NISQ

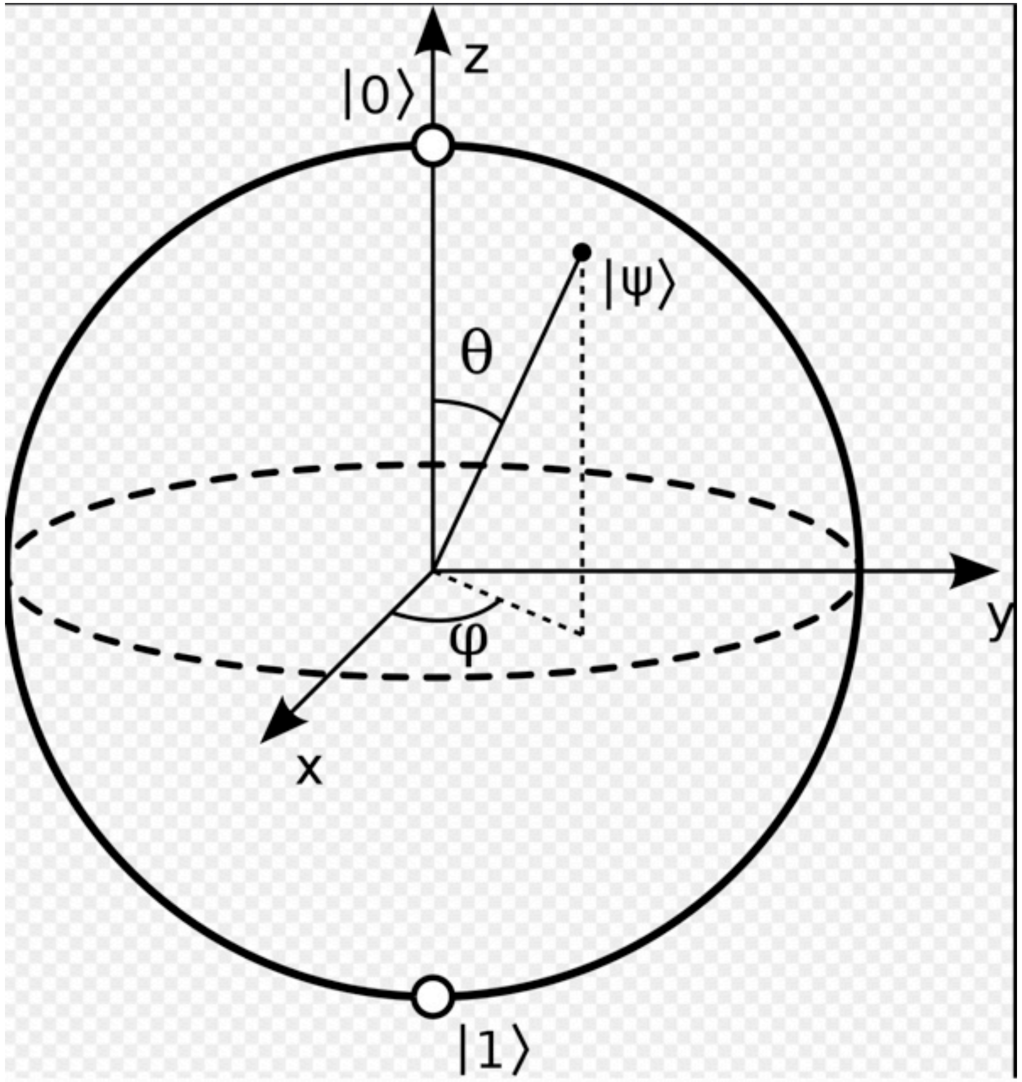
Near term Impact on Silicon of Quantum Research
in the next 3 to 5 years
And what it means to Networks as we know them

