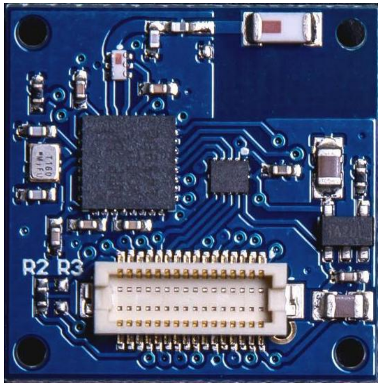
EE107 Spring 2019

Lecture 4

Serial Busses



Embedded Networked Systems

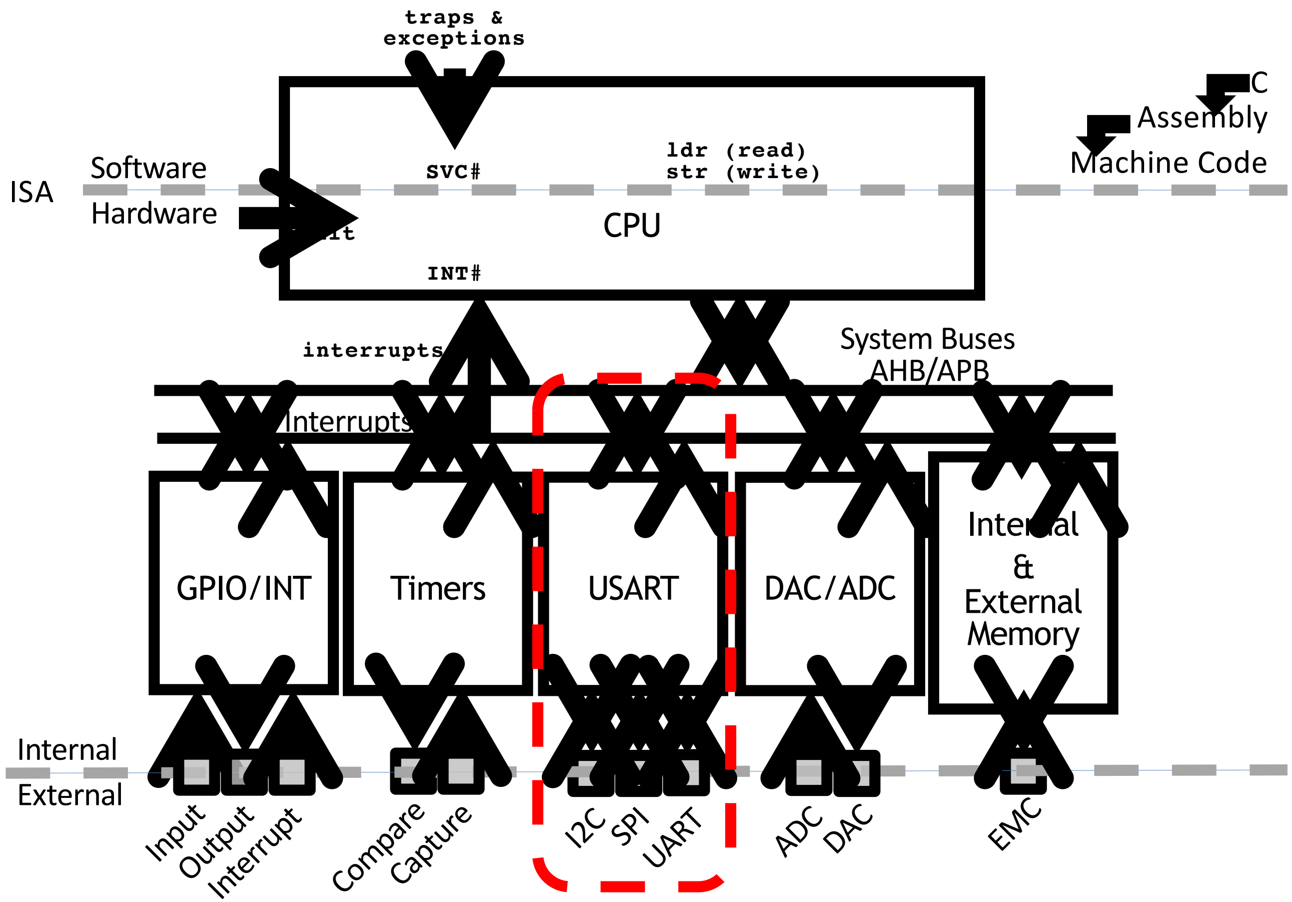
Sachin Katti

*slides adapted from Aaron Schulman's CSE190

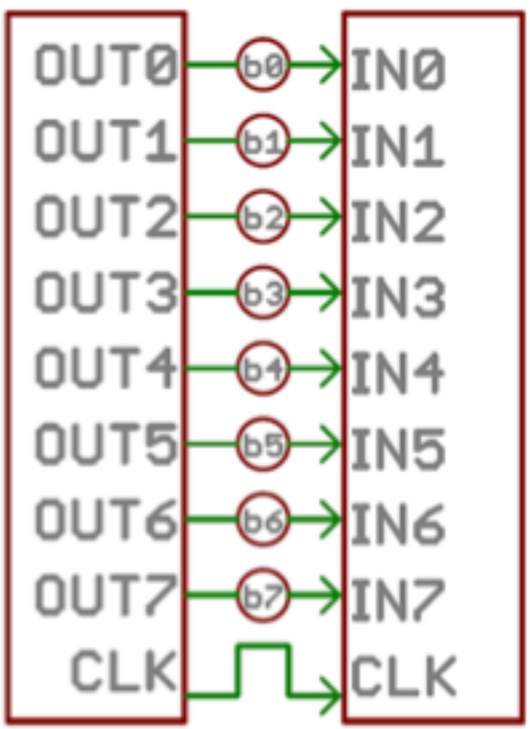
Serial Buses in our project

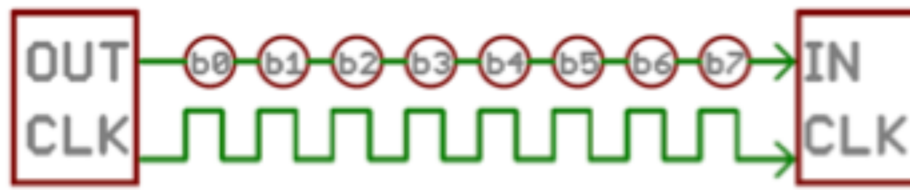
- UART serial bus for sending debug messages to your development host
- I2C serial bus for communicating with sensors (e.g., the accelerometer)
- SPI serial bus for communicating with the Bluetooth Low Energy radio

