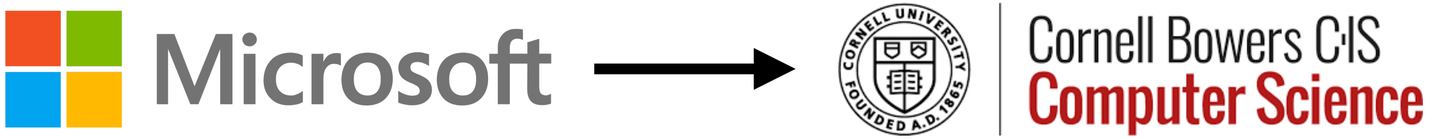
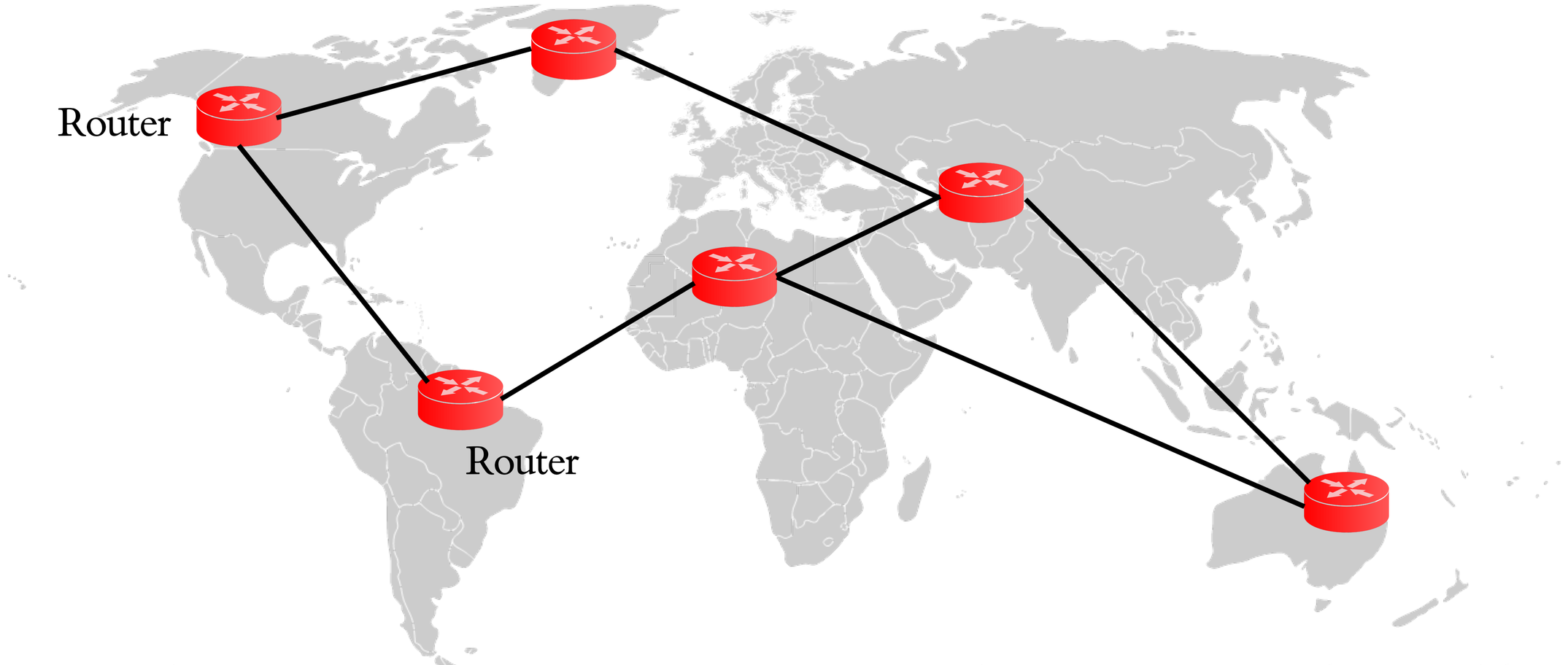
A physical layer perspective on wide-area networks (WANs)

Guest lecture: Rachee Singh



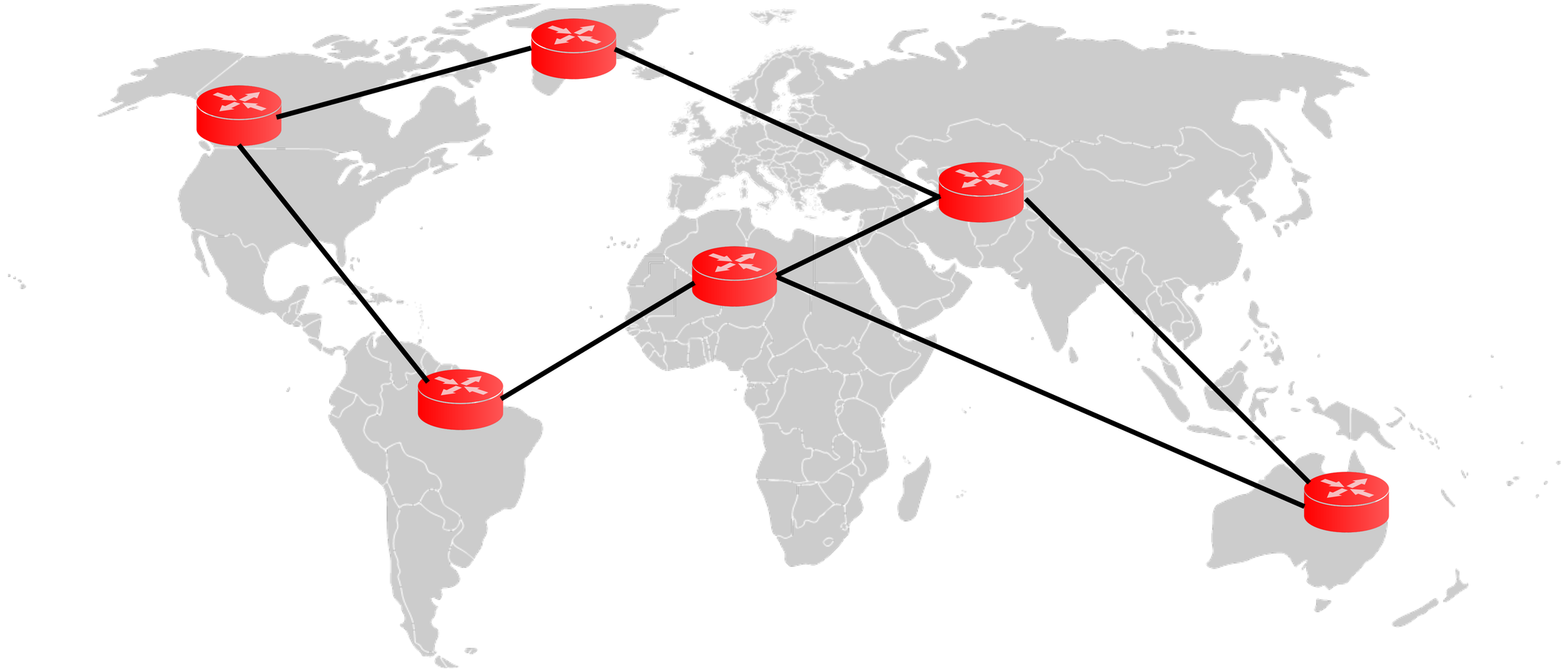
CS4450: Introduction to Computer Networks

