intervals. The default value is 1000, corresponding to 2 milliseconds.

Property	Values	Meaning
<b>BEEPER_ON</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If true, turns the piezo electric buzzer on.

## Methods

**Table 5-15** Methods of the `GUI_BUZZER`.

Method	Inputs	Outputs	Meaning
<b>Buzz</b>	none	none	Turns the piezo electric buzzer on for <b>BEEP_TIME</b> . This method is automatically called when a button receives a press event.

## Graphic Object

A graphic object contains a single image as a property. Images are typically created on a PC but need to be converted and transferred to the QVGA Controller before they can be loaded into a graphic. Images are converted using Mosaic's Image Conversion Program. The Image Conversion Program creates two files, an Image Data File and an Image Header File. The Image Data File contains the converted image data, and the Image Header File associates the location of the image data on the QVGA Controller with a constant named after the file name of the image. Before the GUI Toolkit is initialized and graphics are created, the Image Data File must be transferred to the Controller using QEDTerm. After the Image Data File is transferred and the GUI Toolkit is initialized, a new graphic is created using the **New\_Object** method and its image set using the **Set\_Property** method. The width and height of the graphic object are automatically set when the **IMAGE** property of the graphic is set to a valid image. Error checking is performed to assure the image is valid.

For the optimal performance of the GUI Toolkit, the width of an image must be a multiple of 8 pixels, and graphics must be loaded onto an 8 pixel horizontal grid in a screen. Finer horizontal pixel placement and image widths would require bit shifting of each byte of the image every time it is drawn, significantly slowing performance of the GUI Toolkit. To enforce the alignment there are two properties of the GUI Toolkit that globally affect the placement of objects, **HORIZONTAL\_SNAP\_TO\_GRID** and **VERTICAL\_SNAP\_TO\_GRID**. **HORIZONTAL\_SNAP\_TO\_GRID** is read-only and is always true where as **VERTICAL\_SANP\_TO\_GRID** may be set to either true or false. Images whose width does not fall on 8 pixel boundaries will not be converted with the Image Conversion Program. The images must be cropped or stretched appropriately using an image-editing program before the Image Conversion Program is used.

## Properties

**Table 5-16** Properties of Graphic Objects.

Property	Values	Meaning
<b>WIDTH_IN_PIXELS</b>	8 to 320 pixels	Read only. Contains the width of the image in pixels.

Property	Values	Meaning
<b>HEIGHT_IN_PIXELS</b>	1 to 240 pixels.	Read only. Contains the height of the image in pixels.
<b>IMAGE</b>	Extended Address	Contains a pointer to the image contained in the graphic.

### ***Image Conversion Program***

Mosaic's Image Conversion Program allows you to easily transfer images created on a PC to your Panel-Touch QVGA Controller for use with the GUI Toolkit. The image conversion program takes all of the images in a selected directory and concatenates them into a single text file called an Image Data File. The Image Data File is stored in the selected directory and is sent to the Controller using QEDTerm, the terminal program provided by Mosaic Industries. The Image Data File, by default, puts the converted image data into RAM on page 0x60 and then transfers the data into Flash at page 0x70. For more information about the memory map of the QVGA Controller, see section XX.

Another file, called an Image Header File, is created to associate the names of the images (which is just the filename of the image) with their location in memory on the Controller. The Image Header File contains constants named after the file names of the images and must be included in your program to tell the GUI Toolkit where the images are stored. Supported image formats are monochrome, grayscale, color bitmap (\*.bmp), and PCX (\*.pcx) files with 1, 2, 4, and 8 pixel bit depth. If you have a monochrome or EL display, be sure all of your images are monochrome and you select a bit depth of 1 before converting your images. The following sections describe the user interface and the error messages returned by the Image Conversion Program.

### ***Image Conversion Program Interface***

The user interface for Mosaic's Image Conversions Program has a main screen, an advanced options screen, and a help screen. On the main screen there are controls that select the directory that contain your image files, specify the type of image file (PCX or BMP) to convert, and select the bit-depth of your image files (1, 2, 4, or 8 bits per pixel). A button labeled "Convert Files Now" starts the conversion process. In the advanced options screen there are controls that select your programming language, desired target memory location for the image data, and filenames for the Image Data and Image Header files. All of the advanced options are set to default values that will work for most applications. The help screen provides additional information for each of the options and controls.

### ***Image Conversion Program Errors***

Mosaic's Image Conversion Program detects and reports the following error conditions:

- ❑ "Error changing to the specified directory". The directory does not exist, it was moved, or deleted. A new directory has to be specified.
- ❑ "Error opening an image file, Image Data File, or Image Header File".
- ❑ "Not a valid bitmap file (no valid file identifier) or pcx file (no valid manufacturer or encoding)".
- ❑ "Bit depth of the image file does not match the specified value".

- “Image width does not fall on an 8-pixel boundary”. All images must have a width that is a multiple of eight pixels. This is required to quickly draw the images onto screens. Please crop or stretch the image using any photo or image editing program such as Photoshop or Paint.

## Font Object

A font object renders ASCII string data into images that can be displayed on a screen in a textbox. A font object is like a graphic object in that it contains an image, with the bitmaps for the 95 printable ASCII characters starting from ASCII space (0x20 or 32 decimal) to ASCII tilde (0x7E or 126 decimal). Fonts are created on the PC. Each character bitmap must be the same size. The GUI Toolkit provides a Courier New font that is 8 pixels wide by 10 pixels tall and is called the **GUI\_FONT**. The demo program provides two additional Courier New fonts that are 16 pixels wide by 20 pixels tall and 32 pixels wide by 40 pixels tall. Examples of their use are included with the demo program. While you can’t create another instance of the **GUI\_FONT**, you can create your own custom fonts as described in the next section.

### Properties

**Table 5-17 Properties of the Font Object.**

Property	Values	Meaning
<b>WIDTH_IN_PIXELS</b>	8 to 320 pixels	Read only. Contains the width of a single character in pixels.
<b>HEIGHT_IN_PIXELS</b>	1 to 240 pixels.	Read only. Contains the height of a single character in pixels.
<b>IMAGE</b>	Extended Address	Contains a pointer to the image of ASCII characters contained in the font.

### Creating Custom Fonts

You can easily create your own custom fonts on a PC to use with the GUI Toolkit. In this section, we show you how to create a custom font using Adobe Photoshop 4.0.

1. Start Photoshop and create a new image file with dimensions of 760 pixels wide x 10 pixels tall in bitmap mode. This will create a font that is 8 pixels wide and 10 pixels tall (since  $760 = 95 \text{ ASCII characters} \times 8 \text{ pixels per character}$ ).
2. Use the text tool, selecting Courier New as the font, to create the font by typing in all 95 characters in order.
3. Set the font size to 12 pixels with 1 leading pixel and 1 pixel space between characters. The font size in Photoshop is a bit misleading since the 12-pixel font is really 10 pixels tall and 8 pixels wide.
4. Save this font as a bitmap image so you can process the file using the Image Conversion Program.

For a larger Courier New font, say 16 pixels wide by 20 pixels tall, create a 1520 pixel wide x 20 pixel tall image and set Photoshop’s font size to 22 with 3 leading pixels and 3 pixel spacing. Any font can be used as long as each character has the same width (for non-fixed spaced fonts, you may

have to manually reposition each character). The width of a font must also be a multiple of 8 pixels. There are no limitations on the height of the font.

## Textbox Object

Textboxes are used in conjunction with fonts to render ASCII string data on a screen so it can be shown on the display. Textboxes are useful for displaying information that constantly changes, like the status of a process or the state of an instrument.

When textboxes are created, the font referenced by the **STANDARD\_FONT** property of the GUI Toolkit, is stored into the **TEXTBOX\_FONT** property of the textbox. If you did not store a custom font into the **STANDARD\_FONT** property of the GUI Toolkit, the **GUI\_FONT** is stored into the **TEXTBOX\_FONT** property of the textbox. The **GUI\_FONT** is Courier New and is 8 pixels wide by 10 pixels tall. The initial size of a textbox is 10 columns or characters wide by 2 rows or lines tall.

### Properties

**Table 5-18 Properties of the Textbox Object.**

Property	Values	Meaning
<b>WIDTH_IN_PIXELS</b>	8 to 320 pixels	Read only. Contains the width of the textbox in pixels. This value is the product of the font width and the number of columns in the textbox.
<b>HEIGHT_IN_PIXELS</b>	10 to 240 pixels	Read only. Contains the height of the textbox in pixels. This value is the product of the font height and the number of rows in the textbox.
<b>COLUMNS</b>	1 to 40 columns	Contains the number of characters per line of the textbox.
<b>ROWS</b>	1 to 24 rows	Contains the number of rows of characters of the textbox.
<b>TEXTBOX_FONT</b>	Font reference	Contains a reference to the font object used to render the ASCII data in the textbox.
<b>BORDER</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If true, draws a one-pixel border around the textbox.

### Methods

**Table 5-19 Methods of the Textbox Object.**

Method	Inputs	Outputs	Meaning
<b>String_To_Textbox</b>	textbox reference, string, row, column	none	Writes an ASCII string into a textbox at the specified row and column.
<b>Textbox_To_String</b>	textbox reference, count, row, column	string	Read count characters from the textbox at the specified row and column into an ASCII string.
<b>Clear</b>	textbox reference	none	Sets all of the characters in the textbox to ASCII space.

## Errors

**Table 5-20 Errors of the Textbox Object.**

Error	Associated Method	Meaning
<b>INVALID_OBJECT</b>	<b>Clear</b>	The object reference is not a textbox.
<b>INVALID_TEXTBOX</b>	<b>Textbox_To_String</b> , <b>String_To_Textbox</b>	The object reference is not a textbox.
<b>STRING_LENGTH_OUT_OF_RANGE</b>	<b>Textbox_To_String</b> , <b>String_To_Textbox</b>	For <b>Textbox_To_String</b> , the length of the string being read is longer than 40 characters or goes past the end of the textbox. For <b>String_To_Textbox</b> , the length of the string being written is longer than 40 characters or the string is being written past the end of a line of the textbox.
<b>COLUMN_OUT_OF_RANGE</b>	<b>Textbox_To_String</b> , <b>String_To_Textbox</b>	The column is greater than the number of columns in the textbox.
<b>ROW_OUT_OF_RANGE</b>	<b>Textbox_To_String</b> , <b>String_To_Textbox</b>	The row is greater than the number of rows in the textbox.

## Controls

Controls are objects that have a graphical representation on a screen and respond to touchscreen events. Controls must have exclusive active regions on a screen, which means that controls can not overlap one another.

## Button Object

A Button is the most basic and essential control. A button typically has an image that is drawn to a screen when it is loaded. The coordinates used to load the button into the screen specify the button's top left corner. The image that is drawn to the screen when it is loaded is called the button's **DRAW\_GRAPHIC** and it defines the active area of the button. When someone touches the touchscreen anywhere within the area of the **DRAW\_GRAPHIC**, the button receives a **PRESS\_EVENT**. When the button receives the **PRESS\_EVENT**, it could beep the buzzer, draw a different image (called a **PRESS\_GRAPHIC**) to the screen at the button's top left corner, and/or execute a user defined function called a **PRESS\_EVENT\_PROCEDURE**. If the user continues to press the touchscreen within the active area of the button, the button receives a **HELD\_EVENT** and will execute the user defined **HELD\_EVENT\_PROCEDURE** if it is available. When the user removes their finger from the touchscreen or moves off the button, the button receives a **RELEASE\_EVENT**. The button, depending on the settings of its properties, may beep the buzzer, draw a third image called a **RELEASE\_GRAPHIC** to the button's top left corner, and finally execute a **RELEASE\_EVENT\_PROCEDURE**. A textbox, called a **BUTTON\_TEXTBOX**, may also be associated with a button if you need text in your button. The textbox is rendered to the button's top left corner when the button is loaded, overwriting the **DRAW\_GRAPHIC**. If present, the textbox is redrawn when the button receives a release event.

## Properties

**Table 5-21 Properties of the Button Object.**

Property	Values	Meaning
<b>WIDTH_IN_PIXELS</b>	8 to 320 pixels	Read only. Set based on the width of the draw graphic.
<b>HEIGHT_IN_PIXELS</b>	1 to 240 pixels	Read Only. Set based on the height of the draw graphic.
<b>DRAW_GRAPHIC</b>	Graphic object reference	Graphic shown when the button is drawn. Required to define the active area.
<b>PRESS_GRAHIC</b>	Graphic object reference	Graphic shown when the button is pressed. If zero, no graphic is drawn.
<b>RELEASE_GRAPHIC</b>	Graphic object reference	Graphic shown when the button is released. If zero, no graphic is drawn.
<b>BUTTON_TEXTBOX</b>	Textbox object reference	Contains the Textbox shown when the object is drawn.
<b>BEEP_ON_PRESS</b>	<b>GUI_TRUE,</b> <b>GUI_FALSE</b>	If true, beep the buzzer when the button is pressed.
<b>BEEP_ON_RELEASE</b>	<b>GUI_TRUE,</b> <b>GUI_FALSE</b>	If true, beep the buzzer when the button is released.
<b>PRESS_EVENT_PROCEDURE</b>	Extended Address	Execute this user defined event procedure when the button is pressed. If zero, no event procedure is executed.
<b>HELD_EVENT_PROCEDURE</b>	Extended Address	Execute this user defined event procedure when the button is held. If zero, no event procedure is executed.
<b>RELEASE_EVENT_PROCEDURE</b>	Extended Address	Execute this user defined event procedure when the button is released. If zero, no event procedure is executed.

## Plot Object

Plot objects are used to render data (such as temperature, voltage, or pressure) into a graphical form onto a screen. Plot objects contain a one-dimensional circular byte array, called the plot buffer, that holds the data. The initial size of a plot is 240 pixels wide by 120 pixels tall, with a 240-byte buffer. The size of the plot buffer is limited by the size of the GUI Heap and must be greater than or equal to the width of the plot in pixels. The data in the plot buffer specifies the y coordinate, as the vertical distance in pixels, measured from the top edge of the plot object. Data is added into the plot buffer sequentially; the position of the data in the plot buffer represents the x coordinate and sequential points are connected by lines. For example, if we enter the two data values 4 and 57 into a new plot object and the plot's upper left corner is at (8,10), a line would be drawn from point (8,14) to (9,67). When the plot buffer is the same size as the plot width and you get to the end of the buffer, the next data point you add will be written into the first position of the buffer and the data will be plotted to the left-edge of the plot (over-writing the previous point on the screen and data in the buffer). When the buffer is larger than the plot width and you get to the end of the plot, the next data point that you add will be written to the next position of the buffer and the data will be plotted

to the left-edge of the plot (over-writing only the previous point on the screen). This provides plots that look like oscilloscope traces.

The **Add\_Data** method adds a single data value into a plot object. The **Refresh** method must be called after data is added to re-render the plot on the screen. The plot is rendered from left to right. For example, the following code creates a new plot, loads it into **GUI\_SCREEN0**, and then repeatedly adds a random data value from 0 to 119 into the plot buffer and refreshes the plot on the screen.

*Listing 5-12 Using the Plot Object.*

```
int plotRandom;
void Example_Plot( void )
{
    int random_num;
    // Create a new plot object.
    plotRandom = New_Object( PLOT );
    // Center plot object on the screen. Plot size is 240 x 120 pixels.
    Load(GUI_SCREEN0, plotRandom, 40, 60);
    random_num = Random();
    Add_Data(plotRandom, (random_num % 119));
    while(1)
    {
        random_num = Random ();
        Add_Data(plotRandom, (random_num % 119));
        Refresh(GUI_SCREEN0);
        Pause();
    }
}
```

## Properties

**Table 5-22 Properties of the Plot Object.**

Property	Values	Meaning
<b>WIDTH_IN_PIXELS</b>	8 to 320 pixels	Contains the width of the plot in pixels.
<b>HEIGHT_IN_PIXELS</b>	1 to 240 pixels	Contains the height of the plot in pixels.
<b>BUFFER_SIZE</b>	Long	Sets the size of the circular plot buffer. The plot buffer must be greater than or equal to the width of the plot in pixels.
<b>BORDER</b>	<b>GUI_TRUE</b> , <b>GUI_FALSE</b>	If true, draws a one pixel border around the plot

## Methods

**Table 5-23 Methods of the Plot Object.**

Method	Inputs	Outputs	Meaning
<b>Add_Data</b>	plot reference, data	none	Adds a single data value into a plot object. Data is added to the next position in the circular plot buffer. The data value represents the distance in pixels as measured from the top edge of the plot.

**Errors****Table 5-24 Errors of the Plot Object.**

Error	Associated Method	Meaning
DATA_OUT_OF_RANGE	Add_Data	The data value is larger than the height of the plot in pixels.
INVALID_PLOT	Add_Data	The object reference is not a plot.



# Chapter 6

## Chapter 6: Real Time Programming

### The Timeslicer and Task Switching

#### *The Built-In Elapsed Time Clock*

The QVGA Controller's multitasking executive maintains an elapsed time clock whenever the timeslicer is active. Please consult the `TIMEKEEP.C` program in the `\MOSAIC\DEMOS_AND_DRIVERS\MISC\C EXAMPLES` directory for examples of using the elapsed time clock.

Your program can start the timeslice clock by calling the function:

```
StartTimeslicer()
```

The timeslicer increments the long variable named `TIMESLICE_COUNT` each timeslice period. The default timeslice period is 5 milliseconds (ms), and this can be modified by calling

```
ChangeTaskerPeriod()
```

as described in the Control-C Glossary. The function

```
InitElapsedTime()
```

sets `TIMESLICE_COUNT` equal to zero. The function

```
ReadElapsedSeconds()
```

returns a long result representing the number of elapsed seconds since `InitElapsedTime()` was called.

To attain the full 5 millisecond resolution of the elapsed time counter, we can write a simple function that converts the `TIMESLICE_COUNT` into elapsed seconds as well as the number of milliseconds since the last integral second. For example, let's examine some code from the `TIMEKEEP.C` file in the `\MOSAIC\DEMOS_AND_DRIVERS\MISC\C EXAMPLES` directory:

```
#define DEFAULT_TIMESLICE_PERIOD    5    // {ms}; system default
#define MS_PER_SECOND    1000
static long start_time;                // saves starting count of TIMESLICE_COUNT
_Q void MarkTime(void)
{    start_time = TIMESLICE_COUNT;
}
```

```
_Q void PrintElapsedTime(void)
{   long elapsed_ms =
    DEFAULT_TIMESLICE_PERIOD*(TIMESLICE_COUNT - start_time);
    long seconds = elapsed_ms / MS_PER_SECOND;
    int ms_after_second = elapsed_ms % MS_PER_SECOND;
    printf("\nTime since mark is: %ld seconds and %d ms.\n",
        seconds, ms_after_second);
}
```

The **MarkTime()** function simply stores the **TIMESLICE\_COUNT** in the **start\_time** variable. The timeslicer is continually incrementing its counter, and when you later call **PrintElapsedTime()**, **start\_time** is subtracted from the latest **TIMESLICE\_COUNT** and multiplied by the timeslice period to calculate the elapsed number of milliseconds. This is converted into the elapsed seconds by dividing by 1000, and the remainder is the number of milliseconds since the last integral elapsed second.

To try it out, use the Mosaic IDE's editor to open the **TIMEKEEP.C** file in the **\MOSAIC\DEMOS\_AND\_DRIVERS\MISC\C EXAMPLES** directory, click on the Make Tool (the Make icon) to compile the program, and use the terminal to send **TIMEKEEP.DLF** to the QED Board. At your terminal, type:

```
main←
```

to start the timeslicer and initialize the program. Now at any time you can mark a starting time by typing at the terminal:

```
MarkTime( )←
```

and you can print the elapsed seconds and ms since the last mark by typing:

```
PrintElapsedTime( )←
```

which will produce a response of the form:

```
Time since mark is: 3 seconds and 45 ms.
```

## Using Interrupt Service Routines (ISRs)

The on-chip resources of the 68HC11 include an A/D converter, timer system, pulse accumulator, watchdog timer, serial communications port, high speed serial peripheral interface, and general purpose digital I/O. The 68HC11's 21 interrupts can enhance the performance of these facilities. Interrupts allow rapid response to time-critical events that often occur in measurement and control applications. For example, you can use an interrupt to create a pulse-width modulated (PWM) output signal.

### Interrupt Recognition and Servicing

68HC11 interrupts fall into two main categories: nonmaskable and maskable.

#### **Maskable Interrupts**

Maskable interrupts may be freely enabled and disabled by software. They may be generated as a result of a variety of events, including signal level changes on a pin, completion of predetermined time intervals, overflows of special counting registers, and communications handshaking.

Recognition and servicing of maskable interrupts are controlled by a global interrupt enable bit (the I bit in the condition code register) and a set of local interrupt mask bits in the hardware control registers. If a local interrupt mask bit is not enabled, then the interrupt is “masked” and will not be recognized. If the relevant local mask bit is enabled and the interrupt event occurs, the interrupt is recognized and its interrupt flag bit is set to indicate that the interrupt is pending. It is serviced when and if the global interrupt bit (the I bit) is enabled. An interrupt that is not in one of these states is inactive; it may be disabled, or enabled but waiting for a triggering event.

When an interrupt is both recognized and serviced, the processor pushes the programming registers onto the stack to save the machine state, and automatically globally disables all maskable interrupts by setting the I bit in the condition code register until the service routine is over. Other maskable interrupts can become pending during this time, but will not be serviced until interrupts are again globally enabled when the service routine ends. (The programmer can also explicitly re-enable global interrupts inside an interrupt service routine to allow nesting of interrupts, but this is not recommended in multitasking applications). Non-maskable interrupts (reset, clock monitor failure, COP failure, illegal opcode, software interrupt, and XIRQ) are serviced regardless of the state of the I bit.

When an interrupt is serviced, execution of the main program is halted. The programming registers (CCR, ACCD, IX, IY, PC) are pushed onto the return stack. This saves the state of execution of the main program at the moment the interrupt became serviceable. Next, the processor automatically sets the I bit in the condition code register. This disables interrupts to prevent the servicing of other maskable interrupts. The processor then fetches an address from the “interrupt vector” associated with the recognized interrupt, and starts executing the code at the specified address. It is the programmer’s responsibility to ensure that a valid interrupt service routine, or “interrupt handler” is stored at the address pointed to by the interrupt vector.

The CPU then executes the appropriate interrupt handler routine. It is the programmer’s responsibility to ensure that a valid *interrupt service routine* is stored at the address pointed to by the interrupt vector. The interrupt vectors are near the top of memory in the onboard ROM. The ROM revector the interrupts (using jump instructions) to point to specified locations in the EEPROM. The **ATTACH()** routine installs a call to the interrupt service routine at the appropriate location in the EEPROM so that the programmer’s specified service function is automatically executed when the interrupt is serviced. **ATTACH()** also supplies the required **RTI** (return from interrupt) instruction that unstacks the programming registers and resumes execution of the previously executing program.

An interrupt handler must reset the interrupt flag bit (not the mask bit) and perform any tasks necessary to service the interrupt. When the interrupt handler has finished, it executes the RTI (return from interrupt) assembly code instruction. RTI restores the CPU registers to their prior values based on the contents saved on the return stack. As explained below, this also re-enables interrupts by clearing the I bit in the CCR (condition code register). Thus other interrupts can be serviced after the current interrupt service routine has completed.

### ***Nonmaskable Interrupts***

Six of the 68HC11F1’s 21 interrupts are nonmaskable, meaning that they are serviced regardless of the state of the global interrupt mask (the I bit in the CCR). Events that cause nonmaskable inter-

rupts include resets, clock monitor failure (triggered when the E-clock frequency drops below 10 kHz), Computer-Operating- Properly (COP) failure (triggered when a programmer-specified timeout condition has occurred), execution of illegal opcodes, execution of the SWI (software interrupt) instruction, and an active low signal on the nonmaskable interrupt request pin named /XIRQ.

Three types of interrupts initiate a hardware reset of the 68HC11:

- Power-on or activation of the reset button
- Computer-Operating- Properly (COP) timeout
- Clock monitor failure

These are the highest priority interrupts, and are nonmaskable. Serviced immediately, they initialize the hardware registers and then execute a specified interrupt service routine. QED-Forth sets the interrupt vectors of these interrupts so that they execute the standard startup sequence. The service routines for all but the main reset interrupt may be changed by the programmer with the ATTACH utility.

If a nonmaskable interrupt is enabled, it is serviced immediately upon being recognized. The importance of these interrupts is reflected by the fact that most cause a hardware reset when serviced. The following table gives the name of each nonmaskable interrupt and a description of its operation. They are listed in order of priority from highest to lowest:

**Table 6-1 Nonmaskable Interrupts.**

Interrupt Name	Description
Reset	Recognized when the /RESET (active-low reset) pin is pulled low, this highest priority nonmaskable interrupt resets the machine immediately upon recognition and executes the standard QED-Forth restart sequence.
Clock Monitor Failure	Enabled or disabled via the CME (clock monitor enable) bit in the OPTION register, this interrupt is recognized if the E-clock frequency drops below 10 kHz. It resets the processor hardware and executes a user-defined service routine. QED-Forth installs a default service routine for this interrupt that performs the standard restart sequence.
COP Failure	After enabling the computer operating properly (COP) subsystem, failure to update COP registers within a predetermined timeout period triggers this interrupt which resets the processor and executes a user-defined service routine. QED-Forth installs a default service routine for this interrupt that performs the standard restart sequence.
Illegal Opcode Trap	This interrupt occurs when the processor encounters an unknown opcode. QED-Forth installs a default service routine for this interrupt that performs the standard restart sequence.
SWI	Software interrupts are triggered by execution of the SWI opcode. After being recognized, an SWI interrupt is always the next interrupt serviced provided that no reset, clock monitor, COP, or illegal opcode interrupt occurs. SWI requires a user-installed interrupt handler.
/XIRQ	Enabled by clearing the X bit in the condition code register, an /XIRQ interrupt is recognized when the /XIRQ (active-low nonmaskable interrupt) pin is pulled low. This interrupt is serviced immediately upon recognition. It requires an appropriate user-installed interrupt handler.

The service routine for the reset interrupt cannot be modified by the programmer. The service routines for the clock monitor, COP failure, and illegal opcode trap interrupts are initialized to perform the restart sequence, but this action may be changed by the programmer (see the Glossary entry for **InitVitalIRQsOnCold()** for more details). No default actions are installed for the SWI and /XIRQ interrupts, so before invoking these interrupts the user should install an appropriate interrupt service routine using the **ATTACH()** command.

### ***Servicing Maskable Interrupts***

Maskable interrupts are controlled by the I bit in the condition code register (M68HC11 Reference Manual pp.5-22...5-26). When the I bit is set, interrupts are disabled, and maskable interrupts cannot be serviced. When clear, interrupts can be serviced, with the highest priority pending interrupt being serviced first. In sum, a locally enabled maskable interrupt is serviced if:

- it has been recognized, and
- it has the highest priority, and
- the I bit in the condition code register is clear.

If a maskable interrupt meets these criteria, the following steps are taken to service it. First, the programming registers are automatically saved on the return stack. Note that the condition code register, CCR, is one of the registers saved, and that the saved value of the I bit in the CCR is 0. Next, the CPU sets the automatically I bit to 1 to temporarily prevent maskable interrupts from being serviced. Control is then passed to the interrupt handler code, which you must provide, pointed to by the contents of the interrupt vector. The interrupt handler clears the interrupt flag bit set by the trigger event and performs any tasks necessary to service the interrupt. It terminates with an RTI instruction which restores the saved values to the programming registers. Execution then resumes where it left off.

Recall that when the interrupt service began, the processor's first action was to store the programming registers on the return stack. At that time, the I bit in the CCR equaled 0 indicating that interrupts were enabled, and the bit was stored as 0 on the return stack. After stacking the machine state, the processor set the I bit to disable interrupts during the service routine. When the programming registers are restored to their prior values by RTI, note that the I bit is restored to its prior cleared state, indicating that interrupts are again enabled. In this manner the processor automatically disables interrupts when entering a service routine, and re-enables interrupts when exiting a service routine so that other pending interrupts can be serviced.

### ***Nested Interrupts***

The programmer can explicitly clear the I bit inside an interrupt service routine to allow nesting of interrupts. Make sure that the return stack is large enough to accommodate the register contents placed there by the nested interrupts. The default size of the return stack is 768 bytes, and it can be easily resized.

### ***Interrupt Priority***

Multiple pending interrupts are serviced in the order determined by their priority. Interrupts have a fixed priority, except that the programmer may elevate one interrupt to have the highest priority

using the HIPRIO register. Nonmaskable interrupts always have the highest priority when they are recognized, and are immediately serviced. The following table lists the fifteen available maskable interrupts in order of highest to lowest priority:

**Table 6-2 Maskable Interrupts, from Highest to Lowest Priority.**

Interrupt Name	Description
/IRQ	/IRQ is an active-low external hardware interrupt which is recognized when the signal on the /IRQ pin of the 68HC11 is pulled low (MC68HC11F1 Technical Data Manual, p.2-4).
Real Time Interrupt	The RTI provides a programmable periodic interrupt (MC68HC11F1 Technical Data Manual, p.6-8).
Input Capture 1	An IC1 interrupt is recognized when a specified signal transition is sensed on port A, pin 2 (MC68HC11F1 Technical Data Manual, p.7-1 ff.).
Input Capture 2	An IC2 interrupt is recognized when a specified signal transition is sensed on port A, pin 1 (MC68HC11F1 Technical Data Manual, p.7-1 ff.).
Input Capture 3	An IC3 interrupt is recognized when a specified signal transition is sensed on port A, pin 0 (MC68HC11F1 Technical Data Manual, p.7-1 ff.).
Output Compare 1	An OC1 interrupt is recognized when the main timer's count becomes equal to OC1's timer compare register (MC68HC11F1 Technical Data Manual, p.7-4 ff.).
Output Compare 2	An OC2 interrupt is recognized when the main timer's count becomes equal to OC2's timer compare register (MC68HC11F1 Technical Data Manual, p.7-4 ff.).
Output Compare 3	An OC3 interrupt is recognized when the main timer's count becomes equal to OC3's timer compare register (MC68HC11F1 Technical Data Manual, p.7-4 ff.).
Output Compare 4	An OC4 interrupt is recognized when the main timer's count becomes equal to OC4's timer compare register (MC68HC11F1 Technical Data Manual, p.7-4 ff.).
I4O5	Depending on its configuration, an I4O5 (input capture 4/output compare 5) interrupt is recognized when a specified signal transition is sensed on port A, pin 3, or when I4O5's timer compare register is equal to the main timer's count (MC68HC11F1 Technical Data Manual, p.7-1 ff.).
Timer Overflow	A TOF interrupt occurs when the free-running count in the TCNT (timer count) register overflows from FFFFH to 0000H (MC68HC11F1 Technical Data Manual, p.7-1).
Pulse Accum Overflow	A PAOVF interrupt occurs when the PACNT (pulse accumulator count) register overflows from FFH to 00H (MC68HC11F1 Technical Data Manual, p.7-11 ff.).
Pulse Accum Edge	A PEDGE interrupt occurs after a signal edge is detected on port A, pin 7 (MC68HC11F1 Technical Data Manual, p.7-11 ff.).
SPI Event Interrupt	An SPI (serial peripheral interface) interrupt occurs after a byte transfer is completed, or a write collision or a mode fault is detected (MC68HC11F1 Technical Data Manual, p.10-1 ff.).
SCI Event Interrupt	An SCI (serial communications interface) interrupt occurs when the transmit data register is empty, or the transmission is complete, or the receive data register is full, or an idle line is detected. The handler must determine which of these four events caused the interrupt (MC68HC11 Reference Manual, p.9-16).

### ***Elevated Priority***

After being recognized, a locally enabled maskable interrupt will be serviced when the I bit is clear, and when it has the highest priority among the pending interrupts. Note that interrupts are not nec-

essarily serviced in the order in which they are recognized, but in order of priority among those pending.

You can elevate one maskable interrupt at a time to receive highest priority servicing. This is accomplished by configuring four priority-selection bits named PSEL0, PSEL1, PSEL2, and PSEL3 located in the HPRIO (high priority) register (MC68HC11F1 Technical Data Manual, pp.6-15...6-16). The default highest priority maskable interrupt is /IRQ. A table in MC68HC11F1 Technical Data Manual, p. 6-16 lists the states of the priority selection bits needed to elevate an interrupt's status to the highest priority. ***Interrupt Flag and Mask Bits***

Each maskable interrupt enabled and disabled by a local mask bit. An interrupt is enabled when its local mask bit is set. When an interrupt's trigger event occurs, the processor sets the interrupt's flag bit.

The local mask bit should be used to enable and disable individual interrupts. In general, you should avoid setting the global I bit in the condition code register (CCR) using **DISABLE\_INTERRUPTS()** unless you are sure that you want to disable all interrupts. Time-critical interrupt service routines such as the timesliced multitasker cannot perform their functions when interrupts are globally disabled.

Some of the QVGA Controller's library functions globally disable interrupts for short periods to facilitate multitasking and access to shared resources. A list of these functions is presented in the Control-C Glossary document.

Interrupt trigger events can occur whether or not the interrupt is enabled. For this reason, it is common for flag bits to be set before an interrupt is ready to be used. Unless an interrupt's flag bit is cleared before it is enabled, setting the local mask bit will force the system to recognize an interrupt immediately. Unfortunately, the event which set the interrupt's flag bit occurred at an unknown time before the interrupt was enabled. Depending on the interrupt handler's task, this can cause erratic initial behavior, collection of an incorrect initial data point, or begin an improper sequence of events (for example, cause a phase shift in an output waveform). To avoid these problems, it is recommended that you enable an interrupt by first clearing its flag bit and then immediately setting its mask bit.

