Chapter 12: IO, IO, It's Off To Work We Go On The LCD

You should be noticing that the course development board is becoming more and more useful as each chapter is completed. Hopefully as the driver set is completed, you can start to imagine some applications for the board or at least some embedded applications that you could build with different hardware and a similar driver set. We continue adding functionality by getting the LCD up and running in this chapter which presents a few new challenges since we must interface to a system external to our own microcontroller.

Even though a UART debugging port can provide all the access an engineer requires to check on system status or get information in or out of the system, it is not very helpful to the average user. Very simple user interfaces can get by with a few LEDs since many people can understand that a green LED is probably good and a red LED is probably bad. You might be tempted to add a few more colors of LEDs for status, and then start blinking those LEDs or turning on different combinations of them to mean various things. For engineers and maybe even product support people whom you can train, that approach is okay and understandable. However, if you think that a regular consumer will have any hope of understanding what a 1Hz blinking LED vs. a 4Hz blinking LED looks like, you are in for a surprise!

A liquid crystal display (LCD) offers a HUGE advantage for a user interface since it can communicate graphically or in plain text. Gray scale text or dot matrix displays are relatively inexpensive and quite easy to implement. If you want really high resolution, TFTs (thin film transistor) can be used but at a cost of complexity, power consumption and dollars (the screen in the iPhone 4S, for example, is said to cost around $23 + $14 for the capacitive touch screen – but that is in volumes of tens of millions of units). On the downside, LCDs are fragile since they are pieces of glass with ultra tiny wires, and they do not do well in cold temperatures since the liquid actually freezes or at least gets very thick and slow.

LCDs come in many shapes and forms, but all rely on the same basic technology to make them work. This chapter starts by looking at the physical characteristics of an LCD display, discusses the various configurations you will come across, and then looks specifically at the part used on the development board.

12.1 LCD Hardware

There is nothing magical about the way an LCD works. Every pixel has a positive and return connection through which that pixel can be told to be on or off. If you look at an LCD, you might not think that can be physically possible, but if you look under high magnification, you will see tiny wires embedded in the glass and tiny vias connecting different layers in the glass. For LCDs with very small and dense pixels, there will be multiple signal layers and multiple ground layers / backplanes. As resolution increases further, the displays use a different technology called "TFT" (thin film transistor) where every pixel has a transistor switch. This allows row and column addressing of each pixel. You might think that is a lot of transistors, especially on a big 2500 x 1600 pixel display – 4 million! But considering how physically big a display like that is, a few million transistors is nothing compared to the billions of transistors that are in microprocessors these days. It is still impressive technology, though, and there are only a few factories in the world that produce these displays that various vendors use in the LCD monitors and TVs.

12.1.1 LCD Pixels Characteristics

In the context of this course, the LCD is an "FSTN" type, filtered super-twisted nematic display. A pixel is lit by biasing it with a positive voltage, which aligns the particles in the liquid crystal solution. The pixel does not actually light up, in fact a pixel that is "on" and visible is actually just blocking light from reflecting off the back surface of the glass. The front side of the glass is polarized as well, so when the crystals are aligned 90° different than the glass, all the reflected light is blocked. The exact same effect can be observed with a pair of polarization filters for a camera or two pairs of polarized sun glasses. Stack the lenses on top of each other and look through them in different orientations - suddenly LCDs will make more sense.

LCDs draw very little current though the circuit does need to remain energized and refreshes continuously to keep the crystal solution polarized. New LCDs are emerging that do not even need to be refreshed, making static images with nearly zero current draw possible (check out "E ink" and zero-power (bi-stable) LCDs). An analogy is dynamic RAM where each memory cell is like a pixel and has capacitance that must be charged and refreshed periodically to stay energized. Eventually the charge will drain if it is not refreshed. To improve the look of LCDs, a backlight is often added which will make the overall power draw considerably higher since the light must always be on.

Dot-matrix LCDs are common and allow the programmer to draw any character or image they want (as long as they can make it out of the dots). Though this provides some freedom, it also comes with more overhead as more care must be taken to draw shapes and you can only get detail in resolution of the smallest size of you square pixels. However, pixels do not have to be small squares in a grid. LCDs can be created with "pixels" that are whole images or symbols. For example, an alarm icon showing a small ringing clock can be done as a single pixel, even if the icon is not entirely continuous. A 7-segment-like display can be made with 7 "pixels," and thus numerical characters can be shown with 7 pixels per character just like an alarm clock that uses 7-segment LED displays.

Custom LCDs are also relatively inexpensive though they include some tooling costs at the beginning where the vendor creates the design you want. You can choose how the pixels are hooked up, what kind of controller (if any) is on the LCD device, and how it will connect to your product. Once the design is complete, the custom LCD can be produced in mass quantity for only a few dollars each. The instrument shown here has a custom LCD with predefined symbols as well as dot-matrix areas for writing numbers and letters. The Key symbol is a single segment, as are the tiny gas names under each reading.

12.1.2 LCD Controllers

Making pixels light up is easy in theory and it is barely different than turning on a discrete LED. The hard part comes more from the physical side of things since, as you have learned, every pixel needs to be addressed which can result in a lot of hardware to manage. Stand-alone LCDs have a controller chip that takes care of most of the hard parts about setting and clearing LCD segments. All your host micro has to do is tell the LCD controller which pixel(s) you want on or off, and it will take care of any addressing, backplane management or voltage waveform generation to make it happen.

There are a few microcontrollers that have built-in LCD drivers in them. These are peripherals built to work with LCDs (either custom or standard) and connect directly to the LCD pixel and backplane wires. The programmer is responsible for all the mapping, though the peripheral provides some help with backplane management and generates a somewhat complex waveform to make sure all the pixels work together with their backplanes. The downside of built-in controllers is that they are usually limited

The micro requires connections to GPIO for all the pixel lines, so there will usually be a specification for the maximum number of pixels that the controller can support (say, for example 16 lines). Since 16 pixels is barely enough to make two characters, the controller will probably support two or more back planes, each of which require an additional output signal line that is capable of producing a "backplane waveform." This brings the total number of pixels that can be supported to (pixel lines) x (backplanes). So the 16 pixel device that can run 4 backplanes can actually support 64 pixels, and that starts to look a lot better. For example, you could run six 7-segment characters and still have 22 other symbols available. However, you still are using 20 pins of the microcontroller which will occupy a lot of the processor GPIO just for the LCD.

If you need more pixels, then you probably have no choice but to go to an external LCD controller. There is added cost to this, but also many advantages. Many LCDs are "chip on glass" (COG) which means you buy the whole LCD and controller as one piece. If it is not a custom design, these can actually be quite reasonably priced even in low quantity. This is exactly what the MPG LCD is. Other LCDs might have the glass on a small PCB and have an LCD controller chip on that PCB. Communication to tell the controller what pixels to light up now takes place with a digital interface like SPI, I²C, parallel, or others.

12.1.3 LCD Interface

Ultimately, wiring up an LCD system requires three parts as shown in Figure 12.1.3.1.

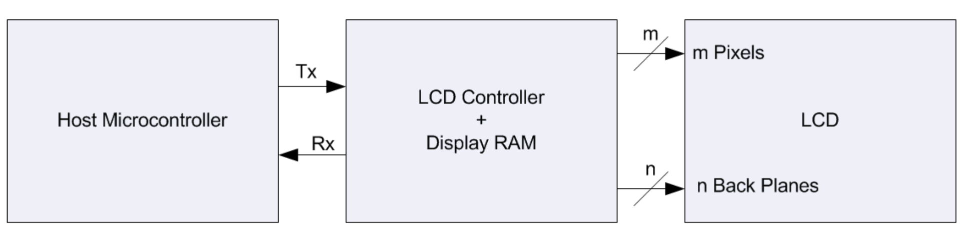


Figure 12.1.3.1: Three main components in an LCD system

The Host Microcontroller is what triggers the LCD controller to drive pixels on or off on the LCD. The LCD controller takes commands and data from the Host and configures its display RAM that maps to the LCD pixels. Then the controller updates its output lines that cause the pixels to update on the LCD itself. The work required to generate the data and organize it into display RAM is pretty much the same in any LCD system, but the share of the work between the host and the LCD controller can vary significantly. For most of the basic character display LCDs that you work with, the LCD controller takes care of most of the work.

The MPG LCD is a very common type of alpha-numeric display. Though this particular display is a two-line by 20-character display, the controller chip will support LCDs down to one-line, 8-characters all the way up to four-line, 20-characters. The controller chip itself runs a basic application that allows other devices to send commands and ASCII characters that the controller will interpret. This particular controller uses an I^2C interface which was very important for the development board due to limited GPIO lines available on the processor. Character LCDs often have a parallel data interface (8 lines) along with 3 control lines, thus requires 11 processor lines to communicate with. Though that makes them slightly easier to use since the communication is very intuitive, the hardware overhead can be impractical.

Correctly attaching the LCD into the development board PCB involves carefully looking at the LCD data sheet to put the right parts on the board. With I^2C, there are only two communication lines, but the LCD requires additional hardware for the controller to work properly as well as an external interface to the three LEDs that make up the backlight.

Figure 12.1.3.2 shows the hardware connections as described by the LCD data sheet and the corresponding hardware connections implemented for the course development board. Note that the 5V rail is used for the LEDs with relatively small resistors so they are quite bright. Since we need to switch 5V lines, transistor switches are used to help reduce the overall current that the processor will have to sink when an LED is on. The red backlight LED happens to be connected to an open-drain driver pin on the processor which cannot drive a transistor switch, so we let that current sink through the processor.

