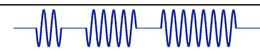
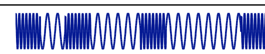
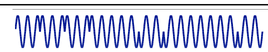
# Communication methods

- Communication methods
  - Media and signaling conventions used to transmit data between digital devices
  - Different physical layers methods including:
    - wires, radio frequency (RF), optical (IR, fiber)
  - 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, USB3 625M bytes/s
    - 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
  - Fewer 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-coupled 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
- SPI (Motorola)
  - 10Mbits/sec, commonly used for microcontroller to peripheral connections
- I2C (Philips) TWI (Atmel)
  - up to 400Kbits/sec, serial bus for connecting multiple components
- USB (Intel – followed by USB-2, and now USB-3)
  - 12-480Mbits/sec, isochronous transfer, desktop devices
- Bluetooth (Ericsson – cable replacement)
  - 700Kbits/sec, multiple portable devices, special support for audio
- 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)
- IEEE1394 (Apple's Firewire)
  - 12.5-50Mbytes/sec, consumer electronics (video cameras, TVs, audio, etc.)

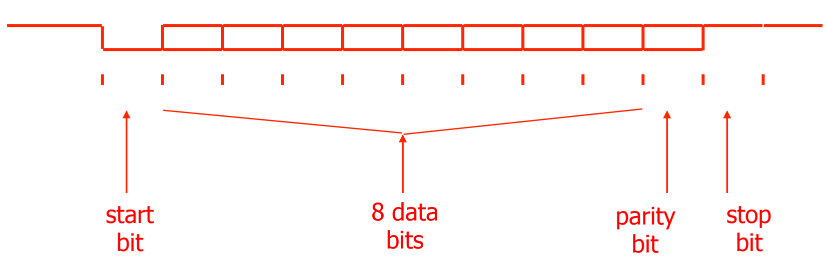
# RS-232

standard serial line