**! An Interrupt Flag Bit Is Cleared By Writing a 1 to it !**

**Although mask bits can be set and cleared by storing the desired value in them, flag bits are unusual. Since flag bits are set by trigger events, it is not possible to set them via software. In order to clear an interrupt flag bit, a one must be stored into the flag bit's location.**

To clear a specified flag bit, write a pattern to the flag register with a 1 in the bit position of the flag that must be cleared. All of the other flag bits in the flag register then remain unchanged. See M68HC11 Reference Manual p.10-14 for examples.

## External Hardware Interrupts /IRQ and /XIRQ

Two external interrupts, /IRQ (active-low interrupt request) and /XIRQ (active-low nonmaskable interrupt request) allow external hardware to interrupt the 68HC11F1 (M68HC11 Reference Manual, p.2-17). The / prefix to each of these names indicates that the signals are active-low. Pull-up resistors on the QVGA Controller hold these signals high during normal operation, and an interrupt is recognized when either signal is pulled low by an external source. The /IRQ input is maskable and is not serviced unless the I bit in the condition code register is clear. If the CPU is servicing an interrupt when the /IRQ line goes low, the external interrupt will not be recognized until the interrupt being serviced has been handled. Unlike all the other maskable interrupts, /IRQ does not have a local interrupt mask.

/XIRQ is nonmaskable. After a one-time enabling (clearing) of its X control bit in the CCR, an /XIRQ request will be immediately serviced. For this reason it can be used to warn of critical situations such as impending power failure.

The /IRQ and /XIRQ pins are accessed and controlled via the Digital I/O and Control bus (for pin locations see Appendix A). They operate as active-low inputs to the processor. An external device can drive either of these lines LOW to signal an interrupt. Alternatively, several open-collector devices can be wired together on the same line, so that any one of them can interrupt the processor by pulling the request line low. This is called “wired-or” operation. In either case, the external device must pull the line low long enough to be detected by the CPU.

Note that the PORTA input capture lines described in Chapter 4 can also be configured to interrupt the processor when an external event occurs.

### **Configuring /IRQ and /XIRQ Interrupts**

In its default state after each reset or restart /IRQ pin is configured as an edge-triggered input. In this mode, the 68HC11 latches the falling edge, causing an interrupt to be recognized. This frees peripheral devices from having to hold the /IRQ line low until the CPU senses the interrupt, and prevents multiple servicing of a single external event.

The disadvantage of this configuration is that multiple edge-triggered interrupts cannot be reliably detected when used with wired-OR interrupt sources. If you are using multiple wire-or /IRQ inputs, you can specify level-sensitive interrupt recognition by clearing a bit named IRQE (IRQ edge-sensitive) in the OPTION register (M68HC11 Reference Manual, p.5-24). IRQE is a “protected bit” in OPTION that must be written within the first 64 E cycles after a reset. The QED-Forth word `INSTALL.REGISTER.INITS` (described in the glossary) may be used to specify a value that is automatically stored into OPTION upon each reset.

The /XIRQ external interrupt supports only level-sensitive operation, and is a nonmaskable interrupt. Most interrupts, including /IRQ, are globally disabled (“masked”) if the I bit in the condition code register (CCR) is set. /XIRQ is not affected by the state of the I bit. Rather, it is controlled by the X bit in the CCR. Whenever the 68HC11 is reset, the X bit is set in the CCR, thus disabling the /XIRQ external interrupt. The QED-Forth startup routine does not modify the X bit. To use the /XIRQ interrupt, install an appropriate interrupt handler using the `ATTACH` command, and then

enable the /XIRQ interrupt after each reset by clearing the X bit. A short routine that clears the X bit is presented below.

After being enabled, only an in-process /XIRQ service routine or a reset can prevent an /XIRQ interrupt request from being recognized. The /XIRQ interrupt is commonly used to detect power loss as described below.

### ***Using /IRQ and /XIRQ***

To use the /IRQ external interrupt, define an interrupt handler and install it using the pre-defined identifier IRQ.ID and the interrupt **Attach** utility, as described in the Glossary entry for **Attach**.

If interrupts have not yet been enabled globally, then execute:

```
ENABLE_INTERRUPTS←
```

Whenever /IRQ is pulled low, your interrupt handler will be executed. Note that there is no local interrupt mask for the /IRQ interrupt, so your interrupt handler routine need not clear an interrupt request flag.

Similarly, to use /XIRQ, install an interrupt handler using **Attach**.

Next enable the interrupt by clearing the X bit in the CCR. Now that /XIRQ is enabled, your external interrupt handler will be called whenever the /XIRQ line on the I/O and Control Bus is pulled low. A 68HC11 reset will again set the X bit.

## **Routines that Temporarily Disable Interrupts**

Certain kernel routines temporarily disable interrupts by setting the I bit in the condition code register. These routines are summarized in the “Library Functions that Disable Interrupts” chapter of the Control-C Glossary. A review of that list will assist you in planning the time-critical aspects of your application.

### ***Interrupt Latency***

The time required between the processor’s initiation of interrupt servicing and the execution of the first byte of the specified service routine is called the interrupt latency. Most of the 68HC11’s interrupts have an inherent latency of 12 machine cycles during which the registers are saved on the return stack and the interrupt vector is fetched. This corresponds to 3 microseconds ( $\mu$ s) if the board is clocked at 16 MHz. QED-Forth’s interrupt latency is longer because the interrupts are re-vectorized via the EEPROM to allow the programmer to modify the vectors, and because the page must be changed. The latency of service routines installed with **ATTACH ()** is 34 machine cycles, or 8.5  $\mu$ s with a 16 MHz crystal. That is, the first opcode of the user’s service routine is executed 8.5  $\mu$ s after interrupt service begins. After the service routine’s concluding **RTS** executes, an additional 20 cycles (5  $\mu$ s) lapses before the originally interrupted program resumes execution. 12 of these cycles are accounted for by the **RTI** instruction, and the other 8 cycles are required to restore the original page.

***Interrupt Latency***Time to Enter an Interrupt Service Routine: 8.5  $\mu$ secTime to Leave an Interrupt Service Routine: 5.0  $\mu$ sec**Writing Interrupt Service Routines**

Maskable interrupts have a local mask bit which enables and disables the interrupt, and a flag bit which is set when a trigger event occurs. For maskable interrupts, an interrupt triggering event is recognized when the flag and mask bits are both set. In order to avoid premature recognition of a maskable interrupt, it should be enabled by first clearing its flag bit and then setting its mask bit. Once an interrupt has been recognized, it will be serviced if it is not masked by the I bit (or, for the /XIRQ interrupt, by the X bit) in the CCR. Multiple pending interrupts are serviced in the order determined by their priority. Interrupts have a fixed priority, except that the programmer may elevate one interrupt to have the highest priority. Nonmaskable interrupts always have the highest priority when they are recognized, and are immediately serviced.

When an interrupt is serviced, the machine state (specified by the programming registers) is saved and the I bit in the CCR register is set. This prevents other pending interrupts from being serviced. The CPU then executes the appropriate interrupt handler routine. The interrupt handler is responsible for clearing the interrupt flag bit. For most interrupts this is accomplished by writing a one to the flag bit. After completing its tasks, the interrupt handler executes an RTI instruction to restore the machine state, subsequently clearing the I bit in the CCR. The CPU is now ready to service the next, highest priority, pending interrupt. If there is none, processing of the main program continues.

To use interrupts you need to create and post an interrupt service routine using the **ATTACH()** macro. We'll look at this process in detail, then discuss how interrupts are implemented on the 68HC11.

To use an interrupt to respond to events, follow these four steps:

1. Use **#define** to name all required bit masks related to servicing the interrupt, and look in the Motorola 68HC11F1 documentation and the **QEDREGS.H** file (in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory) to find the names of all registers that relate to the interrupt. These bit mask and register names will simplify the creation of a readable service routine.
2. Use C or assembly code to define an interrupt service routine which will be executed every time the interrupt occurs. The function must have a **void** stack picture; it cannot return a value or expect input parameters. This function must reset the interrupt request flag (by writing a 1 to it!) and perform any necessary actions to service the interrupt event. Note that the service routine is a standard function; it is not defined using the **\_interrupt** keyword.
3. Write a function that installs the interrupt service routine using the **ATTACH()** command. **ATTACH()** initializes the interrupt vector in EEPROM to call the specified service routine, and **ATTACH()** also supplies the **RTI** (return from interrupt) instruction that correctly terminates the service routine.

4. Write functions to enable and disable the interrupt. Enabling the interrupt is accomplished by clearing the interrupt's flag bit and then setting its mask bit. It may also be necessary to clear the **I** bit in the **CCR** to globally enable interrupts. This can be accomplished by executing **ENABLE\_INTERRUPTS ()**.

### ***ATTACH() Makes It Simple***

It is easy to define an interrupt service routine and **ATTACH** it to a specified interrupt. You define your service routine in either assembly code or in high level C. Thus the service routine can be debugged just like any other C function. You then call **ATTACH ()** to bind the service routine to the interrupt.

The following constants have been defined as identifiers for the 68HC11 interrupts in the **INTERUPT.H** file in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory:

**Table 6-3 68HC11 Interrupts.**

Identifier	Interrupt description
<b>SCI_ID</b>	Serial communications interface
<b>SPI_ID</b>	Serial peripheral interface
<b>PULSE_EDGE_ID</b>	Pulse accumulator edge detection
<b>PULSE_OVERFLOW_ID</b>	Pulse accumulator overflow
<b>TIMER_OVERFLOW_ID</b>	Timer overflow
<b>IC4_OC5_ID</b>	Timer input capture 4/output compare 5
<b>OC4_ID</b>	Timer output compare 4
<b>OC3_ID</b>	Timer output compare 3
<b>OC2_ID</b>	Timer output compare 2
<b>OC1_ID</b>	Timer output compare 1
<b>IC3_ID</b>	Timer input capture 3
<b>IC2_ID</b>	Timer input capture 2
<b>IC1_ID</b>	Timer input capture 1
<b>RTI_ID</b>	Real-time interrupt
<b>IRQ_ID</b>	IRQ external pin
<b>XIRQ_ID</b>	IRQ external pin (pseudo-nonmaskable)
<b>SWI_ID</b>	Software interrupt
<b>ILLEGAL_OPCODE_ID</b>	Illegal opcode trap
<b>COP_ID</b>	COP failure (reset)
<b>CLOCK_MONITOR_ID</b>	Clock monitor failure (reset)

The **ATTACH ()** macro expects as inputs a function pointer to your service routine, and an interrupt identifier. It sets up the interrupt vector in EEPROM so that subsequent interrupts will execute the specified service routine. The code installed by **ATTACH** includes the **RTI** instruction that terminates the interrupt service sequence. The **StartFunctionTimer ()** routine presented earlier shows how **ATTACH ()** is called.

## Implementation Details

The interrupt vectors near the top of memory are in ROM locations that cannot be modified by the programmer. The contents of these locations point to a series of locations in the EEPROM (at AE20-AEBFH) which can be modified and, if desired, write-protected using the BPROT register. **ATTACH()** writes some code at the EEPROM locations corresponding to the specified interrupt. This code loads the code field address of the user's service function into registers and jumps to a routine that saves the current page, changes the page to that of the user's service function, and calls the service function as a subroutine. When the user-defined service function returns, the code installed by **ATTACH()** restores the original page and executes **RTI** (return from interrupt) to complete the interrupt service process. This calling scheme ensures that the interrupt service will be properly called no matter which page the processor is operating in when the interrupt occurs. And because the interrupt calling routine which is installed by **ATTACH()** ends with an **RTI**, your service routine can end with a standard **RTS**, return or **}** which makes debugging much easier.

The following chapters explain how to define and install interrupt service routines that enhance the usefulness of many of the 68HC11's hardware features.

The following example illustrates how to write and use an interrupt service routine.

## An Example: Periodically Calling a Specified Function

Many times a program needs to execute a specified action every X milliseconds, where X is a specified time increment. We can use an output compare interrupt to accomplish this. We'll set up an interrupt service routine that executes once per millisecond (ms), and maintains a **ms\_counter** variable that is incremented every millisecond. The variable **time\_period** specifies the time increment, in ms, between calls to the specified function which is named **TheFunction()**. For this simple example, **TheFunction()** simply logically inverts the contents of the static variable named **action\_variable**.

### Listing 6-1 *TIMEKEEP.C, an Example of an Interrupt Service Routine*

```
#define OC3_MASK 0x20          // used to set/clear OC3 interrupt flag and mask
#define ONE_MS 500             // 500 counts of 2us TCNT = 1 ms
#define DEFAULT_TIME_PERIOD 1000 // Execute once per second

static int ms_counter;         // runs from 0 to 65535 before rolling over
static uint time_period;       // specifies time in ms between function calls
static int next_execution_time; // next scheduled value of ms_counter
static int action_variable;     // state is toggled by TheFunction()

_Q void TheFunction(void)      // the function simply complements
{
    action_variable = !action_variable; // a variable
}

_Q void FunctionTimer(void)
// This interrupt service routine is called by an OC3-based clock interrupt and
// simply calls TheFunction periodically.
{
    ms_counter++;
    if(ms_counter == next_execution_time)
    {
        TheFunction();
        next_execution_time = next_execution_time + time_period;
    }
    TOC3 += ONE_MS;           // set OC3 count for next interrupt in 1 ms
    TFLG1 = OC3_MASK;         // reset the oc3 interrupt flag by writing a 1
}
```

```

}

_Q void StopFunctionTimer(void)
{ TMSK1 &= ~OC3_MASK; // clear OC3I to locally disable OC3
}

_Q void StartFunctionTimer(void)
// inits variables and locally enables OC3 interrupt;
// does not globally enable interrupts!
{ StopFunctionTimer(); // locally disable OC3 while we set it up
  ATTACH(FunctionTimer, OC3_ID); // post the interrupt service routine
  ms_counter = 0;
  time_period = next_execution_time = DEFAULT_TIME_PERIOD; // 1/second
  action_variable = 0; // state is toggled by TheFunction()
  TOC3 = TCNT + ONE_MS; // start after a 1 ms delay
  TFLG1 = OC3_MASK; // clear interrupt flag OC3F
  TMSK1 |= OC3_MASK; // set OC3I to locally enable OC3
}

```

In this program, we define a bit mask named **OC3\_MASK** which has bit 5 set and all other bits clear. From inspection of the register summary in the Motorola 68HC11F1 booklet, we see that this mask isolates the Output Compare 3 (**OC3**) mask bit in the **TMSK1** register, and isolates the **OC3** interrupt flag bit in the **TFLG1** register. The other relevant registers are the 16 bit free-running counter register named **TCNT** which increments every 2 microseconds, and the Timer Output Compare 3 register named **TOC3**. If the **OC3** interrupt is enabled by setting its mask bit = 1 in **TMSK1** and by globally enabling interrupts using **ENABLE\_INTERRUPTS()** or the assembly instruction **CLI**, then an interrupt occurs when the count in **TCNT** matches the count in **TOC3**. Thus we can control when the next interrupt occurs by writing a specified count to **TOC3**.

**TheFunction()** is our prototypical function that simply toggles the **action\_variable** between the values 0 and 1. The goal of our interrupt service routine is to call **TheFunction()** exactly once per second.

**FunctionTimer()** is the **OC3** interrupt service routine. It increments the **ms\_counter** variable, and checks if **ms\_counter** equals **next\_execution\_time**. If so, it calls **TheFunction()** and updates **next\_execution\_time** by adding **time\_period** to it. Then **FunctionTimer()** increments the contents of the **TOC3** register to set up the next interrupt in 1 ms, and clears the interrupt request flag by writing a 1 to the **OC3** flag bit in the **TFLG1** register. Note that **FunctionTimer()** does not have any input parameters or a return value. Moreover, it is not defined using the **\_interrupt** keyword which would insert an **RTI** (return from interrupt) instruction at the end of the function. Rather, **ATTACH()** will supply the **RTI** instruction for us. Because **FunctionTimer()** does not end with an **RTI**, we can easily test the **FunctionTimer()** service routine using our standard interactive debugging techniques.

**StopFunctionTimer()** simply clears the local **OC3** interrupt mask bit in the **TMSK1** register to disable the **OC3** interrupt.

**StartFunctionTimer()** first locally disables **OC3** to prevent an interrupt while the service routine is being posted. Then it calls:

```
ATTACH(FunctionTimer, OC3_ID);
```

to ensure that **FunctionTimer()** is called every time the **OC3** interrupt occurs; **ATTACH()** also installs a return sequence that supplies the required **RTI** (return from interrupt) opcode. **ATTACH()**

is described in detail later in this chapter. Note that its input parameters are a pointer to the interrupt service routine **FunctionTimer**, and a pre-defined constant named **OC3\_ID** that identifies the interrupt. All of the interrupt identifier constants are summarized later in this chapter.

After calling **ATTACH()**, **StartFunctionTimer()** initializes the timing variables, and initializes **TOC3** so that the first interrupt will occur in 1 ms. It then clears the interrupt flag by writing a 1 to the **OC3F** flag bit in the **TFLG1** register using the statement:

```
TFLG1 = OC3_MASK;
```

Clearing the interrupt flag bit before enabling the interrupt is a highly recommended procedure that ensures that all prior pending **OC3** interrupts are cleared before the interrupt occurs. Finally, **StartFunctionTimer()** locally enables the **OC3** interrupt by setting the mask bit in **TMSK1** with the statement:

```
TMSK1 |= OC3_MASK;
```

To start the interrupt, **main()** simply calls **StartFunctionTimer()** followed by **ENABLE\_INTERRUPTS()**. After you compile and download the **TIMEKEEP.C** program and type:

```
main←
```

from your terminal, the **OC3** interrupt is running *in the background*. To monitor the state of the **action\_variable**, interactively type at your terminal:

```
See( )←
```

and you will see the variable's value change from 0 to 1 exactly once per second. Type any key to terminate the **See( )** function.

This short program provides a template that shows how a function can be periodically called with a period specified by the variable **time\_period**. Of course, in your application the called function would perform a more useful action than does **TheFunction()** in this simple example. You could make other enhancements; for example, a foreground task could manipulate the contents of **time\_period** to change the frequency at which **TheFunction()** is called, and you could use **ms\_counter** to measure elapsed time with 1 ms resolution.

Note that, to maintain timing accuracy, the interrupt service routine should have a worst-case execution time of under 2 ms; otherwise the **FunctionTimer()** will miss the interrupt when **TCNT** matches **TOC3**, and an extra delay of 131 ms will occur while the **TCNT** timer rolls over. In general, interrupt service routines should be short and simple. Complex calculations should be done by foreground tasks, and the interrupt routines should perform the minimum actions necessary to service the time-critical events. An example of this approach is presented in the *Turnkeyed Application Program* in the next chapter.

### **Cautions and Restrictions**

Note that the **OC2** interrupt is used as the multitasker's timeslice clock. Before using this interrupt for another purpose, make sure that you don't need the services provided by the timeslicer which supports the multitasking executive and the elapsed time clock.

The main restriction on interrupt service routines is that they must not call **\_forth** library functions; the Glossary document and the header files in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory specify which functions are of the **\_forth** type. (For the curious: The reason is that **\_forth** functions assume that the Y register has been pre-initialized to point to common RAM that is usable as a data stack. Because C functions use the Y register for other purposes, it is difficult to ensure that the Y register is properly initialized for **\_forth** functions upon entry into an interrupt routine. )

## Summary

Using interrupts requires:

- ☒ coding an interrupt service routine;
- ☒ using **ATTACH ()** to bind it to the appropriate interrupt; and,
- ☒ enabling its local interrupt mask.

## Calling Kernel Functions From Within ISRs

There is a special consideration when calling **\_forth** library functions from interrupt service routines. Fortunately, this restriction can be overcome by simply including the **FORTHIRQ.C** file with your source code, and following the simple example presented in the file. **FORTHIRQ.C** is present in the **\MOSAIC\DEMOS\_AND\_DRIVERS\MISC\C EXAMPLES** directory of the C compiler.

The method is very simple: just place a call to the function

```
BeginForthInterrupt();
```

at the top of your interrupt service routine (or, at the minimum, before any **\_forth** functions are called). Before the final exit point of the interrupt service routine, place a call to the function

```
EndForthInterrupt();
```

That's all there is to it. The ability to call **\_forth** library functions from interrupt service routines makes it easier to manage page-mapped I/O devices on an event-driven basis.

## Multitasking

The QVGA Controller provides a real time operating system that allows cooperative and preemptive multitasking. Multitasking allows the programmer to partition the processor's time among tasks so that time critical tasks don't have to wait unnecessarily for the completion of less critical tasks.

For example, suppose that in a mission critical application an instrument must check several conditions frequently, say every 10 milliseconds, and if an error condition is detected immediately invoke a shut-down sequence or signal an alarm. Suppose too, that the instrument must periodically compute the rms average value of a 1000-point waveform. Written in C this latter task would take over a second. Without a multitasker the processor would need to wait the full second for the completion of the computationally intensive task before returning to the time critical task. With multitasking, each activity is set up as an autonomously running task and the operating system switches rapidly

between them at a rate the programmer chooses. The tasks appear to be operating simultaneously. If in this example we cause a task switch every 5 msec the time critical task would be guaranteed the opportunity to check for its error conditions at least every 10 msec. In the majority of cases in which it does not find an error it can just return immediately to the other task, and is called again in 5 msec. In this way the time critical task has guaranteed periodic use of the processor while still not significantly robbing time from the computationally intensive task.

Multitasking has other less obvious but equally important advantages: it allows a complex program to be decomposed into modules that can be coded and debugged independently; it simplifies the structure of the code making it more understandable; and, it allows an instrument to accomplish diverse tasks with less chance of unintentional interactions among them.

Multitasking requires little overhead on the QVGA Controller. The following table provides the overhead for task switching and interrupts on a QVGA Controller clocked at 16 MHz:

**Table 6-4 Multitasking and Interrupt Overhead Times**

Operation	Time (microseconds)
Task switch time	30
Interrupt latency	9
Interrupt exit time	5

*About ACTIVATE ()*

When a new task is ACTIVATED it inherits the condition code register at the time of activation, which includes the interrupt mask bit. Consequently, before activating a task make sure that interrupts are globally enabled. That way, when the task's action routine is entered the first time, interrupts are enabled, ensuring operation of the timeslicer. If interrupts are globally disabled when the task is activated, then when it is first entered interrupts will be disabled, and the timeslicer will stop – freezing execution in that task if you are using only preemptive multitasking.

## The Battery-Backed Real Time Clock

The QVGA Controller supports an optional battery-backed real time clock. This *smart watch* and integrated battery are packaged as a sealed 32-pin DIP memory device. When this device is installed in socket S3 on the QED-Flash Board, it provides a battery backed calendar and watch that can be set and read by built-in functions. Accuracy is better than  $\pm 1$  minute per month. These sealed units are guaranteed to run for at least ten years. The watch correctly accounts for the differing numbers of days in each month, and also handles leap years.

### Setting and Reading the Real Time Clock

The built-in library functions **SetWatch ()** and **ReadWatch ()** make it easy to set and read the real time clock. These functions gain access to the smart watch by sending a special 64 bit pattern on the

lowest order data bit; when the smart watch detects this pattern, it takes control of the next 64 read or write cycles to set or read the time.

### *The Smart Watch Disables Interrupts for a Short Time*

The routines that access the watch automatically disable all maskable interrupts while the watch is in control (about 0.5 msec).

The **SetWatch()** and **ReadWatch()** functions use the top 16 bytes of the 68HC11F1's on-chip RAM as a buffer to hold intermediate results during the data transfers, and the top 8 bytes at addresses 0xB3F8-0xB3FF serve as the **watch\_results** structure that contains the results returned by the most recent call to **ReadWatch()** as described below.

The battery-backed clock is pre-set at the factory to Pacific Time in the United States. To re-set the smart watch to your time zone, your program can call the function:

```
void SetWatch(hundredth_seconds,seconds,minute,hour,day,date,month,year)
```

The interactively callable routine named **SetTheWatch()** is defined in the **TIMEKEEP.C** file so you can set the watch from your terminal. As explained in the Control-C Glossary, the hour parameter ranges from 0 to 23, the day from 1 to 7 (Monday=1 in this example), and the year parameter ranges from 00 to 99. For example, if it is now 10 seconds past 5:24 PM on Wednesday, May 26, 2004, you could interactively set the watch by typing:

```
SetTheWatch( 0, 10, 24, 17, 3, 26, 5, 4)←
```

The watch is set and read using 24-hour time, where midnight is hour 0, noon is hour 12, and 11 PM is hour 23. Note that you may assign any day of the week as "day number 1".

The function **ReadWatch()** writes the current time and date information into a structure named **watch\_results** that occupies the top 8 bytes of on-chip RAM at addresses 0xB3F8-0xB3FF. Pre-coded macros name the structure elements so it is easy to access the time and date information. For example, the following simple function in the **TIMEKEEP.C** file reads the smart watch and prints the time and date:

```
_Q void SayDate(void)
{   ReadWatch();           // results are placed in watch_results structure
    printf("\nIt is now %d:%d:%d on %d/%d/%d.\n",
        WATCH_HOUR, WATCH_MINUTE, WATCH_SECONDS,
        WATCH_MONTH, WATCH_DATE, WATCH_YEAR);
}
```

It simply calls **ReadWatch()**, and then executes a **printf()** statement using the pre-coded structure macros to reference the time parameters in the **watch\_results** structure. If you called this function immediately after setting the watch as described in the prior section, the response at your terminal might be:

```
It is now 17:24:31 on 5/26/04.
```

After compiling **TIMEKEEP.C**, you can interactively type at your terminal:

```
SayDate( )←
```

at any time to see a display of the current time and date.



# Chapter 7

## Chapter 7: Failure and Run-Time Error Recovery

*Aa variety of useful hardware features of the 68HC11F1 enhance its real-time capabilities and enable recovery from failures:*

- ⇒ *The processor's two external hardware interrupts, /XIRQ and /IRQ, may be used by external devices to request immediate service.*
- ⇒ *Three nonmaskable interrupts cause a hardware reset: the external reset, the COP, and the clock monitor. The main reset is activated on power-up or when the /RESET pin is pulled low for more than 4 machine cycle. Enabling the computer operating properly circuit, COP, sets up a watchdog timer that resets the processor unless a special register is periodically updated. This provides a means of recovering from crashes in an embedded application. Use of the COP feature requires installation of an autostart routine which services the COP. The clock monitor backs up the COP by resetting the machine if the system clock fails.*
- ⇒ *STOP and WAI instructions are available to put the CPU in low power modes with different degrees of power savings*
- ⇒ *A buffered clock signal, 4xOut, can be used to synchronize additional devices with the QED Board's processor*
- ⇒ *Finally, an on-board DIP switch allows selection of the standard operating mode or the special cleanup mode.*

## Getting Started and Getting Stopped – Restarts and Resets

### **External Hardware Resets**

The main reset interrupt of the 68HC11 processor is activated upon power-up or when the active-low /RESET signal is pulled low. The processor does not distinguish between a power-on reset and a reset caused by a low level on the /RESET input pin; both result in the same hardware initialization and software restart sequence.

The /RESET line is normally held high by a pull-up resistor. You can pull the /RESET line low by toggling the reset switch, DIP switch #7. You can also connect a momentary contact switch between /RESET and ground; the /RESET signal is available on both the Address/Data connector and

the Digital I/O connector. Moreover, any peripheral device can reset the processor by driving the /RESET signal low for at least 2 microseconds using an open-collector output.

Both the active-low /RESET signal is controlled by the power monitor circuitry. On power-up, the monitor asserts the reset signal until the positive supply has stabilized above 4.5 Volts.

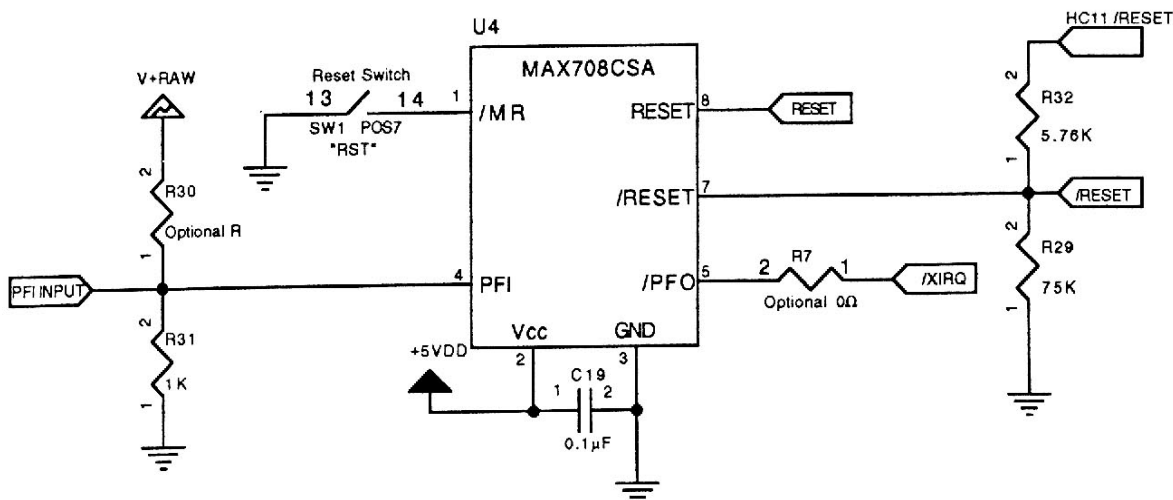
### Internal Resets

The 68HC11 resets itself when a failure condition is detected by either the computer-operating-properly (COP) or the clock monitor circuit. When either of these failure conditions occur, the processor drives the /RESET line low for less than 4 machine cycles to reset itself and any peripherals that are connected to the /RESET line. The processor then determines which failure (COP or clock monitor) caused the reset, and branches to the associated service routine. QED-Forth initializes the interrupt vectors for the COP and clock monitor to perform the standard restart sequence, and the programmer may change the vectors if desired. The operation of the COP and clock monitor are described in the following sections.

## Power Fail Monitor – Recovering from Brown-outs and Power Loss

### Detection of Impending Loss of Power

The QVGA Controller has a power fail monitoring circuit shown in Figure 7-1 that can be used to warn the application program of an impending power failure. The processor then has a short period of time in which necessary cleanup and data saving operations can be performed before the processor shuts down.



**Figure 7-1** The MAX708CSA Power Fail Input and Power Fail Output circuitry. Other circuitry not related to the power-fail detection is not shown here.

By installing an appropriate resistor, you can select the supply voltage at which the power fail signal is asserted. The power fail warning can be configured to generate a nonmaskable interrupt, /XIRQ. This allows the application program to perform any required "cleanup" tasks (such as saving crucial status information in battery-backed RAM) before power is lost.

The following 3 steps configure the power fail feature of the QVGA Controller:

1. Connect PFI Input (pin 21 on the Digital I/O Connector) through an external resistor to the external power source that you wish to monitor. Resistor value selection is discussed below. Volume OEM users can install the resistor as a surface-mount device at position R30 on the QED-Flash Board.
2. Install a zero-ohm resistor at location R7, located just above the flash socket (S1) on the top of the QED-Flash Board, to connect the power fail output to the processor's XIRQ input.
3. Enable the nonmaskable interrupt after every reset.

When the PFI Input (pin 21 on the Digital I/O Connector) falls to less than 1.25 V, the Power Fail Output (/PFO) of the MAX708 chip in Figure 7-1 goes active low, triggering the /XIRQ interrupt if it is enabled and if R7 is installed. The value of the user-supplied resistor between the PFI input and the monitored voltage supply named V.supply is calculated using a simple voltage divider equation as,

$$\text{Eqn. 7-1} \quad R = (V.\text{supply} / 1.25) - 1$$

where R is expressed in units of k $\Omega$ . For example, to configure a power fail warning when V.supply goes below 6V, choose R30 = 3.8k $\Omega$ . Typically, V.supply is the V+raw input to the QED Board, but any power supply voltage can be monitored using this circuit.

The /Power.Fail signal is an active-low output. It is asserted (it goes low) when the +5 Volt digital supply (denoted as +5V on the connector diagrams) falls to within 0.15 Volts of the voltage at which the /RESET signal is asserted. Assuming a current drain of 100 mA, the time it takes the voltage to drop 0.15 Volts equals 1.5 microseconds per microfarad of filter capacitance.

A relatively small filter capacitance of 22  $\mu$ F is installed across the +5V digital supply, so if no additional capacitance is added to the board only  $22 * 1.5 = 33$  microseconds are available between the power fail warning and the shutdown of the processor if there is a sudden disconnect of power. With an interrupt latency of 17 usec (see Chapter 3), only 16 usec is available to the /XIRQ interrupt service routine to perform cleanup operations. To increase the available time, simply connect a capacitor from the +5V supply to digital ground (labeled DGND). +5V and DGND are available at the Power connector, Address/Data bus connector, and the Digital I/O connector.

For example, using the 1.5 microseconds per microfarad relationship, a 470  $\mu$ F capacitor would allow the /XIRQ interrupt approximately 700 microseconds to "clean up" and save any required data before the processor is shut down by the /RESET signal.

$$\text{Eqn. 7-2} \quad \text{cleanup.time} = [ 1.5 \text{ us}/\mu\text{F} ] * [ 470 \mu\text{F} ] = 700 \text{ microseconds}$$

In addition to installing the filter capacitor, you should connect the /Power.fail output (pin 21 on the Digital I/O connector) to the adjacent /XIRQ input (pin 19 on the Digital I/O connector). Your /XIRQ service routine should finish with an endless loop; simply waiting for power to go down. If we allowed the interrupt service routine to terminate, it would be immediately called again because the /Power.fail signal would still be active -- only this time there would be less time to perform the required clean up!