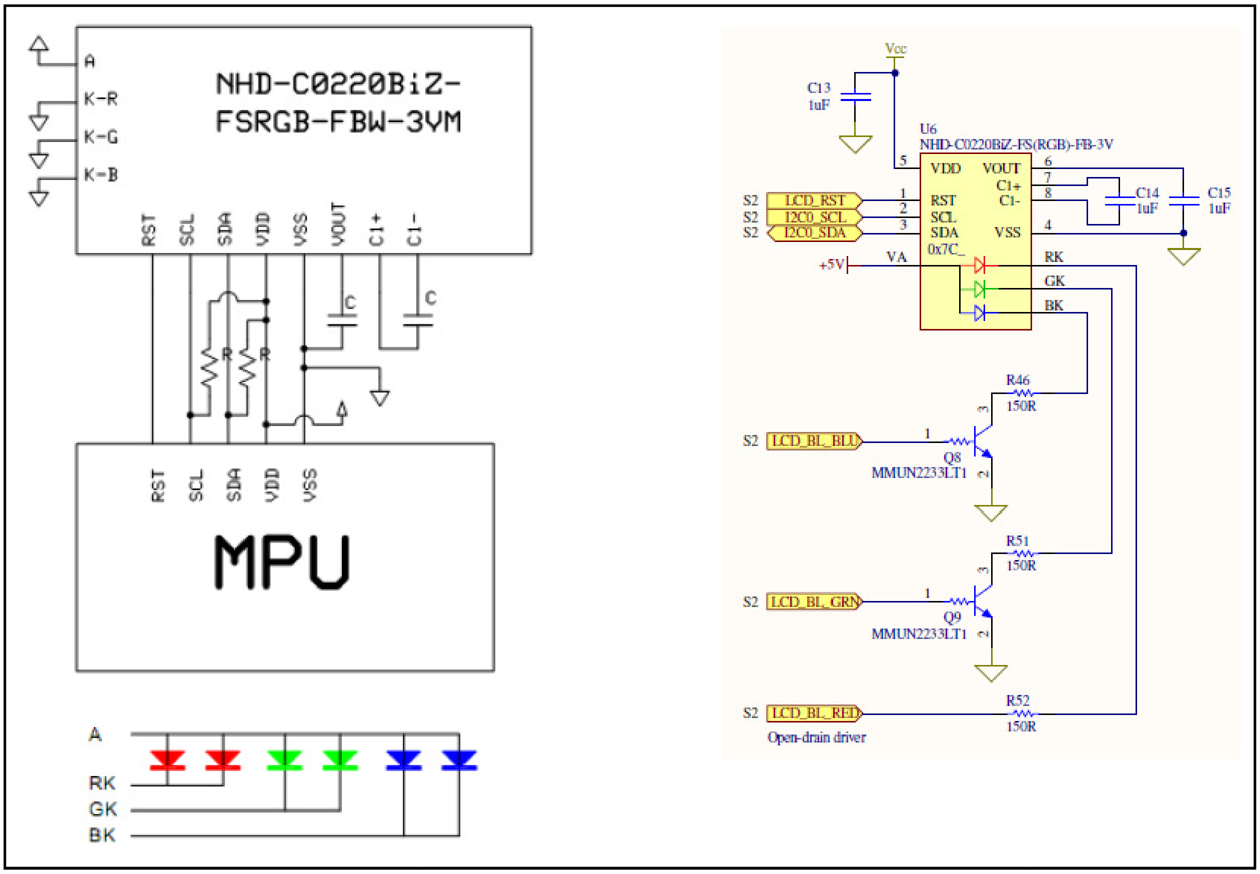


Figure 12.1.3.2: Hardware connections from LCD data sheet (left) and in development board schematic (right)

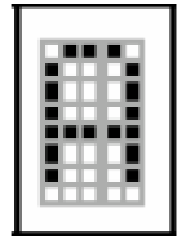
12.1.4 Character and Control Data

When communicating to an LCD, two modes are used: character and control. This determines how the LCD controller will interpret the binary data it receives from the host. It is likely that every LCD that you work with will use this strategy or something very similar. For the course LCD, the mode is selected in the first few bytes of communication sequence.

If you have not done so already, now would be a good time to open up the LCD data sheet and take a quick read through to set up the rest of this discussion. A copy of the data sheet is stored on the Engenuics web site. It is a very good idea to keep a copy of LCD data sheets in particular, because they tend to disappear from the web on occasion.

http://www.engenuics.com/mpg/hardware/LCD_Character_Newhaven_NHD-C0220BiZ-FSRGB-FBW-3VM.pdf

In character mode, an ASCII LCD will take the bytes you send it with the assumption it is ASCII character data and light up the correct pixels based. In other words, you send the character 'A' (0x60) and magically the pixels required to make an 'A' will light up (at the current cursor location). But what really is happening here? The controller sees that you want to write the letter A because you have sent the character using the defined protocol. To know what an 'A' looks like, the LCD controller has to look up the bitmap for the character that it has stored in its memory that tells it what pixels need to be on to make an ‘A’ appear. The block of pixels for each character bitmap in this LCD is 5 columns by 8 rows as shown on the right. Each character can exist at any of the 20x2 character positions on the display screen. Though each pixel on the screen has an address accessible to the LCD controller, only full character addresses are used by the host MCU to indicate where on the screen the character should be placed. Once the bitmap is determined, the controller can activate the corresponding pixels. While most character LCDs have built-in bitmaps for at least one font, custom LCDs and many graphical / dot matrix LCDs do not have any data, so it is up to you provide all the bitmaps. Check out MPG Level 2 if you want to see an example of a fully customized dot matrix LCD!



In addition to having a font stored in ROM for you to use, there are other features that may be available to you. For example, the controller allows you to set the cursor position or blank the display. This LCD even supports a blinking cursor. When characters are being sent to the display, the controller can be set to automatically change addresses after each character so that it is ready in the correct position when the next character request comes in on the interface. Instructions to move the cursor to a different location, erase characters, hide the cursor, erase the whole screen, etc. are also available. These commands are accessed when the controller is in command mode.

All that functionality is included in the price of the LCD and makes integrating an alphanumeric LCD relatively easy. The data sheet lists the commands available, the font set available, and the memory organization of the LCD. The main information is looked at further on in the chapter. We need some of the data sheet information now because we have to write the first part of the driver to communicate to the LCD which will handle communication using the I^{2}C peripheral. Though we will make the I^{2}C driver itself fairly generic, it is important to look for anything specific in the target device’s data sheet to ensure your driver is going to provide the services needed.

12.2 Inter-Integrated Circuit (I^{2}C) Communication

I^{2}C is a synchronous protocol where the clock is provided by the master in a master-slave relationship. It uses only a single data wire and can therefore only be half duplex unlike some other standard full duplex protocols like RS-232. I^{2}C supports multi-master and multi-slave configurations, however we will talk only about single master (but multi-slave) set ups which are most common in an embedded system.

12.2.1 Legal Stuff

Up until October 2006, any device that used I^{2}C was subject to royalties since the official standard invented by Phillips (now NXP who makes the MPG LPC processor) was licensed intellectual property. Designers wishing to build an I^{2}C device and use the I^{2}C logo paid a fee which was usually incorporated in the device cost so you were not really even aware of it (though you may wonder why a device with I^{2}C seems a bit expensive).

The I²C standard also regulated device addresses. Multi-slave configurations work by using unique addresses with all the slaves connected on the bus. When a master initiates communication, the first byte sent is the address of the slave on the bus it wants to talk to. All devices on the bus hear this address, but if the address is not theirs then they ignore the remaining data until a "Stop condition" appears on the bus, at which time they start listening for the address of the next transaction. The protocol started with 7-bit addresses but allows 10-bit addresses these days. Still, that is only 1023 unique addresses, and certainly there are more than that many I²C devices. In fact, some vendors might have that many parts themselves!

Device addresses are supposed to be grouped depending on their function. As an arbitrary example, memory devices might be allowed addresses from 0x01 to 0x0F, and accelerometers are allowed 0x10 to 0x1F. The whole concept makes sense until you start trying to manage an exponentially increasing number of device types and devices within those types. Plus, every other manufacturer was coming up with their own implementation of I²C that dodged the patent but still allowed compatibility. Lawyers eventually got involved and decided to find a way around the licensing requirements because it did not really make sense anymore, and people did not want to pay royalties. In the end, the fee was relaxed in 2006 though a few rules remain.

Nowadays, instead of offering "I²C" communications, a simple "2-wire interface" is offered and the addressing specification is quite relaxed (though if you want, you can still pay NXP and get an officially registered address and then probably win in court if anyone's non-registered device conflicts with yours). Most companies are careful to never say "I²C" in their documentation, but even that seems to be a non-issue these days since the legal hoopla around the whole thing has run its course and there are probably enough court case examples to cite to avoid any litigation. All that being said, if you happen to build (or integrate) a device with two-wire serial communication and you have not paid to use the name I²C, then you should probably avoid saying it!

12.2.2 I²C Hardware

Now that we have handled the legal aspects, we can discuss the technical side of I²C. In the hardware realm, the I²C bus (or two-wire bus) has a serial clock line (SCL) and a serial data line (SDA). The one data line is used for both transmit and receive data (thus the half-duplex restriction) and device selection is entirely address-based. That means that regardless of the number of devices on the bus, I²C only requires two IO lines to hook everything together, making it one of the lowest hardware overhead protocols available. Both lines require a pull-up resistor to drive the high state, and all devices use open-drain GPIOs to drive the low state. Figure 12.2.2.1 shows an example of a single master – multi-slave I²C configuration (the slaves have random addresses that must be unique on the bus).

