A Tutorial Guide to Programming PIC18, PIC24 and ATmega Microcontrollers with FlashForth.

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Abstract

Modern microcontrollers provide an amazingly diverse selection of hardware peripherals, all within a single chip. One needs to provide a small amount of supporting hardware to power the chip and connect its peripheral devices to the signals of interest and, when powered up, these devices need to be configured and monitored by a suitable firmware program. These notes focus on programming the 28-pin PIC18F26K22 microcontroller and its 40-pin PIC18F46K22 sibling in a simple hardware environment. A number of example programs, in the Forth language, are provided to illustrate the use of some of each microcontroller's peripheral devices. The examples cover the very simple "flash a LED" exercise through to driving a character-based LCD via its 4-bit parallel interface. The set-up and use of FlashForth 5 on the PIC24FV16KM202 and AVR ATmega328P microcontrollers is also covered.

Contents

1   A selection of microcontrollers

Over the past couple of decades, microcontrollers have evolved to be cheap, powerful computing devices that even Mechanical Engineers can use in building bespoke instrumentation for their research laboratories. Typical tasks include monitoring of analog signals, sensing pulses and providing timing signals. Of course these things could be done with a modern personal computer connected via USB to a commercial data acquisition and signal processing system but there are many situations where the small, dedicated microcontroller, requiring just a few milliamps of current, performs the task admirably and at low cost.

Modern microcontrollers provide an amazingly diverse selection of hardware peripherals, all within a single chip. One needs to provide a small amount of supporting hardware to power the chip and connect its peripheral devices to the signals of interest and, when powered up, these devices need to be configured and monitored by a suitable firmware program. These following sections provide an introduction to the details of doing this with an 8-bit Microchip PIC18F26K22 or PIC18F46K22 microcontroller, a 16-bit Microchip PIC24FV16KM202 microcontroller and an 8-bit Atmel ATmega328P microcontroller, all programmed with the FlashForth version 5 interpreter [1].

Within each family of Microchip or Atmel microcontrollers, the individual microcontroller units (MCUs) all have the same core, *i.e.* same instruction set and memory organisation. Your selection of which MCU to actually use in your project can be based on a couple of considerations. If you are on a tight budget and will be making many units, choose an MCU with just enough functionality, however, if convenience of development is more important, choose one with "bells and whistles". For this tutorial guide, we will value convenience and so will work with microcontrollers that have:

- a nice selection of features, including a serial port, several timers and an analog-to-digital converter. See the feature list and the block diagram of the PIC18F26K22 and PIC18F46K22 MCUs on the following pages.

- a 28-pin narrow or 40-pin DIL package, which is convenient for prototyping and has enough I/O pins to play without needing very careful planning.

- an ability to work as 3.3V or 5V systems.

- a pinout as shown at the start of the datasheets (books) [2, 3, 4]. You will be reading the pages of these books over and over but we include the following couple of pages from the PIC18F22K26/PIC18F46K22 datasheet to give an overview.

- an internal arrangement that is built around an 8-bit or 16-bit data bus.

- the "Harvard architecture" with separate paths and storage areas for program instructions and data.

We won't worry too much about the details of the general-purpose registers, the internal static RAM or the machine instruction set because we will let the FlashForth interpreter handle most of the details, however, memory layout, especially the I/O memory layout is important for us as programmers. The peripheral devices, which are used to inferface with the real world, are controlled and accessed via registers in the data-memory space.

PIC18(L)F2X/4XK22

28/40/44-Pin, Low-Power, High-Performance Microcontrollers with XLP Technology

High-Performance RISC CPU:

- C Compiler Optimized Architecture:
  - Optional extended instruction set designed to optimize re-entrant code
- Up to 1024 Bytes Data EEPROM
- Up to 64 Kbytes Linear Program Memory Addressing
- Up to 3896 Bytes Linear Data Memory Addressing
- Up to 16 MIPS Operation
- 16-bit Wide Instructions, 8-bit Wide Data Path
- Priority Levels for Interrupts
- 31-Level, Software Accessible Hardware Stack
- 8 x 8 Single-Cycle Hardware Multiplier

Flexible Oscillator Structure:

- Precision 16 MHz Internal Oscillator Block:
  - Factory calibrated to ± 1%
  - Selectable frequencies, 31 kHz to 16 MHz
  - 64 MHz performance available using PLL – no external components required
- Four Crystal modes up to 64 MHz
- Two External Clock modes up to 64 MHz
- 4X Phase Lock Loop (PLL)
- Secondary Oscillator using Timer1 @ 32 kHz
- Fail-Safe Clock Monitor:
  - Allows for safe shutdown if peripheral clock stops
  - Two-Speed Oscillator Start-up

Analog Features:

- Analog-to-Digital Converter (ADC) module:
  - 10-bit resolution, up to 30 external channels
  - Auto-acquisition capability
  - Conversion available during Sleep
  - Fixed Voltage Reference (FVR) channel
  - Independent input multiplexing
- Analog Comparator module:
  - Two rail-to-rail analog comparators
  - Independent input multiplexing
- Digital-to-Analog Converter (DAC) module:
  - Fixed Voltage Reference (FVR) with 1.024V, 2.048V and 4.096V output levels
  - 5-bit rail-to-rail resistive DAC with positive and negative reference selection
- Charge Time Measurement Unit (CTMU) module:
  - Supports capacitive touch sensing for touch screens and capacitive switches

Extreme Low-Power Management PIC18(L)F2X/4XK22 with XLP:

- Sleep mode: 20 nA, typical
- Watchdog Timer: 300 nA, typical
- Timer1 Oscillator: 800 nA @ 32 kHz
- Peripheral Module Disable

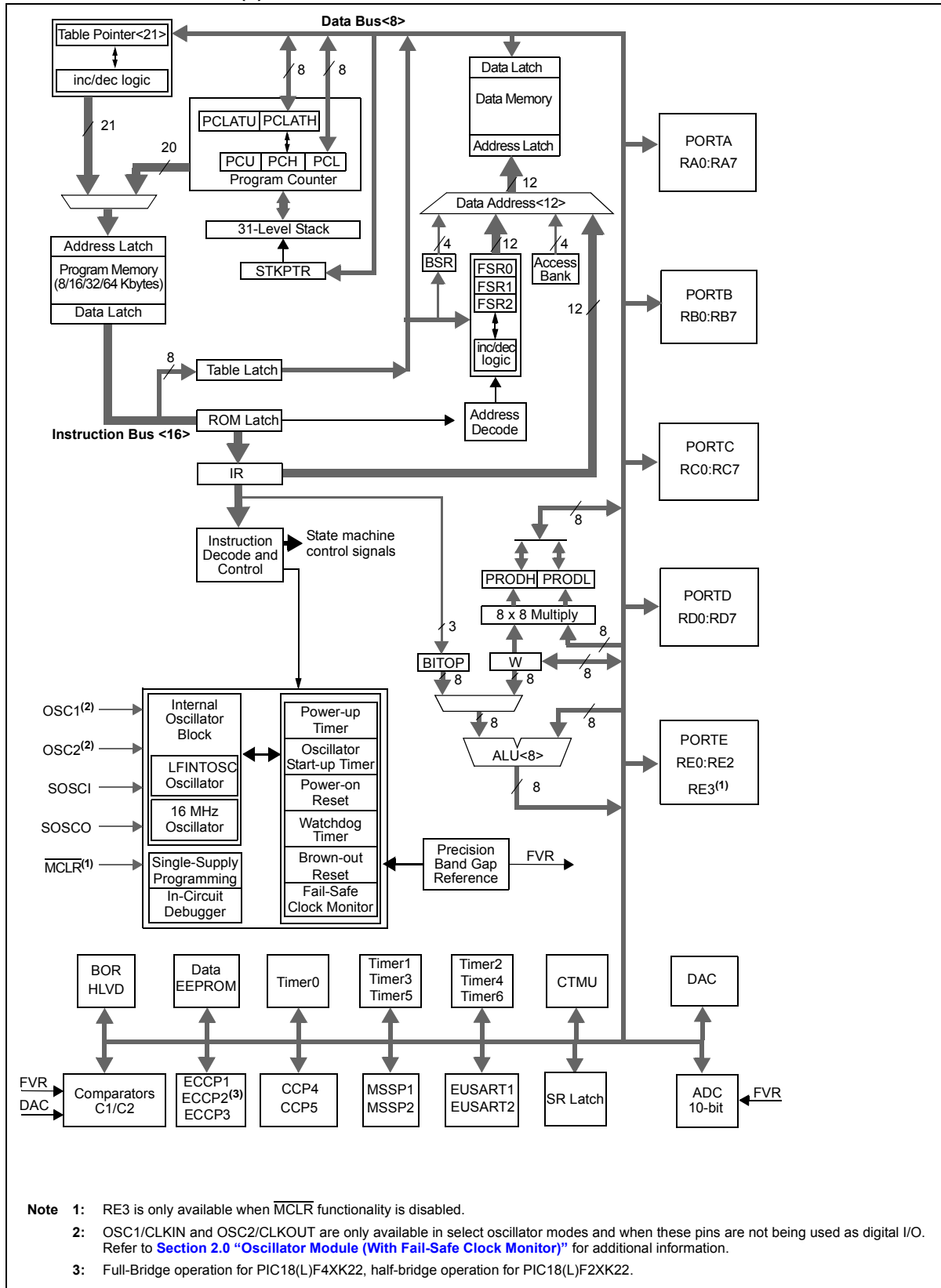### Special Microcontroller Features:

- 2.3V to 5.5V Operation – PIC18FXXK22 devices
- 1.8V to 3.6V Operation – PIC18LFXXK22 devices
- Self-Programmable under Software Control
- High/Low-Voltage Detection (HLVD) module:
  - Programmable 16-Level
  - Interrupt on High/Low-Voltage Detection
- Programmable Brown-out Reset (BOR):
  - With software enable option
  - Configurable shutdown in Sleep
- Extended Watchdog Timer (WDT):
  - Programmable period from 4 ms to 131s
- In-Circuit Serial Programming™ (ICSP™):
  - Single-Supply 3V
- In-Circuit Debug (ICD)

Peripheral Highlights:

- Up to 35 I/O Pins plus 1 Input-Only Pin:
  - High-Current Sink/Source 25 mA/25 mA
  - Three programmable external interrupts
  - Four programmable interrupt-on-change
  - Nine programmable weak pull-ups
  - Programmable slew rate
- SR Latch:
  - Multiple Set/Reset input options
- Two Capture/Compare/PWM (CCP) modules
- Three Enhanced CCP (ECCP) modules:
  - One, two or four PWM outputs
  - Selectable polarity
  - Programmable dead time
  - Auto-Shutdown and Auto-Restart
  - PWM steering
- Two Master Synchronous Serial Port (MSSP) modules:
  - 3-wire SPI (supports all 4 modes)
  - I^{2}C™ Master and Slave modes with address mask

PIC18(L)F2X/4XK22

FIGURE 1-1: **PIC18(L)F2X/4XK22 FAMILY BLOCK DIAGRAM**

Note 1: RE3 is only available when $\overline{MCLR}$ functionality is disabled.

2: OSC1/CLKIN and OSC2/CLKOUT are only available in select oscillator modes and when these pins are not being used as digital I/O.
Refer to **Section 2.0 "Oscillator Module (With Fail-Safe Clock Monitor)"** for additional information.

3: Full-Bridge operation for PIC18(L)F4XK22, half-bridge operation for PIC18(L)F2XK22.

2   Development boards

This tutorial is based around simple support hardware for each of the microcontrollers. If you don't want to do your own soldering, there are easy-to-buy demonstration boards available as a convenient way to get your hardware up and going. If you are a student of mechatroncis, however, you must eventually design and build your own hardware. The strip-board versions are aimed at you.

