CSE 291: Wireless and Communication in the Internet of Things

WiFi – Return of the MAC

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Today's Goals

- Introduce MAC layer concepts in 802.11

- Understand what exists, what is actually used, and why

- Explore two additional areas in 802.11
  - Microcontroller use of WiFi
  - Future of WiFi

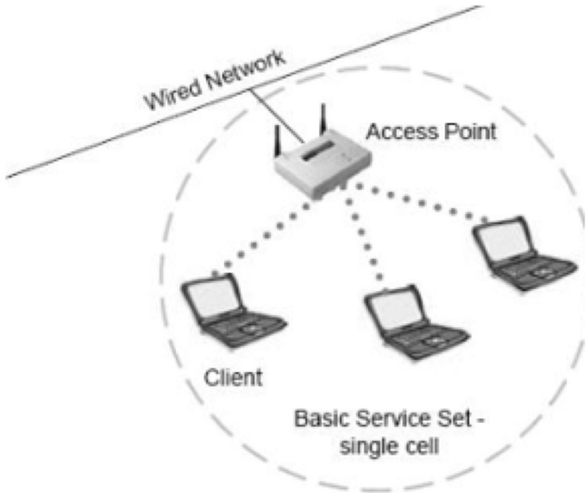
Outline

- **802.11 Access Control**
- 802.11 Frame format
- 802.11e Improvements to MAC

- Bonus topics
  - Microcontrollers and WiFi
  - Future of WiFi

Basic WiFi network

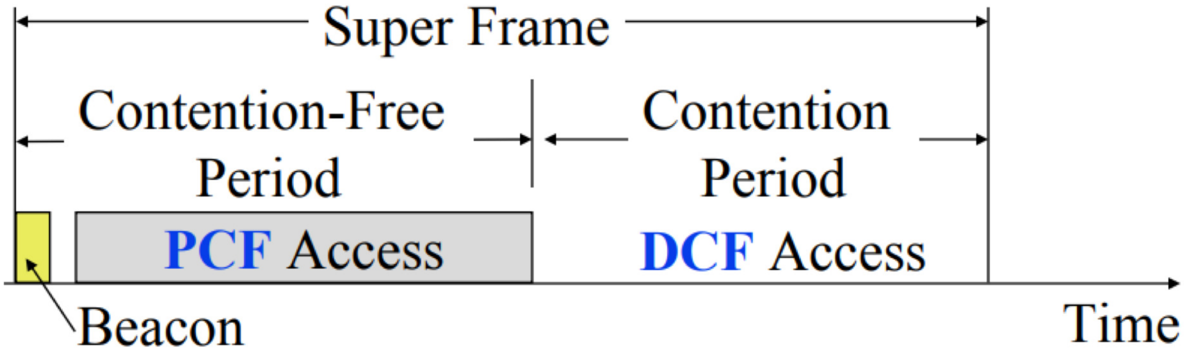
- Star topology network
- Basic Service Set (BSS)
  - Access point(s)
  - Multiple connected clients
- Service Set ID (SSID)
  - Identifies network
  - Broadcast by access point in beacons



WiFi superframe structure

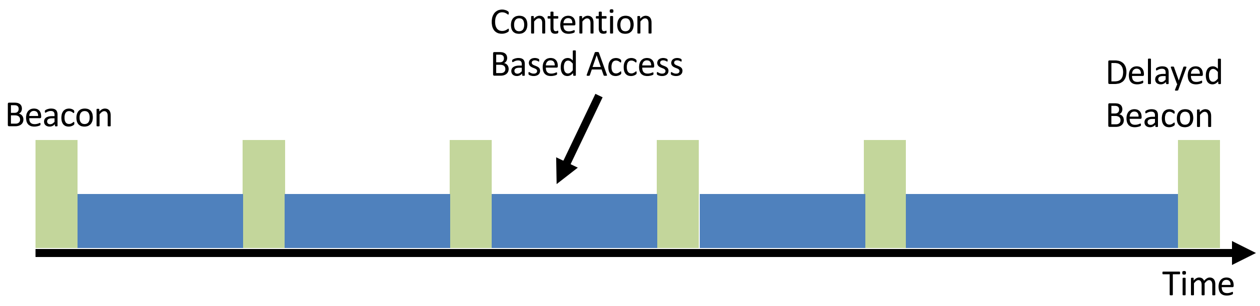
- Beacon followed by contention-free period followed by contention
  - Repeats periodically (default ~100 ms)
  - 802.15.4 adopted a similar superframe

- This is more hypothetical than real



WiFi superframe in practice

- Continuous contention access period
  - Any device may send at any time
  - PCF is unused in practice
- Periodic beacons
  - Which also use CSMA and therefore may be delayed



802.11 beacons

- Transmitted periodically (~100 ms by default)
  - Enable discovery of network
    - Contain capabilities and SSID for the network (802.11b/g/n/ac/ax…)
  - Assign contention-free slots if used
  - Notify devices of waiting packets
    - Traffic Indication Map (TIM) has a bitmap specifying which devices data is for
    - Enables devices to sleep, skipping a number of beacons
  - Handles broadcast/multicast messages
    - Every N beacons includes a notation of available broadcast messages
    - Messages are transmitted during next contention access period using normal CSMA
    - Defines maximum sleep period for devices (must listen to these beacons)

Contention-free access

- Known as Point Coordination Function (PCF)
  - Allocates a contention-free period for specific devices
  - Access Point decides when to grant based on requests

- Drawbacks
  - Latency depends on beacon intervals
  - Mechanism for explicit Quality of Service is unclear

- PCF is not used in practice

Contention-based access

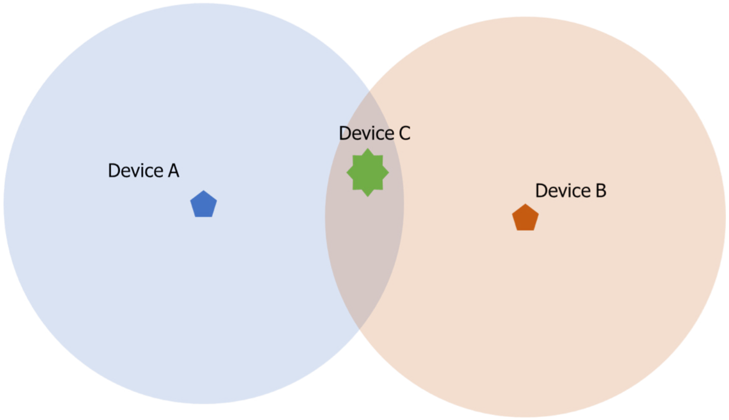
- Known as Distributed Coordination Function (DCF)
  - Base communication method for WiFi (essentially always)
  - All packets are immediately ACK'd by receiving device

