Universal Asynchronous Receiver/Transmitter

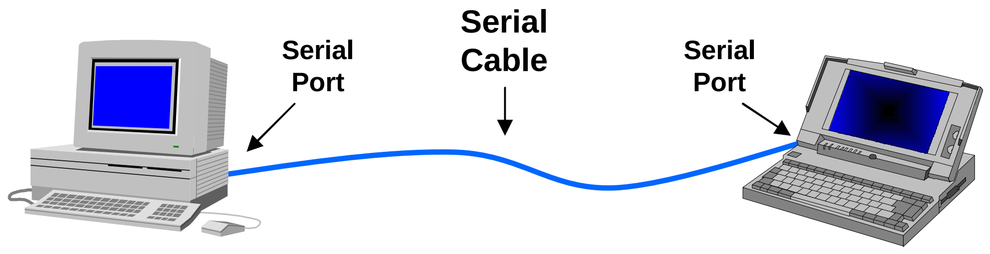
UART

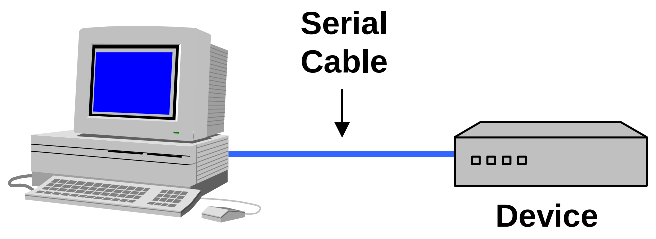
Why use a UART?

- A UART may be used when:
  - High speed is not required
  - A cheap communication line between **two** devices is required
- Asynchronous serial communication is very cheap
  - Requires a transmitter and/or receiver
  - Single wire for each direction (plus ground wire)
  - Relatively simple hardware
  - Asynchronous because the
- PC devices such as mice and modems used to often be asynchronous serial devices

UART Uses

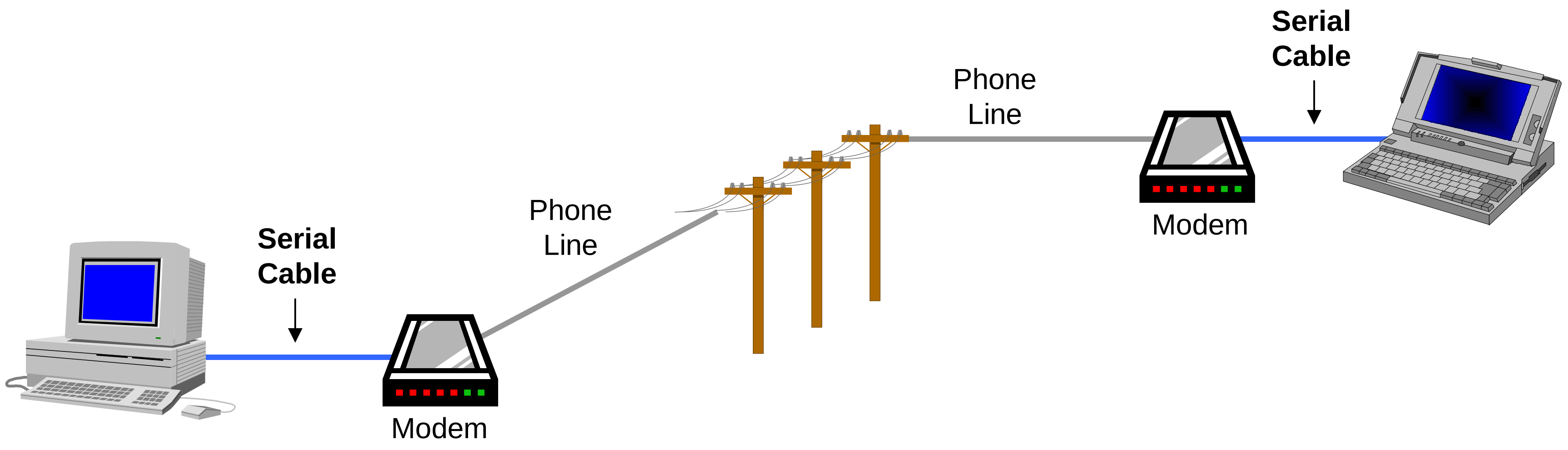
- PC serial port is a UART!
- Serializes data to be sent over serial cable
  - De-serializes received data





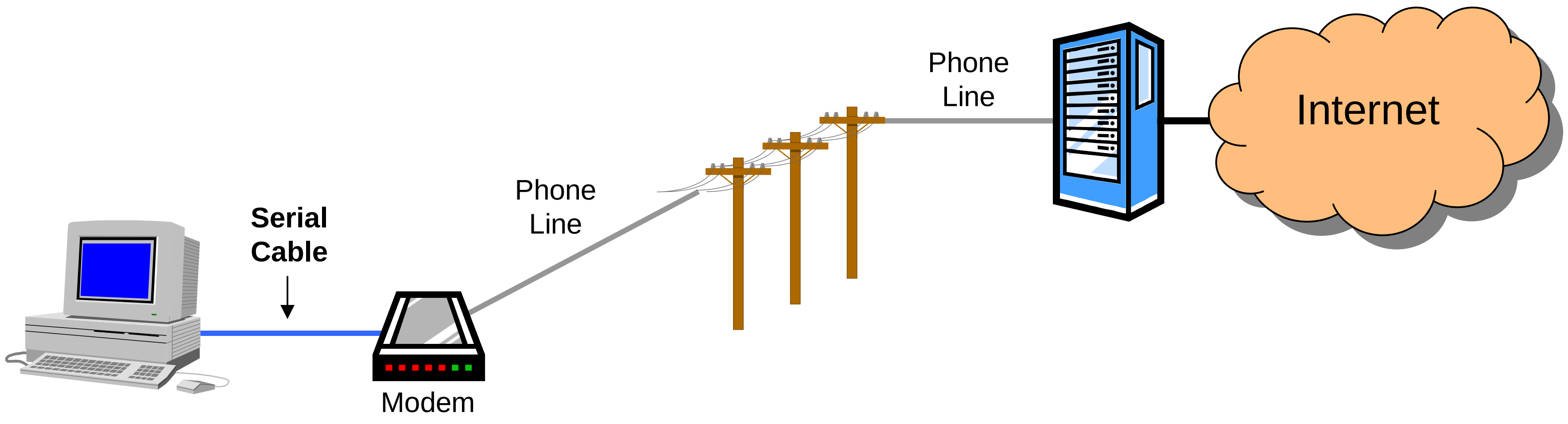
UART Uses

- Communication between distant computers
  - Serializes data to be sent to modem
  - De-serializes data received from modem