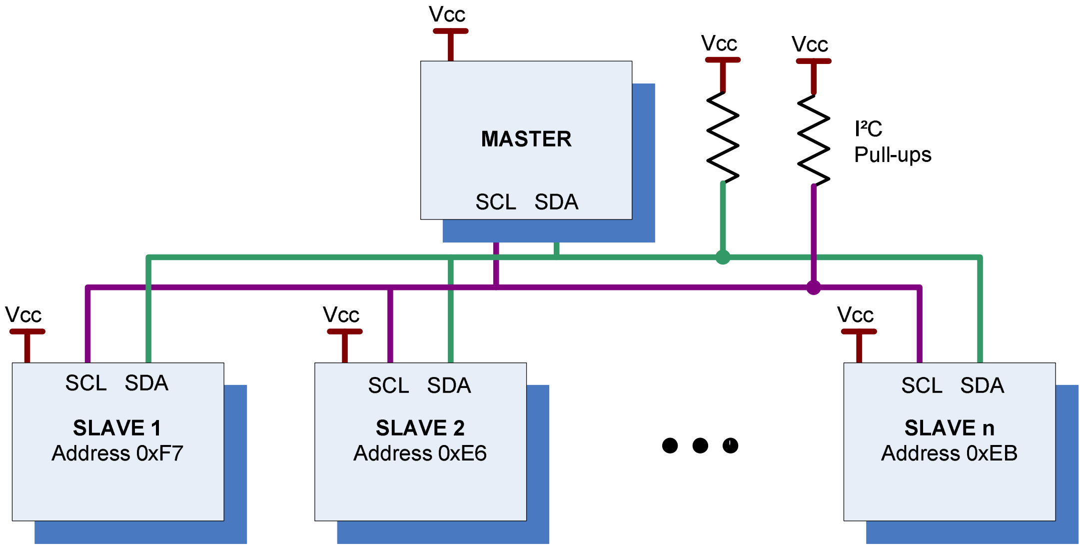


Figure 12.2.2.1: Single-master, multi-slave I²C connections

If you look at the development board schematics for this course, you will see another example of a single master, multi-slave system. The LPC214x is the master device on I²C0, and the LCD and Blade daughter board are slaves on the bus. Though you probably do not have a daughter board connected right now, there are many possible devices that you could tie-in to the development board very easily. Memories, sensors, input devices, etc. Even things like Arduino shields could be attached and used with this system. Of course, any custom device you want to build could also be attached as long as you give it I²C connectivity. No matter how many daughter boards with I²C devices you attached (up to the limit of the addresses available, anyway), the same two wires from the MCU will be used to talk to them all.

When no communication is occurring we call this the idle state, during which the master and all the slaves keep their respective SCL and SDA GPIOs in a high-impedance state. Low signals are driven by the device that has control of the bus lines, but high states are always achieved by resetting the line to a hi-z state and letting the pull-up do the work. Because of this, the designer must consider the speed of the bus and the capacitance that each device on the bus adds. There is a tradeoff to select the correct pull-up resistor size to get a good low signal level voltage and to minimize current draw during communication (since in the low state, the resistor is between Vcc and Vss). It also impacts the signal response time due to the bus capacitance. If there is one master and one slave on the bus, then 10k pull-ups are usually selected. As you add more devices (or longer bus lengths), the resistor size is reduced perhaps to 4.7k but may be as low as 1k or less to provide a stronger pull-up. At some point in the design phase, you should put an oscilloscope probe on SCL and observe the clock signal to determine if the edges are fast enough. Figure 12.2.2.2 shows a rough example of what the SCL signal might look like with and without proper pull-ups. System capacitance also plays a role, as does clock speed. While you will never achieve an absolutely perfect square wave, you should have a reasonably good quality signal.

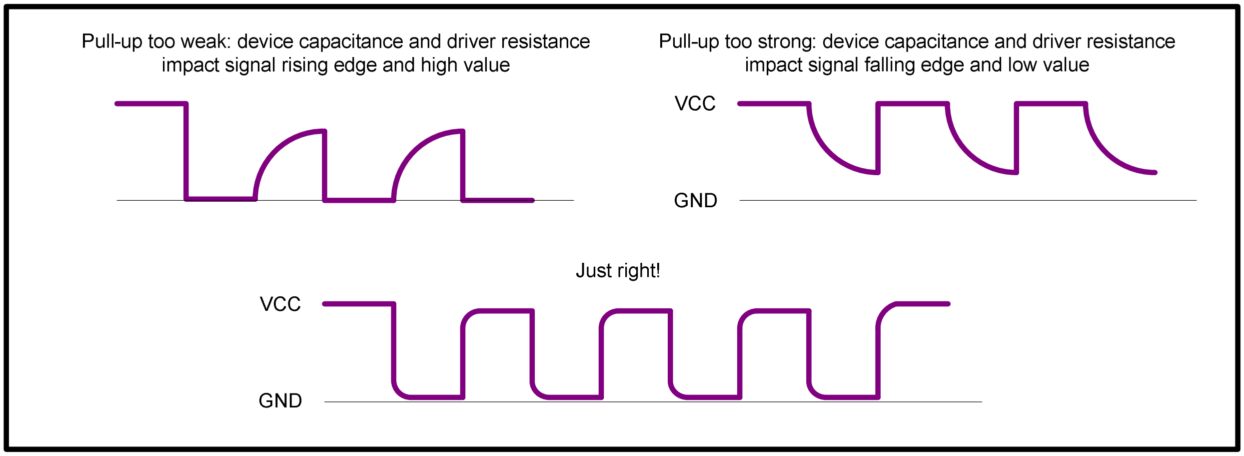


Figure 12.2.2.2: Signal examples for I²C clock lines

I²C communication speed is typically 100 kHz, but there is a 400 kHz hi-speed version that some devices support and even faster speeds on newer devices. Since the protocol is synchronous and the clock is always provided by the master, the clock does not have to be perfect and can start and stop as needed. In fact, there is a special mode called "clock stretching" that allows communications to pause. This is allowed by both the slave and master, though on single-master systems only one master has exclusive control of the clock so clock stretching does not apply. However, it is a valuable option to have for the slaves. Allowing the slave to hold the clock line low is a great feature of the protocol that lets the slave do basic flow control without adding any additional hardware lines. Remember that the SCL and SDA lines are only driven low by devices and it is up to the pull-up resistors to pull the lines back high. When the master is driving the clock, it releases the line (changes to high-impedance) and expects the line to return to Vcc. An edge detector allows the master to know when this happens. The slave can take extra time to process the received information whenever it needs between bytes or groups of bytes by activating its SCL driver to keep the line low until it is ready for the next byte. Because of the output low / high impedance signaling, there is no risk of hardware problems like shorting high signals to ground. Depending on the master, there may be a certain maximum time that the slave can hold the clock line low before the master decides that the communication has failed and tries to reset the bus (and perhaps reset the external device).

12.2.3 I²C Logical

Signaling for I²C is quite neat as there is a fair bit of control and handshaking information communicated between devices on the bus even though there are only two physical lines. For discussion in MPG (and probably for most of the systems you will work with), 7-bit addresses will be used which makes it easier to look at since the complete address is contained in a single byte. If 10-bit address are required, be sure to set up the I²C peripheral accordingly on both the master and slave(s) on the bus. Some devices may not support 10-bit addressing, so be careful when specifying parts that will share the same bus.

When no communication is taking place, SDA and SCL are high and the bus is idle. To begin communication, the master initiates a "start condition" on the bus, which is the act of bringing SDA low while SCL remains high. This transition order is a known special case per the protocol and never occurs during data transmission so it can be identified by all devices on the bus. As a rule of the system, all slaves on the bus are normally idle and looking for the start condition to occur. The master then broadcasts the 7-bit address in the top 7 MSbs of the first byte and adds a read (1) or write (0) bit for the 8^{th} bit (the LSb). The master toggles the clock line for each bit in the address byte, and always adds an additional clock cycle for a ninth bit. When the slave sees its 7-bit address on the bus plus a read/write bit, it will acknowledge the address by holding the data line low on the 9^{th} clock provided by the master. As long as one of the slaves on the bus sees its address, the master will get an ACK and know that the slave it addressed is ready. This is illustrated in Figure 12.2.3.1.

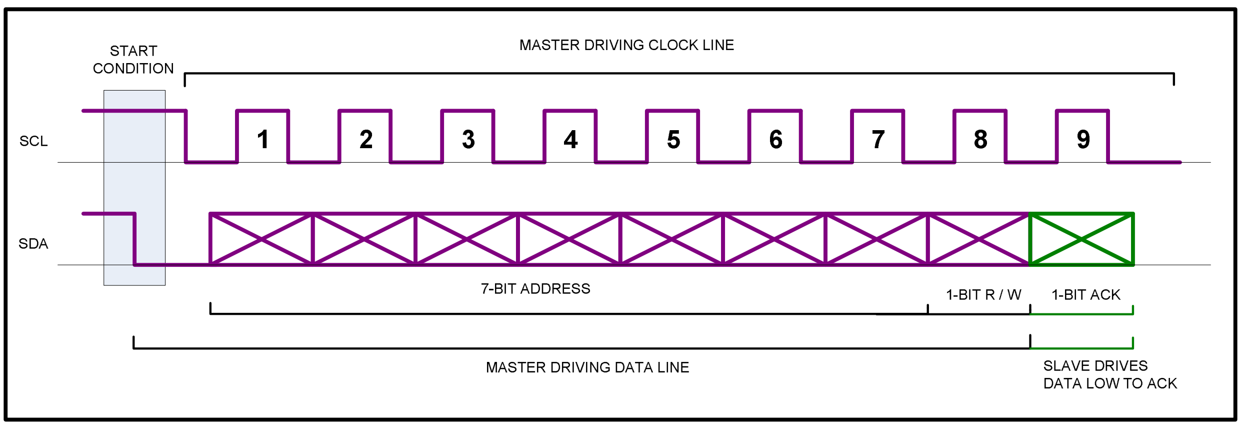


Figure 12.2.3.1: Start condition and address byte

If the master has sent an address that does not match any of the devices on the bus, then nothing will hold the data line low and therefore no ACK will be seen by the master. At this time, the master would set a Stop condition on the bus and then try to figure out why a device that should have responded did not. There is no provision to handle two devices on the bus with the same address – that is a problem that is up to you has a designer to avoid. It is also assumed that the master knows what device it expects to talk to for every given address it uses to communicate. Though there are ways to "discover" devices on the bus, the most typical applications have known devices at known addresses that the master uses.

