CpE5160 Experiment #3
SPI Peripheral and SD Card Initialization

Introduction

The purpose of this experiment is to set up the SPI peripheral and use it to initialize the SD card. The serial port routines developed in experiment #2 will be used to display the information read from the SD card. Information read from the SD card and printed using the UART will be used in the fifth experiment to investigate the FAT file system. This experiment will also encourage the use of some hardware debugging tools such as an oscilloscope or a logic analyzer.

SPI Peripheral functions

The functions that access the SPI registers are hardware specific and should be placed in their own source code file for easier portability. There are two SPI ports in the ATMEGA324PB (SPI0 and SPI1). The functions described below should be written so that a pointer passed to the function can select which SPI port to use. The SD card, MP3 decoder and OLED will all use SPI0 in this project.

Any peripheral device needs an initialization routine to set it up for the specified operating parameters. The SPI peripheral requires three items to be set up. The first is the clock rate for transmission. The ATMEGA324PB has seven choices for clock rate that divide the peripheral clock by a power of 2 from 2^1 to 2^7 or 2 to 128. When initializing the SD card, the initial setting of the clock should be 400KHz or less. It can be increased after the SD card has been initialized. The second item is setting the clock phase and polarity. The clock polarity bit (CPOL) determines the state of the clock during the idle state. If CPOL='0', then the clock will be at '0' when no transmission is occurring, and the first clock edge will be from low to high. If CPOL='1', then the clock will be at '1' when no transmission is occurring, and the first clock edge will be from high to low. There are two possible choices of clock phase. If the clock phase bit (CPHA) is '0', then the data is sampled on the first clock edge so the data must be shifted before the first clock edge. If CPHA='1', then the data is shifted on the first clock edge and sampled at the second clock edge. The SD card specification does not have the required timing information for determining the proper clock phase and polarity, but CPHA='0' and CPOL='0' worked for me. The final item is to determine if the microcontroller will act as a master or slave device and in this experiment the microcontroller is the master device. Make sure the SPE bit (SPI Port Enable) is set to '1' to enable the SPI port, the MSTR bit is set for master mode. The SPI output pins are not set up automatically. The MOSI pin must be set as an output with an initial value of '1.' The SCK pin must also be set as an output. The initial value should be determined by the CPOL value.

Another SPI function that is needed is a transmit/receive function. Each time a transmitted value is shifted out of the SPI port, a received value is shifted in. Therefore, separate transmit and receive functions are not needed. A single SPI Transfer function will handle both functions. However, the programmer may wish to write separate SPI_Transmit and SPI_Receive functions for similarity to other communication peripherals or so the direction of communication can be determined by which function is used. A transfer is started by writing a byte value to SPDR. The SPIF bit in the SPSR register will be low during the transfer and it will be set to '1' when the transfer is complete. The received data can then be read from SPDR.

The programmer may wish to do some error checking. The WCOL bit in SPSR will be '1' when a write collision has occurred which means a value was written to SPDR while a transfer was in progress. A timeout can used in the loop waiting for SPIF to be set, as long as the timeout is long enough for a transfer to be completed at the slowest SCLK rate.

SD Card functions

The first SD card function that will be needed is one that can send a command to the SD card. Every SD card command consists of 6 bytes. The first byte starts with a leading '0' and '1' bit for the START and TRANSMISSION bits. The rest of the byte is the six-bit command number. The next four bytes are the argument as a 32-bit number which is sent most significant byte (MSB) first. Not all commands require an argument, but the 32-bit number is always sent. The command summary table found in the SD card specification refers to arguments that are not needed as "stuff bits" and they are sent as zeros. The function will need to break the 32-bit value into four bytes that can be sent MSB first. The final byte is a checksum. The SD card specification shows how to calculate the checksum, but it is only required for the CMD0 and CMD8 commands. The checksums can be defined in the C code to be sent when CMD0 or CMD8 is sent. The checksum for CMD0 is '1001010.' The final bit of the last byte is the end bit which should always be a '1.' Therefore, the last byte sent for CMD0 is 0x95. The checksum for CMD8 depends upon the argument sent. The first two bytes and the upper half of the third byte of the argument are reserved bits and should be '0.' The lower half of the third byte indicates the host supply voltage. The least significant bit of the third byte should be a '1' to indicate a 2.7V to 3.6V host supply voltage. The least significant byte is a check pattern which will be echoed back in the response. If a check pattern of 0xAA is used resulting in an argument of 0x000001AA, then the checksum will be '1000011.' The END bit of '1' is placed in the least significant bit (lsb) of the final byte which results in the value of 0x87 for CMD8. The last byte sent for all other commands is 0x01.

Each command sent to the SD card causes the SD card to send a response. The response may be 1 to 5 bytes long depending on the type of response expected. Some of the commands will cause the SD card to respond with several data bytes. These responses are a little different and will be handled by a different function. The first byte of a response is always the R1 response which has the most significant bit (msb) cleared to '0.' There is a delay between the command being sent and the response being received. Therefore, the function should repeatedly send 0xFF to the SD card while it is waiting for a response and while it is receiving the response. The SD card will respond with 0xFF or the R1 response which can be detected by the msb being '0.' As with any wait loop, good programing practice should include a loop timeout to exit the loop in the event of an error or hardware failure. The R1 response indicates if an error has occurred by setting bits in the response. This response should be checked when more bytes are expected because if an error occurs, then only the R1 response is sent. If more bytes are expected in the response and the R1 response shows no errors, then the function should keep sending 0xFF and reading the data received for the other bytes of the response. After the bytes of the response are received, a final 0xFF is sent to give the SD card clocks to go to standby mode. Since the response can be multiple values, one approach to return these values is to place the response values in an array sent by the calling function as a parameter (a pointer to the array). The return value can then be an error value which indicates if a timeout or other error occurred. Another required input parameter for this function is either the type of response expected, or the number of bytes expected in the response.