Robert Broberg
Darmstadt Crossing Conference September 08, 2019

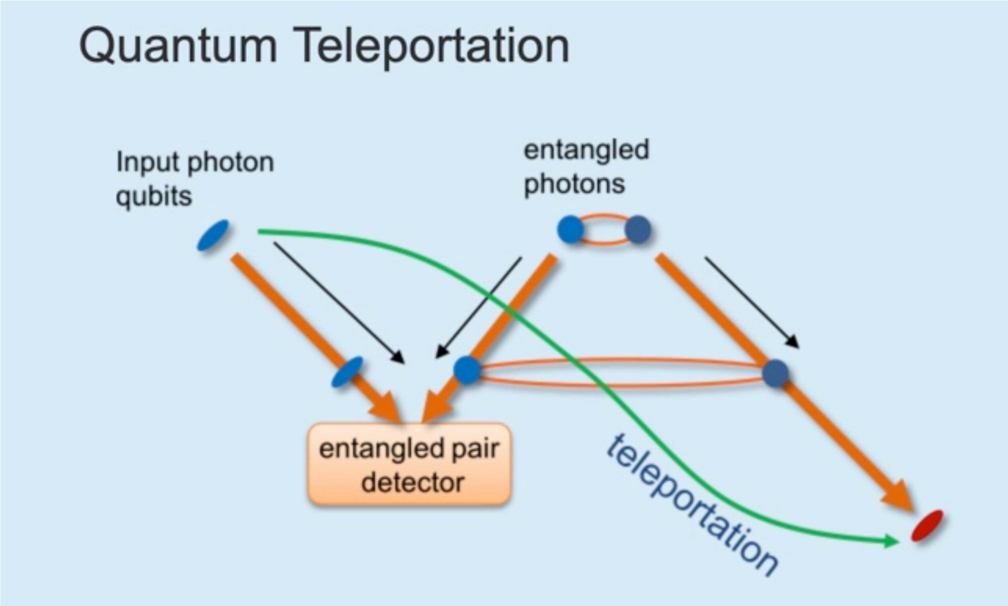
Agenda

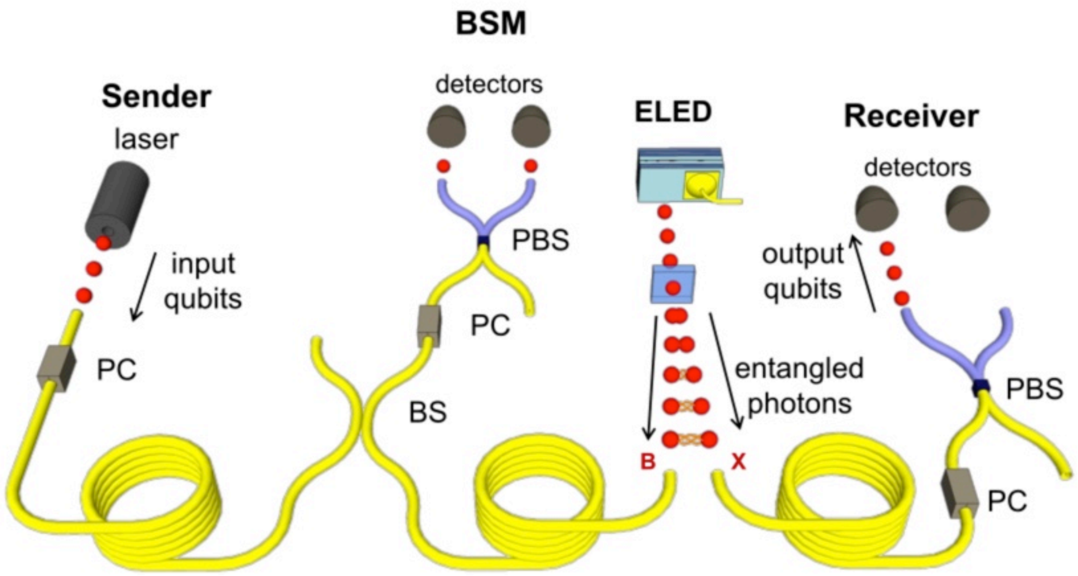
- Quantum Networking
- Security
- Classical Encoding discrete signals->continuous encodings
- Quantum Devices
- Quantum encoding
- Quantum Landscape

QuBit-Quantum Bit as a photon



Quantum Network Repeaters





Quantum Network Advancements

Current Network Problems:

1. Security Bolted on

- No Privacy
- Censorship or information steering
- Anonymity of Users without accountability
- Vulnerable to Hackers and Criminals

2. Fiber capacity limit: ~26 to ~50 Terabits/s

- Practical limits due to Shannon's Law

Quantum Solutions:

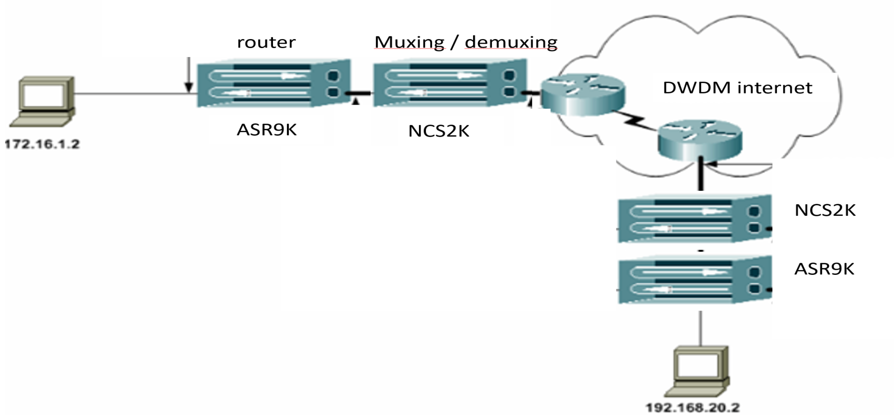
1. Security Built in by underlying principles

- Inherently Private transactions
- Censorship free—inherently secure communications
- Anonymity of Users with accountable transactions
- Hacker and Cyber Criminal tools do not work

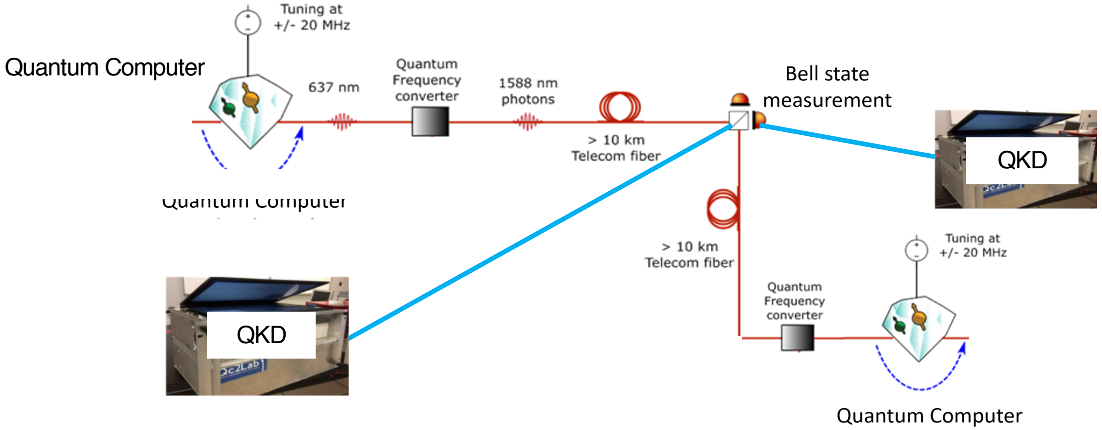
2. Research Improved fiber capacity (multiple orders of magnitude)

- Use individual/grouped photons for bits (new encodings)

Current Classical State of the Art Cisco Equipment:



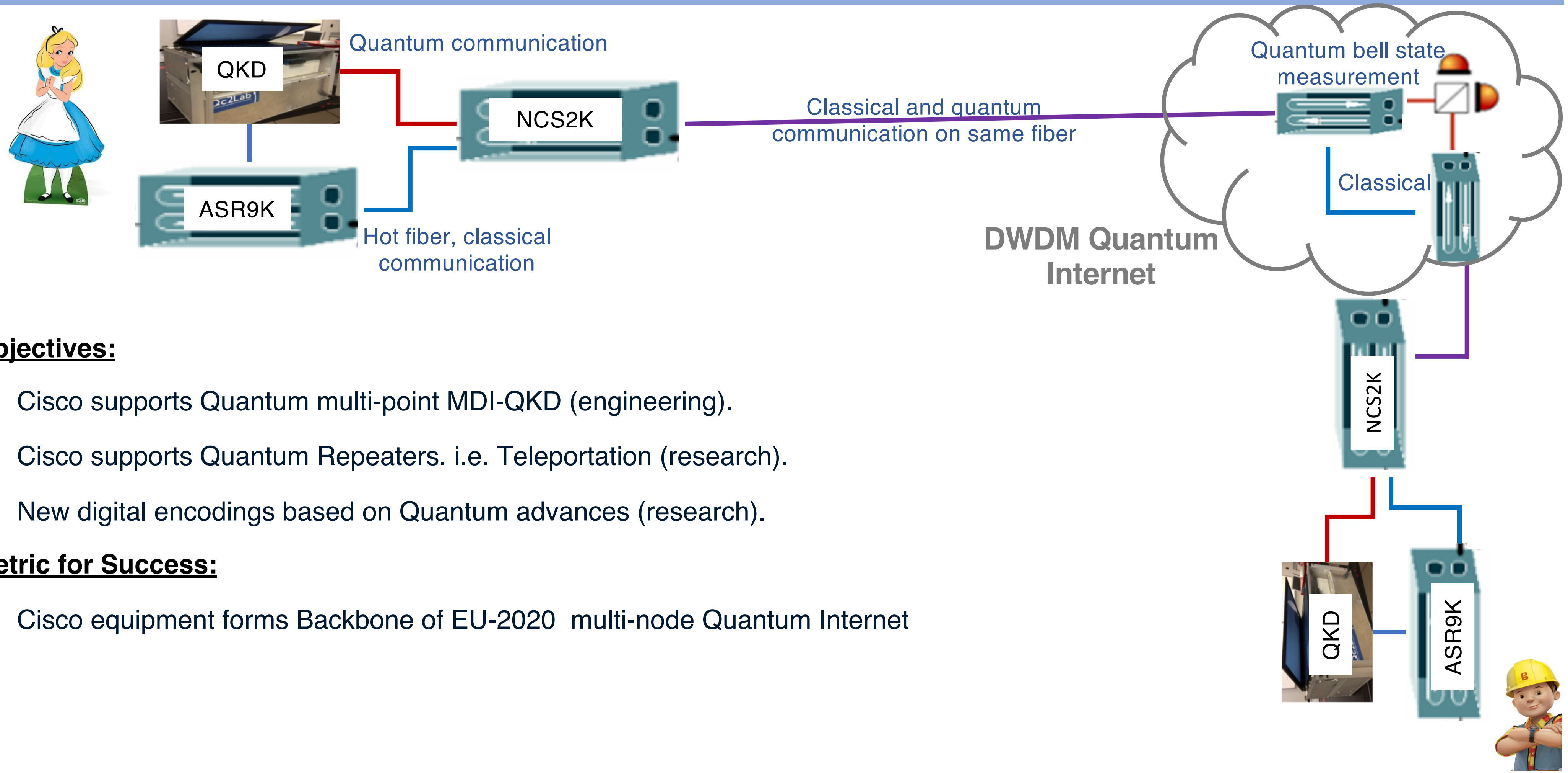
Quantum Networks & Current State of the Art at QuTech:



QuTech/ Quantum Internet Alliance 2021

The quantum network in The Netherlands

Cisco - QuTech Hybrid Quantum Internet Demonstration:



Objectives:

1. Cisco supports Quantum multi-point MDI-QKD (engineering).
2. Cisco supports Quantum Repeaters. i.e. Teleportation (research).
3. New digital encodings based on Quantum advances (research).

Metric for Success:

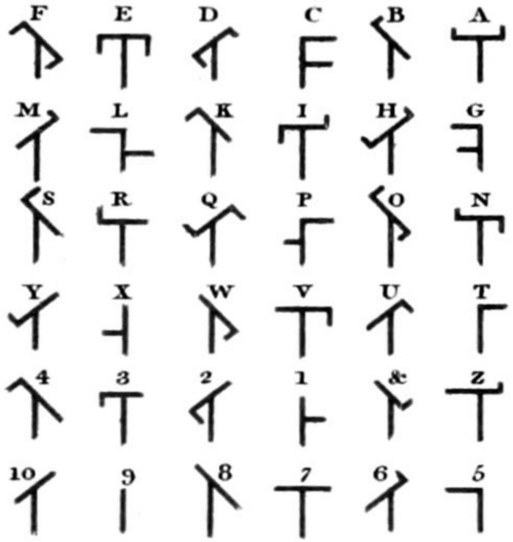
1. Cisco equipment forms Backbone of EU-2020 multi-node Quantum Internet

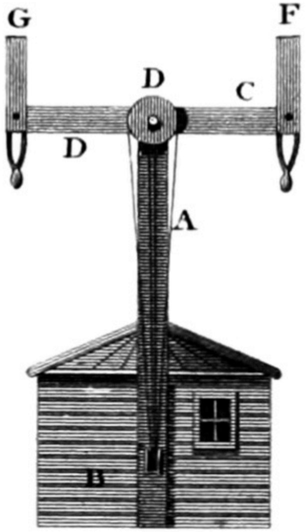
IETF - Internet Research Task Force

- Abstract:
  The vision of a quantum internet is to fundamentally enhance Internet technology by enabling quantum communication between any two points on Earth. To achieve this goal, a quantum network stack should be built from the ground up as the physical nature of the communication is fundamentally different. The first realisations of quantum networks are imminent, but there is no practical proposal for how to organise, utilise, and manage such networks. In this memo, we attempt lay down the framework and introduce some basic architectural principles for a quantum internet. This is intended for general guidance and general interest, but also to provide a foundation for discussion between physicists and network specialists.

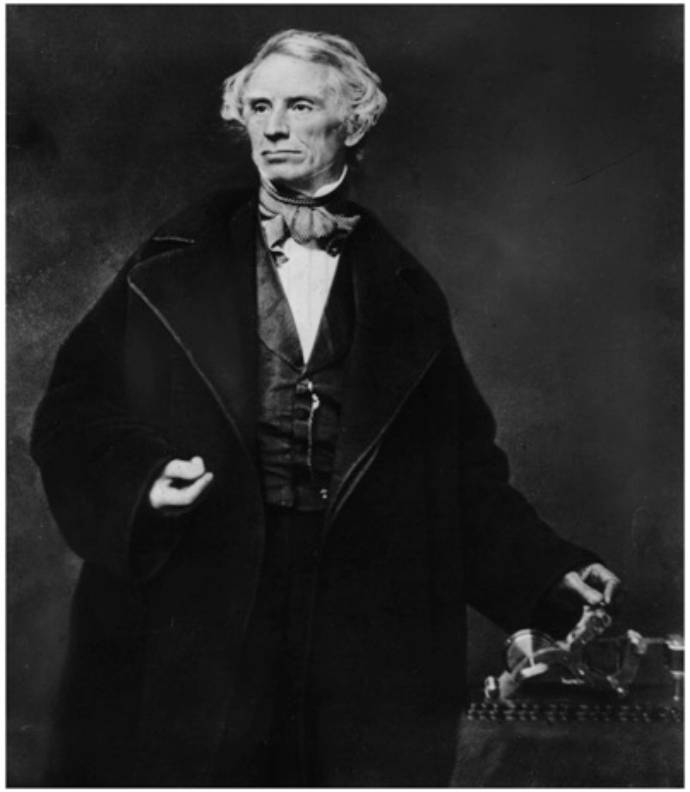
https://datatracker.ietf.org/doc/draft-irtf-qirg-principles/