  - Uses CSMA/CA to determine when it can send
    - With random backoff

  - Problem: packets can be very long (up to 20 milliseconds)
  - Solution: Network Allocation Vector (NAV)
    - Packets include a notation of their duration
    - Sensing the beginning of a packet allows backoff to skip the whole packet duration before continuing

Reminder: hidden terminal problem

- Two devices communicating with Access Point may not be able to hear each other
  - CSMA fails and Access Point losses both messages



- A solution: RTS/CTS (Request/Clear To Send)

Drawbacks of RTS/CTS

- Four packets per data (RTS, CTS, Data, Ack)
  - Could have just sent data instead of RTS

- Significant portion of traffic are application-layer Acks
  - Probably better to just have it fail and try again later

- RTS/CTS only used for very large packets in practice
  - *It's mentioned still in 802.11n and 802.11ac, so not entirely unused

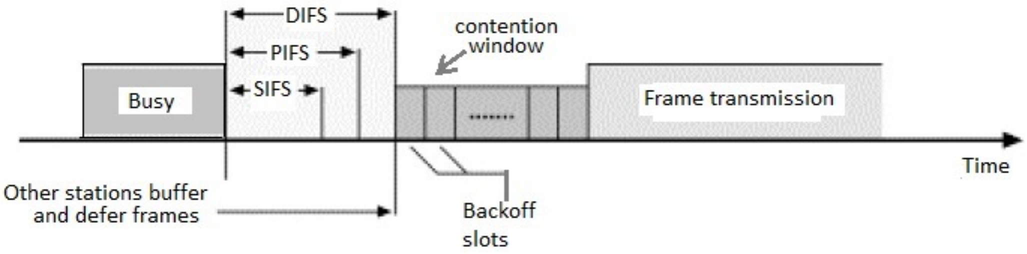
Backoff in WiFi

- Listen for activity
  - If free
    - Wait for Inter Frame Spacing (IFS)
    - If still free, transmit
  - If busy
    - Randomly select a number of backoff Slots
    - Count down slots whenever medium is not busy
    - If busy when backoff completes:
      - Increase maximum backoff Slots
      - Repeat
- Slot time: basic time unit for protocol
  - Total time of: switch from Rx to Tx, plus processing time, plus propagation delay

Prioritizing packets with varying IFS

- Tiered Contention Multiple Access (TCMA)
  - Idea: assign different inter-frame spacing based on traffic class
  - Inherently prioritizes communication

- Acknowledgements sent with Short IFS (SIFS)
  - Will always transmit before new data clears CSMA check
- New data sent with DCF IFS (DIFS)



Putting backoff together

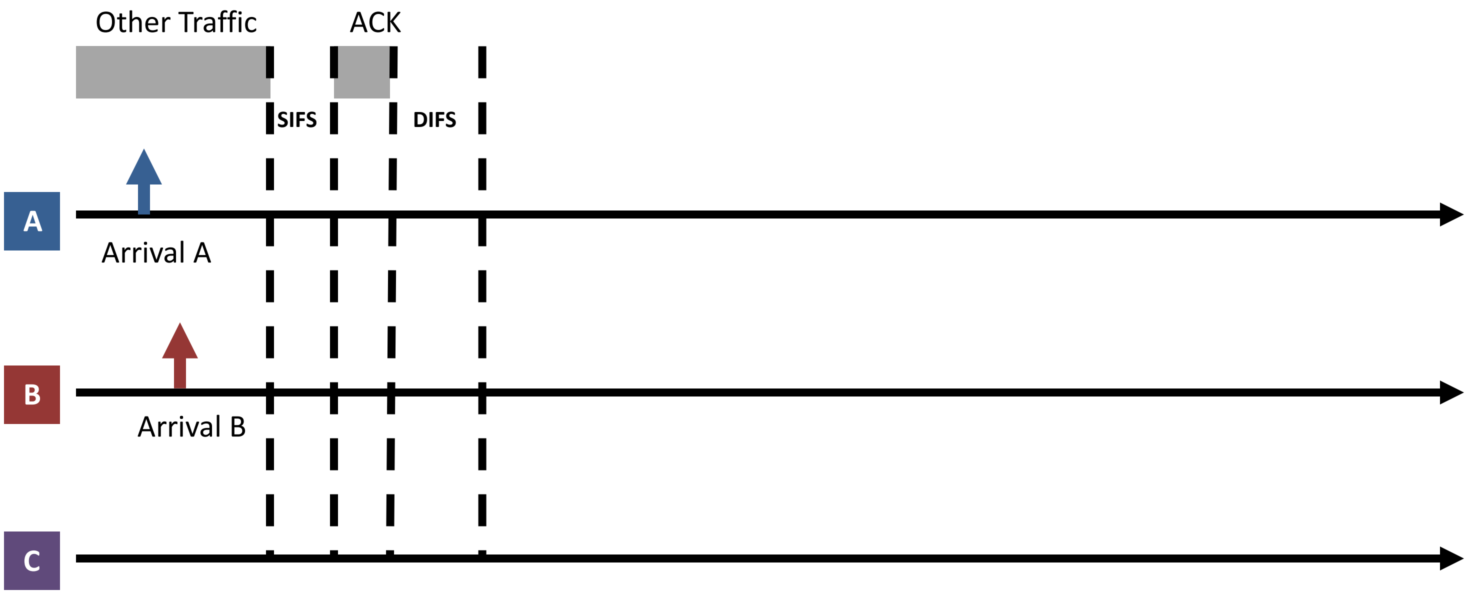
- Two variables
  - Contention Window (CW) – maximum backoff amount
  - Backoff Count (BO) – current remaining backoff