Serial Interfaces

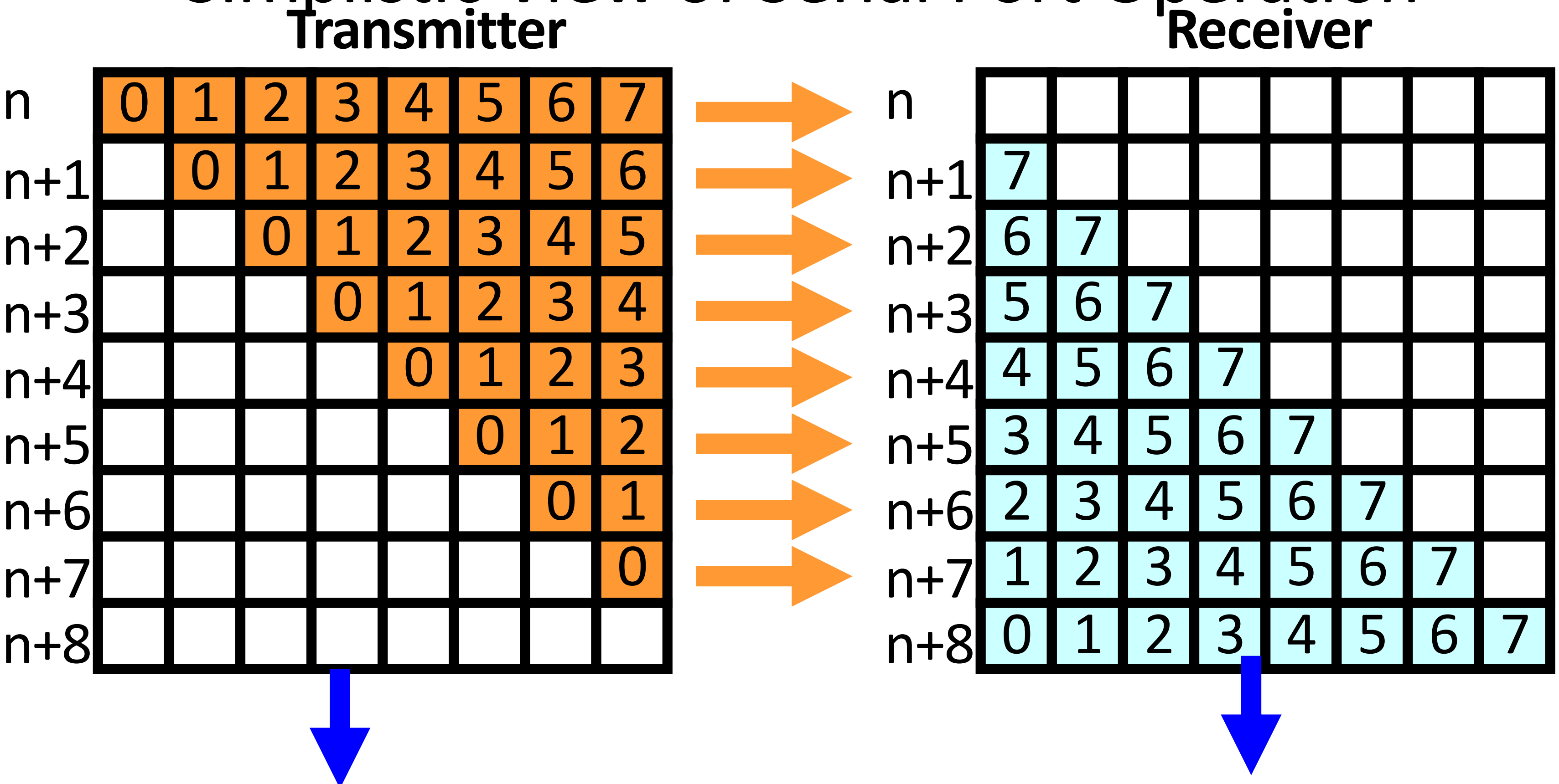


Parallel Bus VS Serial Bus





Simplistic View of Serial Port Operation



Interrupt raised when
Transmitter (Tx) is empty
⇨ Byte has been transmitted
and next byte ready for loading

Interrupt raised when
Receiver (Rx) is full
⇨ Byte has been received
and is ready for reading

Serial Bus Interface Motivations

- Motivation
  - Without using a lot of I/O lines
    - I/O lines require I/O pads which cost $$$ and size
    - I/O lines require PCB area which costs $$$ and size
  - Connect different systems together
    - Two embedded systems
    - A desktop and an embedded system
  - Connect different chips together in the same embedded system
    - MCU to peripheral
    - MCU to MCU
  - Often at relatively low data rates
  - But sometimes at higher data rates
- So, what are our options?
  - Universal Synchronous/Asynchronous Receiver Transmitter
  - Also known as USART (pronounced: "you-sart")

Serial Bus Design Space

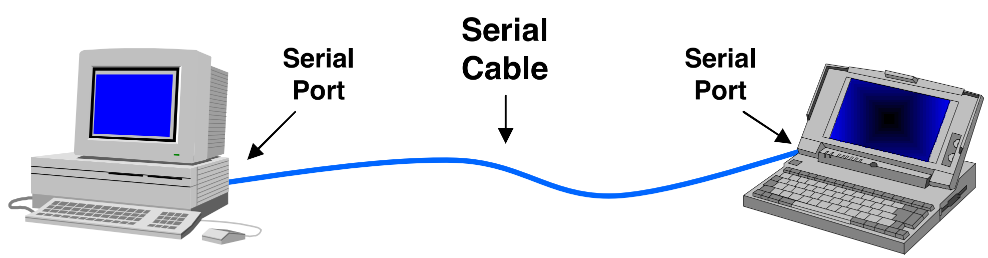
- Number of wires required?
- Asynchronous or synchronous?
- How fast can it transfer data?
- Can it support more than two endpoints?
- Can it support more than one master (i.e. txn initiator)?
- How do we support flow control?
- How does it handle errors/noise?
- How far can signals travel?

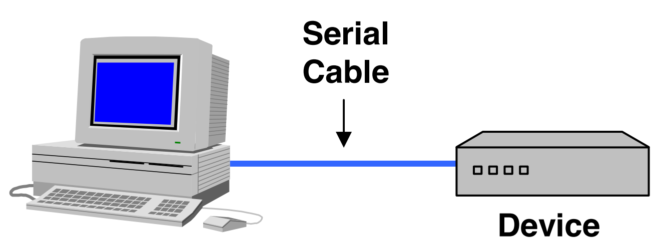
Serial Bus Examples

	S/A	Type	Duplex	#Devices	Speed (kbps)	Distance (ft)	Wires
RS232	A	Peer	Full	2	20	30	2+
RS422	A	Multi-drop	Half	10	10000	4000	1+
RS485	A	Multi-point	Half	32	10000	4000	2
I2C	S	Multi-master	Half	?	3400	<10	2
SPI	S	Multi-master	Full	?	>1000	<10	3+
Microwire	S	Master/slave	Full	?	>625	<10	3+
1-Wire	A	Master/slave	half	?	16	1000	1+

UART Uses

- PC serial port is a UART!
- Serializes data to be sent over serial cable
  - De-serializes received data

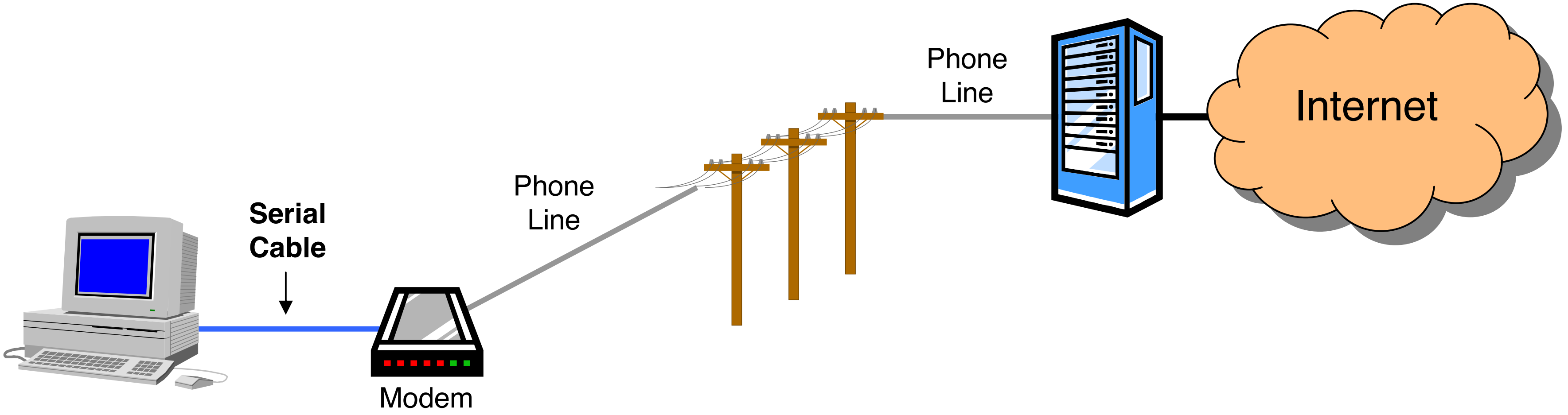




Slides from BYU CS 224

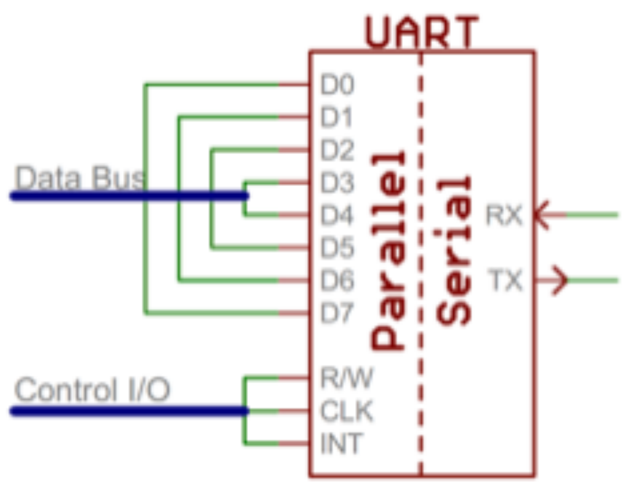
UART Uses

- Used to be commonly used for internet access



UART

- Universal Asynchronous Receiver/Transmitter
- Hardware that translates between parallel and serial forms
- Commonly used in conjunction with communication standards such as EIA, RS-232, RS-422 or RS-485