Wide-area networks

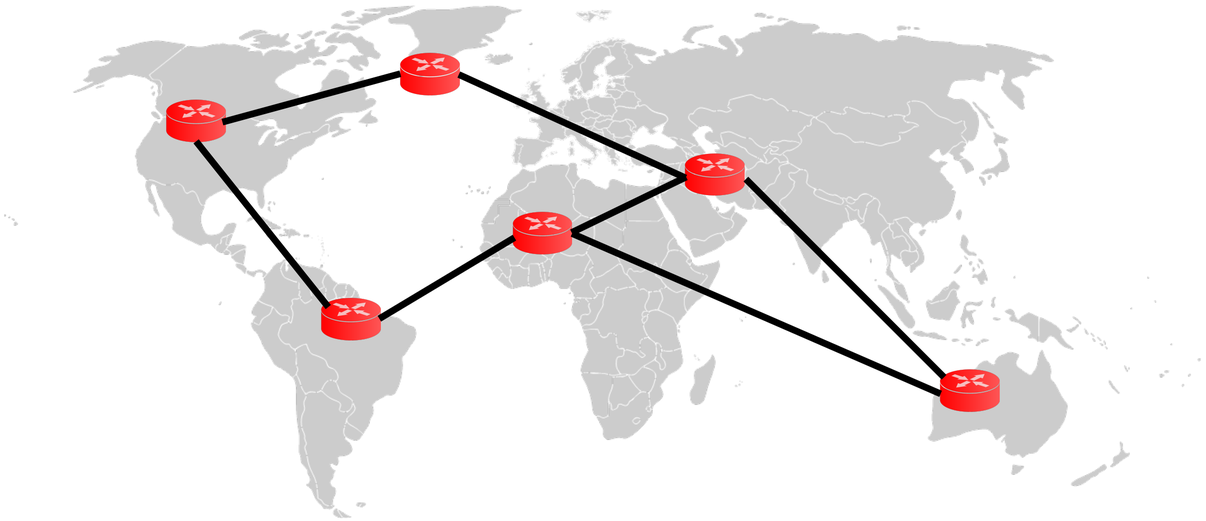


Span large geographic areas to interconnect locations across the world

Wide-area networks

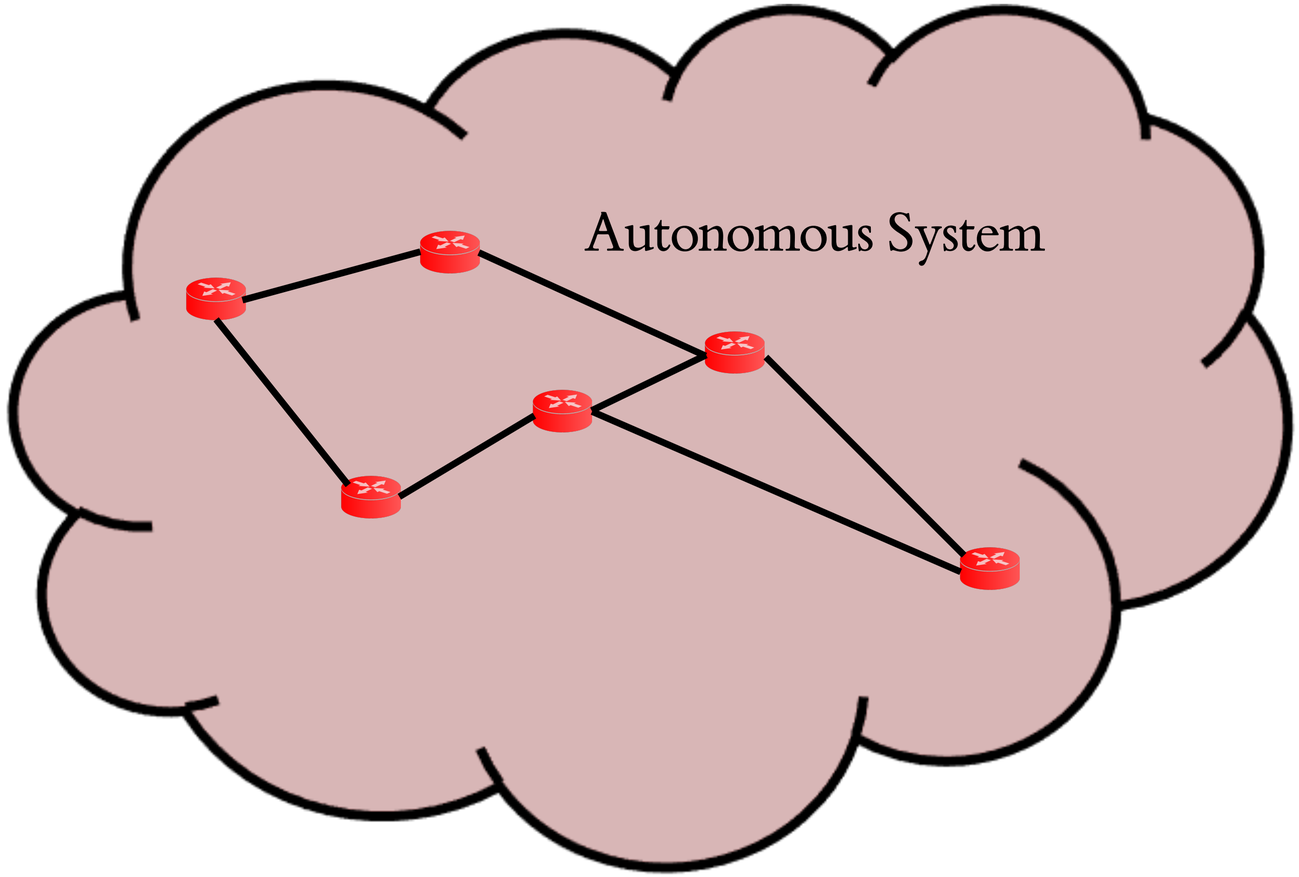


Wide-area networks



A wide-area network (WAN) forms an administrative domain or an AS.

Wide-area networks



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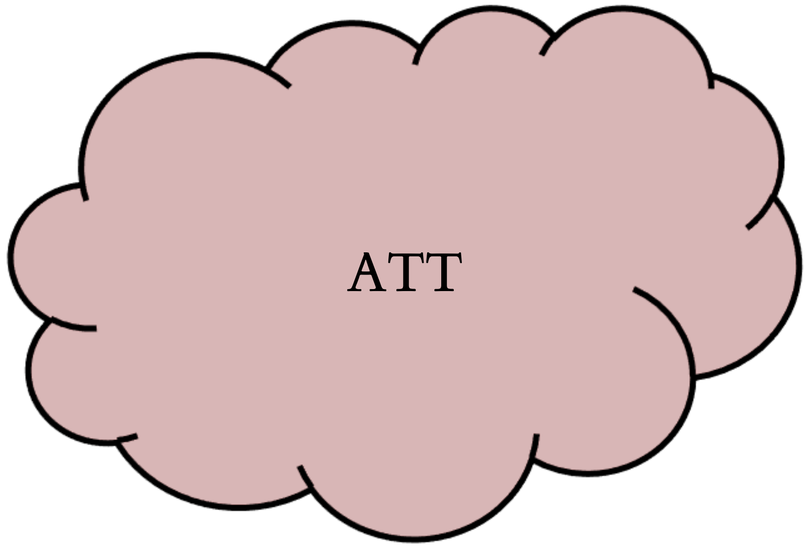
Wide-area networks

Many WANs on the Internet that carry traffic for applications we care about.

Wide-area networks



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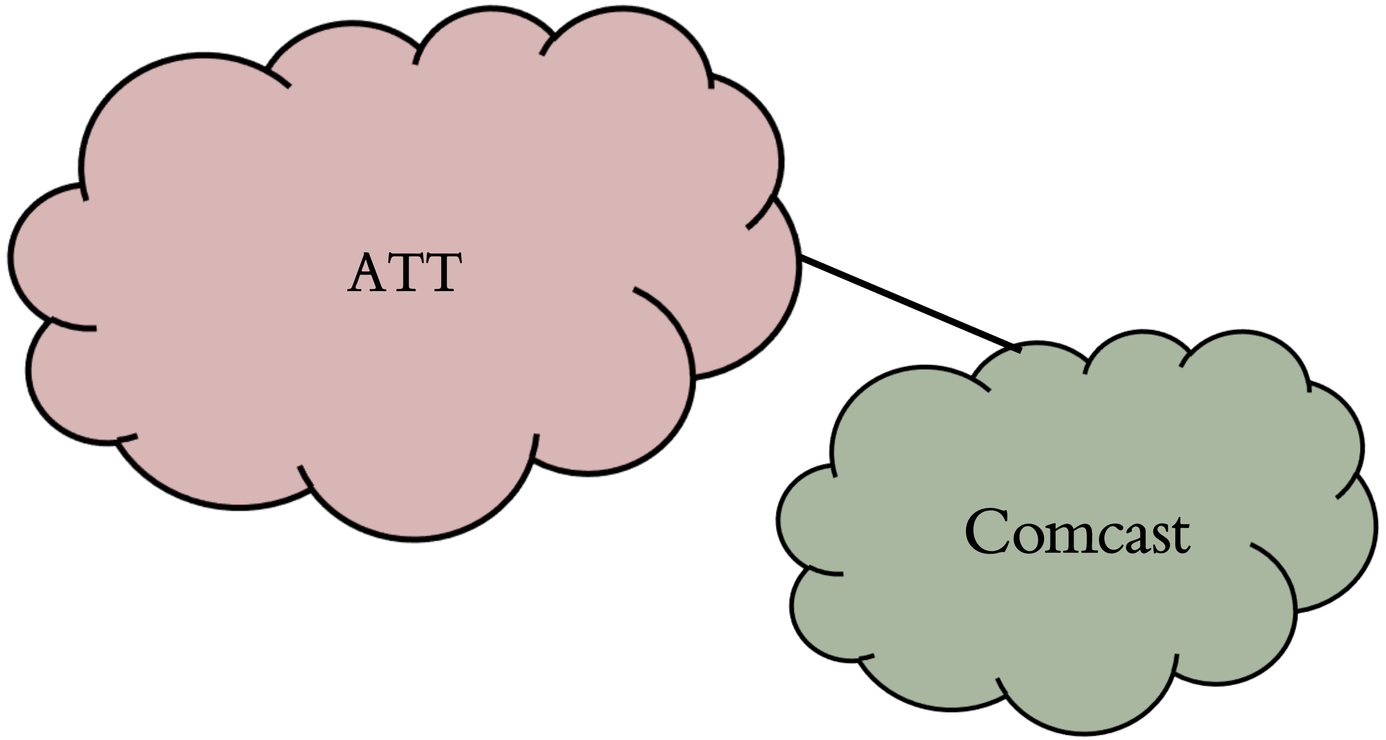

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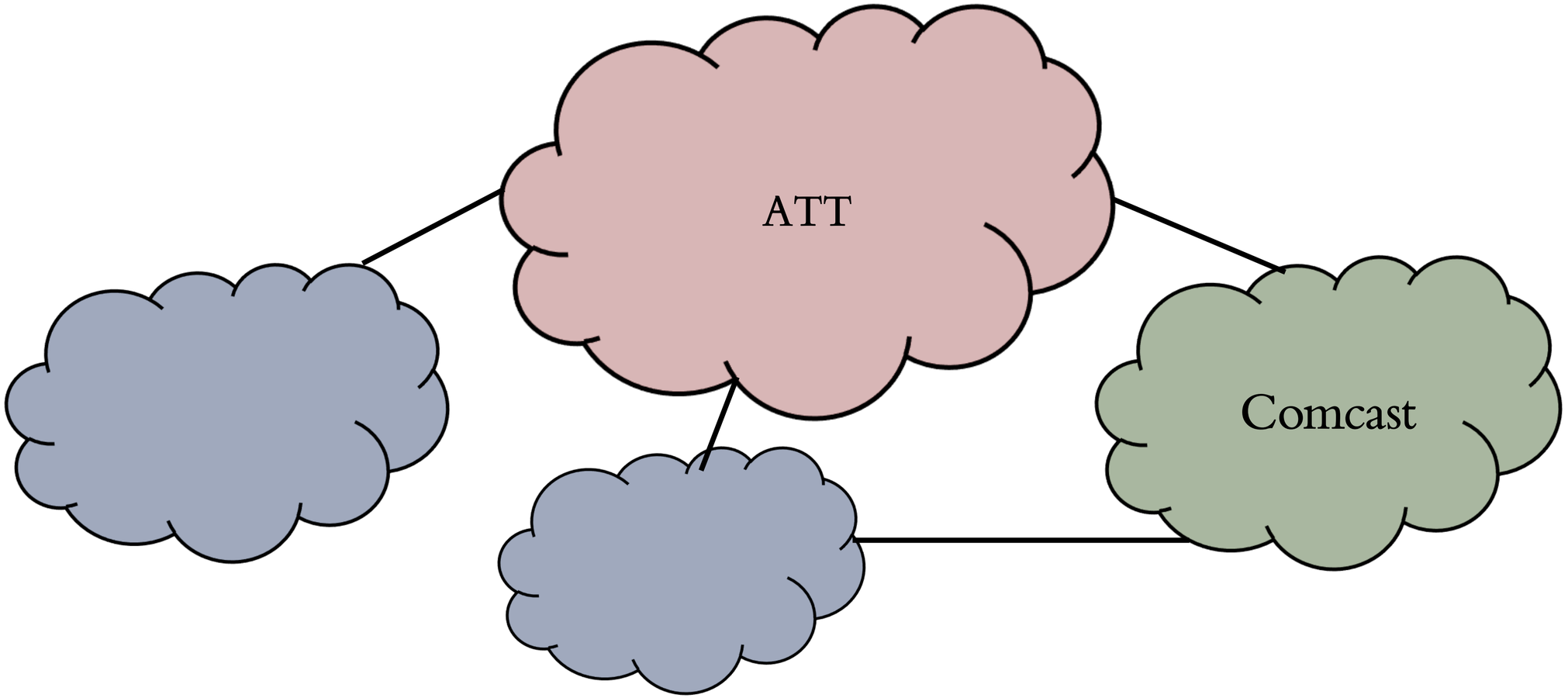