If your clean-up routine has to perform a lot of functions, consider using a large filter capacitance and/or assembly coding the /XIRQ service routine. Storage of values in EEPROM is not recommended as part of a power-fail clean-up routine, as 20 msec are required to modify each EEPROM byte; instead, consider saving key transient parameters in battery-backed RAM. If you want crucial information in the EEPROM, save it periodically before there is a chance that power goes down.

## The COP Watchdog Timer and Clock Monitor

In many embedded control applications, it is important that processor crashes be detected quickly so that the system can rapidly be returned to a proper operating condition. The Computer Operating Properly subsystem, also known as a “watchdog timer” or “COP”, provides this capability. It gives the programmer a way to force a processor reset if an application program crashes or gets lost. When enabled, the COP resets the processor if the application program fails to periodically update a specified register within a predetermined time-out period. The COP time-out period is programmable to any of four values between 8 msec to 0.5 seconds.

To use the COP, design and debug an application program that, in addition to performing all of its normal tasks, periodically writes a 2-byte pattern to the COP reset (COPRST) register as described below. The specified pattern must be written before the COP “times out”. Then install the application as an autostart routine using the QED-Forth word AUTOSTART, and enable the COP.

If the application program ever allows the time-out period to be exceeded without writing the specified pattern, the COP resets the processor. Presumably the pattern will not be properly written if the processor crashes for any reason, so the COP provides a way of automatically resetting the processor to recover from crashes. Then, because the application program has been installed as an autostart routine, the application is automatically restarted when the COP forces a reset.

### ***Be Careful with the COP***

Before enabling the COP, make sure that a debugged application program that properly updates the COPRST register has been installed as an Autostart() or PriorityAutostart() routine. If the startup program is improperly designed so that it is unable to service the COP on time, the COP will reset the machine, thereby invoking the startup program again, and leading to an infinite series of COP resets.

If you find yourself in this situation you can return the QVGA Controller to its “pristine” state by entering the special clean-up mode: turn DIP switch 6 On, toggle DIP switch 7 On then Off, then turn DIP switch 6 back Off to resume normal operation with the COP disabled and any autostart routine removed.

The COP feature should prove trouble-free as long as the application program is:

- ☒ fully debugged;
- ☒ capable of updating the COPRST in a timely fashion; and,
- ☒ installed as an autostart routine.

### **Configuring the COP**

Three bits are used to configure and enable/disable the COP. They are named CR0, CR1, and NOCOP. CR0 and CR1 are located in the OPTION register. These bits determine the amount of time which can elapse between updates of the COPRST register by the application program. If the time-out period is exceeded, the COP forces a reset. The four available time-out periods are:

**Table 7-1 COP Time-out Period**

CR1	CR0	Time-out Period
0	0	8.192 ms
0	1	32.768 ms
1	0	131.07 ms
1	1	524.5 ms

The CR1 and CR0 bits in the OPTION register may be modified only during the first 64 cycles after a reset. The QED-Forth word `INSTALL.REGISTER.INITS` makes it easy to specify a value that will be automatically stored into the OPTION register after every reset; consult its glossary entry for details, or see the coded example presented below.

The third control bit is called NOCOP and is located in the CONFIG register. The QED-Board is shipped with this bit set so that the COP is disabled. To enable the COP, clear this bit; the example code presented below demonstrates how to do it. The CONFIG register's contents are non-volatile, and so are maintained even after the processor has been powered down.

### **Servicing the COP**

Servicing the COP is accomplished by writing 55H and AAH to the COPRST register. Although the order of the writes is important, the number of intermediate instructions between them is inconsequential. The two writes must be performed before the time-out period has elapsed. Once AAH has been stored, the COP will need to be serviced again before the next time-out period has elapsed.

## **The Clock Monitor**

The clock monitor provides a second level of security by monitoring the main system clock and resetting the processor if the clock signal disappears or oscillates too slowly. The clock monitor does not initiate a reset as long as the E-clock frequency is greater than 200 kHz (the E-clock frequency is one quarter the frequency of the on-board crystal). A reset is always triggered at E-clock frequencies below 10 kHz, and may be triggered at frequencies as high as 200 kHz.

The clock monitor is primarily used as a backup for the COP. The COP relies on the clock's presence for reliable operation, and the clock monitor can ensure that the processor is safely reset if the clock fails.

Enabling the clock monitor is accomplished by setting the CME (clock monitor enable) bit in the OPTION register. This bit may be set or reset at any time. A second bit named FCME (force clock monitor enable) is also involved. When the FCME bit is in its default state of 0, the bit has no effect, and when FCME is set, the clock monitor feature cannot be disabled until a reset occurs. We will assume that FCME is 0, and that the CME bit controls the clock monitor. See MC68HC11F1 Technical Data Manual, p.6-5 for further details. Note also that if the clock monitor is enabled, a STOP assembly instruction will trigger a reset because it stops the clock, as discussed in the "Low Power Modes" section below.

## Processor Operating Modes

### Low Power Modes

The 68HC11F1 has two low power modes. These modes are enabled by assembly instructions STOP and WAI (wait). The STOP command puts the CPU into its lowest power-consumption mode by stopping all clocks, thereby stopping all processing (MC68HC11F1 Technical Data Manual, p.6-17). If the clock monitor is enabled, a reset will be triggered when the clocks stop due to a STOP instruction. To use a STOP instruction when the clock monitor reset is enabled, disable the monitor before the STOP instruction, and re-enable it after returning from the STOP.

Pulling either /RESET, /IRQ or /XIRQ low wakes the processor up after a STOP instruction. Pulling the reset line low awakens the CPU and performs the standard reset startup sequence. Pulling /XIRQ low to awaken the CPU triggers a normal /XIRQ interrupt if the X bit in the CCR register is clear (i.e., if /XIRQ interrupts are enabled). After execution of the /XIRQ interrupt handler, processing returns to the instruction following the STOP command. If the X bit is set, (i.e., if /XIRQ is not enabled), pulling /XIRQ low awakens the CPU, but processing will begin at the instruction following the STOP instruction, and no interrupt will be called. For the CPU to be awakened by the /IRQ line going low, the I bit in the CCR register must be clear so that interrupts are globally enabled. When /IRQ goes low and the I bit is clear, execution begins with the /IRQ handler and then executes the code following the STOP instruction.

The STOP instruction is executed as a NOP unless the S bit in the CCR is cleared. After clearing the S bit, any occurrence of a STOP instruction puts the CPU into its lowest power mode. After each reset or restart, QED-Forth leaves the S bit in the CCR in its default set position, meaning that the STOP mode is disabled.

### **WAI Low Power Mode**

The WAI instruction also puts the 68HC11F1 in a low power mode. However, clocks are not disabled in the wait mode, so power consumption is greater than the STOP mode. After a WAI instruction, the machine state is stacked and processing stops. Power savings can be increased by setting the I bit in the CCR and disabling the COP. Further savings can be achieved by disabling the

on-chip subsystems, including executing A/D8.OFF to turn off the A/D (MC68HC11F1 Technical Data Manual, pp.6-17...6-18).

The WAI low power state can only be exited by an unmasked interrupt or by pulling the /RESET pin low. When an unmasked interrupt occurs, (for example /IRQ or /XIRQ goes low, the COP is not serviced, clock monitor failure or reset occurs), the appropriate interrupt handler is executed and then processing continues with the instructions following the WAI. Implementing the WAI lower power mode is accomplished by simply executing WAI. **Summary of Low Power Modes**

In sum, power can be saved by putting the CPU in a low power mode while processing is not required. The 68HC11F1 has two low power modes with different degrees of savings. Both modes are terminated by unmasked interrupts. While the WAI instruction can be called without any preparation, the STOP instruction must be enabled by clearing the S bit of the CCR register.

## Operating Modes of the 68HC11F1 CPU

The 68HC11F1 microcontroller has four operating modes: expanded nonmultiplexed, special test, single chip, and special bootstrap modes (M68HC11 Reference Manual, chapter 3 and MC68HC11F1 Technical Data Manual, pp.2-1...3). The standard operating mode is expanded nonmultiplexed, meaning that the processor has access to expanded memory beyond its on-chip memory, and that the address and data lines are not multiplexed together (as they are on other members of the 68HC11 family). The QED Board also makes use of the special test mode, renaming it the “special cleanup” mode. This mode makes it possible to rapidly recover from any programming error that causes repeated machine crashes. The single chip mode takes away the ability of the processor to address external memory, and special bootstrap allows startup code to be inserted into the processor; these two modes are not used on the QED Board.

The processor’s operating mode is determined by the states of two pins named MODA and MODB (refer to the schematic in Appendix A). On the QED Board, MODA is always high and MODB may be pulled LOW by turning onboard DIP switch #5 ON; this invokes the special cleanup mode. When DIP switch #5 is in its standard OFF position, the board is in the standard operating mode.

### **Special Cleanup Mode**

The Special Cleanup Mode is useful if a buggy startup routine has been installed (using the AUTOSTART or PRIORITY.AUTOSTART words) or if invalid register initializations have been specified (for example, using the INSTALL.REGISTER.INITS word). To recover from these problems, simply enter the special cleanup mode by keeping turning DIP switch #6 ON, and then powering up the board or actuating the reset button (DIP switch #6), then turning DIP switch #6 back OFF. This completely re-initializes the system software to its “pristine” state, and displays the QED Forth startup message at your terminal. The special cleanup mode is also discussed in the “Interrupts and Register Initializations” chapter in the QED Software Manual.



# *Part 3*

## *Communications, Measurement, and Control*



# Chapter 8

## Chapter 8: Digital and Timer-Controlled I/O

### Overview of Available Digital I/O

The QVGA Controller provides 30 digital I/O lines, 24 analog I/O lines, and three communications channels. The digital I/O lines originate in four ports on the CPU (68HC11), designated PORTA, PORTB, PORTC, and PORTD, and three additional ports provided by a peripheral interface adapter (PIA) chip (82C55A), designated PPA, PPB and PPB. Table 8-1 summarizes the digital I/O available, its alternate uses, and port assignments.

**Table 8-1 The QVGA Controller's Digital I/O**

I/O Lines	Type	Port Address	Comments / Alternate Uses
8	Configurable either as all digital inputs or outputs	PPA 0-7	Initialized on start-up and resets as inputs.
5	Digital outputs	PPB 0-4	Initialized as outputs, but if the high-current drivers that use PPB 5-7 are not needed, PPB may be software reconfigured to all inputs.
4	Open-drain high-current outputs	PPB 5-7 and PAL bit	
4	Digital inputs	PPC 0-3	Initialized on start-up and resets as inputs, but may be reconfigured as all outputs.
3	Configurable either as all digital inputs or outputs	PPC 5-7	Initialized as inputs but if RS485 is used PPC5-7 must be reconfigured as outputs.
6	Timer-controlled inputs or outputs including 3 input-capture, 3 output-compare, and pulse accumulator	PA 0-2, 5-7	Bit-by-bit configured by the application as inputs or outputs, including: Timed inputs: PA 0-2 Timed outputs: PA 5-7 Pulse accumulator: PA 7
30	Digital I/O lines		

There are a total of 30 fully uncommitted digital I/O lines for your use. After initialization or reset these are configured as 21 digital inputs and 9 digital outputs, but as Figure 8-1 shows many of these I/O lines are reconfigurable. Up to 21 of these I/O lines can be configured as inputs, all can be configured as outputs.

In addition to these I/O lines there are several committed to other services on the controller; these are summarized in Table 8-2.

**Table 8-2 Committed I/O pins**

Service	Port	Pins
RS-485	PIA PPC	PPC 4
8-bit A/D	CPU PORTE	PE 0-7
Serial 2	CPU PORTA	PA 3-4
SPI	CPU PORTD	PD 2-5

For applications requiring even more digital I/O, I/O lines usually committed to the 8-bit A/D, the RS485 port, the secondary serial port or the SPI may be redirected as general purpose digital I/O if these other services are not needed, providing up to 15 additional digital I/O lines. Table 8-3 summarizes the digital I/O lines gained if other services are not used. The services uses are ordered from the least-used (the RS485) to the most frequently used (the SPI). Note that the SPI is required to use the 12-bit A/D and any Wildcard I/O expansion modules. The five of the 9 output lines that originate on PPB (PPB 0-4) may be converted to input lines if the high current drivers are not needed. In that case, PPB can be reconfigured as all inputs, 9 outputs can be traded for 5 inputs, for a loss of 4 total lines but a gain of 5 more inputs.

**Table 8-3 Additional digital I/O lines made available if other services are forfeited and their committed I/O pins freed.**

Services Used				Digital I/O Available				
RS485	8-bit A/D	Serial 2	SPI	Inputs		Outputs		Total
				Initial	Max	Initial	Max	
Yes	Yes	Yes	Yes	21	21	9	30	30
No	Yes	Yes	Yes	22	22	9	31	31
No	No	Yes	Yes	30	30	9	39	39
No	No	No	Yes	32	32	9	41	41
No	No	No	No	36	36	9	45	45

Many of these 57 I/O lines are digital inputs and outputs. Including the high current drivers the maximum number of digital inputs and outputs is 41 (up to 32 can be configured as inputs, up to 29 as outputs) if none are used for the 8-bit A/D, the RS485, or the secondary serial port. Table 8-1 summarizes the *digital* I/O and alternate use of some of the I/O pins.

Digital inputs and outputs are very useful in data acquisition, monitoring, instrumentation and control applications. A low voltage (approximately 0 Volts) is established on a digital output pin when the processor writes a logical 0 to the corresponding bit in a data register associated with the digital output port. A high voltage (approximately 5 Volts) is established on the digital output pin when the processor writes a 1 to a corresponding bit in the port's data register. This allows software to control external events and processes. For example, an application program can use digital outputs to activate solenoids and turn switches and lights on and off, or to interface the QVGA Controller with a wide variety of digital accessories.

A digital input allows the processor to monitor the logical state of an external voltage by reading a data register associated with the port. External voltages near 0 Volts connected to a digital input cause the corresponding bit in the port's data register to be read as a logical 0, and external voltages near 5 Volts connected to a digital input are read as a logical 1. Application programs can use digital inputs to read switches and keypads or to interface to digital devices such as A/D converters and real-time clocks.

In addition, there are four high current drivers available. These N-channel MOSFET outputs can sink 150 mA continuously, and up to 1 amp on an intermittent basis. Onboard snubber diodes allow control of inductive loads. They are particularly useful for driving relays, solenoids, and low power stepper motors.

Using digital I/O is very easy: simply configure the output port as input or output as explained below, and then use functions or assignment statements to read from or write to the port. The names of the data and direction registers and all required initialization routines are pre-defined in the header files so you don't have to worry about hexadecimal register addresses in your code.

The following sections describe the available digital I/O ports and how to use them.

The digital I/O signals on the QVGA Controller originate from a Motorola 68HC11 processor chip and an 82C55A peripheral interface adapter (PIA) chip. The 68HC11 provides two 8 bit ports named PORTA and PORTE, and 4 available bits on PORTD (PD2 through PD5). The PIA supplies three 8 bit digital I/O ports named PPA, PPB, and PPC.

Table 8-4 summarizes the digital input/output available on the QVGA Controller including the names, addresses, and number of signals associated with the digital ports on the 68HC11 and PIA. The "configurable as" column specifies whether the direction of the port may be changed on a bit-by-bit, nibble-by-nibble, or byte basis (or in the case of PORTE, configured as digital or analog input). The final column lists alternate uses (other than standard digital I/O), the signal pins and the number of signals associated with the alternate uses. Note that a fourth High Current driver output is controlled by the onboard PAL.

**Table 8-4 Digital I/O Port Addresses and Configurability.**

Port Name	Address (HEX)	I/O Line	Configurable As	Alternate Use (Signals Used)
<b>68HC11:</b>				
PORTA	8000	8	Bitwise I/O	Serial2: PA3 & PA4 (2) Pulse accumulator: PA7 (1) Timed inputs: PA0-3 (3 or 4) Timed outputs: PA3-7 (4 or 5)
PORTD	8008	4	Bitwise I/O	SPI controls AD12 & DAC (4)
PORTE	800A	8	Bytewise digital or analog input	8 bit A/D: PE0-7 (8)
<b>PIA:</b>				
PPA	8080	8	Bytewise I/O	
PPB	8081	8	Bytewise I/O	High Current Outs: PPA5-7 (3)

Port Name	Address (HEX)	I/O Line	Configurable As	Alternate Use (Signals Used)
PPC lower	8082	4	Nibblewise I/O	Keypad Inputs: PPC0-3 (4)
PPC upper	8082	4	Nibblewise I/O	RS485: PPC4 (1)

Table 8-5 specifies the named data direction register which controls the input/output direction, or specifies the functions that configure each digital I/O port.

**Table 8-5 Digital I/O port data direction registers and configuration functions.**

Port Name	Configured By
<b>68HC11:</b>	
PORTA	DDRA
PORTD	DDRD
PORTE	AD8On() AD8Off()
<b>PIA:</b>	
PPA	InitPIA()
PPB	InitPIA()
PPC lower	InitPIA()
PPC upper	InitPIA()

## Using the Digital I/O Ports on the 68HC11 Chip

This section describes how to configure and access the PORTA and PORTE digital ports in the 68HC11 chip on the QED Board.

As you work through the examples in the remaining sections of the chapter, you can use a voltmeter to verify that the outputs are behaving as you expect. You can also connect the input signals through a 1 kOhm resistor to +5V or GND to verify that you can digitally read their values. (The 1 kOhm resistor is just a safety precaution to minimize the chance that you'll "blow out" a port bit by mistakenly connecting an output bit to a supply voltage; even if you make this mistake, the resistor would limit the current to safe levels.)

Digital inputs and outputs are very useful in data acquisition, monitoring, instrumentation and control applications. A low voltage (near 0 Volts) is established on a digital output pin when the processor writes a logical 0 to the corresponding bit in a data register associated with the digital output port. A high voltage (near 5 Volts) is established on the digital output pin when the processor writes a 1 to a corresponding bit in the port's data register. This allows software to control external events and processes. For example, an application program can use digital outputs to activate solenoids and turn switches and lights on and off, or to interface the QVGA Controller with a wide variety of digital accessories such as D/A converters, displays, etc.

A digital input allows the processor to monitor the logical state of an external voltage by reading a data register associated with the port. External voltages near 0 Volts connected to a digital input cause the corresponding bit in the port's data register to be read as a logical 0, and external voltages near 5 Volts connected to a digital input are read as a logical 1. Application programs can use digital inputs to read switches and keypads or to interface to digital devices such as A/D converters and real-time clocks.

## PORTA

**PORTA** is configurable as input or output on a bit-by-bit basis. To configure **PORTA**, use an assignment statement to write to the **DDRA** (Data Direction Register A) register. **DDRA** and all 68HC11 register names are defined in the **QEDREGS.H** file in the **\FABIUS\INCLUDE\MOSAIC** directory. Writing a 1 to a bit position in **DDRA** configures the corresponding port bit as an output, and writing a 0 to a bit position configures the corresponding bit as an input. For example, the following C statement configures **PORTA** as all outputs:

```
DDRA = 0xFF;
```

To configure **PORTA** as all inputs, use the statement:

```
DDRA = 0x00;
```

If we want to configure bits 0-6 as inputs, and bit 7 as output, we can execute:

```
DDRA = 0x80;
```

To change the state of an output bit on **PORTA** of the 68HC11 chip, use an assignment statement with **PORTA** on the left hand side to write to the port's data register named **PORTA**. For example, if **PORTA** is configured as all outputs, the following C statement sets all **PORTA** bits high:

```
PORTA = 0xFF;
```

To read the state of **PORTA**, use an assignment statement with **PORTA** on the right hand side to read the port's data register. For example, the following code fragment reads **PORTA** and places the results in the variable named **latest\_porta\_state**:

```
static unsigned char latest_porta_state;
latest_porta_state = PORTA;
```

## PORTE

**PORTE** (named in the **QEDREGS.H** file) is an 8 bit analog or digital input port. **PORTE** is configured as a digital input after a reset or restart, and is read in the same way that **PORTA** is read: simply use it as the right hand side of an assignment statement. For example, to read the digital state of **PORTE**, your program could execute the statements:

```
static unsigned char latest_porte_state;
latest_porte_state = PORTE;
```

To configure **PORTE** for analog input, use the function:

```
AD80n()
```

To turn off the 8 bit A/D and revert to a digital input port, use:

```
AD8Off()
```

(For experts and the curious: **AD8Off()** turns the 8 bit analog converter off by clearing the A/D power up bit named **ADPU** in the **OPTION** register; **AD8On()** sets the **ADPU** bit.)

## Using the PIA

This section describes how to configure and access the available I/O ports of the Peripheral Interface Adapter (PIA) on the QED Board.

### **PIA Initialization**

The function

```
void InitPIA( int ppa_output_flag, int upper_ppc_output_flag)
```

writes to the PIA configuration register to set the data direction for PPA and the upper 4 bits of PPC. If **ppa\_output\_flag** is true (non-zero), **InitPIA()** configures PPA as output, and if **ppa\_output\_flag** is false (zero), it configures PPA as input. Likewise, if **upper\_ppc\_output\_flag** is true, **InitPIA()** configures the upper four bits of PPC as output, and if **upper\_ppc\_output\_flag** is false, it configures upper PPC as input. **InitPIA()** sets the direction of PPB as output and lower PPC as input to ensure compatibility with the built-in keypad and high current driver interfaces. It clears bits 5, 6 and 7 of PPB which control high current driver outputs HC1, HC2, and HC3.

#### **Warning!**

**There may be a short transient ON condition on the three high current outputs during power-up and reset. The state of the PIA chip can not be controlled when it is initially turned on or reset. A consequence of this is that in the interval of time between power-up and the operating system's initialization of the output to an OFF condition, there may be a short transient ON. You may need to take appropriate precautions in critical applications.**

**Additionally, if the specified PIA configuration is different than the prior configuration, **InitPIA()** writes to the PIA's configuration register and this automatically zeros any outputs in PPA or upper PPC, even if the direction of PPA or PPC was not changed!**

If the specified input/output configuration of the PIA is the same as the prior configuration, **InitPIA()** does not modify the PIA configuration register, and thus does not change the state of any output pins in PPA or upper PPC. But, if the specified PIA configuration is different than the prior configuration, **InitPIA()** writes to the PIA's configuration register and this automatically zeros any outputs in PPA or upper PPC, even if the direction of PPA or PPC was not changed! Consequently, **InitPIA()** may disrupt in-progress operations involving the 12 bit A/D, keypad, or display. Consult the PIA data sheet for details of the PIA operation.

When designing your application, the safest course is to perform all required initializations in an autostart routine as soon as the application program begins. This avoids the problem of a late initialization that disturbs an in-progress I/O operation.

Upon each reset or restart, the PIA is configured as follows:

Port	Direction
PPA	input
PPB	output
lower PPC	input
upper PPC	input

### ***Accessing PIA Ports PPA, PPB and PPC***

Because the timing of the PIA chip are slightly too slow for simple assignment-statement accesses to be “guaranteed by design” at a 16 MHz clock speed, a set of access functions has been defined that inserts a wait state while the PIA is being accessed. This guarantees reliable performance over all device variations and temperature extremes. To access the ports of the PIA (Peripheral Interface Adapter) chip, use the following functions defined in the **PIA.H** file and described in the Control-C Glossary:

```
void PIAStore( uchar c, xaddr address )
uchar PIAFetch( xaddr address )
void PIACheckBits( uchar data, uchar mask, xaddr address )
void PIAClearBits( uchar mask, xaddr address )
void PIASetBits( uchar mask, xaddr address )
void PIAToggleBits( uchar mask, xaddr address )
```

The three PIA port addresses are also defined as macros in the **PIA.H** file:

```
#define PPA_ADDRESS ((xaddr) 0x8080)
#define PPB_ADDRESS ((xaddr) 0x8081)
#define PPC_ADDRESS ((xaddr) 0x8082)
```

where “**xaddr**” is a 32-bit extended address type specifier defined in the **TYPES.H** file.

These functions are easy to use, as illustrated by the following brief examples. If your program has called **InitPIA()** to configure PPA as an output port, it can store the value **0x55** to the port by executing the C statement:

```
PIAStore(0x55, PPA_ADDRESS);
```

You can set the least significant bit in PPA by calling:

```
PIASetBits(0x01, PPA_ADDRESS);
```

where **0x01** is a mask; the 1’s in the mask specify which bits are to be set.

Your program can invert the state of the lower 4 output bits in PPA using the statement:

```
PIAToggleBits(0x0F, PPA_ADDRESS);
```

Again, **0x0F** is a mask; the 1's in the mask specify which bits are to be toggled, and the 0's in the mask specify bits that are to be left unchanged.

If you've configured upper PPC as an input port, you can read its value with the statements:

```
static unsigned char nibble_contents;  
nibble_contents = PIAFetch(PPC_ADDRESS);
```

The upper 4 bits of **nibble\_contents** will then contain the upper PPC input values.

### ***Characteristics of the PIA's I/O Ports***

The 82C55A peripheral interface adapter (PIA) chip is the industry standard part for providing digital I/O ports. This brief summary is intended to clarify some of the features of this chip.

The PIA is configured by writing to a control register at address 8083H. The pre-defined routine **InitPIA()** described earlier writes to this register. It configures the PIA for simple digital I/O ("mode 0") and sets the data direction of ports PPA and upper PPC according to user-supplied flags. **InitPIA()** configures PPB as an output and the lower half of PPC as an input.

Whenever the PIA is configured by writing to the control register, all outputs are set to the logic low state. This is true whether or not the new configuration is different from the prior configuration. The **InitPIA()** routine tries to minimize the impact of this (often undesirable) "feature" by checking the control register before writing to it. If the PIA configuration requested by the programmer is the same as the existing configuration, the PIA's control register is not modified. In general, it is best to use a static configuration for the PIA; dynamically changing the direction of PIA ports while the application is running can cause troublesome glitches on the PIA output pins.

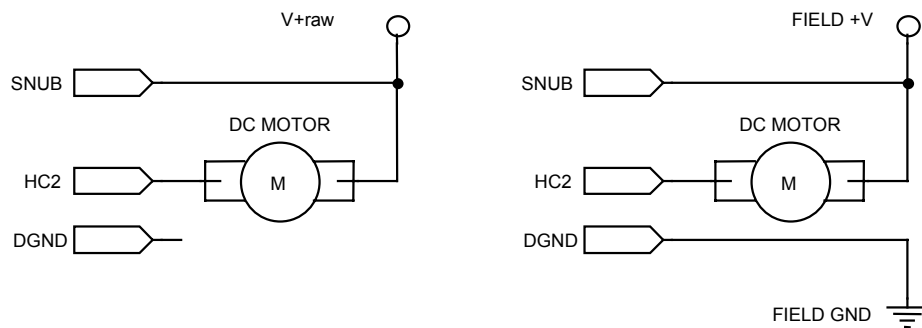
The PIA has another unusual "feature" called "bus hold circuitry". The PIA tries to maintain specified logic levels on pins that are configured as inputs (rather than the standard approach of leaving the input pins in a "floating" high impedance state). After a reset or change in configuration, the PIA holds all inputs high by sourcing between 50 and 400 microamps into the external load attached to the input pin. If your design requires that the inputs settle to a voltage near ground, you will need to pull the pins low with external pull-down resistors that connect each input pin to ground. The resistors should have a value less than 1 K-ohm; the manufacturer suggests that the pull-down should be 640 ohms to ensure a logical 0 under worst-case conditions. Port PPA also has bus hold circuitry that can hold an input in the low condition. If your design requires that PPA inputs be held at a logical high state, install external pull-up resistors of less than 3 K-ohms from the PPA input pins to the +5 Volt supply.

PIA output pins have good current drive capabilities. The data sheet states that the chip can maintain an output high voltage of at least 3.0 Volts while sourcing up to 2.5 mA. The manufacturer's technical support staff claims that the typical performance is much better; they say that a typical chip can maintain 3.0 Volts or higher while sourcing up to 20 mA. In the worst case the PIA outputs can sink up to 2 mA while maintaining the output voltage below 0.4 Volts. There is no internal current limiting on the outputs, so your custom circuitry should include current-limiting resistors if significant current will be required from the output pins.

## Using the High Current Drivers

Four N-channel MOSFET high current drivers are available at the Supplementary I/O connector. Each driver can sink up to 150 mA continuously, or up to 1 amp on an intermittent basis at voltages as great as 60 V. Onboard snubber diodes suppress inductive kickback, so the drivers can be used to control solenoids, motors, and other inductive loads.

Figure 8-1 shows how to connect a DC load (a DC motor is shown) to the MOSFETs.



**Figure 8-1 Connecting a DC load (for example, a DC motor) to the high current drivers using onboard power (left) and using external power (right).**

HC0 is controlled by a PAL signal and HC1 - HC3 are controlled by the PIA port bits PPB5 - PPB7 respectively. NOTE: Upon power-up and reset, the high current MOSFETs, HC1 - HC3, may momentarily sink current until the QED-Forth startup software initializes them. The PAL-controlled HC0 output does not exhibit this transient turn-on behavior at startup.

Two simple functions control these four high current drivers:

```
void ClearHighCurrent( uchar mask )
void SetHighCurrent(  uchar mask )
```

**SetHighCurrent()** accepts a 4-bit mask and turns on the drivers that correspond to "1"s in the mask. **ClearHighCurrent()** accepts a 4-bit mask and turns off the drivers that correspond to "1"s in the mask. Note that "turning on" a driver allows it to sink current, thereby pulling the voltage at the output pin towards ground. "Turning off" a driver prevents it from sinking current. For example, to turn on all four high current drivers, execute

```
SetHighCurrent( 0x0F )
```

Then, if you execute

```
ClearHighCurrent( 0x01 )
```

you will turn off driver number 0 while leaving the state of the other three drivers unchanged.

You can verify the operation of the high current outputs by connecting a pullup resistor (say, 1 kOhm) from the output to +5V and measuring the output voltage with a voltmeter. Note that the

output voltage goes LOW when the output is ON (sinking current to ground), and the voltage goes HIGH when the output is OFF (no current flowing in the load resistor).

## Using Uninterruptable Operators

### *The Importance of Uninterruptable Operators*

Care must be taken when performing “read/modify/write” operations in applications that use interrupts or multitasking. Operations such as setting or clearing individual bits in a byte while leaving other bits unchanged are called “read/modify/write” operations because they involve reading the port, modifying the read contents, and writing the result back to the port. Unpredictable results can occur if more than one interrupt service routine or task tries to access a single port or memory location at the same time using a read/modify/write sequence. The simplest solution to this problem is to access the memory location or port using an “uninterruptable” read/modify/write operator.

The following scenario illustrates the importance of uninterruptable operators when more than one task or interrupt routine is writing to a memory location. Let’s assume that two different tasks are controlling the bits of PORTA. Assume that TASK1 is controlling the state of bit 4, and TASK2 controls bit 7. Let’s assume that bit 4 is low when TASK2 tries to execute the following code:

```
static unsigned char mask = 0x80;
PORTA |= mask;
```

TASK2 is merely trying to set the top bit in PORTA to 1, but this statement may have unintended consequences. The compiler generates code that reads the contents of PORTA, performs a bitwise OR with the contents of mask, and stores the result back into PORTA. Assume that the timeslicer interrupt is serviced just after the OR instruction and transfers control to TASK1. TASK1 may change the state of bit 4 to a 1. When control is then transferred back to TASK2, the final store to PORTA is executed. Unfortunately, this store command erroneously sets bit 4 back to the low state! TASK2 was interrupted after it read the state of PORTA but before it had a chance to write the new contents, so it undoes the change that TASK1 made in the state of PORTA bit 4! This can indeed cause problems in an application program.

### *Pre-coded Read/Modify/Write Functions*

The pre-coded PIA and High Current Driver read/modify/write functions described earlier in this chapter avoid this problem by disabling interrupts for ten to sixteen cycles (2.5 to 4 microseconds at a 16 MHz crystal speed). This prevents the corruption of the contents when different tasks or interrupts share access to a single location. The following functions are uninterruptable:

```
void PIAChangeBits( uchar data, uchar mask, xaddr address )
void PIAClearBits( uchar mask, xaddr address )
void PIASetBits( uchar mask, xaddr address )
void PIAToggleBits( uchar mask, xaddr address )
void ClearHighCurrent( uchar mask )
void SetHighCurrent( uchar mask )
```

Additional uninterruptable operators are declared in the **XMEM.H** header file in the **\MOSAIC\FABIUS\INCLUDE\MOSAIC** directory; these routines are described in detail in the Control-C Glossary.

## Create Your Own Uninterruptable Functions

It is easy to create your own uninterruptable functions using the `_protect` keyword. For example, the following uninterruptable function sets specified bits in a port or memory byte:

```
void _protect SetBitsUninterrupted( uchar mask, char* address )
{ *address |= mask;
}
```

In response to the `_protect` keyword, the compiler ensures that interrupts are temporarily disabled while `SetBitsUninterrupted()` is executing, and that the global interrupt mask (the I bit in the condition code register) is restored to its prior state after the function terminates.

Simple stores to and fetches from 1-byte or 2-byte memory locations are intrinsically uninterruptable because they are implemented with single assembly-language opcodes. However, the 68HC11 processor does not have a single opcode that can access a 32 bit memory location. Thus, problems can arise when one task writes to a floating point or long variable, and a second task needs to read the saved value. The data that is read may be invalid if the read or the write is interrupted between the time of the writing/reading of the first 16 bits and the writing/reading of the second 16 bits. In these cases uninterruptable operators should be used. An example is presented by the functions named:

```
PeekFloatUninterrupted()
PokeFloatUninterrupted()
```

which are defined using the `_protect` keyword in the `TURNKEY.C` program in the `\MOSAIC\DEMOS_AND_DRIVERS\MISC\C EXAMPLES` directory; this program is discussed in detail later in this book.