There is a possible error condition that can occur if the SD card gets confused during initialization and is powered off and back on to try and reset the card. The card may initially send back a byte of 0x7F, 0x3F, or 0x1F before the actual R1 response is sent. Since the R1 response is recognized by having the most significant bit as '0,' this can lead to an errant value being received as the R1 response. The easiest way to deal with this is to reset your microcontroller without powering off the SD card and execute your code again. It should work the second time. Another way to handle this is to retry the SD card initialization in software by placing the SD card initialization in a loop that retries a few times before declaring an initialization error. You can also look for the false R1 responses and ignore those and continue to look for the real R1 response.

Another error that occurs when a data block is requested but is not completely read because of some mistake in the code. The SD card may attempt to continue to send data even when the programmer is attempting to re-initialize the SD card. This will result the initialization commands being ignored, and some strange values being returned. One fix for this is to power off the SD card by removing it from the circuit, which results in the problems stated in the previous paragraph. Another solution is to set the CS=0 and send 515 transfers to clear out any data being returned by the SD card before attempting to re-initialize the SD card.

The fixes listed in the previous paragraphs are not required for student submissions. However, they are examples of what may need to be done in a commercial system to make sure the SD card initializes properly. The more robust a system is, the less likely it will be sent in for some warranty repair and cause customer complaints.

A different function should be used when the SD card is expected to respond with bytes of data. The response when the SD card is sending data starts with the R1 response after a short delay like the other responses. The SD card must be in active mode and have no errors to read data from it so the R1 response must be 0x00. This is followed by another short delay. The block of data will start with the START BLOCK token which is the byte 0xFE. The data follows immediately with the next byte. The number of bytes that follow depends on the command that was sent and the SD card setup. For example, the SEND_CSD (CMD9) or SEND_CID (CMD10) commands cause the SD card to respond with 16 bytes of data. The READ_SINGLE_BLOCK (CMD17) command causes the SD card to respond with one block of data. On a standard capacity SD card, a single data block may be configured to be one byte, which is the default, up to 1024 bytes. A high-capacity SD card has a fixed block size of 512 bytes. Since the number of bytes expected in a data block is not always the same, the number of bytes should be specified as an input parameter. The data bytes are immediately followed by two bytes which are the CRC16 checksum. Just like the previous response function, a final 0xFF should be sent to give the SD card clocks to go to standby mode. Possible input parameters for this routine could be the number of bytes to be read and the address of an array where the data bytes are to be stored. An output parameter could be an error flag that indicates an R1 response that is different than expected, a data error token was received or that a timeout error occurred.

SD Card Initialization

The steps for SD card initialization can be found in a flow chart in figure 7-2 in section 7.2 SPI Bus Protocol of the SD Specifications document. Those steps are explained in the following paragraphs. The initialization can be written as a function that has a return value that can indicate if the initialization was successful or if an error occurred. A suggestion is to enclose each step in an “if statement” that checks an error status variable. The error status is updated in each step. If the error status is no longer “no errors,” then none of the rest of the steps will be executed. Another suggestion is to have a printed output after each step to show what command was sent and what the response was from the SD card. This will help the programmer know where the initialization stopped if an error occurs.

The first step is to set the SPI peripheral to a clock rate of 400KHz or less. The /CS pin on the SD card should be set high and then at least 74 clock pulses are applied to the SCK pin. This will initialize the SD card into SD card mode. The clock pulses can be manually generated or at least 10 bytes can be sent through the SPI port (10*8=80 clock pulses).

Set the /CS pin to ‘0’ and send the SD card command 0 (CMD0). The argument for CMD0 is 0x00000000. This will put the SD card into SPI mode. The expected response for this command is R1=0x01 which indicates that the SD card is in the idle state. If the R1 response is not 0x01 or if there is no response, then an error flag should be set, and the initialization routine should stop. The /CS pin should remain at ‘0’ for the command and response and then it can be switched back to ‘1.’ The /CS pin should be switched to ‘0’ before each SD Card command and remain at ‘0’ until the entire response is received.

The next command is CMD8. This command checks the interface voltage for the SD card. The argument consists of two parts and some reserved bits. Bits 31 through 12 are reserved bits and should be set to ‘0.’ Bits 11 through 8 are the VHS (host supplied voltage) field. Table 4-16 in the SD card specification gives the valid values for this field. Bits 7 through 0 are a check field. Any values placed in this field will be echoed back in the response. The response should be the R7 response which is five bytes long. The details of all the possible responses can be found in section 4.9 Responses in the SD Specifications document. The first byte is the R1 response and should be 0x01. If this byte is 0x05, it indicates an illegal command, and that the SD card is an older version card (v1.x). No more bytes will follow this response. The programmer may wish to have a static global variable to store the SD card version. This will allow the initialization routine to support a wider range of SD cards. This variable would be set to indicate a v1.x card if the R1 response was 0x05. If the R1 response is the 0x01 idle state response, then four more bytes will immediately follow. Bits 31 through 28 indicate the command version and are expected to be '0000.' Bits 27 through 12 are reserved bits and will also be '0.' Bits 11 through 0 should be an echo of the bits sent in the command indicating that the voltage is compatible. If the R1 response is neither 0x01 nor 0x05, then an error flag should be returned, and the initialization should stop. If the voltage is not compatible (bits 11 to 8 do not match), then an error flag should be returned, and the initialization should stop. If the check byte does not match (bits 7 to 0), then the initialization should stop.

If CMD8 is successful, then CMD58 is sent. The argument is 0. This command reads the operating conditions register and the response is the R3 response. The response consists of five bytes. Again, the first byte is the R1 response, and this is followed by the four-byte operating conditions register. See section 4.9 Responses and section 5.1 OCR register in the SD Specifications document for details on the operating conditions register. The main concern at this point is the voltage range specified by this register and that it matches our 3.3V power supply. As with the previous steps, if the R1 response is not 0x01 or if the voltage is incompatible with 3.3V, then an error flag should be returned, and the initialization should stop.