## 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

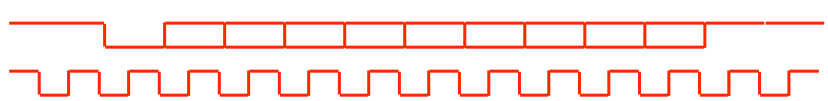
"0" = -12v, "1" = 12v

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



# Serial Peripheral Interface (SPI)

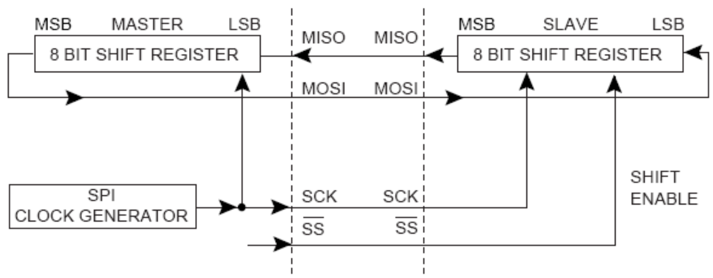


## Serial Peripheral Interface

- 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

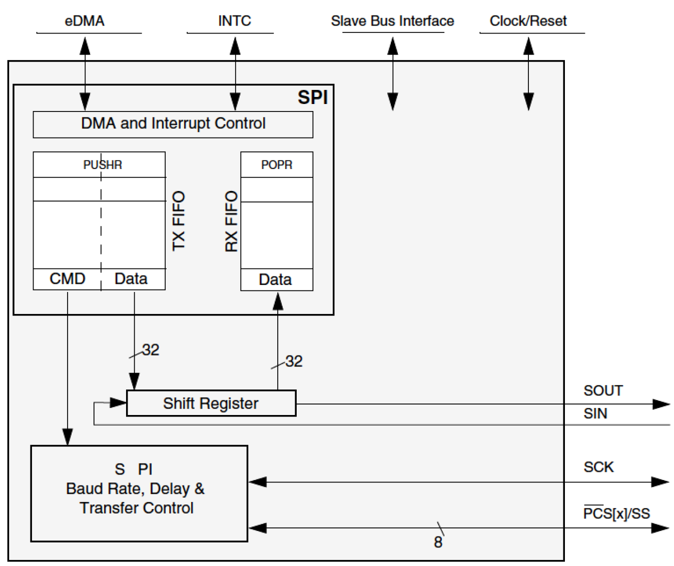
# SPI Block Diagram

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






# Freescale SPI module

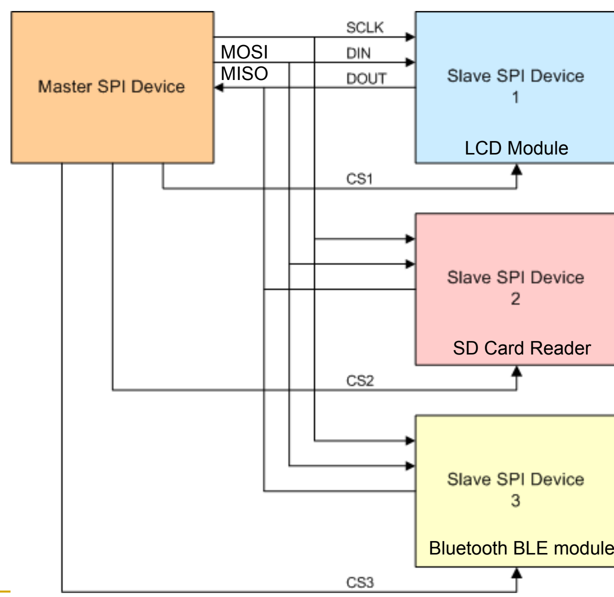


# Data Payload on SPI

- 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



# Multiple Slaves on SPI

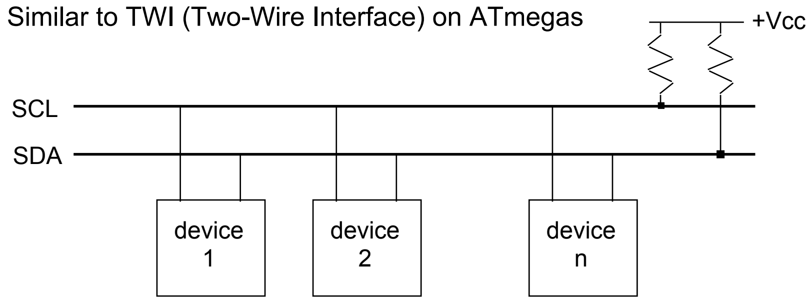


# Inter-Integrated Circuit Bus (I2C)



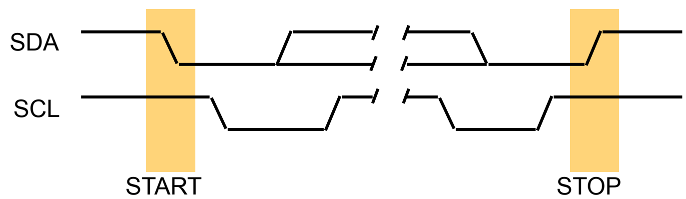
# Inter-Integrated Circuit Bus (I2C)

- 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

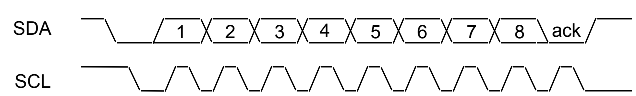
- SDA going low while SCL high signals start of data
- SDA going high while SCL high signals end of data
- SDA can change when SCL low
- SCL high (after start and before end) signals that a data bit can be read






## Byte transfer

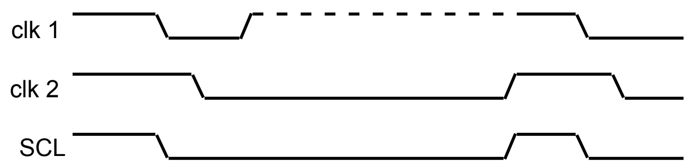
- Byte followed by a 1 bit acknowledge from receiver
- Open-collector wires
  - sender allows SDA to rise
  - receiver pulls low to acknowledge after 8 bits