2.1   PIC18 family boards

Here is a picture of PICDEM 2 PLUS with PIC18F46K22-I/P in the 40-pin socket (U1) and running the LCD, as described in Section 14. We'll make use of the serial RS-232 interface (MAX232ACPA, U3) to both program Forth application and to communicate with running applications. Other conveniences include on-board LEDs, switches, a potentiometer (RA0) and I²C devices, such as a TC74 temperature sensor (U5), just below the MCU and a 24LC256 serial EEPROM (U4). Initial programming of the FlashForth system into the MCU can be done via jack J5 (labelled ICD in the lower left of the photograph) with a Microchip MPLAB-ICD3, PICkit3, or similar device programmer.
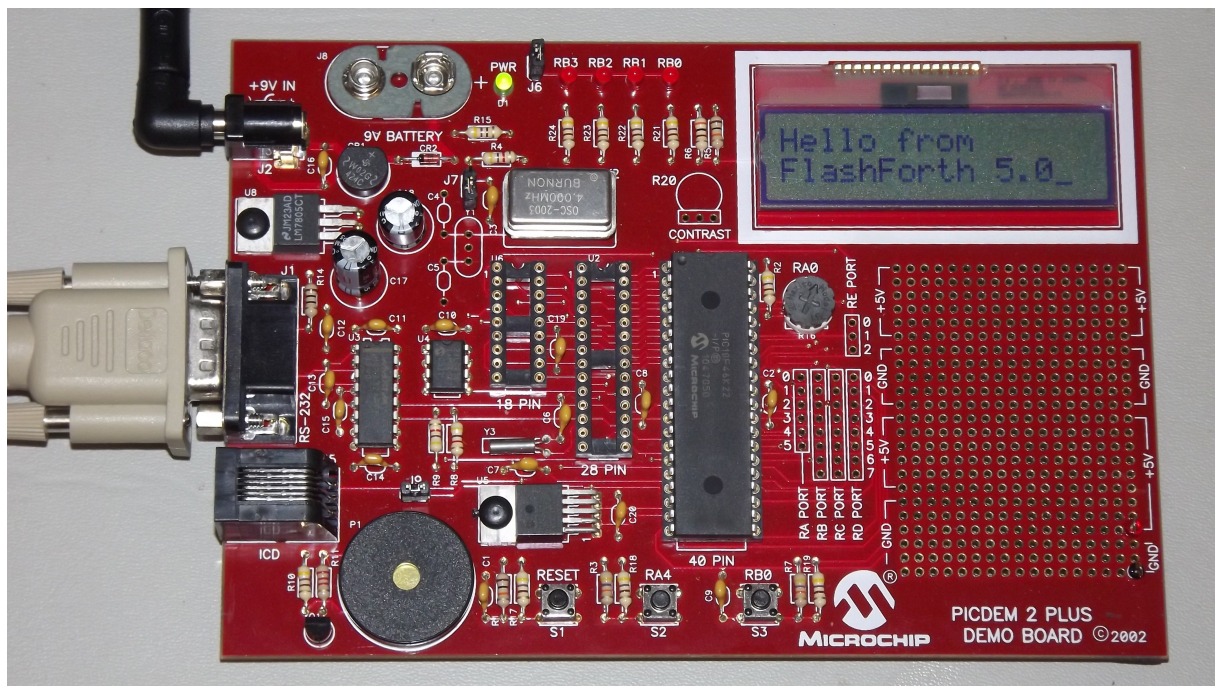

If you want a homebrew system, you can build a minimal system on strip-board that works well. One of the nice things about such a strip-board construction is that you can easily continue construction of your bespoke project on the board and, with careful construction, your prototype can provide years of reliable service.
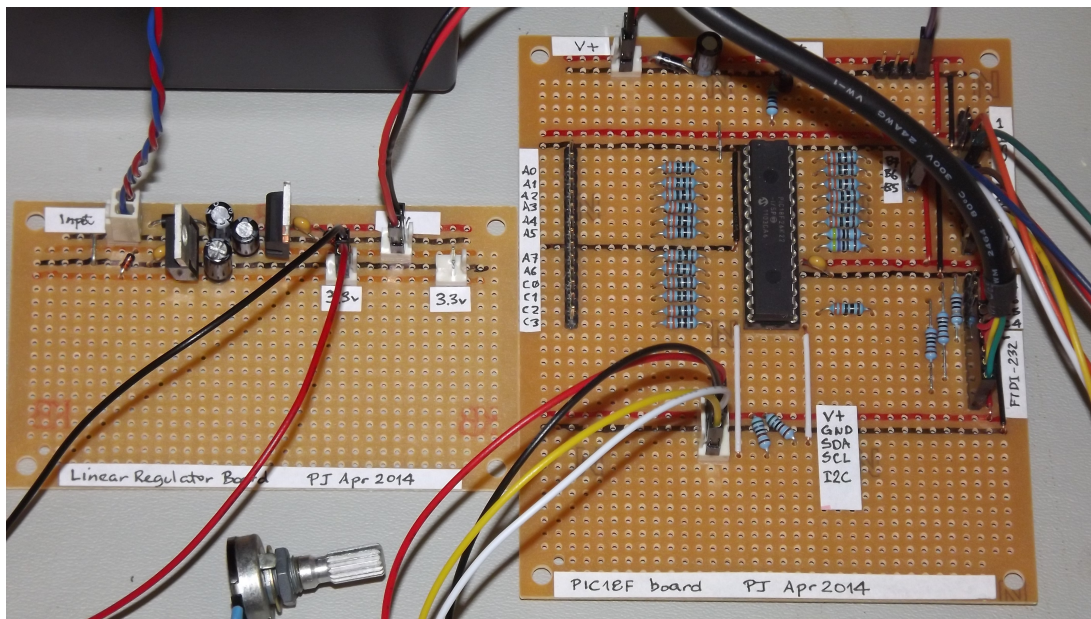
Here is a detailed view of the home-made demo board with PIC18F26K22 in place. This board is suitable for the exercises in this guide. A separate regulator board is to the left and a current-limited supply provides the input power. The board is simple to make by hand, with header pins for the reset switch and connections to the LEDs. The 4-pin header in the foreground provides an I^{2}C connection. The ICSP header is only needed to program FlashForth into the MCU, initially. All communication with the host PC is then via the TTL-level serial header (labelled FTDI-232) at the right. Beyond the minimum required to get the microcontroller to function, we have current-limit resistors and header pins on most of the MCU's I/O pins. This arrangement is convenient for exercises such as interfacing to the 4x3 matrix keypad (Section 9).

The schematic diagram of this home-brew board is shown on the following page. Note that there is no crystal oscillator on the board; the internal oscillator is sufficiently accurate for asynchronous serial port communication. Note, also, the 1k resistors in the TX and RX nets. These limit the current going through the microcontroller pin-protection diodes in the situation where the microcontroller board is unpowered and the FTDI-232 cable is still plugged in to your PC. This will happen at some point and, without the current-limit resistors, the FTDI cable will power the microcontroller, probably poorly.
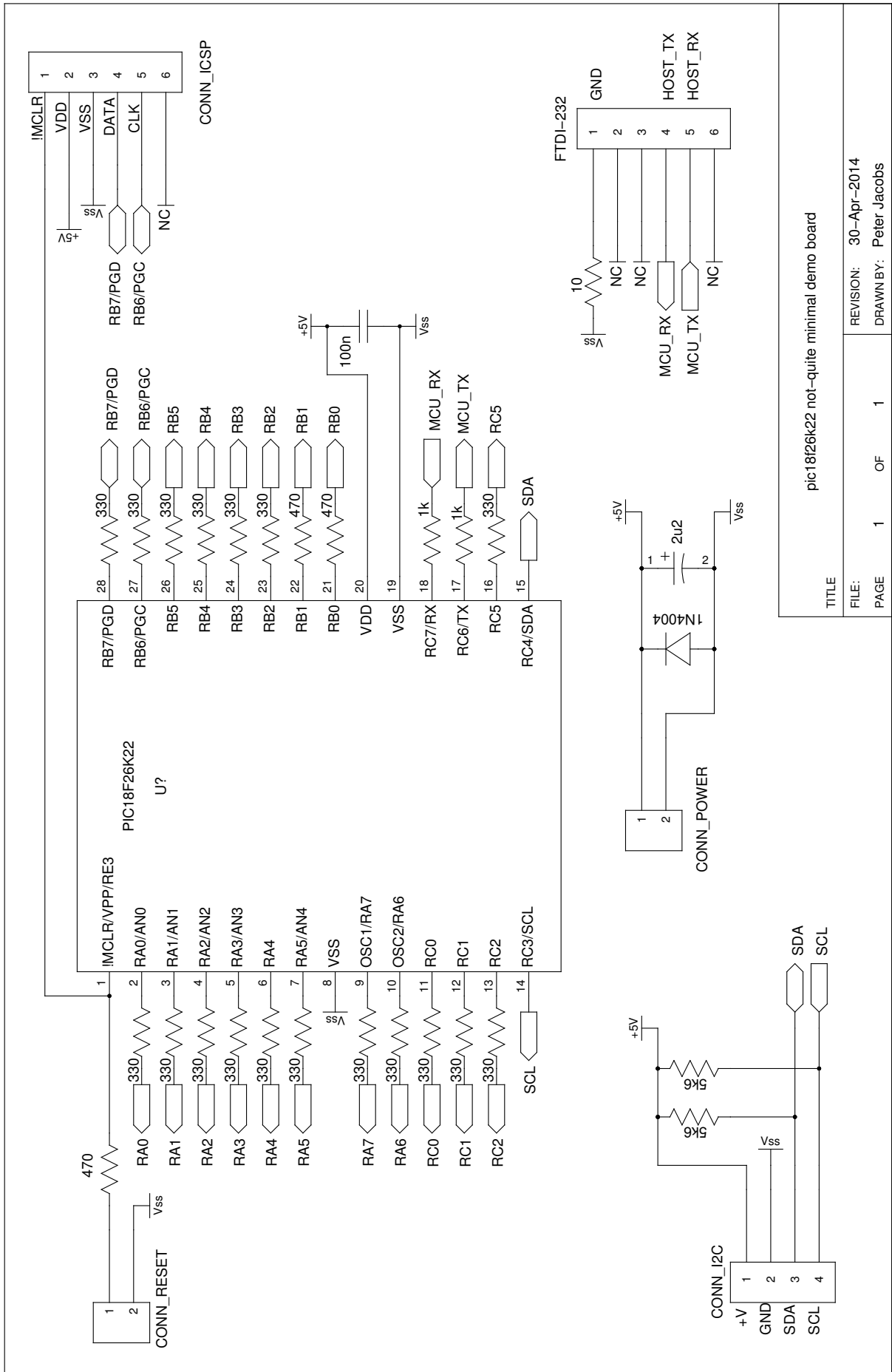
pic18f26k22 not-quite minimal demo board

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2.2   AVR and PIC24 boards

The Eleven from Freetronics, shown in the left half of the following photograph, is an Arduino-compatible board carrying an ATmega328P microcontroller. This is a convenient piece of hardware with many prototype-friendly boards available to plug into the headers around the periphery of the board. Although these boards come with the Arduino bootloader preprogrammed into the ATmega328 microcontroller, the standard AVR 6-pin programming header on the right-hand end of the board (in the photo) can be used to reprogram the microcontroller with the FlashForth interpreter. Power and serial port access is through the USB connector at the left.

