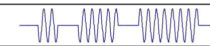
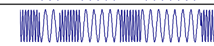
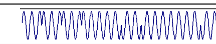
Communication

Communication methods

- Communication methods
  - Media and signalling conventions used to transmit data between digital devices
  - Different physical layers methods including:
    - wires, radio frequency (RF), optical (IR)
  - Different encoding schemes including:
    - amplitude, frequency, and pulse-width modulation

Modulation Technique	Waveform
No encoding (Baseband)	
On-Off Keying (OOK)	
Frequency Shift Keying (FSK)	
Binary Phase Shift Keying (BPSK)	

Communication methods

- Dimensions to consider
  - bandwidth – number of wires – serial/parallel
  - speed – bits/bytes/words per second
  - timing methodology – synchronous or asynchronous
  - number of destinations/sources
  - arbitration scheme – daisy-chain, centralized, distributed
  - protocols – provide some guarantees as to correct communication

Bandwidth

- Serial
  - Single wire or channel to trasmit information one bit at a time
  - Requires synchronization between sender and receiver
  - Sometimes includes extra wires for clock and/or handshaking
  - Good for inexpensive connections (e.g., terminals)
  - Good for long-distance connections (e.g., LANs)
  - Examples: RS-232, Ethernet, I2C, IrDA, USB, Firewire, Bluetooth
- Parallel
  - Multiple wires to transmit information one byte or word at a time
  - Good for high-bandwidth requirements (CPU to disk)
  - More expensive wiring/connectors/current requirements
  - Examples: SCSI-2, PCI bus (PC), PCMCIA (Compact Flash)
- Issues
  - Encoding, data transfer rates, cost of connectors and wires, modularity, error detection and/or correction

Speed

- Serial
  - low-speed, cheap connections
    - RS-232 1K–20K bits/sec, copper wire
  - medium-speed efficient connections
    - I2C 10K-400K bits/sec, board traces
    - IrDA 9.6K-4M bits/sec, line-of-sight, 0.5-6.0m
  - high-speed, expensive connections
    - USB 1.5M bytes/sec, USB2 60M bytes/sec
    - Ethernet 1.5M-1G bits/sec, twisted-pair or co-axial
    - Firewire 12.5-50M bytes/sec
- Parallel
  - low-speed, not too wide
    - SCSI-2 10M bytes/sec, 8 bits wide
    - PCI bus, 250M bytes/sec, 32 bits wide
    - PCMCIA (CF+), 9-10M bytes/sec, 16 bits wide
  - high-speed, very wide – memory systems in large multi-processors
    - 200M-2G bytes/sec, 128-256 bits wide

Speed

- Issues
  - length of the wires (attenuation, noise, capacitance)
  - connectors (conductors and/or transducers)
  - environment (RF/IR interference, noise)
  - current switching (spikes on supply voltages)
  - number and types of wires (cost of connectors, cross-talk)
  - flow-control (if communicating device can't keep up)

Timing methodology

- Asynchronous
  - less wires (no clock)
  - no skew concerns
  - synchronization overhead
  - appropriate for loosely-coupled systems (CPU and peripherals)
  - common in serial schemes
- Synchronous
  - clock wires and skew concerns
  - no synchronization overhead
  - can be high-speed if delays are small and can be controlled
  - appropriate for tightly-couple systems (CPU and memory/disk)
  - common in parallel schemes

Timing methodology

- Issues
  - clock period and wire delay
  - synchronization and skew
  - encoding of timing and data information
  - handshaking
  - flow-control
  - power consumption

Number of devices communicating

- Single source – single destination
  - point-to-point
  - cheap connections, no tri-stating necessary
- Single source – multiple destination
  - fanout limitations
  - addressing scheme to direct data to one destination
- Multiple source – multiple destination
  - arbitration between senders
  - tri-stating capability is necessary
  - collision detection
  - addressing scheme
  - priority scheme
  - fairness considerations