The next step is to send ACMD41. Commands that start with an "A" are application specific commands. This means that they must be preceded with CMD55 (APP_CMD). The argument for CMD55 is 0 and the response is the R1 response. Send the ACMD41 next with an argument that has bit 30 (the host capacity support (HCS) bit) set to '1' to indicate that the host supports high-capacity SD cards. If the programmer wishes to support older SD cards, then the ACMD41 argument should be 0 when v1.x SD cards are detected. This command also starts the SD card initialization process. The response should be the R1 response; however, it could be 0x01 to indicate the idle state or 0x00 to indicate the active state. The /CS pin should remain '0' for both CMD55 and ACMD41 and their responses. If the SD card responds with 0x01 indicating the idle state, then the command sequence of CMD55 and ACMD41 should be repeated and continue to be repeated until the active state response is returned, or a loop timeout occurs. The /CS pin may remain at '0' for the entire loop of these commands if desired. If the R1 response is neither 0x01 nor 0x00 or if a timeout occurs, then an error flag should be returned, and the initialization should stop.

If a v2.0 SD card has been detected and the HCS bit was set in ACMD41, then CMD58 should be sent again. This time the card capacity status bit (CCS, bit 30) and the power up status bit (bit 31) should be checked when the R3 response is received. The CCS bit is only valid if the power up status bit is a '1' indicating the power up routine is finished. If the CCS bit is '1,' it indicates that the SD card is a high-capacity card and a '0' indicates that the SD card is a standard capacity card. High-capacity cards have a fixed block size of 512 bytes and standard capacity cards have a user defined block size. It is recommended to switch standard capacity cards to have a block size of 512 bytes to be more compatible with the rest of the software for this project. This is done with CMD16, and the argument is the block size in bytes.

This completes the initialization. The SPI port can now be switch to a higher frequency. The maximum frequency for an SD Card is 25MHz, however, the maximum SPI frequency of our microcontroller is the CPU clock frequency divided by 2. With a 16MHz CPU clock, the maximum SPI clock frequency of 8MHz.

Information can then be read from the SD card after the initialization is complete. There are three recommended commands that can be used to read information from the SD card. CMD9 (SEND_ CSD) reads the card specific data register. It is a 16-byte register which is sent as a data block. CMD10 (SEND_CID) reads the card identification register and responds with a 16-byte data block. CMD17 is the READ_SINGLE_BLOCK command and responds with the data block specified in the argument of the command. In high-capacity cards the argument is the data block number, and the response is a 512-byte block. In standard capacity cards the argument is the byte address of the start of a data block and the response depends on the data block length. If the data block length is set to 512 bytes to be the same as a high-capacity card, then the data block number can be converted to the byte address by multiplying by 512 (or left shifting by 9). The calculations that the file system software will do calculate the block number on the SD Card. Using the conversion between block number and byte address can allow standard capacity cards to be easily used with the file system software.

Using the Serial Port to Enter Integer Numbers

In this experiment, we will need to enter an unsigned long (uint32_t) through the serial port. The values that are received by the serial port are ASCII values. A software routine is needed to determine which received values are numeric ASCII characters and convert them into an integer. A number is entered as a string of ASCII characters such as: 123 which are 0x31, 0x32 and 0x33 in ASCII. The following paragraphs discuss some different options for converting a series of numeric characters into an integer value.

The most direct method is to keep a running total of numeric values until the enter key is pressed. In this method, the running total is set to zero until a numeric value is received. Any non-numeric characters can be ignored. Numeric values range from 0x30 (48 decimal) for a 0 to 0x39 (57 decimal) for a 9. The upper nibble is masked off leaving a value from 0 to 9. The running total is multiplied by 10 and the new value is added to it. This continues until the enter key is pressed which would send either a linefeed (LF, ASCII 0x0A) or a carriage return (CR, ASCII 0x0D) from the terminal to the UART. At that point, the running total is saved as an unsigned long (uint32_t) and then the running total is cleared to zero.

If you are using the terminal in the Data Visualizer, it does not send out a string of characters until the user presses the enter key and it does not send the CR or LF character. Therefore, a provision was added so that the user can enter a period ('.') after the number and then press the enter key to type in a number with the Long_Serial_Input function.

The source code that is given has another method that uses the standard library (stdlib.h) function ***long** atol (**const char** *str)*. This function converts a string of numeric characters into an unsigned long (uint32_t). The string should be terminated by a null (0x00) or some other non-numeric ASCII value. If there are no numeric values in the string, then the function returns zero. A character string is an array of byte values where the last byte is a null (0x00). The name of the array is also the pointer to the string which is used as the parameter sent to this function. This function can be used by creating an array of characters and filling the array with entered numeric values. When a non-numeric value is received, it is ignored. When a linefeed (LF, 0x0A) or a carriage return (CR, 0x0D) is received, the function is called with the name of the array as the input parameter. Note that a negative sign (-, 0x2D) is a non-numeric value and is ignored, so only positive integers can be entered. The programmer could add statements to detect these values, but they are not needed for this project. An additional feature that is nice to have is the ability to back space when an error is made. When backspace is pressed on the keyboard, Putty will send either a delete (DEL, 0x7F) or a backspace (BS, 0x08). The function should respond by moving back one element in the array and overwrite that value with a null (0x00).

Procedure

The following equipment will be required for this part of the experiment:

- Long_Serial_In.c
- Long_Serial_In.h
- UART and GPIO files from Exp#2 solution
- ATMEGA324PB Xplained development board and USB-Micro B cable
- IO1 Xplained board with microSD card. Connect to EXT1 of development board
- PC with
    - Microchip Studio
    - Terminal Program (Putty or Data Visualizer)

The SPI functions are part of the hardware layer and should be in separate source code file than the SD Card functions.