Assuming a device ACKs the address byte, data transfer will begin on the next transmitted byte. All other devices that did not see their address will ignore subsequent communication for the current session. If the master is transmitting data to the slave (LSB in the address byte was 0), the slave is expecting that the next byte on the bus is the first data byte in the transfer from the master. The slave ACKs every byte sent by holding SDA low at the end of each byte just like it did when it ACKed its address. The master can continue transmitting bytes for as long as it wants and as long as the slave can handle all the data and keeps ACKing. Once the last byte is sent, the master puts the stop condition on the bus (SDA goes high while SCL is high) which terminates that communication session.

To receive data from a slave, the master puts a start condition on the bus and sends the slave's address with a "1" bit as the LSB. Once the address byte is sent and acknowledged by the slave, the master assumes the slave is ready to send data and activates SCL to clock in bytes which the slave should be sending. The master will ACK every byte from the slave during transmission, which indicates to the slave that it should keep sending data, though it is still up to the master to provide the clock to enable the slave to send. When the master has had enough data, it NAKs the last byte and then puts a stop condition on the bus. The master has full control over how many bytes the slave sends.

The question you might be thinking about is how does the slave know what data to send? The situation depends on what the slave is, as it will have data available in different ways. One of the most common schemes is setting an address pointer in the slave by writing a register address prior to reading data, and then clocking out a known number of bytes. Both the master and slave know how many bytes will be sent for any given transaction. The master might also tell the slave how many bytes it is looking for, which requires the master to first address the slave with a write to send it a command or other information to setup the data transfer. The master would terminate the write frame, and then immediately start another frame but this time in read mode. The slave, having just been told what the master is looking for, can then expect to provide the data to the master.

A complete I²C read transaction might proceed like this:

1. Master issues start condition and sends slave's address with write bit
2. Slave acknowledges the write address
3. Master transmits the start address that it wants to read data and the number of bytes it wants to read
4. Slave acknowledges each data byte and knows what the purpose of each byte is based on a predefined protocol
5. Master issues a repeated start condition (which is essentially a stop condition and then a start condition)
6. Master transmits the slave's address with the read bit
7. Slave acknowledges the read address
8. Master clocks in the number of bytes it wants, ACKing each one as it is received
9. Master NAKs the final byte to confirm it is done and puts the stop condition on the bus.

Typically the slave is set up to read the register address the master sends and set a pointer to that location in memory. The slave will then automatically increment its internal pointer after every byte it sends. In a simpler case, a slave may only have a single register to output so the same data is sent each time (like an 8-bit temperature sensor). In this case, the master would only ever have to read data and not worry about specifying an address or sending commands. If the master tried to read multiple bytes, then it might just keep getting the same information over and over again. There are lots of scenarios that you can come up with that may need to be handled depending on the system you are working with. Regardless of what you are trying to communicate with, the key is to read the device datasheets to see what it can do and how to do it. You may then write a specific driver set to run with your system to access the slave, or it might fit in with a more generic I^2C driver you can write. At the very least, you can write generic I2CStart(), I2CStop() and I2CData() functions, and incorporate the target device protocol within an application state machine that will read or write data use the base functions.

The last feature of this protocol to mention is the reserved addresses in the scheme, of which there are five or six. The one you see the most and will probably use is the "general call" or generic address, 0x00. All devices will listen to the general call address and ACK it, and will then receive a single command byte. These special addresses and data bytes along with every other detail about I^2C can be found on www.i2c-bus.org.

I^2C tends to be a very popular choice for on-board communications in an embedded system due to the addressing capability and simple hardware requirements, though some high throughput devices requiring more speed may choose a different protocol. No matter how many devices you have on the bus (as long as you do not go over some physical resistive and capacitive limits or the physical address size), you only ever need two GPIOs on your microcontroller. You can probably make a safe bet that you will implement I^2C at some point in your embedded career.

12.3 Implementing I^2C on the LPC214x

Hopefully the implementation of I^2C does not sound too complicated. Though there is certainly more involved than with RS-232, I^2C is still relatively simple. While most MCUs have I^2C peripherals now, you still might end up bit-bashing a driver if you are working with some legacy product or if you run out of peripherals on your microcontroller. That becomes a bit challenging and you would need to do some further investigation to understand and implement the full I^2C protocol. As far as writing the driver for the course, we will make use of the I^2C peripheral on board the LPC214x and write a nice little driver for all of our needs. Download the Chapter 12 start code now if you have not yet already done so.

We will focus on master mode only and consider just transmit functions. Because of the way that this peripheral works, interrupts are essential. There are quite a few things to take care of to make everything work the way we want.

1. Peripheral configuration in i2c_lpc214x.c/h.
2. Interrupt configuration and handler in interrupts.c/h.
3. I^2C application initialization and operation.

12.3.1 I^2C Peripheral Registers and Configuration

This peripheral is a bit more complicated than the peripherals we have worked with so far, but that is because it has a lot more to do. The peripheral itself operates as a state machine and is quite strict in how it implements the I^2C protocol. It is definitely different than some other microcontrollers where the I^2C peripherals are much more manual in their operation. Remember that the microcontroller vendor, NXP, is responsible for adding all the peripherals to make up this microcontroller, so this I^2C peripheral hardware is specific to NXP. If you work with an ARM7 core on a different vendor's microcontroller, all of the peripherals will be different – some substantially so – than this one. The good news is that if you stay with NXP, then you will see very similar peripherals on other processors in their ARM family (ARM7, ARM9, Cortex-M3, etc.) and may be able to easily port over your code.

The I^2C chapter in the processor reference guide is quite lengthy, but there is a lot of information that does not apply to the case we want to design for. You can ignore anything that talks about slave mode since we will use master mode exclusively. You can also skip all of the details on how the bus works since that information has already been covered in these notes (though if you want a second explanation, take a read from NXP!). As we have done many times before, reading through the register description is essential to correctly set up the peripheral registers. Lastly, there are four pages that are worth printing for developing the algorithm that works with the peripheral's state machine – the Master Transmit and Master Receive mode transmit flowcharts on pages 224 and 225, and the corresponding status code tables on page 228 and 229 of the Rev. 3 October 2010 guide. If you print them 4-up on a single page you will have all the information you need to reference at hand.

As it turns out, there are not that many registers involved with the I^2C peripheral. Most of the available registers are used while the application is running, so very little setup is required.

I2CxCON: Control register accessed through I2CxCONSET and I2CxCONCLR. Only the interface enable bit (bit 6) needs to be set by writing 0x40 to the set register. Other bits are used to initiate I^2C actions like Start and Stop conditions, and some bits provide status information.

I2CxSCLH and I2CxSCLL: Duty cycle configuration registers. These hold the number of processor peripheral cycles that the serial clock signal will spend high and low. Remember from the UART baud calculation that the peripheral clock, PCLK, is set the same as the main clock of 12MHz. If we target a 100 kHz I^2C clock, a full period is 1/100 kHz = 10us. With 50% duty cycle, the high and low times are both the same duration and equal to half the total period, 10us / 2 = 5us. To pass 5us with a system clock period of 1/12MHz = 83.3ns, we need 5us / 83.3ns = 60 = 0x3c. Note that for higher speed communication, the I^2C specification requires a non-50% duty cycle, so these registers will not always necessarily match.

I2CxSTAT: Status register. Bits 3-7 hold a status code that will guide your application through the I^2C state machine. More on this later.

I2CxDAT: Transmitted or received data register. Since I²C is half-duplex, only one register is needed for data. Just make sure you do not forget to read this register before writing to it if data has arrived! Note the bit order for transmission is not selectable for MSb or LSb first, so you have to make sure that the target system is sending and receiving the same else you will have to flip bits prior to writing the register or flip bits on received data.

I2CxADR: Address register that sets the microcontroller's I²C address if it is a slave. This is not required for master mode since a master in a single-master system is never addressed.

The peripheral registers are loaded in I2C0Setup() which is called from main() during initialization. The setup function power cycles the peripheral with the PCONP bit and the peripheral enable bit to try to ensure a full reset in case something has gone horribly gone and setup is called when the bus is not idle. This should, technically, never happen, but a stuck bus is never a good thing so doing everything possible to start it correctly is worthwhile.

If you interrupt an I²C transaction with the debugger and then do a software reset, it is quite possible to have the bus stuck in a strange state that you cannot seem to get out of without power cycling the whole board.

12.3.2 Interrupts

It is virtually impossible to use the NXP I²C peripheral without interrupts and get any decent transmit or receive speed, so we will set up the required interrupt driver now. While you might be thinking you will need to enable transmit and receive interrupts just like in the UART, the I²C peripheral happens to have just a single interrupt signal and enabling a single bit in the VIC is all it takes to make the interrupt active. The peripheral relies on firmware to read a status code that tells the firmware what just happened to cause the interrupt. Based on the status code, our firmware will take the necessary action to progress through the peripheral's state machine as we will see shortly.

First, do the easy task of setting up the interrupt source in the VIC. Since I²C is handling fairly important data and the data rate is quiet fast, make its interrupt priority the highest under IRQ. The following tasks are left for you:

1. Activate the I²C0 interrupt by setting the bit in VICIntEnable_INIT (interrupts.h)
2. Declare the I2C0ISR function (interrupts.h)
3. Set VIC_I2C0 as the first priority in IRQ and shift the others down (interrupts.h)
4. Add/adjust appropriate initializations for the updated VICVectCntlx registers (interrupts.c)
5. Add/adjust appropriate initializations for the VICVectAddrx registers (interrupts.c)

After some playing around with this I²C peripheral, the best strategy for implementing the driver was determined which involves doing quite a bit in the interrupt handler. The ISR code ends up looking fairly long and integrated into the I²C functionality, which goes against the preferred guidelines of writing short, non-integrated ISRs. However, the nature of the communication protocol practically demands it and even though there is quite a bit of code, only a few lines get executed for any given interrupt. The first version of this driver relied on disabling and enabling interrupts all over the place to avoid having a lot of code in the ISR, though there was still a fair amount in there. You might say it was resisting the way that the peripheral intended for it to be used and was rather ugly and almost impossible to describe in notes. So a second version was written for the course and follows the intended flow dictated by the I²C peripheral. You might want to take a few moments to think about how you might design it a different (a possibly better) way! Note also that we are writing the ISR very specifically for I2C0 and only worrying about the transmit case since the development board LCD cannot send back data that we would have to receive. So it is really only half done and not very generic, but could be easily completed and applied to other I²C peripherals when required.