Arbitration schemes

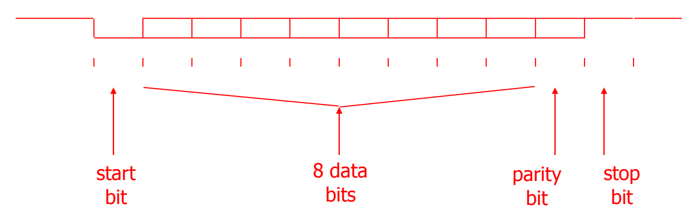
- Daisy-chain or token passing
  - devices either act or pass to next
  - fixed priority order
  - as many wires as devices
  - fairness issues
- Centralized
  - request to central arbiter
  - central arbiter implements priority scheme
  - wires from/to each device can be costly
  - can be dynamically changing priority/fairness
- Distributed
  - no central arbiter
  - common set of wires (or ether) observed by all devices
  - fixed priority/fairness scheme

Serial case studies

- RS-232 (IEEE standard)
  - serial protocol for point-to-point, low-cost, low-speed applications for PCs
- I2C (Philips)
  - up to 400Kbits/sec, serial bus for connecting multiple components
- Ethernet (popularized by Xerox)
  - most popular local area network protocol with distributed arbitration
- IrDA (Infrared Data Association)
  - up to 115kbps wireless serial (Fast IrDA up to 4Mbs)
- Firewire (Apple – now IEEE1394)
  - 12.5-50Mbytes/sec, consumer electronics (video cameras, TVs, audio, etc.)
- SPI (Motorola)
  - 10Mbits/sec, commonly used for microcontroller to peripheral connections
- USB (Intel – followed by USB-2)
  - 12-480Mbits/sec, isochronous transfer, desktop devices
- Bluetooth (Ericsson – cable replacement)
  - 700Kbits/sec, multiple portable devices, special support for audio

RS-232 (standard serial line)

- Point-to-point, full-duplex
- Synchronous or asynchronous
- Flow control
- Variable baud (bit) rates
- Cheap connections (low-quality and few wires)
- Variations: parity bit; 1, 1.5, or 2 stop bits



RS-232 wires

- TxD – transmit data
- TxC – transmit clock
- RTS – request to send
- CTS – clear to send

- RxD – receive data
- RxC – receive clock
- DSR – data set ready
- DTR – data terminal ready

- Ground

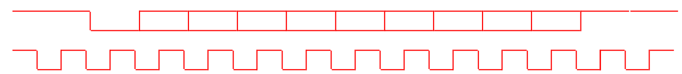
all wires active low

"0" = -12v, "1" = 12v

special driver chips that generate ±12v from 5v

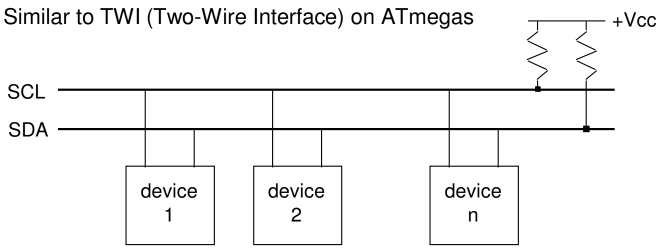
Transfer modes

- Synchronous
  - clock signal wire is used by both receiver and sender to sample data
- Asynchronous
  - no clock signal in common
  - data must be oversampled (16x is typical) to find bit boundaries
- Flow control
  - handshaking signals to control rate of transfer



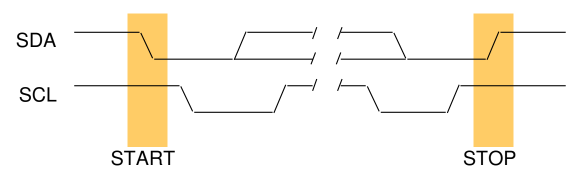
Inter-Integrated Circuit Bus (I2C)