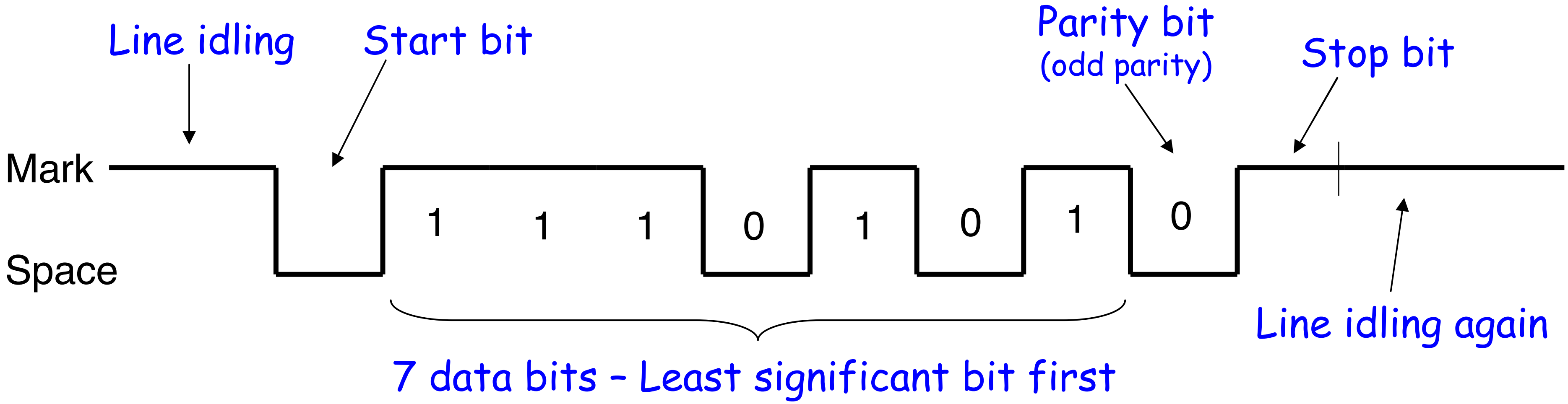


Protocol

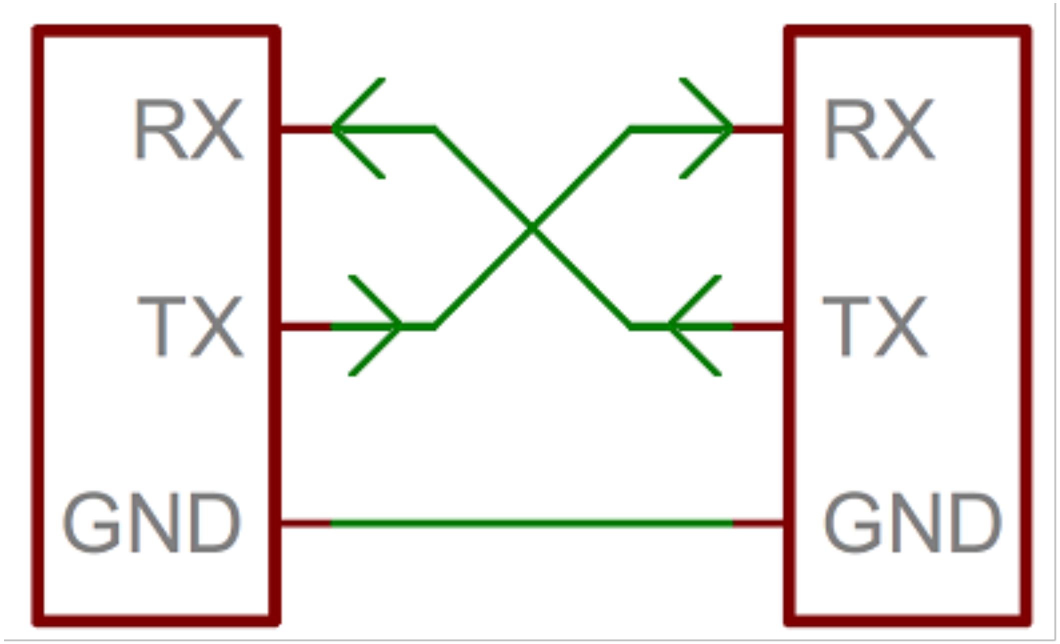
- Each character is sent as
  - a logic *low* **start** bit
  - a configurable number of data bits (usually 7 or 8, sometimes 5)
  - an optional parity bit
  - *one or more logic high* **stop** bits
  - with a particular bit timing ("baud")

UART Example

- Send the ASCII letter 'W' (1010111)



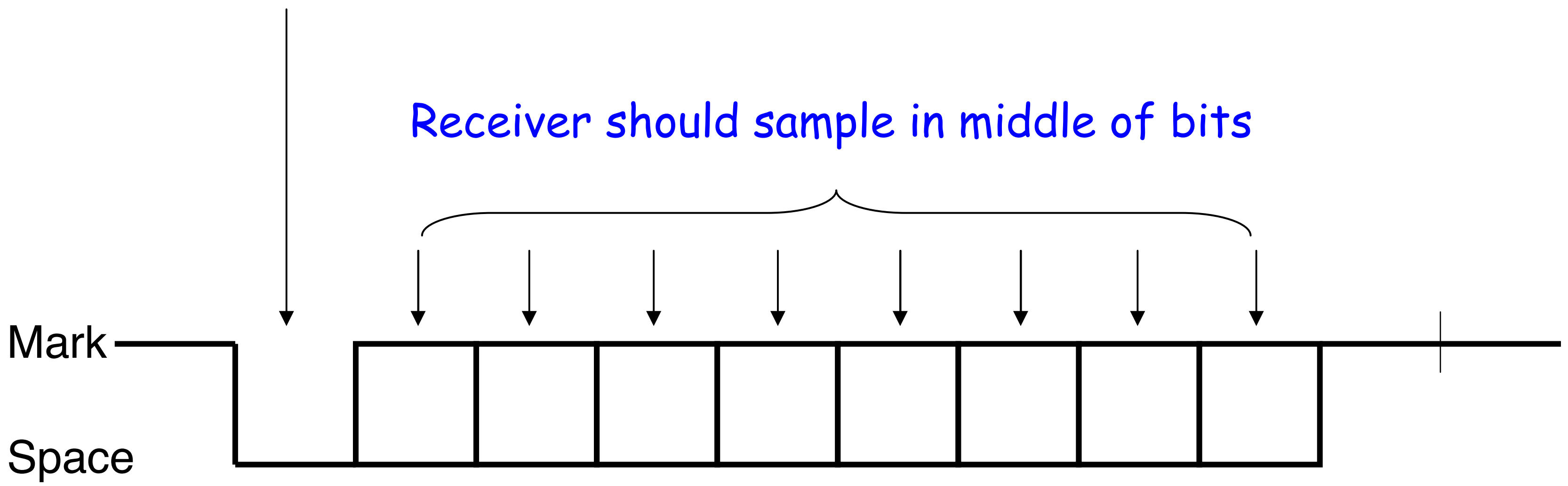
UART Hardware Connection



UART Character Reception

Start bit says a character is coming,
receiver resets its timers

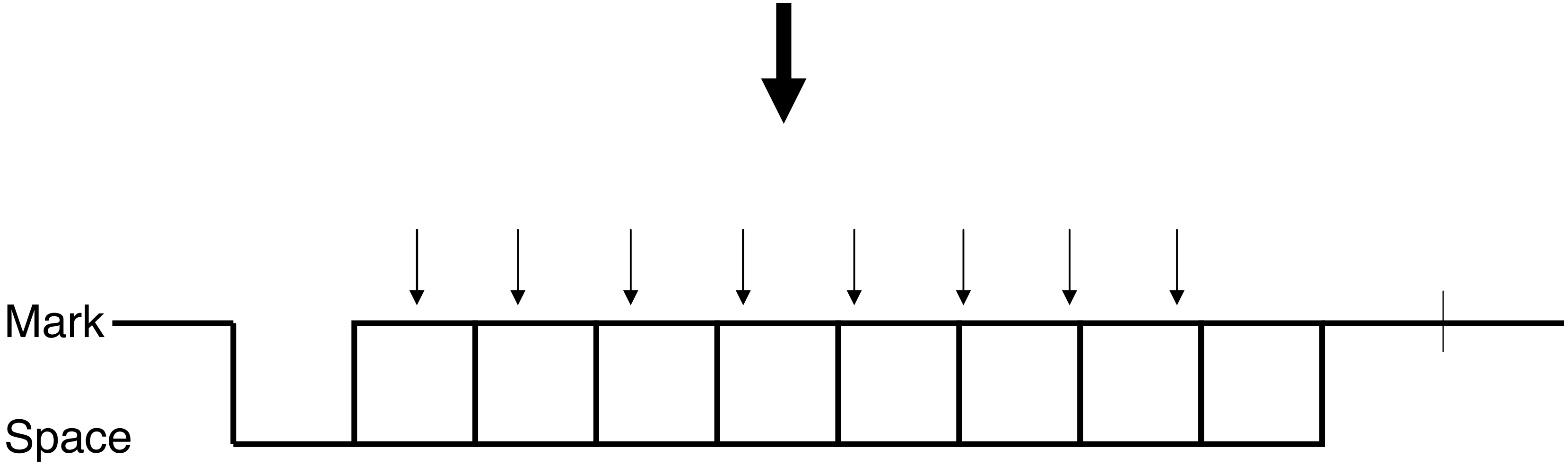
Receiver should sample in middle of bits



Receiver uses a timer (counter) to time when it samples.
Transmission rate (i.e., bit width) must be known!