- When attempting to send, if busy Backoff selected in [0, CW]
  - Countdown Backoff slots whenever medium is not busy
  - At 0, attempt to transmit if not busy
  - If busy, double Window and select Backoff again

- 802.11g values:
  - Slot time= 20 μs, CWmin= 15 slots, CWmax= 1023 slots
  - SIFS= 10 μs, PIFS= 30 μs, DIFS= 50 μs

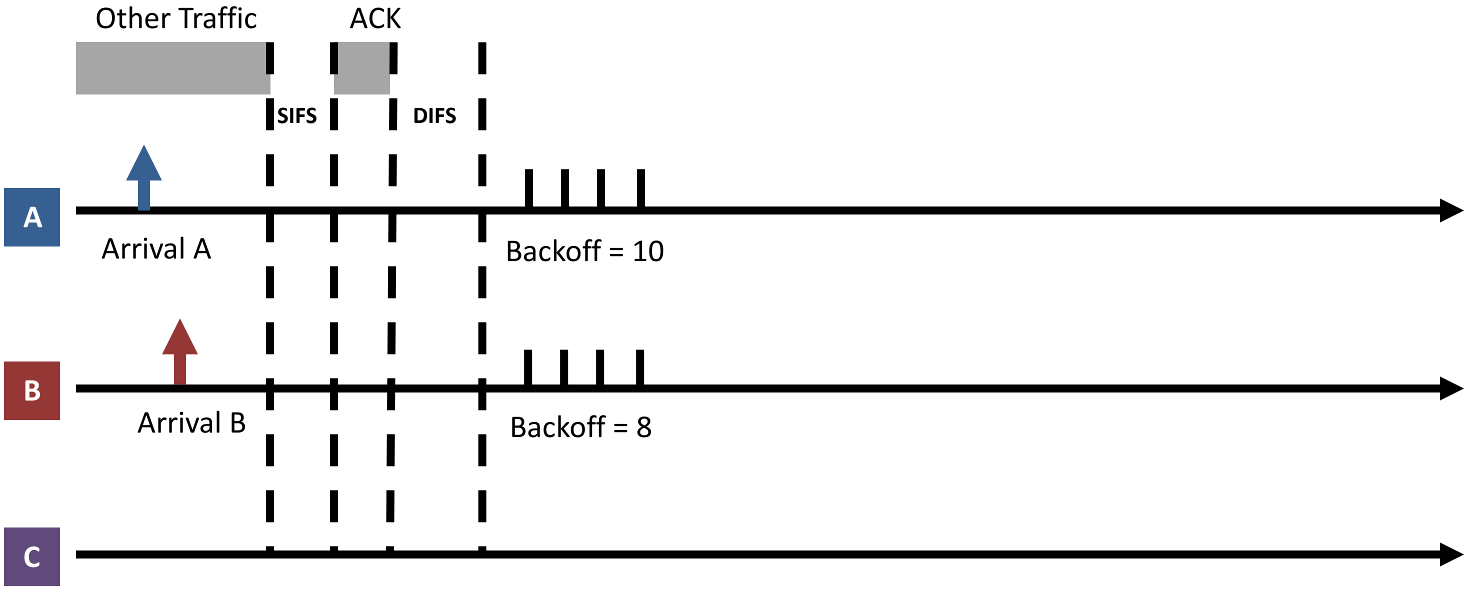
802.11 backoff example

- A and B want to send and see the medium is busy
  - Followed by an Acknowledgement after SIFS



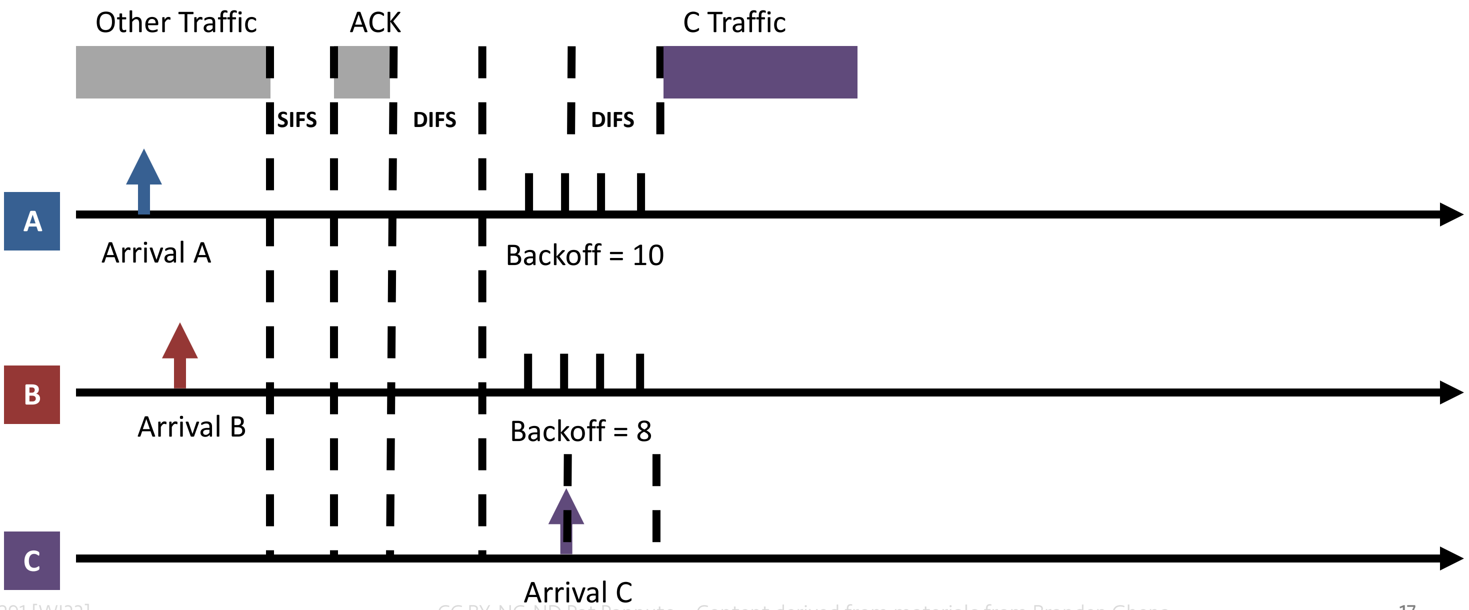
802.11 backoff example

- Each chooses a random backoff [0, CW] (we'll say CW is 32)
  - Start counting down backoff slots