- Modular connections on a printed circuit board
- Multi-point connections (needs addressing)
- Synchronous transfer (but adapts to slowest device)
- Similar to Controller Area Network (CAN) protocol used in automotive applications
- Similar to TWI (Two-Wire Interface) on ATmegas



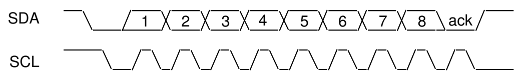
Serial data format

- SDA going low while SCL high signals start of data
- SDA going high while SCL high signals end of data
- SDA can change when SCL low
- SCL high (after start and before end) signals that a data bit can be read



Byte transfer

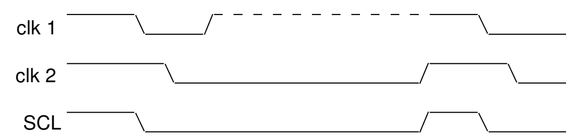
- Byte followed by a 1 bit acknowledge from receiver
- Open-collector wires
  - sender allows SDA to rise
  - receiver pulls low to acknowledge after 8 bits



- Multi-byte transfers
  - first byte contains address of receiver
  - all devices check address to determine if following data is for them
  - second byte usually contains address of sender

Clock synchronization

- Synchronous data transfer with variable speed devices
  - go as fast as the slowest device involved in transfer
- Each device looks at the SCL line as an input as well as driving it
  - if clock stays low even when being driven high then another device needs more time, so wait for it to finish before continuing
  - rising clock edges are synchronized



Arbitration

- Devices can start transmitting at any time
  - wait until lines are both high for some minimum time
  - multiple devices may start together - clocks will be synchronized
- All senders will think they are sending data
  - possibly slowed down by receiver (or another sender)
  - each sender keeps watching SDA - if ever different (driving high, but its really low) then there is another driver
  - sender that detects difference gets off the bus and aborts message
- Device priority given to devices with early 0s in their address
  - 00….111 has higher priority than 01…111

Inter-Integrated Circuit Bus (I2C)

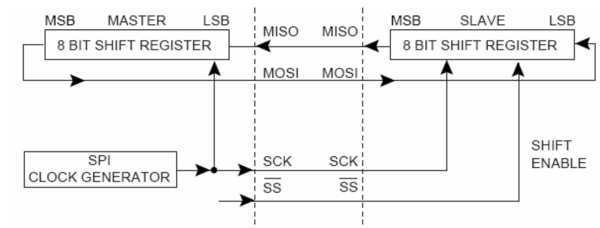
- Supports data transfers from 0 to 400KHz
- Philips (and others) provide many devices
  - microcontrollers with built-in interface
  - A/D and D/A converters
  - parallel I/O ports
  - memory modules
  - LCD drivers
  - real-time clock/calendars
  - DTMF decoders
  - frequency synthesizers
  - video/audio processors

Serial Peripheral Interface

- Common serial interface on many microcontrollers
- Simple 8-bit exchange between two devices
  - Master initiates transfer and generates clock signal
  - Slave device selected by master
- One-byte at a time transfer
  - Data protocols are defined by application
  - Must be in agreement across devices

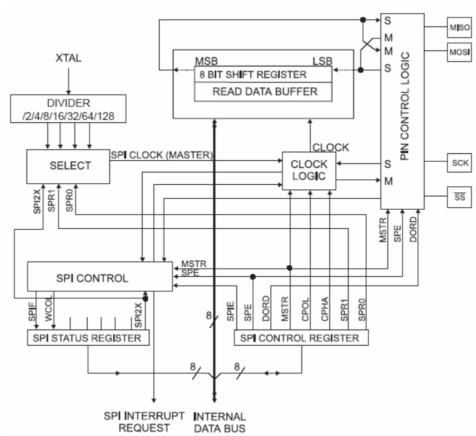
SPI Block Diagram

- 8-bits transferred in each direction every time
- Master generates clock
- Shift enable used to select one of many slaves