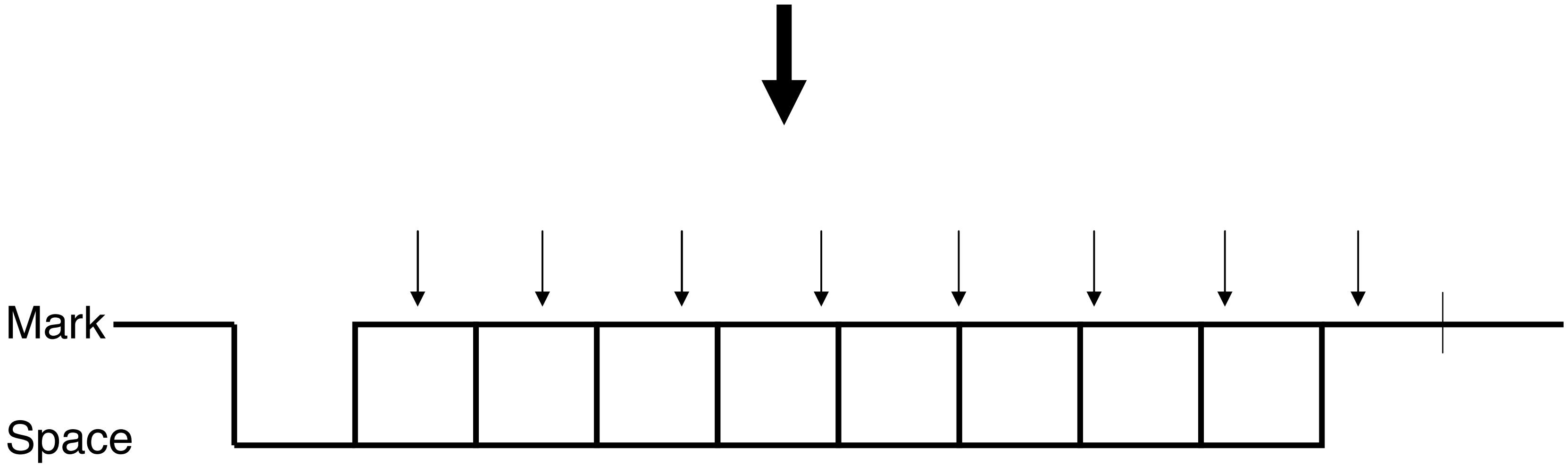
UART Character Reception

If receiver samples too quickly, see what happens…



UART Character Reception

If receiver samples too slowly, see what happens…



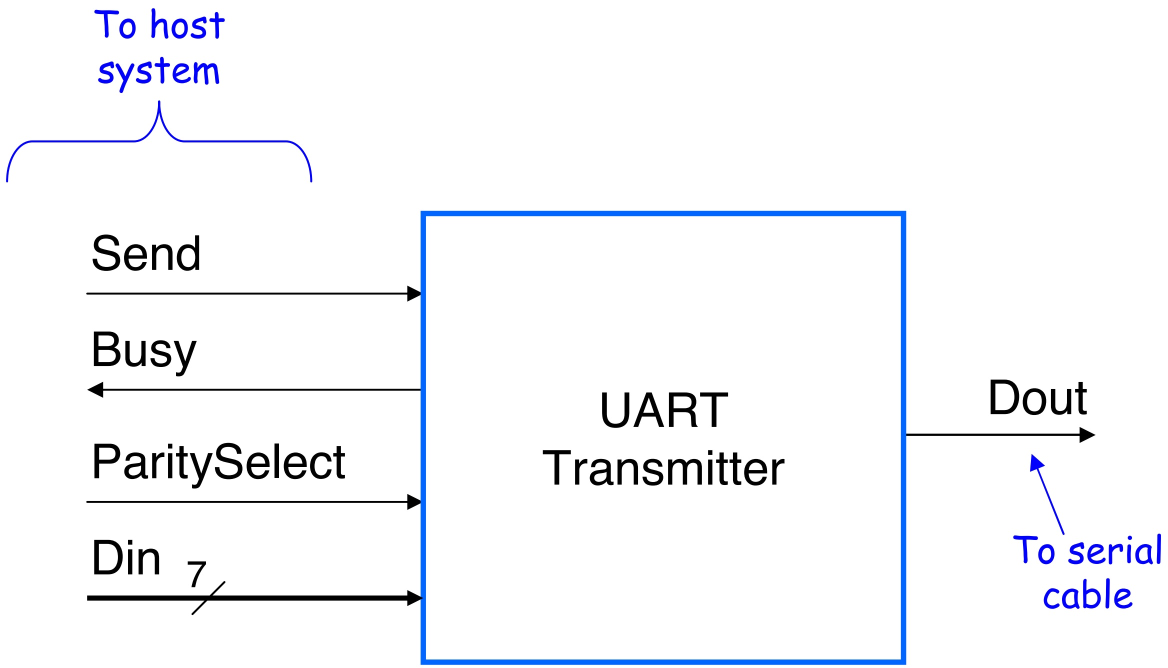
Receiver resynchronizes on every start bit.
Only has to be accurate enough to read 9 bits.

UART Character Reception

- Receiver also verifies that stop bit is ‘1’
  - If not, reports “framing error” to host system

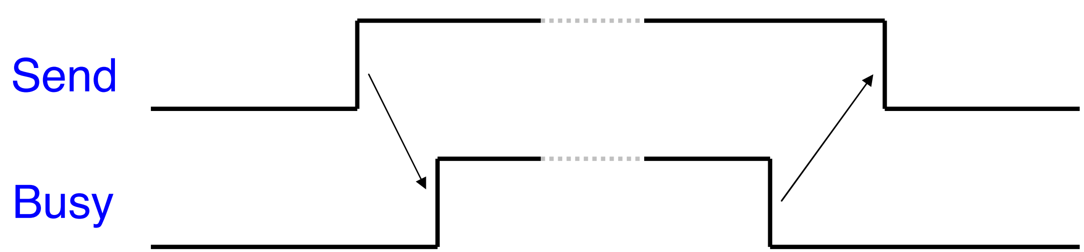
- New start bit can appear immediately after stop bit
  - Receiver will resynchronize on each start bit

Let us design a UART transmitter

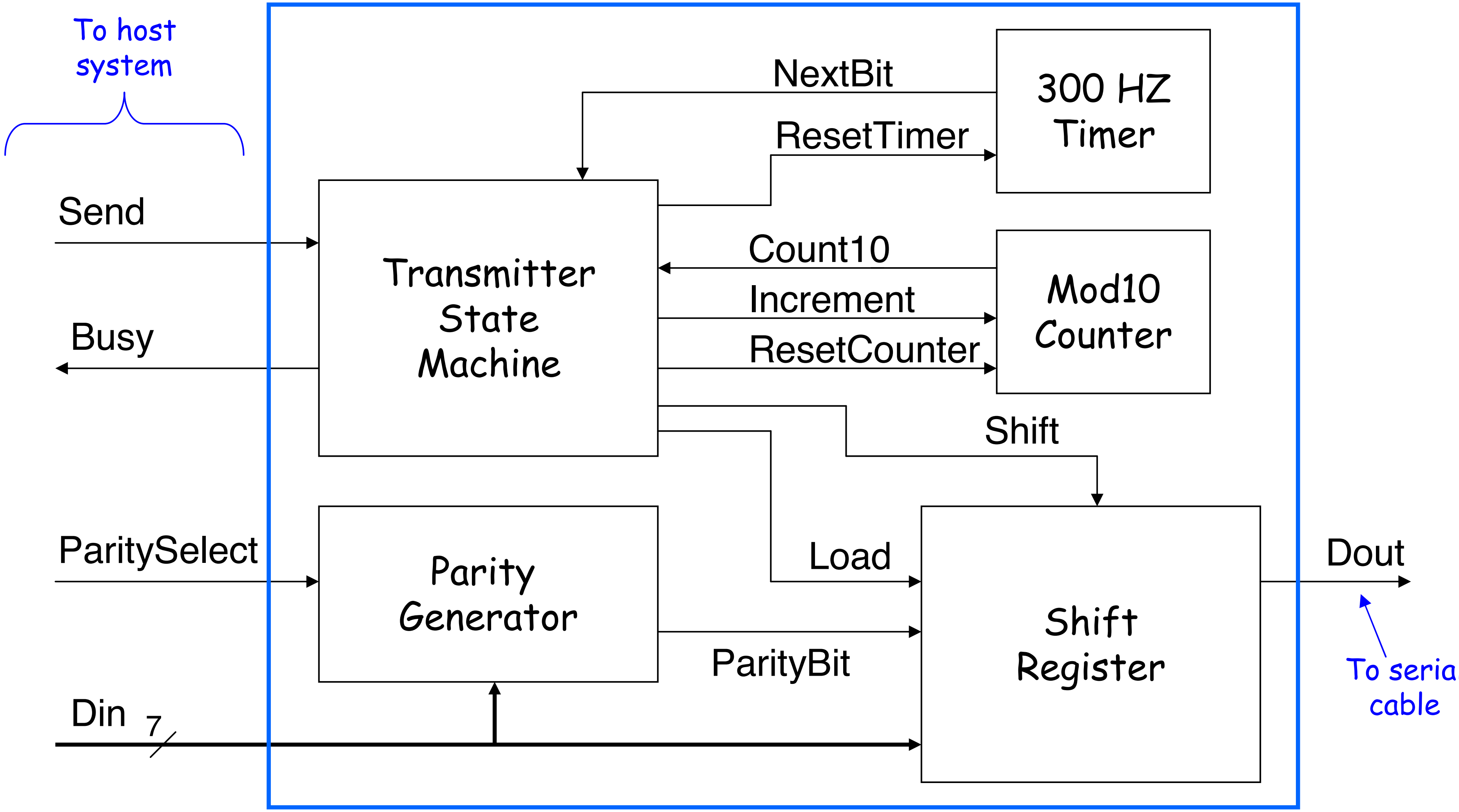


Transmitter/System Handshaking

- System asserts Send and holds it high when it wants to send a byte
- UART asserts Busy signal in response
- When UART has finished transfer, UART de-asserts Busy signal
- System de-asserts Send signal