Post Smoke Signal……





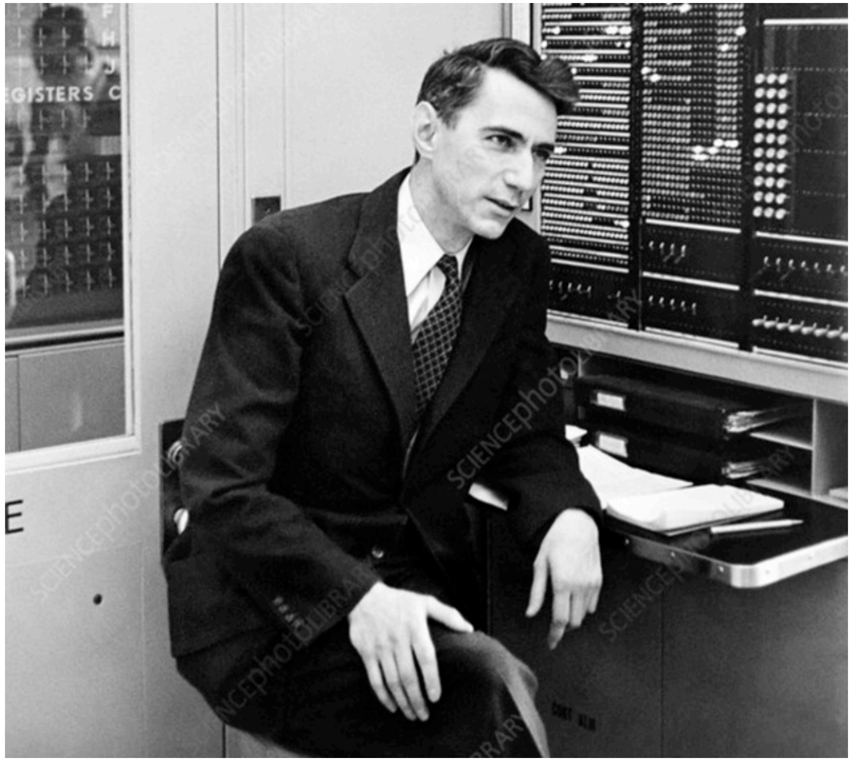
Post Semaphore……



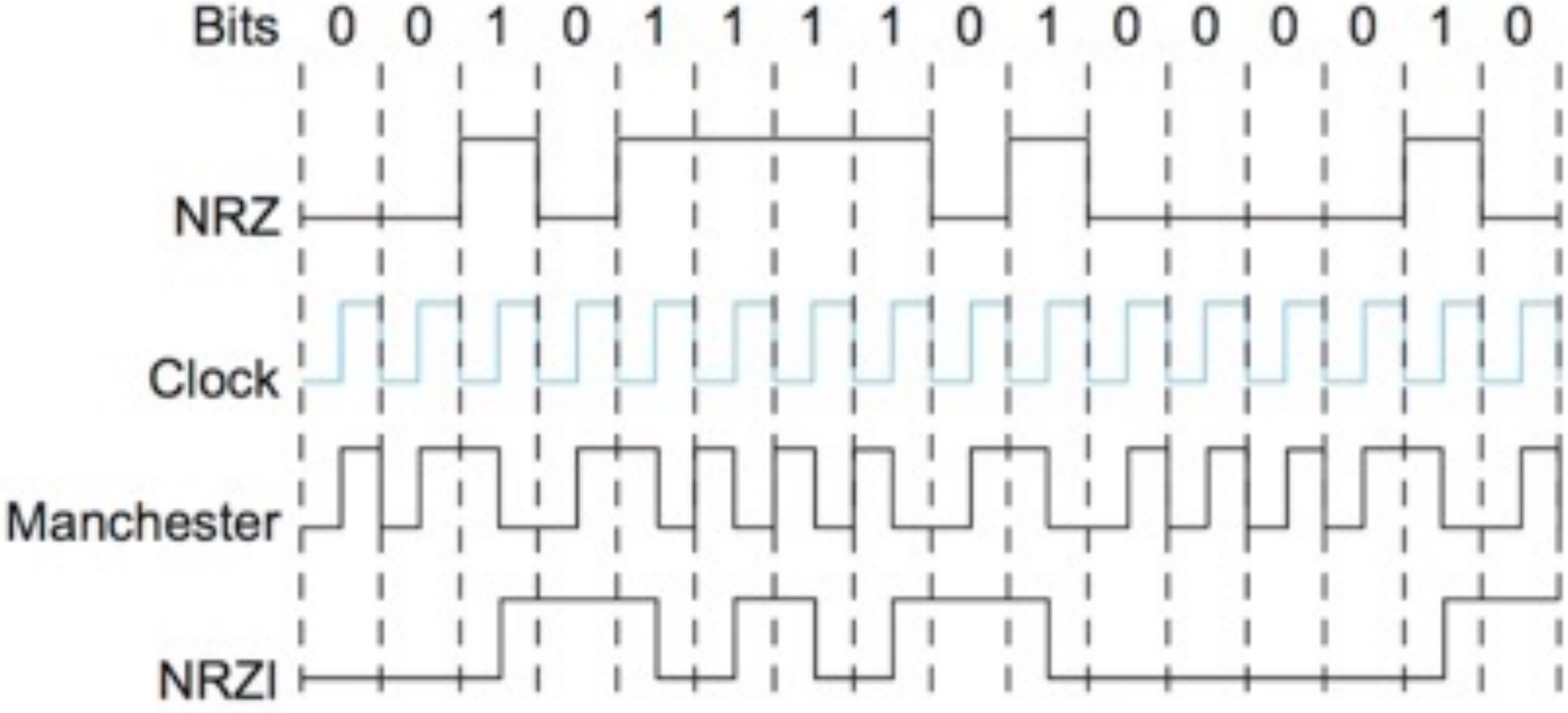
Early information transfer

- Morse Code
  - Different length symbols
- Transition from single symbols to modulated signals
- Baudot Teletype
  - 32 symbols
    - 5 bits
    - 26 alphabet characters
    - 0-9