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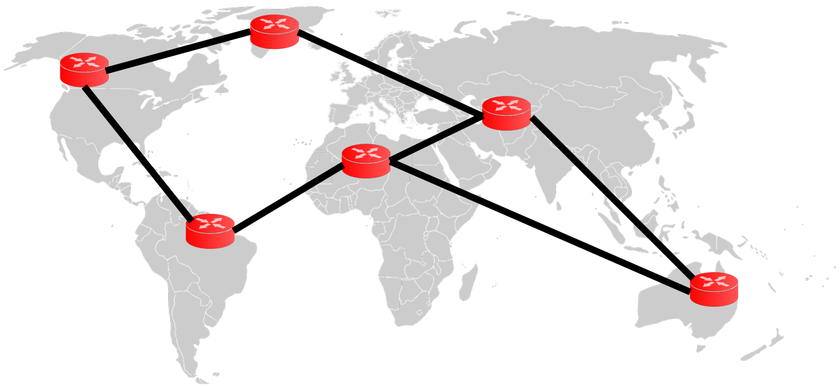
Types of wide-area networks



ISP WANs

(Comcast, ATT)

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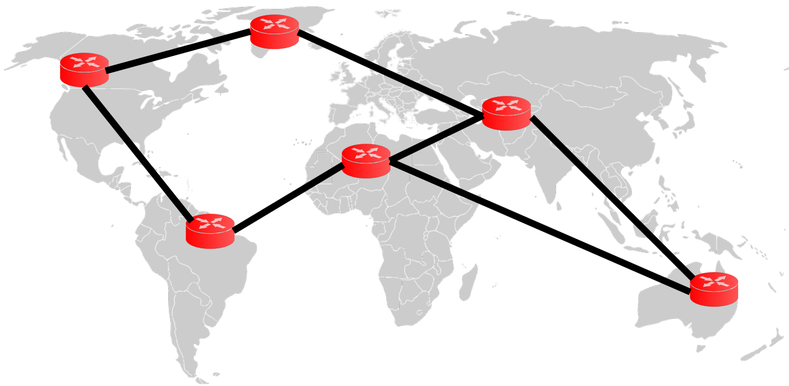

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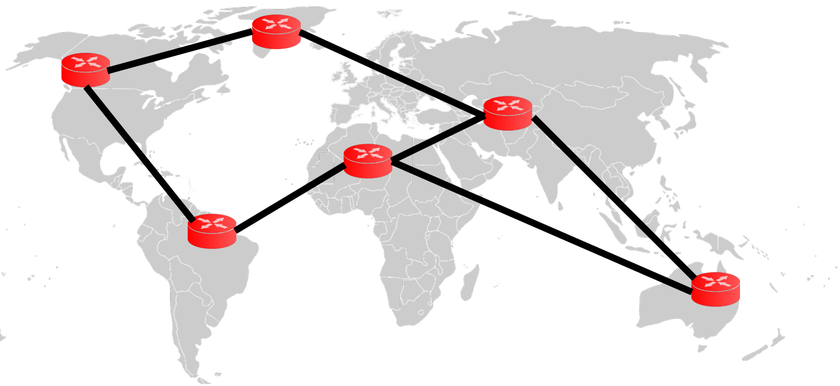

Cloud WANs

(MSFT, Google, Meta)

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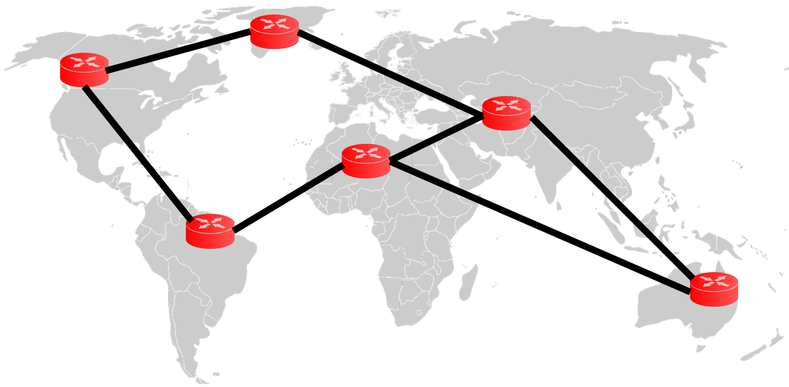

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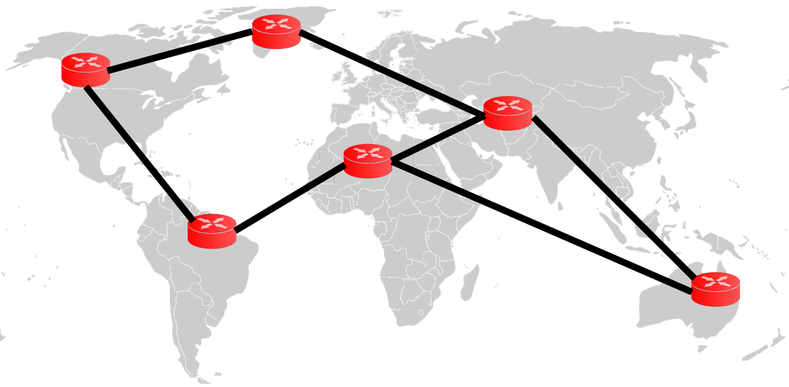

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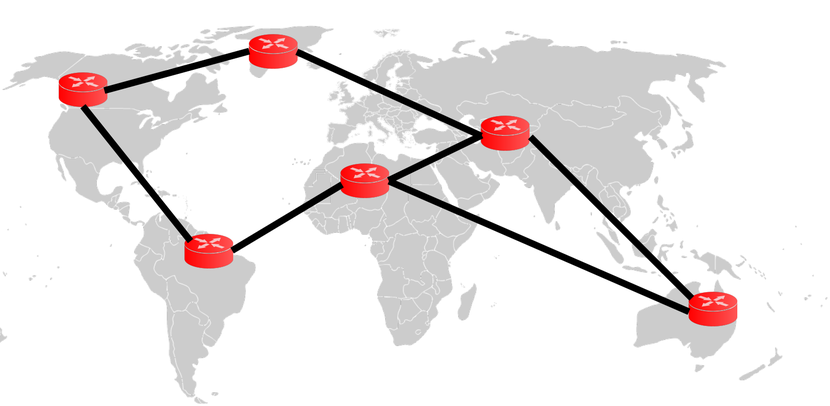
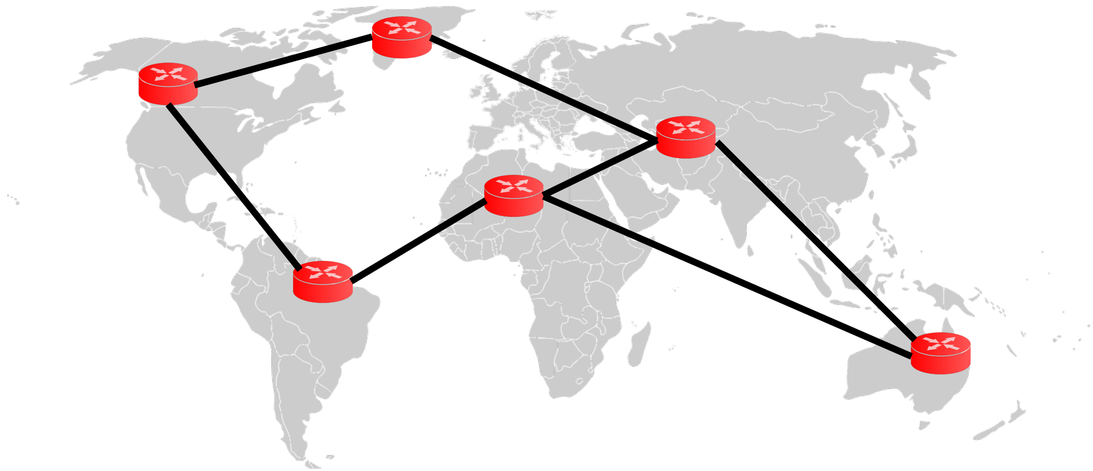


Non-terrestrial WANs

(Loon, Starlink)

Challenges of implementing WANs

1. "long-haul" connectivity
2. High operating expenses
   - Billions of dollars to provision (capital expense)
   - Millions of dollars to maintain (operating expense)