- 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

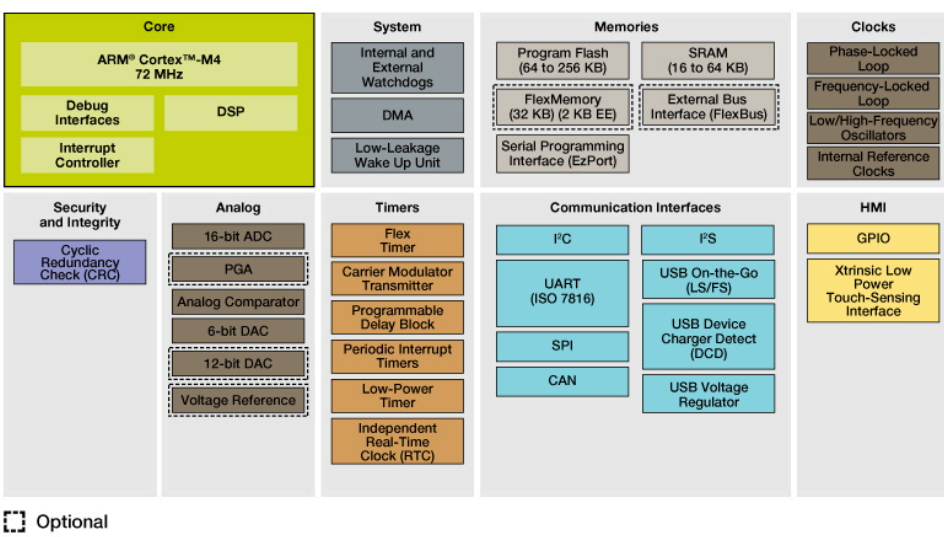
# Inter-Integrated Circuit Bus (I2C)

- 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

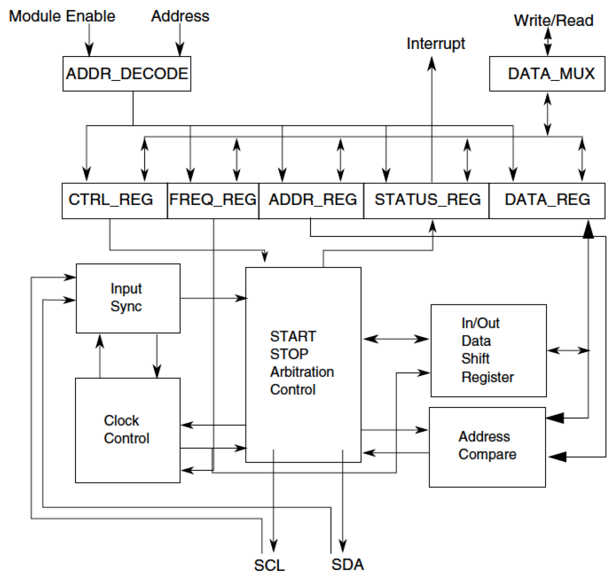


# Freescale Block Diagram

**Kinetis K20 Mid-Performance USB MCUs**



# Freescale I2C module






# USB

# 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 (USB 2.0)
    - 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 versions

| Feature | USB 2.0 | USB 3.0 |
|---|---|---|
| Transmit/Receive | Half-Duplex | Duplex |
| Data Rate | 1.5Mbs/12Mbs/480Mbs | USB 2.0 Data Rates + 5Gbs |
| Useful Data Rate | 480Mbs (Including NRZ overhead) | 4Gbs * 2 (Excluding 8b10b overhead) |
| Burst | No | 16 bursts |
| Stream | No | Each Bulk endpoint can have 64K Stream (more pipes) |
| Host – Device Communication | Broadcast | Unicast (Addressed) |
| Device Data Throttle | ACK, NYET/PING | ACK, NRDY/ERDY |
| Device Initiated Packets | No | ERDY, LMPs and Device notifications |
| Power States | Low Power Mode (LPM), Suspend | U1, U2, and U3 Power States |
| SOF/ITP | Fixed at 125µs | ITP-variable |
| Packet Size (bytes) | 64 Control, 512 Bulk, 1024 ISOC | 512 Control, 1024 Bulk & ISOC |
| Error Rate | 10**-9 | 10**-12 |