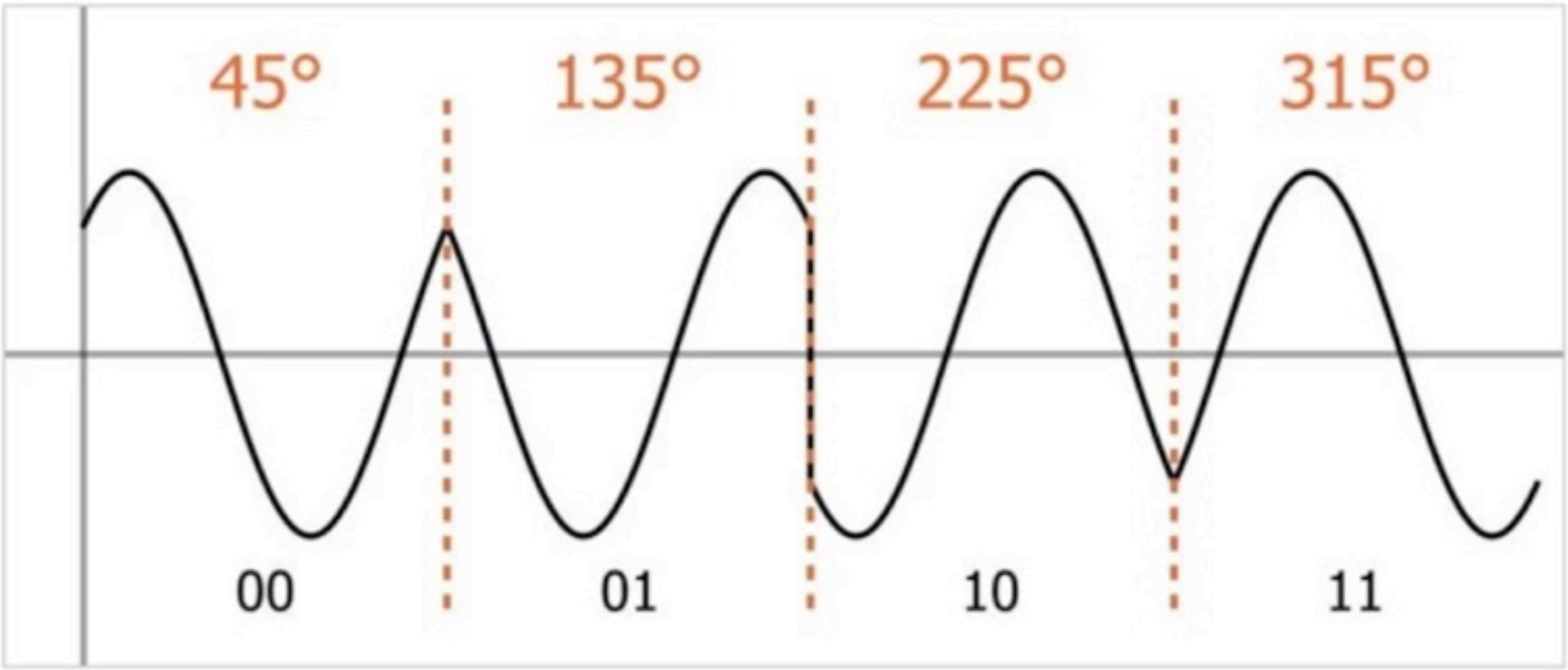
Denser codes



Transmitter and Receiver Synchronization

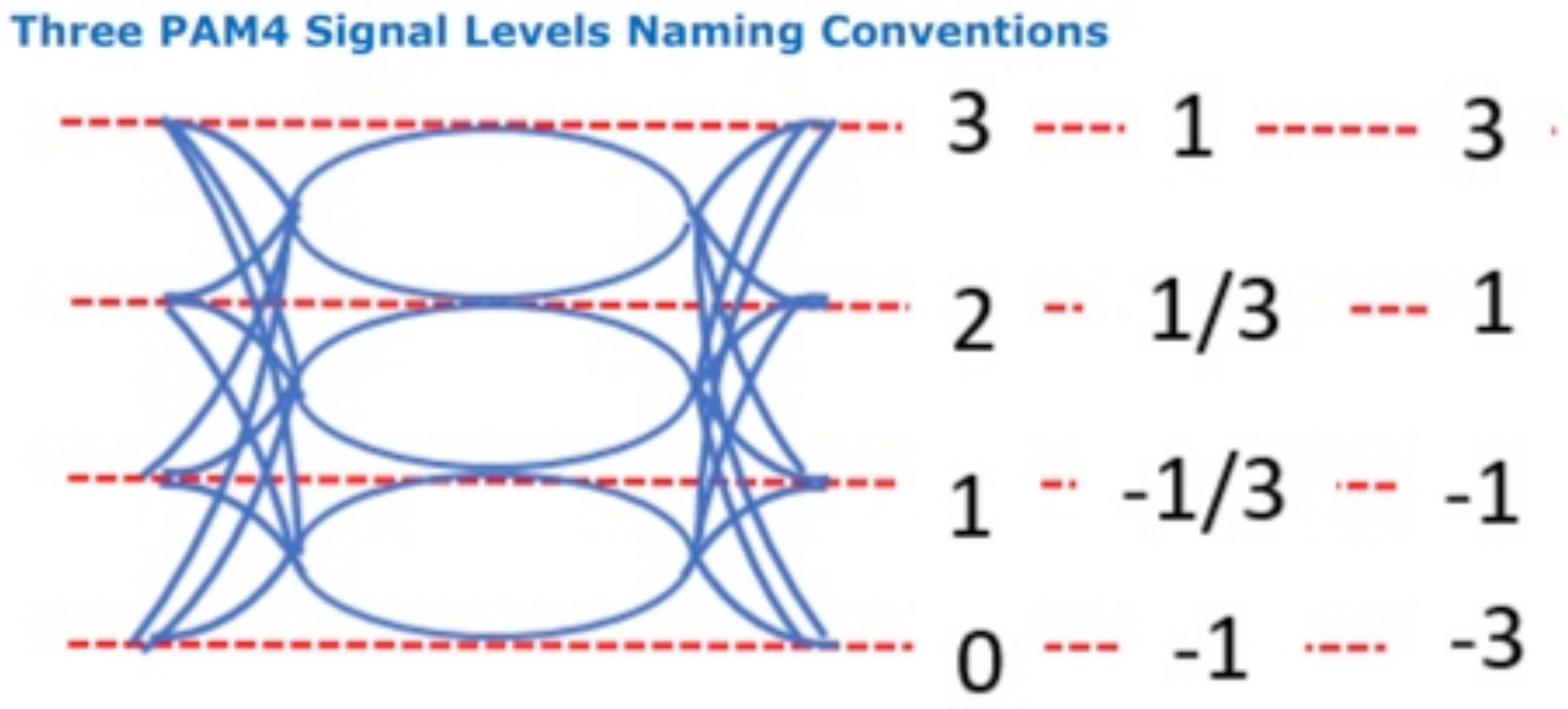


QPSK - Quadrature Phase Shift Keying



https://www.allaboutcircuits.com/technical-articles/quadrature-phase-shift-keying-qpsk-modulation/

Pulse-Amplitude Modulation 4-Level (PAM4)