1) (3pts) Write an initialization function for the SPI peripheral. A pointer to specify which SPI port (SPI0 or SPI1) to access is the first parameter. The function should set the clock to a frequency less than or equal to the value specified by the clock_rate input parameter. The CPOL and CPHA bits should be set to '0.' The SPI peripheral should also be enabled and set to operate in the master mode. The MOSI pin (PB5, SPI0 or PE3, SPI1) must be set as an output with an initial value of '1.' The SCK pin (PB7, SPI0 or PD7, SPI1) must be set as an output with an initial value the same as CPOL.
   A possible prototype for this function is:
   *uint8_t SPI_master_init(volatile SPI_t *SPI_addr, uint32_t clock_rate);*

2) (3pts) Write SPI_transmit, SPI_receive and/or SPI transfer functions. The SPI Transmit function should have an input parameter of the byte that is to be sent out. The SPI Receive function sends out 0xFF and returns the received value. The programmer may wish to do some error checking and return error flags in addition to the received byte. Typically, the return value is the error flag, and the received value is returned using a pointer to a variable passed to the function. Possible prototypes for the functions are:

```
//**** No Error Checking, return value is received value
void SPI_transmit(volatile SPI_t *SPI_addr, uint8_t send_value);
uint8_t SPI_receive(volatile SPI_t *SPI_addr);
uint8_t SPI_transfer(volatile SPI_t *SPI_addr, uint8_t send_value);
//**** With Error Checking, return value is error value
uint8_t SPI_transmit(volatile SPI_t *SPI_addr, uint8_t send_value);
uint8_t SPI_receive(volatile SPI_t *SPI_addr, (uint8_t send_value,)# uint8_t *rec_value);
uint8_t SPI_transfer(volatile SPI_t *SPI_addr, uint8_t send_value, uint8_t *rec_value);
//**** # Indicates an optional value: (uint8_t send_value,)
```

An SPI transfer is started by writing the byte to be sent to SPDR. The function should wait until the SPIF flag in SPSR is set and then read the received byte from SPDR. Possible error checking would put a timeout in the wait loop just in case SPIF is never set. This is an example of returning an error flag in addition to the received byte to show that a byte was never received because a timeout error occurred. The write collision error flag can be found in SPSR, and its description can be found in the ATMEGA324PB datasheet.

The SD Card functions are part of the external hardware layer. The external hardware layer should call standard functions to separate them from the device drivers. This allows the device driver functions to be changed to port to a new microcontroller and the external hardware layer remains the same.

3) (6pts) Write a function that allows you to send a command to the SD card. A command consists of six bytes. The six-bit command with the start bit (‘0’) and transmission bit (‘1’) in the two most significant bits is the first byte. This is followed by a 32-bit (4-byte) argument sent most significant byte first. The final byte is a checksum or zeroes with the end bit (‘1’) as the least significant bit. The CMD0 and CMD8 commands require a checksum while all other commands just need the end bit with seven leading zeroes (0x01). The recommended function prototype for this function is:

```
uint8_t send_command (volatile SPI_t *SPI_addr, uint8_t command,
                                        uint32_t argument);
```

If the SD Card port is specified as a constant then the prototype can be:

```
uint8_t send_command (uint8_t command, uint32_t argument);
```

The function should perform the following tasks:

a. Check to see if the command is only 6 bits (63 or less). If not, an error flag should be set to indicate an illegal command value and the function should exit.

b. The command should be OR'ed with 0x40 to append the start and transmission bits to the first byte to send.
c. Send the first byte using the SPI transfer function described in an earlier step. If you have error checking in the *SPI_transfer()* function, an error flag could be returned if a timeout or an SPI error occurs and the *send_command()* function could exit..
d. The 32-bit argument should be sent next starting with the most significant byte (MSB). If using error checking for the SPI, then you could exit if an error occurs.
e. The checksum byte with the lsb set to '1' for the end bit is sent last. If the command is 0 or 8, then a checksum must be sent (see background information for values), otherwise 0x01 can be sent.
f. The return value is the error status.

This function can be checked for proper byte transmission order using the debugger, and then examining the values written to the SPI port. An oscilloscope or logic analyzer can be used to check the output on the SCK and MOSI pins. This is not required, but it can help with debugging later in this experiment.

4) (5pts) Write another function that can receive the response from the SD card after a command is sent. The response that will be returned depends on the command. The most common response is the one-byte R1 response. Other possible responses may have up to four additional bytes. The response will have a short delay so the response function should repeatedly send 0xFF to the SD card and read the received byte until the msb of the received byte is '0.' (It is possible that an errant value of 0x7F or 0x3F will be received after the system is first switched on. Checking for a lower nibble of all ones (0bxxxx1111 or 0hxF) may be able to reject this errant value.) A timeout should be used so that this does not become an infinite loop. The recommended approach is to have a function that is passed the expected number of bytes of the response. Keep in mind that if an error occurs, the only response will be the one-byte R1 response that indicates the error condition. If no error occurs, any additional bytes will follow immediately after the R1 response. An additional 0xFF byte should be sent after the entire response has been received. The response can be returned to the main function using an uint8_t <u>**array**</u> that is passed to the function as a pointer.

This would make the function prototype look like this:

*uint8_t receive_response (volatile SPI_t *SPI_addr, uint8_t number_of_bytes, uint8_t * array_name);*

If the SD Card port is specified as a constant then the prototype can be:

*uint8_t receive_response (uint8_t number_of_bytes, uint8_t * array_name);*

The function should perform the following tasks:

a. The microcontroller will repeatedly send 0xFF out of the SPI port and read the value that is received using the SPI transfer function. This repetition should continue until the msb of the received byte is ‘0’ or until a timeout occurs. A byte with the msb as ‘0’ is the R1 response and it should be stored in the array. If the R1 response is 0x01 (idle state) or 0x00 (active state), then no errors have occurred. If an error or a timeout occurs, then an error value should be set, and the function should send the final 0xFF and exit.

b. If more than one byte is expected, then a 0xFF should be sent out of the SPI port and each received byte should be stored in the array. This step should be repeated until all the expected bytes have been received.
c. The function should end with one additional 0xFF being sent out of the SPI port. The received value does not matter.
d. The return value is the error value.