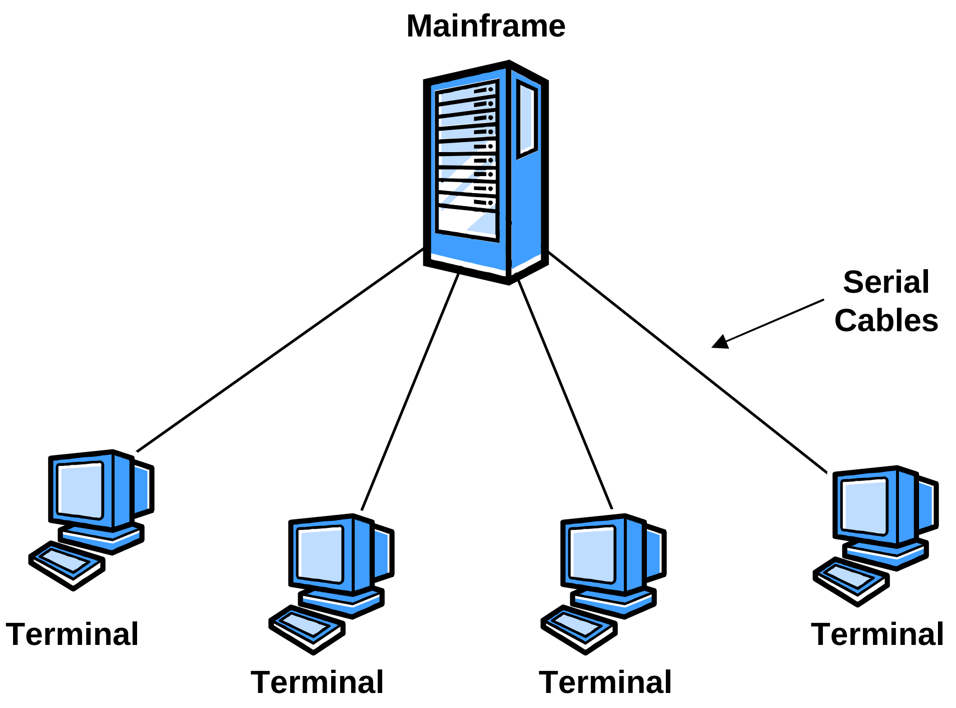
UART Uses

- Used to be commonly used for internet access



UART Uses

- Used to be used for mainframe access
  - A mainframe could have dozens of serial ports



UART Uses

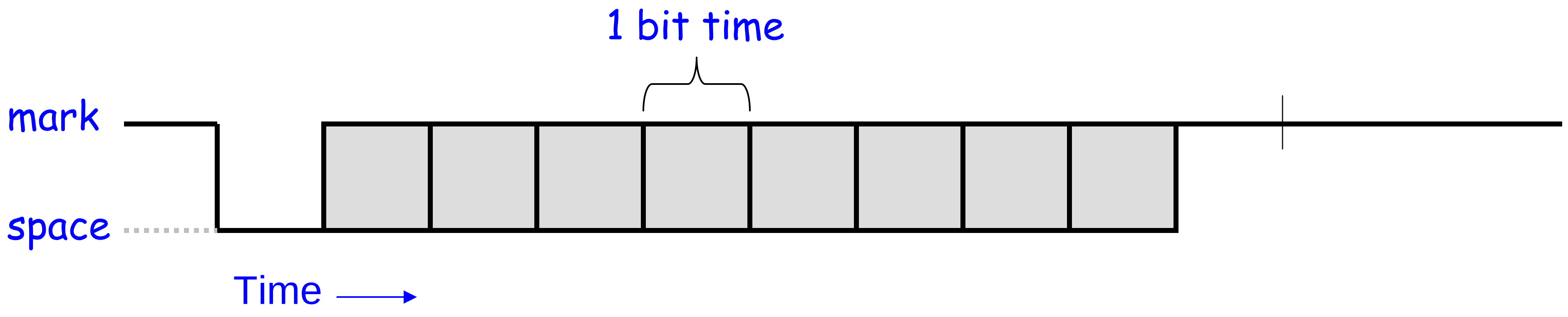
- Becoming much less common
- Largely been replaced by faster, more sophisticated interfaces
  - PCs: USB (peripherals), Ethernet (networking)
  - Chip to chip: I2C, SPI
- Still used today when simple low speed communication is needed

UART Functions

- Outbound data
  - Convert from parallel to serial
  - Add start and stop delineators (bits)
  - Add parity bit
- Inbound data
  - Convert from serial to parallel
  - Remove start and stop delineators (bits)
  - Check and remove parity bit

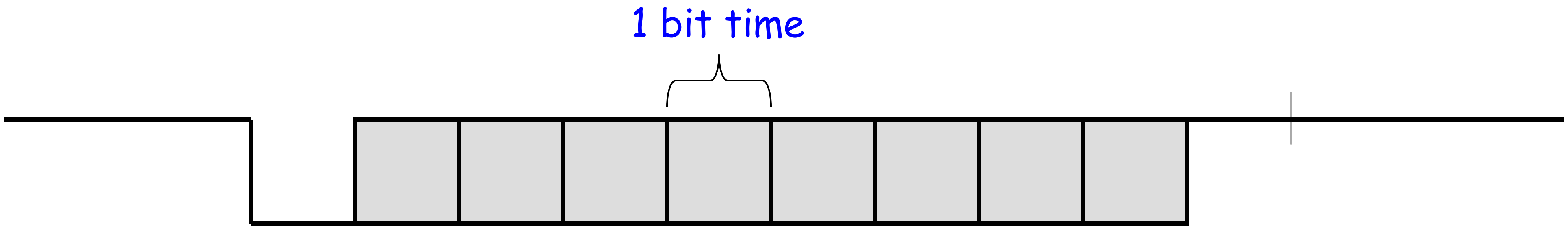
UART Character Transmission

- Below is a timing diagram for the transmission of a single byte
- Uses a single wire for transmission
- Each block represents a bit that can be a **mark** (logic '1', high) or **space** (logic '0', low)