Transmitter Block Diagram



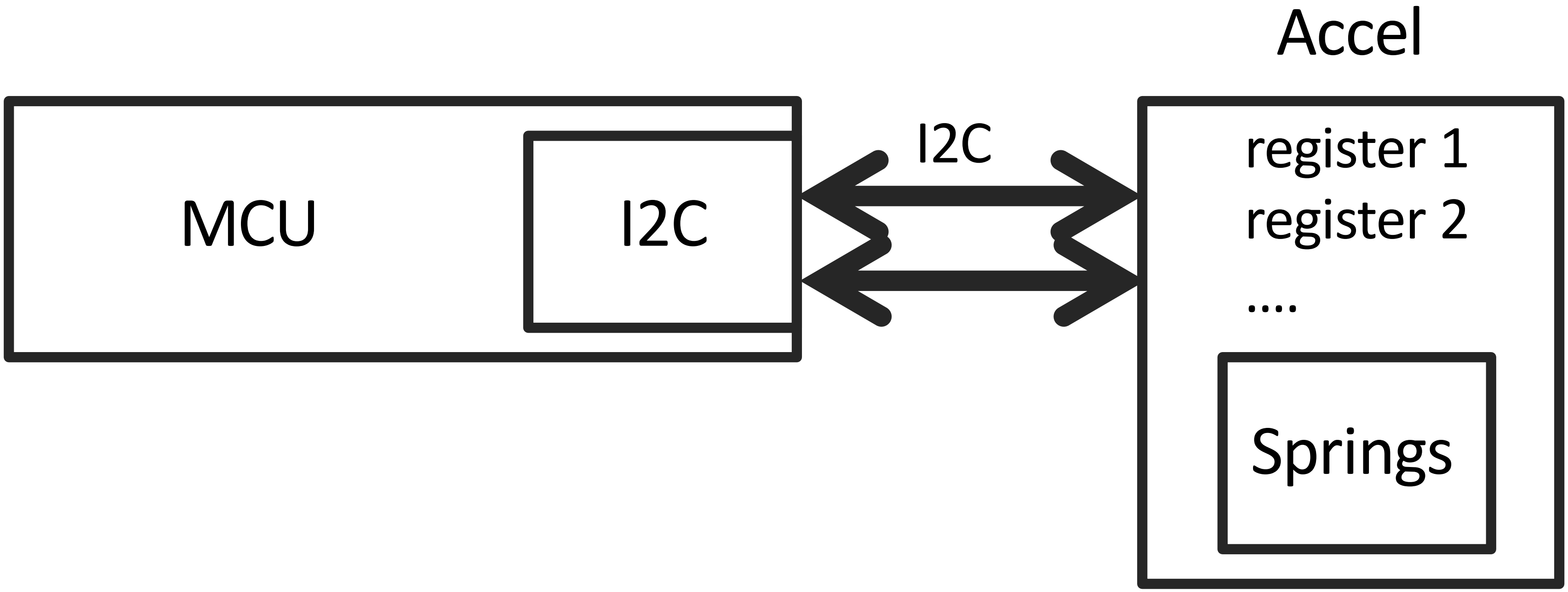
Discussion Questions

- How fast can we run a UART?
- What are the limitations?
- Why do we need start/stop bits?
- How many data bits can be sent?
  - 19200 baud rate, no parity, 8 data bits, 1 stop bit

I2C bus in our projects

- Communication with the accelerometer
  - Read from the accelerometer
- Pros
  - Simple wire connection
  - Two wires bus that can connect multiple peripherals with the MCU
- Cons
  - Complexity is significantly higher

How to operate the accel?

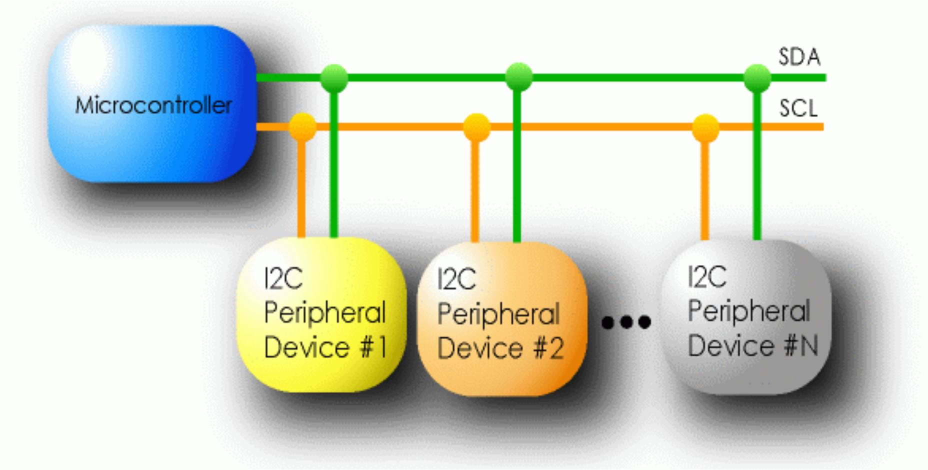


https://www.youtube.com/watch?v=eqZgxR6eRjo

I2C Details

- Two lines
  - Serial data line (SDA)
  - Serial clock line (SCL)

- Only two wires for connecting multiple devices

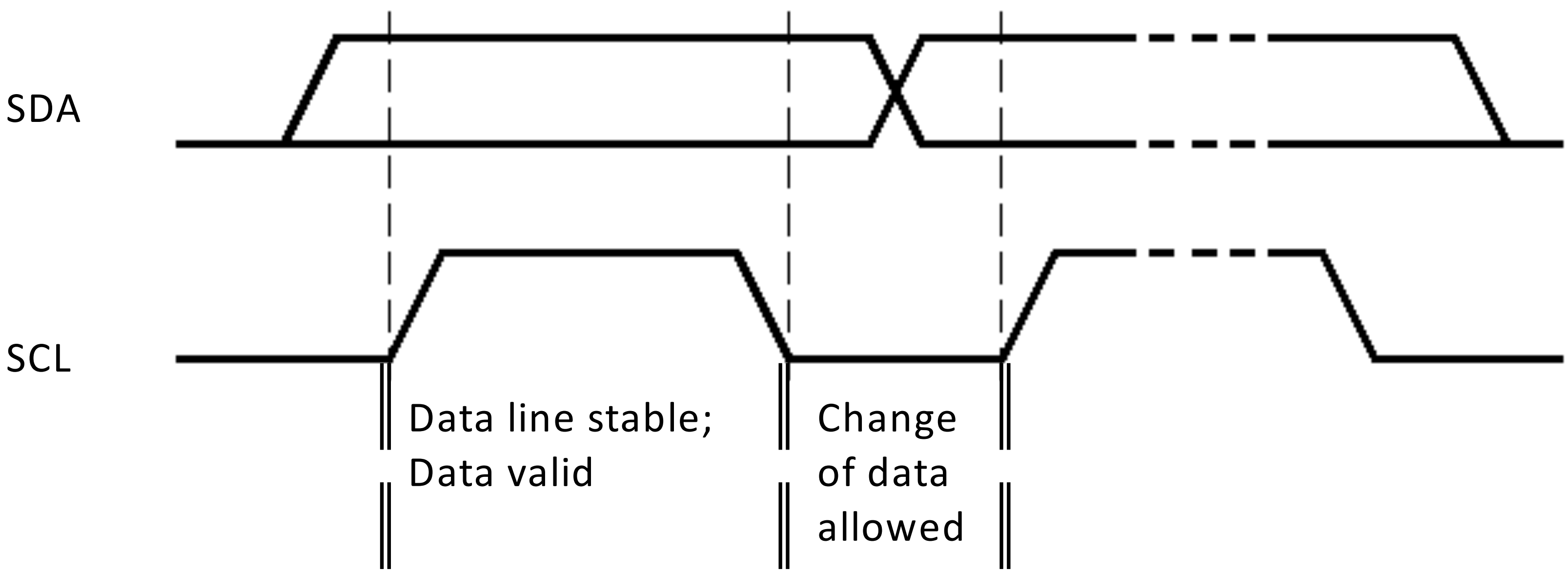


I2C Details

- Each I2C device recognized by a unique address
- Each I2C device can be either a transmitter or receiver
- I2C devices can be masters or slaves for a data transfer
  - Master (usually a microcontroller): Initiates a data transfer on the bus, generates the clock signals to permit that transfer, and terminates the transfer
  - Slave: Any device addressed by the master at that time