Look at the I2C0ISR handler in interrupts.c, which is partially finished in the “start” code. At the same time, look at the I²C peripheral state machine flowchart on pg. 224 of the reference guide. Figure 12.3.2.1 below shows the relevant portion of the flowchart that the ISR will handle.

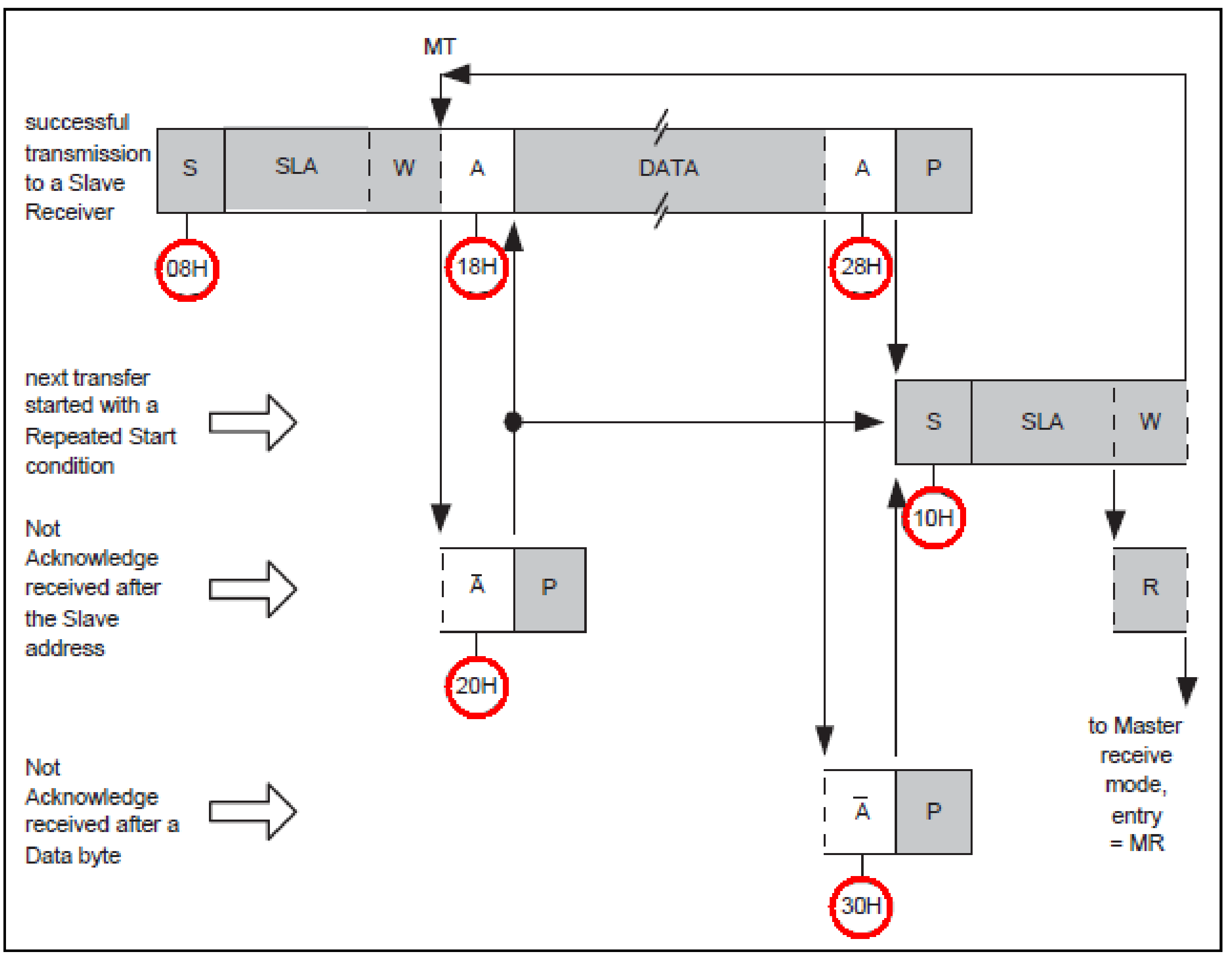


Figure 12.3.2.1: I²C peripheral flow chart: Master Transmitter
Source: LPC214x User manual Rev. 3 – 4 October 2010, pg. 224, NXP Semiconductors, UM10139.pdf

Each of the red circles is the status code that will be present in I2C0STAT after the I²C interrupt occurs. I2C0ISR() parses the status code with a switch statement to determine the next action. While the interrupt flag bit remains set (it was set to trigger the ISR), the I²C peripheral is waiting to continue and will not carry on until the interrupt flag is cleared. The peripheral proceeds immediately once the flag is clear, which brings about the trickiest part about writing code for this peripheral and thus necessitates taking action inside the ISR.

What has to happen in firmware ends up breaking down quite easily once you have spent some time trying to figure out what exactly is going on and how it all works. Debugging skills are important for something like this to be able to step through code in the main application and interrupt service routine while ensuring you observe the right peripheral registers. An oscilloscope is nice to have, too, but not entirely necessary. The difficult part is understanding what triggers advancement to the next state in the I²C peripheral state machine. To sum it up simply, you must always do things in this order:

1. Interrupt occurs
2. Write the I²C data register with either the external address or the data byte you want to send
3. Clear the interrupt flag
4. Exit the interrupt service routine

You MUST write the data byte before clearing the interrupt flag, because as soon as the flag is cleared the I²C peripheral advances states and will send whatever is in I2C0DAT even if the program counter is still stepping through I2C0ISR. Since you have to clear the flag to get out of the interrupt service routine and back to your main program, you have (almost) no choice but to update I2C0DAT within the ISR. If you are sending a long message, that means you have to manage the transmit buffer in the ISR, too.

For the record, you *could* disable the I²C interrupt inside the ISR and then avoid clearing the interrupt flag until you have loaded I2C0DAT inside your I²C application. This would let your main program control the peripheral writes and avoid doing it in the ISR. It does not end up working very nicely though and requires considerable effort to work around what the I²C peripheral really wants to do.

During the main program, the I2C0ISRs take care of the entire message transmission. The I²C application is responsible for setting up the message to be sent and initiating the Start condition that gets the I²C peripheral going to transmit the message. Once that has stared, the application simply waits for all the bytes in the message to be sent while watching for an error or timeout. The only exception is during LCD initialization where special timing requirements of the LCD controller during initialization make the interrupt-driven approach unfeasible. So this will be handled as a special case with interrupts off. Once you see the I²C application in the next section this will make sense, and then you will be able to add the necessary code to the ISR.

Some oscilloscopes and logic analyzers have software I²C serial decoders for those times when you need to do some serious debugging. These would be most likely be used to find data errors or problems between two devices communicating back and forth with hundreds or thousands of transmissions.

12.3.3 I²C application initialization and operation

The I²C application occupies i2c_lpc214x.c/h and holds the specific functions to run the peripheral and handle messaging. On its own, it does not really do anything and there is not really any test functions that can be written just for testing the I²C peripheral. If you really wanted to test the driver, it would be a great idea to hook up I²C0 to I²C1 and run a few billion bytes between the two peripherals over a weekend. However, our development board exercise does not require such thorough testing.

The set of functions you would find in an I²C driver file will most likely include some initialization plus Start(), Stop(), Write() and Read() functions that interface directly to the peripheral – these are the staples of any I²C peripheral regardless of processor. By building a standard interface to those functions and using them in the rest of your code, you get good abstraction from the hardware and thus good portability for the higher level part of the driver. The function implementations are mostly done, but you need to complete I2C0Stop(). All of these functions are considered protected. They are not private because some low-level access will be required from the LCD application and possibly from other I²C device applications that use the same bus.

Three other functions are specific to this driver implementation, so we will take a quick look here along with a look at the state machine that monitors data transmission.

12.3.3.1 void I2CForceSend(void)

As you have seen with other applications, a "manual mode" for the state machine is necessary so the application can be used during initialization when the regular main program loop is not running.

12.3.3.2 bool QueueI2C0Message(u16 u16DataSize_, u8 *pu8Data_)

This is the one and only public API function that other applications will use to queue messages to the I²C peripheral for transmission. It takes an array of bytes along with the size of the array so exactly the right amount of memory can be allocated and we do not have to worry about parsing termination characters. It is up to the calling application to correctly format the message, including getting the right target address with read/write bits as the first byte and all the other bytes in the right place so the message makes sense to whatever will receive it.

Messages are kept in dynamic memory in a linked list. There is no error checking beyond some while(1) traps to ensure that there is enough space on the heap to accommodate all the messages that might be queued. However, it is not expected that any problems would occur in this system given the small amount of messaging taking place to the LCD. That might not hold true for other systems, so be sure to code accordingly!

Dynamic memory is often "outlawed" by companies because of the potential chaos that could result from heap overflow and/or memory leakage. Be sure you know the acceptable practice when you write code for someone.

12.3.3.3 void DeQueueI2C0Message(void)

As you can guess, this function takes care of cleaning up the transmit linked list for the message that was just sent. The I^2C state machine takes care of calling this function, so it is considered private. Removing the responsibility of managing dynamic memory correctly from the user of the class is a great way of ensuring no heap-related errors will start appearing in the system. Since you probably love managing linked lists correctly, the implementation of this function is left for you to do in the code, though the completed function is shown below.

```
void DeQueueI2C0Message(void)
{
  MessageStructType *psNextMessage = NULL;

  if(GGsI2C0CurrentMessageToSend != NULL)
  {
    /* Point to the list node after the doomed node */
    psNextMessage = GGsI2C0CurrentMessageToSend->psNextMessage;

    /* Kill the doomed node's data and the doomed node itself */
    free(GGsI2C0CurrentMessageToSend->pu8MessageData);
    free(GGsI2C0CurrentMessageToSend);
  }

  /* Update the list pointer to the new first element */
  GGsI2C0CurrentMessageToSend = psNextMessage;
  if(GGsI2C0CurrentMessageToSend == NULL)
  {
    LGsMsgLastMessage = NULL;
  }

} /* end DeQueueI2C0Message() */
```

12.3.3.4 I^2C0 State Machine

Since most of the work of sending data is taken care of by interrupts, the state machine for the I^2C driver is fairly simple. The state diagram for the system is shown in Figure 12.3.3.4.1.