## Connecting Hardware to the Digital Outputs

On the QVGA Controller the processor's ports A and D are available for you to connect to external devices. You can use them to directly drive LEDs, relays, transistors, opto-isolators or other digital logic devices. But please be careful -- whenever these outputs are connected to external devices you must stay within the voltage and current capabilities of the output pins. Because the MC68HC11 reference manuals don't specify the electrical capability of these ports very well we provide some additional information here.

### Electrical Characteristics of the 68HC11's I/O Ports

The electrical characteristics of the 68HC11F1's digital I/O signals are specified in detail in section 13.4 of the MC68HC11F1 Technical Data Manual. This table lists the "DC Electrical Characteristics" of the processor.

Pins on the 68HC11 configured as digital inputs report a logical "high" if the input voltage is greater than 0.7 times the supply voltage, or 3.5 Volts. They report a logical "low" if the input voltage is less than 0.2 times the supply voltage, or 1.0 Volt. Input voltages between 1.0 and 3.5 Volts may be read as either high or low.

Pins on the 68HC11 configured as digital outputs in the “high” state can maintain the output voltage within 0.8 Volts of the positive supply if 0.8 mA or less is being drawn from the pin. If less than 10 microamps is being drawn, the output high voltage is within 0.1 Volt of the positive supply. In the low state, the digital outputs can keep the voltage below 0.4 Volts while sinking up to 1.6 mA of current. Load circuitry that requires significant current to be sourced or sunk by the digital output should include external resistors to ensure that the absolute maximum rating of 25 mA per output pin is never exceeded.

### ***Protecting the Input and Output Pins***

These output pins are very useful because they can directly drive a wide range of devices. Nevertheless, any circuitry connected to the processor should take care to:

- Prevent excessive voltage levels at the pin; and,
- Prevent excessively great currents.

We’ll address each of these concerns in turn.

### ***Preventing Excessive Voltages***

Excessive voltages are prevented by ensuring that voltages of less than a diode drop below  $V_{SS}$  ( $-0.6$  V) or greater than a diode drop above  $V_{DD}$  ( $V_{DD}+0.6$  V) are never applied to the processor. For some applications, particularly when driving inductive loads such as relays, you may need to provide Schottkey diode clamps between the pin and  $V_{DD}$  and between the pin and ground. All pins on the processor have inherent diode clamps to the processor’s ground voltage,  $V_{SS}$ , but it is best not to rely on these; if there is the possibility of the output pin being driven to a negative voltage level it is better to prevent excessive power dissipation in the processor package by externally clamping the voltage to ground ( $V_{SS}$ ) with a Schottkey diode. Processor ports A and D also have inherent diode clamps to the chip’s +5V supply voltage,  $V_{DD}$ , but it is likewise better not to rely on these; instead external Schottkey clamps to  $V_{DD}$  should be used.

### ***Preventing Excessive Currents***

The current into or out of any pin on the MC68HC11 should also be limited to prevent damage. The specified maximum current is 25 mA into or out of any one pin at a time, although these pins can typically withstand transients of more than 100 mA at room temperature. In driving more than one pin at a time it is necessary only to stay within the processor’s maximum power dissipation. Unfortunately, Motorola doesn’t specify what this maximum is, but we recommend that you don’t exceed a total of 100 mW for all processor I/O pins combined. The chip’s total power dissipation is the sum of its internal power (which varies from device to device so much that it can only be determined by actually measuring it, but which is specified at less than 150 mW) and the power associated with the I/O pins. Pin currents must be limited using external resistors.

### ***Output Pin V-I Characteristics***

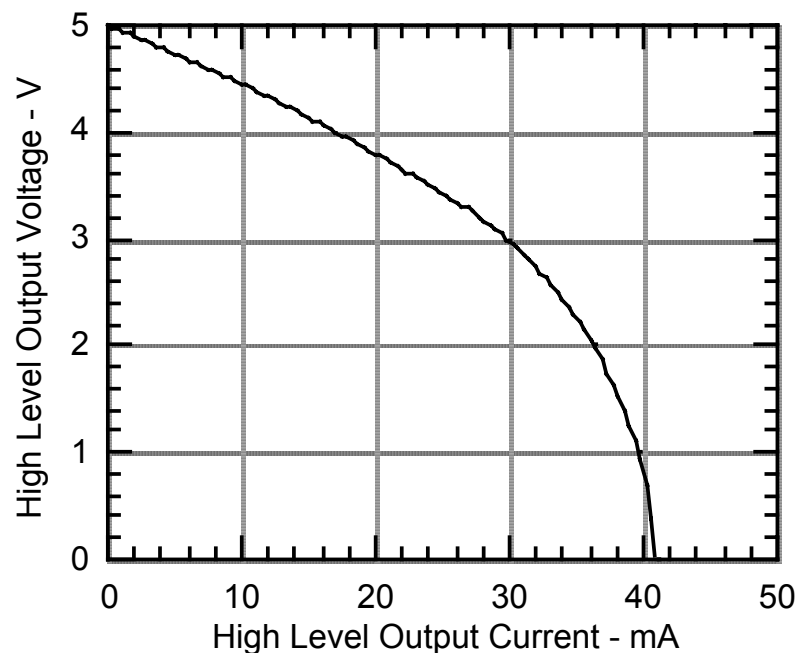
The output pins of the MC68HC11 are similar in electrical characteristics to the SN54/74HC digital logic family. They can source or sink up to 25 mA and are guaranteed to source 0.8 mA while providing a valid logic high and to sink 1.6 mA at a valid logic low, although they generally do much

better. A valid logic high level is between  $V_{OH} = V_{DD}$  and  $V_{OH} = V_{DD} - 0.8 \text{ V}$ , and a valid low level is between  $V_{OL} = V_{SS} = 0 \text{ V}$  and  $V_{OL} = V_{SS} + 0.4 \text{ V}$ . As the output is loaded, the  $V_{OL}$  and  $V_{OH}$  levels rise or fall. It is often useful to know just how much to expect the  $V_{OL}$  and  $V_{OH}$  levels to degrade with current. For currents of less than 10 mA the voltage change is linear with current; that is, it can be modeled as a voltage source of either zero or five volts and an equivalent series resistance of 40 ohms. At greater output currents the resistance increases until at the greatest specified current for any one pin, 25 ma., the equivalent resistance is 60 ohms. At this current the voltage degradation of the  $V_{OL}$  or  $V_{OH}$  is 1.5 volts. Figure 8-2 and Figure 8-3 illustrate this variation.

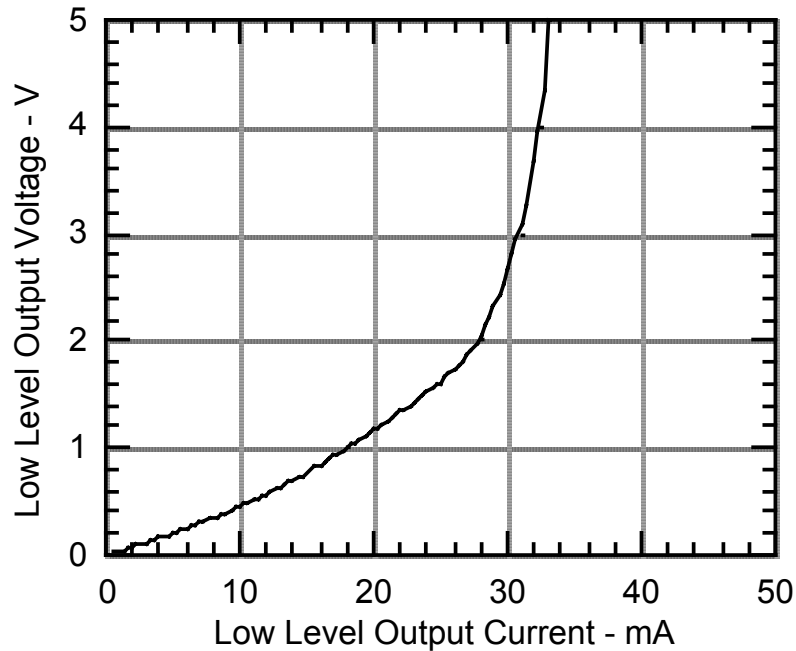
These figures can be used to choose component values for particular circuits. For example if we wish to use a pin of Port A or D to drive a light-emitting diode we would place the LED in series with a resistor and connect them between an output pin and ground. The resistor limits the current, to the LED. From the LED data sheet we note that its forward voltage at a current of 10 mA is specified to be 2.2 V. What should the resistor value be? We calculate it as,

$$\text{Eqn. 8-1} \quad R = (V_{OH} - 2.2 \text{ V}) / 10 \text{ mA}$$

Consulting the  $V_{OH}$  vs  $I$  curve for the output pin we find that at 10 mA  $V_{OH} = 4.4 \text{ V}$ . We therefore need a resistance of 220 ohms.



**Figure 8-2** Degradation of the Port A or Port D output high voltage with current. The maximum current allowed for continuous operation is 25 ma.



**Figure 8-3** Degradation of the Port A or Port D output low voltage with current. The maximum current allowed for continuous operation is 25 ma.

## The Processor's Output Compare Functions

The processor's programmable timer subsystem contains 5 output compare (OC) functions (named OCx for x from 1 to 5) associated with PORTA output pins PA7 through PA3 (in descending order). These output compare functions allow you to specify actions that take place at particular, well determined times. Using output compares, it is easy to set up real-time clocks, cause periodic execution of code, and generate precisely timed synchronous or asynchronous waveforms. They can be used to implement a stepper motor controller, pulse generator, pulse width modulation (PWM) signals, precisely timed output pulses, timesliced multiplexing, or serial communications.

Output-compare functions work by automatically changing PORTA output pins and/or invoking an interrupt service routine (ISR) whenever the contents of a free-running 16-bit counter (TCNT) matches the contents of user-set output-compare registers, TOCx. When these contents match, we say that a "successful output compare" has occurred. Thus the programmer can precisely specify a future time at which an action will occur by simply storing the time as a 16-bit value in the appropriate output compare register, TOCx. The free running counter counts at a programmable rate, from 0 to 65536, then rolls over to zero and continues counting. Its rate is one count each 2 microseconds, for a rollover period of 131.072 milliseconds. Consequently, you can set up output compares to trigger events with a resolution of 2 microseconds, and up to 131.072 milliseconds into the future (or arbitrarily longer if you keep track of rollovers on TCNT).

Because TCNT is clocked by a prescaler driven from the system E clock, you can change the count rate by modifying the prescaler's division ratio, from its current value of 8 to 1, 4, or 16, changing its rollover period to 16.384, 65.536, or 262.144 milliseconds. If you do though, the system timeslicer will be affected. We find that a 2 microsecond tick rate provides sufficient resolution for most applications.

Each of the five output compare subsystems has a 16-bit TOCx register, a successful compare OCxF (interrupt) flag, and an interrupt mask OCxI, where "x" is the output compare number. OC1 can control any of pins PA3 through PA7 and it has its own register to specify which of PORTA pins are affected. Output compares OC2, OC3, OC4 and OC5 each control a single pin. They each have a pair of output mode/level bits, OMn and OLn, which determine the effect that each successful compare has on PORTA bits PA6, PA5, PA4, and PA3 respectively. The processor automatically sets an output compare's OCxF flag bit in the TFLG1 register when the contents of the TCNT register and the OC's TOCx register are equal. At the same instant, the state of the associated PORTA pin is set, cleared, or toggled as specified by the output mode bits. In addition, if the output compare's OCxI mask bit in the TMSK1 register is set, an interrupt is recognized when a successful compare occurs.

An active output compare function can cause a signal change on a PORTA pin at a specified time T, and/or trigger an interrupt at time T:

- **Signal Change** – To cause a signal change on a PORTA pin when time T equals the contents of TCNT, the PORTA pin must be configured as an output, and the output compare function must be enabled. OC1 is enabled by storing the data to be output in OC1D and specifying the pins to be changed in OC1M, and OC2-OC5 are enabled simply by storing a 2-bit code into TCTL1 specifying the desired signal change. Using the CFORC register, it is also possible for software to immediately force a state change on a timer-controlled signal without causing an interrupt.
- **Interrupt** – To trigger an interrupt when time TCNT = T, an interrupt handler must be installed, and the output compare's local interrupt must be enabled by setting bits in TMSK1.

**Table 8-6 Output Compares and their properties**

Output Compare	Controlled PORTA Pin	Comparison Register	Comments and Alternate Use
OC1	PA3, 4, 5, 6, and/or 7	TOC1	May control multiple pins simultaneously, or be paired with another OC to jointly control pin PA3, 4, 5, or 6.
OC2	PA6	TOC2	The OC2 timer is used by the kernel's timeslicer and elapsed time clock functions. If you do not use these functions, pin PA6 may be controlled by OC1 or used for general purpose I/O.
OC3	PA5	TOC3	Not used by the kernel.
OC4	PA4	TOC4	Used as an output by the secondary serial port. Available if you do not need Serial 2.
OC5	PA3	TI4O5	Shared with Input Capture 4, which is used as an input by the secondary serial port. Available if you do not need Serial 2.

As summarized in the table, the output compares are not all identical in function, and some are used by the operating system. OC1 and OC5 differ from the others slightly in function, OC2 is used by the operating system's timeslicer, and OC4 and OC5 are used by the secondary serial port:

- OC1 is special in that it can synchronously control any of PORTA pins PA7, PA6, PA5, PA4, and PA3. Even when OC1 is used to control several PORTA pins, the timer and interrupt functions of those pin's output compares may still be used independently of the pin (to implement clocks, etc.). While the other output compares can be used to set, clear, or toggle an output pin, OC1 can be used only to set or clear a pin, but not to toggle it.
- OC2 is used by the timeslicer. Consequently, if you need the services of the timeslicer (timesliced task switching, elapsed time clock, or BENCHMARK: function) make sure that you do not use OC2 for other functions. Even if you do use the timeslicer, pin PA6 is still available for use as general purpose I/O, or as an output controlled by OC1.
- OC4 is used as an output by the secondary serial port, so you can't use it or its associated pin PA4 if you need the second RS232 serial link.
- OC5 shares its timer register and output pin with input capture 4 (IC4). OC5 operates like the other output compares, but it must be initialized by clearing the I4/O5 bit of the PACTL (pulse accumulator control) register before it may be used. Also, IC4/OC5 and associated pin PA3 are used by the secondary serial port, so be sure not to use these resources if you need the second RS232 serial link.

## Pulse and PWM Generation Techniques

The processor's output compare functions provide lots of flexibility for creating single pulses or pulse-width-modulated waveforms. Most methods are variations on this algorithm:

1. The desired start time of the pulse is programmed by storing an appropriate count in the output-compare register (TOCx) of OCx, and the OCx interrupt is enabled by setting a flag bit in TMSK1.
2. OCx's mode/level bits (OMx and OLx) are configured to automatically set the output compare's corresponding output either high or low, depending on the polarity of the desired pulse (this action enables the output compare).
3. When the compare occurs, the pin state is automatically changed and an interrupt service routine called.
4. The interrupt service routine (ISR) reprograms the output compare to automatically change its pin back to its inactive level on the next compare;
5. The ISR also increments the output-compare register by a value corresponding to the desired duration of the pulse.

Since the pin-state is changed by hardware automatically at specific values of the free-running counter, the pulse width is controlled accurately to the resolution of the free-running counter irrespective of software latencies. By repeating the actions for generating a pulse, you can generate an output signal of a specific frequency and duty cycle. While software latency and execution times do

not affect the timing of the waveform, they do impose limits on the frequency and duty cycles attainable. The different methods of generating PWM signals differ primarily on where the software execution times are constrained to fit, either within the on time, the off time, or the waveform's period as a whole.

The following is a quick summary of some of some specific ways you can use output compares to generate pulses or PWM waveforms. You can find complete descriptions of the registers mentioned in Motorola's MC68HC11F1 Technical Data Manual. Example 1 shows you how to generate a triggered pulse, Examples 2 and 3 represent exceptional and instructive methods of generating PWM signals, and examples 4-6 are commonly used PWM methods. Example 6 provides code for generating "failsafe" PWM signals.

### ***Example 1 – Creating a Single Precise Pulse from an External Trigger***

Suppose you'd like to output a single pulse on PA5 with very precise duration in response to a triggering event, for example the leading edge of an input pulse on PA0. You'd like the output pulse to start a precise, fixed time after the initiating trigger and to last some precise duration, between 2 microseconds and 131 milliseconds. Further, the output pulse should occur after the first occurrence of the trigger (after enabling the system) and then stay off rather than being retriggered by subsequent input pulses.

To do this you would use one input capture (IC3) and two output compares (OC1 and OC3). Because the trigger may occur anytime an input capture is used to determine the precise time of its leading edge. And because the output pulse width must be precisely controlled, and its duration can potentially be shorter than any interrupt service routine, the pulse should be turned on and off by output compares. The input capture invokes an interrupt service routine that enables the output compares. For our example we'll assume the desired pulse start time is 10 milliseconds (or 5000 TCNT counts) after the trigger is detected, and its duration is precisely 10 microseconds (5 TCNT counts). Here's one way to do it using three routines:

- ⇒ An initialization routine (called `ENABLE`) that configures and enables IC3 to capture a rising edge on PA0, forces PA5 off to initialize it, and configures and enables OC3 to turn off pin PA5;
- ⇒ An interrupt service routine for IC3 (called `IC3_ISR`) that programs the comparator registers of OC1 and OC3 and enables OC1; and,
- ⇒ An interrupt service routine for OC1 (called `OC1_ISR`) that disables OC1 so that after the output pulse is first turned on it is not turned on again.

Here's how to write the routines:

**ENABLE** – Inhibit IC3, OC1, and OC3 interrupts by storing 0x0xxx0 to TMSK1 (using `CLEAR.BITS` with a mask of 0xA1). Configure OC1 to set PA5 high on an output compare by setting bit 5 of OC1D, but don't enable it using OC1M yet – the `IC3_ISR` will be responsible for doing that. Configure OC3 to clear its associated pin (PA5) on an output compare by storing appropriate mode/level bits (OM3 and OL3), that is xx10xxxx, into the timer control register (TCTL1). Initialize PA5 to the OFF state by forcing an early output compare on OC3. This is done by setting bit 5 of CFORC. Configure and enable IC3 to capture a rising edge

PA0. This is done by clearing bit 0 of DDRA (to set the data direction of PA0 to input), and setting the lower two bits of TCTL2 (the two corresponding to IC3) to xxxxxx01 to capture a rising edge. Clear the interrupt flag bit (IC3F) left over from any prior edge detection, if any, by writing a one to IC3F in TFLG1. Finally, enable an IC3 interrupt by setting the IC3I bit in TMSK1.

**IC3\_ISR** – On entering the ISR routine first disable further interrupts by clearing the IC3I bit in TMSK1, and clear the interrupt flag bit (IC3F) by writing a one to IC3F in TFLG1. Then read TIC3 to determine the trigger time, we'll call it TT. Set up OC1 to turn on output pin PA5 at time TT+5000 by setting TOC1=TT+5000 and configure OC3 to turn it back off just 5 counts later, by setting TOC3=TT+5000. Enable an OC1 interrupt by setting the OC1I bit in TMSK1. Finally enable OC1 and tie it to PA5 by setting bit 5 in OC1M.

**OC1\_ISR** – This interrupt service routine will be invoked when the output pulse is turned on. It only needs to disable OC1 so that further pulses are not produced until the system is re-enabled by executing ENABLE again. Disable OC1 by clearing bit 5 in OC1M. Disable interrupts on OC1 by first clearing the OC1I bit in TMSK1, then clear the interrupt flag bit (OC1F) by writing a one to OC1F in TFLG1.

### ***Example 2 – Two OCs Generate a PWM Waveform Without Interrupts***

Using two output compares you can generate a PWM waveform of any duty cycle (from 1/65536 to 65535/65536) without using interrupt service routines. As no ISR is used, no software resources are needed to maintain the waveform, and there is no impact on overall system performance. The PWM waveform is free – from a software perspective. So what's the catch? The catch is that the waveform must have a fixed period, equal to the rollover period of the free-running counter, or 131.072 milliseconds. If you can live with that, here's how it's done: Two output compares are used, one sets the output pin at a particular value of TCNT, and the other simply resets the pin at another TCNT value. One of the output compares must be OC1 – because it can be used in conjunction with another to control the same pin. Let's use OC1 to turn ON an output pin (PA5) whenever TCNT hits 0x0000, and OC3 to turn it OFF whenever TCNT hits 0x1000. More specifically,

1. Disable interrupts caused by OCs by storing 0x00 to the timer interrupt mask register 1 (TMSK1). Now, output compares will not cause interrupts. Even so, they can still control output pins.
2. Use OC3 to turn OFF the pulse whenever TCNT=0x1000 (for example, for a duty cycle of 1/16) by storing 0x1000 into TOC3. Configure OC3 to clear its associated pin (PA5) on a successful compare by storing appropriate mode/level bits (OM3 and OL3), that is xx10xxxx, into the timer control register (TCTL1). Now, whenever TCNT hits 0x1000 pin PA5 will be cleared. We configure the OFF transition first because we don't want the pin to get stuck ON before we're done configuring our output compares, just in case.
3. Use OC1 to turn ON the pulse whenever TCNT=0x0000 by storing 0x0000 into TOC1. Associate OC1 with pin PA5 by setting bit 5 in the output compare mask register OC1M. Configure OC1 to set the pin high by storing 0x20 into the OC1 data register, OC1D. Now, whenever TCNT hits 0x0000 pin PA5 will be set high.

Because an ISR isn't used, there is no possibility of software delays influencing the PWM output.

Advantages: Precise transition time control, all duty cycles possible with 16-bit resolution, no software needed to keep things running, failsafe in that a software crash is not likely to affect operation.

Disadvantages: Only a single channel, only a single PWM period.

### ***Example 3 – A Single OC-Driven ISR Generates Many PWM Channels***

What if you want to generate many channels of PWM waveforms, more than there are output compares? In the prior example output compares were used to generate a precisely-timed high-resolution waveform on a single channel without the assistance of an ISR. This example provides the other extreme, an unlimited number of channels of low-resolution PWM signals are generated by a single output-compare-driven interrupt service routine.

The scheme uses a single output compare to periodically invoke an interrupt service routine. The OC is not tied to a PORTA pin, rather it is used only as a dedicated clock that calls the ISR at a fixed interval corresponding to the smallest ON or OFF time that can be produced. Each time the ISR is called it updates all the PWM outputs using any general purpose output pins available. It may do this by reading values from a look-up table, counting, or more computationally.

Because the ISR latency can vary depending on what other interrupt-driven services are running on the controller there is some jitter (or variance) on the transition times, producing a slightly varying PWM duty cycle. This variation can be compensated on the average if the ISR reads TCNT to determine the actual ON and OFF times and modulates the next ON or OFF time to attain the desired PWM duty cycle averaged over a number of cycles – but of course that requires greater execution time.

The sum of the ISR latency and execution times must be less than the difference between adjacent OC times, placing a limit on the smallest ON or OFF time attainable. If the ISR is delayed so long that the next OC time is missed, the next ISR doesn't occur until TCNT rolls over and another match occurs. Consequently rollover delays of a TCNT period may be inserted into the desired ON or OFF times.

For an example of software generated PWM signals with 8-bit resolution and best averaging properties see “MI-AN-056 Optimal PWM Algorithm” and “MI-AN-058 Using Port PPA for PWM”.

Advantages: Any number of channels can be accommodated.

Disadvantages: ISR latency causes jitter in the transition times; ON or OFF times smaller than the ISR latency and execution time are not possible; rollover delays possible if timing criteria not met; not failsafe.

### ***Example 4 – One OC and ISR Generates a “No Jitter” PWM Signal***

The simplest way of generating a precise PWM waveform with arbitrary duty cycle and period is to use a single output compare to automatically turn on and off an output pin and an interrupt service routine that reprograms the output compare after each transition. The “off” transition invokes the ISR which sets up the turn-on time and programs the next output state to be “on”, and the “on” transition invokes the same ISR to set up the turn-off time and the next “off” state. The on and off times must each be great enough to contain the latency and execution time of the ISR. So duty cycles that

would require very small on or off times are not attainable. If the ISR is delayed so that it does not program the next transition in time, then the output compare doesn't find a match until TCNT rolls all the way around. In this case rollover delays of approximately 131 msec may be inserted into either the on or off time.

Advantages: Transitions are precise, with no jitter; duty cycle and period are programmable over a wide range.

Disadvantages: ON or OFF times smaller than the ISR execution time and latency are not possible; rollover delays are possible; not failsafe – a software crash can leave the output stuck ON.

### ***Example 5 – Two OCs and ISRs Generate a “No Jitter” PWM Signal of any Duty Cycle***

To obtain ON and OFF times that may be each as small as a single clock tick, two OCs and ISRs are required. The “off” transition invokes an ISR which sets up the next turn-off time, and the “on” transition invokes a different ISR to set up the next turn-on time. Each ISR simply increments the next ON or OFF comparison register by the period. There is no particular restriction on the shortness of the ON or OFF times, either can extend down to just a single count of TCNT, but their sum, the period, must be great enough to contain the latency and execution times of both ISRs. Because OCs are used to drive the output pin, the transition times are exact, with no jitter. If service of either ISR is delayed for more than a period then a rollover delay may be inserted into either the on or off time.

Advantages: Transitions are precise, with no jitter; duty cycle and period are programmable over a wide range, duty cycle extends fully from 1/65536 to 65535/65536.

Disadvantages: Rollover delays are possible; not failsafe – a software crash can leave the output stuck ON.

### ***Example 6 – One OC and ISR Generates a “Failsafe” PWM Signal***

A single OC and associated ISR is used. The OC invokes an ISR for each transition. For the ON transition, the ISR is responsible for setting the output pin. It also computes the next turn-off time based on the time at which the pulse is actually turned on, and programs the OC to automatically turn it back OFF at the turn-off time. At the next OC the pin is turned off by hardware and the ISR is again called. This time the ISR just sets the turn-on time for the next OC time, disconnecting the OC from the pin so that the pin is not automatically set. This sequence of events produces pulses whose duration is invariant with respect to ISR delay, but that may jitter back and forth within their fixed period. Despite any jitter, the duty cycle and period are both precisely controlled. If the ISR is delayed by more than the off time, rollovers are inserted into only the off time, never the on time. So the pulse on times are failsafe so long as the processor's clock is running.

Advantages: Failsafe operation assures an ON pulse is never longer than desired and the pulses turn off on a software crash. ON time may be as small as a single TCNT count.

Disadvantages: Pulse position jitter; rollover delays are possible in the OFF time; minimum OFF time must be greater than the IST latency and execution time.

**Table 8-7 PWM Methods.**

Method	ISR Used	Output Compares	Turn ON/OFF	Jitter	D.C. Accuracy	D.C. Range	Rollovers inserted?	Period
2	no	OC1 and one other	OC/OC	none	perfect	any	no – failsafe	Fixed at 131.072 ms
3	yes	any OC	ISR/ISR	yes	limited by ISR delays	Ton, Toff >ISR	yes	on and off times must each be greater than ISR latency and execution times
4	yes	any OC	OC/OC	no	perfect	Ton, Toff >ISR	yes	on and off times must each be greater than ISR latency and execution times
5	yes	OC1 and one other	OC/OC	no	perfect	Ton, Toff unlimited	yes	P>ISR1+ISR2
6	yes	any OC	ISR/OC	yes	perfect	Ton unlimited, Toff>ISR	failsafe – into only the off time	



## Chapter 9

### Chapter 9: Data Acquisition Using Analog to Digital Conversion

*This chapter shows how to use the 24 channels of analog input/output on the QVGA Controller. The QVGA Controller includes a high performance 8- channel 12-bit analog to digital (A/D) converter. The 12-bit A/D can be configured to convert 8 channels of single-ended inputs or 4 channels of differential signal inputs, or combinations of single-ended and differential signals. The input voltages can be unipolar, with a range from 0 to 5 volts, or bipolar, with a nominal range from -5 to +5 volts. This voltage range can be adjusted using low and high reference voltages. The demonstration code for this chapter in the ANALOGIO.C file also shows how to use C arrays and FORTH\_ARRAYS as buffers, and describes how to store semi-permanent information in the QVGA Controller's Electrically Erasable PROM (EEPROM).*

*This chapter describes the analog I/O devices available on the QED Board, explains how to connect the converters to external signals, and details the built-in driver routines that make analog I/O easy to use. Simple code is presented to calculate measured voltages based on A/D readings and to calculate the digital values required to instruct a DAC to output a specified voltage. At the end of the chapter, sample circuitry and code is presented to convert a pair of 8 bit DACs into a high resolution DAC.*

### Data Acquisition Using the QVGA Controller

Many instrument applications require monitoring of analog signals and generation of analog control voltages. Analog to digital (A/D) converters and digital to analog converters (DACs) can perform these functions. An A/D converter samples analog signals and converts them to digital values that can be stored, processed, or displayed. A DAC generates an analog voltage whose value is proportional to a specified digital number.

The resolution of an A/D or DAC is specified in bits. For example, an 8-bit DAC can output any of  $2^8$  or 256 distinct analog levels; 256 is the maximum number of levels representable by an 8 bit binary number. Similarly, a 12-bit A/D converts an analog signal into one of 4096 discrete digital numbers.

**Table 9-1 Analog I/O**

I/O Lines	Type	Port Address	Comments / Alternate Uses
8	8-bit 0-5 V analog inputs	PE 0-7	Alternately may be used as digital inputs.
8	12-bit analog inputs		8 channels single-ended or 4 channels differential, unipolar (0-5 V) or bipolar ( $\pm 5$ V).
8	8-bit analog outputs		Multiplying, cascadable, 0-3V output DACs.
24	Analog I/O lines		

The QVGA Controller hosts both analog to digital and digital to analog converters to address a wide variety of instrumentation and control applications. It includes three 8-channel analog I/O devices:

- An 8-channel 8-bit analog to digital (A/D) converter that is built into the 68HC11 processor chip converts unipolar signals with a nominal 0 to +5 volt range;
- An 8-channel 12-bit A/D converter; and,
- An 8-channel 8-bit digital to analog converter (DAC), discussed in the next Chapter.

The 16 analog inputs and 8 analog outputs are brought out to a 40 pin analog connector (H2) on the QED-Flash Board (the smaller of the two boards of the QVGA Controller); the connector diagrams in an Appendix specify the pin assignments.

### ***The 8 bit A/D Converter***

The 8 bit A/D converter in the processor converts unipolar signals with a nominal 0 to +5 volt range, and conversion results are returned in registers in the 68HC11. The analog inputs are connected to the PORTE pins on the processor; these can be used as digital inputs if the 8 bit A/D is disabled.

### ***The 12 bit A/D Converter***

The 12 bit A/D converter is interfaced to the processor via the fast serial peripheral interface (SPI). Its chip select is a memory-mapped signal generated by the onboard logic. The 12 bit A/D can be configured to convert 8 channels of single ended inputs or 4 channels of differential signal inputs, or combinations of single-ended and differential signals. The input voltages can be unipolar, with a range from 0 to 5 volts, or bipolar, with a nominal range from -5 to +5 volts. This voltage range can be adjusted via the low and high reference voltages named VRL and VRH.

## **Examining the Demonstration Program**

The code discussed in this section is located in the file named **ANALOGIO.C** in the `\MOSAIC\DEMOS_AND_DRIVERS\MISC\C EXAMPLES` directory. Most of the functions in this file are interactive versions of functions declared in the **ANALOG.H** file in the `\MOSAIC\FABIUS\INCLUDE\MOSAIC` directory; they are described in detail in the Control-C Glossary.

We recommend that you compile and download the **ANALOGIO.C** program now so that you can interactively work through the exercises in this chapter. Simply use your TextPad editor to open **ANALOGIO.C**, and click on the Make Tool (the Make icon) to create the download file named **ANALOGIO.DLF**. Then enter the Mosaic Terminal program, and type:

**WARM ←**

or:

**COLD ←**

to terminate any prior multitasking program that might be running, and select the “Send Text File” menu item to send **ANALOGIO.DLF** to the QVGA Controller.

## Fundamentals of Analog to Digital Conversion

An analog to digital converter samples an analog signal and outputs a digital number that is proportional to the analog signal. The A/D converters on the QVGA Controller sample input voltages and communicate the digital result to the 68HC11 processor.

The analog input signal must be within the input range of the A/D converter. On the QVGA Controller, the lower bound of the range is equal to the voltage on VRL (voltage reference/low) and the upper bound of the allowable input range is equal to the voltage on VRH (voltage reference/high). The VRL and VRH references are brought out to the 40 pin Analog I/O connector and control the input voltage range of both the 8 bit and 12 bit A/D converters. Their default values are 0 Volts (analog ground) and 5.0 Volts (analog +5V), respectively. They can be driven to different voltages by external circuitry as described below.

The converter measures the input voltage with a certain specified resolution. The resolution is the granularity with which the measurement is performed. It can be specified as a number of bits or as a voltage increment. For example, an A/D converter with only 1 bit of resolution and a 5 Volt input range would classify all voltages from 0 to just under 2.5 Volts as the digital value 0, and voltages from 2.5 Volts to 5 Volts as the digital value 1. This converter has a resolution equal to 1 bit, which corresponds to 2.5 Volts per count.

The converter measures the input voltage with a specified accuracy. The accuracy tells how close the measured value is to the actual voltage. A typical 8 bit A/D converter is accurate to within plus or minus one least significant bit.