If you want an almost-no-solder option for prototyping with the PIC24FV16KM202, Microchip provide the Microstick 5V for PIC24K-series. As shown in the following photograph, this is convenient in that it includes a programmer on-board and can be plugged into a bread-board. The power supply and flash programming access is provided through the USB connector on the left of the board while the serial port connection is via the 6-pin connector on the right-end of the board.
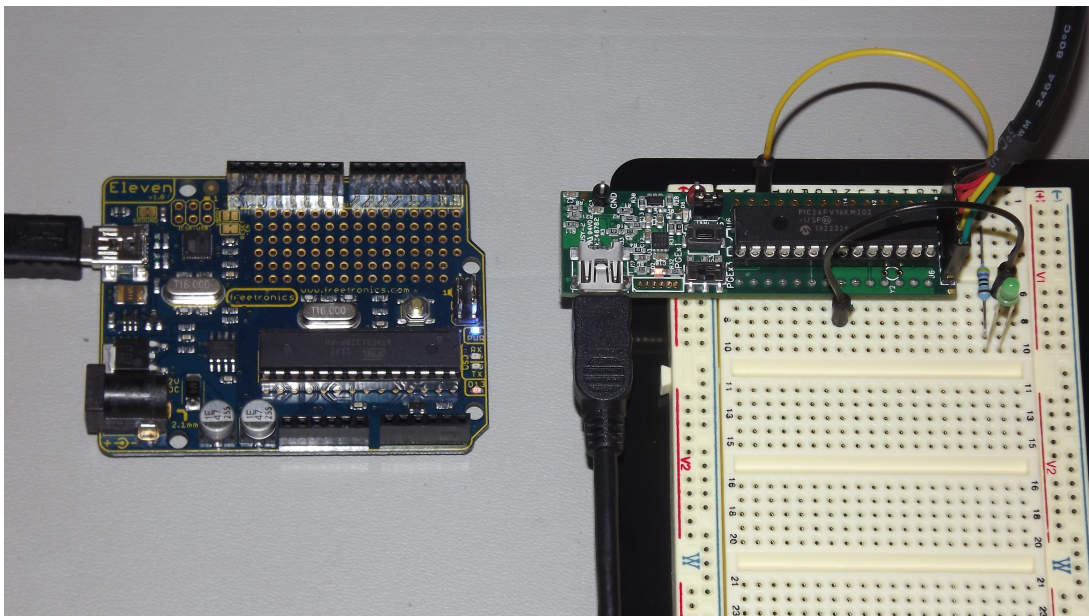
Building a minimal board, by hand, for any of these processors is fairly easy and strip-board versions for each is shown in the following photograph. The left-hand board is for the PIC18F26K22, before all of the extra protection resistors were added. In this state, FlashForth can already be used on this board for nearly all of the exercises in the following sections. Schematic diagrams for the PIC24 and AVR microcontrollers are shown on the following pages.
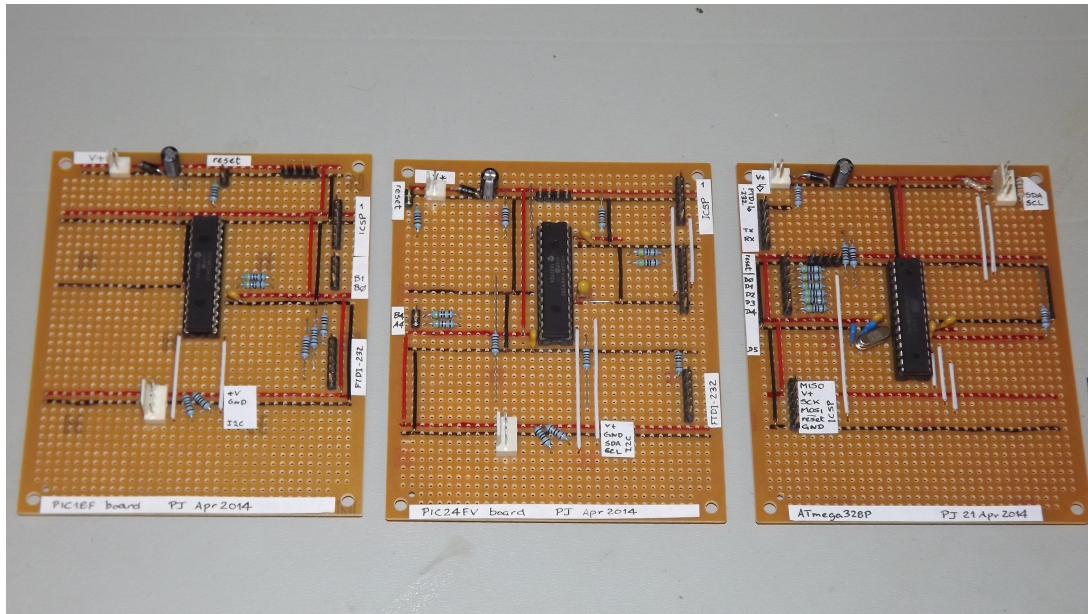
Each of the boards has headers for (1) power, (2) in-circuit serial programming, (3) I2C communication and (4) TTL-level-232 serial communication. The ATmega328 board on the right has a few more protection resistors installed and has an 16 MHz crystal because serial-port communication was found to be unreliable using the internal oscillator.
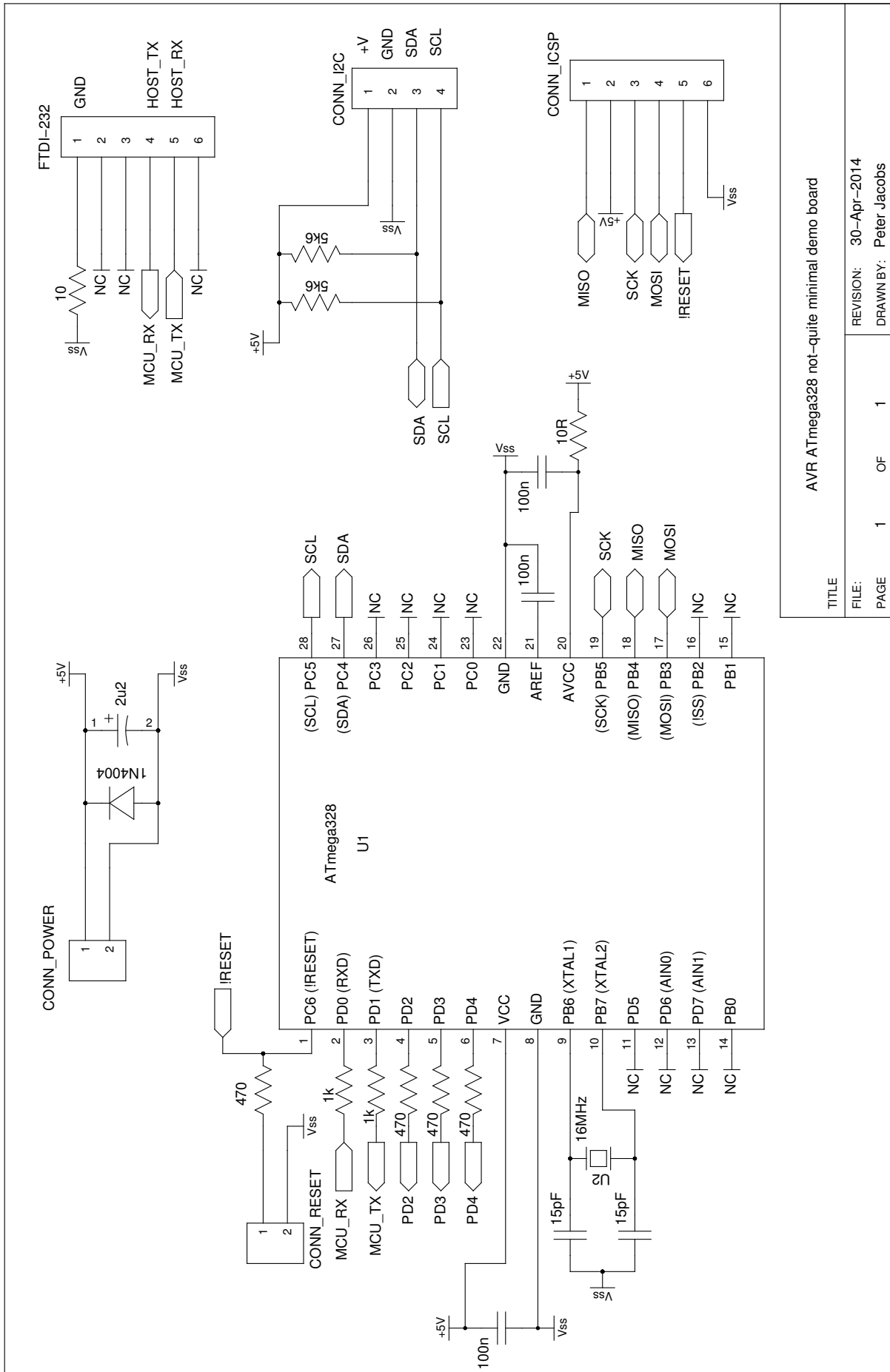
AVR ATmega328 not-quite minimal demo board

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Schematic: PIC24FV16KM202 not-quite minimal demo board
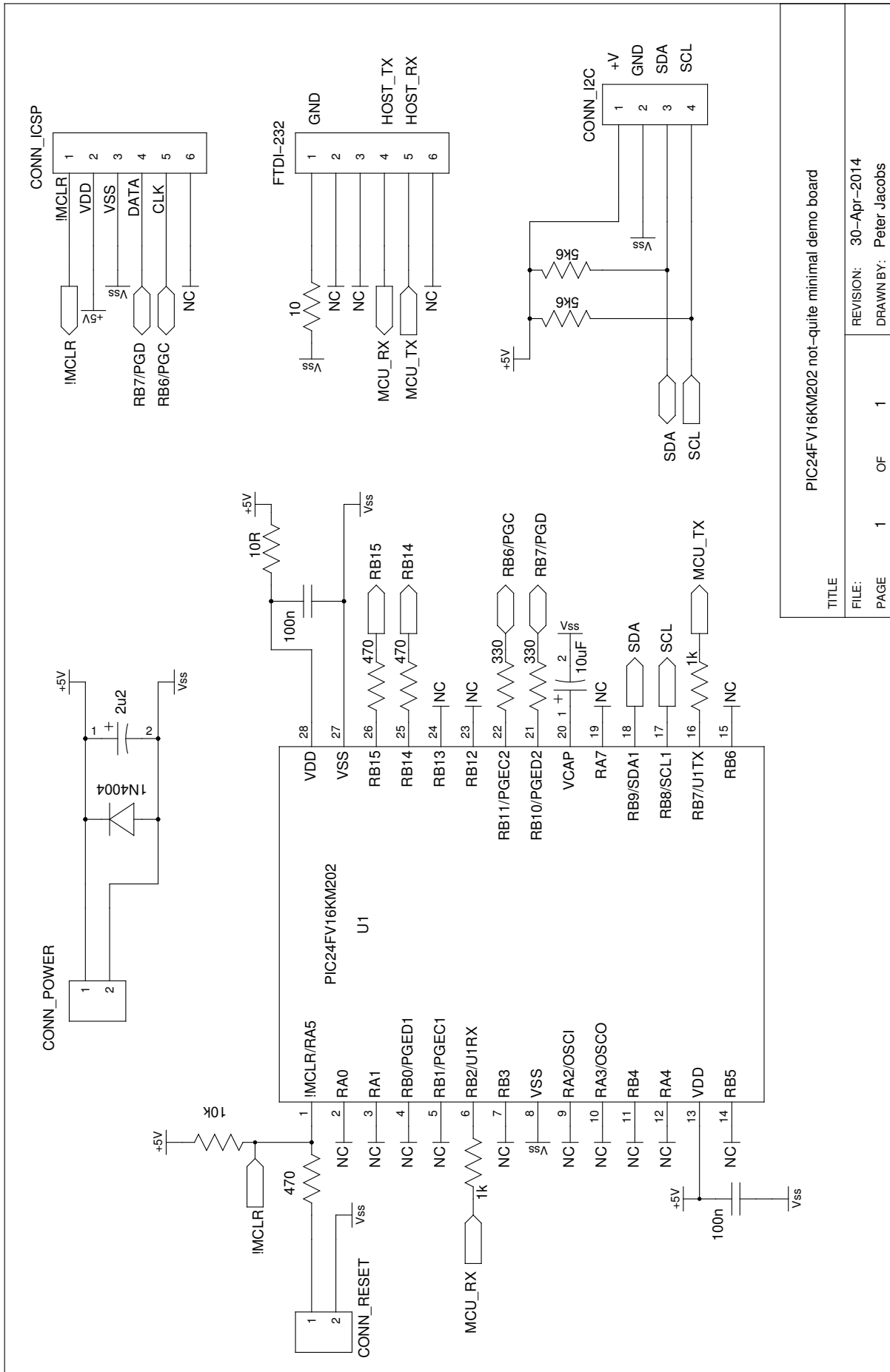
TITLE: PIC24FV16KM202 not-quite minimal demo board

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3 FlashForth

Forth is a word-based language, in which the data stack is made available to the programmer for temporary storage and the passing of parameters to functions. Everything is either a number or a word. Numbers are pushed onto the stack and words invoke functions. The language is simple enough to parse that full interactive Forth systems may be implemented with few (memory) resources. Forth systems may be implemented in a few kilobytes of program memory and a few hundred bytes of data memory such that it is feasible to provide the convenience of a fully interactive program development on very small microcontrollers.

The classic beginners book by Brodie [5] is available online[1], as is Pelc's more recent book [6][2]. A more detailed reference is published by Forth Inc [7]. These books are biased toward Forth running on a personal computer rather than on a microcontroller, however, they are a good place to start your reading. For an introductory document that is specific to FlashForth, see the companion report [8].

FlashForth [1] for the PIC18, PIC24 and ATmega families of microcontrollers is a full interpreter and compiler that runs entirely on the microcontroller. It is a 16-bit Forth with a byte-addressable memory space. Even though there are distinct memory types (RAM, EEPROM and Flash) and separate busses for data and program memory in these Harvard-architecture microcontrollers, FlashForth unifies them into a single 64kB memory.

Above working in assembler, FlashForth does use some resources, both memory and compute cycles, but it provides such a nice, interactive environment that these costs are usually returned in convenience while tinkering with your hardware. Forth programs are very compact so you will have less code to maintain in the long run. The interpreter can also be available to the end user of your instrument, possibly for making parameter adjustments or for making the hardware versatile by having a collection of application functions present simultaneously in the firmware, with the user selecting the required function as they wish.

3.1 Getting FlashForth and programming the MCU

FlashForth is written in assembler, with one program source for each of the microcontroller families and a number of Forth text files to augment the core interpreter. The source code can be downloaded from SourceForge at the URL
`http://sourceforge.net/projects/flashforth/`
There, you will see that you can get a packaged release or you can clone the git repository.

To build from this source, you will need to start up your integrated development environment (be it MPLAB, MPLAB-X or AVR Studio), open the program source and config files in this IDE and edit the config file(s) match your selection of oscillator. There are other options to customize but the choice of oscillator is the main one. The machine code can then be assembled and programmed into your microcontroller with a suitable device programmer (PICkit3, ICD3, STK500, AVRISP MkII, ...). Once programmed with

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[1]`http://home.iae.nl/users/mhx/sf.html` and `http://www.forth.com/starting-forth/`
[2]`http://www.mpeforth.com/`

FlashForth, and mounted in a board that provides power and serial communications as described in the previous section, you will be ready to interact with FlashForth via a serial terminal.

## 3.2 Building for the PIC18F26K22 or PIC18F46K22

For our minimal system with either the PIC18F26K22 or PIC18F46K22 microcontroller, we elect to use the internal (16 MHz) oscillator multiplied by 4 by the PLL. To make the build process a little easier, a set of `MPLAB-X` projects is provided in the `PIC18` directory of the FlashForth source distribution. We select the `FF_UART.X` project to build our Flash-Forth program that will use the microcontroller's UART serial port as the OPERATOR communications channel.

To build the actual machine code that will be programmed into the flash memory of the microcontroller, it is sufficient to assemble the principal source file `ff-pic18.asm` along with the configuration (or header) files `pic18f-main.cfg`, `pic18fxxxx.cfg`, `p18f2x4xk22.cfg`, and use the linker script `FF_0000.lkr`. The source file and config files can be found in the directory `PIC18/src/`, while the linker file is in `PIC18/lkr/`. There may be other configuration files already added to the project but you can ignore them.

We edited the processor-specific config file, `p18f2x4xk22.cfg`, writing "PLLCFG = ON" to have the PLL enabled (giving $F_{OSC} = 64$ MHz), enable the watchdog timer with a 1:32768 postscale (`WDTPS = 32768`), and enable the external reset capability (`MCLRE = EXTMCLR`). Being able to reset the microcontroller by bringing the `MCLR` pin low is something that we find convenient when tinkering with new hardware.

We needed to edit the `pic18f-main.cfg` file only to set the system clock speed as `constant clock=d'64000000'`. There are many other options for customizing the Flash-Forth program in this file, however, the default parameters are fine for the first build of our minimal system. To see your options for all of the configuration bits for your specific microcontroller, it is convenient to open the MPLAB-X view from the main menu: `Window → PIC Memory Views → Configuration Bits`.

