After this class, you are expected to be able to understand:

- how NRZ, RZ, Manchester, and DM, are used to encode 0s and 1s, and their pros and cons.
- how $A$, $f$ and $\phi$ can be used to encode 0s and 1s, and their pros and cons.
- the term bandwidth and the theoretical capacabitity of a medium using Nyquist's and Shannon's formula.
- how a signal can be viewed in frequency domain and how frequency can be shifted to multiplex multiple signals.
- how QAM works and its representation as a constellation.
0s and 1s can be transmitted either as digital signal or analog signal over a medium.

WiFi uses analog signal. Ethernet uses digital signal.
Digital Encoding
A digital signal has a limited number of defined values (e.g., -1, 0, and 1 only).

The value of a digital signal is determined by the voltage sent over the wire.

Polar encoding uses two levels: -1 and 1.

Bipolar encoding uses three levels: -1, 0, and 1.
0s and 1s can be encoded into digital signals in different ways.

NRZ encoding is a polar encoding scheme.

Two variants: NRZ-L encodes the bit value using the level of the signal; NRZ-I inverts the signal if bit 1 is encountered.
NRZ-L
NRZ-I
RZ is a bi-polar encoding scheme, always returning the signal to zero halfway through the bit interval.

It allows synchronization of clock at the sender and receiver, without which clock drift could lead to bit errors.

E.g., if the sender is sending 111111..., the receiver may lost track of how many 1s have been received. This is known as a bit slip.
- **Manchester** coding inverts the signal in the middle of a bit. A -ve to +ve transition represents 1. A +ve to -ve transition represents 0.

- **Differential Manchester (DM)** uses the presence of absence of a transition at the beginning of the interval to identify a bit. A transition means 0. No transition means 1.
Manchester
Differential Manchester
Detecting transition is less error prone than comparing against a threshold.

DM works even if the signals are swapped.
Digital-to-Analog Modulation
The most basic analog signal is a sine wave:

\[ A \sin(2\pi ft + \phi) \]

where \( A \) is the peak amplitude, \( f \) is the frequency and \( \phi \) is the phase.
We can combine sine waves to form composite signals.

Composite signal can be decomposed to multiple sine waves.

It is useful to visualize a composite signal using the frequency of its composition (i.e., in frequency domain instead of time domain).
A transmission medium only allows a frequency range to pass through.

The difference in highest and lowest frequency that can pass through a medium is known as the bandwidth of the medium.

The difference in the highest and lowest frequency that represent a signal is known as the bandwidth of the signal.
A transmission medium also introduces noise, which distorts the signal, limiting the number of bits that can go through.

For an ideal, noiseless channel, the Nyquist bit rate formula gives the theoretical maximum bit rate:

\[ 2B \times \log_2 L \]

where \( B \) is the channel bandwidth (in Hz) and \( L \) is the number of signal levels.
If we use Manchester coding on a noiseless 1 MHz channel, the maximum data rate is 2 Mbps.
For a noisy channel, characterized by a signal-to-noise ratio $SNR$, the theoretical maximum is given by Shannon Capacity

$$B \times \log_2(1 + SNR)$$
Phone line has a bandwidth of 3000 Hz and SNR of 3162. The capacity of the channel is 34860 bps.
Let's revisit how FDM works on a medium with large enough bandwidth to support multiple signals.

The signals' frequencies are shifted, added together, and transmitted.

At the receiver, we filter out different frequency range, and shift the signal back to their original frequency.
Frequency-Division Multiplexing

- 4-8kHz
- 8-12kHz
- 12-16kHz
- 16-20kHz
FDM
To transmit 0s and 1s with an analog signal, we can change either $A$, $f$, or $\phi$.

- Amplitude Shift Keying (ASK) changes peak amplitude to represent 0s and 1s.
- Frequency Shift Keying (FSK) changes frequency to represent 0s and 1s.
- Phase Shift Keying (PSK) changes phase to represent 0s and 1s.
ASK
FSK
- ASK is vulnerable to noise.
- FSK is limited by bandwidth.
PSK
PSK constellation
QPSK constellation
Quadrature Amplitude Modulation (QAM) combines ASK and PSK. Many combinations are possible.

A signal unit in a $2^k$-QAM scheme is a combination of amplitude and phase that represents $k$ bits.

Baud rate is the number of signal units per second (unit is Bd).
QPSK constellation
4-QAM
8-QAM
Singapore TV broadcast uses DVB-T, which uses QPSK, 16-QAM, or 64-QAM.

802.11a uses BPSK, QPSK, 16-QAM or 64-QAM.

Ethernet, RFID, and NFC use Manchester coding.

USB uses NRZ-I.