### Determining the Resolution of an A/D Converter

The  $V_{RL}$  and  $V_{RH}$  analog input reference pins define the lower and upper voltages that can be converted by both the 8 bit A/D and the 12 bit A/D. The resolution depends on the input voltage range. The measurement resolution of a B-bit A/D, expressed in Volts per count, is

$$\text{Eqn. 9-1} \quad \text{Resolution} = (V_{RH} - V_{RL}) / 2^B \quad [\text{Volts per count}]$$

where  $2^B$  is the number of counts that can be represented by a B-bit number. From this equation we see that resolution becomes finer (better) as B grows larger or as the reference voltage range ( $V_{RH} - V_{RL}$ ) gets smaller. For the 8 bit A/D the resolution is

$$\text{Eqn. 9-2} \quad \text{8 bit Resolution} = (V_{RH} - V_{RL})/256 \quad [\text{Volts per count}]$$

and for the 12 bit A/D the resolution is

$$\text{Eqn. 9-3} \quad \text{12 bit Resolution} = (V_{RH} - V_{RL})/4096 [\text{Volts per count}]$$

With the default  $V_{RL}$  and  $V_{RH}$  of 0 V and 5 V, respectively, the resolution of the 8 bit converter is 19.5 mV per count, and the resolution of the 12 bit converter is 1.22 mV per count. The finer resolution of the 12 bit converter combined with its higher accuracy yields a more precise measurement of the analog input.

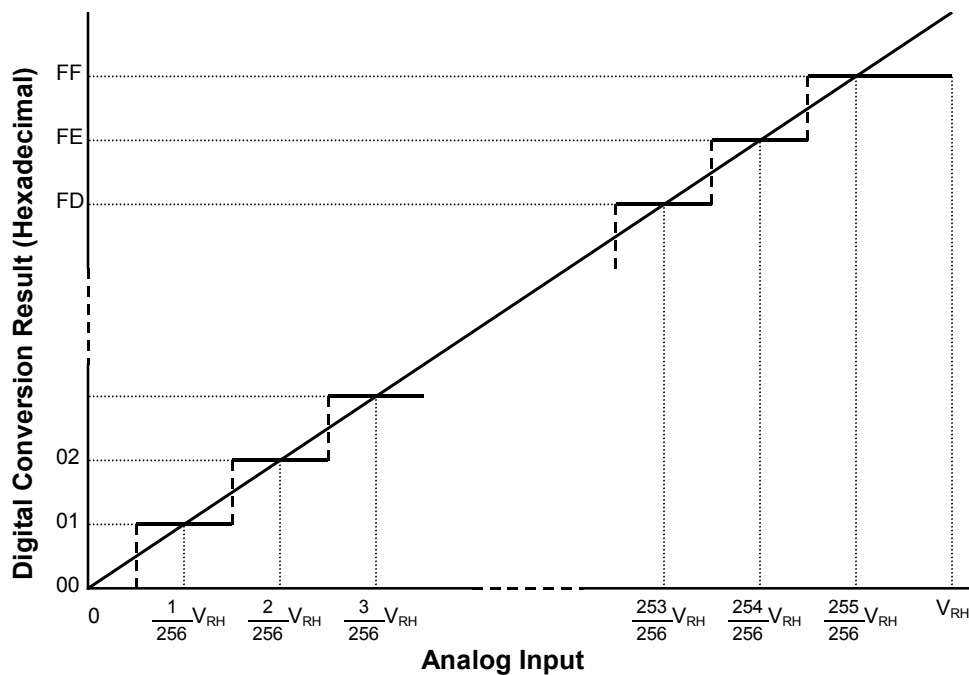
## Converting an A/D Count into Its Equivalent Voltage Reading

To convert the 8-bit count returned by the A/D converter into an equivalent voltage, use the formula

$$\text{Eqn. 9-4} \quad \text{Input Voltage} = V_{RL} + (\text{Count} * \text{Resolution}) \quad \text{Eqn. 6.4}$$

Combining this with Eqn. 6.1 yields

$$\text{Eqn. 9-5} \quad \text{Input Voltage} = V_{RL} + \text{Count} * (V_{RH} - V_{RL}) / 2^B \quad \text{Eqn. 6.5}$$



**Figure 9-1** Conversion function for the 8-bit A/D.

## Using the 8-bit A/D

### *Initializing the 8 Bit A/D*

The 8 bit A/D is inside the 68HC11 processor chip, and is accessed via **PORTE**. This 8 bit port can be used as either an 8 channel A/D or as an octal digital input port. When the QVGA Controller is first powered up, or after a reset or restart, the 8 bit A/D converter is disabled and **PORTE** is configured as a digital input port. To turn on the A/D converter, a program must call the function:

```
AD8On()
```

Another function named **AD8Off()** is available to turn off the 8 bit A/D so that PORTE once again acts as a digital input port.

The function named

```
InitAnalog()
```

defined in the **ANALOGIO.C** file calls **AD8On()**. If you interactively execute **InitAnalog()**, as,

```
InitAnalog( ) ←
```

the 8 bit A/D converter will be turned on and ready for use.

In an autostarting application you should include **InitAnalog()** in your start-up code.

### *Hardware Connections*

To sample an analog voltage, attach a voltage with a value between zero and +5 Volts to the 8 bit A/D channel 0 input named **ANO**. For example, try connecting the 1.5Vref signal (pin 37 on the Analog I/O connector) to the **ANO** input (pin 10 on the Analog I/O connector). See the Appendix for connector diagrams.

The 8 bit A/D inputs are the PortE signals named PE0/AN0 through PE7/AN0 available at pins 3 through 10 on the Analog I/O connector (see Appendix A). Each analog signal is converted to a number between 0 and 255 indicating its value relative to VRL (the low voltage reference) and VRH (the high voltage reference). The default values are VRL = 0 Volts (analog ground) and VRH = 5 Volts (the analog +5 Volt supply, designated +5VAN). The exact voltage difference between VRH and VRL varies slightly from board to board; it is a good idea to measure the value on your board to obtain the most exact voltage equivalents of the measured A/D results.

### *8-bit A/D Reference Voltage*

You may connect circuitry to the VRL and VRH pins to drive these references to desired levels between 0 and 5 Volts. For example, in some applications it may be possible to increase the resolution of the conversion by reducing the input voltage range (VRH-VRL) as specified by Figure 9-1.

Motorola's data books specify some restrictions on the values of the reference signals VRL and VRH (MC68HC11F1 Technical Data Manual, p.13-10) for the 8 bit A/D. First, VRL and VRH must be less than +5.1 Volts and greater than 0 Volts. Second, the voltage on VRL must be less than the voltage on VRH. Third, the difference between the voltages, (VRH - VRL), should be

greater than 3 Volts if the converter is to meet all of its stated specifications. Also note that VRH and VRL are connected to both the 8 bit A/D and the 12 bit A/D, so changing the references affects both converters.

### ***Interactively Perform the Conversion***

The `Convert8()` function is defined near the middle of the `ANALOGIO.C` file; you can see from its definition that it is simply an interactively callable version of the `AD8Sample()` function. Now that you have connected an input voltage to channel `AN0`, you can type from your terminal:

```
Convert8( int 0)←
```

The printed return value summary displays the conversion count; you'll see a printout that looks something like this:

```
Rtn:.....-30722.....77.....=0x87FE004D...=fp:....-3.822E-34
```

We know that this function returns an integer, so we identify “77” (hex 0x004D) as the return value; the other numbers in the summary are irrelevant. If the input is 1.5 volts, the result should be approximately 77 counts ( $256 * 1.5 / 5.0$ ). If the input voltage equals VRL (the low reference voltage, typically at 0 Volts), the result will equal 0. If the input is within 1 bit of VRH (the high reference voltage, typically at 5.0 Volts), the result will equal decimal 255. If the input is exactly half of (VRH - VRL), the result will equal decimal 128.

### ***Multiple 8 Bit A/D Conversions with Results Stored in a C Array***

The function `AD8Multiple()` which is defined in the `ANALOG.H` file expects as inputs a buffer xaddress (32 bit extended address), a sampling interval parameter, the number of samples, and a channel number. When called, it performs the specified number of conversions and saves the results as single bytes in the specified buffer. As explained in the Glossary, the sampling interval parameter specifies the timing of the samples, with 0 representing the fastest sampling, and 65,535 representing the slowest sampling. You can sample at up to 100 kHz (100,000 samples per second) using the 8-bit A/D, and sample at up to 36 kHz using the 12-bit A/D, provided the processor is devoted to this single task.

The `AD8ToArray()` function defined in `ANALOGIO.C` uses a standard C one-dimensional array named `results_8` as the data buffer. The function accepts a channel number as input, performs conversions at the fastest sampling speed (100 kHz), and places the results in the array. The number of samples is specified by the `DEFAULT_NUMSAMPLES` constant which equals 16. Because we have connected the channel 0 input (AN0) to 1.5VREF, let's perform the multiple conversion on this channel. Type at your terminal:

```
AD8ToArray( int 0)←
```

remembering to type at least one space after the `(` character. This function does not return a value, so the printed return value summary is not relevant. To see the results of the conversion, you could write a simple C function that prints the contents of `results_8`; this is left as an exercise for you.

You can also use the debugging routine named **DUMP** to view a hexadecimal dump of the buffer. To do this, type at your terminal:

```
results_8 0 16 DUMP←
```

**DUMP** is a QED-Forth function that expects as inputs an address (in this case, **results\_8** puts the address on the data stack), a page (0, representing the common page), and the number of bytes to be dumped (16). You should see a printout similar to this:

```
pg. addr 00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 0123456789ABCDEF
00 8E2D 4D 4D 4D 4D 4D 4D 4D 4D 4D 4D 4D 4D 4D 4D 4D MMMMMMMMMMMMMMMM
```

This tells us that the contents of the 16 bytes starting at address 0x8E2D (which is the address of **results\_8**) all equal 0x4D. To the right of the hex dump the ascii equivalent of the memory contents is displayed; this is not relevant for the numerical data here. We conclude that the A/D conversion result was 0x4D, equivalent to decimal 77; this is the same value returned by the **Convert8()** function above. Your results may vary slightly depending on the exact value of supply voltage on the QVGA Controller – the +5V supply is used as the default reference voltage.

### ***For Experts: How To Use Additional Features of the 8 Bit A/D***

The built-in driver routines for the 8 bit A/D are easy to use and address the requirements of most applications. If you wish to gain a detailed understanding of the operation of the 8 bit A/D, or need to use one of its special modes, the information in Appendix H may prove useful. For example, one of the operating modes allows the 8 bit A/D converter to continuously sample four different analog inputs in rapid succession. Appendix H describes the operation of the 68HC11's A/D and presents sample code to control the 8 bit A/D.

## **Using the 12-bit A/D**

### ***Initializing the 12-bit A/D***

The 12-bit A/D is interfaced to the 68HC11F1 via the high speed serial peripheral interface (SPI). The function:

```
InitAD12andDAC()
```

initializes the SPI to be compatible with operation of the 12-bit A/D and the digital to analog converter (DAC).

To initialize the hardware now so that you can interactively perform conversions, type the following command lines at your terminal:

```
DECIMAL ←
InitEEChar( char 10, numsamples)←
InitAnalog( )←
```

Remember to include a space after each ( character. The first command ensures that the number base is decimal, and the second command initializes a variable located in the EEPROM which specifies the number of 12 bit samples stored in the **FORTH\_ARRAY** buffer; this will be discussed in more

detail later in the chapter. The `InitAnalog()` function calls `InitAD12andDAC()`, and also dimensions and zeros some buffers that will hold A/D conversion results.

### ***Specifying the Type of Conversion***

The function

```
AD12Sample( int flag, uint channel)
```

expects a configuration flag and a channel number as inputs, performs a single conversion using the 12 bit A/D, and returns the conversion result. The meaning of the flag is as follows:

Flag value	Type of conversion
-1	single ended, unipolar
0	differential, unipolar
1	single ended, bipolar
2	differential, bipolar

### ***Hardware Connections***

To sample an analog voltage, attach a ground-referenced voltage in the range between zero and +5 Volts to the 12 bit A/D channel 0 input named **12AN0**. For example, try connecting the 1.5Vref signal (pin 37 on the Analog I/O connector) to the **12AN0** input (pin 18 on the Analog I/O connector). See the Appendix for connector diagrams, and see Figure 1-3 in Chapter 1 to identify the Analog I/O connector on the QVGA Controller.

If the input voltage equals VRL (the low reference voltage, typically at 0 Volts), the result will equal 0. If the input is within 1 bit of VRH (the high reference voltage, typically at 5.0 Volts), the result will equal decimal 4095. If the input is exactly half of (VRH - VRL), the result will equal decimal 2048. If the input is 1.5 volts, the result should be approximately 1230 counts.

To provide a default 0 to 5.0 Volt conversion range, the VRL and VRH references are tied to AGND and +5VAN through 1 kohm resistors; while this is fine for casual testing as we're doing now, you'll want to make the following connections for your actual design project:

To achieve full 12 bit accuracy, you must connect the low reference VRL signal and the high reference VRH signal to low-impedance supplies such as Analog Ground (AGND) and Analog +5V (+5VAN), respectively. This is accomplished by connecting VRL (pin 1) to AGND (pin 19), and connecting VRH (pin 2) to +5VAN (pin 20) on the Analog I/O connector of the QED Board.

### ***Interactively Perform the Conversion***

The `Convert12()` function is defined near the top of the `ANALOGIO.C` file. It is defined using the `_Q` specifier so that it can be interactively called from your terminal. `Convert12()` simply calls the conversion function `AD12Sample()` with the specified channel number and a flag = -1 (meaning that a single-ended unipolar conversion is performed). Now that you have connected an input voltage (1.5Vref) to channel 12AN0, you can interactively type from your terminal:

```
Convert12( int 0)←
```

As usual, remember to include a space after the ( character. The printed return value summary displays the conversion count; you'll see a printout that looks something like this:

```
Rtn:....-30722...1237...=0x87FE04D5 =fp: ...-3.822E-34
```

We know that this function returns an integer, so we identify “1237” as the return value. (In hexadecimal notation, this is 0x04D5 which is the lower half of the hexadecimal summary value; the other numbers in the return value summary are irrelevant.) If the input is 1.5 volts, the result should be approximately 1230 counts. If the input voltage equals VRL (the low reference voltage, typically at 0 Volts), the result will equal 0. If the input is within 1 bit of VRH (the high reference voltage, typically at 5.0 Volts), the result will equal 4095. If the input is exactly half of (VRH - VRL), the result will equal 2048.

**Multiple 12 Bit A/D Conversions with Results Stored in a FORTH ARRAY** The function **AD12ToBuffer()** which is defined in the **ANALOG.H** file expects as inputs a pointer to a **FORTH\_ARRAY**, a sampling interval parameter, the number of samples, a conversion-type flag, and a channel number. When called, it performs the specified number of conversions and saves the results as integers in the specified **FORTH\_ARRAY**. As explained in the Control-C Glossary, the sampling interval parameter specifies the timing of the samples, with 0 representing the fastest sampling, and 65,535 representing the slowest sampling. The conversion-type flag is the same as the flag for **AD12Sample()** as described above:

Flag value	Type of conversion
-1	single ended, unipolar
0	differential, unipolar
1	single ended, bipolar
2	differential, bipolar

The **AD12ToForthArray()** function defined in **ANALOGIO.C** is an interactive version of **AD12ToBuffer()**. It accepts a channel number as input, performs unipolar conversions at the fastest sampling speed, and places the results in the **FORTH\_ARRAY** named **results\_12**. The number of samples is specified by the variable named

```
numsamples
```

which is located in EEPROM. You'll remember that when we initialized the 12-bit A/D we also initialized **numsamples = 10**, with the statement,

```
InitEEChar( char 10, numsamples)←
```

so we expect that 10 samples will be stored in the **results\_12 array**. Because we have connected the channel 0 input (12AN0) to 1.5Vref, let's perform the multiple conversion on this channel. Type at your terminal,

```
AD12ToForthArray( int 0)←
```

remembering to type at least one space after the (. This function does not return a value, so the printed return value summary is not relevant. To see the results of the conversion, we can print the contents of the **results\_12** array by typing from the terminal:

```
PrintForthArray( int 0, results_12)←
```

where **results\_12** is the name of the **FORTH\_ARRAY** to be printed, and the 0 parameter is a flag that tells the function that the **results\_12 array** does not contain floating point data. You should see the conversion results printed as a column of data on your terminal screen.

## Bipolar Conversions

You can instruct the 12-bit A/D to interpret the input as a unipolar signal in the range 0-5 volts, or a bipolar signal in the range -5 to +5 volts. Even without an external negative supply, voltages as low as -4.0 or -4.5 V can be converted. This is achieved by using a negative voltage generator on the Maxim RS-232 chip. This negative voltage is connected to the V- supply input of the 12 bit A/D chip, and is also accessible at pin 39 on the Analog I/O connector, labeled “Analog Bus V-”. Drawing current out of this “Analog Bus V-” pin to power external circuitry is not recommended, as the RS-232 chip cannot source much current, the output impedance is hundreds of ohms, and the voltage is poorly regulated. Instead, to achieve clean rail-to-rail -5.0 V to +5.0 V conversions, connect an external -5 V supply to “Analog Bus V-” at pin 39 on the Analog I/O connector.

The drivers for the 12-bit A/D converter are:

```
FastAD12Sample()      AD12Sample()
FastAD12Multiple()    AD12 Multiple()
```

The configuration flag passed to these routines lets you select unipolar or bipolar conversion as discussed above, in addition to single-ended (ground-referenced) or differential conversions.

## Running the Sample Program

We have worked through much of the **ANALOGIO.C** file. Its routines that use the digital to analog convertor (DAC) to output voltages are discussed in the next Chapter, and its use of EEPROM to store nonvolatile variables is discussed in the Chapter *Making Effective Use of Memory*.

Let's run the program, which both acquires data and outputs a voltage. If you have a valid voltage input such as 1.5Vref (pin 37 on the Analog I/O connector) attached to 12AN0 (pin 18), AN0 (pin 10), and Vin1 (pin 21), then the **main** function will work properly. To initialize the analog converters, acquire multiple samples from channel 0 of each A/D, and to establish 2.5 volts at the output of DAC channel 1, simply type:

```
main←
```

at your terminal. The function prints the results of the multiple 12 bit conversions, and you can check the DAC channel 1 output with your voltmeter. To change the number of samples acquired from the 12 bit A/D to 20, you can interactively type:

```
DECIMAL InitEEChar( char 20, numsamples)←
```

which modifies the contents of the **numsamples** variable in EEPROM. When you again execute

```
main←
```

you will notice that 20 values are now printed at your terminal.

## Chapter 10

### Chapter 10: Outputting Voltages with Digital to Analog Conversion

*The 8-channel 8-bit DAC brings to the QED Board a very exciting capability. The DACs are easy to use and flexible.*

The onboard 8 channel 8 bit digital to analog converter (DAC) is interfaced to the processor via the fast serial peripheral interface (SPI), and its chip select is a memory-mapped signal generated by the onboard logic. The octal DAC allows the precise output of analog voltages ranging from 0V to 3V (or higher with the addition of simple off-board operational amplifier circuitry as provided by the QED Analog Conditioning Board). Each of the 8 DACs have an “input” voltage (named  $V_{inx}$  where x is the DAC channel number) that can be connected to a stable voltage reference or a voltage to be multiplied, for example, a time-varying input representing an audio signal. If the input is connected to the steady 1.5 Volt reference which is available on the QVGA Controller, the output of each channel ranges from 0 to 3 Volts in increments of 11.7 mV per digital count. Alternatively, to implement digital volume control you could connect a time-varying sound signal to the input of a DAC, and connect the DAC output to a speaker. Then the volume would be proportional to the digital code that you write to the DAC.

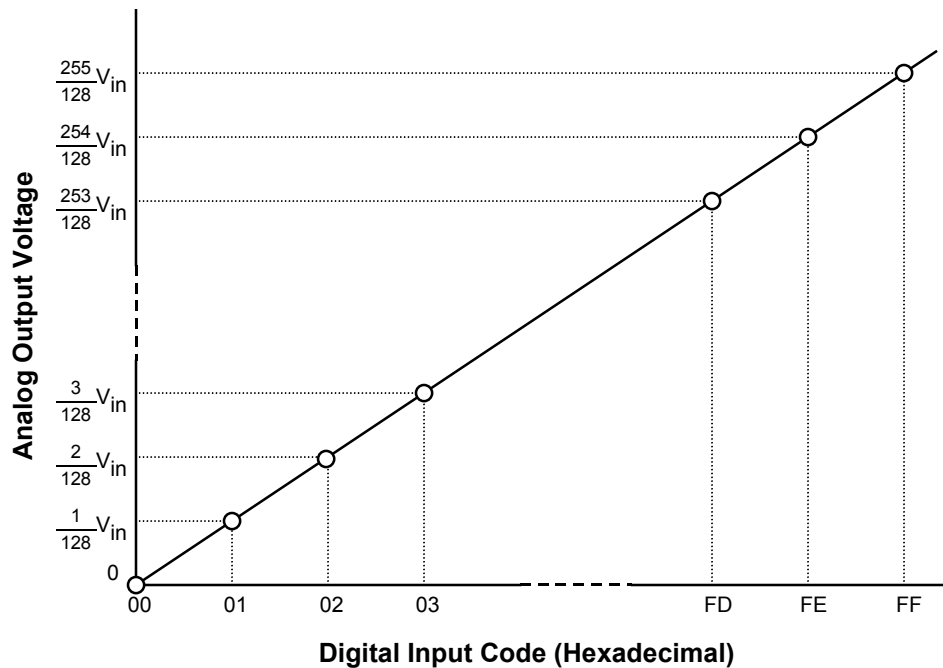
The DAC inputs and outputs are located on the Analog I/O connector; see the appropriate Appendix for the connector pinouts.

### Fundamentals of Digital to Analog Conversion

Each DAC accepts a number between 0 and 255 which we'll designate as N, and outputs a voltage given by

$$V_{out} = N/128 * V_{in}$$

where  $V_{in}$  is the input (reference) voltage applied to the DAC. Thus  $V_{out}$  ranges from 0 Volts to nearly  $2 * V_{in}$  Volts. The maximum allowed value for  $V_{in}$  is 1.5 Volts, so the maximum value of  $V_{out}$  is nearly 3.0 Volts. Note that the output voltage of the DAC is proportional to  $V_{in}$ ; for this reason it is called a “multiplying DAC”.  $V_{in}$  may be a stable DC reference voltage, or it may be a time-varying analog signal. In the latter case, the DAC becomes a automated attenuator/amplifier that can take the place of potentiometers to perform volume control and other common functions.



**Figure 10-1** DAC output vs digital input code.

## Initializing the DAC

Like the 12 bit A/D, the 8 bit DAC is interfaced to the 68HC11F1 via the high speed serial peripheral interface (SPI). The DAC is initialized by the same function that initializes the 12-bit A/D converter:

```
void InitAD12andDAC(void)
```

**InitAD12andDAC()** sets the eight DAC outputs to zero. You can call this function from within your code. If you have compiled and downloaded the file, **ANALOGIO.C**, you can now use some of its useful functions. From the terminal you can execute,

```
InitAnalog( ) ←
```

which calls **InitAD12andDAC** so that the DAC is ready to use. After you execute this command the DAC is ready to communicate with the 68HC11 via the SPI.

## Applying a Reference Voltage

To use the DAC, you'll first need to apply a valid input/reference voltage. To create a standard voltage output DAC with the maximum 0 to 3 volt output range, you can use the 1.5Vref voltage provided on the QVGA Controller to drive the  $V_{in}$  of each of the DAC channels that you want to use. For example, let's connect 1.5Vref (pin 37 on the Analog I/O connector) to  $V_{in1}$  (pin 21 on the Analog I/O connector).

This 1.5 volt reference may be used to provide a stable reference voltage for any or all of the digital-to-analog converters on the QVGA Controller, and can also provide a reference voltage for external circuitry.

## Outputting a Voltage

Setting the 8-channel 8-bit DAC is very easy. To output a voltage, simply call the function:

```
SetDAC( uchar count, uint channel)
```

which expects a count in the range 0 to 255, and a channel in the range 1 to 8. After calling the SetDAC() function the multiplying DAC then outputs a voltage that is proportional to the specified count and to the analog input voltage. The analog input voltage must be between 0 and 1.5 volts, and the output voltage equals:

$$\text{Eqn. 10-1 } V_{\text{out}} = 2 * V_{\text{in}} * \text{count} / 256 = V_{\text{in}} * \text{count} / 128$$

Using the 1.5V reference, after we have compiled and downloaded **ANALOGIO.C** we can interactively type from the terminal:

```
AnalogOut( char 255, int 1)←
```

to create the full-scale output of the DAC which should be just under 3 volts. The output voltage appears at Vout1 on pin 22 of the Analog I/O connector. The **AnalogOut()** function is simply an interactive version (defined using **\_Q**) of **SetDAC()**. Another useful function defined in **ANALOGIO.C** is:

```
VoltsOut( float voltage, int channel)
```

This function assumes that the DAC input voltage is 1.5Vref. It applies a simple formula to calculate the number of counts required to establish the requested voltage, clamps the calculated count to the range 0-255, and sends it to the specified DAC channel. You can interactively specify any voltage you want in the range 0 to 3 volts. For example, you can type:

```
VoltsOut( float 1.0, int 1)←
```

and use a voltmeter connected to Vout1 to see how close the DAC comes to meeting your request.

To output a voltage of one half of the full scale range execute

```
AnalogOut( char 128, int 1)←
```

Since 128 is half of the full 8 bit digital range, a voltage of 1.5 Volts (one half of the full 3 volt analog range) appears at the output of DAC1. You can connect a digital voltmeter to the DAC1 output (pin 22 on the Analog I/O connector) to verify that the DAC is working as expected.

The other DACs may be controlled in a similar manner. Each must have an input voltage reference that establishes that DAC's mid-range value.

## DAC Execution Speed

The DAC driver **FastSetDAC()** executes in approximately 46 microseconds, and the multitasking version **SetDAC()** executes in 131 microseconds. The QVGA Controller maps the chip enable of the onboard D/A converter to page 14 (0x0E); the page addressing is responsible for appx. 6 microseconds of the execution time.

# Chapter 11

## Chapter 11: Serial Communications

### RS-232 and RS-485 Communications

The QVGA Controller has two serial communications ports: a primary serial port called Serial 1 that supports both RS232 and RS485 protocols, and a secondary serial port called Serial 2 that supports RS232. The Serial 1 port is implemented with the 68HC11's on-chip hardware UART (*Universal Asynchronous Receiver/Transmitter*). Serial 2 is implemented by a software UART in the controller's QED-Forth Kernel that uses two of the processor's PortA I/O pins to generate a serial communications channel.

**Table 11-1 Serial Communications Channels**

Channels	Type	Port Address	Comments / Alternate Uses
1	Serial 1: RS232/485 hardware UART at up to 19.2 KBaud	PD 0-1, PPC 4 used for RS-485.	PPC 4 may be used as digital I/O if RS485 is not used.
1	Serial 2: RS232 software UART at up to 4800 Baud	PA 3-4	PA 3-4 may be used as timer-controlled I/O (one input-capture and one output-compare) if Serial 2 is not used. PA 3-4 may also be used for hardware handshaking for Serial 1.
1	Synchronous Serial Peripheral Interface at 2 MBaud	PD 2-5	
3	Serial communications channels		

The primary channel's UART translates the bit-by-bit data on the serial cable into bytes of data that can be interpreted by the QED-Forth Kernel or by your application program. It controls the serial-to-parallel and parallel-to-serial conversion and performs all of the timing functions necessary for *asynchronous* serial communications. The communications is asynchronous because no synchronizing clock signal is transmitted along with the data. Rather, the UART deduces the correct time to sample the incoming signal based on the start and stop bits in the signal itself. (The QVGA Controller also supports fast synchronous serial communications via the Serial Peripheral Interface described later in this Chapter.)

The secondary channel is very useful for debugging application programs that communicate with other computers or I/O via the primary channel. Since both channels can operate simultaneously and independently, debugging can be performed while the application program is communicating

via its primary channel. The dual communications channels also provide an easy way to link systems that communicate using different serial protocols.

## Serial Protocols

There are several *protocols* that govern the format of exchanged data, with the RS232 protocol used primarily by personal computers, and the RS485 protocol used in industrial control systems. The Serial 1 port can be configured for either RS232 or RS485 communications at up to 19200 baud. The Serial 2 port is dedicated to RS232 communications at up to 4800 baud.

### RS232

RS232 is by far the most common protocol. It is supported by virtually all personal computers, and is the default protocol for both of the QVGA Controller's serial ports. Its simplest implementation requires only three wires: one to transmit serial data, a second to receive serial data, and a third to provide a common ground reference. RS232 allows both communicating parties to transmit and receive data at the same time; this is referred to as *full duplex* communications. RS232's greatest benefit is its universality; practically all personal computers can use this protocol to send and receive serial data.

RS232 uses inverse logic; that is, a positive bit at the 68HC11 UART is inverted by the onboard RS232 driver chip and appears as a negative signal on the serial cable. The terminal's serial receiver chip re-inverts the signal to its positive sense. The data bits are also transmitted in reverse order, with the least significant bit transmitted first, after a start bit. The specified signal levels of approximately +/- 9 Volts are derived from the QVGA Controller's +5 Volt supply by a dual RS232 driver chip that has a built-in charge pump voltage multiplier.

The QVGA Controller offers a unique addition to full duplex RS232: it can place its RS232 transmitter into a high impedance *silent* mode under software control. This allows you to configure *full duplex multi-drop networks* in which a single master can sequentially address one of many slaves and start a full-duplex exchange of data.

### RS485

RS485 is another protocol supported by the primary serial port on the QVGA Controller. It is a *half duplex* protocol, meaning that only one party at a time may transmit data. Unlike the standard RS232 protocol, RS485 allows many communicating parties to share the same 3-wire communications cable. Thus RS485 is the standard protocol of choice when *multi-drop* communications are required.

Like RS232, the data bits are transmitted in reverse order, with the least significant bit transmitted first. The RS485 protocol uses differential data signals for improved noise immunity; thus RS485 can communicate over greater distances than RS232. An RS485 transceiver is present on the QVGA Controller, and its data direction is controlled by pin 4 of port PPC of the peripheral interface adapter (PIA).

## Serial Connectors and Configuration Options

The primary and secondary serial communications ports are accessible through the QVGA Controller's 10 pin, dual row Communications Connector (H14) and through the individual Serial 1 and Serial 2 connectors. These standard 9-pin serial connectors are located on the top edge of the QVGA Controller. A serial communications cable is supplied with QVGA Starter Kits.

The pinout of the Communications Connector (H14) is shown in Table 11-2, and the following diagrams show how these signals map to the two serial communications connectors. Although the RS232 protocol specifies functions for as many as 25 pins, each communications channel requires only three for simple serial interfaces: TxD1 (transmit data), RxD1 (receive data), and DGND (digital ground). The RS232 protocol specifies the use of two separate grounds, a signal ground and a protective (or "chassis") ground. The QVGA Controller does not differentiate between these. To provide a convenient means of attaching two grounds to the serial cable, there are several pins (labeled DGND) on the communications connector that are connected to the controller's ground plane.

**Table 11-2 Serial Communications Connector, H14**

Signal	Pins	Signal
TxD1	1	2 – RxD1
DGND	3	4 – DGND
RS485 XCVR-	5	6 – RS485 XCVR+
TxD2	7	8 – RxD2
DGND	9	10 – DGND

**Table 11-3 Serial 1 Connector**

Signal	Pins	Signal
NC	1	
	6 – DSR1/DTR1	
TXD1	2	
	7 – CTS1	
RXD1	3	
	8 – RTS1	
DSR1/DTR1	4	
	9 – NC	
DGND	5	

**Notes:**

NC indicates no connection  
Pins 4 and 6 (DSR1/DTR1) are connected.  
Pins 7 and 8 (CTS1/RTS1) may optionally be connected on the board with zero ohm shorts.

**Table 11-4 Serial 2 Connector**

Signal	Pins	Signal
NC	1	
	6 – DSR2/DTR2	
TXD2	2	
	7 – CTS2/RTS2	
RXD2	3	
	8 – RTS2/CTS2	
DSR2/DTR2	4	
	9 – NC	
DGND	5	

**Notes:**

NC indicates no connection  
Pins 4 and 6 (DSR1/DTR1) are connected.  
Pins 7 and 8 (CTS1/RTS1) are connected.

Given the availability of ready-made communications cables, it is not necessary to study or understand the following descriptions of cable connections. These detailed signal descriptions and cable diagrams are presented to provide complete information for those who have special communications requirements and for those who wish to make their own application-specific communications cables. Most computers conform to IBM PC AT-compatible RS232 interfaces which use 9-pin D-Type connectors, consequently the QVGA Controller brings out its serial ports to two female 9-pin D-Type connectors. Table 11-5 shows the connection diagram for a standard 9-pin serial cable.

**Table 11-5 Serial Cable Connections.**

Cable Pin	PC AT or Terminal	QVGA Controller
1	NC	NC
2	RxD	TxD1
3	TxD	RxD1
4	DTR	DSR1/DTR1
5	GND	GND
6	DSR	DSR1/DTR1
7	RTS	CTS1
8	CTS	RTS1
9	NC	NC

We can gain insight into the operation of the RS232 protocol by examining the signal connections used for the primary serial port in Table 11-5. The transmit and receive data signals carry the messages being communicated between the QVGA Controller and the PC or terminal. The QVGA Controller's transmit data signal TxD1 (pin 2 on the 9-pin serial connector) is connected to the terminal's receive data signal RxD (pin 2 on its 9-pin connector). Likewise, the terminal's transmit signal TxD is connected to the QVGA Controller's receive signal RxD1. Chassis and signal grounds are connected together to the digital ground (DGND) signal.