With the specific microcontroller selected for the project, the config file `pic18fxxxx.cfg` will automatically select the appropriate MPLAB include file for the microcontroller, be it `p18f26k22.inc` for the 28-pin chip on the home-made board or `p18f46k22.inc` for the 40-pin chip on the PICDEM 2 PLUS board. If the build process complains of not being able to find the MCU-specific include file, you may need to adjust the case-sensitivity of the assembler. This check box can be found in the Project Properties dialog, under "General Options" for the `mpasmx` assembler, as shown in the following screen shot.
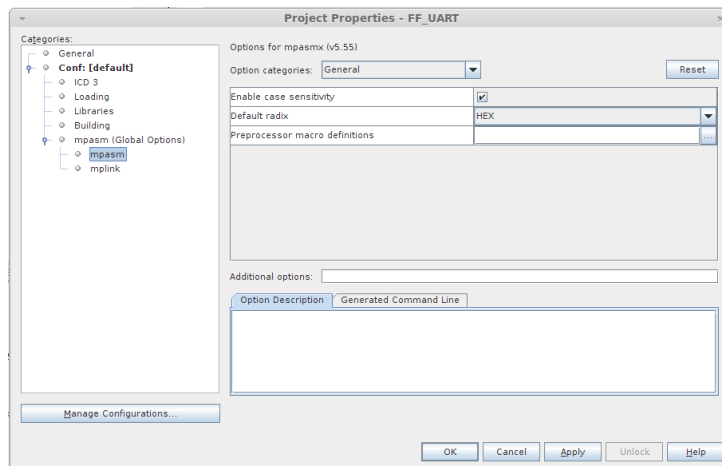
The following image shows the result of building in Microchip's MPLAB X IDE. The lower left frame in the MPLAB-X window shows the MCU resources used. With 423 bytes of SRAM used (another 3473 free) and 8808 bytes of program memory used (56728 free), For the PIC18F26K22 MCU, FlashForth occupies only about one-eighth of the microcontroller's memory. The rest is available for the your application. For more details on the SRAM memory map, see "The Hitchhiker's Guide to FlashForth on PIC18 Microcontrollers". There, Mikael Nordman has provided a memory map that shows how the SRAM memory is allocated within the FlashForth system.
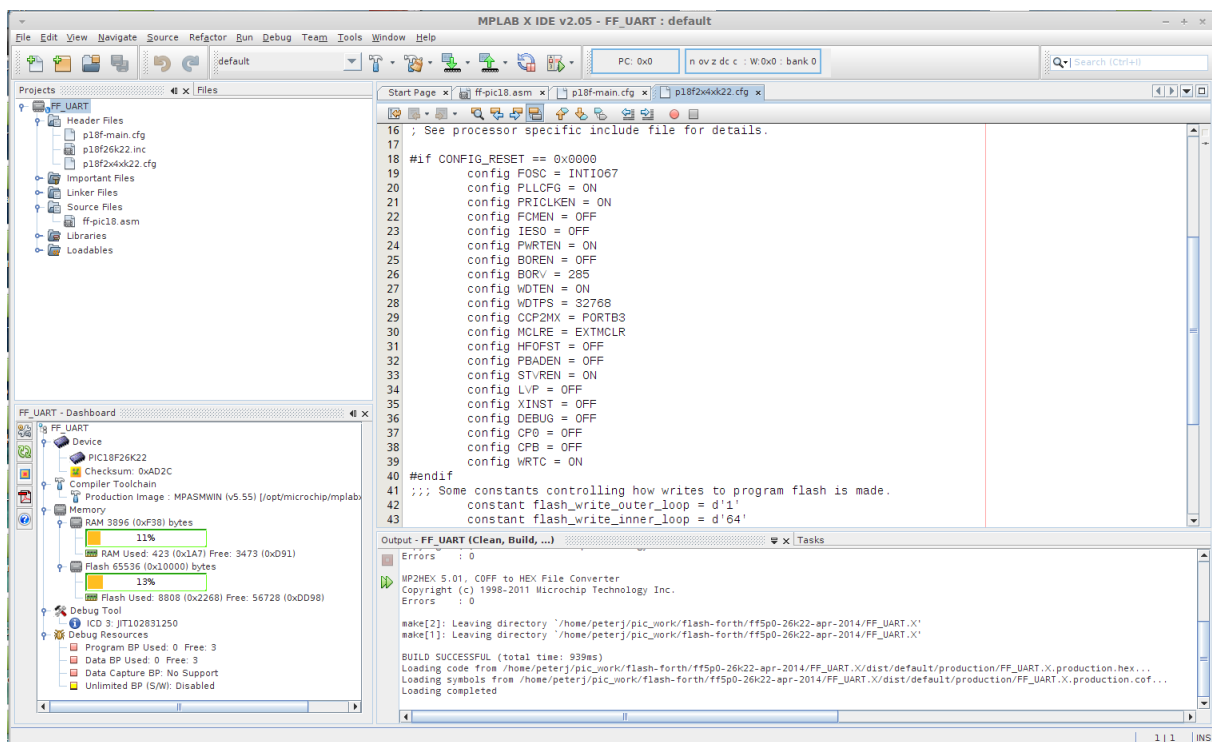
The final step is to program the FlashForth machine code into the flash memory of the microcontroller, using whatever device programmer you happen to have plugged into your development system. The Dashboard view in the screen shot above shows that we have seleted to use of the MPLAB ICD3.

3.3   Building for the PIC24FV16KM202

Building for the 16-bit PIC24 family is similar process. This time look for the source
code files in the `PIC24/` subdirectory. There are fewer config files but you may need
to customize the closest one for your particular processor. Here is the required text in
the `p24f16ka_config.inc` file for our PIC24FV16KM202-I/SP microcontroller using it's
internal 8 MHz oscillator and installed on the 5V Microstick starter board:

```
.ifdef __24FV16KM202
.print "Customize p24f16ka_config.inc for PIC24FV16KM202"
;;; Below is the setting for max amount of ram for PIC24FV16KM202
.equ FLASH_SIZE,     0x2C00  ; Flash size in bytes without the high byte
                             ; See program memory size in the device datasheet.
.equ RAM_SIZE,       0x0800  ; Ram size in bytes
.equ EEPROM_SIZE,    0x0200  ; Eeprom size

config FOSCSEL, FNOSC_FRCDIV & SOSCSRC_DIG & LPRCSEL_LP & IESO_OFF
config FOSC, POSCMOD_NONE & OSCIOFNC_IO & POSCFREQ_MS & SOSCSEL_SOSCLP & FCKSM_CSDCMD
config FWDT, FWDTEN_ON
config FPOR, BOREN_BOR3 & RETCFG_OFF & PWRTEN_ON & I2C1SEL_PRI & BORV_V18 & MCLRE_ON
; ICS_PGx2 for strip-board example
; ICS_PGx1 for 5V Microstick for PIC24 K-series
config FICD, ICS_PGx1

.equ FREQ_OSC, (8000000)  ;Clock (Crystal)frequency (Hz)
.endif
```

Once programmed, FlashForth uses 646 of the microcontroller's 2048 bytes of SRAM and
4431 of the MCU's 5632 words of Flash memory. This leaves 1402 bytes or SRAM and
1201 words of Flash program memory for your Forth application program. Although this
appears to be a lot less than that available in the PIC18F26K22 MCU, this 16-bit MCU
has lots of interesting hardware and 1201 words can hold a lot of Forth instructions.

3.4   Building for the ATmega328P

Assembling the FlashForth program within the AVR Studio IDE is fairly simple but Mike
Nordman has made life even simpler for users of Arduino-like hardware by providing a
prebuilt `.hex` file that can be programmed into the ATmega328P. Here is the command
for doing so with avrdude on a Linux PC.

```
$ sudo avrdude -p m328p -B 8.0 -c jtag3isp -P usb -e \
  -U efuse:w:0xff:m \
  -U hfuse:w:0xda:m \
  -U lfuse:w:0xff:m \
  -U flash:w:ff_uno.hex:i
```

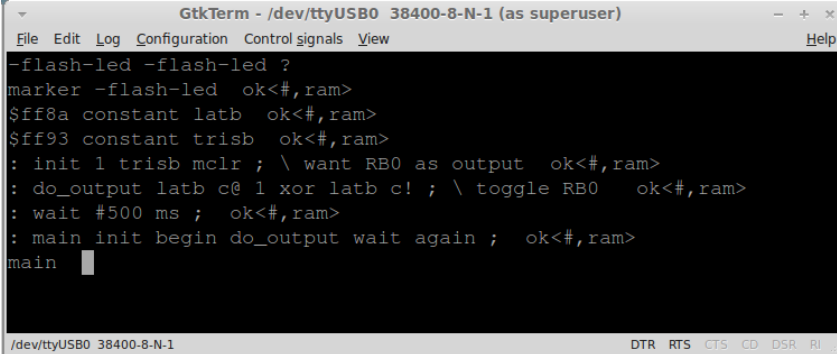The fuses are set to use the 16 MHz crystal on the Arduino-like board.

4   Interacting with FlashForth

Principally, interaction with the programmed MCU is via the serial port. Settings are
38400 baud 8-bit, no parity, 1 stop bit, with software (Xon/Xoff) flow control.

On a linux machine the `cutecom` terminal program is very convenient. It has a line-oriented input that doesn't send the text to the MCU until you press the enter key. This allows for editing of the line before committing it to the MCU and convenient recall of previous lines. `GtkTerm` is available as more conventional terminal program. The following images shows the GtkTerm window just afer sending the content of the `flash-led.txt` file to the PIC18F26K22. The device name of `/dev/ttyUSB0` refers to the USB-to-serial interface that was plugged one of the PC's USB ports. It is convenient to start GtkTerm with the command

```
$ sudo gtkterm
```

and then adjust the communication settings via the `Configuration` → `Port` menu item and its associated dialog window.


There is also a send-file capability and, importantly, the capability to set the period between lines of text that are sent to the serial port so as to not overwhelm the FlashForth MCU. Although USB-to-serial interfaces usually implement software Xon-Xoff handshaking, my experience of using them with a minimal 3-wire connection (GND, RX and TX) has been variable. When sending large files, an end-of-line delay of a few tens of milliseconds has usually been found adequate, however, there have been times that a file would not successfully load until the end-of-line pause was increased to 300 milliseconds. For GtkTerm, this setting is under the `Advanced Configuration Options` in the port configuration dialog, as shown below. This end-of-line delay makes the transfer of large files slow, however, the text still scrolls past quickly but is now at a pace where it is possible to follow the dialog and know how well the compilation is going. Building your application code incrementally, with small files, is a good thing.
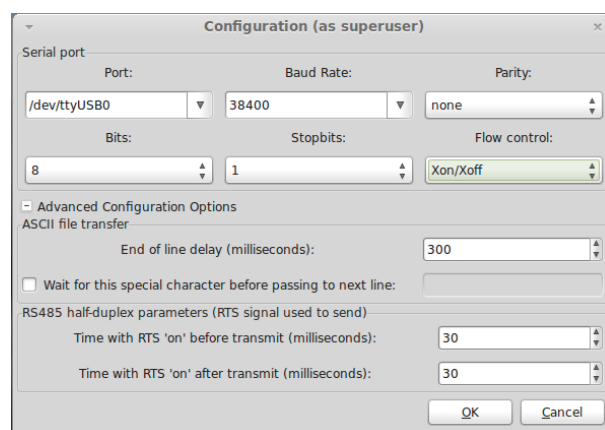
5   Introductory examples

We begin with examples that demonstrate a small number of features of the MCU or of FlashForth. Our interest will primarily be in driving the various peripherals of the MCU rather than doing arithmetic or dealing with abstract data.

5.1   Hello, World: Flash a LED on the PIC18F26K22

The microcontroller version of the "Hello, World" program is typically a program that flashes a single LED. It makes use of a digital input-output pin via the registers that control the IO port. The datasheet [2] has a very readable introduction to the IO ports. Please read it.

```
1 -flash-led
2 marker -flash-led
3 $ff8a constant latb
4 $ff93 constant trisb
5 : init 1 trisb mclr ; \ want RB0 as output
6 : do_output latb c@ 1 xor latb c! ; \ toggle RB0
7 : wait #500 ms ;
8 : main init begin do_output wait again ;
9 main
```

Notes on this program:

- If the word `-flash-led` has been previously defined with the word marker, line 1 resets the dictionary state and continues interpreting the file, else the interpreter signals that it can't find the word and continues interpreting the file anyway.

- Line 2 records the state of the dictionary and defines the word `-flash-led` so that we can reset the dictionary to it's state before the code was compiled, simply by executing the word `-flash-led`.

- Lines 3 and 4 define convenient names for the addresses of the file registers that control IO-port B. Note the literal hexadecimal notation with the `$` character. In the PIC18F family, the special function registers for interacting with the MCU hardware appear near the top of the 64k FlashForth memory space.

- Line 5 is a colon definition for the word `init` that sets up the peripheral hardware. Here, we set pin RB0 as output. The actual command that does the setting is `mclr`, which takes a bit-mask (00000001) and a register address (`$ff93`) and then clears the register's bits that have been set in the mask. Note the comment starting with the backslash character. Although the comment text is sent to the MCU, it is ignored. Note, also, the spaces delimiting words. That spaces after the colon and around the semicolon are important.

- Line 6 is the definition that does the work of fiddling the LED pin. We fetch the byte from the port B latch, toggle bit 0 and store the resulting byte back into the port B latch.

- Line 7 defines a word to pause for 500 milliseconds.

- Line 8 defines the "top-level" coordination word, which we have named `main`, following the C-programming convention. After initializing the relevant hardware, it unconditionally loops, doing the output operation and waiting, each pass.

- Line 9 invokes the `main` word and runs the application. Pressing the `Reset` button will kill the application and put the MCU back into a state of listening to the serial port. Typing `main`, followed by `Enter` will restart the application.

Instead of going to the bother of tinkering with the MCU IO Port, we could have taken a short-cut and used the string writing capability of Forth to write a short version that was closer the the operation of typical Hello World programs.

```
1 : greet-me ." Hello World" ;
2 greet-me
```

Before going on to more examples, it is good to know about the word `empty`. This word will reset the dictionary and all of the allotted-memory pointers. Because FlashForth does not allow you to redefine words that are already in the dictionary, later examples that use the same names for their word definitions, may not compile without complaint if you don't clean up after each exercise.