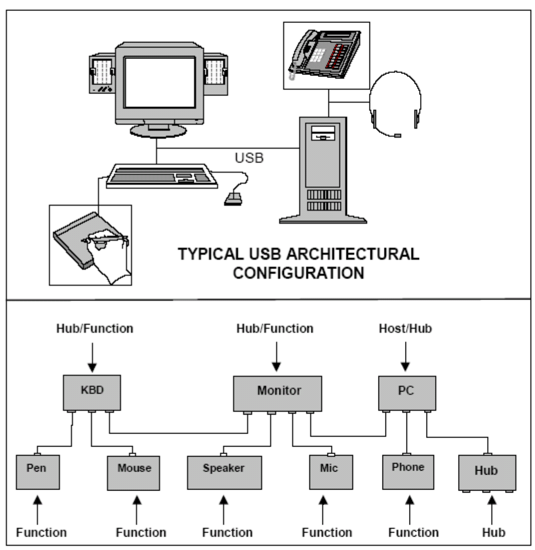
# USB Peripherals

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



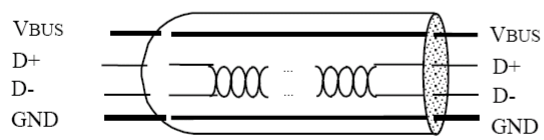
# USB

- Tree of devices
  – one root controller



# USB Data Transfer

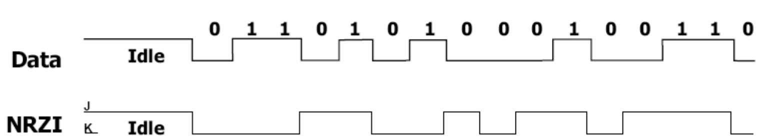
- Data transfer speeds
  - Low is <0.8v, high is >2.0v differential
  - 480Mb/sec, 12Mb/sec, 1.5Mb/sec
  - Data is NRZI encoded (data and clock on one wire)
  - SYNC at beginning of every packet



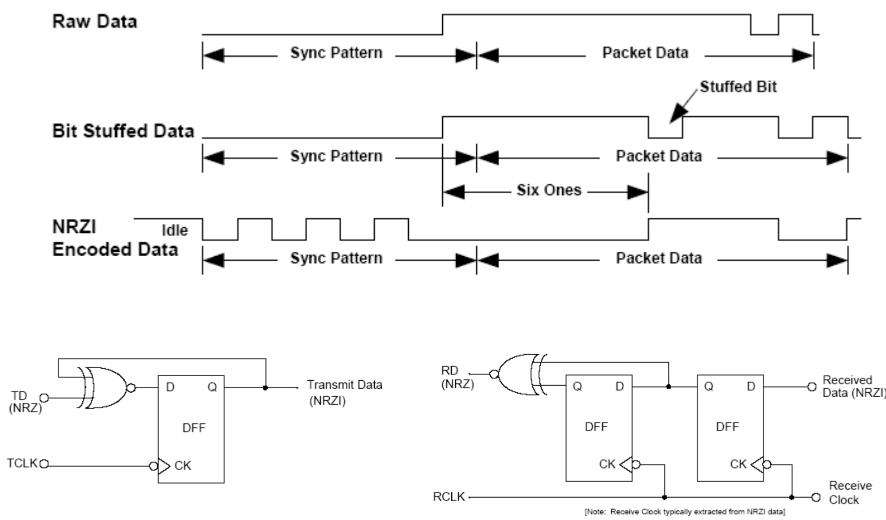



# NRZI Encoding

- 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)