From the QVGA Controller's point of view, these three signals (TxD, RxD, and ground) are the only connections required to perform serial communications. While these signals provide a data path, they do not provide hardware *handshaking* that allows the two communicating parties to let each other know when they are ready to send or receive data.

The RS232 protocol provides for four handshaking signals called *ready to send* (RTS), *clear to send* (CTS), *data set ready* (DSR), and *data terminal ready* (DTR) to coordinate the transfer of information. The QVGA Controller, however, does not implement hardware handshaking. Rather, it relies on software handshaking via transmission of XON/XOFF characters to coordinate data transfer and ensure that information is not lost when one of the communicating parties is busy.

Many terminals and PCs, however, do rely on hardware handshaking to determine when the other party (in this case the QVGA Controller) is ready to accept data. By connecting pairs of these handshaking signals together, the terminal or PC can be made to think that the QVGA Controller is always ready to send and receive data. Thus in Table 11-5, RTS1 is connected to CTS1, and DSR1 is connected to DTR1 onboard the QVGA Controller using zero ohm shorting resistors. These signals may alternatively be redirected to the digital inputs and outputs used by the second serial port if hardware handshaking is required.

The secondary serial port is connected similarly except that the onboard connection of RTS to CTS, and DSR to DTR are permanent.

## Enabling the Secondary Serial Port

To enable the secondary serial port, turn dip switch 5 (labeled “2COM”) on the QED Board ON. Otherwise, dip switch 5 should be OFF so that it frees bit 3 of PORTA for use as general-purpose I/O.

## Enabling RS485 Communications

If your application requires RS485, use the primary serial port (serial1) for RS485 communications, and use the secondary serial port (Serial 2) to program and debug your application code using the RS232 protocol. The default serial routines used by the onboard kernel assume that full duplex communications are available, so you cannot use the RS485 protocol to program the controller. You can use it to communicate with other devices.

A three-post jumper located between the third socket and H6 configures the primary serial port for either RS232 or RS485 operation.

For RS232 operation: Install the jumper shunt across the two pins closest to the crystal (the default configuration). In this case, cable connections may be made to Serial 1 on either the 10-pin Serial Communications Header or the Serial 1 Connector.

For RS485 operation: Install the jumper shunt across the two pins closest to the J3 silk screen. In this case, cable connections must be made to Serial 1 at pins 5 and 6 of the 10-pin Serial Communications Header. The RS485 connections are not brought out to the Serial 1 Connector.

## Using the Serial Ports

Using the primary serial port is easy. In fact, you have been using it all along as you worked through the examples in this document. The standard C serial I/O routines such as `printf()`, `scanf()`, `putchar()`, and `getchar()` give you high level access to the serial ports. All high level routines call the following low level revectorable serial primitives to access the currently active serial port:

```
int   AskKey(void)    // returns a flag that is true if an input char is waiting
char  Key(void)       // waits for and returns the next input char
void  Emit(char)      // outputs the specified char to the serial port
```

Because all of the serial I/O routines on the QVGA Controller are revectorable, it is very easy to change the serial port in use without modifying any high level code.

Let's do a quick experiment to see how easy it is. We'll use code from the `GETSTART.C` program. If you have already downloaded the program, you are ready to go. If your board is presently running a multitasking application, type

```
WARM←
```

to stop the program now.

If you have not yet compiled the `GETSTART` program and you want to do the exercises here, open `GETSTART.C` in your TextPad editor, click on the Make Tool (the *Make* icon), and after the compi-

lation is done, enter the Terminal Program by clicking on the terminal icon and use the “Send Text File” menu item to send **GETSTART.DLF** to the QVGA Controller.

### **Switching the Default Serial Port**

Before running the program, let’s switch to the secondary serial port. The secondary serial port is implemented by a software UART that controls two pins on PortA. Pin 3 of PortA is the Serial2 input, and pin 4 of PortA is the Serial2 output. To switch to the secondary serial port running at 1200 baud, simply flip DIP switch #5 to the ON position to enable the secondary serial port hardware, and type from the terminal the following QED-Forth commands:

```
DECIMAL ←  
1200 BAUD2 ←  
USE.SERIAL2 ←
```

You can operate the port at any baud rate up to 4800 baud; just specify the rate you want before the **BAUD2** command. Now select the “Communications” item in the “Settings” menu of the Terminal program, and click on 1200 baud (or whatever baud rate you selected in the command above). Move the serial cable from the “Serial Port 1” connector to the “Serial Port 2” connector at the QVGA Controller. Typing a carriage return at the terminal should now produce the familiar “ok” response via the Serial2 port.

Now type:

```
main ←
```

and you’ll see the familiar starting message of the **GETSTART.C** program:

```
Starting condition:  
The radius is ..... 0; the circular area is ..... 0.  
ok
```

In fact, the program works the same as it did before, but now it is using the secondary serial port instead of the primary port -- and you didn’t even have to recompile the code!

For those of you interested in the details, here’s how it works: The low-level serial driver routines named **Key()**, **AskKey()** and **Emit()** are revectorable routines that can be redirected to use either of the serial ports. By interactively executing the QED-Forth function

```
USE.SERIAL2 ←
```

before calling **main**, we revectorized these serial primitives to use the Serial2 port.

You can invoke the C version of this routine by calling

```
UseSerial2()
```

anywhere within your C program’s source code file. Function prototypes for this function and other versatile serial I/O routines are defined in the **COMM.H** header file, and are described in detail in the *Control-C Glossary*.

To return to using the primary serial port, simply type from the active terminal the QED-Forth command:

```
USE.SERIAL1 ←
```

which transfers control back to serial port 1 running at the prior established baud rate (typically 9600 baud). A hardware reset (toggling DIP switch #7) has the same effect. If you do this now, remember to move the QVGA Controller's serial connector back to Serial Port 1, and to change the terminal's baud rate back to 9600 baud using the "Communications" item under the terminal's "Settings" menu.

If you always want the QVGA Controller to start up using the secondary serial port as the default serial communications link, you can type at your terminal:

```
1200 SERIAL2.AT.STARTUP←
```

where 1200 is the baud rate that you choose; you can specify any standard baud rate up to 4800 baud. The complementary routine is:

```
SERIAL1.AT.STARTUP
```

which makes the primary serial port the default startup serial link. We recommend that you keep the faster Serial1 port as the default serial link as you work through the exercises in this book.

All of these functions that we are calling interactively via the operating system can also be called from C in your program source code; their C function prototypes are as follows:

```
void UseSerial1( void );  
void UseSerial2( void );  
void Baud2( int baud );  
void Serial1AtStartup( void );  
void Serial2AtStartup( int baud );
```

In summary, the code provided for implementing the second serial port is very flexible and can be used to support dual concurrent communications ports. Data translation between different machines can be performed with ease, and applications that communicate via the primary serial port can be debugged using the secondary channel.

## ***Timing Considerations and Multitasking***

In multitasking systems using both serial ports Serial1 and Serial2, the application code should include one of the commands

```
SERIAL_ACCESS = RELEASE_ALWAYS;  
SERIAL_ACCESS = RELEASE_NEVER;
```

before building the tasks. This prevents contention that can occur if the default **RELEASE\_AFTER\_LINE** option is installed in the **SERIAL\_ACCESS** user variable.

The primary serial port, Serial1, is supported by the 68HC11's on-chip hardware UART, and does not require interrupts to work properly. On the other hand, the secondary serial port (Serial2) is implemented using hardware pins PA3 (input) and PA4 (output), and is controlled by the associated interrupts IC4/OC5 and OC4, respectively. The QVGA Controller's kernel software contains a complete set of high level driver routines for the Serial2 port, and these functions are summarized in the Control-C Glossary.

The maximum Serial2 communications rate is 4800 baud. Because the software UART is interrupt based, competing interrupts that prevent timely servicing of the Serial2 interrupts can cause com-

munications errors on the secondary serial channel. For example, at 4800 baud (bits per second), each bit lasts about 200 microseconds ( $\mu$ s), and if communications are full duplex (e.g., if the QVGA Controller echoes each incoming character), then there is a serial interrupt every 100  $\mu$ s or so. In the middle of a character, each interrupt service routine takes about 35  $\mu$ s. At the end of a received character, the service routine takes about 45  $\mu$ s. At the start of a transmitted character, the service routine takes about 65  $\mu$ s. Thus, as a rough approximation, operating at 4800 baud full duplex requires about 40 to 50% of the 6811's CPU time (that is, an average of approximately 40 to 50  $\mu$ s service time every 100  $\mu$ s).

If you are running Serial2 at 4800 baud, the rest of your application must be able to function properly using the remaining portion of the CPU time. Moreover, if Serial2 is running full duplex at 4800 baud, any other interrupt service routine that takes longer than 100  $\mu$ s is likely to cause a problem. If an interrupt service routine takes longer than 200  $\mu$ s, then an entire serial bit will be missed, causing a communications error. Also, several non-serial interrupts can *stack up*; if they have higher priority than the serial interrupts, they will be serviced before the Serial2 interrupt routine, and again a serial input or output bit may be lost.

Routines that temporarily disable interrupts for significant periods of time can also interfere with the Serial2 port. The Control-C Glossary contains a list of functions that temporarily disable interrupts, and the glossary entries give further information regarding how long interrupts are disabled. In most cases the times are less than 25  $\mu$ s which does not pose a problem. However, note that the Read-Watch() and SetWatch() functions disable interrupts for about one millisecond (msec.), and the functions that write to EEPROM disable interrupts for 20 msec. per programmed byte. Be sure to account for these effects when designing your application.

We have built sophisticated instruments using the QVGA Controller that operate very reliably using multiple interrupts in addition to the software UART. If your application requires use of the secondary serial port as well as other interrupt routines, the key is to keep the interrupt service routines short and fast. You might also consider operating the secondary serial port at a lower baud rate to relax the timing constraints.

## Setting Baud Rates

The rate of data transmission is expressed in bits per second, or *baud*. The primary serial channel can operate at standard speeds up to 19200 baud and can be configured for either RS232 (the default) or RS485 operation. The Serial2 channel is always configured for RS232 communications, and can sustain baud rates up to 4800 baud.

The routines

```
void Serial1AtStartup( void );  
void Serial2AtStartup( int baud );
```

make it easy to establish a standard baud rate at which the board will communicate each time it starts up. Although the maximum standard baud rate of the primary serial port is 19200 baud, non-standard baud rates of over 80 Kbaud can be attained by the 68HC11's on-chip UART and the on-board RS232 driver. The maximum sustainable baud rate on the secondary serial port is 4800 baud.

While the default baud rate of the primary serial port is 9600 baud, you can speed your communications and download times appreciably by switching to a faster baud rate. It's very simple. Just type at your terminal:

```
DECIMAL↵
19200 BAUD1.AT.STARTUP↵
```

The new baud rate takes effect upon the next reset or restart. Thus you can type the command

```
WARM↵
```

or reset the board using DIP switch number 7, or turn the system off and on again. In each case, your QVGA Controller will be communicating at 19200 baud, and this baud rate will remain in effect until another **BAUD1.AT.STARTUP** command is executed, or until you invoke the *Special Cleanup Mode* as described earlier.

To reconfigure the Mosaic Terminal to communicate at 19200 baud, select the "Comm" item under the "Settings" menu and click on 19200 in the "Baud Rate" selection box.

## Multi-Drop Communications Using RS-232

The RS-232 driver (Maxim Part No. MAX242) can be *tri-stated* under software control. This allows standard point-to-point full duplex communications, as well as a multi-drop configuration with one *master* (a single QVGA Controller or a desktop computer) and multiple QVGA Controller *slaves*. To implement this multi-drop scheme, each slave keeps its RS-232 transmitter *silent* until it is addressed by the master and is given permission to transmit. The advantage of such a multi-drop RS-232 network is that the communications are *full duplex*, with each communicating party capable of simultaneous transmission and reception of data. The software routines

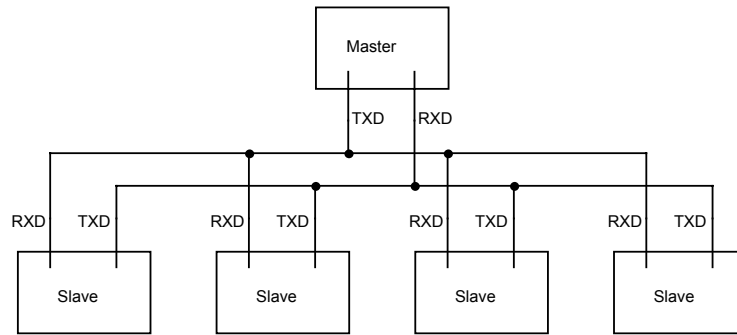
```
void RS232Transmit(void)
void RS232Silent(void)
```

control the dual RS232 transmitters on the board.

Connecting a standard full duplex link RS232 between two computers is the same as with a standard RS232 link, with the TxD (transmitter output) of each computer connected to the RxD (receiver input) of the other computer. A serial cable accomplishes this connection.

In a multi-drop configuration, the TxD of the master is connected to the RxD of each slave, and the RxD of the master is connected to the TxD of each slave. Figure 11-1 shows a typical multi-drop communications network. The QVGA Controller makes it easy to configure a multi-drop network of QVGA Controllers controlled by a single master desktop computer.

To properly operate the network each slave computer executes **RS232Silent** at startup; thus all of the slave transmitters remain silent individually addressed by the master. When a slave is addressed, it executes **RS232Transmit()** at which point full duplex (two-way) communications commences between the master and the selected slave. When the communication is complete the slave silences its transmitter so that the master can talk to a different slave on the network.



**Figure 11-1 Typical RS-232 multi-drop communications network.**

## Multi-Drop Communications Using RS-485

Connecting computers together in multi-drop networks is common in factories and laboratories. In these distributed processing networks, a variety of machines and instruments work locally, but communicate and share data or resources with one another globally using a single serial link. You can use the QED Board's RS485 link to create such a multi-drop serial network.

In the most common multi-drop RS-485 protocol, one computer is designated as a “master” and the rest of the computers or devices on the serial bus are designated as “slaves”. At any given time, only the master and a single “active” slave communicate. The remaining “inactive” slaves may actively receive, or listen to, data on the communications line, but only one slave at a time can transmit a message. If more than one slave tried to drive the transmit line simultaneously, their serial drivers would fight with each other for control of the bus. To ensure that no two devices drive the network at the same time, it is necessary that each slave device be able to disable its own RS-485 data transmitter.

## Synchronous Serial Peripheral Interface (SPI)

The Serial Peripheral Interface, SPI, is a fast synchronous serial interface. It provides a convenient means of connecting the QVGA Controller to a variety of peripheral devices, including analog to digital and digital to analog converters, real time clocks, and other computers which use high speed communication. The QVGA Controller's on-board 12 bit A/D and 8 bit D/A converters communicate with the processor via the SPI.

The SPI can transfer data much more rapidly than an asynchronous serial link – its maximum rate is 2 Megabits/second.

After configuring the SPI system to communicate on a properly connected network of devices, sending and receiving data is as simple as writing and reading a register. The QED-Forth kernel includes pre-coded drivers that configure the SPI for maximum speed data transfer using a format that is compatible with the on-board D/A and 12 bit A/D. This chapter describes those drivers, and presents code that makes it easy to configure the SPI for different data transfer rates and formats.

## SPI Bus Pins

Hardware is interfaced to the SPI via four PORTD pins named /SS, SCK, MOSI, and MISO brought out to pins 11 through 14 on the Digital I/O connector (see Appendix A). The SCK (serial clock) pin is a configurable synchronous data clock output. This signal synchronizes the exchange of bytes between the 68HC11 processor and the peripherals. The byte-sized messages are transmitted and received via the MOSI (master out/slave in) and MISO (master in/slave out) pins. The /SS (active-low slave select) signal enables data transfers by slave devices when it is active low. A ground connection is also necessary to ensure that the communicating devices have a common voltage reference.

When the 68HC11 controls the network, it is referred to as a “master”; otherwise, it is a “slave”. The distinction between master and slave is an important one. The device that initiates a data transfer is the master, and all other devices on the network are slaves. Only one active master may control the network at a time; however, the device that assumes the role of master may change according to an appropriate protocol.

The /SS pin can be configured as either an input or an output. Initializing the 68HC11 as a slave (by clearing the MSTR bit in the SPCR control register as explained below) automatically configures the /SS pin as an input. If the /SS input to a slave is inactive (high), the slave ignores the SCK input, does not transmit or receive data, and keeps its MISO output in a high-impedance state so that it does not interfere with the SPI bus. If the /SS input to a slave is active (low), the slave transfers data in response to the SCK clock input that is initiated by the master.

If the 68HC11 is initialized as a master (by setting the MSTR bit in the SPCR control register as explained below) then bit 5 of the Port D data direction register (DDRD) determines whether /SS is an input or an output. If bit 5 of DDRD is 1, then /SS is a general purpose output that operates independently of the SPI. This allows the processor that is master to control the input /SS pins of other CPU's, for example. If bit 5 of DDRD is 0, then /SS is an input. In this situation, if the /SS input is pulled low while the 68HC11 is the master, the processor detects a “mode fault” (by setting a bit in the SPI status register) meaning that there is more than one master device on the SPI bus.

There are many possible configurations of master/slave networks. Regardless of the network, however, there are only four signals used: SCK provides a synchronized clock, MOSI and MISO signals are used for data transmission and reception, and /SS configures the 68HC11 as a master or slave device. In this chapter we will consider the most general and simple configurations.

## SPI Network Connections

Configured as a master device, the 68HC11 transmits bytes via the “master out/slave in” pin, MOSI. It receives bytes sent by a slave device via the “master in/slave out” pin, MISO. Transmissions are always initiated by the master device, and consist of an exchange of bytes. As the master transmits a byte to an active slave (that is, a slave with its /SS input active low), the master receives a byte from the slave. It may be that only the byte sent from the master to the slave is meaningful; nevertheless, each device simultaneously transmits and receives one byte. The only difference between the master and slave devices is that the master initiates the transmission.

Slave devices use the master in/slave out pin, MISO, for transmitting, and the master out/slave in pin, MOSI, for receiving data. The following wiring diagram illustrates how the MOSI, and MISO pins of a master 68HC11 and a slave 68HC11 would be connected to exchange data:

Master 68HC11	Slave 68HC11
MOSI	→ MOSI
MISO	← MISO
SCK	→ SCK
/SS	→ /SS
GROUND	↔ GROUND

The status of a device as master or slave determines how the various pins must be configured. The arrows in the diagram point to pins configured as inputs, and originate from output pins. Thus, the master 68HC11 has only one input, MISO, which is the slave QVGA Controller's only output. Note that the master device outputs the clock synchronization signal SCK to the slave's SCK which is configured as an input. Also, in the diagram, the master QVGA Controller's /SS (slave select) is configured as an output. By setting this output LOW, the slave's input /SS is pulled LOW. The GROUND line serves as a common voltage reference for the master and slave.

There are a variety of ways the MOSI, MISO, SCK and /SS pins on your QVGA Controller can be connected. The one you choose depends on the specific device, or devices you will be connecting to. In some circumstances a one-way data flow may suffice. For example, a QVGA Controller connected to a serial A/D converter might have these connections:

Master QVGA Controller	Slave Serial A/D Device
MOSI	→ not connected
MISO	← Conversion Output
SCK	→ CLK
/SS	→ /CS
GROUND	↔ GROUND

In this example, the QVGA Controller selects the serial A/D by outputting a LOW signal on /SS. Even though the MOSI pin is not connected to anything, the master initiates a transmission using a "dummy" byte. The SCK pin clocks the serial A/D's CLK input which causes the A/D's conversion result to be transferred to the master via the MISO line.

The 68HC11 allows the details of the synchronous communications protocol to be customized for compatibility with a variety of peripherals. The next section describes the registers that configure and control the QVGA Controller's SPI.

## Configuring the SPI

The SPI is configured and accessed via four registers:

Name	Description	Reference
SPCR	SPI control register	MC68HC11F1 Technical Data Manual, p.10-3
SPSR	SPI status register	MC68HC11F1 Technical Data Manual, p.10-5
SPDR	SPI data register	MC68HC11F1 Technical Data Manual, p.10-5
PORTD.DIRECTION	Port D data direction (DDRD)	MC68HC11F1 Technical Data Manual, p. 4-5

Given a properly wired network and a properly configured SPCR control register, a master device may transmit a message by simply storing the byte to the SPDR data register. This automatically activates the SCK clock which synchronously transmits the data. As the master transmits its data, 8 bits of data are simultaneously received. The received data byte is accessed by reading SPDR data register. This ability to exchange messages means that the SPI is capable of full duplex communication. Once the data has been exchanged, a flag bit in the SPSR status register is set to indicate that the transfer is complete. If the programmer has enabled the local interrupt mask for the SPI, an interrupt is recognized at this point. Any required SPI output signals must be configured as outputs by setting the appropriate bits in the Port D data direction register which is named PORTD.DIRECTION in the QED-Forth kernel.

### ***Initializing the SPI Control Register***

The SPI control register, SPCR, contains 8 bits which must be initialized for proper control of the QVGA Controller's SPI (M68HC11 Reference Manual, p.8-7). These bits are:

Bit Name	Description
SPIE	SPI interrupt enable
SPE	SPI system enable
DWOM	Port D wired-or mode
MSTR	Master
CPOL	Clock polarity
CPHA	Clock phase
SPR1	SPI clock rate select bit1
SPR0	SPI clock rate select bit0

The DWOM bit (port D wired-or mode) should always be set to 0. Setting DWOM to 1 takes away the processor's ability to pull the Port D signals high unless there is a pull-up resistor on each bit of the port. Setting this bit to 1 without installing pull-up resistors corrupts the operation of the serial communications interface which uses bits 0 and 1 of Port D.

Setting SPE (SPI enable) to 1 turns on the SPI system. This bit should be set only after all other SPI configuration is complete.

SPIE is a local interrupt mask that allows an interrupt to be recognized when an SPI data transfer has completed, or if a write collision or mode fault is detected.

Setting the MSTR bit initializes the 68HC11 as a master, and clearing the MSTR bit initializes it as a slave. Clearing the MSTR bit in the SPCR control register automatically configures the /SS (slave select) pin as an input. The /SS input in turn determines whether the slave responds to the SCK input, as described in a previous section. If the 68HC11 is initialized as a master by setting the MSTR bit, then bit 5 of the Port D data direction register (PORTD.DIRECTION) determines whether /SS is an input or an output. If the /SS pin of the master is an output, it can be controlled independently of the SPI system. If the /SS pin of the master is an input and if a low input level is detected, the processor sets the MODF bit in the SPI status register a “mode fault” condition. This detects the presence of more than one master on the SPI bus.

The CPOL, CPHA, SR1 and SPR0 configure the SCK pin’s clock polarity, clock phase, and clock rate. These signals are described in detail below.

### ***SPI Clock Signal Configuration***

The SCK pin’s synchronous clock signal has configurable phase, polarity and baud rate so that it can interface to a variety of synchronous serial devices. In general, all devices on a network should use the same phase, polarity, and baud rate clock signal. In some cases, however, a sophisticated network may have device groups on a network that use different clock configurations. Although the devices would share the same network, communications would only be understandable by members of the same group.

The clock’s polarity is controlled by a bit named CPOL (clock polarity) and its phase is controlled by CPHA (clock phase). CPOL determines whether the clock idles in the low state (CPOL = 0) or the high state (CPOL = 1). If the clock idles in the low state, the leading edge of the clock is a rising edge. If the clock idles in the high state, the leading edge of the clock is a falling edge. The CPHA bit determines whether data is valid on the leading or trailing edge of the clock. Note that the data is changed by the transmitting device one half clock cycle before it is valid.

The following table summarizes the combinations of CPHA and CPOL settings:

CPOL	CPHA	Data is valid on the:
0	0	Rising, leading edge
0	1	Falling, trailing edge
1	0	Falling, leading edge
1	1	Rising, trailing edge

Many serial devices require a clock that idles in the low state (CPOL = 0), and expect valid data to be present on rising clock edges. Thus in this common configuration the transmitting device outputs the data when the clock goes low, and the receiving device samples the valid data when the clock goes high (CPHA = 0). In other words, data is valid on the “rising leading edge” of the clock.

To interface devices that support synchronized serial interfaces, but are not configurable like the 68HC11, determine the device’s requirements for clock phase and polarity and configure the 68HC11’s CPHA and CPOL accordingly. It is important to note that when the CPHA bit is 0, the /SS line must be de-asserted and re-asserted between each successive data byte exchange

(M68HC11 Reference Manual, p.8-3). If the CPHA bit is 1, the /SS line may be tied low between successive transfers.

### ***SPI Baud Rate***

The two lowest order bits in the SPCR control register, named SPR1 and SPR0, determine the data exchange frequency expressed in bits per second; this frequency is also known as the baud rate.

This setting is only relevant for the master device, as it is the master's clock which drives the transfer. SPR1 and SPR0 determine the baud rate according to the following table:

<b>SPR1</b>	<b>SPR0</b>	<b>SPI Frequency (bits/s)</b>
0	0	2.0 MHz
0	1	1.0 MHz
1	0	250 kHz
1	1	125 kHz

### ***Summary of the SPCR Control Register***

The SPIE bit in the SPCR (SPI control register) enables SPI interrupt handling. The SPE bit turns on the SPI system. The DWOM bit determines whether Port D needs pull-up resistors; it should be set to 0. The MSTR bit determines whether the device is a master or slave. The CPOL and CPHA bits configure the synchronous clock polarity and phase and specify when valid data is present on the MISO and MOSI data lines. Finally, for master devices, the SPR1 and SPR0 bits determine the baud rate at which data is exchanged.

### ***SPI Status Register Flags***

There are three flag bits implemented in the SPSR (SPI status register). They are:

<b>Flag</b>	<b>Condition</b>
SPIF	SPI transfer complete
WCOL	Write collision
MODF	Mode fault

Any of these conditions may generate an interrupt if the SPIE (SPI interrupt enable) bit in the SPCR control register is set.

The SPIF is set when a data transfer is complete, and is cleared by a read of the SPSR status register, followed by a read or write to the SPDR data register. Thus, resetting the SPIF flag is very simple. After a data transfer is initiated by writing to the SPDR data register, the processor may poll the SPSR status register until the SPIF flag is set. Then reading the data that was received (by reading the SPDR) or initiating a new data transfer (by writing to the SPDR) automatically clears the SPIF flag. Alternatively, if the SPI interrupts are enabled, the SPI interrupt handler determines what caused the interrupt by reading the SPSR register to see which of the three status bits is set. If SPIF is set, reading the received data or initiating a new data transfer automatically clears the SPIF bit.

A write collision occurs when a byte is written to the SPI data register, SPDR, while data is being exchanged. The WCOL flag is set when a write collision occurs. The data transfer that is in process when the write collision occurs is completed. WCOL is cleared by a read to the SPSR followed by a read or write to the SPDR.

A mode fault occurs when the SPI senses that a multimaster conflict (MC68HC11F1 Technical Data Manual, p.10-5) exists on the network as explained above in connection with the /SS input. When a mode fault is detected, the processor:

1. disables the SPI outputs by clearing the bits in the Port D data direction register (DDRD),
2. clears the MSTR bit in the SPCR to configure the SPI as a slave,
3. clears the SPE bit to disable the SPI, and
4. generates an interrupt if the SPIE bit in the SPCR is enabled

These steps greatly reduce the chance that the communicating devices might be damaged by contention on the SPI bus. The MODF bit is cleared by a read of the SPSR followed by a write to the SPCR.

### ***SPI Data Transfers***

A data transfer is initiated by a master device when it stores a message byte into its SPDR register. If a slave device has already stored a byte into its SPDR register, that byte will be exchanged with the master's byte. Once the bytes have been exchanged, the master may write a new byte to initiate another byte exchange. Although data byte transfers are easily executed once the network has been wired and configured properly, a carefully executed software protocol may be required to ensure data integrity.

## **Summary**

The flexibility and power of the 68HC11's serial peripheral interface supports high speed communication between the 68HC11 and other synchronous serial devices. The interface can be used to support analog to digital and digital to analog converters, networks of many computers controlled by a single master, or networks of devices controlled by several coordinated masters. Pre-coded device drivers configure the SPI for a standard data format, and routines defined in this chapter make it easy to customize a data format and baud rate for your application. With careful design, many peripherals can communicate via the SPI, and powerful multi-processor systems can be linked using this high speed bus.

# Chapter 12

## Chapter 12: The Battery-Backed Real-Time Clock

The battery backed real time clock is set and read using the Control-C functions **ReadWatch()** and **SetWatch()**. In C, these two routines access a fixed pre-allocated structure in the 68HC11's on-chip RAM using structure macros defined in the **WATCH.H** header file. For example, the following code reads the watch and stores the current minute (after the hour) in the variable named **current\_minute**:

```
static int  current_minute;
ReadWatch();
current_minute = WATCH_MINUTE;
```

Because the structure that is written to by **ReadWatch()** is at a fixed location, this code is not re-entrant. This is not a problem in single-task applications or applications where only one task uses the watch. But it can cause problems if multiple tasks are executing **ReadWatch()**. For example, assume that task #1 calls **ReadWatch()**, but before it can access the contents of the structure using the assignment statement, the timeslice interrupt occurs and task#2 proceeds to call **ReadWatch()**, then the contents of **WATCH\_MINUTE** could be changed before task#1 is able to execute its assignment statement. To avoid this situation, the multitasking application can be configured so that only one task calls **ReadWatch()** and **SetWatch()** and shares the data with other tasks.

Another option is to define a resource variable to mediate access to the watch. The routines needed to accomplish this are declared in the **MTASKER.H** file and described in detail in the Control-C Glossary. The following brief example illustrates how to design a re-entrant function that returns the current **WATCH\_MINUTE**:

```
RESOURCE watch_resource;    // declare resource variable: controls
                             // watch access
_Q int CurrentMinute(void) // reads watch, returns current minute
{ int minute;
  GET(watch_resource);      // get access to watch; Pause() if
                             // another task has it
  ReadWatch();              // updates contents of watch structure
  minute = WATCH_MINUTE;
                             // you can also transfer other contents
                             // from the watch structure to
                             // "task-private" variables here
  RELEASE(watch_resource); // release access to watch so other
                             // tasks can use it
  return minute;
}
```

The **CurrentMinute()** function can be simultaneously called from multiple tasks without causing any conflicts. The **GET()** and **RELEASE()** macros automatically mediate access to the watch, ensuring that only one task has access at a time.

Interrupts are disabled during the entire operation of the functions **ReadWatch()** and **SetWatch()** for approximately 0.5 and 0.45 msec respectively.

The words that access the watch use the top 16 bytes of the 68HC11F1's on-chip RAM (at addresses 0xB3F0-0xB3FF) as a buffer to hold intermediate results during the data transfers. You may use these locations for other purposes when the watch is not being accessed.

# **Part 4**

## **Putting It All Together**



# Chapter 13

## Chapter 13: A Turnkeyed Application

*This chapter presents an application program that integrates a range of hardware and software features of the QVGA Controller. The application is "turnkeyed", meaning that it can be placed in Flash and configured to autostart each time the board is powered up. This chapter explains all of the elements of the program.*

The example application reads a voltage using the 8 bit analog to digital (A/D) converter and outputs a pulse width modulated (PWM) signal that, when averaged using a simple resistor and capacitor, tracks the input voltage. In addition, the program calculates and displays the mean and standard deviation of the input signal. This application demonstrates how to:

- Use the pre-coded library routines
- Take advantage of the "Make" utility which automatically sets up a memory map that is compatible with a turnkeyed application in PROM
- Use the 8 bit A/D converter
- Use floating point mathematics to calculate means and standard deviations
- Write and install an interrupt routine that generates a PWM output
- Assemble an interrupt routine for increased performance
- Write to the liquid crystal display (LCD)
- Write the application using a modular multitasking approach
- Configure the application to automatically start upon power-up or reset

The program is called **TURNKEY.C** in the **\MOSAIC\DEMOS\_AND\_DRIVERS\MISC\C EXAMPLES** directory. The commented application code is presented at the end of this chapter. The text of this chapter will frequently refer to the code, offering background and explanation. Some of the section titles in this chapter are keyed to the titled sections in the code which are set off with asterisks.

## Overview of the Application

The main activities of this application are performed by 3 modular tasks and one interrupt routine:

- ⇒ The first “data gathering” task collects data from channel 0 (or any other channel that you designate) of the 8 bit A/D converter (PORTE on the 68HC11), converts the 8 bit reading to its equivalent voltage, and saves it in a floating point variable called **input\_voltage**.
- ⇒ The second “output control” task calculates the duty cycle, high-time and low-time of a pulse width modulated (PWM) output signal so that its average value matches the latest **input\_voltage** measured by the data gathering task.
- ⇒ An interrupt attached to output compare 3 (OC3) controls the PWM output signal appearing at pin 5 of PORTA (PA5) of the 68HC11. The interrupt service routine updates the OC3 timer registers based on the high-time and low-time calculated by the output control task.
- ⇒ Once each second for ten seconds, the third “statistics” task samples the input voltage calculated by Task 1 and stores it as a floating point number in a **FORTH\_ARRAY** called **Last10Voltages**. When 10 seconds have elapsed, this task calculates the mean and standard deviation of the 10 data points and writes them to the LCD display. It then starts filling the array with new data, repeating the entire process.

There is one additional task that is always present in this application: the default task named **FORTH\_TASK** that runs QED-Forth and executes **main()**. In the final version of this application we put the QED-Forth task **ASLEEP**. This prevents the end user of the system from gaining access to the Forth interpreter. We use the interactive QED-Forth task during development and debugging; it allows us to execute commands and monitor the performance of the routines that are being tested.