5.2 Flash a LED on the PIC24FV16KM202

```
1 -flash-led
2 marker -flash-led
3 $02c8 constant trisb
4 $02cc constant latb
5 1 #15 lshift constant bit15
6 : init bit15 trisb mclr ; \ set pin as output
7 : do_output latb @ bit15 xor latb ! ; \ toggle the bit
8 : main init begin do_output #500 ms again ;
9 main
```

Notes on this program:

- This program for the 16-bit microcontroller is essentially the same as that for the 8-bit MCU, with different addresses for the port-control registers, of course. In the PIC24/dsPIC30/dsPIC33 version of FlashForth, the special function registers appear in the lowest 2k bytes of memory.

- On line 5, we compute the bit pattern for selecting the MCU pin rather than writing it explicitly. We start with a 1 in the least-significant bit of the 16-bit word and then shift it left 15 places, to produce the binary value `%1000000000000000`

- On line 7, we use 16-bit fetch `@` and store `!` operations because the hardware special function registers on this microcontroller are 16 bits wide.

5.3   Flash a LED on the ATmega328P

```
1 -flash-led-avr
2 marker -flash-led-avr
3 \ PB5 is Arduino digital pin 13.
4 \ There is a LED attached to this pin on the Freetronics Eleven.
5
6 $0024 constant ddrb
7 $0025 constant portb
8 1 #5 lshift constant bit5
9
10 : init bit5 ddrb mset ; \ set pin as output
11 : do_output portb c@ bit5 xor portb c! ; \ toggle the bit
12 : main init begin do_output #500 ms again ;
13
14 main
```

Notes on this program:

- Again, except for the specific registers and bits, this program is the same as for the other MCUs. As for other high-level languages, we no longer have to think about the specific machine architecture (usually).

- Because we are using load and store instructions, the special function registers start at address $20.

5.4   Set the cycle duration with a variable

We enhance the initial demonstration by making the waiting period setable. Because of the interactive FlashForth environment, the extra programming effort required is tiny. The appearance of the code, however, looks a bit different because we have laid out the colon definitions in a different style and have included more comments.

```
1 -flash-led-var
2 marker -flash-led-var
3 \ Flash a LED attached to pin RB0.
4
5 $ff8a constant latb
6 $ff93 constant trisb
7 variable ms_count \ use this for setting wait period.
8
9 : init ( -- )
10   1 trisb mclr  \ want RB0 as output
11 ;
12
13 : do_output ( -- )
14   latb c@ 1 xor latb c!  \ toggle RB0
15 ;
16
17 : wait ( -- )
18   ms_count @ ms
19 ;
20
21 : main ( n -- )
22   ms_count !  \ store for later use in wait
23   init
```

```
24    begin
25      do_output
26      wait
27    again
28  ;
29
30  #500 main   \ exercise the application
```

Notes on this program:

- If the file has been sent earlier defining the application's words, line 1 resets the state of the dictionary to forget those previous definitions. This makes it fairly convenient to have the source code open in an editing window (say, using emacs) and to simply reprogram the MCU by resending the file (with the `Send file...` button in `cutecom`).

- Line 7 defines a 16-bit variable `ms_count`.

- Line 30 leaves the wait period on the stack before invoking the `main` word.

- On each pass through the `wait` word, the 16-bit value is fetched from `ms_count` and is used to determine the duration of the pause.

5.5   Hello, World: Morse code

Staying with the minimal hardware of just a single LED, we can make a proper "Hello World" application. The following program makes use of Forth's colon definitions so that we can spell the message directly in source code and have the MCU communicate that message in Morse code.

```
1  -hello-world
2  marker -hello-world
3  \ Flash a LED attached to pin RB0, sending a message in Morse-code.
4
5  $ff8a constant latb
6  $ff93 constant trisb
7  variable ms_count \ determines the timing.
8
9  : init ( -- )
10   1 trisb mclr  \ want RB0 as output
11   1 latb mclr   \ initial state is off
12  ;
13
14  : led_on 1 latb mset ;
15  : led_off 1 latb mclr ;
16  : gap ms_count @ ms ; \ pause period
17  : gap2 gap gap ;
18  : dit led_on gap led_off gap2 ;
19  : dah led_on gap2 led_off gap2 ;
20
21  \ Have looked up the ARRL CW list for the following letters.
22  : H dit dit dit dit ;
23  : e dit ;
24  : l dit dit ;
25  : o dah dah dah ;
```

```
26 : W dit dah dah ;
27 : r dit dah dit ;
28 : d dah dit dit ;
29
30 : greet ( -- )
31   H  e  l  l  o   gap   W  o  r  l  d   gap2
32 ;
33
34 : main ( n -- )
35   ms_count !  \ store for later use in gap
36   init
37   begin
38     greet
39   again
40 ;
41
42 #100 main  \ exercise the application
```

6   Read and report an analog voltage

Use of the analog-to-digital converter (ADC) is a matter of, first, reading Section 17 of
the PIC18F26K22 datasheet, setting the relevant configuration/control registers and then
giving it a poke when we want a measurement. Again, the interactive nature of FlashForth
makes the reporting of the measured data almost trivial.

```
 1 -read-adc
 2 marker -read-adc
 3 \ Read and report the analog value on RA0/AN0.
 4
 5 \ Registers of interest on the PIC18F26K22
 6 $ffc4 constant adresh
 7 $ffc3 constant adresl
 8 $ffc2 constant adcon0
 9 $ffc1 constant adcon1
10 $ffc0 constant adcon2
11 $ff92 constant trisa
12 $ff38 constant ansela
13
14 : init ( -- )
15   1 trisa mset \ want RA0 as input
16   1 ansela mset
17   %00000000 adcon1 c! \ ADC references Vdd, Vss
18   %10101111 adcon2 c! \ right-justified, 12-TAD acq-time, FRC
19   %00000001 adcon0 c! \ Power on ADC, looking at AN0
20 ;
21
22 : adc@ ( -- u )
23   %10 adcon0 mset \ Start conversion
24   begin %10 adcon0 mtst 0= until \ Wait until DONE
25   adresl @
26 ;
27
28 : wait ( -- )
29   #500 ms
30 ;
31
32 : main ( -- )
33   init
34   begin
35     adc@ u.
```

```
36      wait
37    key? until
38 ;
39
40 \ Exercise the application , writing digitized values periodically
41 \ until any key is pressed.
42 decimal
43 main
```

Notes on this program:

- Although not much needs to be done to set up the ADC, you really should read the ADC section of the datasheet to get the full details of this configuration.

- Lines 17 to 19 uses binary literals (with the % character) to show the configuration bits explicitly.

- Line 24 conditionally repeats testing of the DONE bit for the ADC.

- Line 25 fetches the full 10-bit result and leaves it on the stack for use after the `adc@` word has finished. Because of the selected configuration of the ADC peripheral, the value will be right-justified in the 16-bit cell.

- Line 35 invokes the `adc@` word and prints the numeric result.

- Line 37 checks if a character has come in from the serial terminal. If so, the loop is terminated and the main function returns control to the FlashForth interpreter.

7   Counting button presses

Example of sensing a button press, with debounce in software.

```
1 \ Use a push - button on RB0 to get user input.
2 \ This button is labelled S3 on the PICDEM2+ board.
3 -pb-demo
4 marker -pb-demo
5
6 $ff81 constant portb
7 $ff8a constant latb
8 $ff93 constant trisb
9
10 variable count
11
12 : init ( -- )
13    %01 trisb mset \ RB0 as input
14    %10 trisb mclr \ RB1 as output
15    %10 latb mclr
16 ;
17 : RB1toggle ( -- )
18    latb c@ %10 xor latb c!
19 ;
20 : RB0@ ( -- c )
21    portb c@ %01 and
22 ;
23 : button? ( -- f )
```

```
24    \ Check for button press , with software debounce .
25    \ With the pull - up in place , a button press will give 0.
26    RB0@ if
27      0
28    else
29      #10 ms
30      RB0@ if 0 else -1 then
31    then
32 ;
33
34 : main ( -- )
35    0 count !
36    init
37    begin
38      button? if
39        RB1toggle
40        count @ 1+ count !
41        count @ .
42        #200 ms \ allow time to release button
43      then
44      cwd
45    key? until
46 ;
47
48 main  \ exercise the application
```

Notes on this program:

- The `main` word clears the `count` variable, calls `init` to set up the hardware and then loops, polling `RB0` and incrementing value of the `count` variable only when the button gets pressed.

- If the pause after acknowledging the button press (line 42) is too long, we may lose later button press events. This depends on how frantically we press S3.

- Line 44 resets the watch-dog timer on each pass of the main loop. If we don't press the RB0 button for a long time, the main loop would not otherwise pause and clear the watch-dog timer. The watch-dog timer is cleared inside the `ms` word, however, if the timer expires before being cleared, the microcontroller would be reset and the FlashForth interpreter would restart.

8   Counting button presses via interrupts

Instead of polling the `RB0` pin attached to the push button, as in the previous example, let's set up the hardware interrupt mechanism to invoke the increment action for us.

```
1 \ Use a push - button on RB0 to get user input , via an interrupt .
2 \ This button is labelled S3 on the PICDEM2+ board .
3 \ Don't have J6 connected because the LED on RB0 loads the pull - up .
4
5 -pb-interrupt
6 marker -pb-interrupt
7
8 $ff93 constant trisb
9 $fff2 constant intcon
```

```
10 $fff1 constant intcon2
11
12 variable count
13 variable last-count
14
15 : int0-irq
16   [i
17     %10 intcon mtst \ INT0IF
18     if
19       count @ 1+ count !
20       %10 intcon mclr
21     then
22   i]
23 ;i
24
25 : init ( -- )
26   %01 trisb mset \ RB0 as input, a button press will give 0.
27   %01000000 intcon2 mclr \ interrupt on falling edge
28   ['] int0-irq 0 int! \ install service word
29   %10 intcon mclr \ INT0IF cleared
30   %10000 intcon mset \ INT0 interrupt enable
31 ;
32
33 : main ( -- )
34   0 count !
35   init
36   begin
37     count @ last-count @ - \ change?
38     if
39       count @ dup last-count ! .
40     then
41     cwd
42   key? until
43 ;
44
45 main  \ exercise the application
```

Notes on this program:

- Again, we use the variable named `count` as the variable to be incremented on pressing the button that pulls RB0 low. The actual increment is done on line 19, inside the interrupt service word `int0-irq`. The second variable, `last-count`, is used on line 36 in the `main` word, to detect when the `count` variable changes.

- The `init` word sets up the bits to enable the INT0 external interrupt to fire on a falling edge at RB0.

- On line 28 in the `init` word, the execution token for our interrupt service word is stored as the high-priority interrupt vector. Because FlashForth supports only high-priority interrupts, the `0` is a dummy value but is still expected by the `int!` word.

- Inside the interrupt-service word, we need to test the INT0IF interrupt flag to see if it is our interrupt to handle and, if it is, do the appropriate work (of incrementing the `count` variable) and clearing the interrupt flag. If you enable several interrupt sources, you need to provide a test and action for each.

- The `main` word clears the `count` variable, calls `init` to set up the interrupt mechanism and then loops, emitting the value of the `count` variable only when it changes.

9 Scanning a 4x3 matrix keypad

We connect a 4x3 matrix keypad to PORTB, using RB0, RB1 and RB2 to drive the columns while sensing the rows with RB4 through RB7. The schematic figure below shows the arrangement of keys and pins.
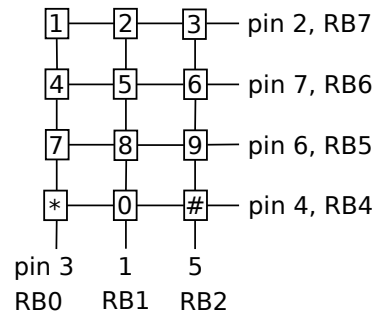
To minimize hardware, we have used the weak pull-ups on PORTB. Pressing a key while it's column wire is held high does nothing, however, pressing a key on a column that is held low will result in its row being pulled low.

```
1 -keypad
2 marker -keypad
3 \ Display key presses from a 4x3 (telephone-like) keypad
4 \ on PIC18F26K22-I/SP
5
6 $ff81 constant portb
7 $ff8a constant latb
8 $ff93 constant trisb
9 $ff39 constant anselb
10 $ff61 constant wpub
11 $fff1 constant intcon2
12
13 : init ( -- )
14   0 latb c!
15   %00000000 anselb c!    \ set as all digital I/O pins
16   %11110000 trisb c!     \ RB7-4 as input, RB3-0 as output
17   %11110000 wpub c!      \ pull-ups on RB7-4
18   %10000000 intcon2 mclr \ turn on pull-ups
19 ;
20
21 flash
22 create key_chars
23   char 1 c, char 2 c, char 3 c,
24   char 4 c, char 5 c, char 6 c,
25   char 7 c, char 8 c, char 9 c,
26   char * c, char 0 c, char # c,
27 create key_scan_bytes
28   $7e c, $7d c, $7b c,
29   $be c, $bd c, $bb c,
30   $de c, $dd c, $db c,
31   $ee c, $ed c, $eb c,
32 ram
33
34 : scan_keys ( -- c )
35   \ Return ASCII code of key that is pressed
36   #12 for
37     key_scan_bytes r@ + c@
38     dup
39     latb c!
40     portb c@
41     = if
42       \ key must be pressed to get a match
43       key_chars r@ + c@
44       rdrop
```

```
45        exit
46      then
47   next
48   0  \ no key was pressed
49 ;
50
51 : keypad@ ( -- c )
52   \ Read keypad with simple debounce.
53   \ ASCII code is left on stack.
54   \ Zero is returned for no key pressed or inconsistent scans.
55   scan_keys dup
56   #20 ms
57   scan_keys
58   = if exit else drop then
59   0 \ inconsistent scan results
60 ;
61
62 : main ( -- )
63   init
64   begin
65     keypad@
66     dup
67     0= if
68       drop  \ no key pressed
69     else
70       emit
71       #300 ms \ don't repeat key too quickly
72     then
73   key? until
74 ;
```

Notes on this program:

- In lines 21–31, we make use of character arrays to store (into the program memory) the the ASCII code and the scan code for each key. The scan code is made up of the 3-bit column pattern to be applied to RB2-RB0 and the resulting 4-bit row-sense pattern (RB7-RB4) expected for the particular key if it is pressed. RB3 is maintained high (and is of no consequence) for this 3-column keypad, however, it would be used for a 4x4 keypad.