SPI on the ATmega16

- Prescaler for clock rate
- Interrupt on receive and on send complete
- Automatically generates SS



SPI Registers

SPI Control Register – SPCR

Bit	7	6	5	4	3	2	1	0	
	SPIE	SPE	DORD	MSTR	CPOL	CPHA	SPR1	SPR0	SPCR
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

SPI Status Register – SPSR

Bit	7	6	5	4	3	2	1	0	
	SPIF	WCOL	–	–	–	–	–	SPI2X	SPSR
Read/Write	R	R	R	R	R	R	R	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Using SPI as a Master

```
void SPI_MasterInit(void)
{
  /* Set MOSI and SCK output, all others input */
  DDRB = _BV(DD_MOSI) | _BV(DD_SCK);
  /* Enable SPI, Master, set clock rate fck/16 */
  SPCR = _BV(SPE) | _BV(MSTR) | _BV(SPR0);
}

void SPI_MasterTransmit(char cData)
{
  /* Start transmission */
  SPDR = cData;
  /* Wait for transmission complete */
  while(!(SPSR & _BV(SPIF)))
  ;
}
```


Using SPI as a Slave

```
void SPI_SlaveInit(void)
{
  /* Set MISO output, all others input */
  DDRB = _BV(DD_MISO);
  /* Enable SPI */
  SPCR = _BV(SPE);
}

char SPI_SlaveReceive(void)
{
  /* Wait for reception complete */
  while(!(SPSR & _BV(SPIF)))
  ;
  /* Return data register */
  return SPDR;
}
```


Data Payload on SPI

- Data is exchanged between master and slave
  - Master always initiates
  - May need to poll slave (or interrupt-driven)
- Decide on how many bytes of data have to move in each direction
  - Transfer the maximum for both directions
  - One side may get more than it needs
- Decide on format of bytes in packet
  - Starting byte and/or ending byte?
  - Can they be distinguished from data in payload?
  - Length information or fixed size?
- SPI buffer
  - Write into buffer, specify length, master sends it out, gets data
  - New data arrives at slave, slave interrupted, provides data to go to master, reads data from master in buffer

Sample code for FTDI SPI

```
int main(void)
{
	FTDI466API usbDevice;
	char buffer[256];
	unsigned char rxBuffer[256];
	unsigned char txBuffer[256];
	DWORD numBytesToSend;
	DWORD bytesSent;
	DWORD numBytesToRead;
	DWORD bytesReceived;
	// setup USB device for MPSSE mode
	bool setup = usbDevice.open();
	if(!setup)
		return 0;
	cout << "INITIALIZING SPI" << endl;
	// setup for SPI communication
	txBuffer[0] = 0x80; // setup PORT
	txBuffer[1] = 0x08; // make CS high
	txBuffer[2] = 0x0B; // outputs: SK, DO, CS, inputs:  DI, GPIOL1-L4
	txBuffer[3] = 0x86; // set clk divisor to Tx at 200kHz
	txBuffer[4] = 0x1D; // speed low byte
	txBuffer[5] = 0x00; // speed high byte
	txBuffer[6] = 0x85; // disconnect TDI/DO output from TDO/DI input for loopback testing
	numBytesToSend = 7;
```

Sample code for FTDI SPI (cont'd)

```
// send the instructions ot the USB device
bytesSent = usbDevice.write(txBuffer, numBytesToSend);

if(bytesSent != numBytesToSend)
        cerr << "Not all the bytes were sent when initializing MPSSE" << endl;

// see if there were any error codes when setting up SPI
numBytesToRead = usbDevice.getReceiveQueueSize();

if(numBytesToRead > 0)
{
        bytesReceived = usbDevice.read(rxBuffer, numBytesToRead);

        if(bytesReceived != numBytesToRead)
                cerr << "Problem when trying to retrieve the error bytes" << endl;

        for(unsigned int i = 0; i < bytesReceived; i++)
                cout << "Error Byte: " << rxBuffer[i] << endl;
}
```