The Idle() state monitors the transmit buffer pointer and does nothing unless a message has been queued. When a message is ready, it initializes a timeout counter and uses I2C0Start() to kick the peripheral into action. As soon as that is done, I2C0ISR() will take care of sending the message out.

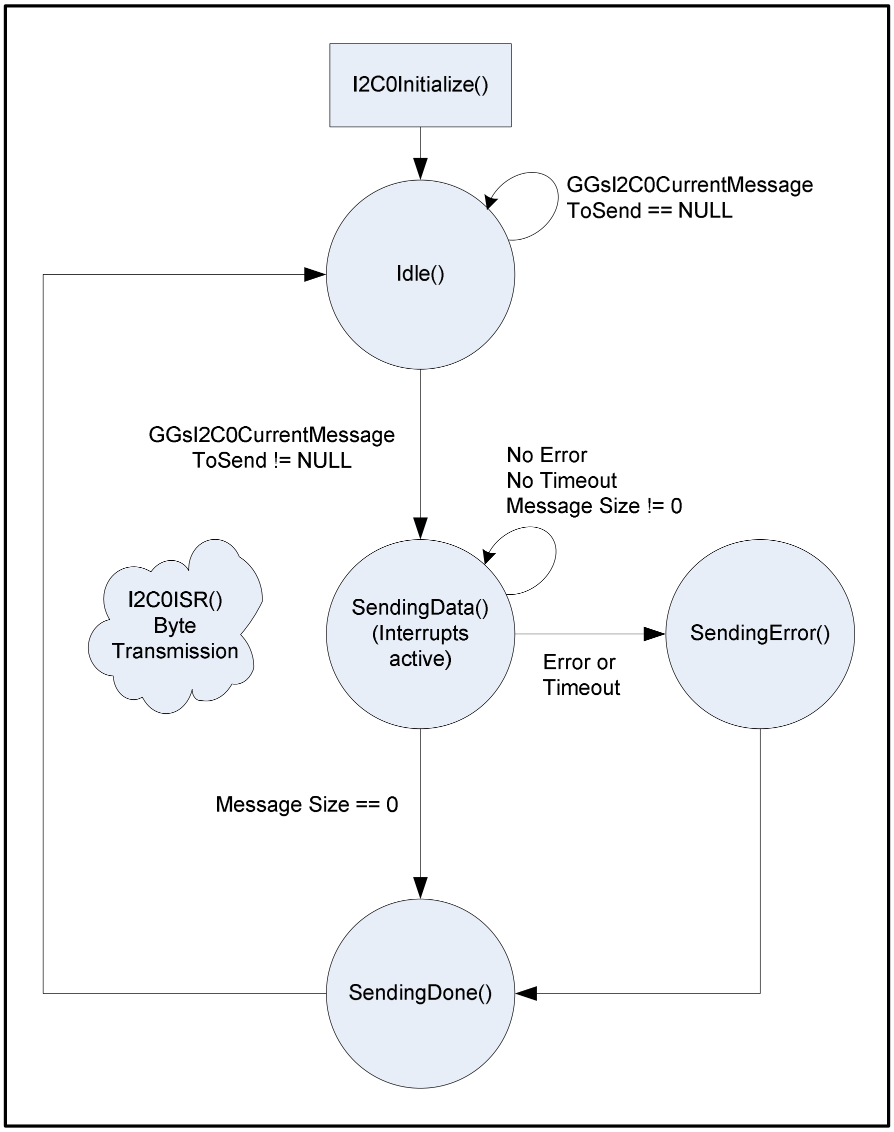


Figure 12.3.3.4.1: I²C application state diagram

The I²C application waits in the SendingData() state looking for either an error, timeout, or the current message size counter reaching 0. Given how short a typical LCD message is, the message is probably finished transmitting by the time the next 1ms period expires and SendingData() is called the first time. This is in sharp contrast to the UART driver we built where transmitted bytes were sent once per 1ms iteration since the baud rate was just 9600bps with two bits of overhead per byte. At 100,000bps and only 1 overhead bit per byte, the I²C driver is way faster!

If an error has occurred, the application goes to the SendingError() state which does not do too much right now beyond stopping the bus and getting things ready for the next message. In the current implementation, the message that was being sent would be lost if an error occurred. You could add some additional code to feed back information to any application that queued the message so that it could decide whether or not to resend the message. One could argue both ways that the I^{2}C application should or should not guarantee that it delivers a message it was given to send. Once again, the programmer is faced with choosing trade-offs in designing for the needs of any particular system.

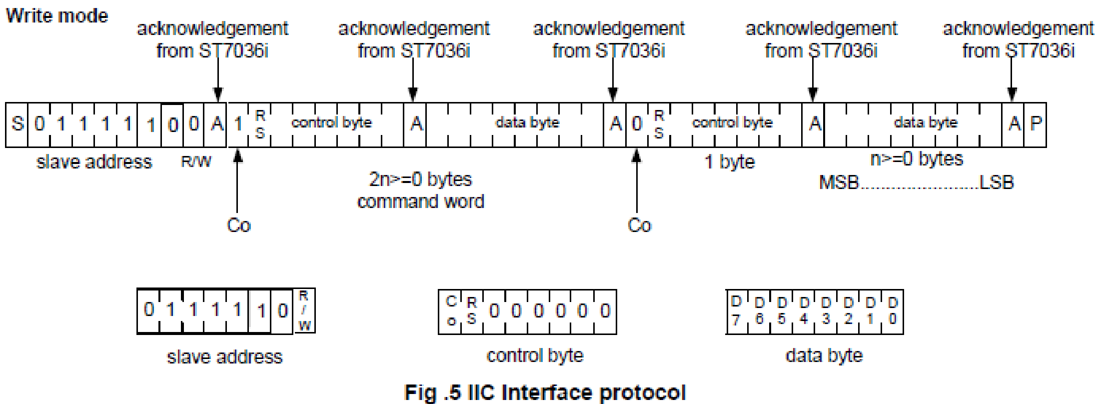
After the error state, or if a message has been transmitted successfully, the SendDone() state is active. SendDone() exists as its own state to give a common conclusion to a cycle through the state machine. It takes care of freeing the memory for the current message and returns the application to Idle. It will never run for more than one consecutive cycle as it does not wait on any event. Like SendingError(), SendDone() could be used to provide more insight back to other applications on the status of the transmission.

12.4 Using the LCD Controller

Now that we have the mechanism for communication to the LCD, it is time to program an interface to the controller to allow access to configuration and message display on the screen. Fortunately, alpha-numeric displays with an ASCII interface are pretty easy to use since the built-in controller will handle the somewhat complex pixel driving tasks. All we need is to program the interface to meet the protocol and write some functions to send character updates. If you have not read the data sheet for the LCD yet, you pretty much cannot go forward without doing so. What you need to note from the data sheet now are five things:

1. LCD I^{2}C address
2. Control byte
3. Character RAM addresses
4. LCD command set
5. LCD initialization sequence

Note that the data sheet linked on the course website is prepared by the LCD vendor, Newhaven Display, and describes the complete LCD and not just the controller. That being said, much of the information is a subset of the full LCD controller data sheet that you can find via a link in the same data sheet. The controller's data sheet is 70 pages long and contains a lot of information that you do not really need to use the LCD, though you may want to browse to learn more. Newhaven's data sheet captures the most useful information from the controller information along with the relevant hardware references, electrical specifications and example code for initialization. There are a few details that did not make it over that might be nice to know, such as how the I^{2}C version of the controller only supports Write mode (see page 14 of the controller data sheet). Both documents have the drawing shown in Figure 12.4.1 that we will reference several times in the following sections.



Co	0	Last control byte to be sent. Only a stream of data bytes is allowed to follow. This stream may only be terminated by a STOP condition.
	1	Another control byte will follow the data byte unless a STOP condition is received.

Figure 12.4.1: I²C command example from controller specification
Source: Sitronix ST7036 Dot Matrix LCD Controller/Driver data sheet, pg. 16

12.4.1 LCD Address

The address byte is the first byte sent to an I²C device after the start condition. Remember that the I²C standard dictates that device addresses are 7 bits in length plus the Read (1) or Write (0) bit that is always the LSb. Specifying the device address does not seem to follow a standard form. For example, if the address of a device is given as 0x64, that might mean the full 8-bit address byte you send to Read the device is 0x65 once you set the LSb high to indicate Read, or it might mean that the first 7 bits are 0x64 (b'1100100x') and you need to add an 8^{th} bit for x=R/W. We attempt to illustrate this in Figure 12.4.1.1. but admittedly it is a little hard to explain in text.

0x64	***Specified device address***							
MSB	**6**	**5**	**4**	**3**	**2**	**1**	**LSB**	**Comment**
0	1	1	0	0	1	0	0	Specified address includes the R/W bit - "Write" address is 0x64
0	1	1	0	0	1	0	1	"Read" address is therefore 0x65
1	1	0	0	1	0	0	0	Address was meant as only upper 7-bits - "Write" address is 0xC8
1	1	0	0	1	0	0	1	"Read" address is 0xC9

Figure 12.4.1.1: Illustration of how a specified I²C address can mean several things

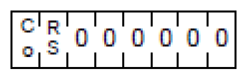
Fortunately, in the case of the LCD controller, the diagram in 12.4.1 shows the actual bit detail of the address byte so you can deduce that the write address is b'01111100' = 0x7C. Unfortunately, that is NOT what the device address is. If you dig through the longer controller data sheet, you will find some explanation on page 16 that describes four different possible addresses that the controller can be set to. The address that Newhaven picked happens to be different than the one the LCD controller vendor picked for their example.