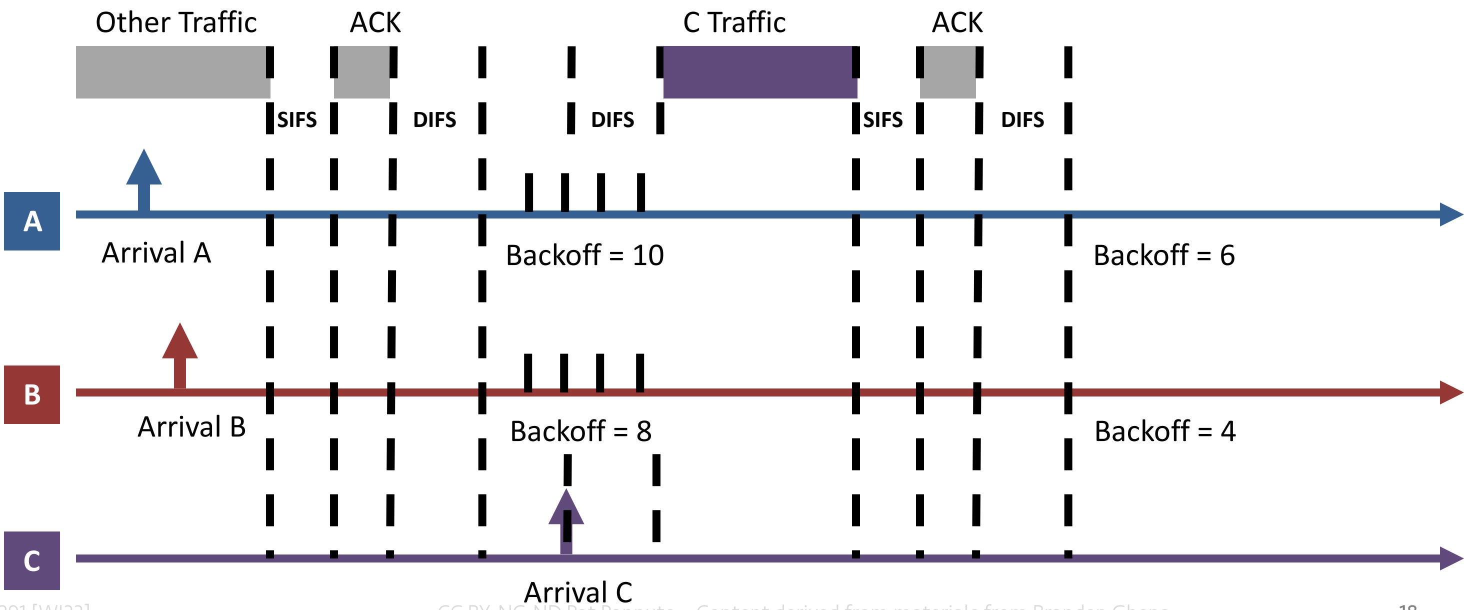
802.11 backoff example

- C wants to send, waits DIFS, and can send immediately
  - No other traffic is going on
  - A and B pause backoff for packet duration



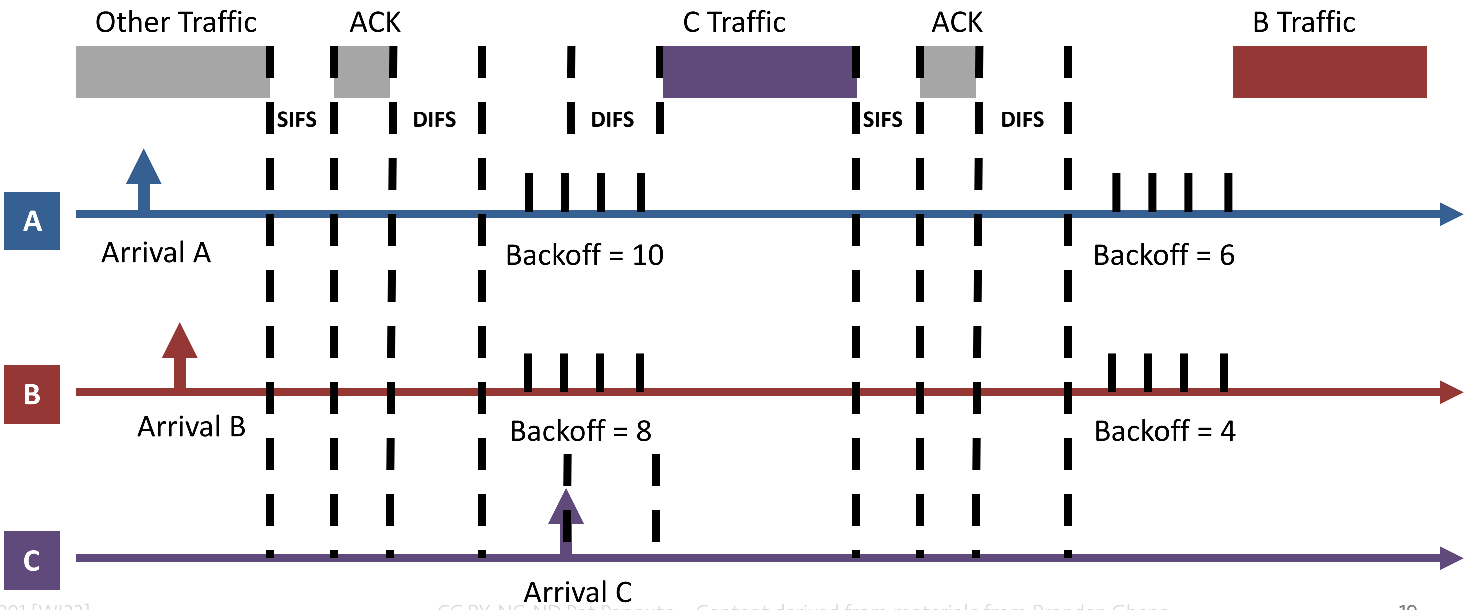
802.11 backoff example

- A and B used NAV to pause backoff for entire traffic plus ACK
  - After DIFS, resume backoff count from its previous value