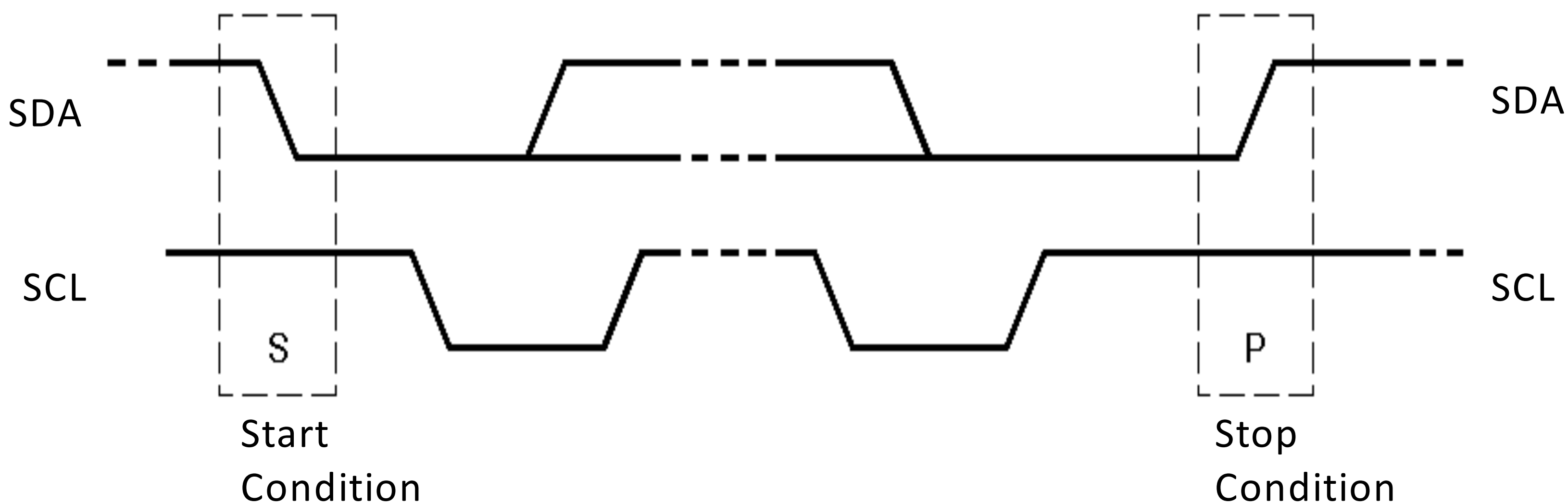
Bit Transfer on the I^2C Bus

- In normal data transfer, the data line only changes state when the clock is low



Start and Stop Conditions

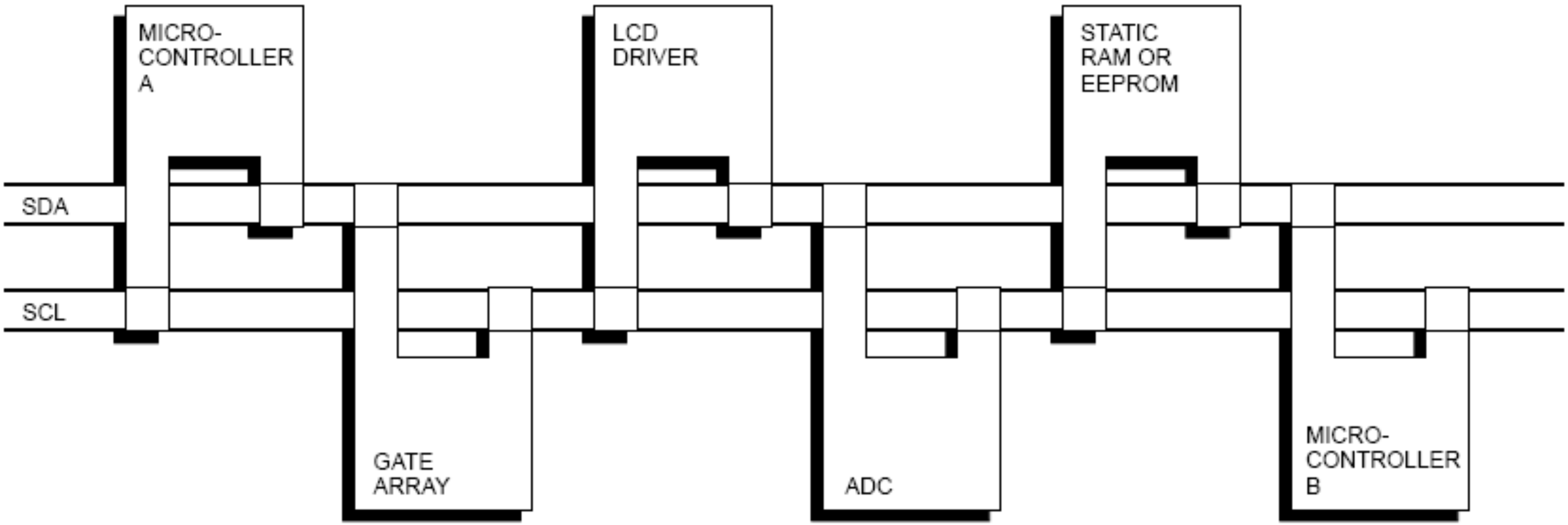
- A transition of the data line while the clock line is high is defined as either a start or a stop condition.
- Both start and stop conditions are generated by the bus master
- The bus is considered busy after a start condition, until a stop condition occurs



I^2C Addressing

- Each node has a unique 7 (or 10) bit address
- Peripherals often have fixed and programmable address portions
- Addresses starting with 0000 or 1111 have special functions:-
  - 0000000 Is a General Call Address
  - 0000001 Is a Null (CBUS) Address
  - 1111XXX Address Extension
  - 1111111 Address Extension – Next Bytes are the Actual Address

I2C-Connected System



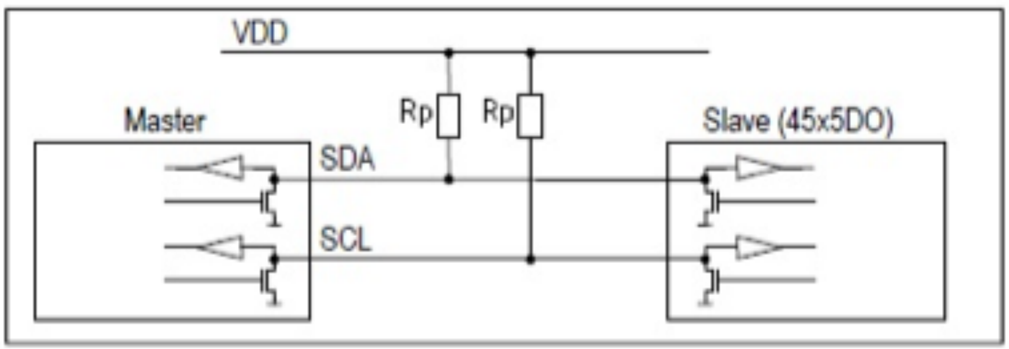
Example I2C-connected system with two microcontrollers

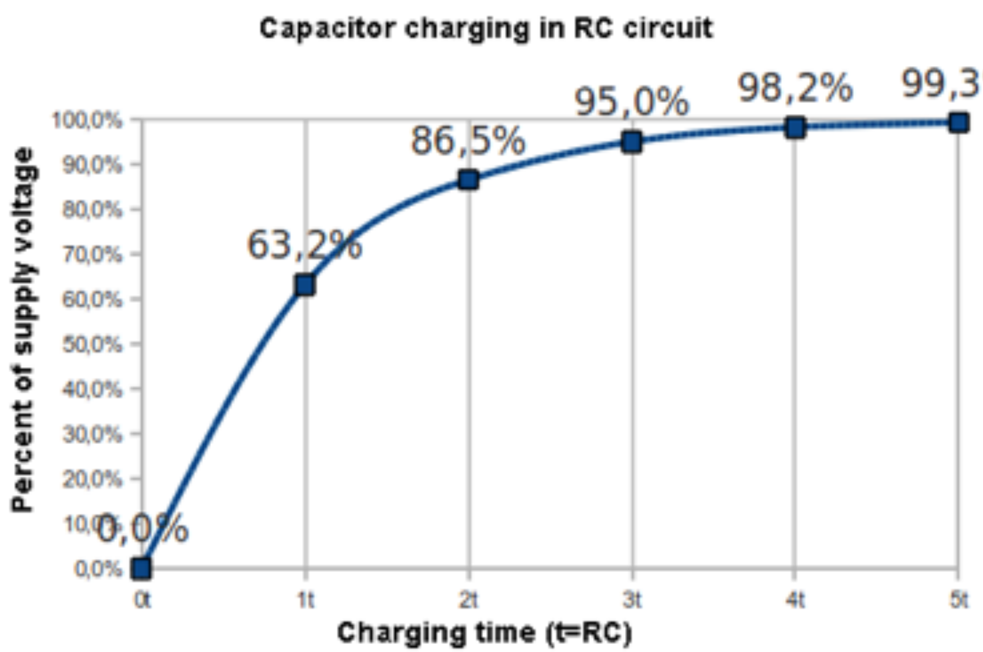
(Source: I2C Specification, Philips)