SD Card Initialization:
I recommend that the SD card initialization should not be all written and debugged at once. Start with the power on (74 clock cycles with nCS=1) step and the CMD0 command and response first. Once this is working, move on to the next step and make sure it is working. It will be easier to debug a small section of code and correct a mistake early than to repeat the mistake over and over again and have to correct it in multiple locations. There are some images captured by the logic analyzer given in the “Debugging SD Card Communication” section later in this document that show what some of the commands and responses should look like.

5) (16pts) The *send_command()* and *receive_response()* functions can be used by an SD card initialization function. The first steps in initializing the SD card are to send it at least 74 clock pulses on SCK with the nCS signal set high. Then switch the nCS signal low and send the SD card CMD0. The response for this command is the one-byte R1 response. If there are no errors, then the response should be 0x01 which indicates the SD card is in idle mode. The programmer may wish to print the command and response for each step taken during the SD card initialization for debugging purposes. For this step my output looked like this:

    Initializing SD card….
    CMD0 sent…. Response is 0x01

It is recommended that the steps given in the initialization flow chart in section 7.2.1 Mode Selection and Initialization of the SD Specifications document be written inside “if statement blocks.” The condition on each “if statement block” is that if any errors have occurred, then that step is not executed. This is one way that the initialization can stop if an error occurs. The programmer may also want to place debugging outputs, as shown above, in each step to help find an error when it occurs. The prototype for the SD card initialization function is:

*uint8_t sd_card_init (volatile SPI_t *SPI_addr);*

If the SD Card port is specified as a constant then the prototype can be:

uint8_t sd_card_init (void);

The initialization function should perform the following tasks:

a. Set /CS=1 and send at least 74 clock cycles on SCK.
b. Clear /CS=0 and send CMD0. Read the R1 response and only continue if it is 0x01. Set /CS=1 after the response is received.
c. Clear /CS=0 and send CMD8. Read the R7 response. Set /CS=1 after the response is received. If the R1 response is 0x05 (illegal command) then the SD card is a v1.x type. It is up to the programmer how they want to handle this. The function can designate this card as unusable or the card type can be stored so that the high-capacity support bit is not set when ACMD41 is sent. Otherwise, if the R1 is not 0x01, then the initialization function should exit with an error flag. The R7 response should also be checked to make sure the voltage range is correct, and the check value has been echoed correctly. If the voltage range does not match, then designate the card as unusable.
d. Clear /CS=0 and send CMD58. Read the R3 response. Set /CS=1 after the response is received. If the R1 response is not 0x01, then the initialization function should exit with an error flag. The R3 response should also be checked for voltage compatibility with your system and designate the card as unusable if it is not compatible (not 3.3V).
e. Clear /CS=0 and send ACMD41. An application specific command (ACMD) is sent by sending CMD55 first and receiving the R1 response, then ACMD41 is sent as CMD41 and the R1 response is received all while the /CS=0. The argument for ACMD41 depends on whether this is a v1.x or v2.0 SD card. If it is a v1.x SD card, then the argument is 0. If it is a v2.0 SD card, then the HCS bit (bit 30) should be set. This command places the SD card into its active state, but this may take a little while. This entire command sequence should be repeated until the R1 response indicates that the card is active (0x00) or that an error has occurred. A timeout should also be used to exit the loop just in case the card fails to go to its active state. The /CS can be set to '0' for the entire loop or it can be set to '0' for CMD55, R1 response, ACMD41, and R1 response. Note that it must be '0' for both commands together. Exit the initialization function if any errors occur.
f. If the SD card is successfully activated and the SD card is a v2.0 card, then CMD58 should be sent again to re-examine the OCR register in the R3 response. The msb of the OCR (bit 31) is the power up status bit. It must be set to '1' in order for the card capacity status (CCS, bit 30) bit to be valid. If both bits are set, then the SD card is a high-capacity (SDHC) card. If only the power up status bit is set, then the SD card is a standard capacity card. The microSD cards in the IO1 Xplained boards should all be SDHC cards, but the programmer may wish to add support for standard capacity. For ease of compatibility between the two types of cards, the block size on the standard capacity should be set to 512 bytes using CMD16. The block address used for a SDHC card would need to be multiplied by 512 (block size) to convert it to the byte address expected by

the standard capacity card. A global variable is needed to keep track of the SD card type for later accesses.

g. The return value is the error status.

6) (2pts) Create the main function for this experiment. It should perform the necessary steps for initialization first. This includes Outputs, UART, SPI and SD card. The SPI should be initialized to a clock rate of 400KHz or less for the SD card initialization. My approach during the initialization was to switch on an LED, print a message and halt in an infinite loop if any errors occurred. This helps identify where the problem is at. After the SD card initialization is complete, the SPI clock rate can be increased up to 25MHz. Note that the fastest clock rate our system can output is one half of the oscillator frequency (8MHz). After all parts of the system are initialized, the program will enter a "super loop" or *for(;;)* loop. At this point, this loop does not have anything in it, so the program just stops here.