802.11 backoff example

- B reaches zero backoff, finds channel empty, transmits
  - A pauses its backoff again for duration plus ACK



Outline

- 802.11 Access Control
- **802.11 Frame format**
- 802.11e Improvements to MAC

- Bonus topics
  - Microcontrollers and WiFi
  - Future of WiFi

Field	Frame control	Duration, id.	Address 1	Address 2	Address 3	Sequence control	Address 4	QoS control	HT control	Frame body	Frame check sequence
Length (Bytes)	2	2	6	6	6	0, or 2	6	0, or 2	0, or 4	*Variable*	4

- Frame control (various bits)
  - Type of packet (Control, Management, Data)
  - Subtype (Association, RTS, CTS, Ack, etc.)
  - Indication of to/from "distribution system" (Internet rather than intranet)

- Duration
  - Specifies on-air time of full packet in µs
  - Note: no actual length field

Surprising, but smart!

Recall MCS vary — but everyone needs to be able to parse header (for duration, for NAV)

Length can be very large (e.g. in ac: 5.5 ms max duration is 4.5 MB length!); sent at full data rate

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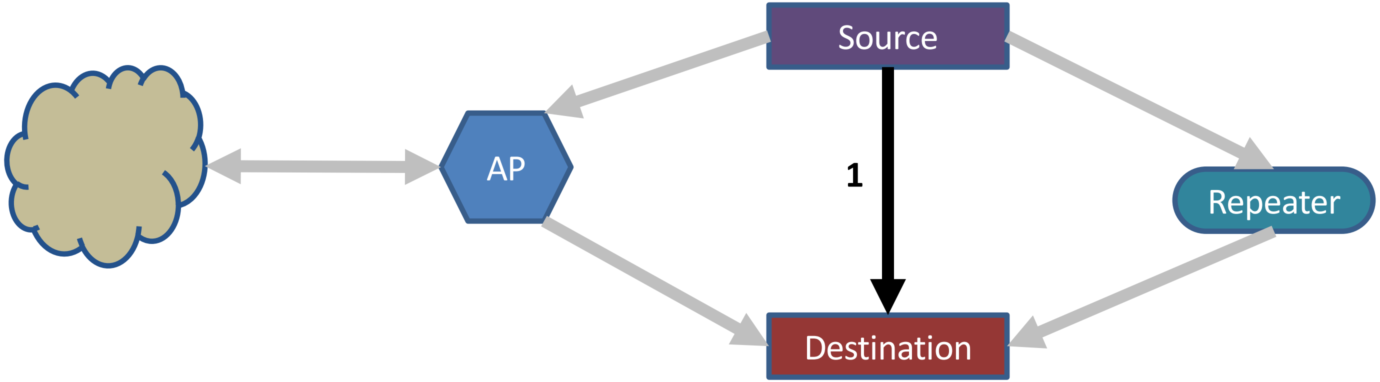
- Sequence control
  - 4-bit fragment number
  - 12-bit sequence number
- Quality of Service control
  - Identifies traffic category
- High Throughput Control
  - Configurations for selecting best data rate
- Frame body
  - Max size depends on PHY
    - ~2000 for lower rates
    - ~8000 for 802.11n
    - ~11000 for 802.11ac
- Frame check sequence
  - 32-bit CRC

Address field use cases



Devices filter on Address 1

	To DS	From DS	Address 1	Address 2	Address3	Address4	Use Case
1	0	0	Destination Addr	Source Addr	BSS ID	-	Direct communication
2	0	1	Destination Addr	BSS ID	Source Addr	-	Traffic from Internet
3	1	0	BSS ID	Source Addr	Destination Addr	-	Traffic to Internet
4	1	1	Receiver Addr	Transmitter Addr	Destination Addr	Source Addr	Repeater

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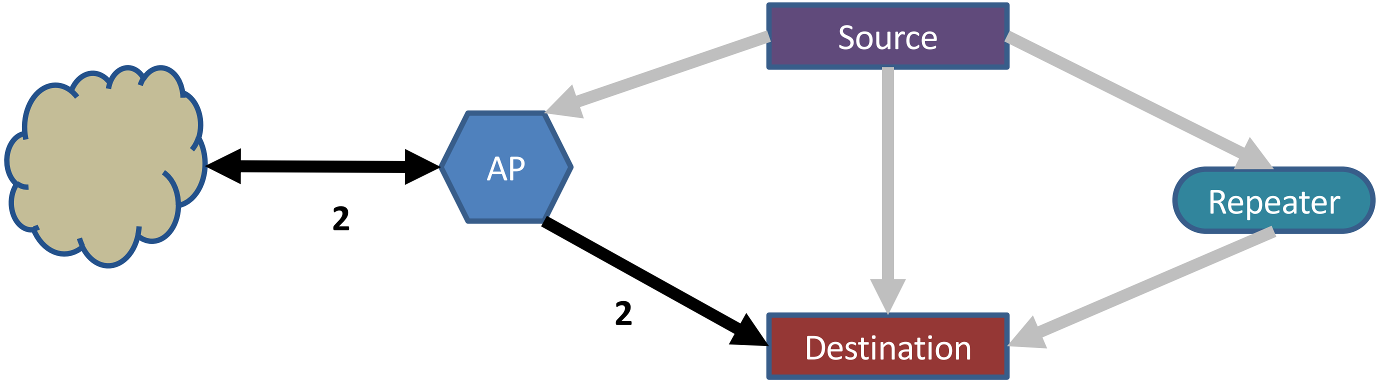