Master-Slave Relationships

- Who is the master?
  - master-transmitters
  - master-receivers
- Suppose microcontroller A wants to send information to microcontroller B
  - A (master) addresses B (slave)
  - A (master-transmitter), sends data to B (slave-receiver)
  - A terminates the transfer.
- If microcontroller A wants to receive information from microcontroller B
  - A (master) addresses microcontroller B (slave)
  - A (master-receiver) receives data from B (slave-transmitter)
  - A terminates the transfer
- In both cases, the master (microcontroller A) generates the timing and terminates the transfer

Exercise: How fast can I2C run?





- How fast can you run it?
- Assumptions
  - 0's are driven
  - 1's are "pulled up"
- Some working figures
  - R_p = 10 kΩ
  - C_{cap} = 100 pF
  - V_{DD} = 5 V
  - V_{in_high} = 3.5 V
- Recall for RC circuit
  - $V_{cap}(t) = V_{DD}(1-e^{-t/\tau})$
  - Where τ = RC

Exercise: Bus bit rate vs Useful data rate

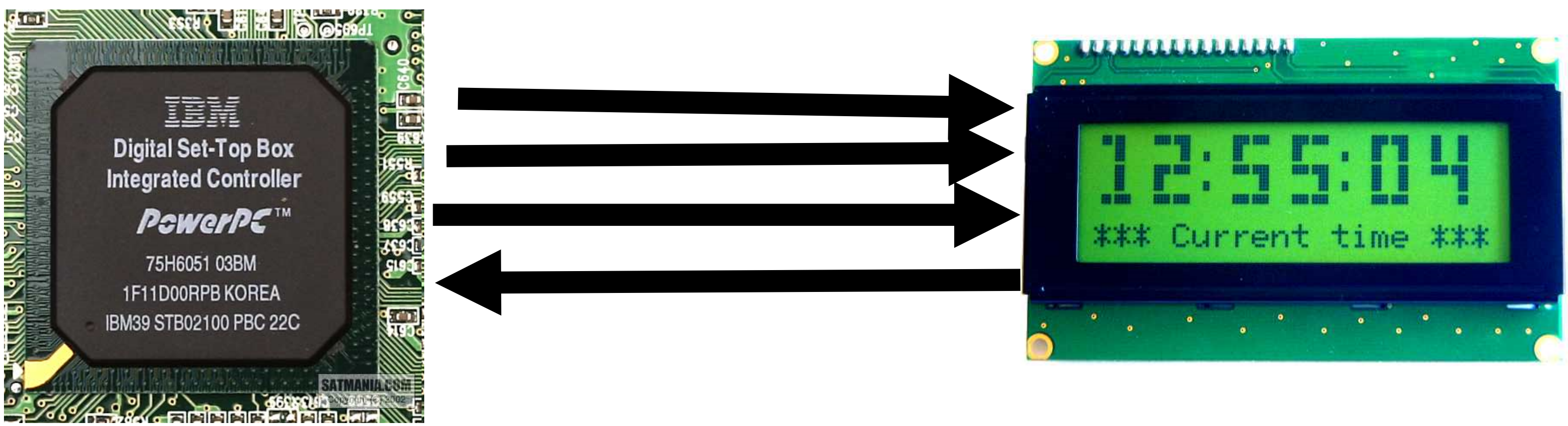
- An I2C “transactions” involves the following bits
  - <S><A6:A0><R/W><A><D7:D0><A><F>
- Which of these actually carries useful data?
  - <S><A6:A0><R/W><A><D7:D0><A><F>
- So, if a bus runs at 400 kHz
  - What is the clock period?
  - What is the data throughput (i.e. data-bits/second)?
  - What is the bus “efficiency”?

Serial Peripheral Interconnect (SPI)

- Another kind of serial protocol in embedded systems (proposed by Motorola)
- Four-wire protocol
  - SCLK — Serial Clock
  - MOSI/SIMO — Master Output, Slave Input
  - MISO/SOMI — Master Input, Slave Output
  - SS — Slave Select
- Single master device and with one or more slave devices
- Higher throughput than I2C and can do "stream transfers"
- No arbitration required
- But
  - Requires more pins
  - Has no hardware flow control
  - No slave acknowledgment (master could be talking to thin air and not even know it)

What is SPI?

- Serial Bus protocol
- Fast, Easy to use, Simple
- Everyone supports it



SPI Basics

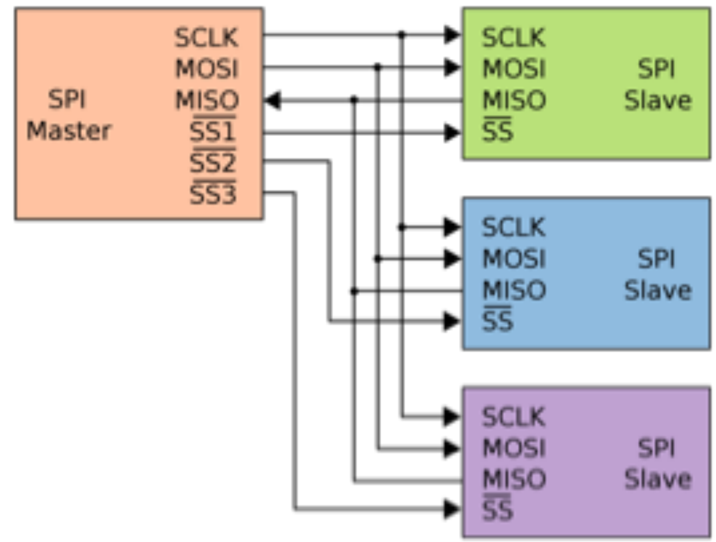
- A communication protocol using 4 wires
  - Also known as a 4 wire bus
- Used to communicate across small distances
- Multiple Slaves, Single Master
- Synchronized

SPI Capabilities

- Always Full Duplex
  - Communicating in two directions at the same time
  - Transmission need not be meaningful
- Multiple Mbps transmission speed
- Transfers data in 4 to 16 bit characters
- Multiple slaves
  - Daisy-chaining possible

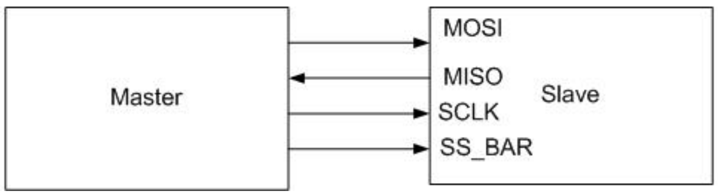
SPI Protocol

- Wires:
  - Master Out Slave In (MOSI)
  - Master In Slave Out (MISO)
  - System Clock (SCLK)
  - Slave Select 1…N
- Master Set Slave Select low
- Master Generates Clock
- Shift registers shift in and out data