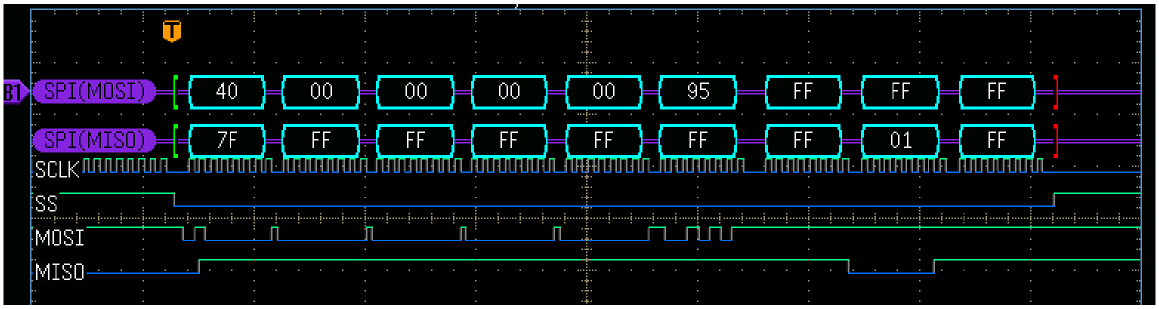
Debugging the SD Card Communication

The following figures are waveforms captured by the MDO3024 Oscilloscope and may help you in determining what to look for if your system is not working. Using a horizontal setting of about 50us/div will allow you to see most of the communication. You can use a slower horizontal setting to make sure you capture the entire communication and use the zoom feature to view specific parts.

Select Bus #1 (B1 button) to select the SPI bus decoding (It should be already set up). If it is not set up, the connections should be: D0-SCLK, D1-MOSI, D2-MISO, and D3-SS. Press the trigger button to switch to the trigger menu. Change the trigger source to BUS and SPI. You can trigger on the SS going low or you can trigger on a specific value on the MOSI or MISO pin. I would recommend using triggering on SS active to start with. I recommend using Normal Mode which will only update the screen if a trigger occurs and keeps the last captured data on the screen. You can also press the Single button to capture one screen of data. Press the Run button to return to regular captures.
You can also use an I/O pin, such as an LED output, going low right before the send command function or right after the receive response function as a trigger to capture the signals. This trigger signal can only go low once during the program, so that it identifies the SD card communication you are trying to see. The connections for the LEDs are: LED0-D4, LED1-D5, LED2-D6, and LED3-D7. The trigger source should be set to edge and select the channel and falling edge for the I/O pin you want to use.

The debugger in Microchip studio can be used to start and stop the execution of the code to help with capturing waveforms. For example: if you want to capture the CMD8 communication using the SS active triggering, execute up to before the /CS is set low; press the single button on the oscilloscope and then resume execution. It should capture the CMD8 communication when the /CS goes low. Use the reset in the debugger menu of Microchip Studio to execute the code again if you did not capture a signal the first time.

Note that printing to the serial port takes a long time relative to the signals being captured. If you are printing commands and responses, then make sure the print statements are outside of the actual send command and receive response functions and the trigger used to capture these waveforms.

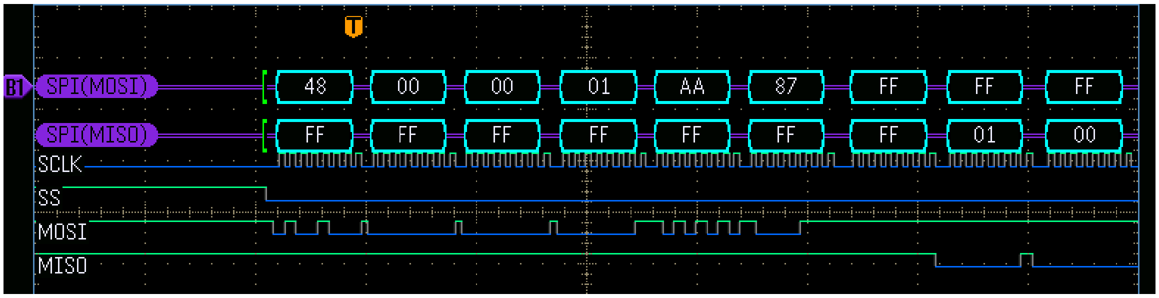


Complete CMD0 and R1 response

The first figure shows a complete CMD0 and R1 response. In this figure you will see sets of eight clock pulses on SCLK for each SPI transfer. The first six transfers show CMD0 being sent on MOSI (0x40, 0x00, 0x00, 0x00, 0x00, and 0x95). The R1 response is received on MISO. Note that it typically takes two transfers to get the 0x01 response and then a final SPI transfer should be sent.

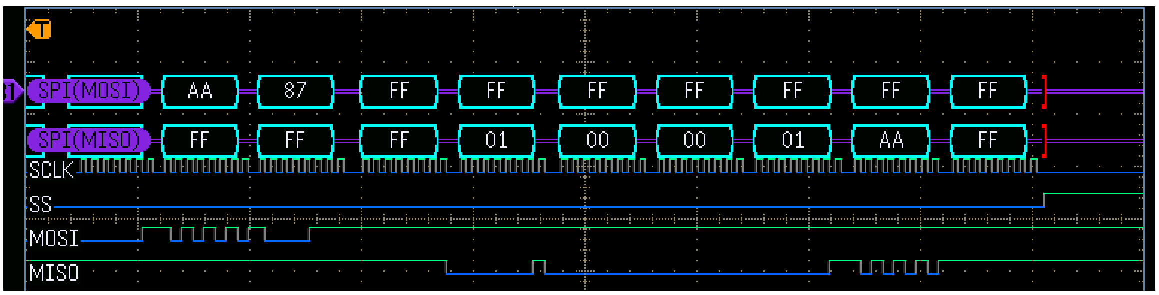
When viewing the SD card communications, verify that the values sent by the send command function are the expected values. These will be on the MOSI pin and the sent bit value is read when SCLK transitions from low to high. Examine the received values on the MISO pin. The LabView project for remote accessing the lab has the ability to decode the values on the SPI bus if the sample rate and /CS signal are set correctly.

A common mistake is to use a pointer instead of declaring an array to store the received values. If you print the hexadecimal received values and they do not match what was seen on the MISO pin, it is possible that the values were not stored properly in memory. An array reserves locations in memory for these values, a pointer does not.