Long-haul network connectivity

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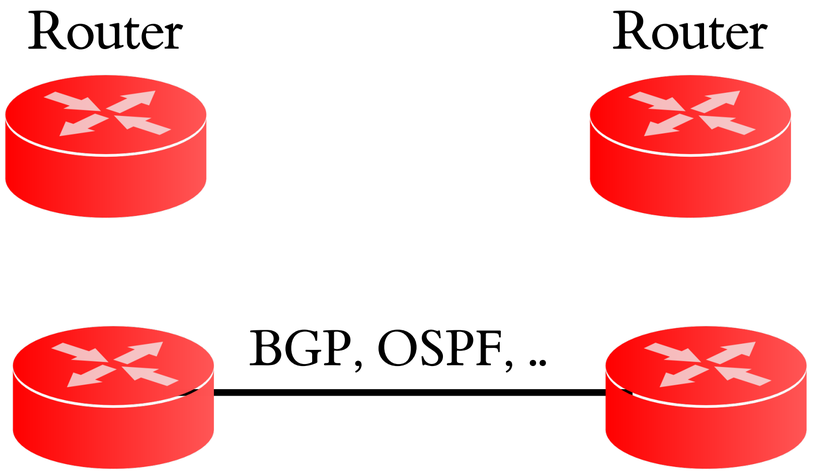

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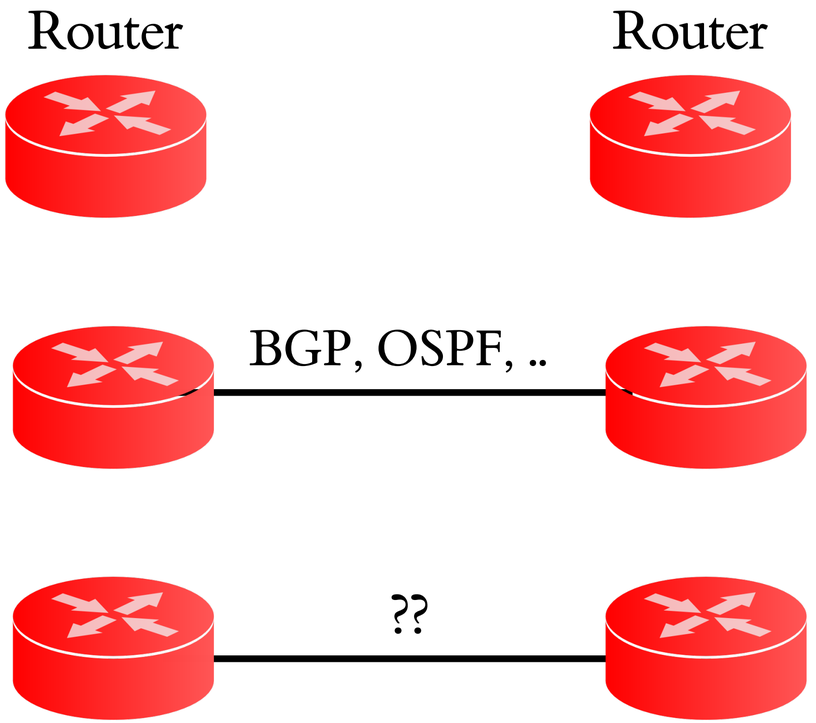

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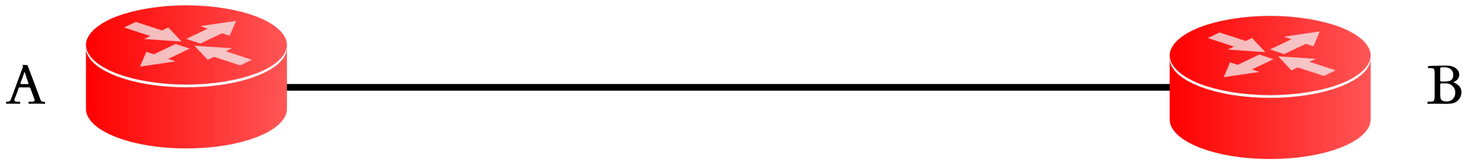

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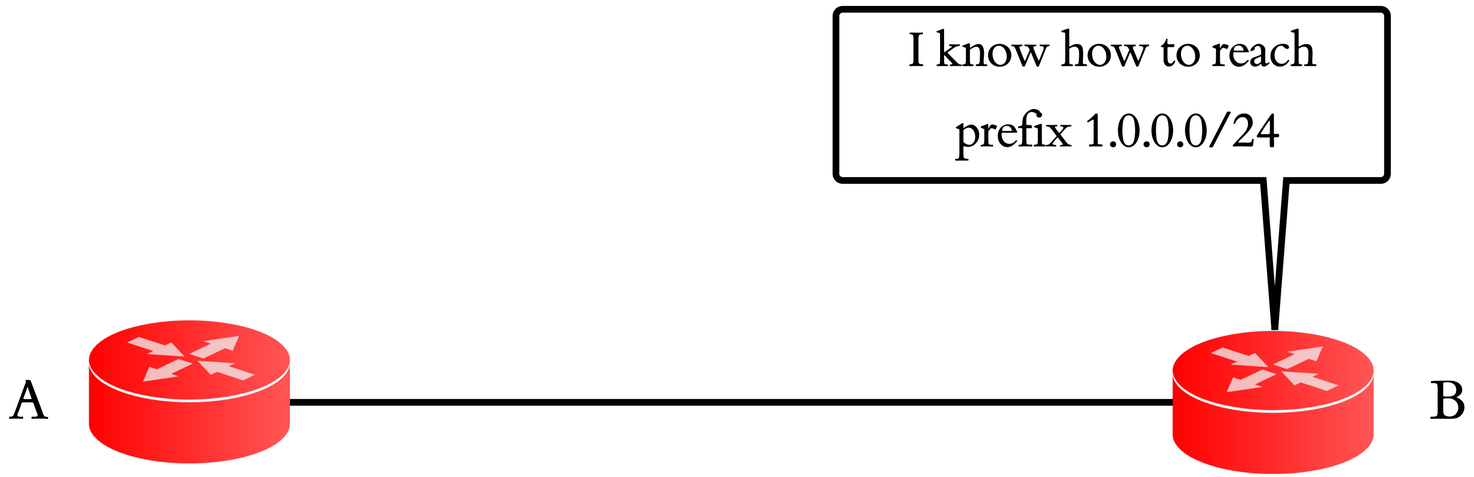

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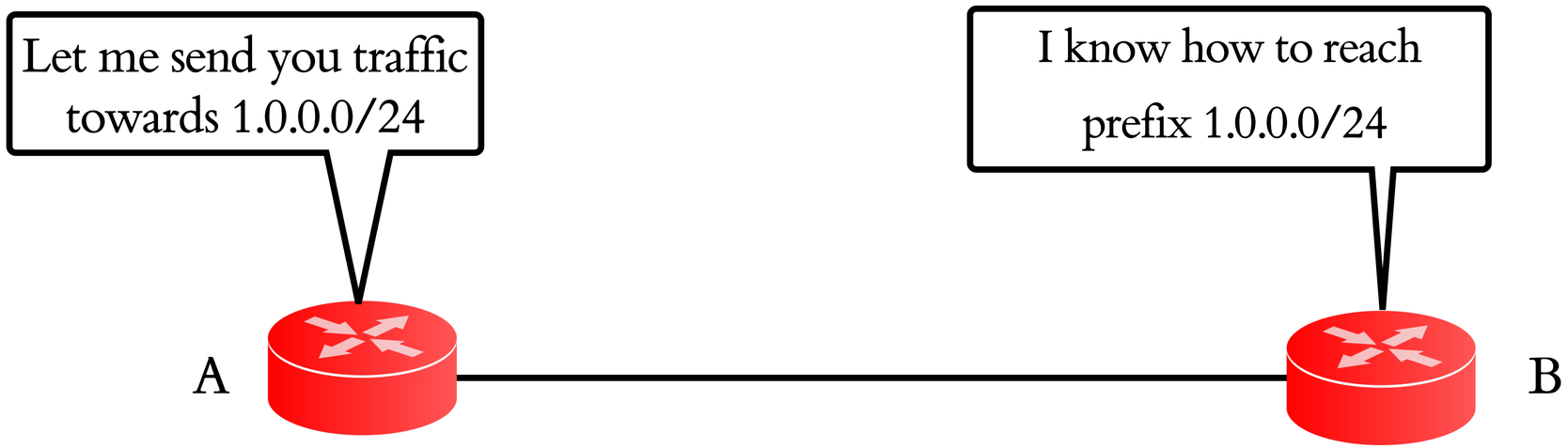

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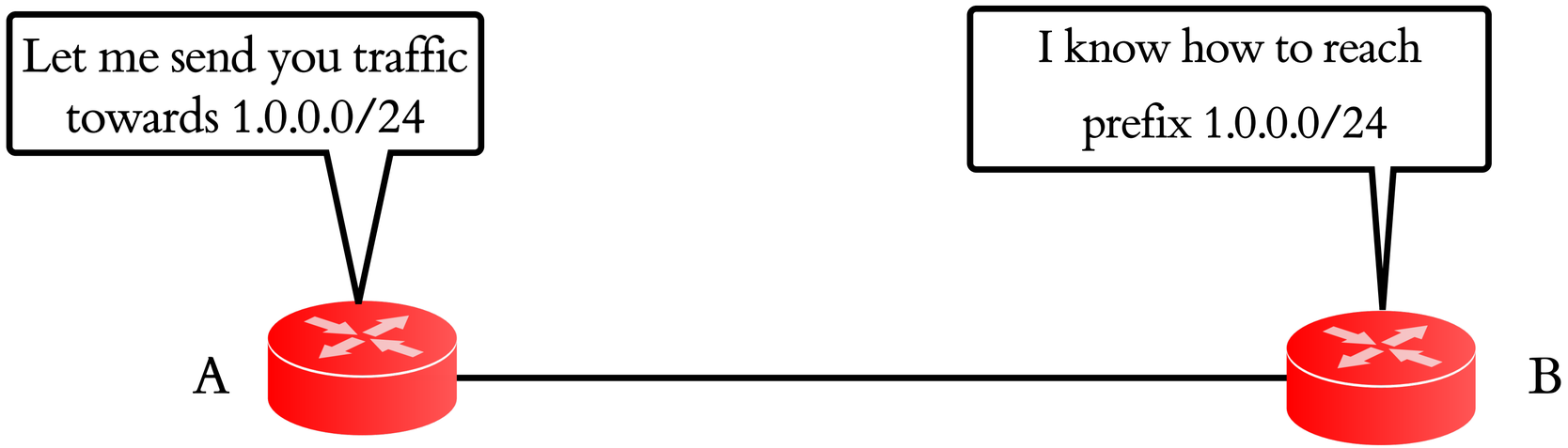

