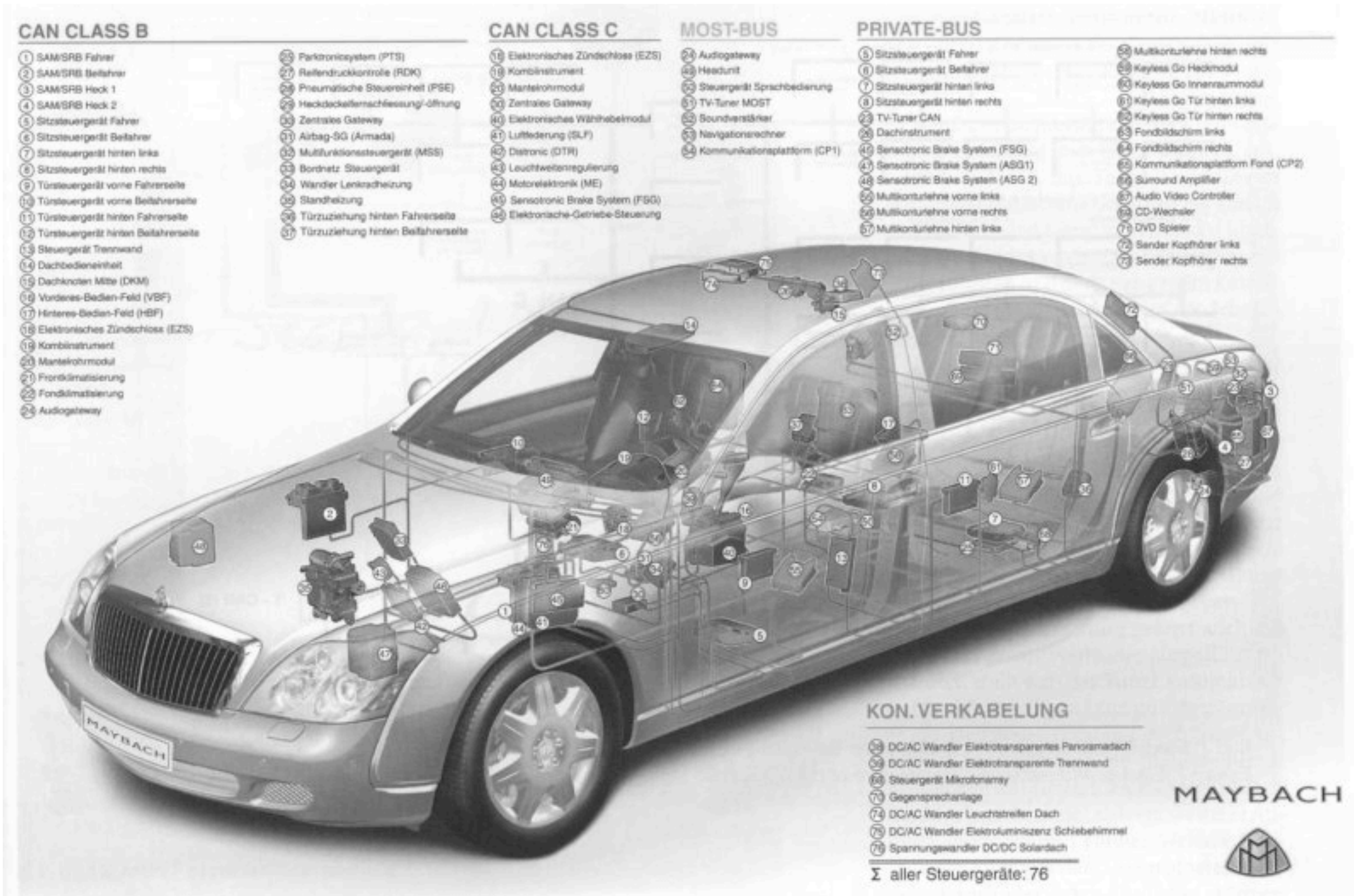
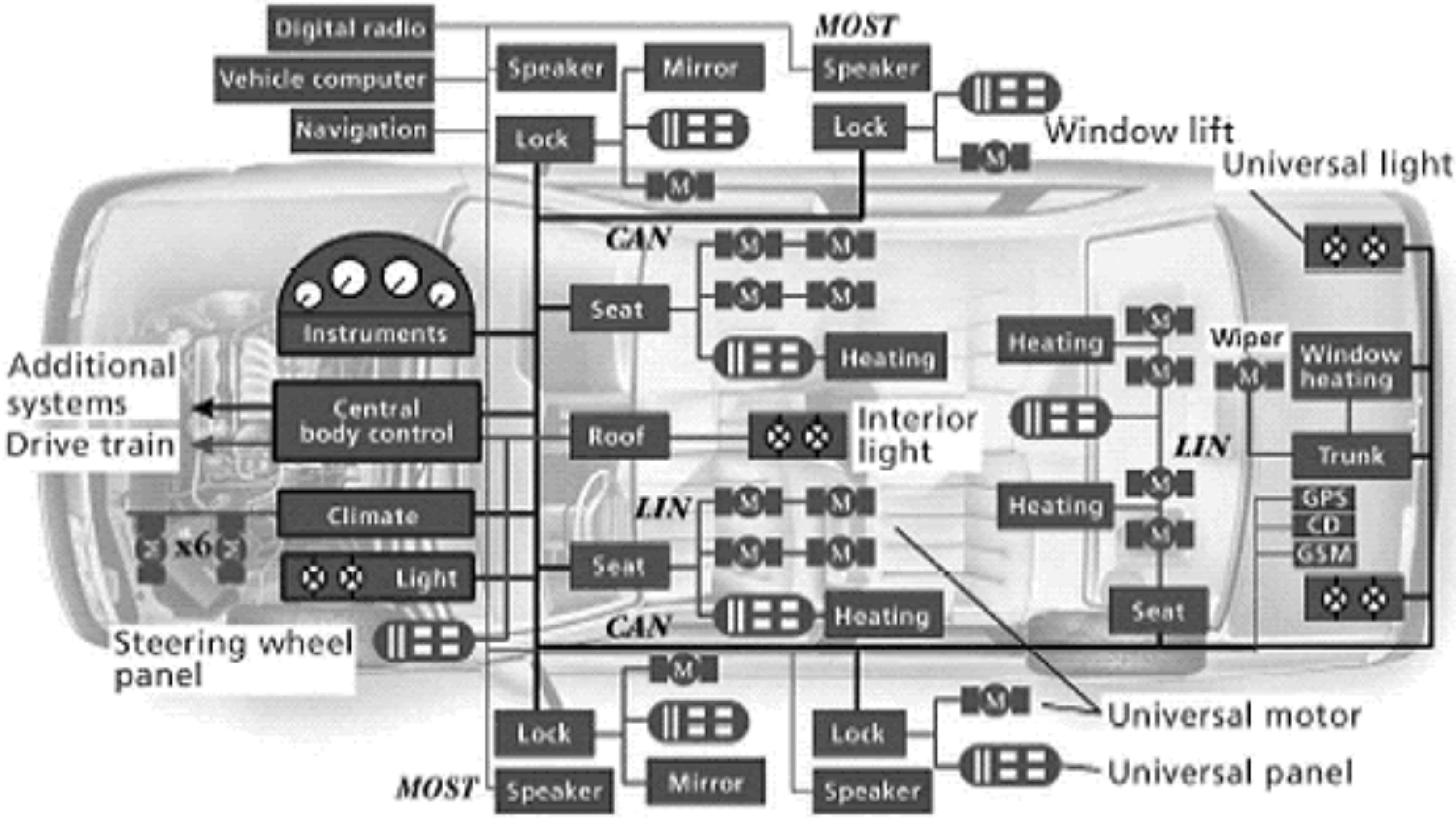
- Today: Wired embedded networks
  - Characteristics and requirements
  - Some embedded LANs
    - SPI
    - I2C
    - LIN
    - Ethernet