Sample code for FTDI SPI (cont'd)

```
// loop to demonstrate the SPI protocol
for(int loop = 0; loop < 10; loop++)
{
        Sleep(1000);

        txBuffer[0] = 0x80; // setup PORT
        txBuffer[1] = 0x00; // make CS low
        txBuffer[2] = 0x0B; // outputs: SK, DO, CS, inputs:  DI, GPIOL1-L4
        txBuffer[3] = 0x35; // clock out on negative edge, in on negative edge, MSB
        txBuffer[4] = 0x04; // low byte of length : note a length of zero is 1 byte, 1 is 2 bytes
        txBuffer[5] = 0x00; // high byte of length
        txBuffer[6] = 0x71; // payload
        txBuffer[7] = 0x72;
        txBuffer[8] = 0x73;
        txBuffer[9] = 0x74;
        txBuffer[10] = 0x75;
        txBuffer[11] = 0x80; // setup PORT
        txBuffer[12] = 0x08; // make CS high
        txBuffer[13] = 0x0B; // outputs: SK, DO, CS, inputs:  DI, GPIOL1-L4

        numBytesToSend = 14;

        // send bytes
        bytesSent = usbDevice.write(txBuffer, numBytesToSend);
        if(bytesSent != numBytesToSend)
                cerr << "Not all the bytes were sent when initializing MPSSE" << endl;
```


Sample code for FTDI SPI (cont'd)

```
        Sleep(5); // make sure the usb device has enough time to execute command - 5 ms latency timeout is set

        // get number of bytes in the received queue
        numBytesToRead = usbDevice.getReceiveQueueSize();
        cout << "Received " << numBytesToRead << " Bytes" << endl;
        if(numBytesToRead > 0)
        {
                // get the received bytes
                bytesReceived = usbDevice.read(rxBuffer, numBytesToRead);

                if(bytesReceived != numBytesToRead)
                        cerr << "Problem when trying to retrieve the bytes from the receive queue" <<
endl;
                else
                {
                        // print out the bytes received over SPI in hex
                        for(unsigned int i=0; i < bytesReceived; i++)
                                cout << itoa(rxBuffer[i],buffer,16) << " ";
                        cout << endl;
                }
        }
}
```


Universal Serial Bus

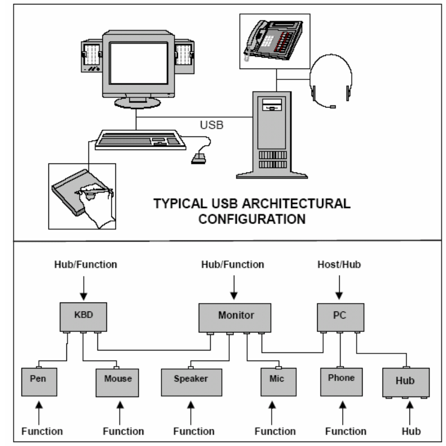
- Connecting peripherals to PCs
  - Ease-of-use
  - Low-cost
  - Up to 127 devices (optionally powered through bus)
  - Transfer rates up to 480 Mb/s
    - Variable speeds and packet sizes
    - Full support for real-time data for voice, audio, and video
    - Protocol flexibility for mixed-mode isochronous data transfers and asynchronous messaging
  - PC manages bus and allocates slots (host controller)
    - Can have multiple host controllers on one PC
    - Support more devices than 127