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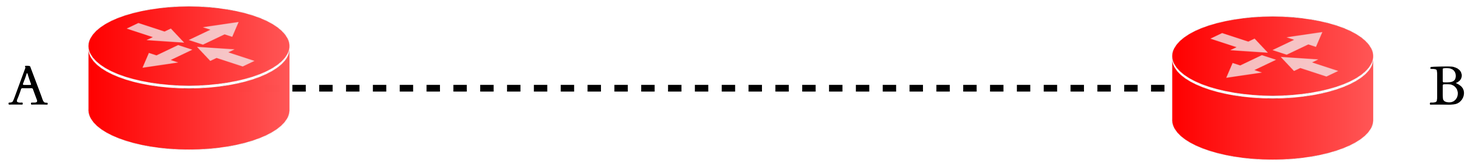

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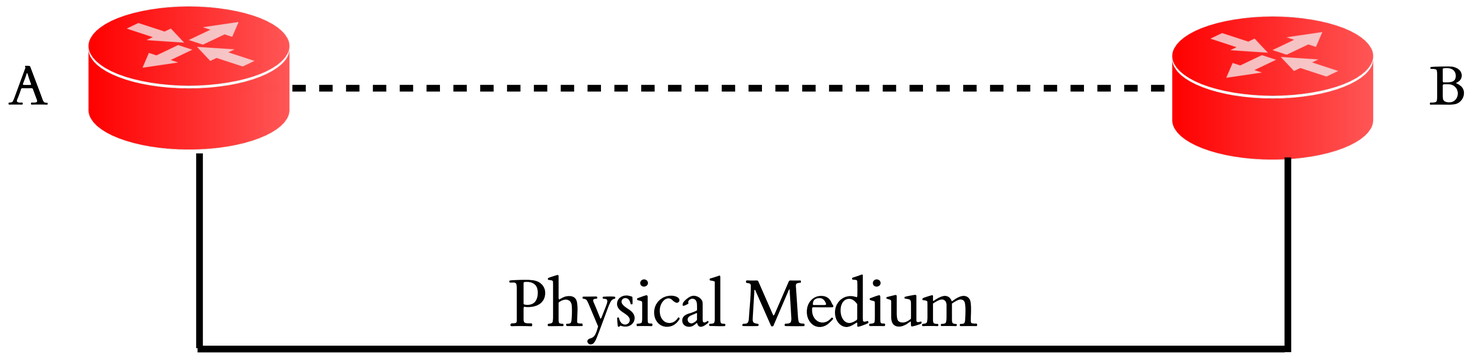

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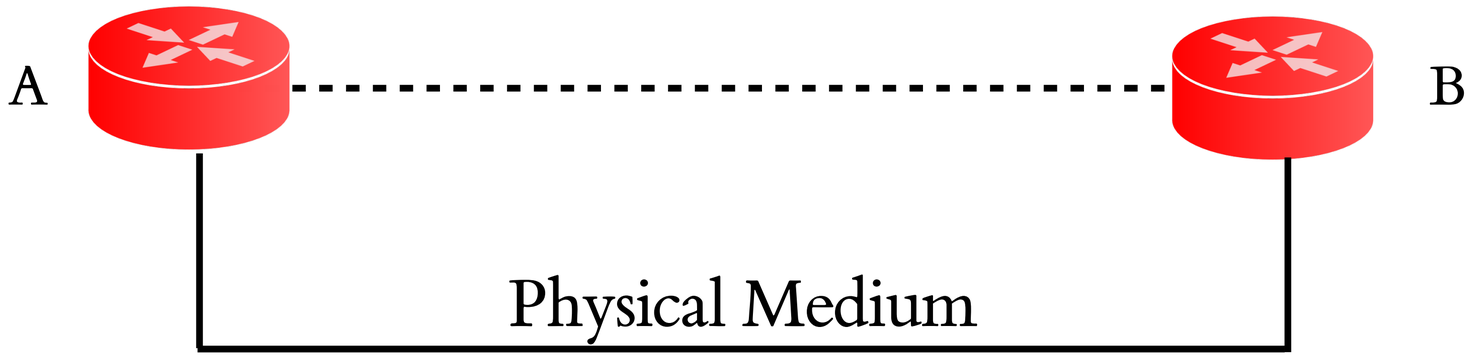

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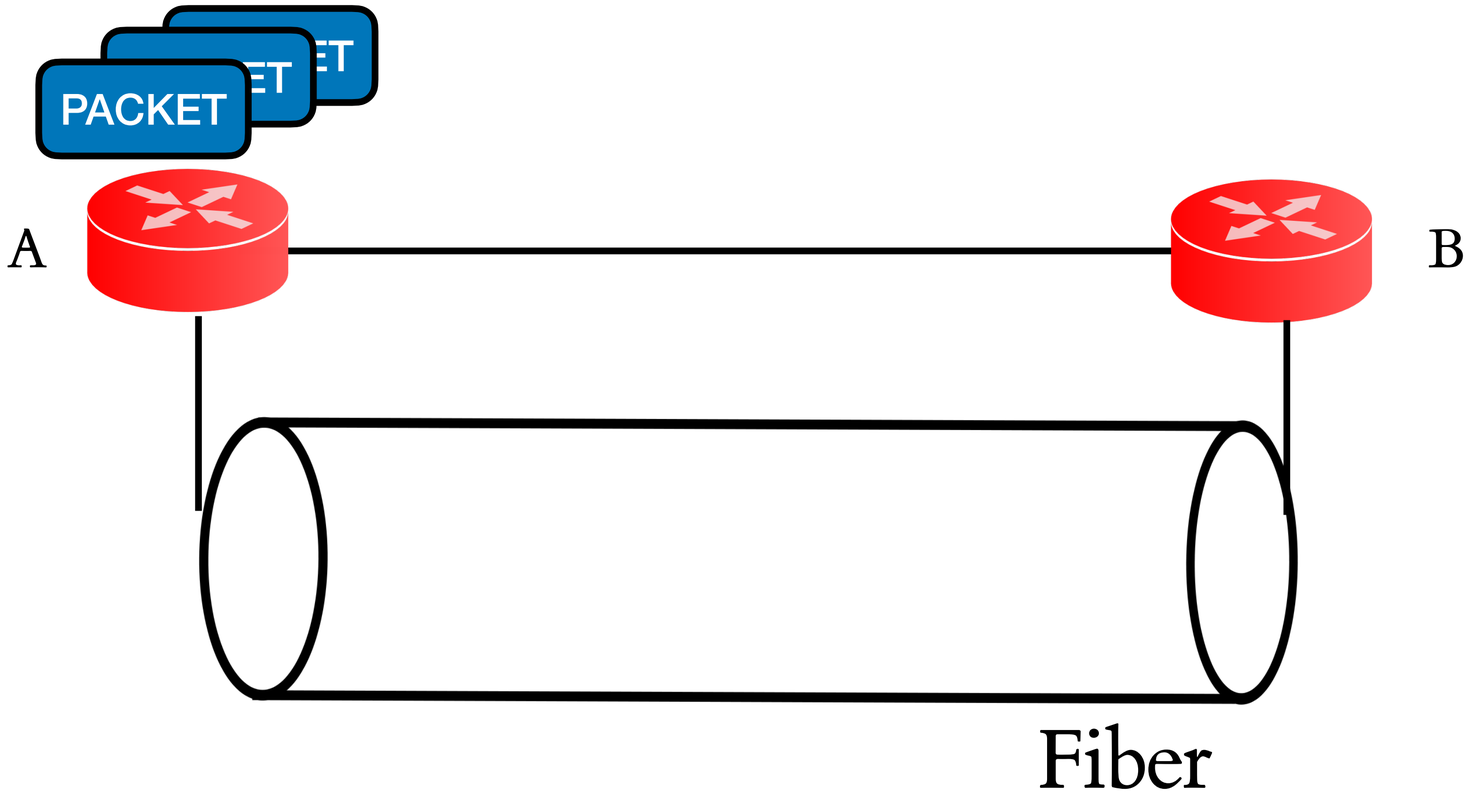
Long-haul network connectivity: optical fiber



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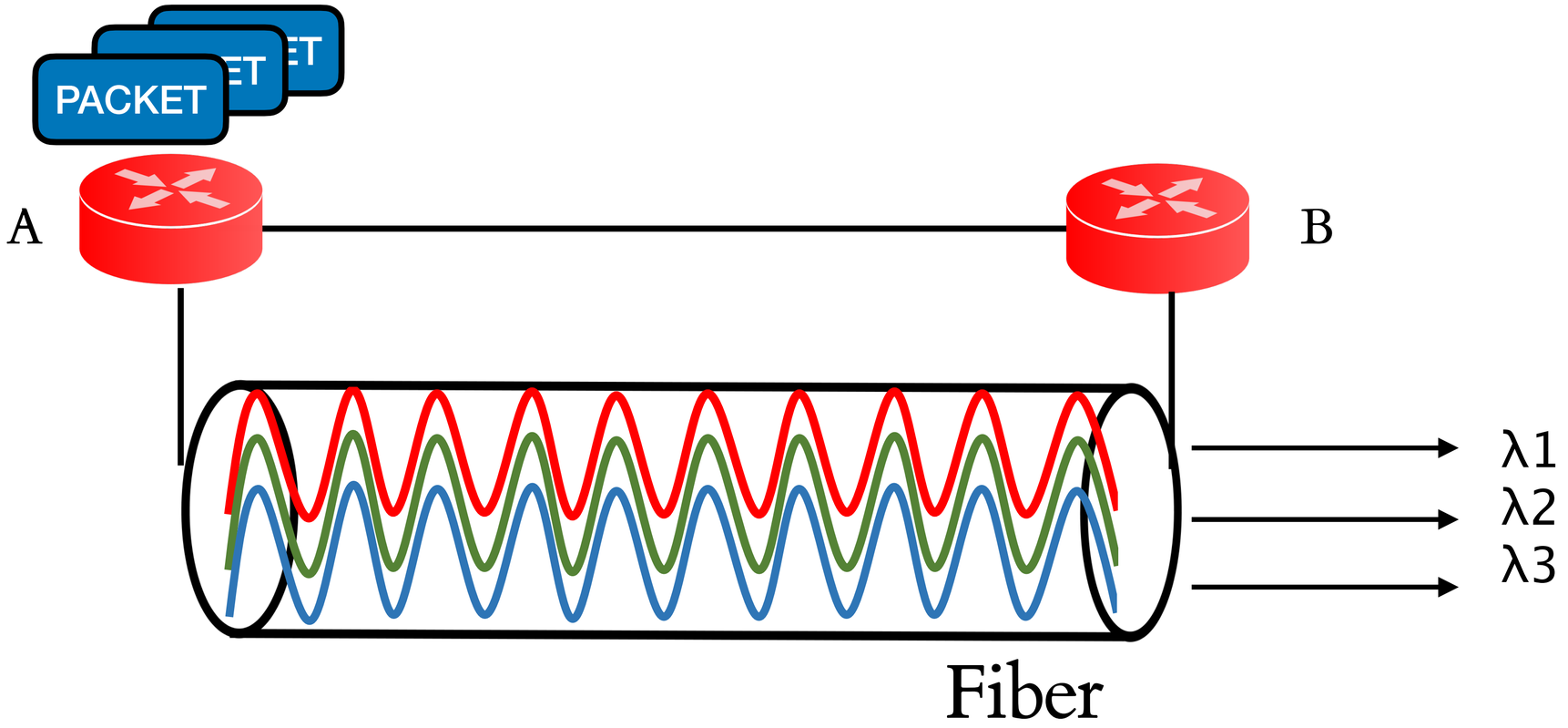
Long-haul network connectivity: optical fiber