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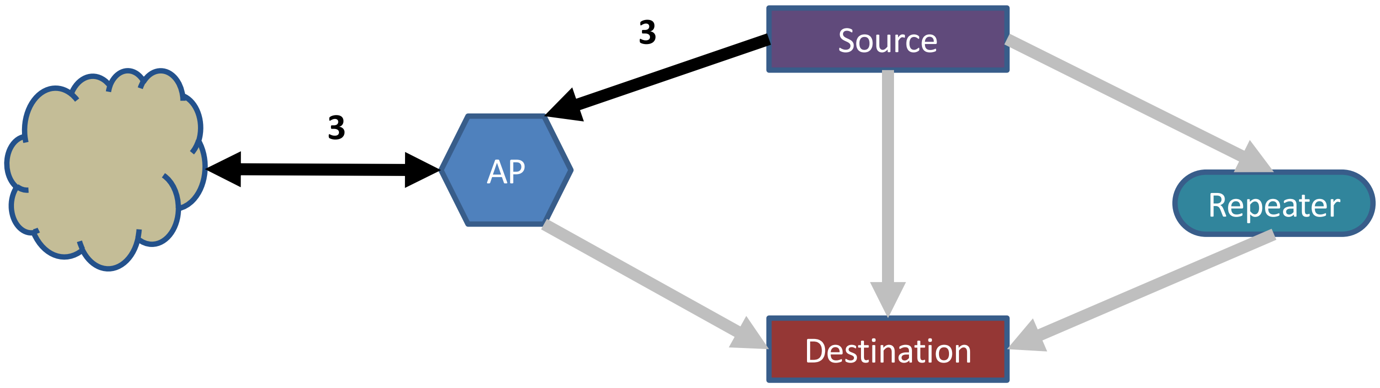

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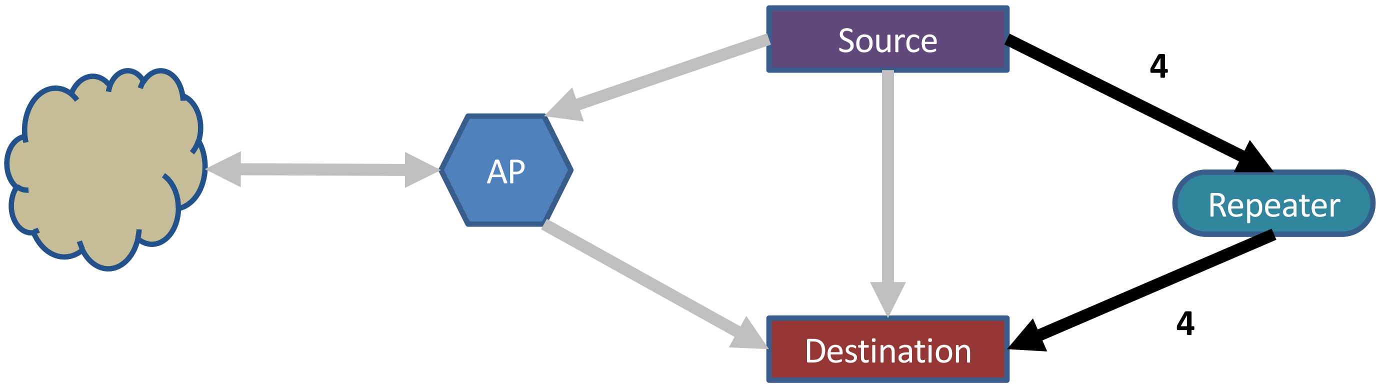

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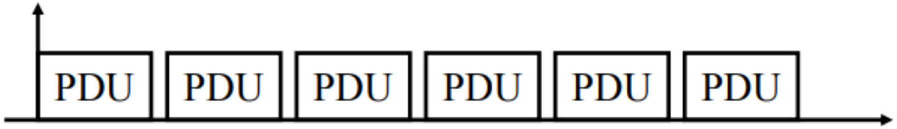
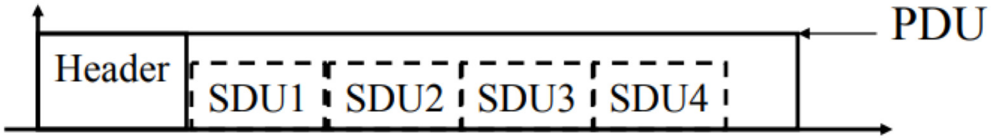
Sending frames in WiFi

- Frame bursting
  - Transmit multiple frames in a row



- Frame fragmentation
  - Split service data over multiple frames

- Frame aggregation
  - Multiple service data in a single frame
  - Allows multiple packets to reach Access Point in a single transmission



Calculating packet durations

- Example duration for a 1500 byte 802.11g packet
  - 6 Mbps for header
  - 24 Mbps for payload
  - 566 µs for total packet
    - Plus 10 µs for SIFS
    - Plus 34 µs for ACK

- https://sarwiki.informatik.hu-berlin.de/Packet_transmission_time_in_802.11

	Data transmission bitrate (802.11g / a*):		24 Mbps	
		Bitrate (Mbit/s)	Length (bits)	Time (µs)
	DIFS			28
D	PHY header: PLCP preamble	-	-	16
A	PHY header: PLCP header	6	24	4
T	MAC headers (28 bytes) + MAC body	24	12246	512
A	signal extension time			6
	tx time data:			**566**
	SIFS			10
A	PHY header: PLCP preamble	-	-	16
C	PHY header: PLCP header	6	24	4
K	MAC headers + PHY pad	24	134	8
	signal extension time			6
	tx time ack:			**44**
	tx time data + ack:			**610**

Implementation Drives Specification Sometimes

- SIFS nominally defined by processing time
  - Aside: Big challenge for SDRs
- Convolutional decoders need(ed) 16 µs to finish processing
  - For highest-rate MCS (ERP-OFDM)
- Processing must finish before next packet starts
  - To be able to decode NAV in header