## Hardware Required for the Example Application

This sample application requires a QVGA Controller, a resistor, capacitor, potentiometer, and a voltmeter to verify proper operation. An optional operational amplifier would allow the output signal to drive loads other than a high impedance voltmeter or oscilloscope. Please be careful not to short pins together when working with the on-board connectors.

A 10 Kohm (or any other reasonably valued) potentiometer is connected to place a controllable voltage on AN0, which is channel 0 of the 8 bit A/D converter on the HC11. The potentiometer is connected between +5VAN (the analog +5 Volt supply) and AGND (analog ground), with the potentiometer’s wiper connected to AN0 (pin 10 of the analog I/O connector).

The PWM output appears on PA5 (that is, pin 5 of PORTA). A resistor and capacitor are connected to integrate the square-wave output signal to a steady average voltage across the capacitor. The capacitor voltage can be measured with a high impedance voltmeter or oscilloscope. An optional amplifier can be used if the output must drive lower impedance loads.

The statistical report generated by Task 3 is sent to the LCD display.

## The Memory Map

The first step in programming an application is assigning the memory areas that will be occupied by the object code, variable area, and also the heap which holds **FORTH\_ARRAYS** in paged memory. Fortunately, the Mosaic IDE Make Tool (invoked by clicking on the Make icon) automatically sets

up a very versatile memory map. For reference, here is a brief summary of the main memory areas allocated by the Make Tool:

- 0x0000-0x7FFF (32K) in page 4 is the program's object code which will eventually be in Flash.
- 0x4600-0x7FFF (14.5K) in page 0x0F is the RAM heap area that holds **FORTH\_ARRAY** data in paged memory.
- 0x3000-0x45FF (5.5K) in page 0F is a reserved heap for the graphics display buffer.
- 0x8E00-0xADFF (8K) is available common RAM (the C .data and .init sections) which hold C variables, C arrays, TASK areas, and pfa's (parameter field areas) of **FORTH\_ARRAYS**.
- 0xB000-0xB3FF (1K) is 68HC11 on-chip RAM (the C .onchipRAM section); the top 48 bytes at 0xB3D0-0xB3FF are reserved.
- 0xAE00-0xAFFF (320 bytes) is available EEPROM (the C .eeprom section); EEPROM at 0xAE00-0xAEBF is reserved for startup utilities and interrupt revectoring.
- 0x4000-0x7FFF (16K) on page 0x05 is used for QED-Forth debugging definitions that are present in the .DLF download file
- QED-Forth ROM occupies 0x0000-0x7FFF on page 0, 0x0000-0x2FFF on page 0x0F, and 0xB400-0xFFFF in common ROM.

While the object code ends up in Flash memory, the variable area and heap must always be located in RAM. The variable area includes the areas where variable values are stored, where **TASK** areas (the tasks' stacks, buffers, pointers, etc.) are allocated, and includes the parameter fields that hold addressing and dimensioning information associated with heap items. The heap in paged memory holds **FORTH\_ARRAYS** and other data structures. Both variables and the contents of the heap must be subject to rapid change while the application is running, so they can never be placed in Flash.

### Other Memory Areas

The upper half of page 5 is used to hold the QED-Forth definitions (names and object code) that facilitate interactive debugging. This region is typically not needed after debugging is done, and so is typically not included in the final Flash. If interactive function calling capability is required in the final application (for example, if you want to give the end user or a customer service person the ability to execute interactive commands from a terminal), then this area can be included in nonvolatile Flash memory in the final turnkeyed system.

While downloading an application, the object code area must be RAM so that the specified bytes can be stored in memory. As described earlier, proper use of **SAVE** and **RESTORE** utilities can save you from having to re-download all of your code after a crash or mistaken command.

## 8 Bit A/D Data Gathering Task

The first section of the example application code uses the 8 bit analog to digital (A/D) converter to convert the voltage input derived from the external potentiometer to a digital value between 0 and

255. The task converts the 8 bit A/D reading into its equivalent floating point voltage which spans 0.0 to 5.0 Volts, and stores it in a variable called `input_voltage`.

We define some simple constants that specify the high and low reference voltages of the A/D, and the number of counts ( $2^8 = 256$  counts). The `CountToVolts()` function converts the 8 bit A/D reading into its equivalent floating point voltage (a number between 0.0 and 5.0 Volts).

`GatherData()` is the activation routine for this task. It calls `AD8On()` to power up the 8 bit A/D, and enters an infinite loop that acquires an A/D sample, converts it to a voltage, and stores it in the variable `input_voltage` which other tasks can read.

A special storage operator named `PokeFloatUninterrupted()` is declared using the `_protect` keyword, which causes the compiler to disable interrupts before calling the function, and restore the global interrupt enable flag (the I bit in the Condition Code Register) to its prior condition after the function returns. This uninterruptable function is used because the `input_voltage` variable holds data that is accessed by more than one task. The uninterruptable store and fetch operators ensure that 32 bit data is not misread because of intervening interrupts or task switches.

The `Pause()` cooperative task-switch command forces at least one task switch on each pass through the infinite loop of `GatherData()`; we also rely on the timeslicer to switch tasks every 5 ms.

## Pulse Width Modulation Task

The goal is to create a PWM output whose average voltage is equal to the input voltage read by the data gathering task. This code specifies the activity of the task that calculates the high-time and low-time parameters needed to generate the pulse width modulated output signal. An interrupt routine (described in the next section) controls the output signal subject to the high- and low-times calculated by this task.

We could perform all of the duty cycle computations in the interrupt service routine that controls the PWM output, but this is not a good practice. Long interrupt service routines can delay the processor's ability to respond to other interrupts in a timely manner. The best approach is to perform the more time-consuming computational functions in *foreground* tasks so that the associated *background* interrupt service routines execute very rapidly.

We define static integer variables to hold the high-time and low-time which, as their names imply, hold the number of timer counts that the PWM signal is high and low. Floating point constants `LOW_OUTPUT_VOLTAGE` and `HIGH_OUTPUT_VOLTAGE` are defined to specify the voltage levels corresponding to logic level 0 and logic level 1; for maximum accuracy you could measure the voltage levels on PA5 (pin 5 of PORTA on the 68HC11) and set these constants accordingly.

The period of the PWM output is chosen to be 130 msec, which corresponds to 65,000 counts on the free-running timer. The resident QED operating system automatically configures the free-running counter to increment every 2 microseconds.

We enforce a minimum time between interrupts via the constant `MINIMUM_HIGH_OR_LOW_TIME` which is approximately equal to the maximum number of timer counts divided by 256. That is, we only require 8 bits of resolution from our PWM. The benefit of imposing a minimum high or low

time is that by doing so we can ensure that the minimum time between PWM interrupts is more than adequate to allow the service routine to execute.

We next define a routine that calculates the PWM duty cycle such that the average output signal matches the latest measured `input_voltage`. The `HighAndLowTimes()` function converts the calculated duty cycle into the parameters needed by the interrupt service routine, and `SetPulseParameters()` is the infinite loop that serves as the activation word for the PWM task. Note once again that we have put `Pause()` in the loop so that both cooperative and timesliced multitasking are used.

## Output Compare 3 Interrupt Code

This code defines an interrupt service routine and an installation routine for the OC3 (Output Compare 3) interrupt which controls the output signal. We first define constants to name the relevant bit masks. The relevant 68HC11 hardware register names are defined in the `QEDREGS.H` file in the `\FABIUS\INCLUDE\MOSAIC` directory.

`OC3Service()` is the interrupt service routine that controls the state of the PA5 output bit. It relies on the ability of the output compare (OC) function to automatically change the state of an associated PORTA output bit at a specified time. Specifically, OC3 can be configured to automatically change the state of the output PA5 when the count in the `TOC3` register matches the contents of the free-running counter (`TCNT`) register. Setting the “mode bit” specified by the constant `OC3_MODE_MASK` in the timer control 1 (`TCTL1`) register enables the automatic output control function. The OC3 “level bit” specifies whether the output bit will be set high or low upon a successful compare. The `OC3Service()` routine simply reverses the state of the OC3 level bit (specified by the constant `OC3_LEVEL_MASK`) and adds the appropriate `high_time` or `low_time` increment to the OC3 register to specify when the next interrupt will occur. Recall that `high_time` and `low_time` are calculated by the foreground PWM task, so the interrupt has very little to do and can execute rapidly (typically in under 50  $\mu$ sec).

`InstallOC3()` enables direct hardware control of PA5 by setting the OC3 mode bit, calls `ATTACH()` to post `OC3Service()` as the OC3 interrupt handler routine, initializes PA5 by forcing an output compare, and enables the OC3 interrupt. The `main()` routine defined at the end of the code example calls the `InstallOC3()` initialization routine each time the processor restarts.

## Assembly Coding a Function Definition

`AssembledOC3Service()` is an assembly coded version of the interrupt service routine. While it is only slightly faster than the high level version, it is included to illustrate how assembly coding is performed within this programming environment.

Assembly mnemonics use the standard Motorola format as described in the Motorola 68HC11 book. After the function is declared and the opening `{` is entered, the `#asm` preprocessor directive indicates that the following code is to be passed straight through to the assembler, bypassing the C compiler. The `#endasm` preprocessor directive returns control to the compiler. These preprocessor directives must appear alone on a line. Each opcode instruction must occupy a separate line that starts with at least one tab or space. Labels (such as branch destinations) should appear alone on a

line, with no leading spaces. The `*` is the comment character; text after the first `*` on a line is ignored.

Assembly constants are defined using **EQU** (equate) statements. Note that just above the function definition of **AssembledOC3Service()**, the required constants are defined as **EQU** statements within the delimiting **#asm ... #endasm** preprocessor directives.

## Statistics Task

The code in this section continuously loads a matrix with one input voltage acquired in each of the last 10 seconds, and writes the mean and standard deviation of this data to the liquid crystal display every 10 seconds. We define a single-row **FORTH\_ARRAY** called **Last10Voltages** to hold the data; this array resides in the heap associated with the statistics task. Two variables keep track of the current and prior matrix indices; these aid in managing storage of data into **Last10Voltages**.

The **SetupDisplay()** function writes the headings to the LCD display. The **STRING\_TO\_DISPLAY** macro (defined in the **INTERFACE.H** file) makes it easy to write a text string to a portion of the display buffer in system RAM, and the **UpdateDisplay()** command writes the contents of the buffer to the LCD display. **CalcStats()** calculates the latest calculated mean and standard deviation values, and **ShowStats()** writes them to the display. **ShowStats()** uses **sprintf()** to convert the floating point numbers to ASCII strings that can be written to the display buffer. The format is specified so that each floating point number will occupy the same number of spaces each time it is displayed. **LogDataAndShowStats()** fills the **Last10Voltages** array with measured voltages and calls the subsidiary functions to display the statistical results every 10 seconds.

**Statistics()** is the activation routine for the task; it dimensions and initializes the data array, sets up the display, and enters an infinite loop that logs the data and displays the statistics. **Pause()** is included in the infinite loop so that both cooperative and timesliced task switching are used.

## Build and Activate the Tasks

Now that we have defined the activation routines for the tasks, it is time to execute the **TASK** statement to name the tasks, allocate their 1K task areas in common RAM and set up the tasks.

The routine **BuildTasks()** initializes the user area and stack frame of each task, and links the tasks into a round-robin loop. The first statement of this routine is very important:

```
NEXT_TASK = TASKBASE;
```

When executed, this command makes the currently operating task (which will always be the default **FORTH\_TASK**) the only task in the round-robin loop. This sets a known startup condition from which the task loop may be constructed.

Note that the **ReadInputTask** and **ControlOutputTask** are built with a null heap specification because they do not access any heap items. The **StatisticsTask**, however, does access a heap item. It requires a heap specified by **DEFAULT\_HEAPSTART** and **DEFAULT\_HEAPEND** which are defined in the **HEAP.H** header file in the **\FABIUS\INCLUDE\MOSAIC** directory. Note that we also

use the same heap specification for the default **FORTH\_TASK**; see the **INIT\_DEFAULT\_HEAP()** routine. The **FORTH\_TASK** is not active in the final application, so the sharing of this heap space does not cause a conflict during operation.

**ActivateTasks()** simply activates each of the three tasks with the appropriate action routine. Each action routine is an infinite loop that performs the desired activity of the task.

## Define the main Routine

The **main()** function is the top level routine in the application. After execution of the **PRIORITY.AUTOSTART** command as explained below, it will be called each time the board is powered up or reset. The operating system always wakes up and enters the default **FORTH\_TASK** whose task area starts at 0x8400 in common memory upon every restart, so the default QED-Forth task is always the task that calls **main()**.

It is good programming practice to initialize all variables each time the application starts up; this is done by the **InitVariables()** function. After initializing the variables, **main()** calls **INIT\_DEFAULT\_HEAP()** to initialize the heap of the **FORTH\_TASK**, calls **InitElapsedTime()** to initialize the elapsed time clock to zero, installs and initializes the **OC3** (PWM) interrupt service routine, and builds and activates the tasks.

The next command in **main()** is

```
ColdOnReset()
```

which forces a **COLD** restart every time the machine is reset. This enhances the operating security of a turnkeyed application by ensuring that every user variable and many hardware registers are initialized after every restart and reset. This command may be commented out during debugging so that restarts do not cause QED-Forth to **FORGET** all of the defined functions in the application program.

The **main()** function then puts the default **FORTH\_TASK** asleep by executing:

```
STATUS = ASLEEP;
```

This takes effect once multitasking commences, and does not prevent execution of the remainder of **main()**. This command should be commented out during program development so that the awake QED-Forth task can be used to aid in debugging.

The **main()** function then **RELEASES** the **FORTH\_TASK**'s control of the serial line. This is not required in this simple application, but it would be necessary if another task required access to the serial port in the final application. For example, the **RELEASE()** statement would be required if the statistics task printed to the terminal instead of to the LCD display.

The final commands start the timeslicer (which also starts the elapsed time clock and globally enables interrupts) and **Pause()** to immediately transfer control to the next task in the round-robin loop. The final **Pause()** is not essential in this simple application, but it does ensure smooth operation in applications where tasks other than QED-Forth require access to the serial port.

## Compile the Program

To compile, assemble and link the program and create the download file, simply use your editor to open the **TURNKEY.C** file in the **\MOSAIC\DEMOS\_AND\_DRIVERS\MISC\C EXAMPLES** directory, and then click on the Make Tool. When the compilation is complete, you can view the warning messages and highlight the associated source code lines. (None of the warnings adversely affect the operation of this program.)

Make sure that your QVGA Controller is turned on and is communicating with the Mosaic Terminal. Then download the program to the QVGA Controller by using the terminal's "Send Text File" menu item to send the **TURNKEY.DLF** file.

## Using SAVE, RESTORE and Write-Protection During Debugging

After downloading the program, you can interactively type **SAVE** from the terminal; this stores relevant memory map pointers into reserved locations in EEPROM. You can proceed to interactively test each function in the program one at a time as described earlier. If a crash occurs, simply type **RESTORE** to bring back access to all of the interactively callable function names. The use of **SAVE** and **RESTORE** can greatly reduce the number of times that you have to re-download your code during debugging.

## Configure the Board to Autostart the Program

After debugging is completed interactively type the QED-Forth command:

```
CFA.FOR main PRIORITY.AUTOSTART.
```

which installs **main()** as a routine that is automatically executed upon each restart or reset. Note that the *QED-Forth V4.xx* greeting is suppressed when an autostart routine is installed (you could easily print your own greeting by modifying the **main()** function). **PRIORITY.AUTOSTART** installs an autostart pattern in the top 6 bytes of page 4 which is in Flash in the final system. The autostart pattern tells the operating system to automatically call **main()**.

The **PRIORITY.AUTOSTART** command is used to configure systems that will go into production. For one-of-a-kind prototypes, another QED-Forth command (called simply **AUTOSTART**) is available that installs the autostart pattern in EEPROM which resides in the 68HC11 chip itself. Because the pattern installed by **AUTOSTART** is in the processor chip and not in Flash, it is not automatically transferred to a new board when the application Flash is plugged in. In summary, the **AUTOSTART** command is convenient while debugging a prototype, but the **PRIORITY.AUTOSTART** command must be used when generating a Flash for a production system.

After executing the **PRIORITY.AUTOSTART** command, the **main()** routine can be invoked by resetting the QVGA Controller, thus starting the program. If you need to remove the autostart vector (and the QED-Forth monitor is still active and responding to your commands, that is, if you didn't put it **ASLEEP**), you can simply type:

```
NO.AUTOSTART.
```

to remove any **PRIORITY.AUTOSTART** or **AUTOSTART** vectors. If QED-Forth is not awake (and so does not respond to the terminal), you can remove the autostart vector by entering the special cleanup mode. Note that the special cleanup mode configures the system to expect a baud rate of 9600 baud, so if you are using a different baud rate, you'll need to interactively execute the command **BAUD1.AT.STARTUP** to re-establish the desired configuration.

You can monitor the operation of the turnkeyed program by connecting a voltmeter or oscilloscope across the output capacitor C1, and by watching the update of statistics every 10 seconds on your display. Adjusting the input potentiometer should result in an output voltage that tracks the input.

## Turnkeyed Application Code Listing

### *Listing 13-1 Turnkeyed Application*

```
// Turnkeyed Application Code Listing, C Language version.
// This is a complete real-time application program, with instructions on
// how to set up the program to AUTOSTART each time the processor starts up.

// Copyright 2004 Mosaic Industries, Inc. All Rights Reserved.
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// WARRANTIES OR REPRESENTATIONS EXPRESS OR IMPLIED, INCLUDING, BUT NOT
// LIMITED TO, ANY IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS
// FOR A PARTICULAR PURPOSE.

// ***** Turnkeying a QED Application *****
//
// This is the code for an example application. The accompanying chapter
// presents a detailed explanation of this code. The code can run on a QVGA
// Controller with the minimum memory configuration.

// Description of the application:
// This program reads an input voltage, creates a pulse width modulated (PWM)
// signal whose average value tracks the input voltage, and reports the
// mean and standard deviation of the input voltage. The following 3 tasks do
// the work:

// Task 1: Reads 8 bit A/D input AN0, measuring the voltage on a potentiometer
//          connected to PortE pin PE0/AN0.

// Task 2: Outputs on Port A bit 5 a PWM signal whose average equals the A/D
//          input.

// Task 3: Every 1 second puts A/D value into a matrix, and every 10 seconds
//          displays the mean and standard deviation of the last 10 seconds
//          worth of data.
//
// The following issues are addressed:
//
//      Using the default C memory map as set up by the MAKE utility
//      Proper initialization of tasks at startup
//      Autostarting
//      Interrupt service routines and interrupt attaching
//      In-line assembly coding
//      Initialization of the heap memory manager
//      Timesliced multitasking
//      ColdOnReset() for secure restart
//      Floating point calculations
//      Using the display
//      Generation of a PROM image of application
//      Going into production
```

```
// ***** Default Memory Map *****

// 0-7FFF (32K) in page 4 is user application code

// 4600-7FFF (14.5K) in page 0F is RAM Heap area that holds banked array data.

// 3000-45FF (5.5K) in page 0F is a heap for the graphics display buffer.

// 8E00-ADFF is available common RAM (the C .data and .init sections)
// which hold C variables, C arrays, and pfa's (parameter field areas)
// of FORTH_ARRAYs.

// B000-B3FF is 1K 68HC11 on-chip RAM; the top 48 bytes
// at B3D0-B3FF are reserved.

// AEC0-AFFF is available EEPROM referenced by the .eeprom section
// {EEPROM at AE00-AEBF is reserved for startup utilities
// and interrupt revectoring}

// QED-Forth ROM occupies 0-7FFF on page 0, 0-2FFF on page F,
// and B400-FFFF in common ROM.

#include <\mosaic\allqed.h> // include all of the qed and C utilities

// ***** 8 BIT A/D Data Gathering Task *****

// This task gathers data from the 8 bit A/D and places it in a variable
// easily accessed by other tasks.

// Define the control registers and some useful constants:

#define AD8_INPUT_CHANNEL ((char) 0)
// You can use any channel you want and place the input potentiometer on
// the corresponding A/D8 input pin. For example, if 0 is your input
// channel, place the input signal on the pin labeled AN0 (pin 10 of
// the analog connector).

static float input_voltage;
// Holds voltage corresponding to latest result of A/D input. Because the
// contents of this variable are shared among several tasks, we use
// uninterruptable PokeFloatUninterrupted and PeekFloatUninterrupted
// to access it.

// Now we convert a measured count from the A/D that ranges from 0 to 255
// into a voltage that ranges from 0.0 Volts (the low reference voltage)
// to nearly 5.0 Volts (the high reference voltage).
// This involves solving the equation:
// Voltage=[(high.ref.voltage -
// low.ref.voltage)*measured.count/256]+low.ref.voltage

// First let's define some constants:
#define FULL_SCALE_COUNTS 256 // 256 counts in an 8 bit converter
#define LOW_VREF 0.0
#define HIGH_VREF 5.0
// NOTE: For maximum accuracy, measure +5VAN with a voltmeter and
// set HIGH.REF.VOLTAGE equal to the result.

_Q float CountToVolts(int count)
// This routine converts 8 bit A/D measured count n { 0 <= n <= 255 }
// to the corresponding floating point voltage r
// {typically, 0.0 <= r <= 5.0 } by solving the equation:
```

```

        // r = [ (high.ref - low.ref) * count / 256 ] + low.ref
    { return( ((HIGH_VREF - LOW_VREF) * count / FULL_SCALE_COUNTS) + LOW_VREF );
    }

_Q _protect void PokeFloatUninterrupted(float value, float* destination )
// stores value into the address specified by destination;
// the _protect keyword guarantees that
// interrupts will be disabled while this function executes;
// this prevents corruption of data when two tasks are accessing the same
// 4-byte variables
{ *destination = value;
}

_Q _protect float PeekFloatUninterrupted(float * source )
// fetches and returns the contents from the address specified by source;
// the _protect keyword guarantees that
// interrupts will be disabled while this function executes;
// this prevents corruption of data when two tasks are accessing the same
// 4-byte variables
{ return *source;
}

_Q void GatherData(void)
// This is the activation routine for the data gathering task.
// It continually acquires readings from the A/D, converts the readings
// to voltages, and updates the input_voltage variable that is accessed
// by other tasks.
{
    uchar sample;
    float sample_voltage;
    AD8On(); // make sure A/D is powered up
    while(1) // start infinite loop
    {
        sample = AD8Sample(AD8_INPUT_CHANNEL);
        sample_voltage = CountToVolts(sample);
        PokeFloatUninterrupted(sample_voltage, &input_voltage);
        Pause();
    }
}

// ***** Pulse Width Modulation (PWM) Task *****

// This task calculates the high time and low time of the PWM output based on
// the value of the input_voltage which is updated by the data gathering task.
// The goal is to set the duty cycle of the PWM output so that the average of
// the PWM signal equals the input_voltage. This is achieved by solving the
// equation:
//     DutyCycle = (input_voltage - low.output) / (high.output - low.output)
//     in which low.output and high.output are the voltage levels that appear
//     on the PWM output pin in the low and high states, respectively.

// Given the duty cycle, and given our choice of a PWM period of 130 msec, we
// calculate the high.time and low.time of the PWM signal in terms of the timer
// counts; each timer count equals 2 microseconds. high_time is the number of
// timer counts that the signal is in the high state and low_time is the number
// of timer counts that the signal is in the low state during each 130 msec
// period. high_time and low_time are calculated as:
//     high_time = Duty.cycle * TIMER_COUNTS_PER_PERIOD
//     low_time = TIMER_COUNTS_PER_PERIOD - high_time
//     where TIMER_COUNTS_PER_PERIOD = 130 msec/2 microsec = 65,000.

// We also "clamp" high_time and low_time to a minimum value to prevent a
// situation where interrupts are requested so rapidly that the processor
// can't service them.

```

```

// The OC3 (output compare 3) interrupt code in the subsequent section uses
// these calculated values to pulse width modulate the PORTA output port pin
// PA5.
// We define some variables and constants:

static uint high_time; // the number of timer counts that PWM output is high
static uint low_time;  // the number of timer counts that PWM output is low
static float duty_cycle;

#define LOW_OUTPUT_VOLTAGE    0.0 // the voltage on PA5 when it is low
#define HIGH_OUTPUT_VOLTAGE  5.0 // the voltage on PA5 when it is high
// NOTE: for maximum accuracy, the voltage output of pin PA5 could be measured
// in the low and high states and LOW_OUTPUT_VOLTAGE and HIGH_OUTPUT_VOLTAGE
// set accordingly.

#define MS_PER_PERIOD    130 // use a 130 msec period for PWM output
// NOTE: the timer "rolls over" every 131 msec

#define TIMER_COUNTS_PER_PERIOD    65000
// 130 milliseconds corresponds to 65,000 counts of 2 microseconds (usec)
// each on the free-running timer. QED-Forth sets the contents of TMSK2 so
// that each timer count represents 2 usec. This is true whether the crystal
// speed is 8 MHz or 16MHz. We assume here that the programmer has not
// installed a different value in TMSK2 using InstallRegisterInits().

#define MINIMUM_HIGH_OR_LOW_TIME ((int) 250) // corresponds to 500usec
// we choose a minimum high or low time approximately equal to the maximum
// number of timer counts divided by 256. That is, we only require 8 bits of
// resolution from our PWM. The benefit of imposing a minimum high or low time
// is that by doing so we can ensure that the minimum time between PWM
// interrupts is 500 usec. This is more than sufficient time to allow the
// service routine to execute.

_Q void CalculateDutyCycle(void)
// implements the equation:
// duty_cycle = (input_voltage-low.output)/(high_output-low_output)
// duty_cycle is in the range 0.0 to 1.0
{
    duty_cycle = (input_voltage - LOW_OUTPUT_VOLTAGE)
                / (HIGH_OUTPUT_VOLTAGE - LOW_OUTPUT_VOLTAGE);
    duty_cycle = MIN((float) 1.0, duty_cycle);
    duty_cycle = MAX((float) 0.0, duty_cycle); // clamp to 0<=duty_cycle<=1.0
}

_Q void HighAndLowTimes(void)
// saves high and low times as 16bit integer counts in the variables
// high_time and low_time using the equations:
// high_time = duty_cycle * TIMER_COUNTS_PER_PERIOD
// low_time = TIMER_COUNTS_PER_PERIOD - high_time
// both high_time and low_time are clamped to a minimum so that timer interrupts
// don't occur more frequently than they can be reliably serviced.
{
    high_time = MAX((TIMER_COUNTS_PER_PERIOD *
                    duty_cycle), MINIMUM_HIGH_OR_LOW_TIME);
    low_time = MAX((TIMER_COUNTS_PER_PERIOD - high_time), MINIMUM_HIGH_OR_LOW_TIME);
    high_time = TIMER_COUNTS_PER_PERIOD - low_time;
    // make sure that high_time + low_time is exactly one period despite clamping
}

_Q void SetPulseParameters( void )
// this is the activation routine for the pwm task. It updates the
// values in high_time and low_time for use by the oc3 interrupt which
// generates the pwm output waveform on PORTA pin PA5.
{
    while(1)
    {
        CalculateDutyCycle();
        HighAndLowTimes();
    }
}

```

```

        Pause();
    }
}

// ***** OC3 Interrupt Code *****
// This interrupt routine generates a pulse width modulated output on Port A
// bit 5 based on the duty cycle calculated by the PWM task.
// There are 4 steps involved in coding an interrupt service routine:
//     1. Name all required hardware registers (see the QEDREGS.H file in the
//         \MOSAIC\FABIUS\INCLUDE\MOSAIC directory),
//         and name all required bit masks with appropriate mnemonics.
//     2. Use C or assembly code to define an interrupt handler which
//         must clear the interrupt request flag and perform required
//         service actions.
//     3. Install the interrupt handler using the Attach() function.
//     4. Write routines to enable and disable the interrupt. (We combine
//         steps 3 and 4 in a routine that ATTACHes and enables the interrupt).

// Define output mode configuration flags and masks that specify action
// to be performed when a successful output compare occurs:
#define PA5_MASK          0x20 // mask for setting/resetting PA5
#define OC3_MASK          0x20 // to set/clear OC3 interrupt flag & mask
#define OC3_MODE_MASK     0x20 // mask in TCTL1; enables PA5 pin control
#define OC3_LEVEL_MASK    0x10 // mask in TCTL1; controls level of PA5

// Summary of the functions of these registers: OC3 (output compare 3) is
// associated with pin PA5 on PORTA. We can write a 16 bit count into the TOC3
// register, and when the count in TOC3 matches the count in the main counter
// TCNT, an interrupt request can occur. The request only occurs if interrupts
// are globally enabled and if the OC3 interrupt is locally enabled. The OC3
// interrupt is locally enabled by setting the bit specified by the OC3_MASK in
// the TMSK1 register. When the interrupt request occurs, the 68HC11
// automatically sets the bit specified by OC3_MASK in the TFLG1 (timer flag
// #1) register. Our interrupt service routine must clear this bit (oddly
// enough, interrupt request bits are cleared by writing a 1 to the bit
// position!) The register TCTL1 controls whether the state of the PA5 bit is
// automatically changed when TOC3 matches TCNT. In this application we enable
// this automatic "pin control" action by setting the bit specified by
// OC3_MODE_MASK in TCTL1. The bit specified by OC3_LEVEL_MASK in TCTL1 then
// controls the level (high or low) to which PA5 is set upon a successful
// output compare.

_Q void OC3Service(void)
{
    char temp = OC3_LEVEL_MASK;
    TFLG1 = OC3_MASK; // reset the oc3 interrupt flag so that new oc3
                      // interrupts will be recognized. because the flag
                      // is cleared by writing a one to it we can use a
                      // assignment command without affecting other bits.
    if( temp &= TCTL1 ) // look at the oc3/pa5 pin output level
    {
        TCTL1 &= ~OC3_LEVEL_MASK; // AND with complement of mask
        TOC3 += high_time;
    }
    // if the output level just toggled high we'll
    // set the mode/level bit so the next output
    // compare forces the pin low after the high_time
    else
    {
        TCTL1 |= OC3_LEVEL_MASK;
        TOC3 += low_time; // set the mode/level bit so the next output
    }
    // compare forces the pin high after low_time
}

// Pass the required constants through to the assembler:
// Don't insert any leading spaces on a line that contains an EQU directive.
#asm
TOC3          EQU      $801A

```

```

TCTL1      EQU      $8020
TFLG1      EQU      $8023

PA5_MASK   EQU      $205
OC3_MASK   EQU      $20
OC3_MODE_MASK EQU    $20
OC3_LEVEL_MASK EQU    $10
NOT_OC3_LEVEL_MASK EQU $EF

#endasm

_Q void AssembledOC3Service( void )
// This interrupt service routine performs the same functions as the high level
// service routine named OC3Service. This alternative interrupt service routine
// is assembly coded to illustrate the principles of assembly coding with
// this environment. This routine it executes in under 45 usec
// including the call and return overhead. The high level version
// is nearly as fast.
// NOTE: #asm and #endasm in-line assembly directives
//      must be the first on a line,
// AND:  each line of assembly code MUST START WITH A TAB OR SPACE,
// BUT:  labels must NOT be preceeded by a tab or space.
// The comment character for assembly code is the * as shown below.
{
#asm
    ldab TCTL1
    bitb #OC3_LEVEL_MASK      * Look at the OC3/PA5 pin output level
    beq is_low
    * If output just went high, clear the level bit in TCTL1: next OC3 clr PA5
    andb #NOT_OC3_LEVEL_MASK
    stab TCTL1
    ldd TOC3
    addd high_time
    bra finished

is_low
    * If output just went low, set the level bit in TCTL1: next OC3 sets PA5
    orab #OC3_LEVEL_MASK
    stab TCTL1
    ldd TOC3
    addd low_time

finished
    std TOC3                * update the OC count for the next output compare
    ldaa #OC3_MASK          * Reset the OC3 interrupt flag by writing a 1
    staa TFLG1              * so that new OC3 interrupts will be recognized.
#endasm
}

_Q void InstallOC3( void )
// This installation routine enables the "pin control" function, ATTACHES the
// service routine, configures PortA pin 5 as an output, initializes the output
// compare register TOC3, clears the OC3 interrupt request flag (thus ignoring
// prior interrupt requests), and locally enables the OC3 interrupt.
// PWM can begin when interrupts are globally enabled.
{
    TMSK1 &= ~OC3_MASK;          // Disable OC3 interrupts.
    TCTL1 |= OC3_MODE_MASK;
    // Set the OC3 mode bit so that an output compare sets or clears PA5 pin
    // depending on the level bit which is toggled by the interrupt routine.
// ATTACH(AssembledOC3Service, OC3_ID); // optional assembly service routine
ATTACH(OC3Service, OC3_ID);      // use the C-coded version
    TCTL1 &= ~OC3_LEVEL_MASK;    // Set to low before pulses start.
    CFORC |= OC3_MASK;           // and init by forcing a compare.
    TOC3 = TCNT + TIMER_COUNTS_PER_PERIOD; // start after a min 130ms delay
    TFLG1 = OC3_MASK;            // clear interrupt flag OC3F
    TMSK1 |= OC3_MASK;           // set OC3I to locally enable OC3
}