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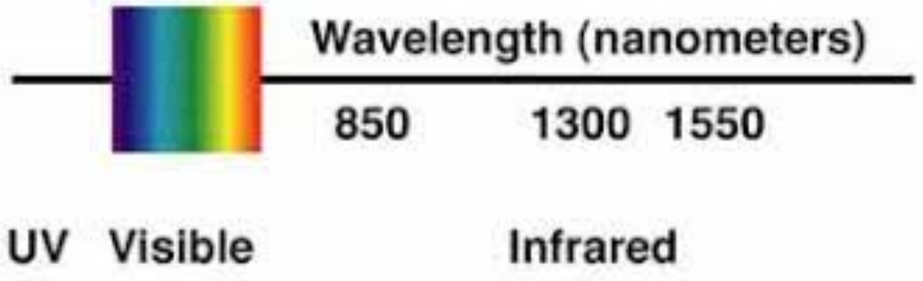

Electromagnetic spectrum

Long-haul network connectivity: optical fiber

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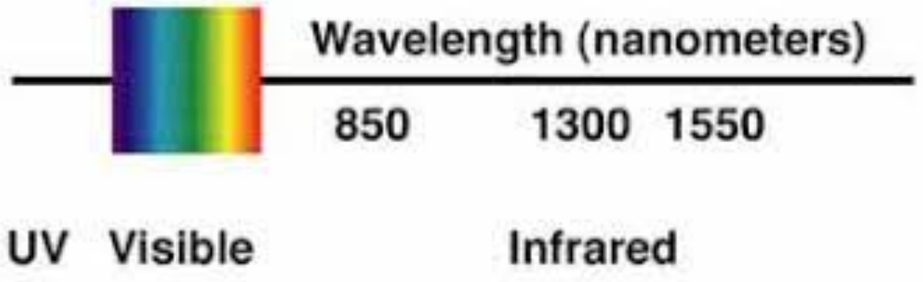

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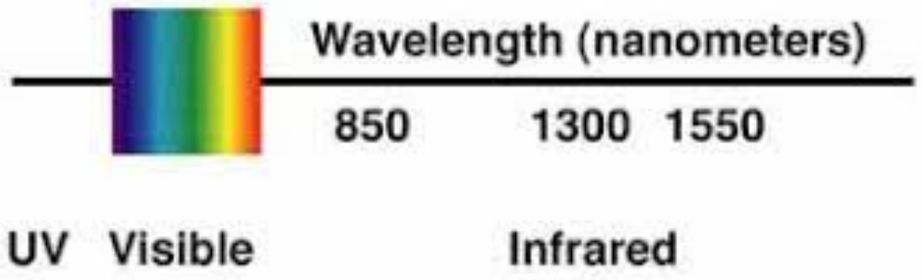

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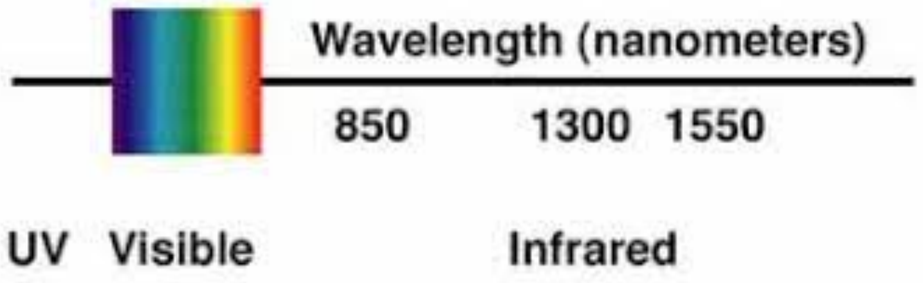

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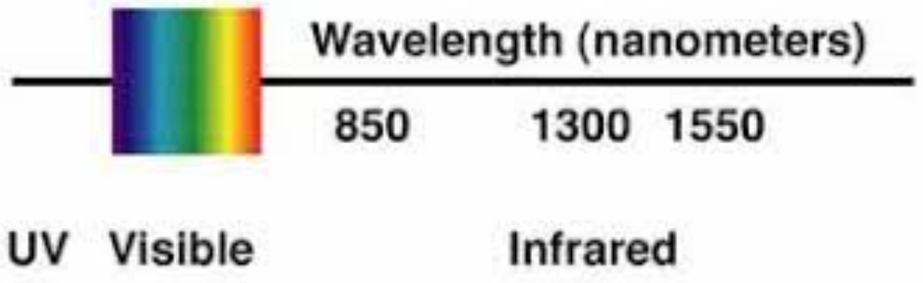

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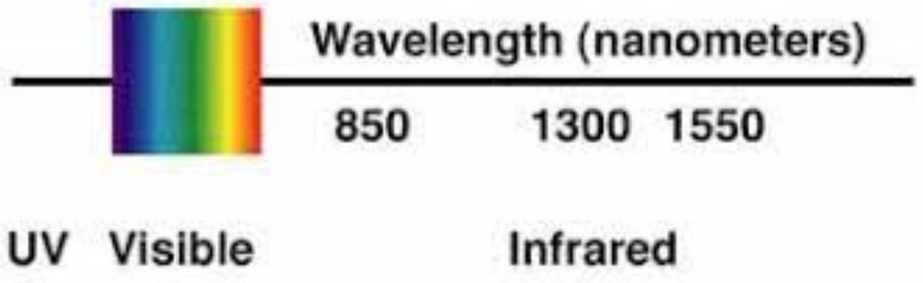

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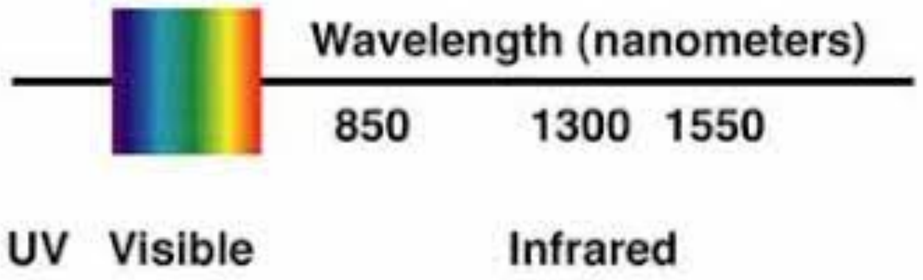
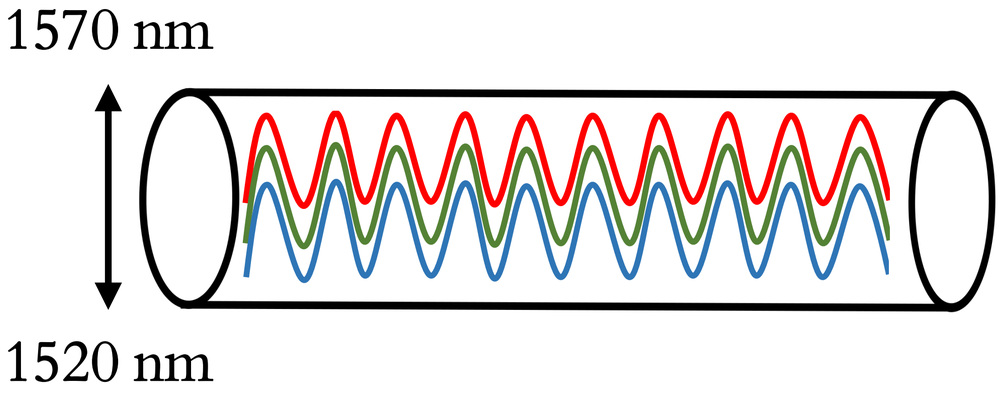
   - Absorption of light