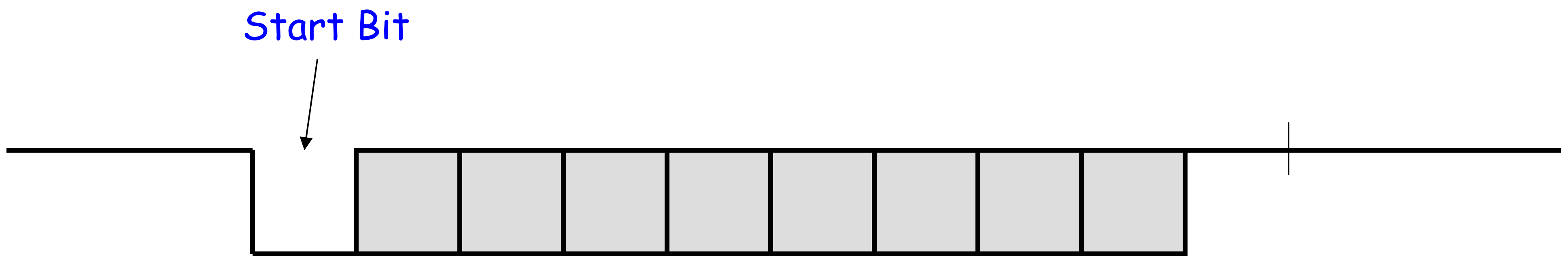
UART Character Transmission

- Each bit has a fixed time duration determined by the transmission rate
- Example: a 1200 bps (bits per second) UART will have a 1/1200 s or about 833.3 μs bit width



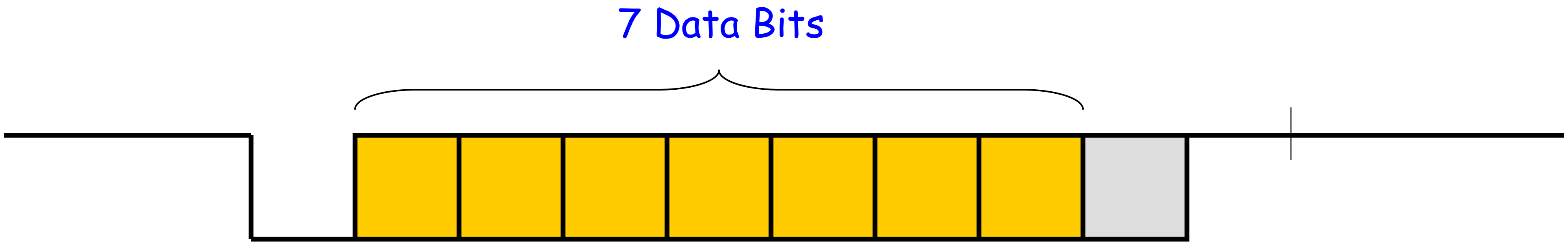
UART Character Transmission

- The **start bit** marks the beginning of a new word
- When detected, the receiver synchronizes with the new data stream



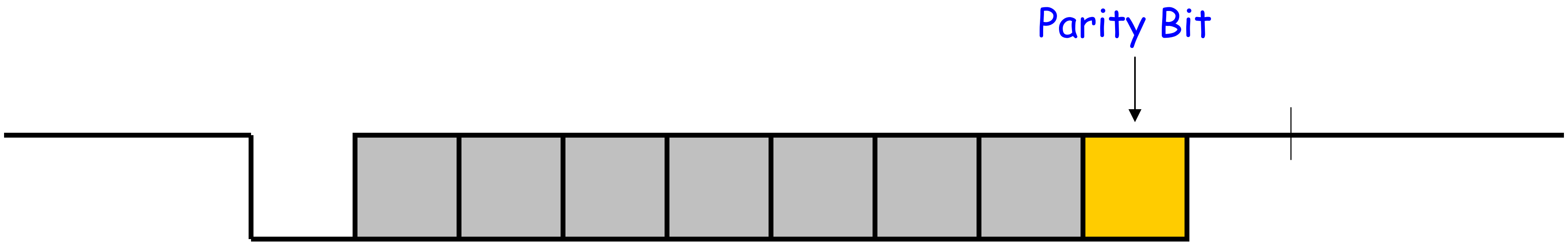
UART Character Transmission

- Next follows the **data bits** (7 or 8)
- The least significant bit is sent first



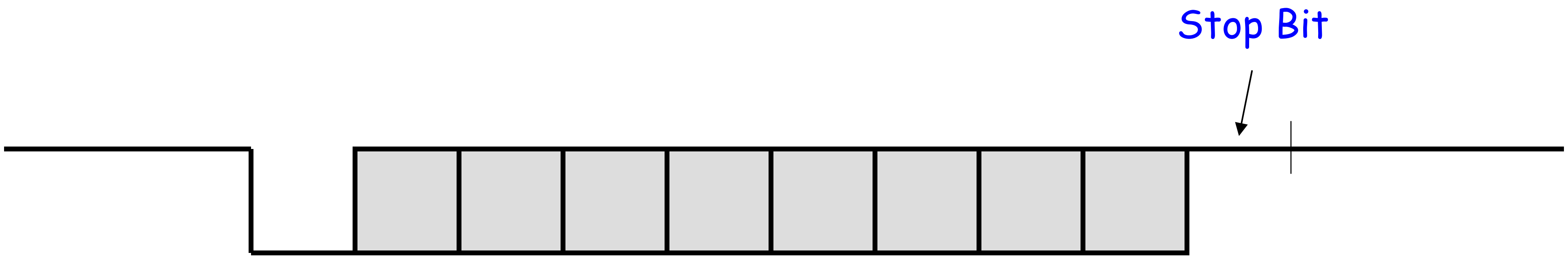
UART Character Transmission

- The **parity bit** is added to make the number of 1's even (even parity) or odd (odd parity)
- This bit can be used by the receiver to check for transmission errors



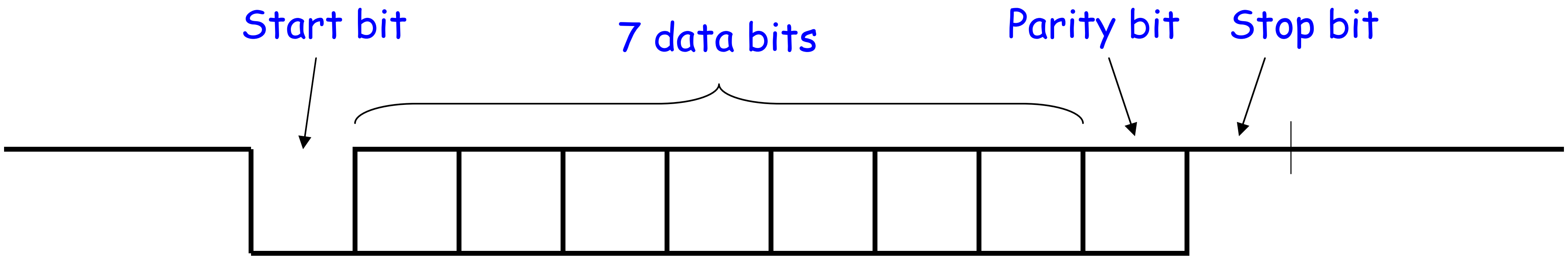
UART Character Transmission

- The **stop bit** marks the end of transmission
- Receiver checks to make sure it is '1'
- Separates one word from the start bit of the next word