- Next lecture: CAN bus
- Then: 802.15.4 – wireless embedded network

Network from a High End Car





CAN Controller area network
GPS Global Positioning System
GSM Global System for Mobile Communications
LIN Local interconnect network
MOST Media-oriented systems transport

PEI Technologies

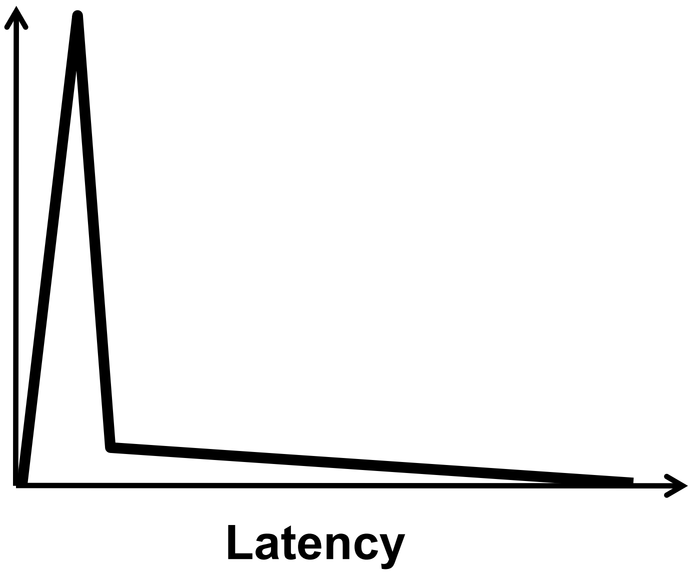
Embedded Networking

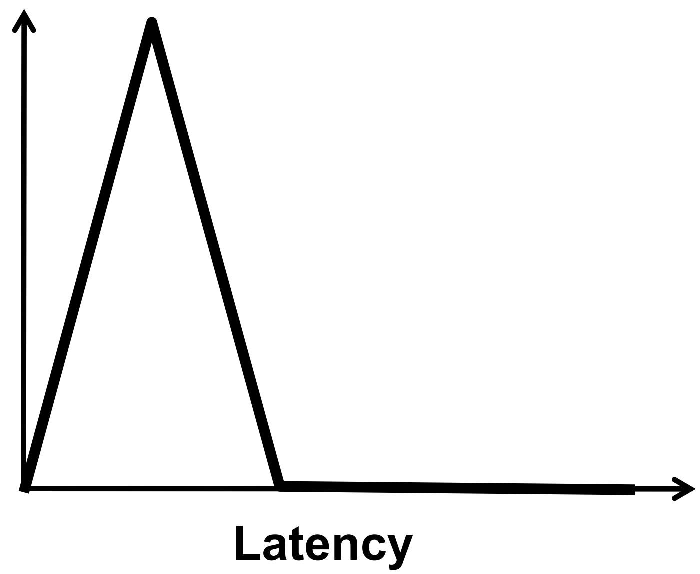
- **In the non-embedded world TCP/IP over Ethernet, SONET, WiFi, 3G, etc. dominates**
- **No single embedded network or network protocol dominates**
  - **Why not?**

Embedded vs. TCP/IP

- Many TCP/IP features unnecessary or undesirable in embedded networks
- In embedded networks…
  - Stream abstraction seldom used
    - Embedded networks more like UDP than TCP
    - Why?
  - Reliability of individual packets is important
    - As opposed to building reliability with retransmission
  - No support for fragmentation / reassembly
    - Why?
  - No slow-start and other congestion control
    - Why?

Which is better?





Characteristics and Requirements

- Determinism more important than latency
- Above a certain point throughput is irrelevant
- Prioritized network access is useful
- Security important only in some situations
- Resistance to interference may be important
- Reliability is often through redundancy
- Cost is a major factor
- Often master / slave instead of peer to peer

A Few Embedded Networks

- Low-end
  - SPI
  - I2C
  - LIN
  - RS-232
- Medium-end
  - CAN
  - MOST
  - USB
- High-end
  - Ethernet
  - IEEE-1394 (Firewire)
  - Myrinet

How do you choose one?