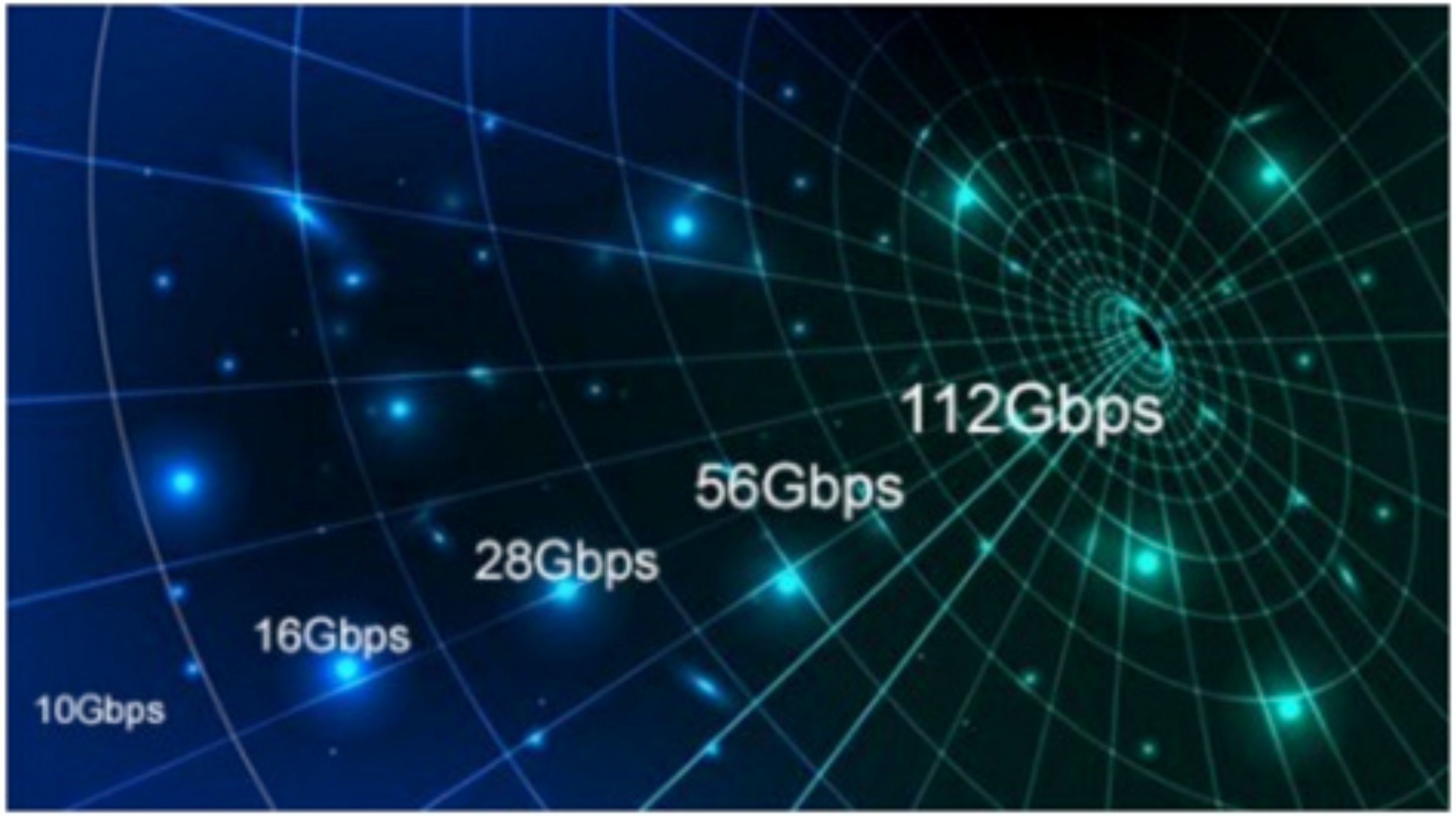


https://www.intel.com/content/dam/www/programmable/us/en/pdfs/literature/an/an835.pdf