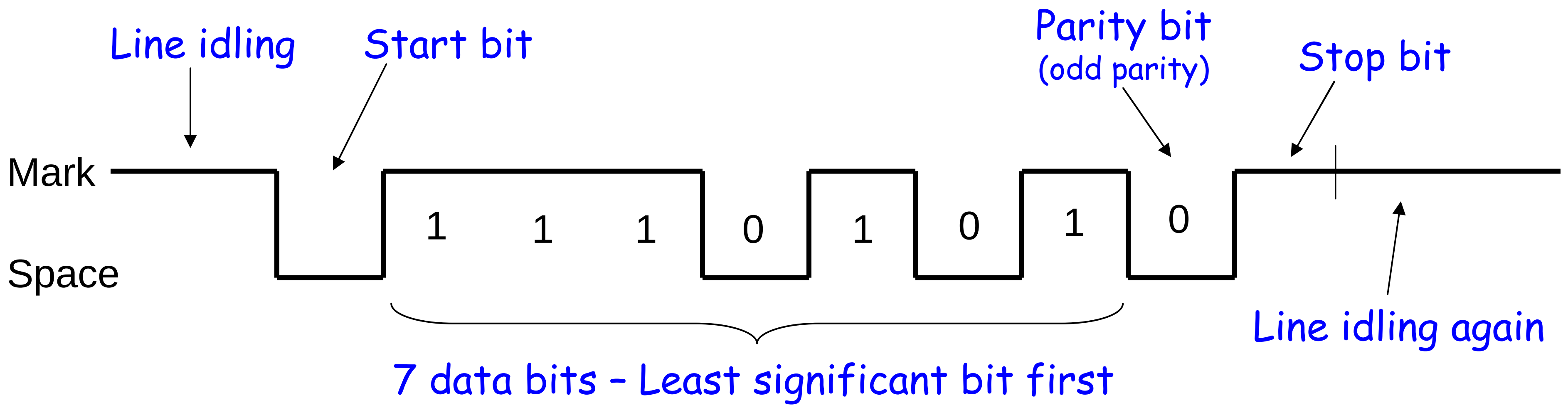
UART Character Transmission

- In the configuration shown, it takes 10 bits to send 7 bits of data

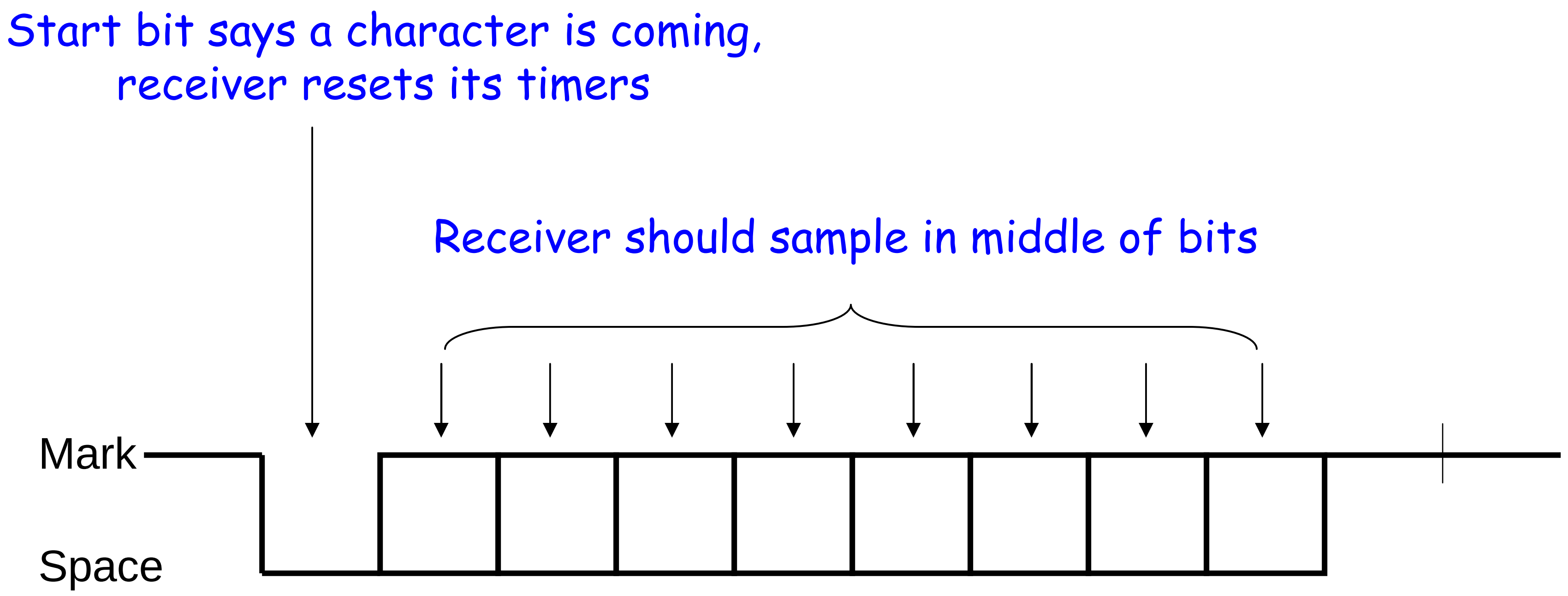


UART Transmission Example

- Send the ASCII letter 'W' (1010111)