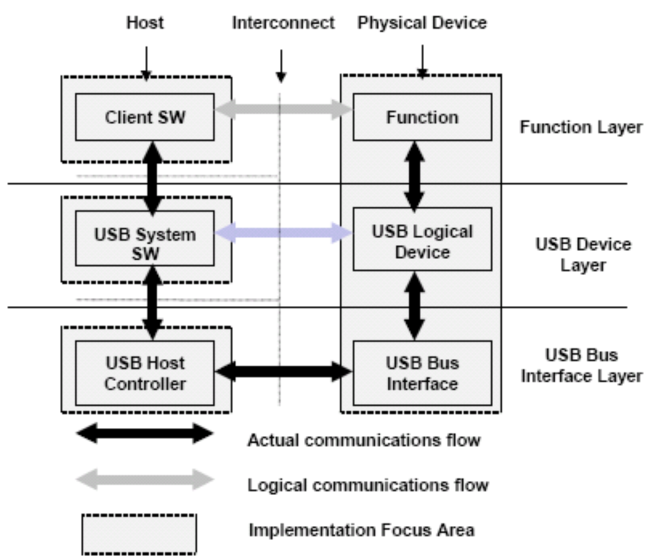
## USB Packet Format

- 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



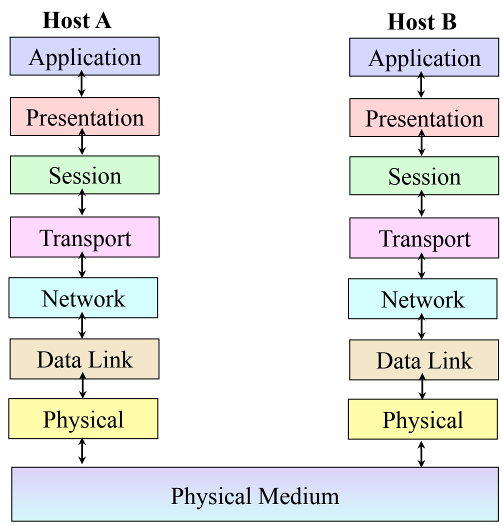
# Ethernet



# Ethernet (Xerox local area network)

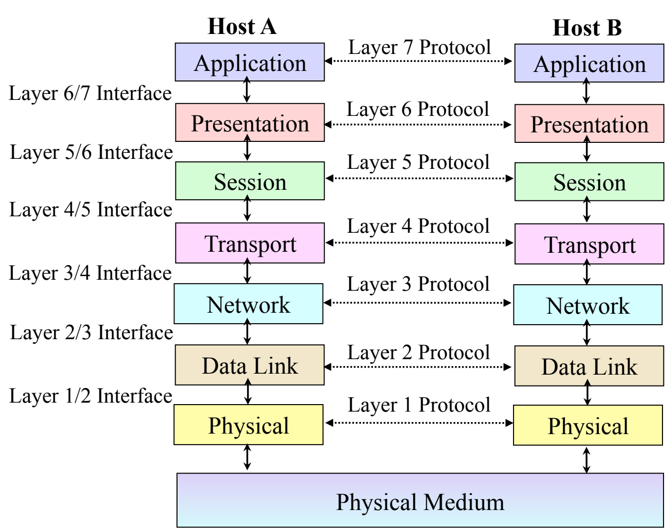
- Local area network
  - up to 1024 stations
  - up to 2.8 km distance
  - 10Mbits/sec serially on shielded co-axial cable
  - 1.5Mbits/sec on twisted pair of copper pair
- Developed by Xerox in late 70s
  - still most common LAN right now
  - being displaced by fiber-optics (can't handle video/audio rates or make required service guarantees)
- High-level protocols to ensure reliable data transmission
- CSMA-CD: carrier sense multiple access with collision detection