Regardless, the Newhaven data sheet says in large bold letters that the address is 0x78 but they fail to mention which of the above formats that value is in. With a quick bit of testing, the complete LCD Write address byte was confirmed as 0x78, so this particular specification format matches the first case shown in Figure 12.4.1.1. This address is captured as a constant in the header file, LCD_ADDRESS_WRITE. This test was carried out during driver testing to confirm that it was acknowledged by the LCD. Fortunately, that part of the example code was correct. Imagine if you were not sure if you had the correct LCD address and spent hours (or days) debugging your I^2C driver and/or board hardware because the LCD refused to respond to its address, only to (finally) try changing the address and discover that everything was working just fine! It is problems like that which are extremely frustrating, especially with the tight deadlines that you will always have in industry.

12.4.2 Control byte with Co and Rs

Communicating to the LCD requires following a strict input and output protocol that is very typical of any MCU-IC interface. After LCD controller acknowledges its address, the next byte sent must be a control byte that has two important bits called Co and Rs. Rs is the bit used to tell the LCD if the bytes that follow are meant as control codes or simply data that should be written to the screen. If you read the controller data sheet, you will see a truth table that shows that Rs works in conjunction with the R/W bit to get four different modes from the LCD controller. However, as we have mentioned already, the I^2C version of the LCD controller does not support Read operations, so there is only in fact two modes that can be accessed:

- Rs = 0: Instruction mode
- Rs = 1: Data mode



control byte

The Rs bit works in conjunction with the Co bit.

- If the Co bit is set, then the next byte sent will be interpreted as a data mode byte or instruction mode byte depending on what Rs was. The byte after will be interpreted as another control byte allowing you to change the Rs bit and thus toggle between data or instruction mode.
- If the Co bit is clear in the control byte, then the controller assumes that all subsequent bytes in the transmission session are of the same Instruction mode or Data mode that is indicated by Rs so you can send a series of bytes in the same mode.

In other words, the Co bit allows you to change modes during a transmission session. There might be a scenario where you wanted to send a command byte, send a data byte, send another command byte, send another data byte, etc. There would be some extra overhead if you had to set a stop condition and restart a new frame each time you wanted to change modes. However, this scenario is unlikely to occur so the Co bit tends to be unused. For all of the communications in the driver we build here, Co is always 0 so each transaction will only ever be a bunch of commands or a bunch of data. If we need to switch modes, the session will be stopped and a new one started.

12.4.3 Character RAM Addresses

This particular LCD controller supports screens up to 20 columns x 4 rows. The ASCII character data that ends up being displayed on the screen is stored in the controller's "Display Data RAM" (DDRAM) in which there is 80 bytes of space. Even if you have an LCD screen that is smaller than that, you can still write to all the character addresses and the data will be stored but not displayed beyond the addresses that are visible on screen. You can use the non-displayed area as general purpose RAM if you really wanted to, or make use of the shifting features to do some message scrolling. For the 20 x 2 implementation of the course LCD, the RAM is organized as shown in Figure 12.4.3.1 from the LCD controller data sheet. Note that the Newhaven LCD data sheet shows an address range for a 16 x 2 display instead of a 20x2 display.

Display Position	1	2	3	4	5	6		38	39	40
DDRAM Address (hexadecimal)	00	01	02	03	04	05	....	25	26	27
	40	41	42	43	44	45	....	65	66	67

Display Position	1	2	3	4	5	6	7	8		17	18	19	20
DDRAM Address	00	01	02	03	04	05	06	07	....	10	11	12	13
	40	41	42	43	44	45	46	47	....	50	51	52	53
For Shift Left	01	02	03	04	05	06	07	08	....	11	12	13	14
	41	42	43	44	45	46	47	48	....	51	52	53	54
For Shift Right	27	00	01	02	03	04	05	06	....	0F	10	11	12
	67	40	41	42	43	44	45	46	....	4F	50	51	52

Figure 12.4.3.1: LCD Character RAM

Source: Sitronix ST7036 Dot Matrix LCD Controller/Driver data sheet, pg. 16

The displayed characters for Line 1 will be at addresses 0x00 thru 0x13 and hidden characters will be at 0x14 thru 0x27. Line 2 visible addresses are 0x40 thru 0x53 with hidden characters 0x54 thru 0x67. The second part of Figure 12.4.3.1 shows what happens when you request a shift command (either left or right). For Line 1, a left shift moves the displayed character range to 0x01 – 0x14; a right shift displays

0x27, 0x00 – 0x12. Line 2 has similar behavior with the important concept being that each line rotates through itself. What all this means is that you should be able to do a bunch of neat scrolling effects on a per-line basis just using control commands to shift the display. The only limitation is that there is just a single shift command so both lines would have to scroll. However, the scrolling behavior does not work like you might expect. Try it during the chapter exercise, but you will find that it will not really work for what the exercise requests you to do.

Scrolling displays aside, you need to be comfortable with the character addressing since you must use it to position the cursor where characters will be displayed. You can write to any location on the screen first by setting the cursor address, then by loading a message.

12.4.4 LCD Command Set

Randomly sending bytes to the LCD will not get you very far – you must use the defined command set to talk to the device correctly. The complete set of commands that you need is shown on pages 7 and 8 of the Newhaven LCD data sheet. Any command where the R/W bit is 1 (Read) is not available in I²C mode.

Most of the commands are pretty obvious for what they do. Many of the commands have configurable bits that need to be set or cleared depending on what you want to accomplish. For example, the Display ON/OFF command is shown as b'00001DCB' so the actual command is b'00001xxx' with three configurable bits (see Figure 12.4.4.1). The command description tells you what the individual bits do.

Display ON/OFF	0	0	0	0	0	0	1	D	C	B	D=1:entire display on C=1:cursor on B=1:cursor position on

Figure 12.4.4.1: Display command example
Source: Sitronix ST7036 Dot Matrix LCD Controller/Driver data sheet, pg. 25

The LCD controller data sheet offers further description of each command and its parameters if you require it. There are some commands like for setting hardware behavior that, to use correctly, you would have to do some reading in the controller data sheet and/or test out some settings. However, Newhaven has done this already and included the information in their suggesting initialization sequence that is discussed in the next section. The only one you might want to play with is the Contrast Set command if your display contrast needs adjustment.

All of the command literals have already been set up in lcd_nhd_c0220biz.h – open up this file and the source code file if you have not done so yet. Most can be used directly, but some, like the Display command above, require you to use a base command word and OR in some other flags that you want set. The Display command shown below uses LCD_DISPLAY_CMD as a root and adds bits to turn the display on, make the cursor visible, and blink the cursor. All those values get packed into a single byte by the compiler so there is no code penalty in using this method.

```
I2C0Write(LCD_DISPLAY_CMD | LCD_DISPLAY_ON | LCD_DISPLAY_CURSOR | LCD_DISPLAY_BLINK);
```

If you are working with a new device, be prepared to spend the time to build a good header file with all of the protocol constants written out. Depending on the type of device you are working with, this might take a few minutes or it might take hours. However, it is worth the time and will save you much frustration continuously referencing the data sheet and/or hard-coding values without meaningful names. Check with the vendor to see if they have a header file that you can download.

12.4.5 LCD Initialization

Before you can start sending regular commands and data to the LCD, it must be initialized in a very specific way (see Figure 12.4.5.1). If you do not follow this sequence, then the LCD will likely not function correctly.