- Lines 36 and 47 make use of the for–next control construct to work through the set of 12 scan codes

- We should go further by making use a state-machine and also keeping track of the last key pressed.

10   Using I²C to get temperature measurements

Using the MSSP peripheral in master mode, one may talk to the TC74A5 temperature measurement chip on the PICDEM 2 PLUS and report sensor temperature.

```
1 \ Read temperature from TC74 on PICDEM2+ board with PIC18F46K22-I/P.
2 \ Modelled on Mikael Nordman's i2c_tcn75.txt.
3 \ This program requires i2c_base.txt to be previously loaded.
4 -read-tc74
```

```
 5 marker -read-tc74
 6
 7 $ff3a constant anselc
 8 %1001101 constant addr-tc74  \ default 7-bit address for TC74
 9
10 : add-read-bit ( 7-bit-c -- 8-bit-c )
11   \ Make 8-bit i2c address with bit 0 set.
12   1 lshift 1 or
13 ;
14 : add-write-bit ( 7-bit-c -- 8-bit-c )
15   \ Make 8-bit i2c address with bit 0 clear.
16   1 lshift 1 invert and
17 ;
18 : sign-extend ( c -- n )
19   \ If the TC74 has returned a negative 8-bit value,
20   \ we need to sign extend to 16-bits with ones.
21   dup $7f > if $ff80 or then
22 ;
23 : init-tc74 ( -- )
24   \ Selects the temperature register for subsequent reads.
25   addr-tc74 add-write-bit i2cws 0 i2c! spen
26 ;
27 : degrees@ ( -- n )
28   \ Wake the TC74 and receive its register value.
29   addr-tc74 add-read-bit i2cws i2c@nak sign-extend
30 ;
31 : main ( -- )
32   %11000 anselc mclr \ enable digital-in on RC3,RC4 (SCL1,SDA1)
33   i2cinit
34   init-tc74
35   begin
36     degrees@ .
37     #1000 ms
38   key? until
39 ;
40
41 \ Now, report temperature in degrees C
42 \ while we warm up the TC74 chip with our fingers...
43 decimal main
```

With a Saleae Logic Analyser connected to the pins of the TC74A5, we can see the I^{2}C signals as a result of calling the `init-tc74` word.

A little later on, the `degrees@` word is invoked. The returned binary value of `0b00010101` corresponds to the very pleasant 21°C that exists in the back shed as this text is being written.


Notes on this program:

- This builds upon the `i2c_base` and `asm` words supplied with FlashForth.

11   Making high-resolution voltage measurements

The Microchip MCP3422 is a $\Sigma\Delta$-ADC that can connected via I^{2}C port. This neat little converter can measure voltages with a resolution of 18 bits (at the lowest data rate of

3.75 samples per second) and includes a programmable gain amplifier [9]. Being available in a surface-mount package only, it was convenient to use a prebuilt evaluation board, the green board between the home-built FlashForth demo board and the fixed-voltage supply board. The MCP3422 evaluation board is connected to and powered from the I²C header on the FlashForth demo board. Separately, the fixed-voltage supply board provides the measurement voltage to channel 1 of the MCP3422 via a potentiometer that is set to give 1.024 V, according to my (fairly cheap) multimeter.
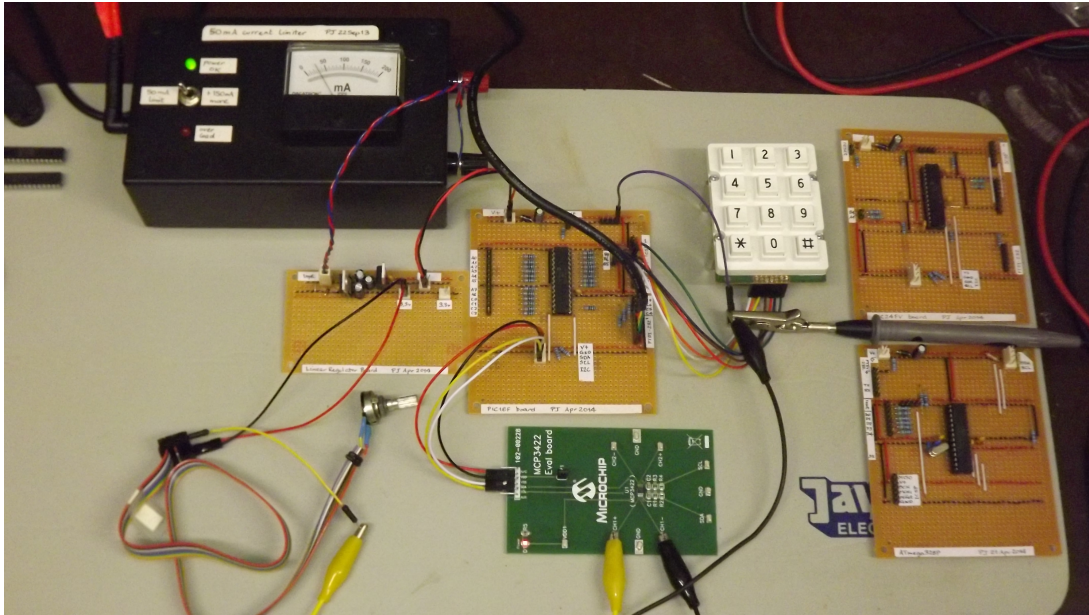

```
1 \ mcp3422.txt
2 \ Play with mcp3422 eval board.
3 \ PJ, 21-Oct-2013
4 \     28-Apr-2014 PIC18F26K22 version
5 \ Needs i2c_base.txt and math.txt.
6
7 -mcp3422
8 marker -mcp3422
9
10 $ff3a constant anselc
11
12 : mcp3422init ( -- )
13   \ $d0 is default mcp4322 address for writing
14   \ $9c is config for 18-bit continuous conversions of ch 1
15   $d0 i2cws $9c i2c! spen
16 ;
17
18 : mcp3422@ ( -- d f ) \ Read the 18-bit result as 3 bytes
19   $d1 i2cws i2c@ak          \ only 2 bits in first byte
20   dup $3 > if $fffa or then  \ sign-extend to full cell
21   i2c@ak $8 lshift i2c@ak or \ next two bytes into one cell
22   swap                      \ leave double result
23   i2c@nak $80 and 0=        \ leave true if result is latest
24 ;
25
26 : microvolts ( d1 -- d2 )
27   \ The least-significant bit corresponds to 15.625 microvolts
28   #125 #8 m*/
29 ;
30
31 : (d.3) ( d -- )
32   swap over dabs
33   <# # # # [char] . hold #s rot sign #>
```

```
34 ;
35
36 : report ( d f -- ) \ Assuming decimal, print millivolt value
37   cr if ." new " else ." old " then
38   microvolts (d.3) type space ." mV "
39 ;
40
41 : mcp3422-run ( -- )
42   decimal
43   %11000 anselc mclr \ enable digital-in on RC3,RC4 (SCL1,SDA1)
44   i2cinit mcp3422init
45   begin
46     mcp3422@ report
47     #1000 ms
48   key? until
49   hex
50 ;
```

Notes on this program:

- `mcp3422-run` is the top-level word that initializes the hardware, then periodically reads the MCP3422 data and reports the voltage (in millivolts) to the user terminal. The program runs until a key is pressed.

- The converted value is read from the MCP3422 as and 18-bit value in 2-complement format. The word `mcp3422@` reads the data as three bytes from the I²C port and then shuffles it into a double-cell value that is left on the stack, along with a flag to indicate whether the value sent by the MCP3422 happened to be the latest data.

- The value is scaled to microvolts and then the resultant double value is output using the pictured numeric output to have 3 decimal places so that it looks like a millivolt reading. Several lines from the terminal look like the following:

```
new 1028.031 mV
new 1028.062 mV
new 1028.046 mV
```

- This program builds upon the `i2c_base` and `asm` words supplied with FlashForth, in order to communicate with the MCP3422. The code for scaling of the measured data requires words from `math.txt`.

12   An I²C slave example

The MSSP in the PIC18F26K22 can also be used in slave mode. Here, the FlashForth demo board is presented as an I²C slave device to an Aardvark serial interface, acting as master. The UART communication is provided by a Future Technology Devices International USB TTL-serial cable.

The core of the program is the `i2c_service` word which is invoked each time a serial-port event is flagged by the SSPIF bit in the PIR1 flag register. This word is an implementation of the state look-up approach detailed in the Microchip Application Note AN734 [10]. The rest of the program is there to provide (somewhat) interesting data for the I²C master to read and to do something (light a LED) when the master writes suitable data to the slave.

```
1  -i2c-slave
2  marker -i2c-slave
3  \ Make the FlashForth 26K22 demo board into an I2C slave.
4  \ An I2C master can read and write to a buffer here,
5  \ the least-significant bit of the first byte controls
6  \ the LED attached to pin RB0.
7  \
8  \ Needs core.txt loaded.
9
10 $ff81 constant portb
11 $ff82 constant portc
12 $ff8a constant latb
13 $ff93 constant trisb
14 $ff94 constant trisc
15 $ff3a constant anselc
16
17 : led_on ( -- )
18   %00000001 latb mset
19 ;
20 : led_off ( -- )
21   %00000001 latb mclr
22 ;
23 : err_led_on ( -- )
24   %00000010 latb mset
25 ;
26 : err_led_off ( -- )
27   %00000010 latb mclr
28 ;
29
30 \ Establish a couple of buffers in RAM, together with index variables.
31 ram
32 8 constant buflen
33 \ Receive buffer for incoming I2C data.
34 create rbuf buflen allot
35 variable rindx
36 : init_rbuf ( -- )
37   rbuf buflen erase
38   0 rindx !
39 ;
40 : incr_rindx ( -- ) \ increment with wrap-around
41   rindx @ 1 +
42   dup buflen = if drop 0 then
43   rindx !
44 ;
45 : save_to_rbuf ( c -- )
46   rbuf rindx @ + c!
47   incr_rindx
48 ;
49
50 \ Send buffer with something interesting for the I2C master to read.
51 create sbuf buflen allot
52 variable sindx
53 : incr_sindx ( -- ) \ increment with wrap-around
54   sindx @ 1 +
55   dup buflen = if drop 0 then
56   sindx !
57 ;
58 : init_sbuf ( -- ) \ fill with counting integers, for interest
59   buflen
60   for
```

```
61     r@ 1+
62     sbuf r@ + c!
63   next
64   0 sindx !
65 ;
66
67 \ I2C-related definitions and code
68 $ffc5 constant sspcon2
69 $ffc6 constant sspcon1
70 $ffc7 constant sspstat
71 $ffc8 constant sspadd
72 $ffc9 constant sspbuf
73 $ff9e constant pir1
74
75 \ PIR1 bits
76 %00001000 constant sspif
77
78 \ SSPSTAT bits
79 %00000001 constant bf
80 %00000100 constant r_nw
81 %00001000 constant start_bit
82 %00010000 constant stop_bit
83 %00100000 constant d_na
84 %01000000 constant cke
85 %10000000 constant smp
86
87 d_na start_bit or r_nw or bf or constant stat_mask
88
89 \ SSPCON1 bits
90 %00010000 constant ckp
91 %00100000 constant sspen
92 %01000000 constant sspov
93 %10000000 constant wcol
94
95 \ SSPCON2 bits
96 %00000001 constant sen
97
98 : i2c_init ( -- )
99   %11000 anselc mclr \ enable digital-in on RC3,RC4 (SCL1,SDA1)
100   %00011000 trisc mset \ RC3==SCL RC4==SDA
101   %00000110 sspcon1 c! \ Slave mode with 7-bit address
102   sen sspcon2 mset \ Clock stretching enabled
103   smp sspstat mset \ Slew-rate disabled
104   $52 1 lshift sspadd c! \ Slave address
105   sspen sspcon1 mset \ Enable MSSP peripheral
106 ;
107
108 : release_clock ( -- )
109   ckp sspcon1 mset
110 ;
111
112 : i2c_service ( -- )
113   \ Check the state of the I2C peripheral and react.
114   \ See App Note 734 for an explanation of the 5 states.
115   \
116   \ State 1: i2c write operation, last byte was address.
117   \ D_nA=0, S=1, R_nW=0, BF=1
118   sspstat c@ stat_mask and %00001001 =
119   if
120     sspbuf @ drop
121     init_rbuf
122     release_clock
123     exit
124   then
125   \ State 2: i2c write operation, last byte was data.
126   \ D_nA=1, S=1, R_nW=0, BF=1
127   sspstat c@ stat_mask and %00101001 =
128   if
129     sspbuf c@ save_to_rbuf
130     release_clock
131     exit
```

```
132    then
133    \ State 3: i2c read operation , last byte was address.
134    \ D_nA=0, S=1, R_nW=1
135    sspstat c@ %00101100 and %00001100 =
136    if
137      sspbuf c@ drop
138      0 sindx !
139      wcol sspcon1 mclr
140      sbuf sindx @ + c@ sspbuf c!
141      release_clock
142      incr_sindx
143      exit
144    then
145    \ State 4: i2c read operation , last byte was outgoing data.
146    \ D_nA=1, S=1, R_nW=1, BF=0
147    sspstat c@ stat_mask and %00101100 =
148    ckp sspcon1 mtst 0=
149    and
150    if
151      wcol sspcon1 mclr
152      sbuf sindx @ + c@ sspbuf c!
153      release_clock
154      incr_sindx
155      exit
156    then
157    \ State 5: master NACK , slave i2c logic reset.
158    \ From AN734: D_nA=1, S=1, BF=0, CKP=1, however ,
159    \ we use just D_nA=1 and CKP=1, ignoring START bit.
160    \ This is because master may have already asserted STOP
161    \ before we service the final NACK on a read operation.
162    d_na sspstat mtst 0 > ckp sspcon1 mtst 0 > and
163    stop_bit sspstat mtst or
164    if
165      exit \ Nothing needs to be done.
166    then
167    \ We shouldn't arrive here...
168    err_led_on
169    cr ." Error "
170    ." sspstat " sspstat c@ u.
171    ." sspcon1 " sspcon1 c@ u.
172    ." sspcon2 " sspcon2 c@ u.
173    cr
174    begin again \ Hang around until watch-dog resets MCU.
175  ;
176
177
178  : init ( -- )
179    %00000011 trisb mclr  \ want RB0,RB1 as output pins
180    init_rbuf
181    init_sbuf
182    i2c_init
183    led_on err_led_on #200 ms led_off err_led_off
184  ;
185
186  : main ( -- )
187    cr ." Start I2C slave "
188    init
189    begin
190      sspif pir1 mtst
191      if
192        sspif pir1 mclr
193        i2c_service
194      then
195      rbuf c@ %00000001 and
196      if led_on else led_off then
197      cwd
198    key? until
199  ;
200
201  \ ' main is turnkey
```