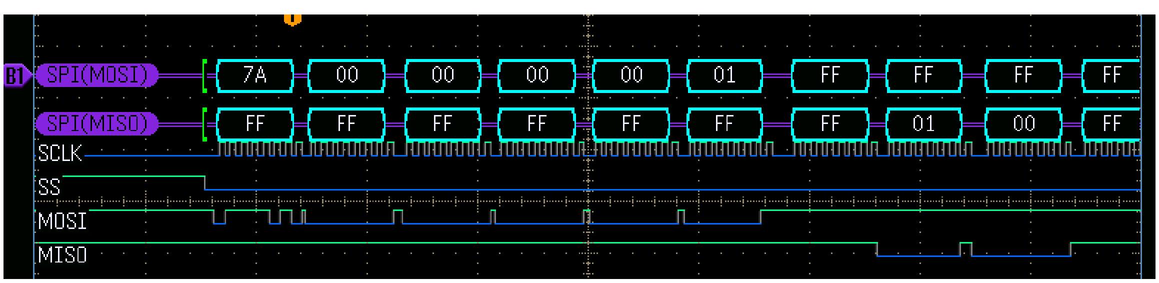
Sending of CMD8

This image shows the bytes of CMD8 (0x48, 0x00, 0x00, 0x01, 0xAA, and 0x87). The trigger was looking for the 0x48 value on the MOSI pin. If a check byte value other than 0xAA is used, then a different CRC7 will need to be calculated. The R1 response of 0x01 is shown. The full response is shown in the next figure.



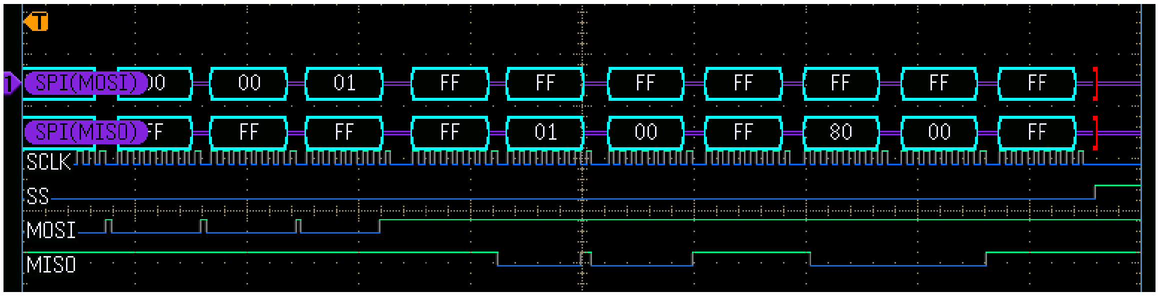
Complete R7 response

This figure shows the end of CMD8 and the complete R7 response being received. It is five bytes, the R1 response of 0x01 (idle state and no errors) and then an echo of the CMD8 argument. Note the delay in receiving the R1 response and one SPI transfer after the response is received. Also note that the /CS (SS) is low for the entire communication (command and response).



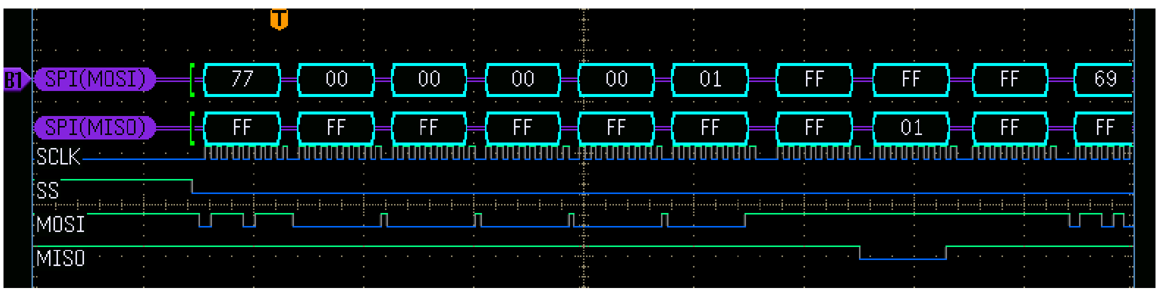
Sending CMD58

The trigger for this waveform detecting 0x7A on MOSI (0b0100 0000 | 58 = 0x7A). CMD58 is sent twice, when the card is idle to check voltage compatibility and then after the card is active to check card capacity. Use the single sweep to capture the first one. Normal triggering may be able to capture the second one or use a GPIO pin as a trigger before the command is sent.

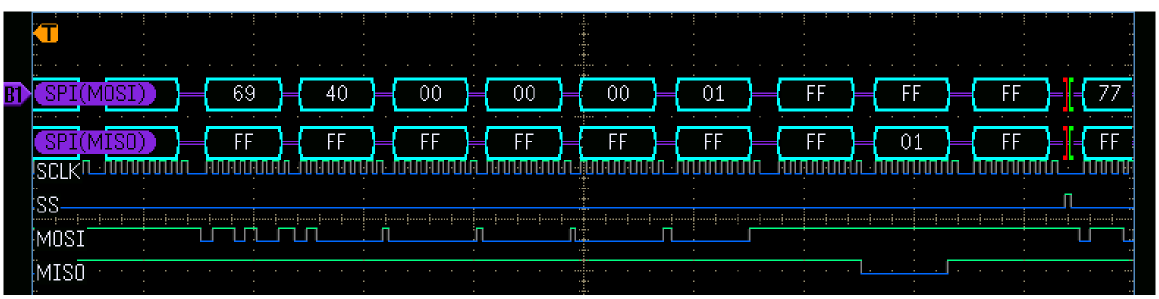


Complete R3 response (R1 + Operating Conditions Register)

The Operating Conditions Register should be check for voltage compatibility before activating the card. The third byte of the response (second of the OCR) and the msb of the next byte are all set to ‘1’ to indicate this card operates from 3.6 to 2.7 volts. Note that bits 31 (power up status) and 30 (card capacity status) are cleared to ‘0.’ Since the power up status bit is ‘0,’ this means the card capacity status bit is invalid. These bits are expected to be ‘1’ when the card is active making the expected value of the first byte of the OCR 0xC0.