- Does it give the necessary guarantees in…
  - Error rate
  - Bandwidth
  - Delivery time – worst case and average case
  - Fault tolerance
- Is it affordable in…
  - PCB area
  - Pins
  - Power and energy
  - $$ for wiring, adapter, transceiver, SW licensing
  - Software resource consumption: RAM, ROM, CPU
  - Software integration and testing effort

Most Basic Embedded Network

- “Bit banged” network:
  - Implemented almost entirely in software
  - Only HW support is GPIO pins
  - Send a bit by writing to output pin
  - Receive a bit by polling a digital input pin
- Can implement an existing protocol or roll your own
- Advantages
  - Cheap
  - Flexible: Support many protocols w/o specific HW support
- Disadvantages
  - Lots of development effort
  - Imposes severe real-time requirements
  - Fast CPU required to support high network speeds

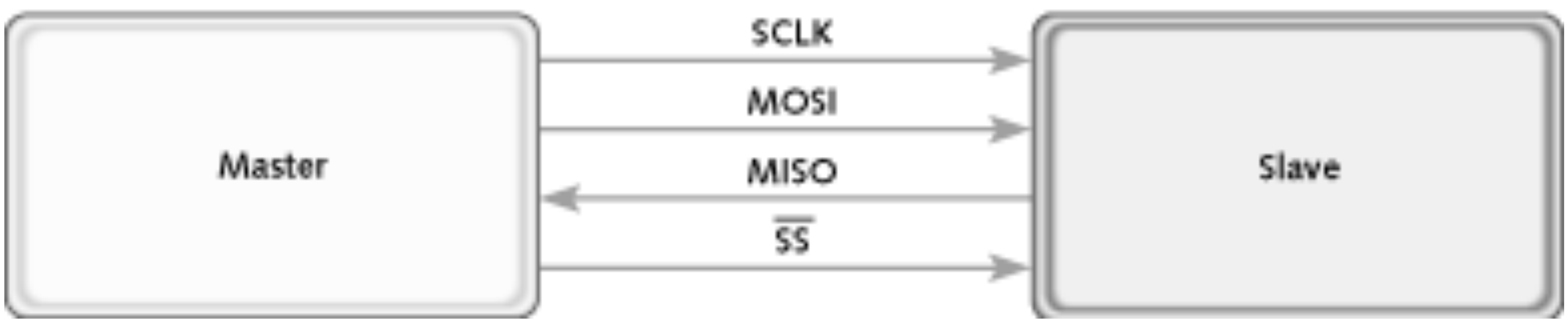
SPI

- Serial Peripheral Interface
  - Say S-P-I or spy
- Characteristics:
  - Very local area – designed for communicating with other chips on the same PCB
    - NIC, DAC, flash memory, etc.
  - Full-duplex
  - Low / medium bandwidth
  - Master / slave
- Very many embedded systems use SPI but it is hidden from outside view
- Originally developed by Motorola
  - Now found on many MCUs