# The ISO OSI Reference Model






# The ISO OSI Reference Model



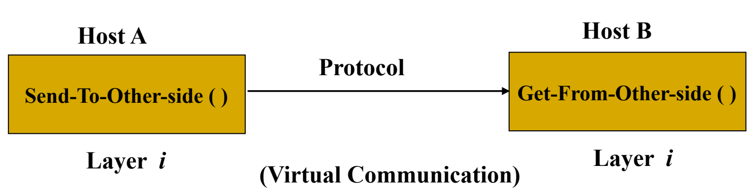
## The ISO OSI Reference Model

- **Interface:** It defines which primitive operations and services the lower layer offers to the upper layer.
- **Peer:** The similar layer on a different machine.
- **Protocol:** It is a set of rules and conventions used by the layer to communicate with similar peer layer in another (remote) system.
- The peer processes communicate with each other using a *protocol*.
- A set of layers and protocols is called a ***network architecture.***



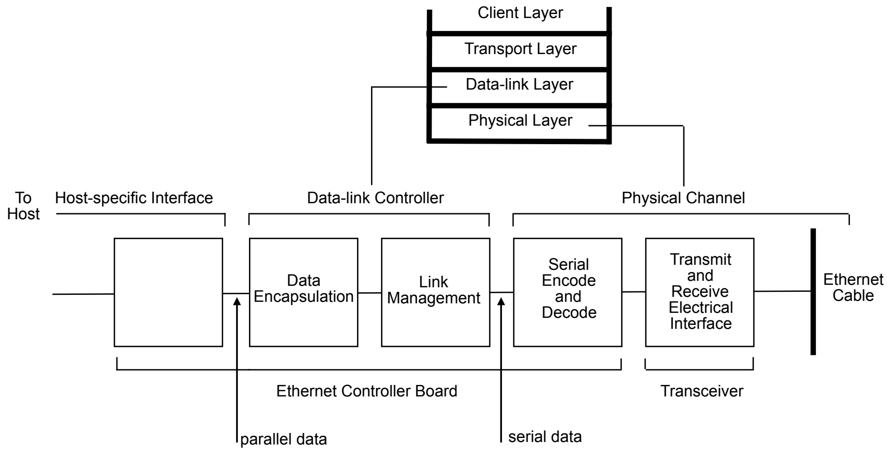
## The ISO OSI Reference Model

- In reality, no data are directly transferred from layer *i* on one machine to layer *i* on another machine. Instead, each layer passes data and control information to the layer immediately below it, until the lowest layer is reached. Below layer 1 is the physical medium through which actual communication occurs.



# Ethernet layered organization

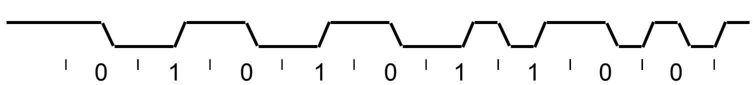
- Physical and data-link layers are our focus






# Serial data format

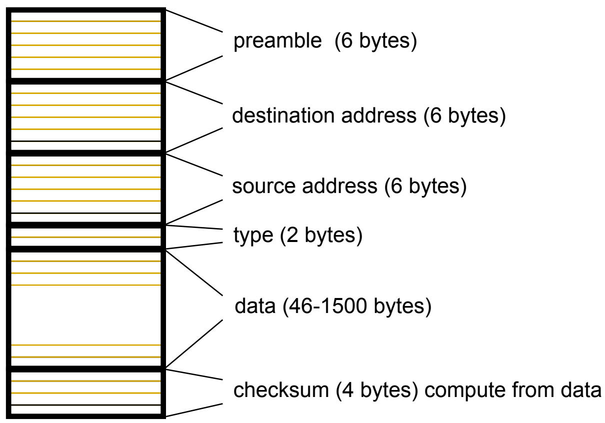
- Manchester encoding
  - signal and clock on one wire (XORed together)
  - "0" = low-going transition
  - "1" = high-going transition




- Extra transitions between 00 and 11 need to be filtered
  - preamble at beginning of data packet contains alternating 1s and 0s
  - allows receivers to get used to where important transitions should be and ignore extra ones (this is how synchronization is achieved)
  - preamble is 48 bits long: 10101. . . 01011