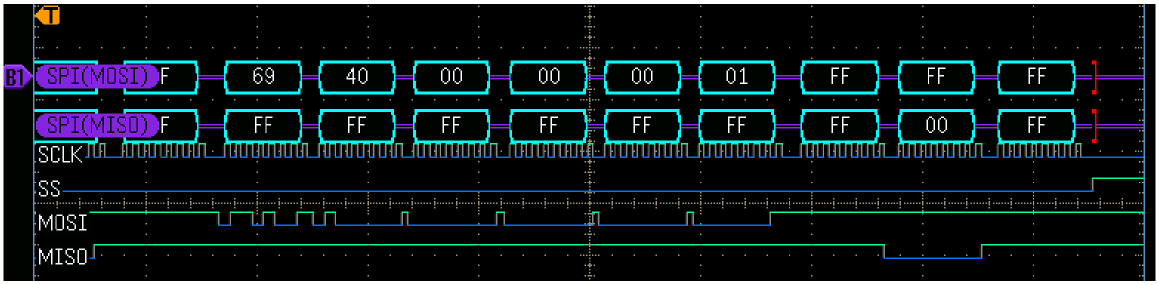
First part of ACMD41 (CMD55 and R1 response)



Second part of ACMD41 (CMD41 and R1 response)

The previous two pictures show the sending of ACMD41. It consists of four parts, first CMD55 is sent with an argument of 0x00000000. Then an R1 response is received. The third part is ACMD41 sent (command number 41) with an argument of 0x40000000. Then another R1 response is received. The /CS is low for all four parts. This is repeated until the R1 response after the

ACMD41 has a value of 0x00 (active mode).



ACMD41 R1 response of 0x00

The number of repeats that is required to activate the SD card is unknown. A while loop or do-while should be used to send ACMD41. This loop should have a timeout in case the card does not become active.

After the SD card is initialized, then data can be read from it using the function described in the next step.

7) (10pts) Write another function that can be used to read a data block of specified size and store the data into an array. The details of a data block response are given in this handout. The function will be passed the number of bytes expected in the response and the address of the array where the data is to be stored. The function may also return a value that indicates if the read was successful or if an error occurred. The function prototype could look like this:
*uint8_t read_block (volatile SPI_t *SPI_addr, uint16_t number_of_bytes, uint8_t * array);*
If the SD Card port is specified as a constant then the prototype can be:
*uint8_t read_block (uint16_t number_of_bytes, uint8_t * array);*

The function should perform the following tasks:

a. The SD card will first respond with the R1 response. Therefore, just like the *receive_response()* function, the microcontroller should send 0xFF out through the SPI port until the R1 response is received. If the R1 response is not 0x00 or if a timeout occurs, then the function should exit with an error value returned.
b. After another delay, the SD card will send a data start block token which is 0xFE or a data error token will be sent. The data error token has the upper four bits cleared to '0' and the lower four bits indicate what error occurred. The microcontroller should send 0xFF out through the SPI port until either value is received. If the data error token is received, then the function should exit with an error value returned. If the data start token is received, then the next value received is the first byte of the data block to be received.
c. The microcontroller should continue to send 0xFF out through the SPI

port for each byte of data to be received. Each byte of data can then be read from the SPI port and placed in the array.

d. After all the expected data bytes have been received from the SD card, the microcontroller should send three more 0xFF values out through the SPI port. The first two are to receive a 16-bit checksum of the received data. The programmer can calculate and compare the checksum or just discard these values. The final 0xFF is to allow the SD card to return to its standby state.

e. The return value is the error status.

8) A function is given with the download files for this experiment that allows the user to enter an unsigned long (uint32_t) through the serial port (UART1) as described in the background material. The function has one input parameter, the base address for the UART, and returns an unsigned long (uint32_t). The value is entered using Putty and typing numbers on the keyboard. The *UART_Receive()* function from the experiment #2 solution is used to input an ASCII character through the UART. Any non-numeric characters (except for '.' which can be used to terminate the numeric string for Data Visualizer users) are ignored and not echoed. When the enter key is pressed the string of ASCII characters is converted into an unsigned long (uint32_t) and returned.

9) (4pts) Modify the main function by adding the following to the "super loop" or for(;;) loop. This loop should prompt the user to enter a block number to read from the SD card. The number is entered using the *long_serial_input* function given with the project files. After the number is entered, the *send_command()* function can be used to send the read block command (CMD17) and the *read_block()* function will be used to read the 512 bytes of one SD card data block. The /CS pin on the SD card should be low during the *send_command()* and *read_block()* functions. The *print_memory)* function from experiment #2 should then be used to display the block contents on Putty or Data Vizualizer. The loop repeats by going back to the prompt asking the user to enter a block number. The blocks that are displayed are the SD card information blocks and the data stored on the SD card. This information will be used in the fifth experiment to access the files stored on the SD card. You can verify that you are reading block 0 correctly if the block is mostly 0's except for line 0x01C0. Also, the bytes at addresses 0x01FE and 0x01FF should be 0x55 and 0xAA, respectfully. It is possible that there are other bytes that are non-zero, but typically these are the only non-zero bytes. Use the value stored at offset 0x1C6 as a block number and print that block. This data block should be the BIOS Parameter Block and look similar to the example in the lecture notes.

Grading:

Functionality:	Code works as described in the assignment: Registers set as needed and actions occur as specified.	Points awarded as specified in the steps marked graded. (50 points)
Compile Errors:	If submitted code does not compile, then a minimum of 25% of the functionality points will be deducted. More may be deducted for multiple errors.	Minimum of 25% of functionality point deducted.
Organization:	Seperating device drivers (microcontroller, SPI), hardware application layer (SD Card) and application code.	10 points
Readability:	Source code is well commented. Descriptive names are used for functions, constants and variables.	10 points
Correctness	No patches or work-arounds are used in the source code to get the correct functionality.	10 points