SPI Signals

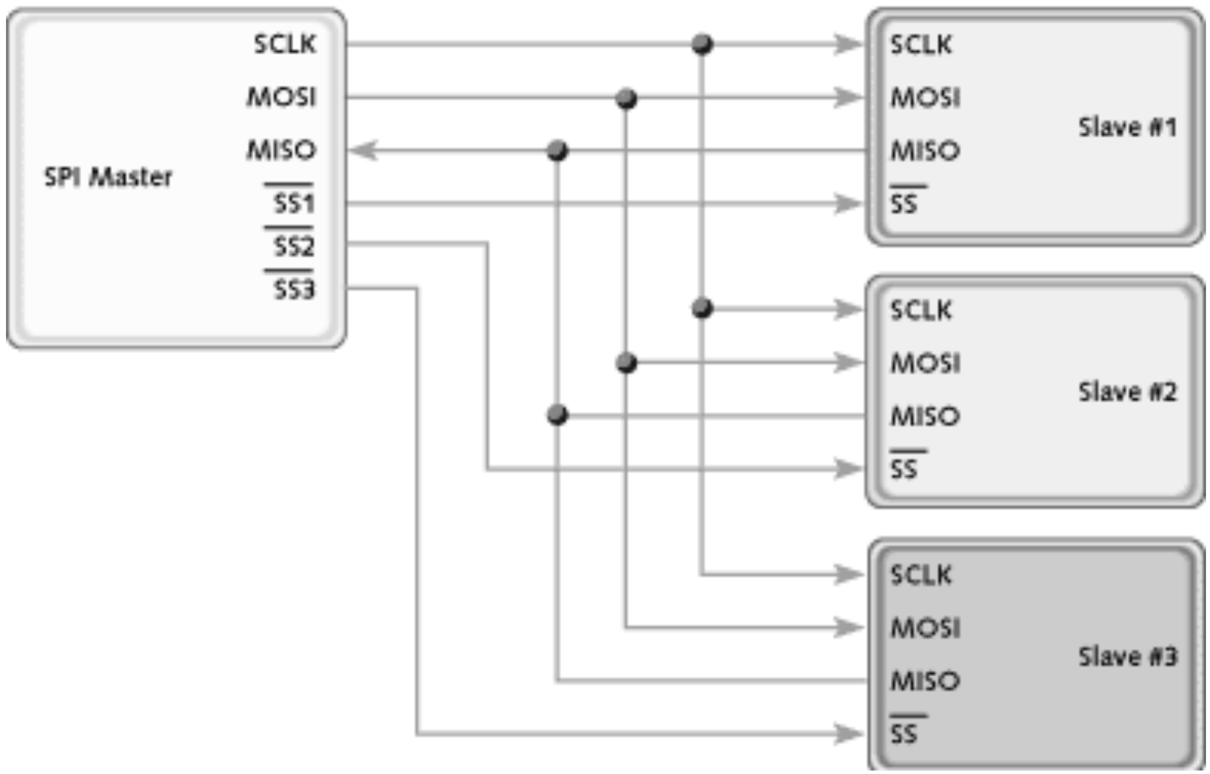
- **Four wires:**
  - **SCLK – clock**
  - **SS – slave select**
  - **MOSI – master-out / slave-in**
  - **MISO – master-in / slave-out**

- **Single master / single slave configuration:**



Multiple Slaves

- **Each slave has its own select line:**



- **Addressing lots of slaves requires lots of I/O pins on the master, or else a demultiplexer**

CPOL and CPHA

- Clock polarity and clock phase
  - Both are 1 bit
  - Configurable via device registers
- Determine when:
  - First data bit is driven
  - Remaining data bits are driven
  - Data is sampled
- Details are not that interesting…
- However: All nodes must agree on these or else SPI doesn’t work

SPI Transfer

1. Master selects a slave
2. Transfer begins at the next clock edge
3. Eight bits transferred in each direction
4. Master deselects the slave

- Typical use of SPI from the master side:
  1. Configure the SPI interface
  2. Write a byte into the SPI data register
     - This implicitly starts a transfer
  3. Wait for transfer to finish by checking SPIF flag
  4. Read SPI status register and data register
- Contrast this with a bit-banged SPI

More SPI

- SPI is lacking:
  - Sophisticated addressing
  - Flow control
  - Acknowledgements
  - Error detection / correction

- Practical consequences:
  - Need to build your own higher-level protocols on top of SPI
  - SPI is great for streaming data between a master and a few slaves
  - Not so good as number of slaves increases
  - Not good when reliability of link might be an issue

I^2C

- Say "I-squared C"
  - Short for IIC or Inter-IC bus
- Originally developed by Philips for communication inside a TV set
- Main characteristics:
  - Slow – generally limited to 400 Kbps
  - Max distance ~10 feet
    - Longer at slower speeds
  - Supports multiple masters
  - Higher-level bus than SPI

I2C Signals and Addressing

- **Two wires:**
  - **SCL – serial clock**
  - **SDA – serial data**
  - **These are kept high by default**

- **Addressing:**
  - **Each slave has a 7-bit address**
    - **16 addresses are reserved**
    - **One reserved address is for broadcast**
    - **At most 112 slaves can be on a bus**
  - **10-bit extended addressing schemes exist and are supported by some I2C implementations**