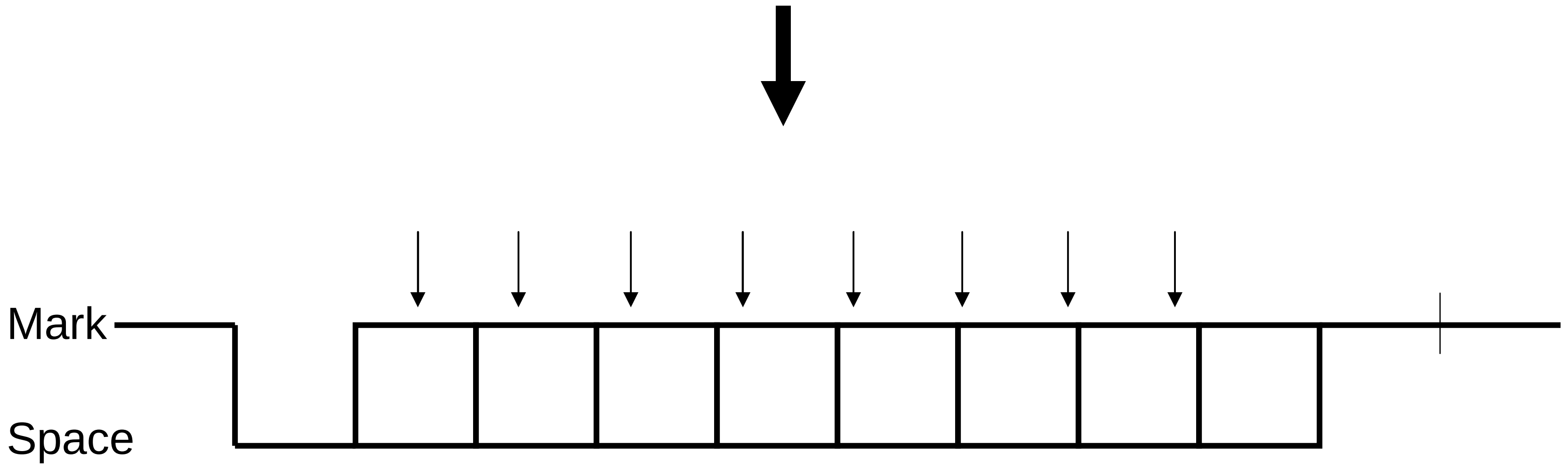
UART Character Reception


Start bit says a character is coming,
receiver resets its timers
Receiver should sample in middle of bits
Mark
Space

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

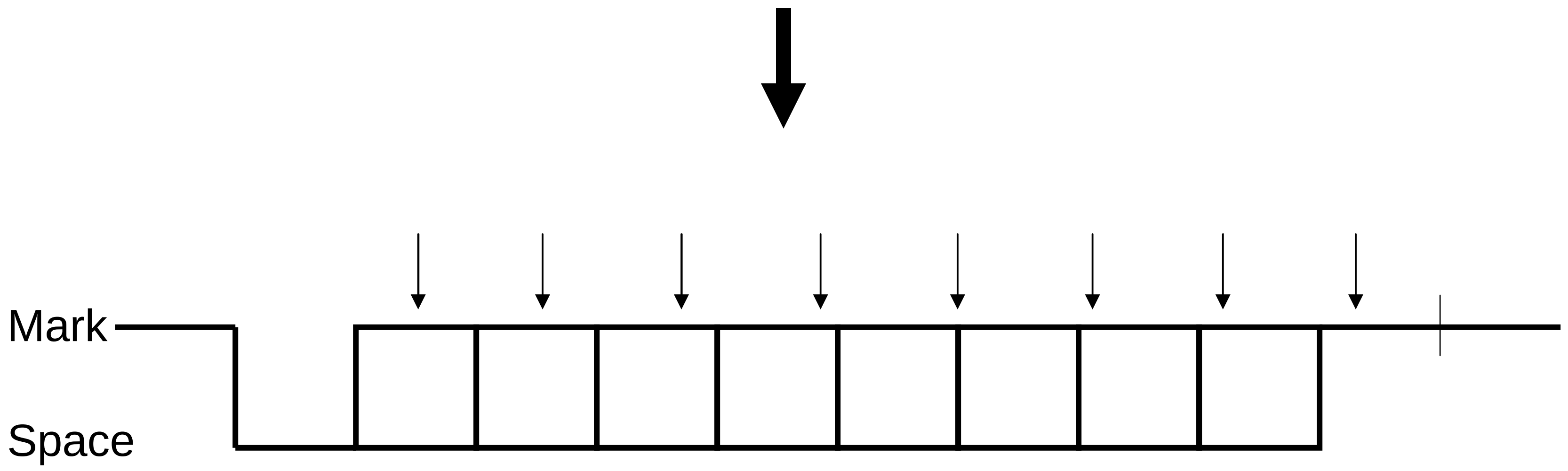
UART Character Reception

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

UART Options

- UARTs usually have programmable options:
  - **Data:** 7 or 8 bits
  - **Parity:** even, odd, none, mark, space
  - **Stop bits:** 1, 1.5, 2
  - **Baud rate:** 300, 1200, 2400, 4800, 9600, 19.2K, 38.4k, 57.6k, 115.2k…

UART Options

- Baud Rate
  - The "symbol rate" of the transmission system
  - For a UART, same as the number of bits per second (bps)
  - Each bit is 1/(rate) seconds wide
- Example:
  - 9600 baud → 9600 Hz
  - 9600 bits per second (bps)
  - Each bit is 1/(9600 Hz) ≈ 104.17 μs long

Not the data throughput rate!