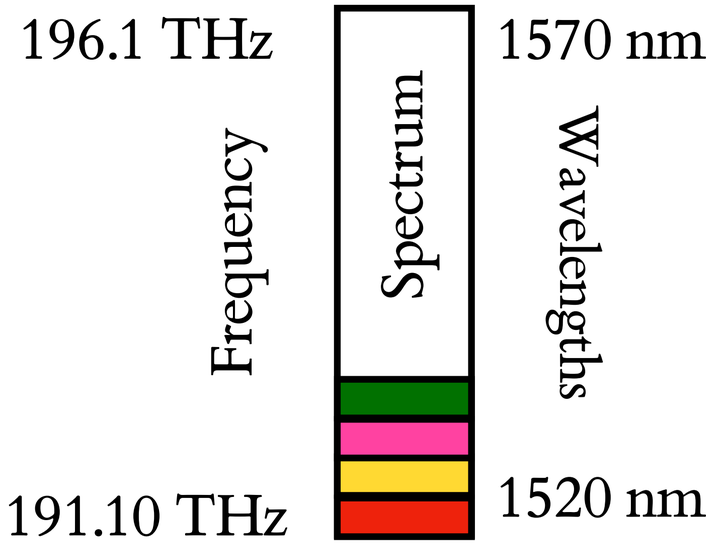


Electromagnetic spectrum

Long-haul network connectivity: optical fiber

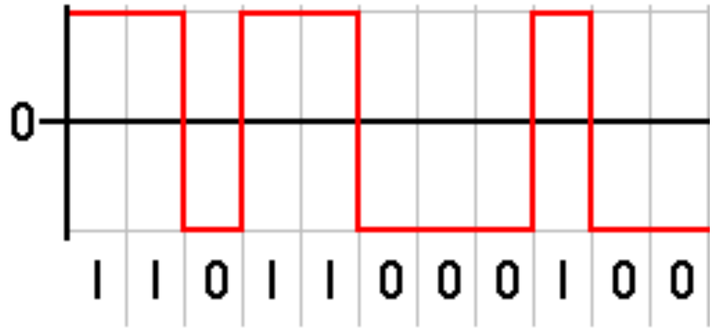
1. A wavelength (λ) carrying bits on fiber is a unit of signal
   - A portion of the optical spectrum
2. Frequency (f) and wavelength (λ) are used interchangeably: $\lambda = \frac{1}{f}$
3. Spacing between wavelengths to ensure signals don't overlap at the receiver
4. 50GHz space between wavelengths, total 4THz bandwidth means 80 wavelengths on fiber (4000/50)





Long-haul network connectivity: signal modulation

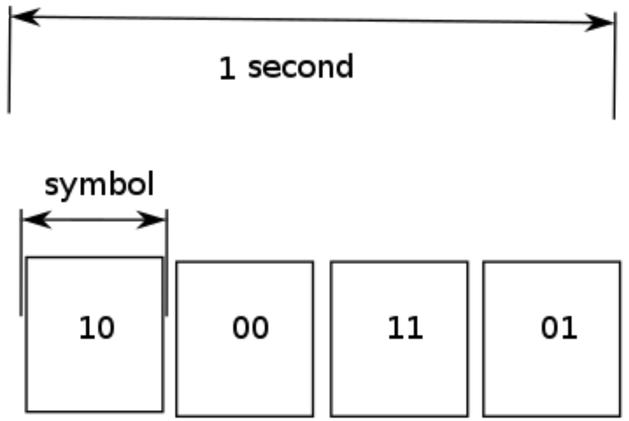
1. Transmitter modulates light signals (wavelengths)
    1. Encode bits on a wave or pulse
    2. By changing the *properties* of the signal
2. Receiver decodes the signal to retrieve bits
3. Digital (bits n Tx) —> analog (optical signal) —> Digital (bits on Rx)
4. Example modulation format: NRZ



Non-return zero (NRZ) modulation

Long-haul network connectivity: signal modulation

1. Modulation format decides:
    1. Changes to the signal from a set of alternatives (symbols)
    2. Each symbol communicates a fixed number of bits
    3. Number of levels in a symbol = M, number of bits per symbol, $N = log_2 M$
2. Symbol rate decides:
    1. number of symbols per second (baud rate)



Baud rate = 4, N = 2

Long-haul network connectivity: optical fiber

Hartley's Law:

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Where,

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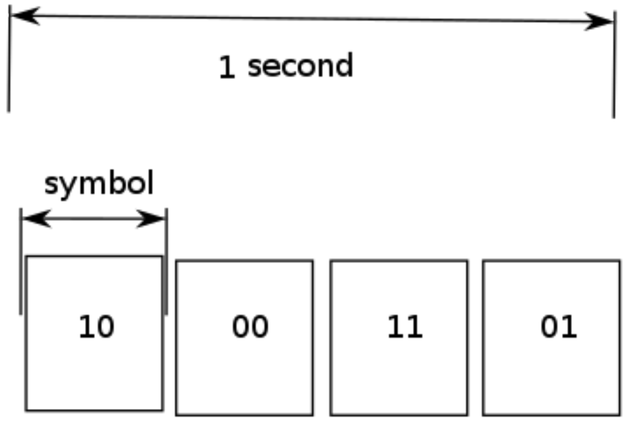

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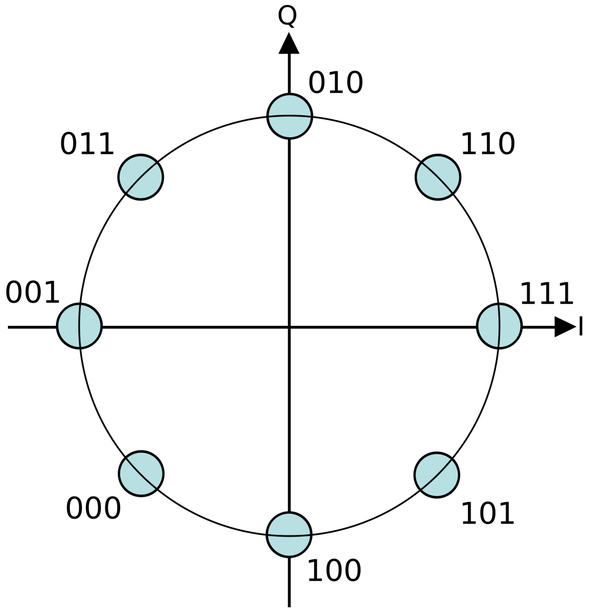
Long-haul network connectivity: signal modulation

1. Modulation packs bits on a signal
   - Some formats pack more bits than others
2. Types of modulations
   1. Change *amplitude* of the signal
   2. Change *phase* of the signal
3. For example: Phase shift keying (PSK) modulation changes the phase of the signal.



Constellation Diagram of 8-PSK modulation

Long-haul network connectivity: exercise

QAM: quadrature amplitude modulation uses a mix of different amplitude levels and phase shifts to create different symbols (see right).

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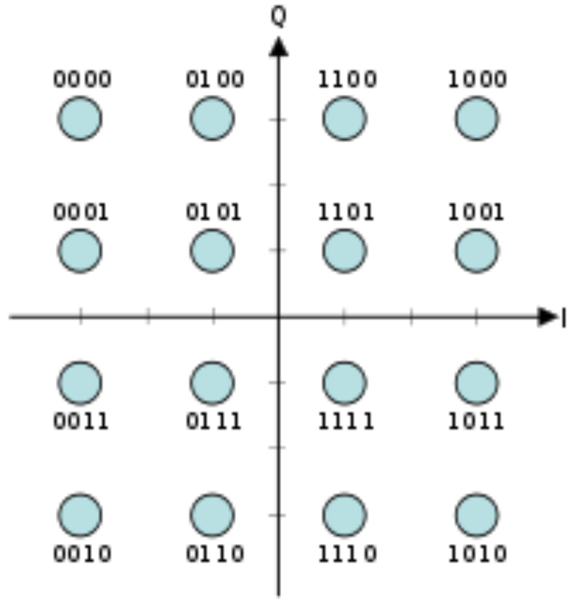

Constellation Diagram of 16-QAM

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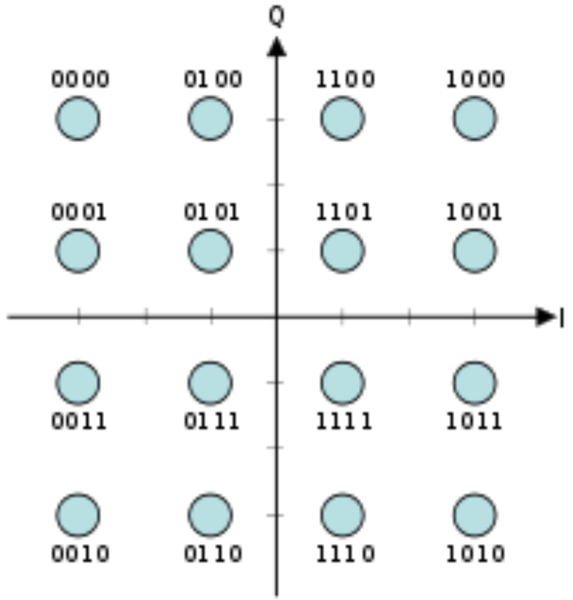

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Exercise: If the baud rate of the transmission is 50 Gbaud, what is the data rate of a wavelength modulated with 16-QAM modulation?

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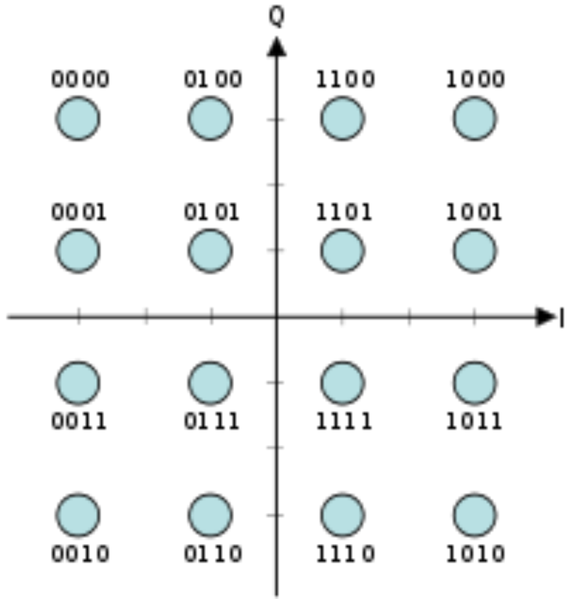

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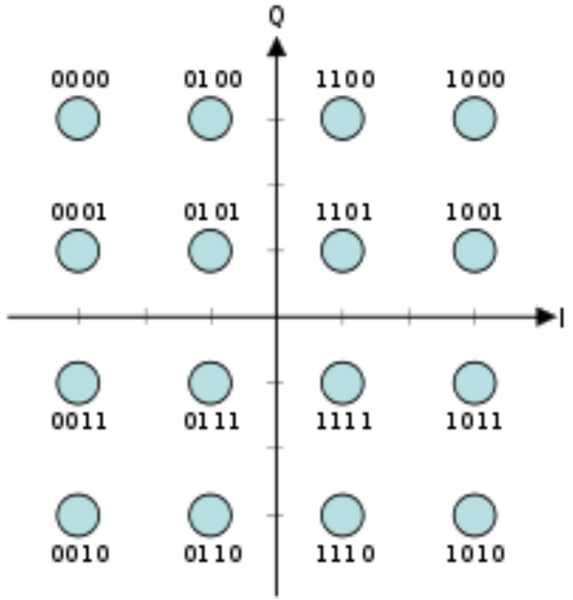