USB Peripherals

PERFORMANCE	APPLICATIONS	ATTRIBUTES
LOW-SPEED • Interactive Devices • 10 – 100 kb/s	Keyboard, Mouse Stylus Game Peripherals Virtual Reality Peripherals	Lowest Cost Ease-of-Use Dynamic Attach-Detach Multiple Peripherals
FULL-SPEED • Phone, Audio, Compressed Video • 500 kb/s – 10 Mb/s	POTS Broadband Audio Microphone	Lower Cost Ease-of-Use Dynamic Attach-Detach Multiple Peripherals Guaranteed Bandwidth Guaranteed Latency
HIGH-SPEED • Video, Storage • 25 – 400 Mb/s	Video Storage Imaging Broadband	Low Cost Ease-of-Use Dynamic Attach-Detach Multiple Peripherals Guaranteed Bandwidth Guaranteed Latency High Bandwidth

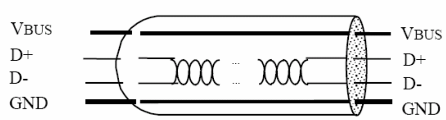
USB

- Tree of devices
  - one root controller



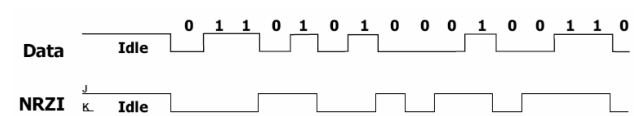
USB Data Transfer

- Data transfer speeds
  - Low is <0.8v, high is >2.0v differential
  - 480Mb/sec, 12Mb/sec, 1.5Mb/sec
  - Data is NRZI encoded (data and clock on one wire)
  - SYNC at beginning of every packet

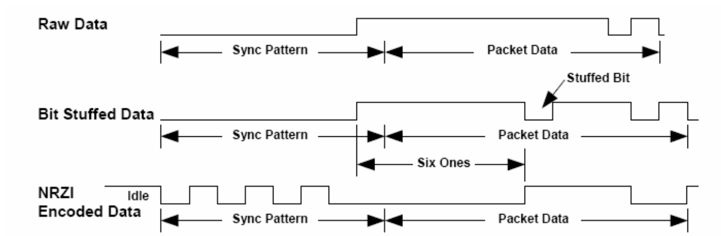


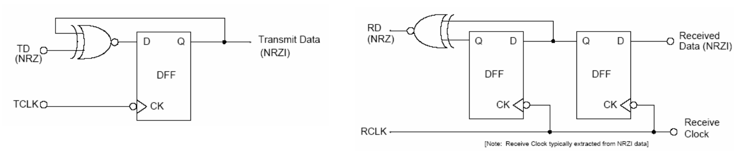
NRZI Encoding

- NRZI – Non-return to zero inverted
  - Toggles a signal to transmit a “0” and leaves the signal unchanged for a “1”
  - Also called transition encoding
  - Long string of 0s generates a regular waveform with a frequency half the bit rate
  - Long string of 1s generates a flat waveform – bit stuff a 0 every 6 consecutive 1s to guarantee activity on waveform



NRZI Encoding (cont'd)





USB Data Transfer Types

- Control Transfers:
  - Used to configure a device at attach time and can be used for other device-specific purposes, including control of other pipes on the device.
- Bulk Data Transfers:
  - Generated or consumed in relatively large and bursty quantities and have wide dynamic latitude in transmission constraints.
- Interrupt Data Transfers:
  - Used for timely but reliable delivery of data, for example, characters or coordinates with human-perceptible echo or feedback response characteristics.
- Isochronous Data Transfers:
  - Occupy a prenegotiated amount of USB bandwidth with a prenegotiated delivery latency. (Also called streaming real time transfers)

USB Packet Format

- Sync + PID + data + CRC
- Basic data packet
  - Sync: 8 bits (00000001)
  - PID: 8 bits (packet id – type)
  - Data: 8-8192 bits (1K bytes)
  - CRC: 16 bits (cyclic redundancy check sum)
- Other data packets vary in size
  - May be as short as only 8 bits of PID

USB Protocol Stack

- FTDI USB chip implements right side
- Communicates to physical device through SPI