UART Throughput

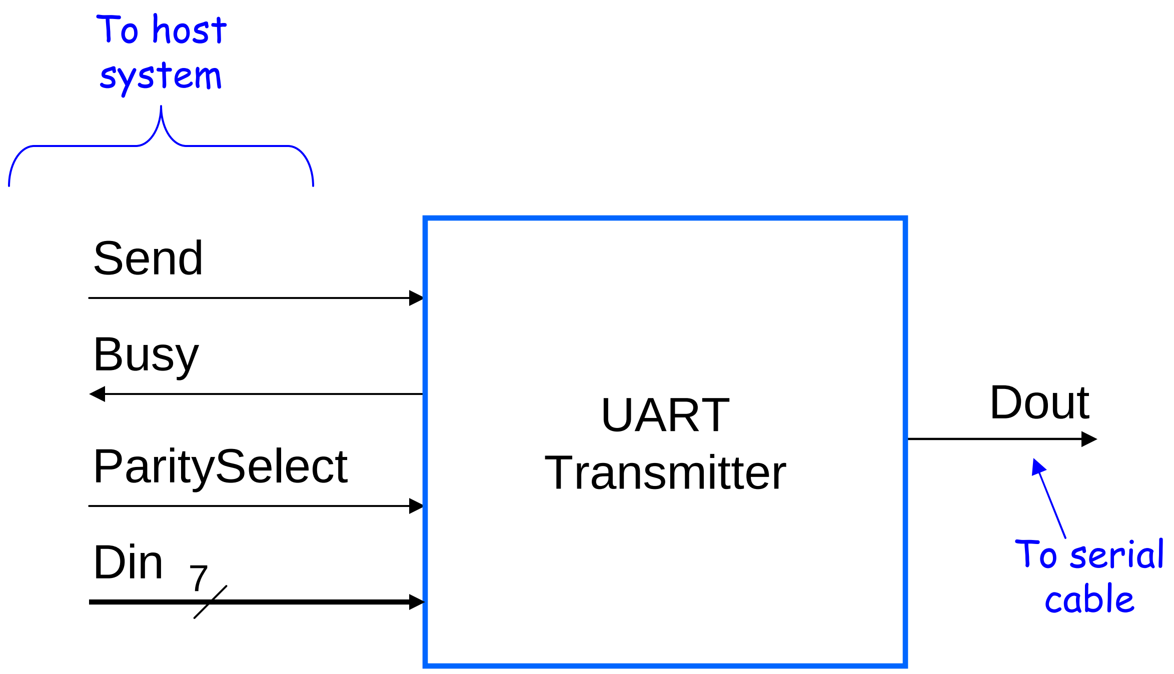
- Data Throughput Example
  - Assume 19200 baud, 8 data bits, no parity, 1 stop bit
    - 19200 baud → 19.2 kbps
    - 1 start bit + 8 data bits + 1 stop bit → 10 bits
  - It takes 10 bits to send 8 bits (1 byte) of data
  - 19.2 kbps • 8/10 = **15.36 kbps**
- How many KB (kilobytes) per second is this?
  - 1 byte = 8 bits
  - 1 KB = 1,024 bytes
  - So, 1 KB = 1,024 bytes • 8 bits/byte = 8,192 bits
  - Finally, 15,360 bps • 1 KB / 8,192 bits = **1.875 KB/s**

Let's Design a UART Transmitter!

Specifications

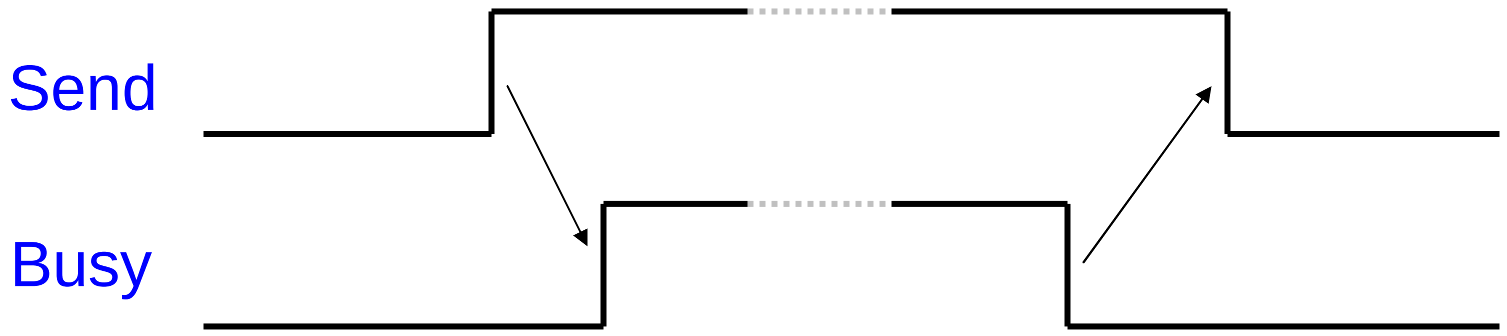
- Parameters: 300 baud, 7 data bits, 1 stop bit, even or odd parity
- Inputs:
  - **Din[6:0]**: 7-bit parallel data input
  - **Send**: instructs transmitter to initiate a transmission
  - **ParitySelect**: selects even parity (ParitySelect=0) or odd parity (ParitySelect=1)
- Outputs:
  - **Dout**: serial data output
  - **Busy**: tells host busy sending a character