Charge Motion, current…….a river

Courtesy Bahram Nabet, Drexel University

Single Channel Electrical SerDes

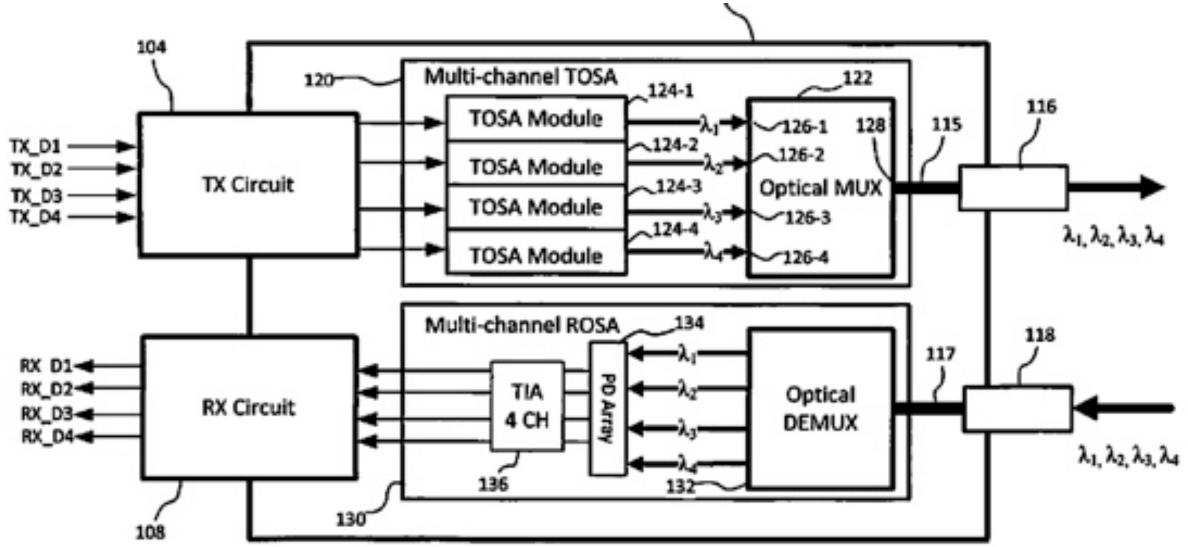


https://www.design-reuse.com/articles/40028/high-speed-serdes.html

Transceiver Diagram

1 watt < for laser

Figure 3. Cisco CFP-100G-ER4



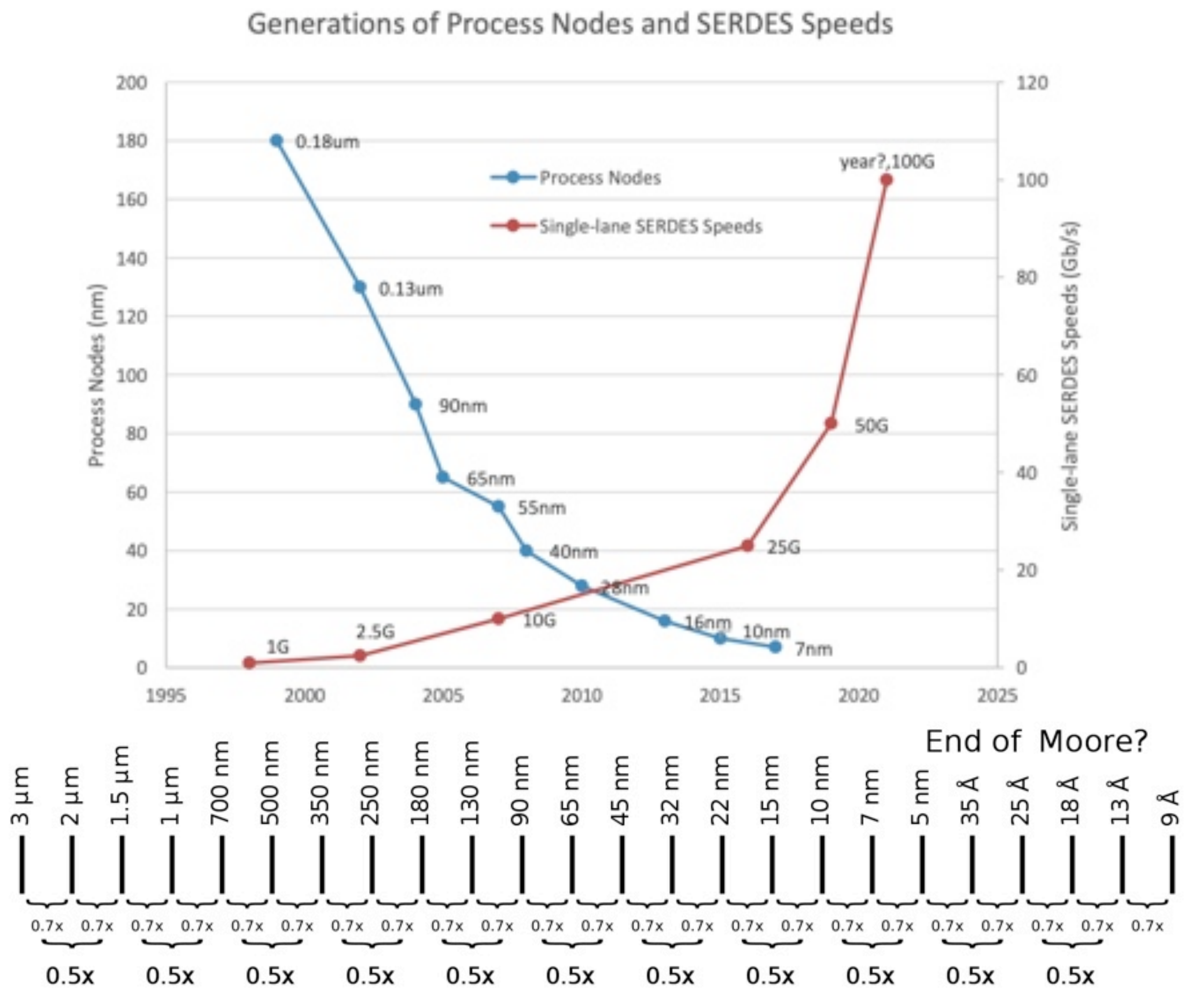
Cisco CFP-100G-SR10 module is 12W < 10 m

Cisco CFP-100G-ER10 module is 24W < 40 km

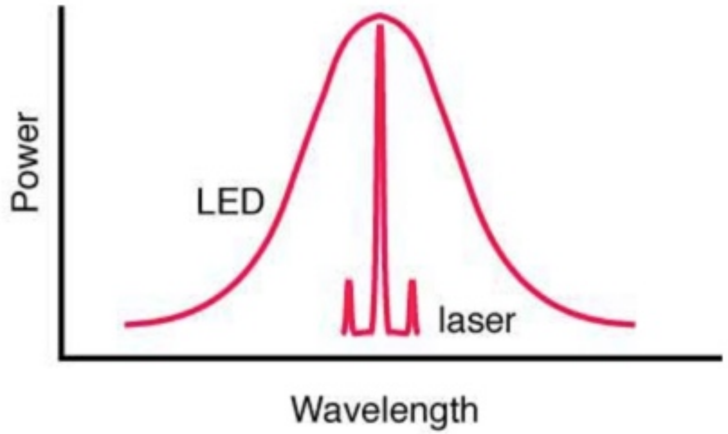
https://patents.google.com/patent/EP3255471A1/en

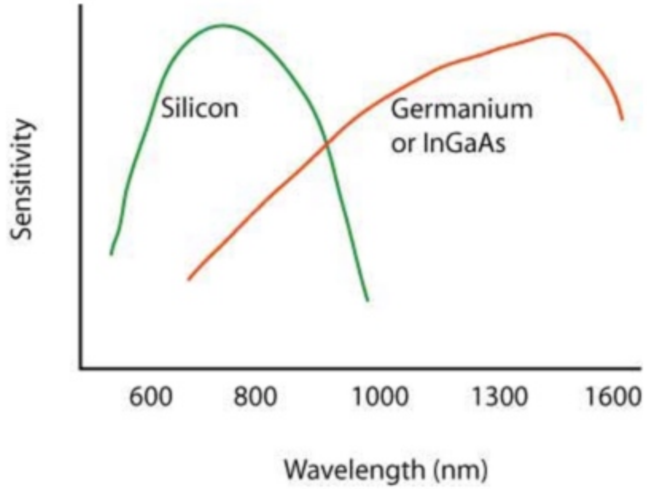
https://www.cisco.com/c/en/us/products/collateral/interfaces-modules/transceiver-modules/data_sheet_c78-633027.html

Predicted limits of electrical interconnects



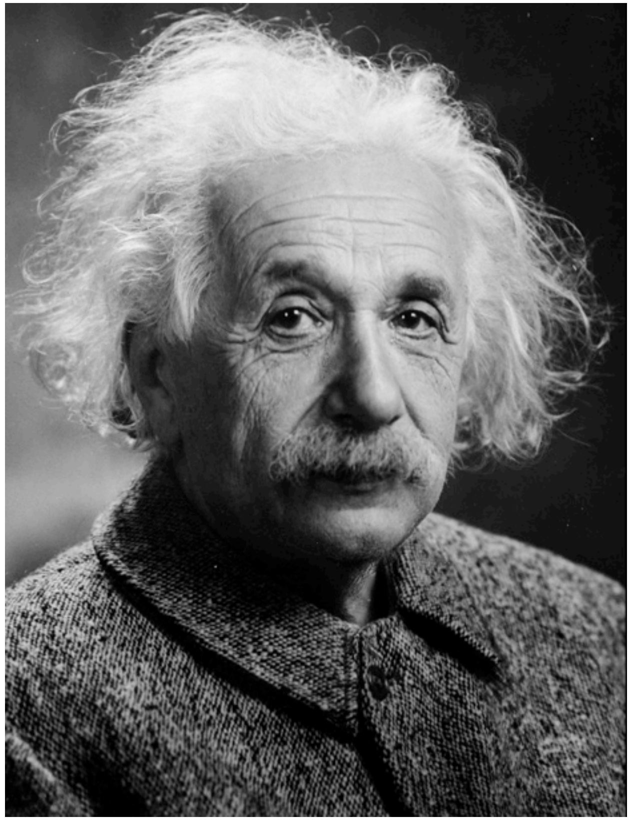
Constant Light Source, Biased Detectors





Photodectors absorb photons emitting electrons in strong electric field amplify

Can we go back to symbols using photons?