With a Saleae Logic Analyser connected, we can see the I²C signals as a result of writing the byte `0x01` to turn on the LED. The following figure shows the data and clock signals from the time that the master asserts the START condition (green circle) until it asserts the STOP condition (as indicated by the red square).
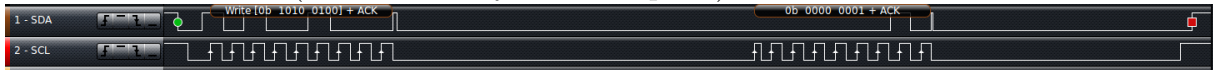
The clock frequency is 100kHz and there is a $138\,\mu$s gap between the ninth clock pulse of the address byte and the start of the pulses for the data byte. This gives an indication of the time needed to service each SSPIF event.

A little later on, the Aardvark reads two bytes from the bus, as shown here.

Zooming in, to show the finer annotation, the same signals are shown below.

Again, the inter-byte gap is $138\,\mu$s resulting in about $200\,\mu$s needed to transfer each byte. This effective speed of $5\,$kbytes/s should be usable for many applications, since the I²C bus is typically used for low speed data transfer.

Notes on this program:

- Need to load `core.txt` before the source code of the `i2c-slave.txt`.

- Slave examples found in documentation on the Web usually have the service function written in the context of an interrupt service routine. The MSSP can be serviced quite nicely without resorting to the use of interrupts, however, you still have to check and clear the SSPIF bit for each event.

- The implementation of the test for State 5 (Master NACK) is slightly different to that described in AN734 because it was found that the master would assert an I²C bus stop after the final NACK of a read operation but before the MCU could service the SSPIF event. This would mean that STOP was the most recent bus condition seen by the MSSP and the START and STOP bits set to reflect this. In the figures shown above, there is only about $12\,\mu$s between the ninth clock pulse for the second read data byte and the Aardvark master asserting the STOP condition on the bus. This period is very much shorter than the (approx.) $140\,\mu$s period needed by the slave firmware to service the associated SSPIF event.

13   Speed of operation

All of this nice interaction and convenience has some costs. One cost is the number of MCU instruction cycles needed to process the Forth words. To visualize this cost, the following program defines a word `blink-forth` which toggles an IO pin using the high-level FlashForth words that fetch and store bit patterns into the port latch register. An alternative word `blink-asm` uses assembler instructions to achieve an equivalent effect, but faster, and a third word `blink-bits` uses the FlashForth `bit0:` and `bit1:` words to create high-level bit-manipulation words that also achieve full machine speed.

13.1   PIC18F26K22

```
1  -speed-test
2  marker -speed-test
3  \ Waggle RB1 as quickly as we can, in both high- and low-level code.
4  \ Before sending this file, we should send asm.txt so that we have
5  \ the clrwdt, word available.  We also need bit.txt.
6
7  $ff8a constant latb
8  $ff93 constant trisb
9
10 : initRB1
11   %10 trisb mclr \ RB1 as output
12   %10 latb mclr \ initially known state
13 ;
14
15 \ high-level bit fiddling, presumably slow
16 : blink-forth ( -- )
17   initRB1
18   begin
19     %10 latb c! 0 latb c! \ one cycle, on and off
20     %10 latb c! 0 latb c!
21     %10 latb c! 0 latb c!
22     %10 latb c! 0 latb c!
23     cwd \ We have to kick the watch dog ourselves.
24   again
25 ;
26
27 \ low-level bit fiddling, via assembler
28 : blink-asm ( -- )
29   initRB1
30   [
31   begin,
32     latb 1 a, bsf,  latb 1 a, bcf, \ one cycle, on and off
33     latb 1 a, bsf,  latb 1 a, bcf,
34     latb 1 a, bsf,  latb 1 a, bcf,
35     latb 1 a, bsf,  latb 1 a, bcf,
36     clrwdt, \ kick the watch dog
37   again,
38   ]
39 ;
40
41 \ high-level bit fiddling with named bits
42 latb #1 bit1: RB1-hi inlined
43 latb #1 bit0: RB1-lo inlined
44 : blink-bits ( -- )
45   initRB1
46   begin
47     RB1-hi RB1-lo \ one cycle
48     RB1-hi RB1-lo
49     RB1-hi RB1-lo
50     RB1-hi RB1-lo
51     cwd
```

```
52    again
53  ;
```

Notes on this program:

- We have had to worry about clearing the watch-dog timer. In the early examples, the FlashForth interpreter was passing through the pause state often enough to keep the watch-dog happy. The words in this example give the FlashForth interpreter no time to pause so we are responsible for clearing the watch-dog timer explicitly.

- In the source code config file for the specific MCU, the watch-dog timer postscale is set to 32768. With a 31.25 kHz oscillator frequency, this leads to a default timeout period of a little over 134 seconds ($3.2\,\text{ms} \times 128 \times 32768$).

- For the PIC18 MCU, the internal oscillator of 16 MHz was multiplied by the PLL to get 64 MHz oscillator driving the MCU. With 4 clock cycles per instruction cycle, this gave an instruction period $T_{CY} = 62.5\,\text{ns}$. Current consumption by the microcontroller was about 13 mA.

- The screen image on the left shows the output signal for running the high-level `blink-forth` word while the image on the right uses the assembler words.
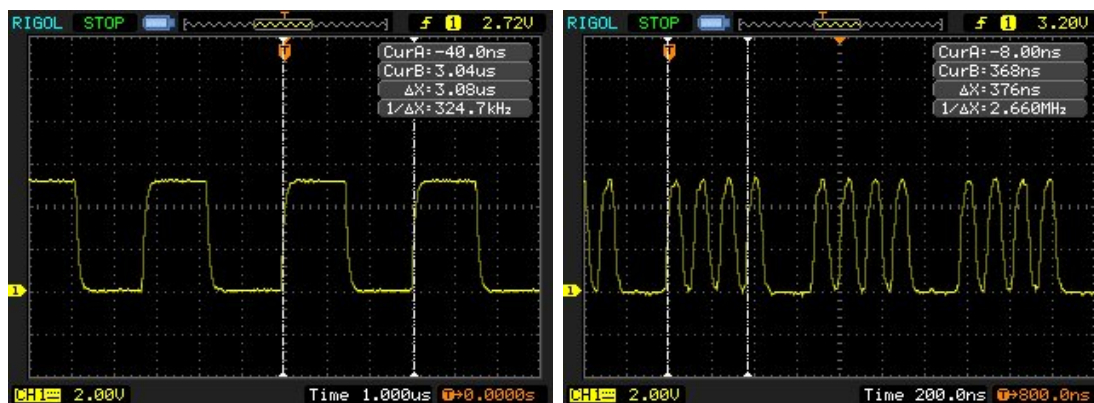
- For the `blink-forth` word, one on+off cycle of the LED executes in 6 words and is seen (in the oscilloscope record) to require about 50 instruction cycles. So, on average, each of these threaded Forth words is executed in about 8 MCU instruction cycles. Note that this overhead includes the cost of using 16-bit cells for the data. Extra machine instructions are used to handle the upper bytes. In other applications, where we actually want to handle 16-bit data, this will no longer be a penalty.

- The assembler version has no overhead and the cycle time for the MCU instructions defines the period of the output signal. One on-off cycle requires 2 instructions so we see a short 125 ns period. This is fast enough that the capacitive loading on the output pin is noticeable in the oscilloscope trace. Also, the time required for the machine instructions to clear the watch-dog timer and the instruction jump back to the start of the loop now shows up clearly in the oscilloscope record.

- The oscilloscope record for the `blink-bits` word is shown here.
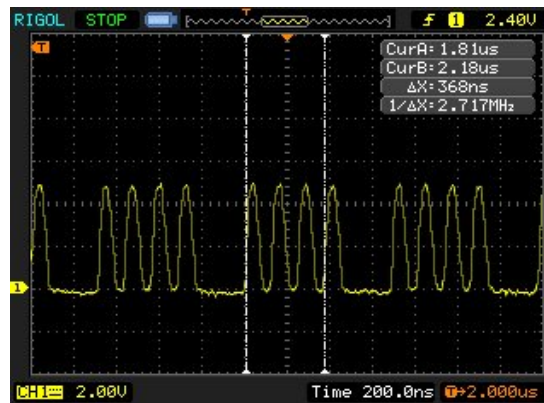
With the newly created bit-manipulation words `RB1-hi` and `RB1-lo` being inlined, they also achieve full machine speed because the generated code is essentially the same as for `blink-asm`.

13.2   PIC24FV16KM202

```
 1 -speed-test
 2 marker -speed-test
 3 \ For the PIC24FV16KM202, waggle RB15 as quickly as we can,
 4 \ in both high- and low-level code.
 5 \ Remember to load bit.txt before this file.
 6
 7 $02c8 constant trisb
 8 $02ca constant portb
 9 $02cc constant latb
10 $02ce constant odcb
11
12 1 #15 lshift constant bit15
13
14 : initRB15
15   bit15 trisb mclr \ RB15 as output
16   bit15 latb mclr \ initially known state
17 ;
18
19 \ high-level bit fiddling, presumably slow
20 : blink-forth ( -- )
21   initRB15
22   begin
23     bit15 latb ! 0 latb ! \ one cycle, on and off
24     bit15 latb ! 0 latb !
25     bit15 latb ! 0 latb !
26     bit15 latb ! 0 latb !
27     cwd \ We have to kick the watch dog ourselves.
28   again
29 ;
30
31 \ low-level bit fiddling, via assembler
32 : blink-asm ( -- )
33   initRB15
34   [
35   begin,
36     #15 latb bset,  #15 latb bclr, \ one cycle, on and off
37     #15 latb bset,  #15 latb bclr,
38     #15 latb bset,  #15 latb bclr,
39     #15 latb bset,  #15 latb bclr,
```

```
40      ] cwd [ \ kick the watch dog
41    again,
42    ]
43 ;
44
45 \ high-level bit fiddling with named bits
46 latb #15 bit1: RB15-hi inlined
47 latb #15 bit0: RB15-lo inlined
48 : blink-bits ( -- )
49    initRB15
50    begin
51      RB15-hi RB15-lo \ one cycle
52      RB15-hi RB15-lo
53      RB15-hi RB15-lo
54      RB15-hi RB15-lo
55      cwd
56    again
57 ;
```

Notes on this program:

- The order of the assembler arguments is bit-number register-address op-code. This is different to that seen in the PIC18 version of the program.

- The MCU was configured for running off its internal 8 MHz oscillator with a 1:1 postscaling. This resulted in an instruction cycle period $T_{CY} = 250$ ns. Although this is 4 times longer than for the PIC18, the current consumption was correspondingly lower at about 3 mA.

- The screen image on the left shows the output signal for running the high-level `blink-forth` word while the image on the right uses the assembler words.
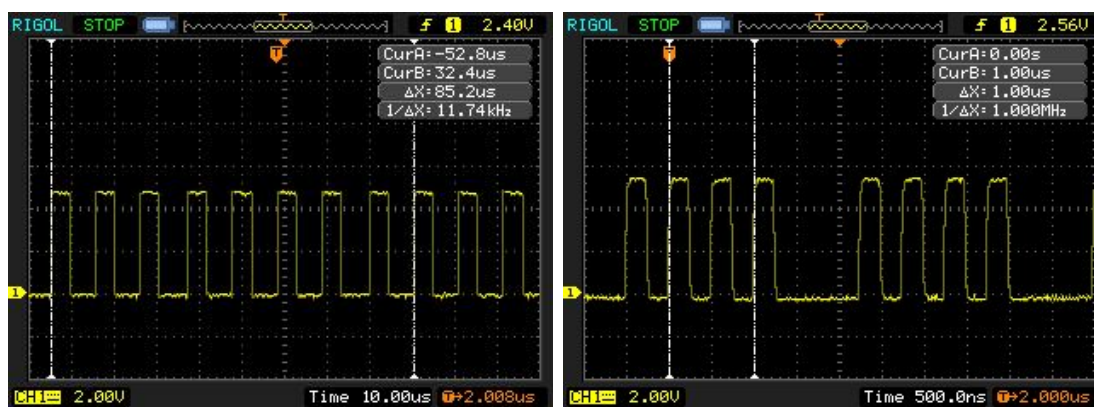
- For the `blink-forth` word, one on+off cycle of the LED executes in 6 words and is seen (in the oscilloscope record) to require about 41 instruction cycles. So, on average, each of these threaded Forth words is executed by the 16-bit PIC24 in about 7 MCU instruction cycles.