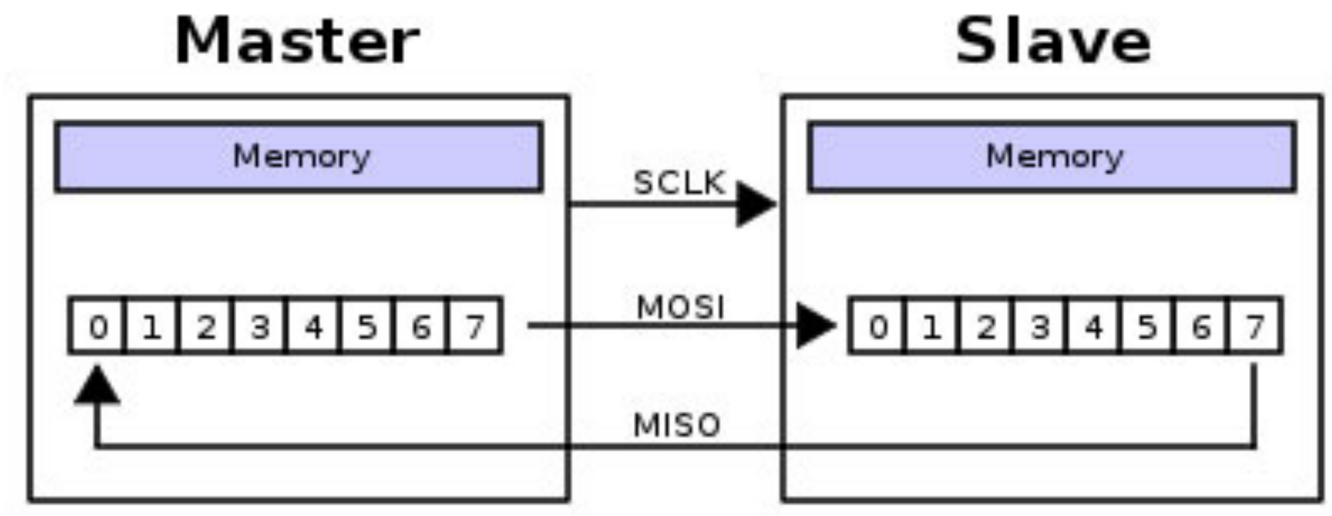


SPI Wires in Detail

- MOSI – Carries data out of Master to Slave
- MISO – Carries data from Slave to Master
  - Both signals happen for every transmission
- SS_BAR – Unique line to select a slave
- SCLK – Master produced clock to synchronize data transfer



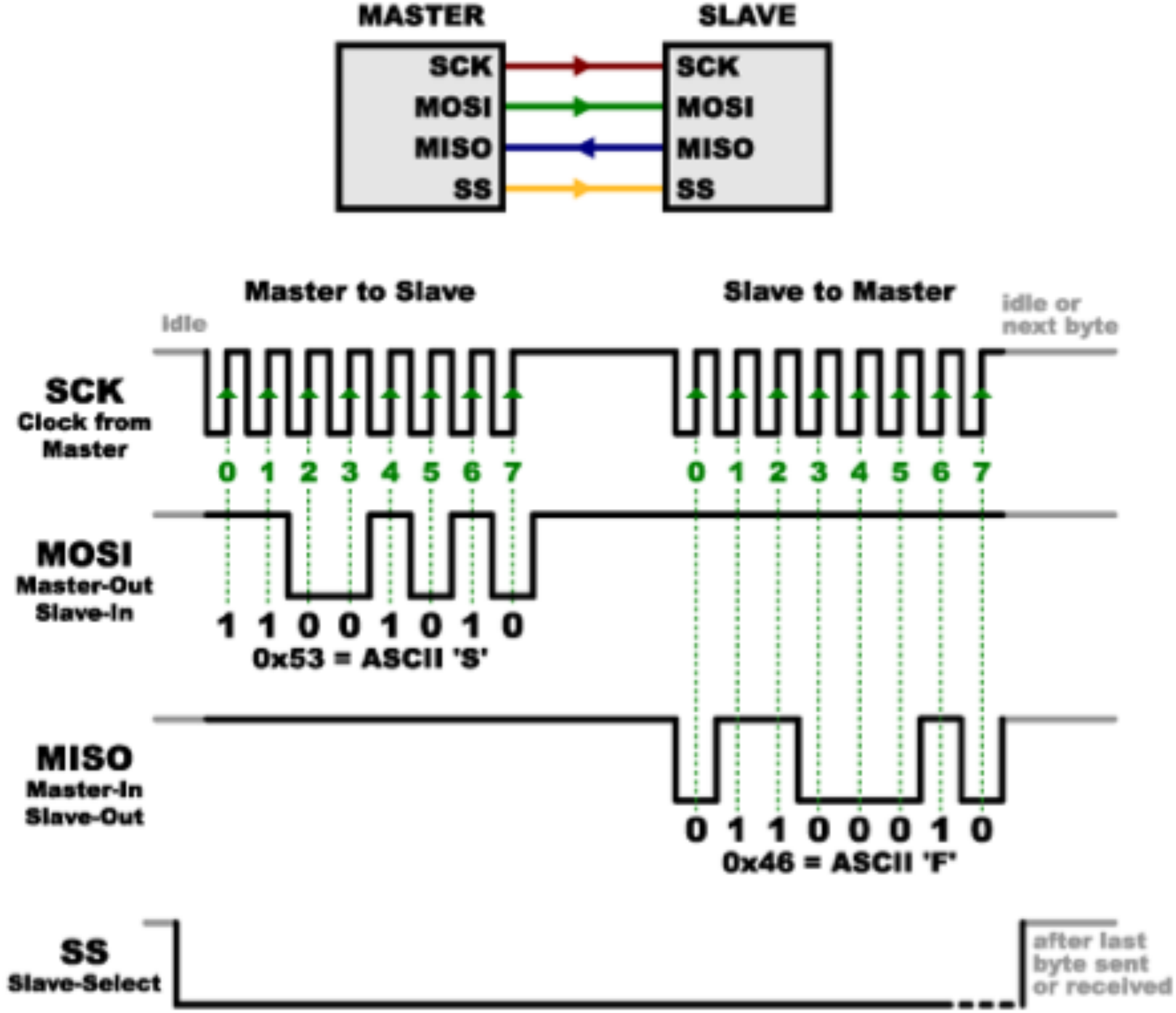
SPI uses a “shift register” model of communications



Master shifts out data to Slave, and shifts in data from Slave

http://upload.wikimedia.org/wikipedia/commons/thumb/b/bb/SPI_8-bit_circular_transfer.svg/400px-SPI_8-bit_circular_transfer.svg.png

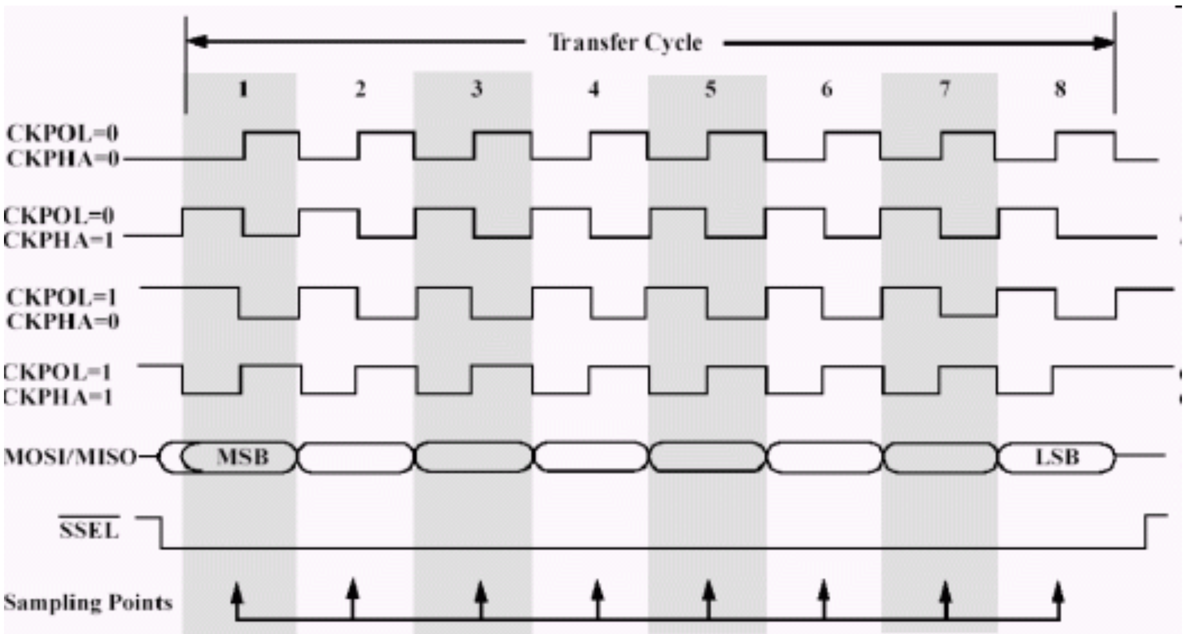
SPI Communication



SPI clocking: there is no "standard way"

- Four clocking "modes"
  - Two phases
  - Two polarities
- Master and *selected* slave must be in the same mode
- During transfers with slaves A and B, Master must
  - Configure clock to Slave A's clock mode
  - Select Slave A
  - Do transfer
  - Deselect Slave A
  - Configure clock to Slave B's clock mode
  - Select Slave B
  - Do transfer
  - Deselect Slave B
- Master reconfigures clock mode on-the-fly!

SPI timing diagram



Timing Diagram – Showing Clock polarities and phases
http://www.maxim-ic.com.cn/images/appnotes/3078/3078Fig02.gif

SPI Pros and Cons

- Pros:
  - Fast and easy
    - Fast for point-to-point connections
    - Easily allows streaming/Constant data inflow
    - No addressing/Simple to implement
  - Everyone supports it

- Cons:
  - SS makes multiple slaves very complicated
  - No acknowledgement ability
  - No inherent arbitration
  - No flow control