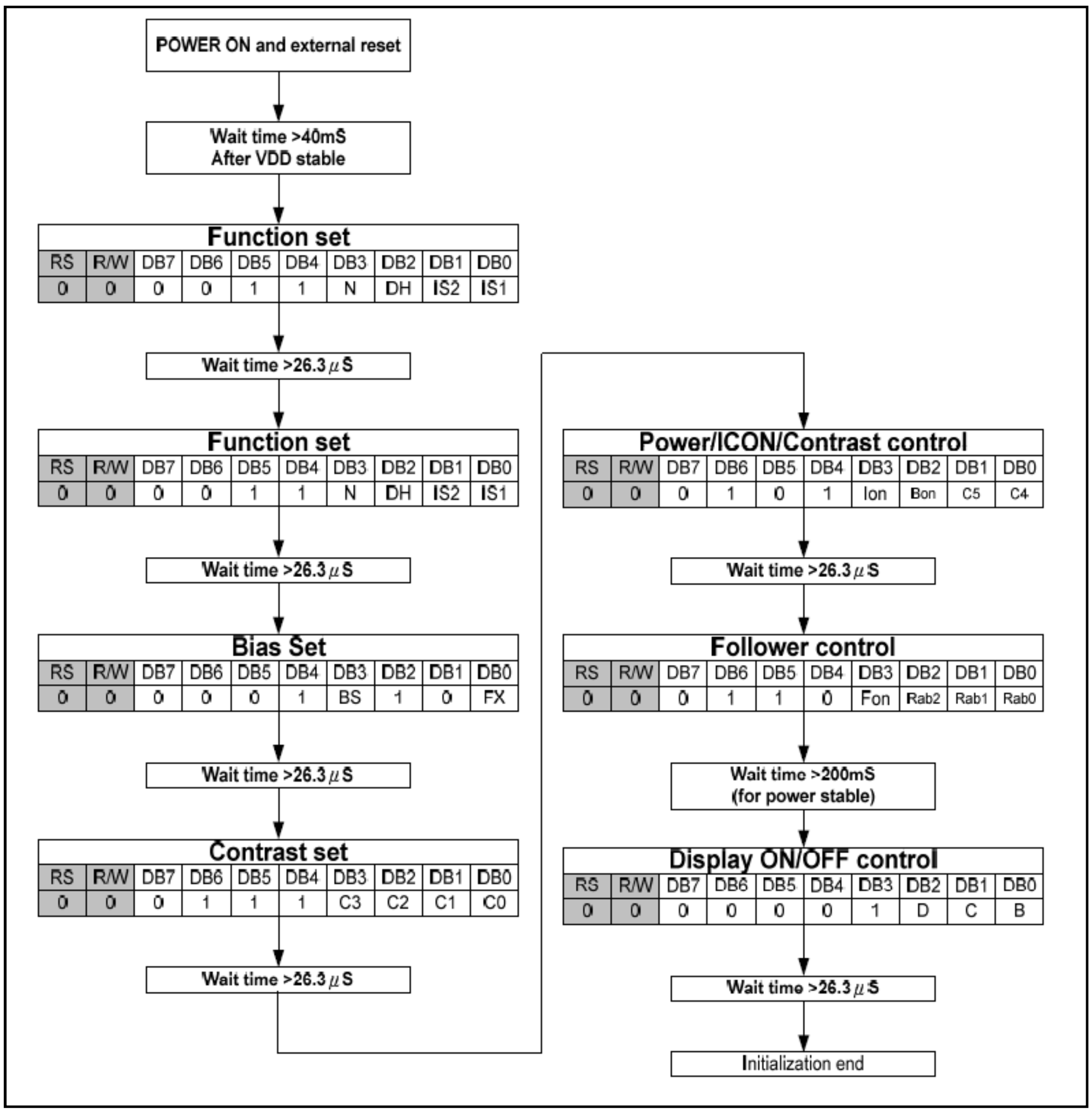


Figure 12.4.5.1: LCD Initialization sequence

Source: Sitronix ST7036 Dot Matrix LCD Controller/Driver data sheet, pg. 41

The sequence shown in the figure is taken from the LCD controller data sheet. The LCD module data sheet from Newhaven does not show this sequence, but instead shows an example initialization code snippet. Since initialization requires specific time delays and our LCD state machine is not even running yet, the function LCDInit() in lcd_nhd_c0220biz.c that implements the initialization uses the I²C commands directly. This is another violation of our general system rules of keeping individual drivers abstracted from others, but working around this would be too cumbersome.

The suggested initialization sequence from Newhaven generally works, though the LCD will often get stuck on the last command 0x06 (LCD_DISPLAY_ON). The command does not get ACKed so the screen does not turn on, which is why every byte is verified that it is ACKed when it is sent from the MCU to the LCD controller. Upon investigation, the timing delays shown in the example code – which are assumed to be 10ms even though that is not made clear -- do not match the specification from the LCD controller. When the LCD controller initialization process is used, the LCD appears to start up more consistently though still suffers errors on occasion. Therefore the driver code provided uses the controller's algorithm instead of the example start-up shown in the module data sheet. The byte verification is left in place because it adds robustness to the system – this is the kind of fail-safe code that you would use for a commercial product where "just press the reset button to try the LCD initialization" is not an option for a user.

All the LCD start-up code is in LCDInit() and it uses a private helper function called LCDWaitSI(). The I²C interrupt is disabled because of the timing requirements and delays between each command byte sent. The LCD's hardware reset line is managed and the function returns TRUE or FALSE depending on whether the LCD is successfully initialized or not. The commands that are sequentially sent with common delays are listed in an array so that they can be index in a loop for code efficiency. As an optional exercise (and since there has not been anything really for you do to in this whole section!), take a moment to verify the command list against the specified initialization flowchart and the values in the header file.

Before moving on, test to make sure the LCD on your board starts up correctly. Put a breakpoint on LedInit() in main and run the code. You should see the display startup message as shown in Figure 12.4.5.2 (cursor is blinking). Adjust one of the commands in LCDInit() so that the cursor is hidden and not blinking after initialization.

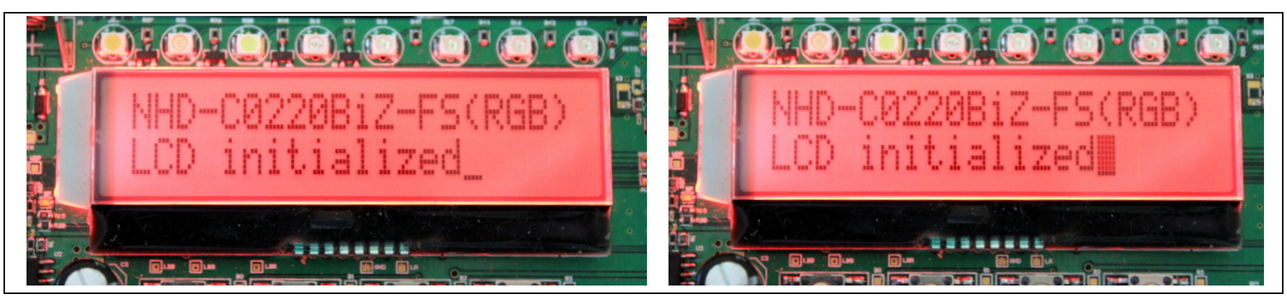


Figure 12.4.5.2: Successful LCD initialization with blinking cursor

Generally speaking, the first time you get something to show up on an LCD is very exciting! If it shows what you expect and does so consistently, that is even more exciting. By getting to this stage, we have proved that the I^2C driver is functioning, the LCD hardware is hooked up correctly, the LCD command set is working and the initialization sequence is correct. Given all the things that *could* go wrong, it is a fair achievement to get to this point. Now comes the easy part of using all the low-level drivers to build the LCD application.

12.5 LCD Application

Even though the lead-up to this point has required a great deal of thought and effort, the final code to write for the LCD application ends up being very simple. The LCD functionality that will be provided is with a set of three API functions that queue appropriate messages to make the LCD perform as required. The functions provided are described in the next sections.

12.5.1 void LCDCommand(u8 u8Command_)

Sending commands is an essential part of using the LCD, especially since the calling application is completely responsible for managing what is on the screen. Moving the cursor and clearing the screen will likely be used most often, but any of the commands might come in handy. The single function parameter takes a literal from the list of LCD Commands in the LCD header file, adds the command into the last location in the command array, and then queues the array to the I^2C application. The array is set up for you, it is up to you to add the two lines of code to update the array and queue the message.

12.5.2 void LCDMessage(u8 u8Address_, u8 *u8Message_)

Loading a character message is the next obvious thing you would want to do. The function takes the LCD address for the first character in the message, and a pointer to a NULL-terminated message string. A command is queued to set the cursor to the desired address, then a message array is populated with the message characters while a character count is kept. Once all the characters have been loaded in the array, the message and its determined size are queued to the I^2C app.

To make this function a little more robust, you could add checks to see if the characters available based on the address provided would fit the intended message. At the very least, you could truncate the message to the available space. Perhaps the function could return a value based on the success of the message or not. You could also add arguments to automatically clear the screen or the line on which the message will be displayed.

12.5.3 void LCDClearChars(u8 u8Address_, u8 u8CharactersToClear_)

The last handy function is one that will clear a smaller group of characters from the screen instead of using the clear screen command that wipes out all display RAM. This is useful for user interfaces or for certain displays where values are changing but you do not want to refresh the whole screen. The parameters are a start address and number of characters to clear. It works almost identically to LCDMessage(), so it is left as an exercise for you to write.

As the LCD functional requirements evolve, it will likely make sense to add an LCD state machine to handle more complex behavior at which point the three API functions would probably become private to the LCD application and a slightly different interface would be provided to applications that would use the LCD service.

For example, perhaps you want to provide vertical or scrolling message capability native to the LCD driver rather than leaving it up to a client application to take care of that (as you will do in the chapter exercise). An application could send text continuously to the LCD which could buffer the strings and display them systematically on screen (e.g. the first message could be displayed for one second on line 1, the 2nd message would be displayed on line 2, and then every subsequent message would be added on line two and bump up the current line 2 message to line 1). It is hard to know exactly what functionality would be desired, so for now we will leave the driver in this state with the basic API.

12.6 Chapter Exercises

This chapter exercise starts out quite similar to Chapter 11 but instead of printing characters out the UART port, characters are printed to the LCD. Copying the relevant part of the Chapter 11 solution will get you going quickly!

Complete the following exercises in chapter12.c/h. All the exercises' functionality should be present in the final code. In the solution provided, each part modifies some of the previous parts, so the solution is not completely sectioned out for each exercise, but you should be able to see how the complete solution progressed especially when you start your own version.

1. When BUTTON1 is pressed, output the string "The counter is: " followed by the 4-digit counter on Line 2 as shown in Figure 12.6.1. Each time the button is pressed, overwrite the value on Line 2 with the new counter value.

Figure 12.6.1: Exercise 1 solution display

2. Adjust the code so that the first instance of the counter output prints on Line 2, and subsequent instances print on Line 2 and bump the previous line up as shown in Figure 12.6.2. You must keep a copy of the current Line 2 and rewrite it to Line1 (i.e. you are not allowed to regenerate the text on Line 1). Hint: <string.h> is included in this package.

Figure 12.6.2: Exercise 2 solution display

3. Make BUTTON2 clear the screen and reset the counter. The counter string should begin printing on Line 1 next time you press BUTTON1.
4. While BUTTON3 is pressed, clear the screen then make the text

```
MPGL1
ROCKS
```

bounce back and forth between the screen edges while the button is held. The character updates should occur at about 4Hz to look good, but make sure you can adjust this easily to speed up or slow down the scrolling action. When the button is released, the screen should clear. While BUTTON3 is pressed, do not respond to any other buttons. Three frames are shown in Figure 12.6.3.

Figure 12.6.3: Three frames in Exercise 3 solution

Bonus: Figure out how to load custom characters to the LCD and create Pac man and ghost characters each with three frames of animation. Then make the ghost chase Pac man across the screen and on different lines. If you have more time, pop up a power pill randomly and if Pac man gets it change the chase direction (and invert the ghost of course!) for five seconds or so. Neither the ghost nor Pac man should ever catch each other. Free MPGL2 development board to whoever does it first and posts the source on the Engenuics forum!