I2C Transaction

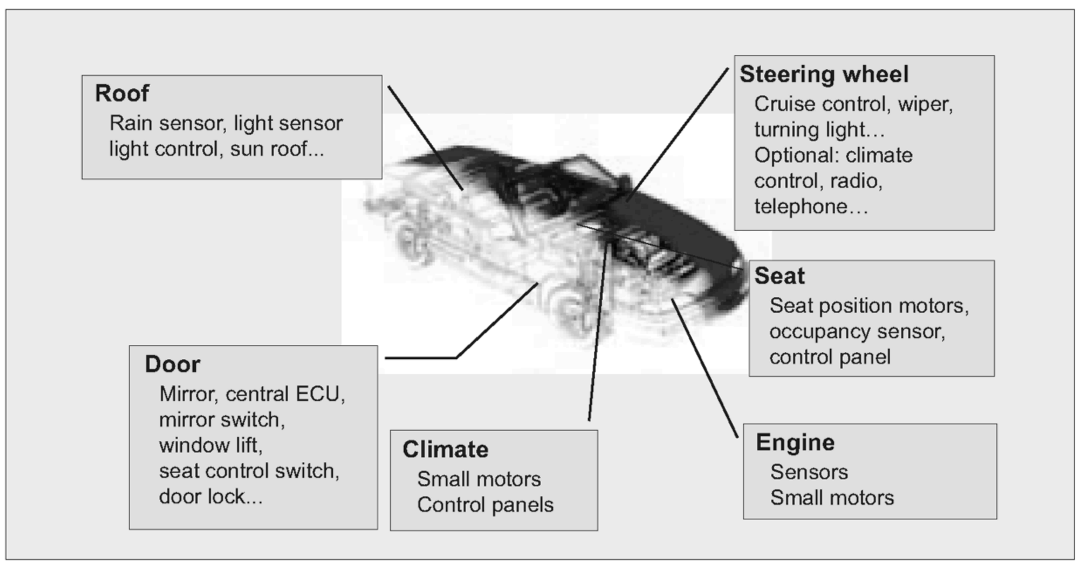
- Master issues a START condition
  - First pulls SDA low, then pulls SCL low
- Master writes an address to the bus
  - Plus a bit indicating whether it wants to read or write
  - Slaves that don t match address don t respond
  - A matching slave issues an ACK by pulling down SDA
- Either master or slave transmits one byte
  - Receiver issues an ACK
  - This step may repeat
- Master issues a STOP condition
  - First releases SCL, then releases SDA
  - At this point the bus is free for another transaction

Multiple-Master I2C

- One master issues a START
  - All other masters are considered slaves for that transaction
  - Other masters cannot use the bus until they see a STOP
- What happens if a master misses a START?
  - When a master pulls a wire high, it must check that the wire actually goes high
  - If not, then someone else is using it – need to back off until a STOP is seen

LIN Bus

- Very simple, slow bus for automotive applications
  - Master / slave, 20 Kbps maximum
  - Single wire
  - Can be efficiently implemented in software using existing UARTs, timers, etc.
    - Target cost $1 per node, vs. $2 per node for CAN



Ethernet

- Characteristics
  - 1500-byte frames
  - Usually full-duplex
  - 48-bit addresses
  - Much more complicated than SPI, I2C
  - Often requires an off-chip Ethernet controller
- Can be used with or without TCP or UDP
- Hubs, switches, etc. support large networks
- Random exponential backoff has bad real-time properties
  - No guarantees are possible under contention

Embedded TCP/IP

- This is increasing in importance
  - Remember that TCP/IP can run over any low-level transport
    - Even I2C or CAN
  - TCP/IP stacks for very small processors exist
- Drawbacks
  - TCP/IP is very generic – contains features that aren t needed
  - TCP/IP targets WANs – makes many design tradeoffs that can be harmful in embedded situations
- Good usage: Car contains a web server that can be used to query mileage, etc.
- Bad usage: Engine controller and fuel injector talk using TCP/IP

Summary

- Embedded networks
  - Usually packet based
  - Usually accessed using low-level interfaces
- SPI, I2C
  - Simple and cheap
  - Often used for an MCU to talk to non-MCU devices
- CAN
  - Real-time, fault tolerant LAN
- Ethernet
  - More often used for communication between MCUs
- Subsequent lectures:
  - CAN bus
  - 802.15.4 – low-power wireless embedded networking