# Ethernet packet

- Packets size: 64 to 1518 bytes + 6 bytes of preamble



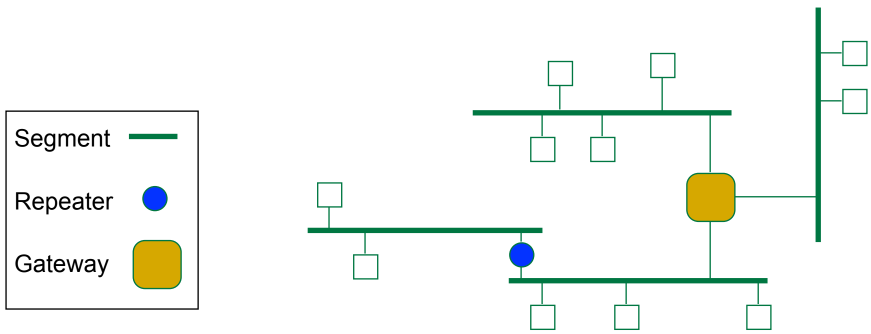



# Arbitration

- Wait for line to be quiet for a while then transmit
  - detect collision
  - average value on wire should be exactly between 1 and 0
  - if not, then two transmitters are trying to transmit data
- If collision, stop transmitting
  - wait a random amount of time and try again
  - if collide again, pick a random number
    from a larger range (2x) and try again
- Exponential backoff on collision detection
- Try up to 16 times before reporting failure

# Extending Ethernet

- Segments, repeaters, and gateways
  - segment: a single cable
  - repeater: transfers all messages on one segment to another and vice-versa
  - gateway: selectively forwards messages to other segments and helps isolate traffic






# IrDA: Infrared Data Association

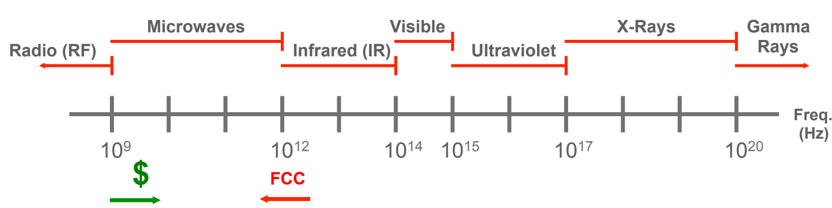
# Infrared Data Association

- Consortium of over 160 companies
- Meet needs of the “mobile professional”
  - Short interactions with other devices (file transfer, printing)
  - Possibly using others’ peripherals (visiting a customer’s office)
- Goals:
  - Suitable replacement for cables
  - Interoperability
  - Minimal cost
  - “Point-and-shoot” model (intended use and to reduce interference)
- History:
  - First standard developed in 1994
  - Revisions as recently as late 1998 (i.e., still active)



# IrDA: Infrared Data Association

- Characteristics of IR:
  - Implementation costs rise significantly around 1-10 GHz
    - one important exception is IR at around 100 THz – very inexpensive
  - Signals above 100 GHz cannot penetrate walls
  - Most signals below 300 GHz are regulated by the FCC



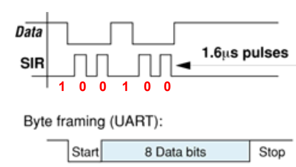
# Speed

- Components include:
  - Transmitter (LED) and paired receiver (photodiode)
- IrDA supports wide range of speeds
  - 2400 bps to 4 Mbps
  - Exact physical-layer protocol used depends on speed of IrDA connection
  - Uses highest speed available on both devices
    - determined when connection is established
- Future promises even higher speeds:
  - 16-50 Mbps is not too far off
- Comparison to other wireless technologies:
  - Low-power RF (e.g., Bluetooth) slightly slower (.5 - 2 Mbps max)
  - Bound by walls, easy to control, intentional aspect
  - Much lower-power than high-speed RF (e.g., 802.11a at 50Mbps)