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Hint:16-QAM has 16 levels per symbol

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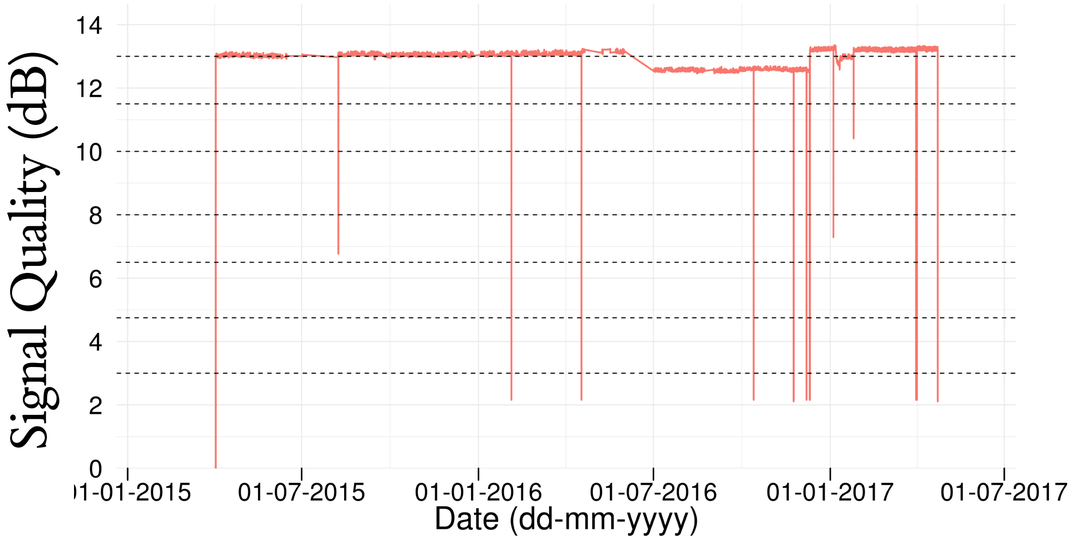
4. The signal quality determines channel capacity
5. Example: signal quality of a wavelength on fiber over time undergoes changes



Signal quality of a wavelength on fiber in North America

Long-haul network connectivity: Shannon capacity

Shannon-Hartley Law states the max. rate at which information can be transmitted over a noisy channel

$$R = B \cdot log_2(1 + SNR)$$

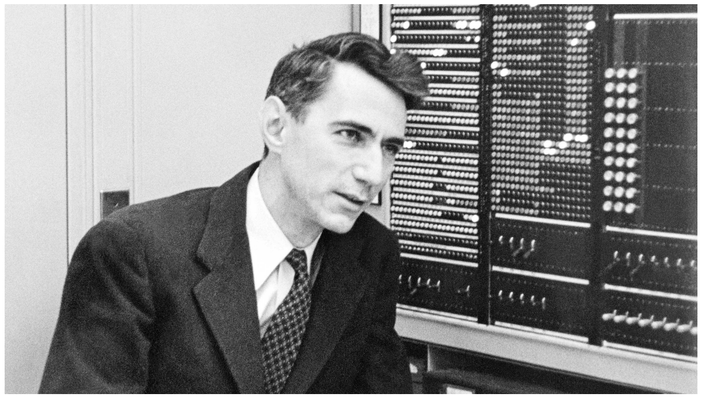
Where,

R = data rate, bit rate in bits/second

B = bandwidth in Hz of the channel

SNR = signal to noise ratio (measures signal quality)

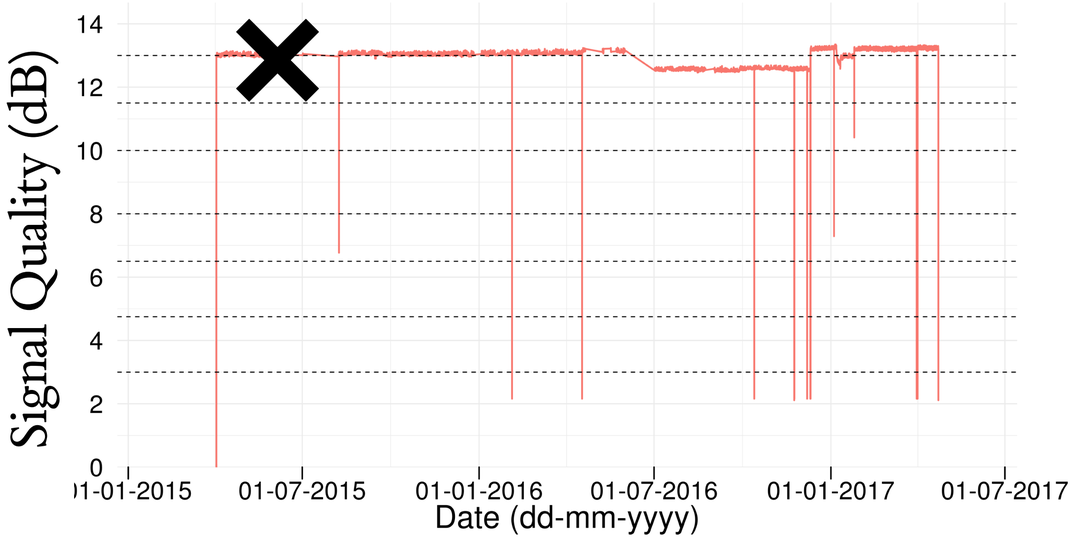
$$R \approx 0.332 \cdot B \cdot SNR$$



Claude Shannon

Long-haul network connectivity: Shannon capacity

Exercise: What is the maximum data rate that could be supported by this wavelength at the time shown by the cross if the bandwidth of the wavelength is 50GHz?



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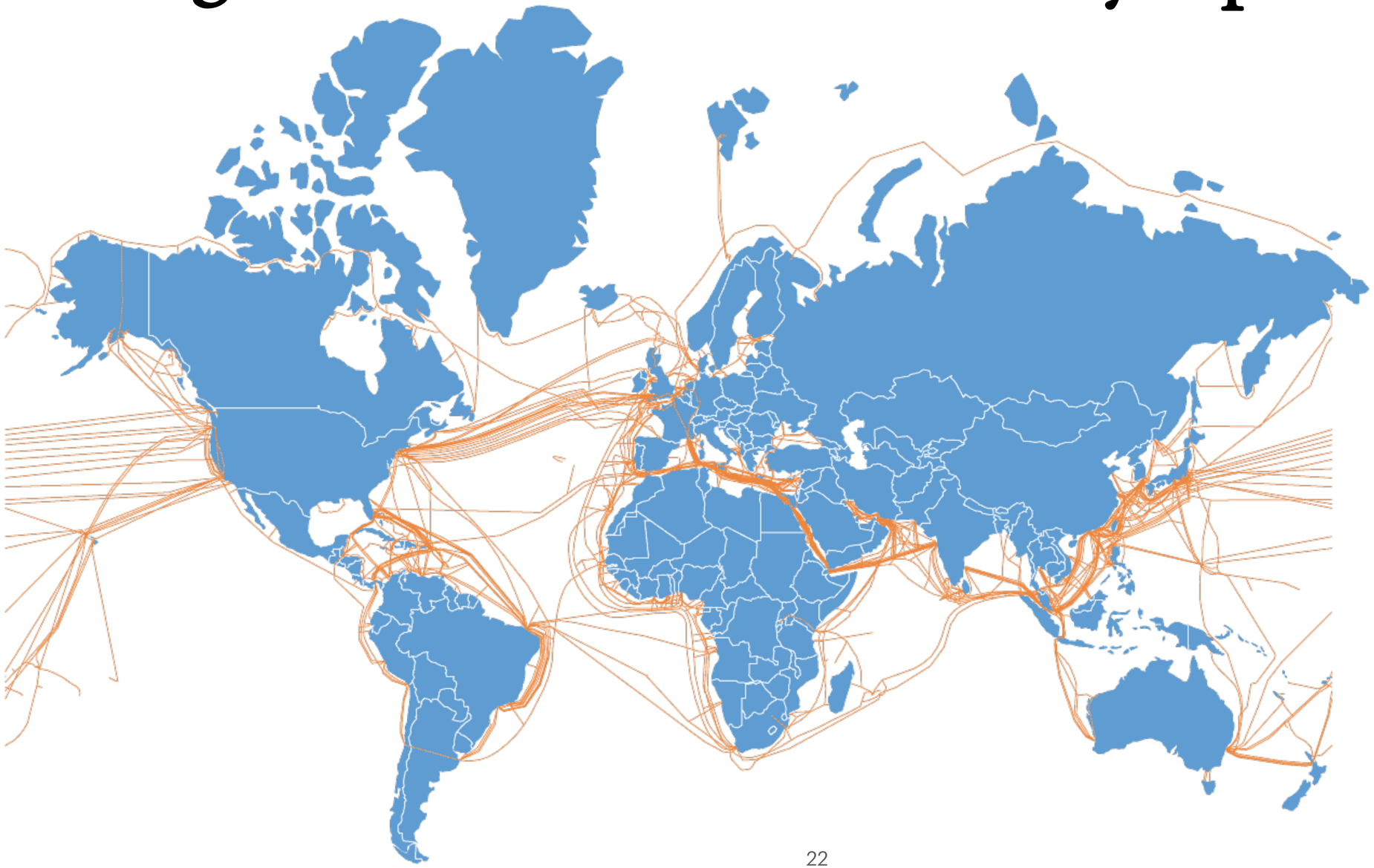
Long-haul network connectivity: optical fiber



Under-sea fiber

Terrestrial fiber

WANs need high infrastructure investment

1. High capital expense (billions of $)
    1. Hardware costs for switches
    2. O(100,000) miles fiber
2. High operational expenses (millions of $ annually)
3. Crucial to operate efficient WANs