System Diagram

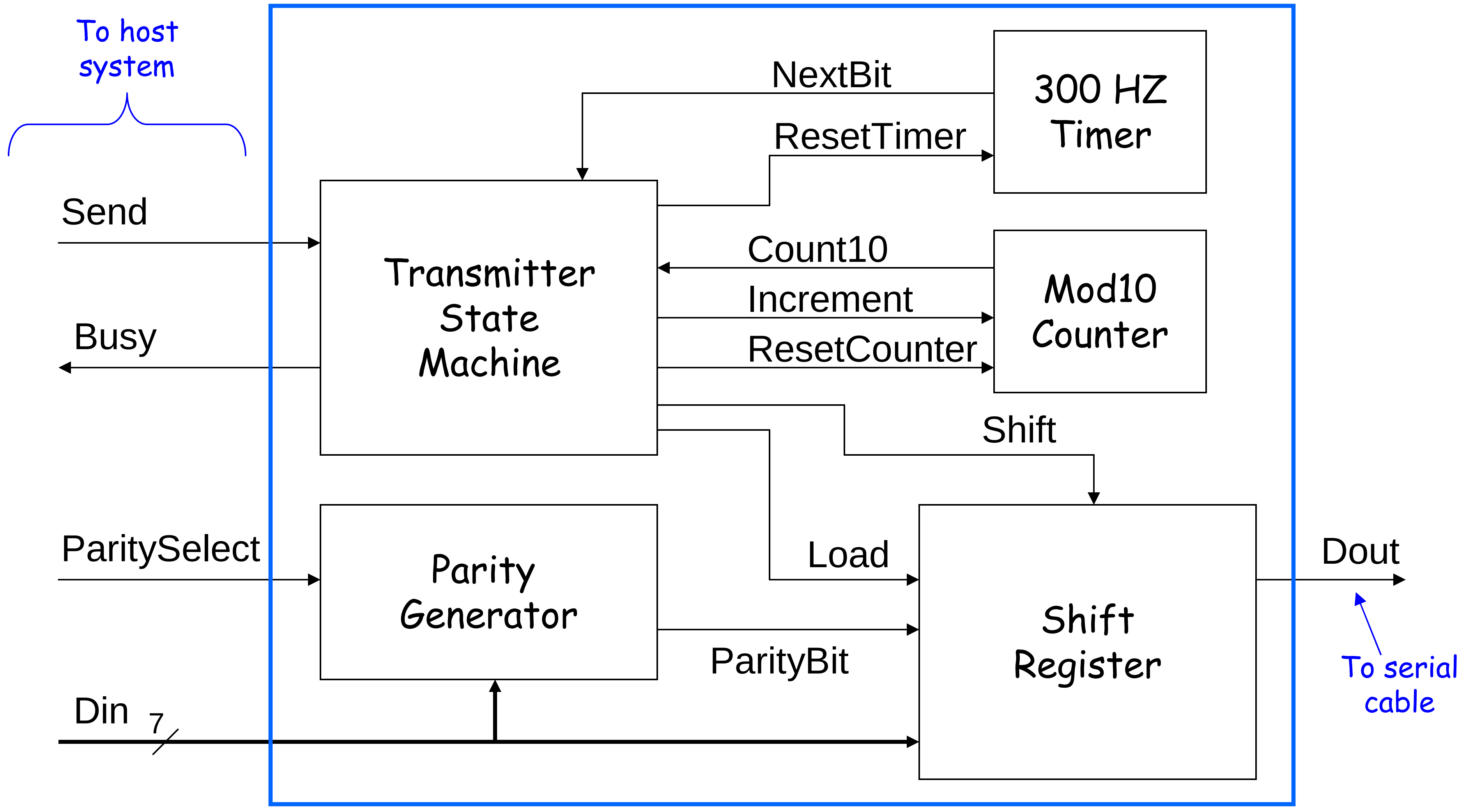


Transmitter/System Handshaking

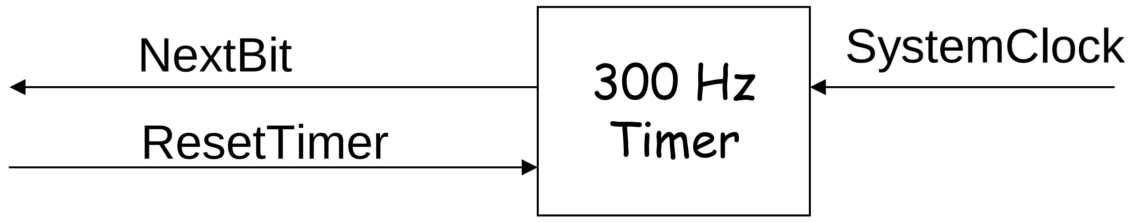
- System asserts Send and holds it high when it wants to send a byte
- UART asserts Busy signal in response
- When UART has finished transfer, UART de-asserts Busy signal
- System de-asserts Send signal



Transmitter Block Diagram

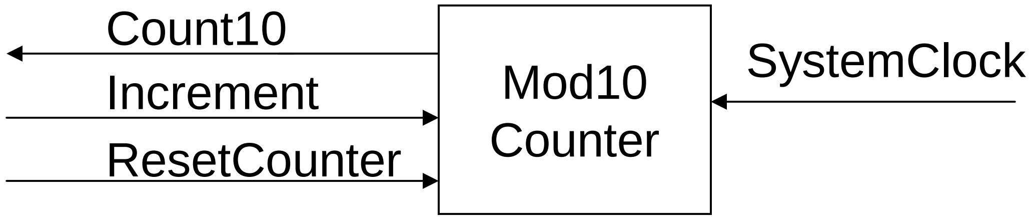


The Timing Generator



- Divides system clock down to 300 Hz
- Output is NextBit signal to state machine
  - Goes high for one system clock cycle 300 times a second
- Simply a Mod(f_{clk}/300) resetable counter where NextBit is the rollover signal
- More sophisticated UARTs have programmable timing generators for different baud rates

The Mod10 Counter



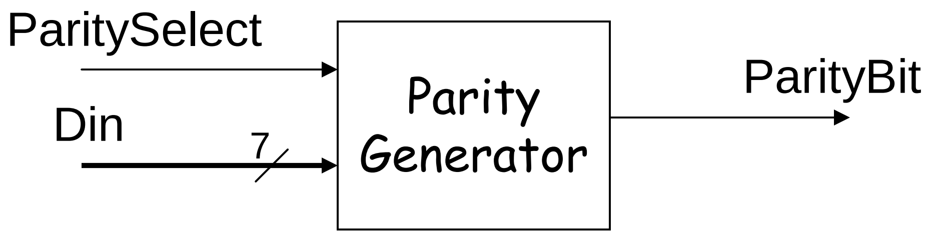
- Resets to 0 on command from state machine
- Increments on command from state machine
- Counts from 0 to 9, then rolls over to 0
- Tells state machine when it's going to roll over from 9 back to 0 (signal Count10)

Mod10 Counter in Verilog

```
module mod10 (clk, reset, increment, count10);
  input clk, reset, increment;
  output reg count10;

  wire [3:0] ns, q, qPlus1;

  assign qPlus1 = (q == 9) ? 0 : q+1;
  assign ns = (reset)     ? 0 :
              (increment) ? qPlus1 :
                            q;
  regn #(4) R0 (clk, ns, q);       // Assume this submodule exists

  assign count10 = increment & (q == 9);

endmodule
```

This could also be written using behavior Verilog (an always block)

The Parity Generator



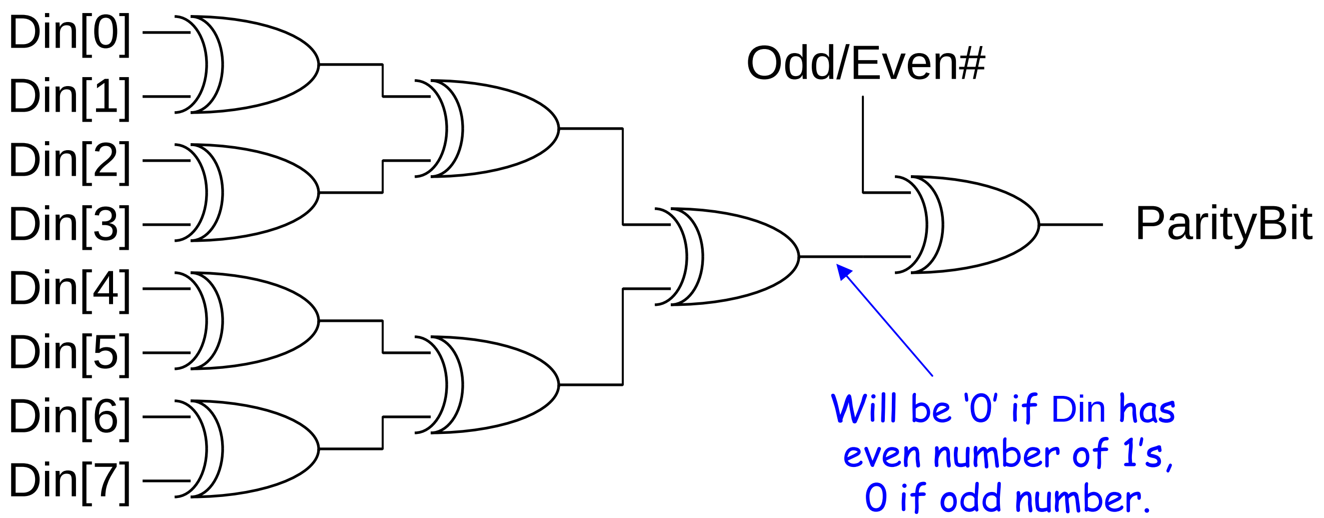
- Combinational circuit
- Generates ParityBit according to value of Din[6:0] and ParitySelect input