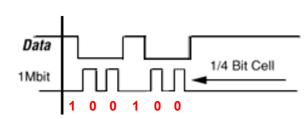


# Low-speed Modulation

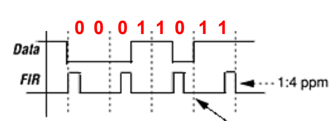
- Speed: 2400 bps - 115 kbps ("Serial Infrared", or SIR)
  - Only 0's require pulse (and thus power) ; pulse < full bit time
  - Standard UART byte framing
  - Pulse is constant 1.6 $\mu$s long (so duty cycle varies with speed)
  - Average duty cycle: $\leq$ 9%




- Speed: 576 kbps - 1 Mbps
  - similar to SIR (pulse only for 0's ; pulse < full bit time)
  - pulse lasts 1/4 of bit time (so pulse varies with speed)
  - Average duty cycle: 12.5%



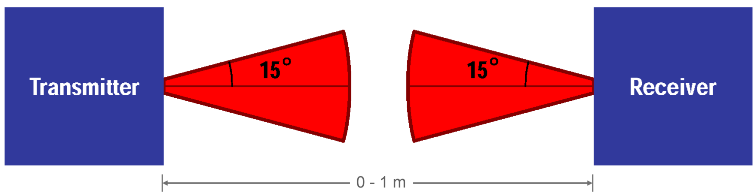

- Speed: 4 Mbps ("Fast Infrared", or FIR)
  - uses four-pulse-position-modulation scheme (4PPM)
  - pulse during exactly 1/4 of each symbol boundary
  - 4PPM makes synchronization easier to maintain
  - Duty cycle: 25% (independent of data)
  - Lowest power/bit




| Bit Pair | PPM Code |
|---|---|
| 00 | 1000 |
| 01 | 0100 |
| 10 | 0010 |
| 11 | 0001 |

# Range

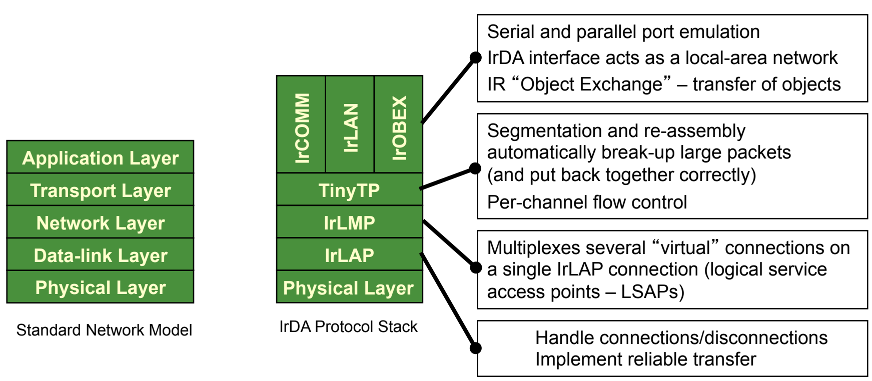
- Linear:
  - IrDA standard requires 0-1 m
  - Realistically, some transceivers work at up to 10 m
- Angular:
  - Limited to a narrow cone (15° half-angle)
  - Done to help reduce interference between devices






# IrDA Protocol Stack

- Analogous to the standard layered network model
- Consists of both required and optional components



# Protocol Overhead

- Very simple model (point-to-point), so can expect reduced protocol overhead
- For layers in IrDA protocol stack, overhead per packet/frame is:
  - IrLAP = 2 bytes
  - IrLMP = 2 bytes
  - TinyTP = 1 byte

  Total: 5 bytes
- For perspective, compare to TCP/IP over Ethernet:
  - Ethernet = 18 bytes minimum
  - IP = 20 bytes
  - TCP = 20 bytes

  Total: 58 bytes (minimum)
- IrDA takes advantage of its simpler model, and keeps protocol overhead very low.