- The assembler version has no overhead and the cycle time for the MCU instructions defines the period of the output signal. One on-off cycle requires 2 instructions so we see a short 500 ns period.

- The oscilloscope record for the `blink-bits` word is shown here.
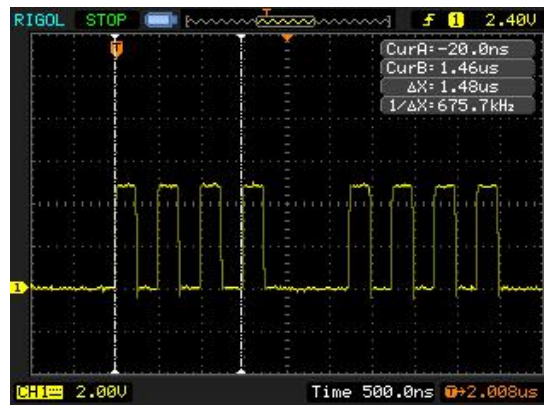
Again, the newly created bit-manipulation words `RB15-hi` and `RB15-lo` also achieve full machine speed.

13.3   ATmega328P

```
1  -speed-test
2  marker -speed-test
3  \ Waggle PB5 as quickly as we can, in both high- and low-level code.
4  \ Before sending this file, we should send asm.txt, bit.txt and bio.txt.
5
6  $0024 constant ddrb
7  $0025 constant portb    \ RAM address
8  $0005 constant portb-io \ IO-space address
9  1 #5 lshift constant bit5
10
11 : initPB5
12   bit5 ddrb mset \ set pin as output
13   bit5 portb mclr \ initially known state
14 ;
15
16 : cwd ( -- ) [ wdr, ] ; inlined \ we might want to reset the watchdog
17
18 \ high-level bit fiddling, presumably slow
19 : blink-forth ( -- )
20   initPB5
21   begin
22     bit5 portb c! 0 portb c! \ one cycle, on and off
23     bit5 portb c! 0 portb c!
24     bit5 portb c! 0 portb c!
25     bit5 portb c! 0 portb c!
26     cwd
27   again
28 ;
29
30 \ low-level bit fiddling, via assembler
31 : blink-asm ( -- )
32   initPB5
33   [
34   begin,
35     portb-io #5 sbi,  portb-io #5 cbi, \ one cycle, on and off
36     portb-io #5 sbi,  portb-io #5 cbi,
37     portb-io #5 sbi,  portb-io #5 cbi,
38     portb-io #5 sbi,  portb-io #5 cbi,
39     wdr,
40   again,
41   ]
42 ;
43
44 \ high-level bit fiddling with named bits
```

```
45 portb #5 bit1: PB5-hi inlined
46 portb #5 bit0: PB5-lo inlined
47 : blink-bits ( -- )
48   initPB5
49   begin
50     PB5-hi PB5-lo \ one cycle
51     PB5-hi PB5-lo
52     PB5-hi PB5-lo
53     PB5-hi PB5-lo
54     cwd
55   again
56 ;
57
58 \ high-level bit fiddling with named bits in IO-space
59 portb-io #5 bio1: PB5io-hi inlined
60 portb-io #5 bio0: PB5io-lo inlined
61 : blink-bits-io ( -- )
62   initPB5
63   begin
64     PB5io-hi PB5io-lo \ one cycle
65     PB5io-hi PB5io-lo
66     PB5io-hi PB5io-lo
67     PB5io-hi PB5io-lo
68     cwd
69   again
70 ;
```

Notes on this program:

- Except for names, this code is essentially the same as for the PIC18 and PIC24 versions of the exercise. FlashForth abstracts away much of the instruction-set architecture of the microcontroller, leaving us to focus on twiddling the bits of the peripheral hardware.

- The MCU was configured for running with the 16 MHz crystal, which resulted in a machine clock cycle period $T_{CY} = 62.5$ ns.

- The screen image on the left shows the output signal for running the high-level `blink-forth` word while the image on the right uses the assembler words.
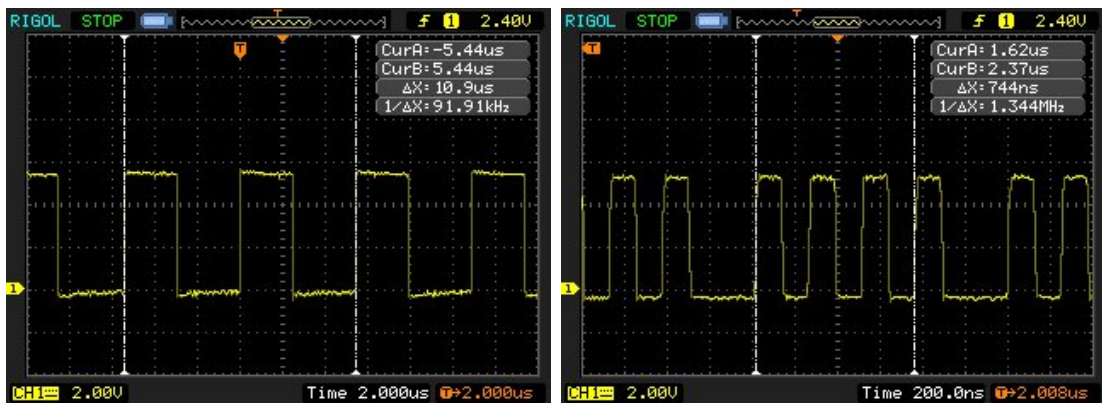
- For the `blink-forth`, one on+off cycle of the LED executes in 6 words and is seen (in the oscilloscope record) to require about 87 instruction cycles. So, on average, each of these threaded Forth words is executed by the 16-bit PIC24 in about 14.5 MCU clock cycles.

- The assembler version has no overhead and the cycle time for the MCU instructions defines the period of the output signal. One on-off cycle requires 2 instructions (`sbi` and `cbi`) each requiring 2 clock cycles, so we see a short 250 ns period.

- The oscilloscope records for the `blink-bits` and `blink-bits-io` words are shown here.
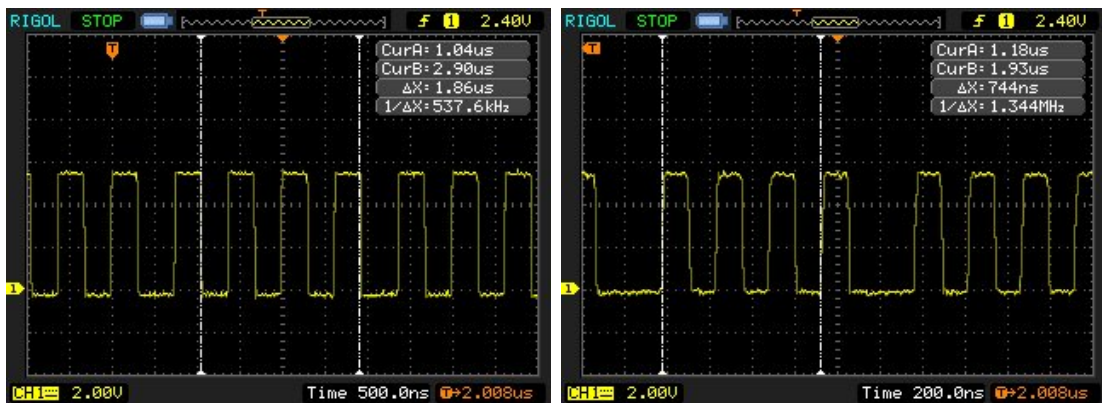
The left screen image shows the pin signal when accessing the bit via memory-space address. Here the pulse width was about 620 ns so each of the 2 words required about 5 MCU clock cycles. Although faster than the threaded words, this is not quite the full machine speed which is available when accessing the bit via IO-space address (right screen image).

14   Driving an Hitachi-44780 LCD controller

The LCD in the photograph on page 6 was driven with the following code. During the
development of this example, a lesson was relearned – that of reading the data sheet [11]
carefully :)

```
1  \ Exercise LCD on PICDEM2+ board.
2  \ Remember to load bit.txt before this file.
3  -xlcd
4  marker -xlcd
5
6  $ff80 constant porta
7  $ff89 constant lata
8  $ff92 constant trisa
9  $ff83 constant portd
10 $ff8c constant latd
11 $ff95 constant trisd
12
13 \ The LCD is operated in nibble mode.
14 \ RA1 = Enable (E) pin
15 \ RA2 = Read/Write (RW) pin
16 \ RA3 = Register Select (RS) pin
17 \ RD0 = DB4 on LCD
18 \ RD1 = DB5
19 \ RD2 = DB6
20 \ RD3 = DB7
21
22 portd constant dataport
23 lata #1 bit0: Elo
24 lata #1 bit1: Ehi
25 lata #2 bit0: RWlo
26 lata #2 bit1: RWhi
27 lata #3 bit0: RSlo
28 lata #3 bit1: RShi
29
30 : data-port-in ( -- )
31   trisd c@ $0f or trisd c!
32 ;
33
34 : data-port-out ( -- )
35   trisd c@ $f0 and trisd c!
36 ;
37
38 : put-nibble ( c -- )
39   \ Make lower 4 bits of c appear on data port pins.
40   $0f and
41   dataport c@ $f0 and
42   or
43   dataport c!
44 ;
45
46 : short-delay ( -- )
47   18 for r@ drop next ;
48
49 : Estrobe ( -- )
50   Ehi short-delay Elo
51 ;
52
53 : lcd-getc ( -- c )
54   \ Read the LCD register in two nibbles.
55   \ Remember to select the register line before calling this word.
56   data-port-in
57   RWhi short-delay
58   Ehi short-delay dataport c@ #4 lshift Elo short-delay \ high nibble
59   Ehi short-delay dataport c@ Elo short-delay \ low nibble
60   or \ assemble full byte and leave it on the stack
61   RWlo short-delay
62 ;
```

```
63
64 : lcd-ready? ( -- f )
65   \ Read the command register and check busy bit.
66   RSlo short-delay
67   lcd-getc $80 and 0=
68 ;
69
70 : wait-for-lcd ( -- )
71   begin lcd-ready? cwd until
72 ;
73
74 : lcd-putc ( c -- )
75   \ Write the LCD register in two nibbles.
76   \ Remember to select the register line before calling this word.
77   dup $f0 and #4 rshift \ high nibble left on top of stack
78   data-port-out
79   RWlo short-delay
80   put-nibble short-delay Estrobe short-delay
81   $0f and \ low nibble now left on top of stack
82   put-nibble short-delay Estrobe short-delay
83   data-port-in
84 ;
85
86 : lcd-clear ( -- )
87   wait-for-lcd
88   RSlo short-delay
89   %00000001 lcd-putc
90 ;
91
92 : lcd-home ( -- )
93   wait-for-lcd
94   RSlo short-delay
95   %00000010 lcd-putc
96 ;
97
98 : lcd-goto ( c -- )
99   \ Set the specified 7-bit data memory address.
100  wait-for-lcd
101  RSlo short-delay
102  $80 or \ sets the highest bit for the command
103  lcd-putc
104 ;
105
106 : lcd-init ( -- )
107  data-port-in
108  Elo RWlo RSlo
109  %00001110 trisa mclr \ RS, RW and E as output
110  30 ms \ power-on delay
111  \ Begin "initialization by instruction"
112  \ Presumably, the LCD is in 8-bit interface mode.
113  %0011 put-nibble Estrobe 5 ms
114  %0011 put-nibble Estrobe 1 ms
115  %0011 put-nibble Estrobe 1 ms
116  \ Function set for 4-bit interface; it is still in 8-bit mode.
117  %0010 put-nibble Estrobe 1 ms
118  \ Now, we should be in 4-bit interface mode.
119  \ Function set for 4-bit interface, 2 display lines 5x7 font.
120  wait-for-lcd
121  %00101000 lcd-putc
122  \ Increment cursor after each byte, don't shift display.
123  wait-for-lcd
124  %00000110 lcd-putc
125  \ Display off
126  wait-for-lcd
127  %00001000 lcd-putc
128  \ Display clear
129  %00000001 lcd-putc
130  5 ms
131  \ End of "initialization by instruction"
132  \ Enable cursor and display, no blink.
133  wait-for-lcd
```

```
134    %00001110 lcd-putc 1 ms
135    wait-for-lcd
136 ;
137
138 : lcd-emit ( c -- ) \ Write the byte into data memory.
139    wait-for-lcd
140    RShi short-delay
141    lcd-putc
142 ;
143
144 : lcd-type ( c-addr n -- ) \ send string
145    for c@+ lcd-emit next
146    drop
147 ;
148
149 : main
150    ." Begin..."
151    lcd-init
152    cr ." lcd-init done."
153    s" Hello from" lcd-type
154    $40 lcd-goto
155    s" FlashForth 5.0" lcd-type
156    cr ." exercise done."
157 ;
```

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