The Parity Generator

- The value of ParityBit is the bit needed to make the number of 1's even (if even parity) or odd (if odd parity)

	Even Parity (ParitySelect = 0)	**Odd Parity** (ParitySelect = 1)
Even number of '1's	ParityBit = 0	ParityBit = 1
Odd number of '1's	ParityBit = 1	ParityBit = 0

An 8-Bit Parity Generator



For 7-bit parity, tie Din[7] to a '0'

7-bit Parity Generator in Verilog

```
module parity_gen (data, oddeven, parity);
  input [6:0] data;
  input oddeven;
  output parity;

  assign parity = (^data) ^ oddeven;
endmodule
```

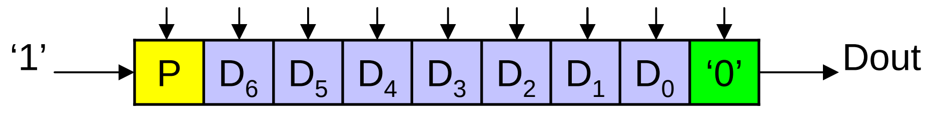
Reduction XOR operator

The Shift Register

- Standard Parallel-In/Serial-Out (PISO) shift register
- Has 4 operations:
  - Do nothing
  - Load parallel data from Din
  - Shift right
  - Reset

The Shift Register

- Make it a 9-bit register
- When it loads:
  - Have it load ‘0’ for the start bit on the right (LSB)
  - Have it load the parity bit on the left (MSB)
  - Have it load 7 data bits in the middle
- When it shifts:
  - Have it shift ‘1’ into the left so a stop bit is sent at the end



Shift Register

- When it resets:
  - Have it load all 1’s so that its default output is a ‘1’ (line idle value)

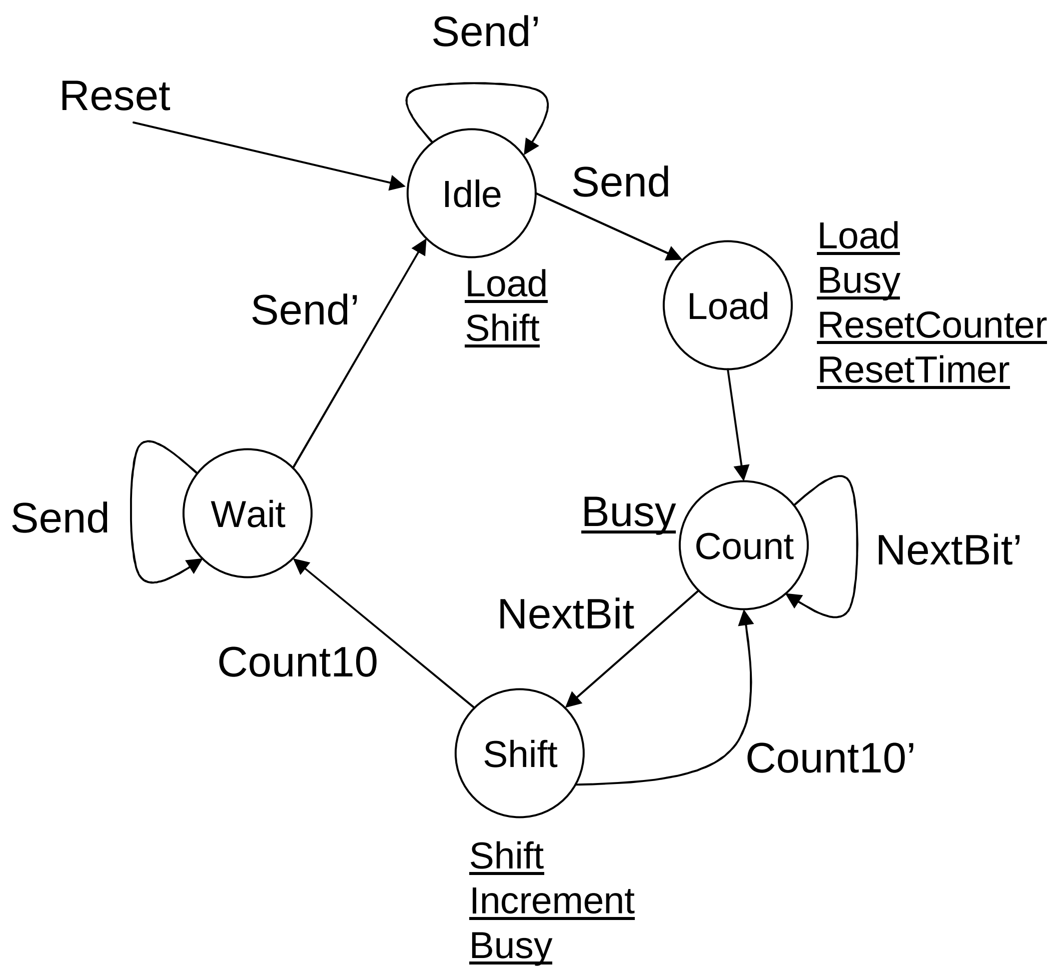
9-bit Shift Register Module

{ Parity, 7 data bits }

"Reset"

```
module shiftReg (clk, loadData, load, shift, sout);
  input clk, load, shift;
  input [7:0] loadData;
  output sout;
  wire [8:0] ns, q;

  assign ns = (load & shift) ? 9'b111111111 :
               load          ? {loadData, 1'b0} :
               shift         ? {1'b1, q[8:1]} :
                               q;
  reg #(9) R0(clk, ns, q);
  assign sout = q[0];
endmodule
```

Transmitter FSM



Be sure to choose state encodings and use logic minimization that ensures **Busy** signal will have no hazards…

The Receiver

- Left for you as an exercise!
- Receiver Issues:
  1. How to sample the middle of bit periods?
  2. How do you check if parity is correct?
  3. What do you do on a framing error?
  4. What do you do on a parity error?
  5. Handshaking with rest of system?