```

```

// ***** Statistics Task *****

// This task samples the analog input voltage (see task 1) once per second,
// stores it in a matrix, and calculates and prints the mean and standard
// deviation of the data every 10 seconds.

FORTH_ARRAY Last10Voltages;
    // row matrix; holds 1 voltage per second for past 10 seconds

// these index variables keep track of where data is placed in Last10Voltages:
static int matrix_index, last_index;

// these hold the derived statistics:
static float mean, standard_deviation;

_Q float RowMean(int rownum, FORTH_ARRAY * array_ptr)
// sums the elements in the specified row of the specified matrix and
// divides by the number of elements in the row to calculate the mean.
{
    float accumulator = 0.0;
    int i, numcolumns = NUMCOLUMNS(array_ptr); // see \Mosaic\ARRAY.H file
    for(i=0; i < numcolumns; i++)
        accumulator += FARRAYFETCH(float, rownum, i, array_ptr);
    return (accumulator / numcolumns);
}

_Q float RowStandardDeviation(int rownum, FORTH_ARRAY* array_ptr, float row_mean)
// subtracts the row mean from each element and sums the squares of all
// resulting differences in the specified row of the specified matrix
// and takes the square root of the sum to calculate the standard deviation.
{
    float accumulator = 0.0, temp;
    int i, numcolumns = NUMCOLUMNS(array_ptr); // see \Mosaic\ARRAY.H file
    for(i=0; i < numcolumns; i++)
    {
        temp = FARRAYFETCH(float, rownum, i, array_ptr) - row_mean;
        accumulator += (temp * temp);
    }
    return sqrt(accumulator);
}

_Q void InitFPArray(float value, FORTH_ARRAY * array_ptr)
// stores specified floating point value in each element of the array
// do not use this function to init arrays that hold char, int or long data
{
    int r, c,
        numcolumns = NUMCOLUMNS(array_ptr), // see \Mosaic\ARRAY.H file
        numrows = NUMROWS(array_ptr);
    for(c=0; c< numcolumns; c++)
        for(r=0; r < numrows; r++)
            FARRAYSTORE(value, r, c, array_ptr);
}

_Q void CalcStats( void )
// This routine calculates mean and standard deviation of the
// Last10Voltages matrix and stores them in variables.
{
    mean = RowMean(0, &Last10Voltages); // row# = 0
    standard_deviation = RowStandardDeviation(0, &Last10Voltages, mean);
}

// These routines manage the LCD display.
// The message on the display will look like this:
//      Mean =
//          x.xxx Volts
//      Standard Deviation =
//          x.xxx Volts

```

```
#define FP_OFFSET      4          // character offset to start of mean or
                                  // std.deviation in display line
#define VOLTS_OFFSET 14          // character offset to start of "Volts" label
                                  // in display line

#define MAX_CHARS_PER_DISPLAY_LINE 40
// large enough for 4x20 character display as well as 16 x 40 graphics display

#define SPACE 0x20              // ascii space {blank}

#define DISPLAY_CONFIG_BYTE ((uchar*) 0xAE1E) // see grphext.c file
#define TOSHIBA_VS_HITACHI_MASK 0x40        // 1 = toshiba; 0 = hitachi

char linebuffer[MAX_CHARS_PER_DISPLAY_LINE+1];
// single line buffer to assist in writing to display
// NOTE: it's all right if this buffer is longer than the display line;
//       StrToDisplay() will ignore the extra characters.

_Q uint Toshiba(void)
// returns flag, = true if toshiba display; false if hitachi
{
    return (((*DISPLAY_CONFIG_BYTE) & TOSHIBA_VS_HITACHI_MASK) ? 1 : 0);
}

_Q void BlankDisplayString(char* string_base, int numelements)
// writes "blanks" into the specified string, taking into account that
// Toshiba graphics displays in text mode use 0x00 as the code for BL
// numelements includes the terminating null character
{
    int i;
    char blankchar = (Toshiba() ? 0 : SPACE);
    for( i=0; i < (numelements-1); i++)
        string_base[i] = blankchar;
    string_base[numelements-1] = 0; // terminating null
}

_Q void SetupDisplay( void )
// writes headings to display; leaves numbers blank.
{
    xaddr display_buffer_base = DisplayBuffer();
    int numlines = LinesPerDisplay();
    int chars_per_line = CharsPerDisplayLine();
    char blankchar = (Toshiba() ? 0 : SPACE);
    FillMany(display_buffer_base, (numlines * chars_per_line), blankchar);
    // FillMany() blanks the display buffer
// blank display buffer
    STRING_TO_DISPLAY("mean = ", 0, 0 ); // line 0
    STRING_TO_DISPLAY("volts", 1, VOLTS_OFFSET); // line 1
    STRING_TO_DISPLAY("standard deviation =", 2, 0 ); // line 2
    STRING_TO_DISPLAY("volts", 3, VOLTS_OFFSET); // line 3
    UpdateDisplay(); // write buffer contents to display
}

// sprintf(char* s, const char *format, ... ) does formatted write to specified
// string. Returns #chars assigned,
// not including the terminating null that it writes after the last char.
// Returns a negative number if an error occurs.

_Q void ShowStats( void )
// displays mean and standard deviation of Last10Voltages on LCD display
{
    int num_chars_placed;
    BlankDisplayString(linebuffer, MAX_CHARS_PER_DISPLAY_LINE);
    num_chars_placed = sprintf(linebuffer, "%7.3f", mean);
    // use field width = 7 chars; 3 digits to right of the decimal point
    if(num_chars_placed > 0)
```

```

        STRING_TO_DISPLAY(linebuffer, 1, FP_OFFSET);    // line 1
BlankDisplayString(linebuffer, MAX_CHARS_PER_DISPLAY_LINE);
num_chars_placed = sprintf(linebuffer, "%7.3f", standard_deviation);
if(num_chars_placed > 0)
        STRING_TO_DISPLAY(linebuffer, 3, FP_OFFSET);    // line 3
UpdateDisplay();    // write to display
}

_Q void LogDataAndShowStats( void )
// increments matrix_index every second,
// loads input_voltage data collected by task 1 into Last10Voltages array,
// and displays statistics on LCD display every 10 seconds
{
    float latest_input;
    // we need this temporary because we must do an uninterrupted fetch
    // from input_voltage, then pass the result to FARRAYSTORE
    matrix_index = (ReadElapsedSeconds()) % 10; // 0<= matrix_index <= 9
    if(matrix_index != last_index) // if a second has elapsed...
    {
        latest_input = PeekFloatUninterrupted(&input_voltage);
        FARRAYSTORE(latest_input, 0, matrix_index, &Last10Voltages);
        // store reading in matrix
        last_index = matrix_index; // update last_index
        if(matrix_index == 9) // if 10 seconds have elapsed...
        {
            CalcStats(); // calculate new statistics
            ShowStats(); // update display
        }
    }
}

_Q void Statistics( void )
// this is the activation routine for the statistics task;
// it calculates and displays the mean and standard deviation of the data.
{
    DIM(float, 1, 10, &Last10Voltages); // dimension as a 1-row array
    InitFPArray(0.0, &Last10Voltages); // initialize array
    last_index = -1; // initialize last_index
    SetupDisplay(); // write headings to display
    while(1)
    {
        LogDataAndShowStats(); // calc and display statistics
        Pause();
    }
}

// ***** BUILD TASKS *****

// Note: we'll keep the Forth interpreter task active during
// development/debugging, and put it ASLEEP in the final turnkeyed version.

// First declare the tasks and allocate their 1K task areas:
// FORTH_TASK (see MTASKER.H) is the default task running QED-Forth;
// this task is automatically built and started upon each reset/restart;
// in the autostart routine FORTH_TASK puts itself ASLEEP so the end
// user can't run Forth.

TASK ReadInputTask; // data gathering task base xaddr

TASK ControlOutputTask; // PWM task base xaddr

TASK StatisticsTask; // statistics reporting task

// BUILD_C_TASK(HeapStart,HeapEnd,Base) and
// ACTIVATE(function_ptr, task_base_addr)
// macros are defined in \mosaic\mtasker.h file.

_Q void BuildTasks( void )
// Empties the round robin task loop and then
// carefully builds the tasks every time we start up.
// Note that only the statistics task has access to the heap.

```

```

{
    NEXT_TASK = TASKBASE;    // important! empties task loop before building
    SERIAL_ACCESS = RELEASE_ALWAYS; // allow sharing of serial ports
    BUILD_C_TASK(0,0,&ReadInputTask);
    BUILD_C_TASK(0,0,&ControlOutputTask);
    BUILD_C_TASK(DEFAULT_HEAPSTART,DEFAULT_HEAPEND,&StatisticsTask);
}

_Q void ActivateTasks( void )
    // associate activation routines with each of the tasks.
{
    ACTIVATE(GatherData, &ReadInputTask);
    ACTIVATE(SetPulseParameters, &ControlOutputTask);
    ACTIVATE(Statistics, &StatisticsTask);
}

// ***** SET UP AUTOSTART ROUTINE *****

// We'll designate the top level word main as the PRIORITY.AUTOSTART routine.
// Every time the QVGA Controller is powered up or reset, the main routine will
// automatically be executed by the default FORTH_TASK
// main() zeros the variable area and initializes the heap.
// During debugging, the FORTH task which runs main() has access to
// all defined function names declared using the _Q keyword;
// the names are sent to the QVGA Controller via the .DLF download file.
// This helps to debug the program.
// main() initializes the elapsed time clock, installs the
// OC3 interrupt service routines, and builds and activates the tasks.
// It releases control of the serial line, starts the timeslicer, and PAUSES
// to begin execution of the application.
// After debugging is complete, the optional commands which
// specify a COLD restart and which put the FORTH_TASK ASLEEP can be inserted;
// these commands are "commented out" in the code shown here.

_Q void InitVariables(void)
{
    // init static variables & strings at runtime, and delete array
    // to clean up the heap before allocating heap items
    input_voltage = 0;
    high_time = low_time = 0;
    DELETED(&Last10Voltages);
    matrix_index = last_index = 0;
    mean = standard_deviation = 0.0;
    BlankDisplayString(linebuffer, MAX_CHARS_PER_DISPLAY_LINE);
}

void main(void)
    // this is the highest level routine in the turnkey application.
{
    InitVariables();           // init variables, delete arrays
    INIT_DEFAULT_HEAP();      // it's important to init heap at startup
    InitElapsedTime();        // initialize qed elapsed time clock
    InstallOC3();             // install service routine for pwm generation
    BuildTasks();             // initialize user areas of the tasks
    ActivateTasks();          // associate action routine with each task
    // the following 2 commands are removed during debugging;present in final version
    // ColdOnReset();          // ensures full initialization upon each reset
    // STATUS = ASLEEP;        // puts forth task asleep;
    RELEASE(SERIAL);          // in case another tasks needs to use serial
    StartTimeslicer();        // starts elapsed time clock, enables interrupts
    Pause();                  // start next task immediately
}

// Now from your terminal, type:

```

```

// CFA.FOR main    PRIORITY.AUTOSTART

// this will install main() as the routine that is automatically executed
// each time the board is reset or powered on.
// The PRIORITY.AUTOSTART routine initializes the priority.autostart vector
// at locations 7FFA-7FFF on page 4 which will be in Flash.

// Then upon the next restart the main() routine will automatically execute.
// NOTE: To erase the autostart vector and return to QED-Forth,
// type at the terminal:
//          NO.AUTOSTART
// If you have put the FORTH_TASK asleep so that it does not
// respond to the terminal,
// activate the Special Cleanup Mode by turning on dip switch #6, toggling
// dip switch #7, and then restoring switch #6 to its original position.
// The Special Cleanup Mode erases the autostart vector and restores the
// board to a "pristine" condition (it also sets the default
// baud rate to 9600, and the LCD display type to 4x20 character
// display; use Baud1AtStartup() and IsDisplay() if you need to
// change these defaults).
//
// ***** BURNING THE FINAL APPLICATION FLASH *****

// To generate a Flash device that contains this application, download the
// download the TURNKEY.DLF file, and execute the
// CFA.FOR MAIN PRIORITY.AUTOSTART
// command to install the autostart vector.
// Before resetting the board or typing main (which could put FORTH asleep
// and make communications difficult), we'll make an image of page 4
// which holds the object code and autostart vector:
// To make a Motorola S2-record file to send to the Flash Programmer,
// set your terminal to capture incoming text to a disk file using the
// "Save File" menu item, and interactively type from the terminal:
//      HEX 0 4 DIN 0 8000 DUMP.S2
// Close the file when the dump terminates, and use Textpad to remove
// any extraneous file contents such as the DUMP.S2 command and Forth's
// "ok" prompts. Then send the resulting file to a Flash Programmer.
// Power up the QVGA Controller and it will automatically run the application!

```



# *Part 5*

## *Reference Data*



# *Appendix A*

## **Appendix A: QVGA Electrical Specifications**

### **General Specifications**

#### ***CPU***

- Motorola 68HC11F1 microcontroller with 16 MHz clock speed and 4 MHz bus speed. Paged memory expands the processor's address space to 8 Megabytes.

#### **Timers**

- 3 or 4 input capture functions facilitate accurate detection of pulse edges and measurement of pulse widths with a resolution of 2 $\mu$ s.
- 4 or 5 output compare functions make it easy to create complex waveforms and pulse-width modulated signals up to 20KHz at 50% CPU load.
- A pulse accumulator facilitates frequency measurement and pulse counting up to 2MHz.

#### **Interrupts**

- 21 interrupts support the 68HC11's on-chip subsystems.

#### **Runtime Security**

- A watchdog timer and clock monitor ensures orderly reset after an error.

#### **Touchscreen/Display User Interface**

- EL option: Bright amber-on-black, high contrast, all angle view TFEL electro-luminescent display.
- MONO option: High contrast CCFL white-on-blue monochrome LCD display with software controlled backlight and contrast.
- 5.7" diagonal (3.5" x 4.6"), 320 x 240 pixel display.

- High resolution transparent analog touchscreen with software controlled beeper for audible feedback. Custom antiglare, clear, and EMI touchscreens are also available.

## Communications

- A hardware UART supports either RS232 or RS485 at up to 19.2 Kbaud.
- A second software UART implements RS232 at up to 4800 baud.
- A fast synchronous serial peripheral interface (SPI) provides communications at speeds up to 2 megabaud.

## High Current Drivers

- Four open-drain MOSFET drivers can sink up to 150 mA continuously, or up to 1 amp intermittently. Onboard snubber diodes allow control of inductive loads.

## Power

Your QVGA Controller includes a high-efficiency switching regulator with surge suppression, transient filtering, and EMI/RFI filtering to provide clean supplies for the onboard analog and digital electronics. You need only supply regulated or unregulated DC power in the range of 8 to 26 volts if using a monochrome display, or 15 to 26 volts if using an EL display.

### ***Surge Suppression***

The raw input is protected by a “varistor” rated at 33 Volts DC. This metal oxide surge suppresser protects the QVGA Controller by clamping high voltage spikes before they have a chance to do any harm. The varistor has no effect if the input voltage is less than the maximum specified, or 26 volts. Above 33 volts the device starts to conduct current, and it acts like a short circuit to high voltages, thus clamping the voltage spikes. To prevent this varistor from consuming current, you should make sure that the maximum DC voltage supplied is always less than 26 volts.

### ***EMI/RFI Filter***

Additional protection is provided by an electro-magnetic interference (EMI) and radio frequency interference (RFI) filter that prevents high frequency noise from invading the circuitry via the power input, and also prevents EMI from propagating back to the external power supply. The EMI filter is implemented by a two stage PI network of inductors and capacitors. The output of the first stage filter, called V+raw, is passed to the Wildcard module bus for supply to Wildcard modules that require their own unregulated DC power. This unregulated voltage is free of high-frequency and high-voltage transients. If you design custom add-on Wildcard boards, we recommend that you use V+raw as the input for local 5 Volt regulators. It is good design practice to place local voltage regulators on each board, as this minimizes noise problems and improves modularity.

The QVGA Controller board is designed for reliable low noise operation. It is implemented as a state of the art 6-layer surface-mount board. Two inner layers are dedicated ground and power planes, providing low-impedance return paths for digital current spikes.

Parameter	Min	Typ.	Max	Units	Conditions
Input Voltage – Monochrome Display	8		26	Volts	
Input Voltage – EL Display	15		26	Volts	
Power Usage – Monochrome Display		5	6	Watts	No Wildcards
Power Usage – EL Display		12	20	Watts	No Wildcards
Power Usage – per Wildcard		0.5			Each Wildcard

## Operating Conditions

Parameter	Min	Max	Units	Conditions
Operating Temperature Range – Electronics	0	70	°C	Industrial Temp also available (-40 to 85°C)
Operating Temperature Range – Monochrome Display	-20	60	°C	
Storage Temperature Range – Monochrome Display	-20	70		
Temperature Range – EL Display	-25	65	°C	
Humidity	0	95	% Relative Humidity	At 0 to 45°C, no condensation
Humidity	0	85	% Relative Humidity	At 50°C, limited by the monochrome display. At other temperatures the absolute humidity must be less than that provided by 85% RH at 50°C, or 100% at 47°C.

## Memory

Parameter	Standard	With Option	Units
Flash	384	768	KBytes
RAM	257	641	KBytes
EEPROM	512		Bytes
Battery-Backed RAM	128		KBytes
Battery-Backed Real-Time Clock			
Compact Flash Wildcard		64-256	MBytes

## CPU I/O (CPU Ports A, D, E)

Parameter	Min	Max	Units	Conditions
I/O Voltage Range	-0.1	5.3	Volts	
Input Low Voltage		1.0	Volts	$0.2 \times V_{DD}$
Input High Voltage	3.5		Volts	$0.7 \times V_{DD}$
Input Leakage Current		$\pm 1$	$\mu A$	
Output Low Voltage		0.4	Volts	at 1.6 mA
Output High Voltage	3.7		Volts	at $-0.8$ mA and $V_{DD}=4.5$ V
Output Source		25	mA	$<65 \Omega$ output drive impedance, one pin at a time, observing max power dissipation limits.
Output Sink		25	mA	$<65 \Omega$ output drive impedance, one pin at a time, observing max power dissipation limits.

Note: We recommend limiting total package power dissipation accruing from I/O current to 800 mW or less, to assure that the junction temperature remains below 125°C.

## PIA I/O (Ports PPA, PPB, PPC)

Parameter	Min	Max	Units	Conditions
I/O Voltage Range	-0.5	5.5	Volts	
Input Low Voltage		0.8	Volts	Inputs latch high or low. With an input high, the input pin will source up to 350 $\mu A$ . An external device must sink this current to pull the input low. Under worst-case conditions, 2 Kohms or less to ground will always pull an input low. Latched low, the input will sink up to 350 $\mu A$ before it can be pulled high. Under worst case conditions, 5 Kohms or less to a 5V supply will always pull the input high. PPA contains both "pull-up" and "pull-down" bus hold, PPB and PPC pull-up only.
Input High Voltage	2.0		Volts	
Input Leakage Current	-1.0	1.0	$\mu A$	
Bus Hold Current	$\pm 50$	$\pm 350$	$\mu A$	
Output Low Voltage		0.4	Volts	at 2.5 mA
Output High Voltage	3.0 $V_{CC} - 0.4$		Volts	$I_{OH} = -2.5$ mA worst case, $-20$ mA typical $I_{OH} = -100 \mu A$
Output Source	-2.5	-4	mA	$\pm 2.5$ ma. guaranteed to 1.7 V through 500 ohms. $-4$ ma. at $V_{OH}=3.0$ V. The max current must be limited by external circuitry.
Output Sink	2.5	4	mA	4 ma. at $V_{OL}=0.4$ V. The max current must be limited by external circuitry.
Power Dissipation		1	W	

Note: We find that these pins easily provide up to  $\pm 20$  ma. at their  $V_{OH}$  and  $V_{OL}$ . The 4 ma. in the data sheet may be based on a max package power dissipation assuming that all 24 outputs are driven simultaneously.

## 8-Bit Digital to Analog Conversion

Parameter	Min	Typical	Max	Units	Conditions
Number of Output Channels		8			
Update Rate			25,000	Samples per second	
Full-Scale Output Range	0		3	Volts	
Settling Time		3.5		$\mu\text{s}$	
Slew Rate		4		Volts / $\mu\text{s}$	
Integral Nonlinearity		0.5		LSB	
Differential Nonlinearity			1	LSB	
Load Drive Capability			1	k $\Omega$	In parallel with 20pF

## 8-bit Analog To Digital Conversion

Parameter	Min	Typical	Max	Units	Conditions
Number of Input Channels		8			
Sampling Frequency			100,000	Samples per second	
Input Voltage Range	-0.1	0.0 to 5.0	5.1	Volts	
Nonlinearity			1	LSB	
Absolute Accuracy			2	LSB	

## 12-bit Analog To Digital Conversion

Parameter	Min	Typical	Max	Units	Conditions
Number of Input Channels	4		8		4 differential or 8 single ended
Sampling Frequency			30,000	Samples per second	
Input Voltage Range	-5.3	-5.0 to 5.0	5.3	Volts	
Nonlinearity			0.5	LSB	
Input Noise		200		$\mu\text{V}$	
Effective Resolution		11.9		Bits	



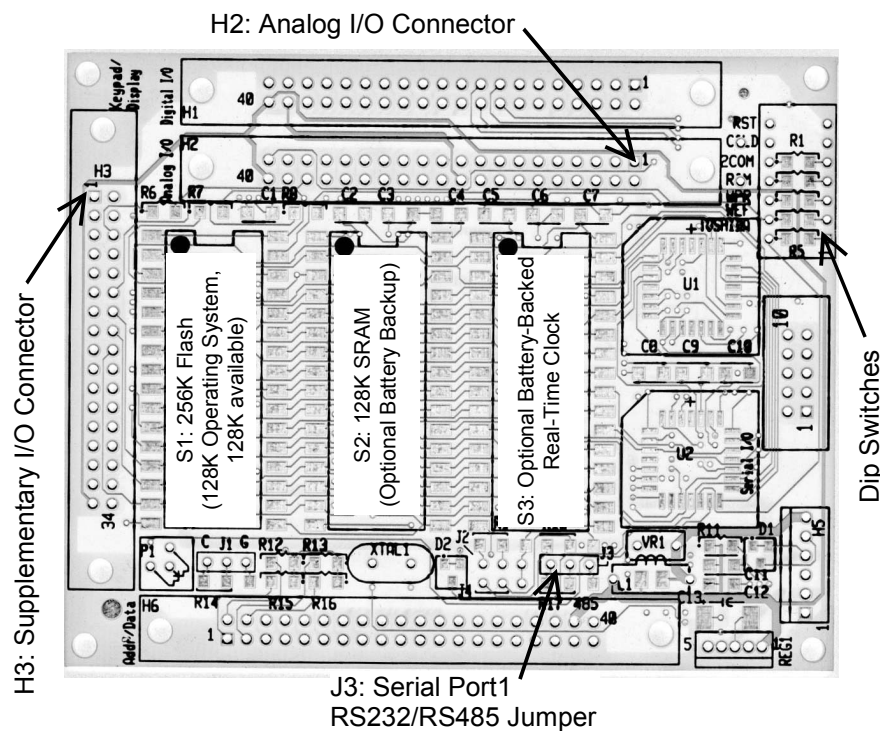
# Appendix B

## Appendix B: Connector Pinouts

*The QVGA Controller comprises a stack of three boards: a display backplane, the QVGA Board, and the smaller QED-4-QVGA Board (aka QED-Flash Board). Pin-outs for all I/O connectors on the QED-Flash Board or the QVGA Board are provided here.*

### QED Flash Board Connectors

The pinouts of all of the connectors on the QED-Flash Board are presented below. To locate the connectors on the board, consult Figure B-1 and the white silk-screened labels on the visible side of the QED-Flash Board. The arrows in the figure point to the locations of pin 1 on each connector.



**Figure B-1 QED-Flash Board Connectors and Switches. Arrows locate pin 1 of each connector.**

**Table B-1 H3: Supplemental I/O Connector**

Signal	Pins	Signal
PPB4	1	2 – GND
PPB3	3	4 – +5V
PPC3	5	6 – Vcontrast
PPC0	7	8 – A1
PPB2	9	10 – R/W
PPC1	11	12 – Display.E
PPC2	13	14 – D0
PPB1	15	16 – D1
PPB0	17	18 – D2
DGND	19	20 – D3
HC0*	21	22 – D4
HC1 (PB5)*	23	24 – D5
HC2 (PB6)*	25	26 – D6
HC3 (PB7)*	27	28 – D7
DGND	29	30 – DGND
SNUB	31	32 – +5VDD
V+RAW	33	34 – VEE

\* HC0 is generated by the PAL, HC1–HC3 are generated from PB5–PB7 respectively.

**Table B-2 H6: Address/Data**

Signal	Pins	Signal
PG7	1	2 – PG6
PG5	3	4 – PG4
PG3	5	6 – PG2
PG1	7	8 – PG0
A15	9	10 – A14
A13	11	12 – A12
A11	13	14 – A10
A9	15	16 – A8
A7	17	18 – A6
A5	19	20 – A4
A3	21	22 – A2
A1	23	24 – A0
D7	25	26 – D6
D5	27	28 – D4
D3	29	30 – D2
D1	31	32 – D0
/RESET	33	34 – R/W
/OE	35	36 – /WE
E	37	38 – V+Raw
DGND	39	40 – +5V

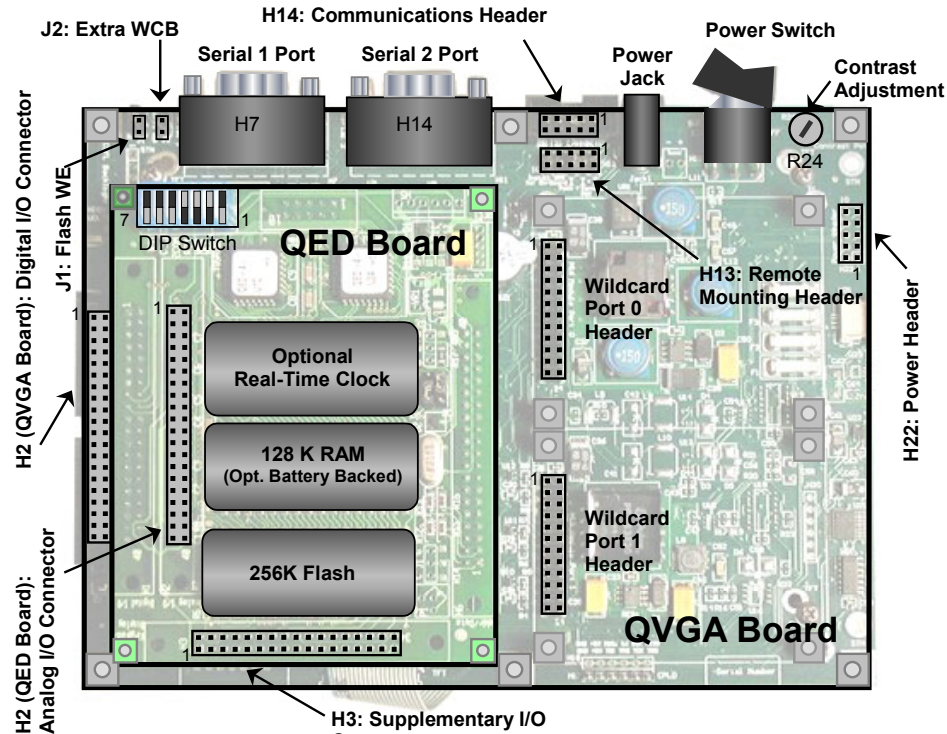
**Table B-3 H2: Analog I/O Connector**

Signal	Pins	Signal
Vrl	1	2 – Vrh
PE7/AN7	3	4 – PE6/AN6
PE5/AN5	5	6 – PE4/AN4
PE3/AN3	7	8 – PE2/AN2
PE1/AN1	9	10 – PE0/AN0
12AN7	11	12 – 12AN6
12AN5	13	14 – 12AN4
12AN3	15	16 – 12AN2
12AN1	17	18 – 12AN0
AGND	19	20 – +5VAN
Vin1	21	22 – Vout1
Vin2	23	24 – Vout2
Vin3	25	26 – Vout3
Vin4	27	28 – Vout4
Vin5	29	30 – Vout5
Vin6	31	32 – Vout6
Vin7	33	34 – Vout7
Vin8	35	36 – Vout8
1.5Vref	37	38 – +5V
Analog Bus V–	39	40 – V+Raw

Processor Port E may be used as either 8-bit A/D inputs (AN0–7) or as digital inputs. 12AN0–7 are 12-bit A/D inputs. Vin1–8 and Vout1–8 are the 8-bit multiplying DAC inputs and outputs.

# QVGA Board Connectors

The pin-outs of all of the connectors on the QVGA Board are presented below. To locate the connectors on the board, consult Figure B-2 and the white silk-screened labels on the visible side of the QVGA Board.



**Figure B-2** Connectors and Switches on the QVGA Controller

**Table B-4** H22: Power Header

Signal	Pins	Signal
GND	1	2 – GND
V+Raw	3	4 – V+Bias
+12 V / +5 V ALT	5	6 – +5 V
+5 VAN	7	8 – +3.3 V
MONO_VEE	9	10 – GND

**Table B-5 Serial 1 Connector**

Signal	Pins	Signal
NC	– 1	
TXD1	– 2	6 – DSR1/DTR1
RXD1	– 3	7 – CTS1
DSR1/DTR1	– 4	8 – RTS1
		9 – NC
DGND	– 5	

Notes:

NC indicates no connection

Pins 4 and 6 (DSR1/DTR1) are connected.

Pins 7 and 8 (CTS1/RTS1) may optionally be connected on the board with zero ohm shorts.

**Table B-6 Serial 2 Connector**

Signal	Pins	Signal
NC	– 1	
TXD2	– 2	6 – DSR2/DTR2
RXD2	– 3	7 – CTS2/RTS2
DSR2/DTR2	– 4	8 – RTS2/CTS2
		9 – NC
DGND	– 5	

Notes:

NC indicates no connection

Pins 4 and 6 (DSR1/DTR1) are connected.

Pins 7 and 8 (CTS1/RTS1) are connected.

**Table B-7 H14: Serial Communications Connector**

Signal	Pins	Signal
TxD1	– 1	2 – RxD1
DGND	– 3	4 – DGND
XCVR-	– 5	6 – XCVR+
TxD2	– 7	8 – RxD2
DGND	– 9	10 – DGND

**Table B-8 Wildcard Port Header**

Signal	Pins	Signal
GND	– 1	2 – +5V
/IRQ	– 3	4 – V+Raw
PG1/XMIT-	– 5	6 – PG0/XMIT+
MOSI/XCV-	– 7	8 – MISO/XCV+
/RESET	– 9	10 – SCK
/MOD.CS	– 11	12 – 16 MHz
E	– 13	14 – R/W
/OE	– 15	16 – /WE
AD7	– 17	18 – AD6
AD5	– 19	20 – AD4
AD3	– 21	22 – AD2
AD1	– 23	24 – AD0

**Table B-9 H2, H4: Digital I/O Connector**

Signal	Pins	Signal
GND – 1	2 – +5V	
PA7 – 3	4 – PA6	
PA5 – 5	6 – PA4	
PA3 – 7	8 – PA2	
PA1 – 9	10 – PA0	
PD5//SS – 11	12 – PD4/SCK	
PD3/MOSI – 13	14 – PD2/MISO	
E – 15	16 – R//W	
/OE – 17	18 – /WE	
/XIRQ – 19	20 – /IRQ	
PFI Input – 21	22 – 4xOut	
/Reset – 23	24 – /Shutdown	
PPC7 – 25	26 – PPC6	
PPC5 – 27	28 – PPC4/RS485.XMIT	
PPA7 – 29	30 – PPA6	
PPA5 – 31	32 – PPA4	
PPA3 – 33	34 – PPA2	
PPA1 – 35	36 – PPA0	
AGND – 37	38 – +5VAN	
DGND – 39	40 – V+Raw	

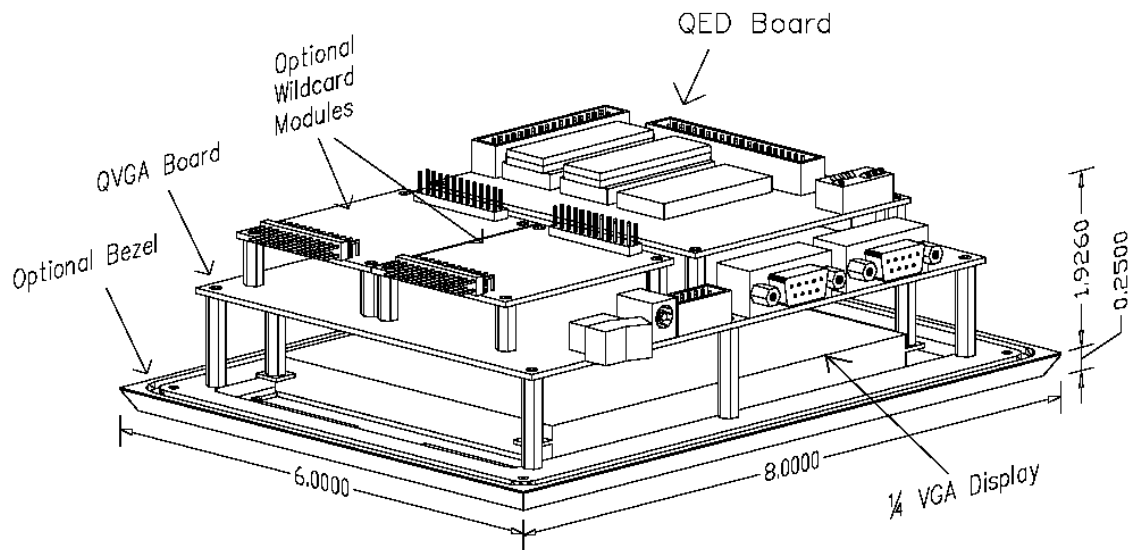
**Notes:**

Headers H2 and H4 are connected in parallel.



## *Appendix C*

### Appendix C: Physical Dimensions



**Figure C-1** The QVGA Controller, display facing down.