		Bitrate (Mbit/s)	Length (bits)	Time (µs)
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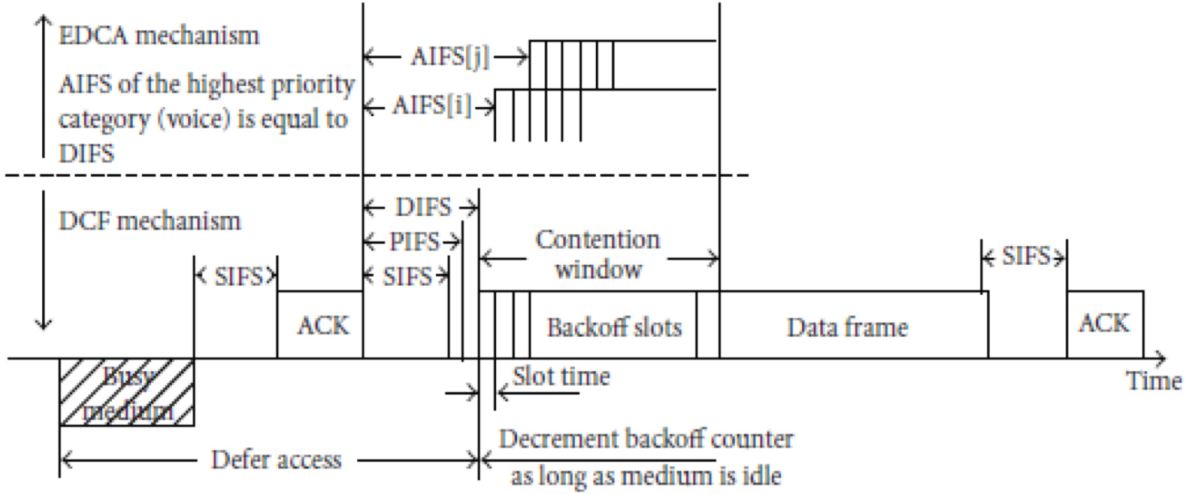
802.11e improves MAC layer

- Hybrid Coordination Function (HCF)
  - Modifies contention-free access (still no one uses it)
  - Modifies contention-based access: Enhanced Distributed Channel Access (EDCA)

- EDCA: Modifies Quality of Service based on application
  - Example of breaking layering for an optimization
  - Categories (lowest to highest priority):
    - Background
    - Best Effort
    - Video
    - Voice

Different priority for different application category

- Expand to more IFS lengths for different traffic categories
  - Smallest AIFS (equal to DIFS) goes to Voice, Largest to Background
  - Contention Window min and max also change for each category
    - 

Multiple queues within a single device

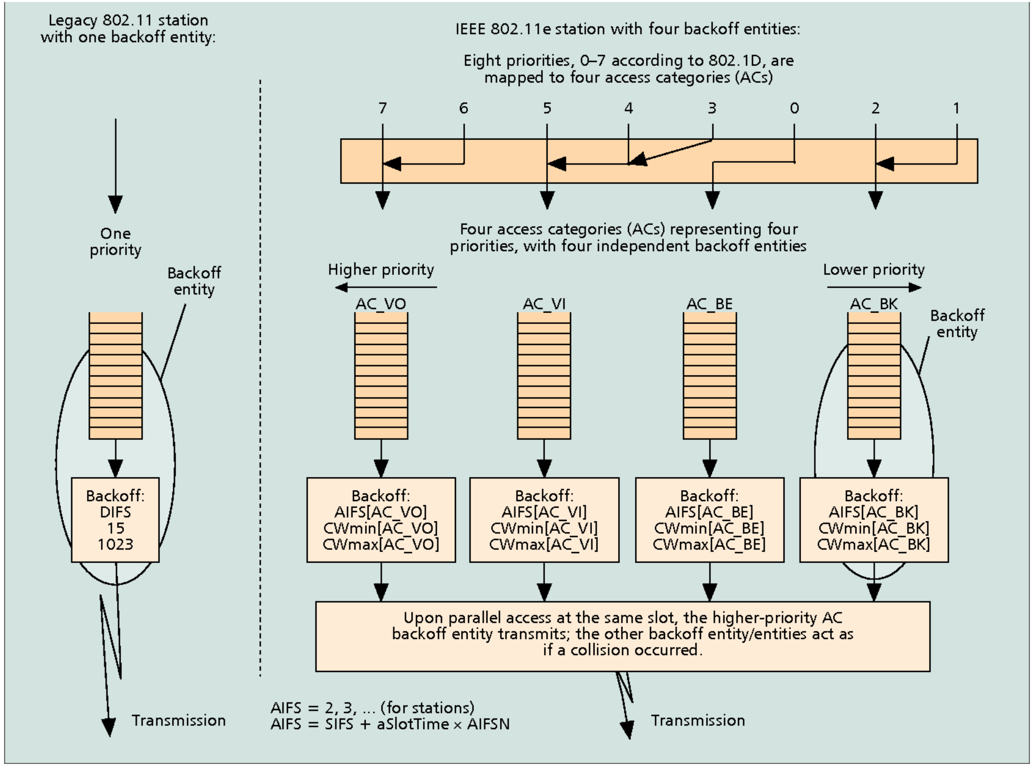


Figure 4. *[3] Legacy 802.11 station and 802.11e station with four ACs within one station.*

802.11e also adds maximum durations

- 802.11e also defines duration a device can transmit for
  - Based on PHY in use and Application category
  - Background/Best Effort: one frame per contention win
  - Example, up to 11 ms for Voice on 802.11ac
    - Could be one really big frame at a low data rate
    - Could be multiple frames in a row separated by SIFS

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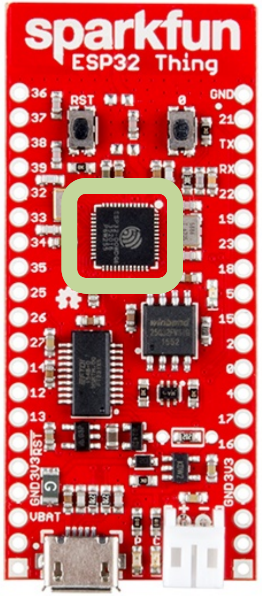
Why, why not, talk WiFi in a wireless for IoT class

- Pros
  - Ubiquitous
  - High-performance
- Cons
  - Complex configuration
  - And security requirements
    - UCSD-DEVICE anyone?
  - Expensive in e^-, \$

WiFi capability in microcontrollers

- ESP32 (extremely popular; there are others)
  - Microcontroller plus WiFi radio in single chip
  - (Same idea as nRF52840)

- Capabilities
  - 802.11b/g/n 2.4 GHz only
  - 20 MHz or 40 MHz channels
  - Single antenna only (no MIMO)
  - MCS0-7
    - 7 Mbps – 150 Mbps
  - Tx power up to 20.5 dBm



Low power WiFi

- Question: should a microcontroller stay connected or reconnect?
  - Light sleep: stay connected always, only listening to beacons
  - Deep sleep: reconnect to network each time data is ready
- Answer for ESP32 depends on security and data interval
  - Resecuring during connection takes lots of energy
    - Crossover point is about 60 seconds
  - Insecure transmissions have a crossover of 5-15 seconds

https://blog.voneicken.com/2018/lp-wifi-esp-comparison/#conclusions

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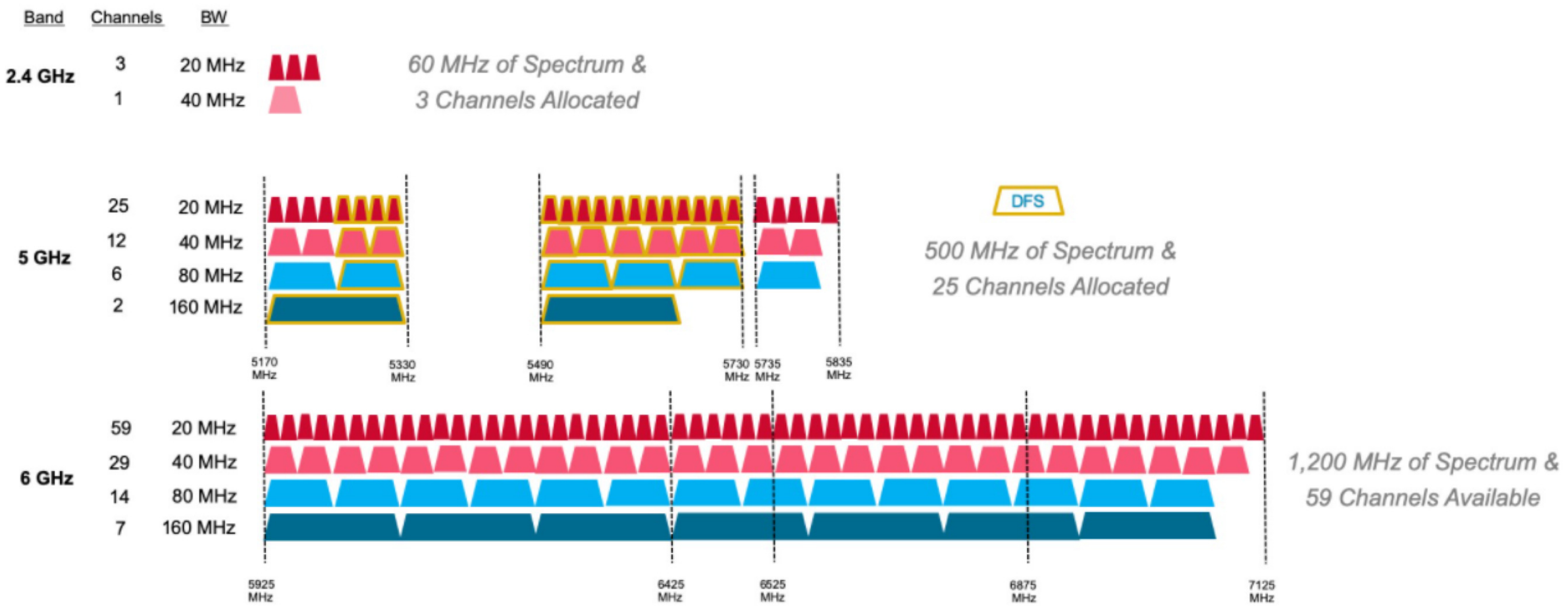
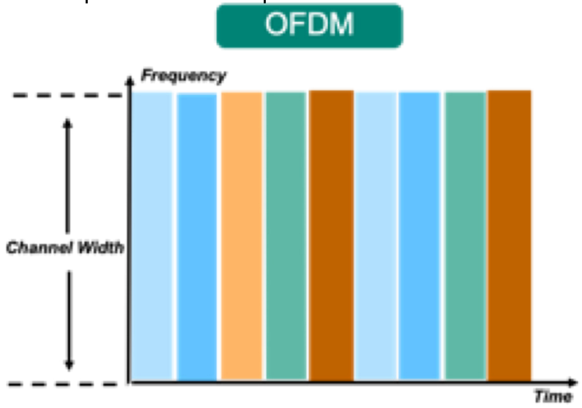
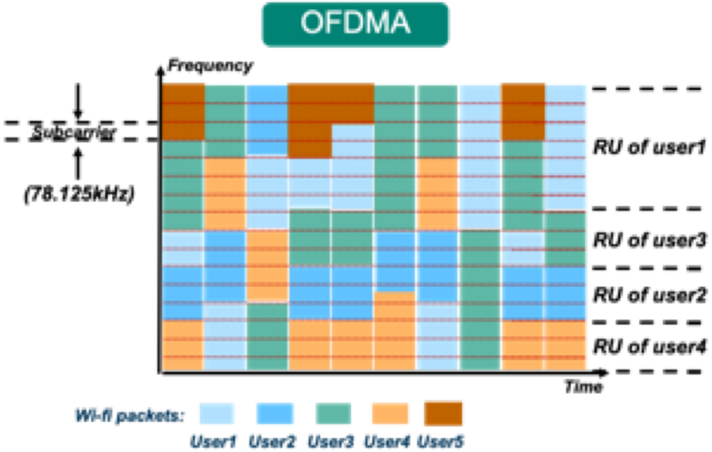
802.11.ax:
6 GHz band is an enormous amount of bandwidth



802.11.ax:
Orthogonal Frequency Division Multiple Access

- OFDM: split channel into subcarriers and transmit on those
- OFDMA: allocate subcarriers to a device for an amount of time
  - Turns OFDM into an access control mechanism
  - Complicated question: which device gets which subcarriers at which time?





WiFi 7: 802.11.be
“EHT — Extremely High Throughput”

- Targeting release ~Q2 2023
- Goals / plans
  - 40 Gbps [~= Thunderbolt 3, #WhoNeedsWires]
    - Up to 320 MHz channels (from 160 now)
    - 16-stream MIMO
  - Better support for many devices
    - Enhance AP coordination
    - Better link adaptation and retransmission
  - Lots of timing related features
    - For sync, video streaming, QoS, and cross-network performance

Next week: Weirder stuff