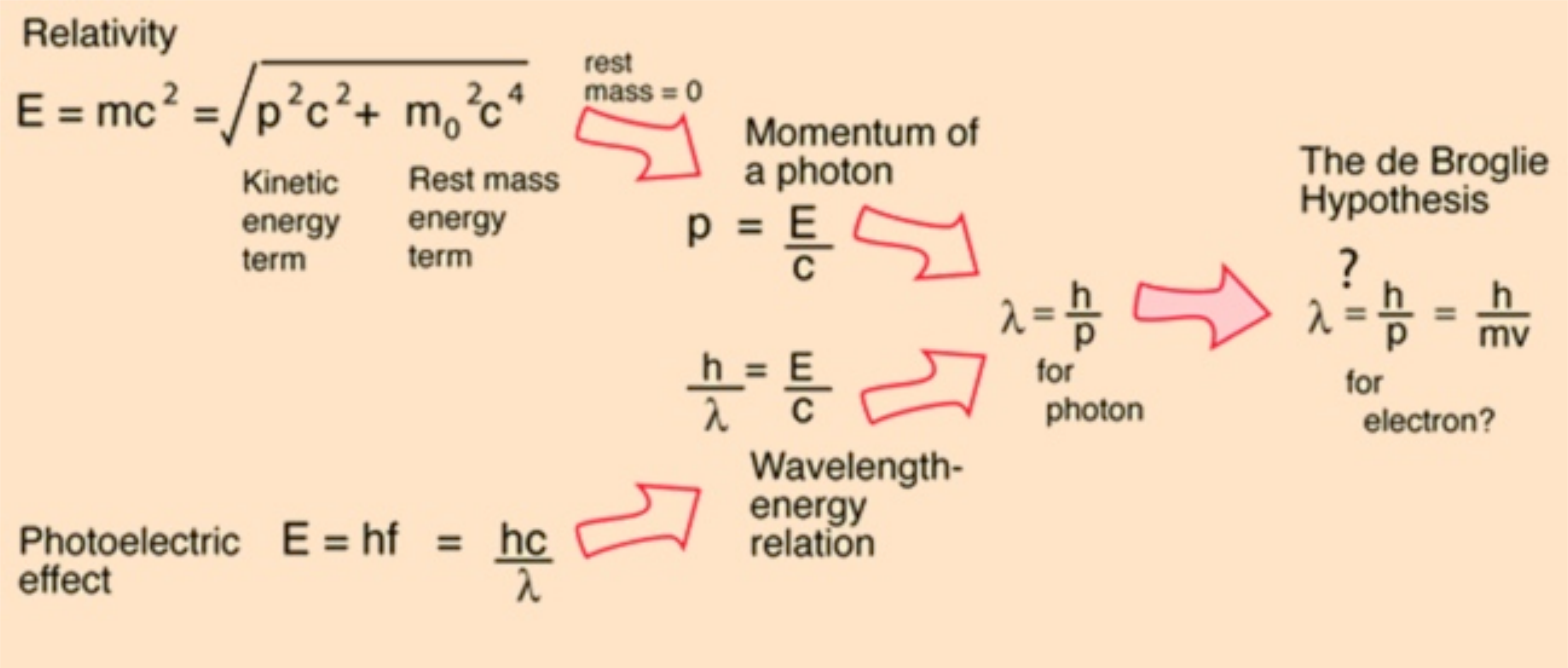


Wave and Particle duality

- In 1900, Max Planck introduced the notion that radiation is quantized to derive the black body radiation spectrum.
- In 1905, Albert Einstein used Planck's idea to explain photoelectric effect, which led to wide acceptance of the quantum nature of radiation.
- In 1913, Niels Bohr used quantization of radiation along with the Bohr hypothesis (that the angular momentum of electrons is quantized) to correctly predict the line spectrum of hydrogen atom and explain .
- In 1923, Lois de Broglie took this idea further and proposed that matter has wave nature as radiation has particle nature.

https://www.quora.com/What-is-de-Broglie-hypothesis

Photo Electric Effect



Optical transmission

DWDM Band Wavelength Range

Band Name	Wavelengths	Description
O-band	1260 – 1360 nm	Original band, PON upstream
E-band	1360 – 1460 nm	Water peak band
S-band	1460 – 1530 nm	PON downstream
C-band	1530 – 1565 nm	Lowest attenuation, original DWDM band, compatible with fiber amplifiers, CATV
L-band	1565 – 1625 nm	Low attenuation, expanded DWDM band
U-band	1625 – 1675 nm	Ultra-long wavelength

Let‘s not modulate light but use particles!

- To determine number of photons per second used for current modulation scheme at a given wavelength we use the Planck - Einstein relation.
- $E = h \cdot \nu$

- E - the energy of the photon
- h - Planck's constant, equal to $6.626 \cdot 10^{-34}$ J s(joules-seconds)
- ν - the frequency of the photon

100g using PAM4 encoding....

Current PM=QPSK delivers 1*10**11bits/second

laser at 1551 nanometers

laser output power -5dBm for short distance (loss .2dB/km)

3.16*10**-4J/s * 1photon/1.31642*10**-19J =

2.4*10**15Photons/second

Electronic Medium, Collective Excitations

“We found that, in general, the electron gas displays **both collective and individual** particle aspects. The primary manifestations of the collective behavior are organized oscillation of the system as a whole, the so called "plasma" oscillation….
In a collective oscillation, each individual electron suffers a small periodic perturbation of its velocity and position due to the combined potential of all the other particles…
…. these density fluctuations could be split into two approximately independent components, associated with collective and individual particle aspects of -the electronic motion. The collective represents the "plasma" oscillation.”

D. Bohm, D. Pines, A collective description of electron interactions: III. Coulomb interactions in a degenerate electron gas, *Phys. Rev.* **92**, 609-625 (1953).

Courtesy Bahram Nabet, Drexel University

Photon to Plasmonic Wave

Courtesy Bahram Nabet, Drexel University

Plasmonics

with waves we can move electrons (actually information) from A to B,

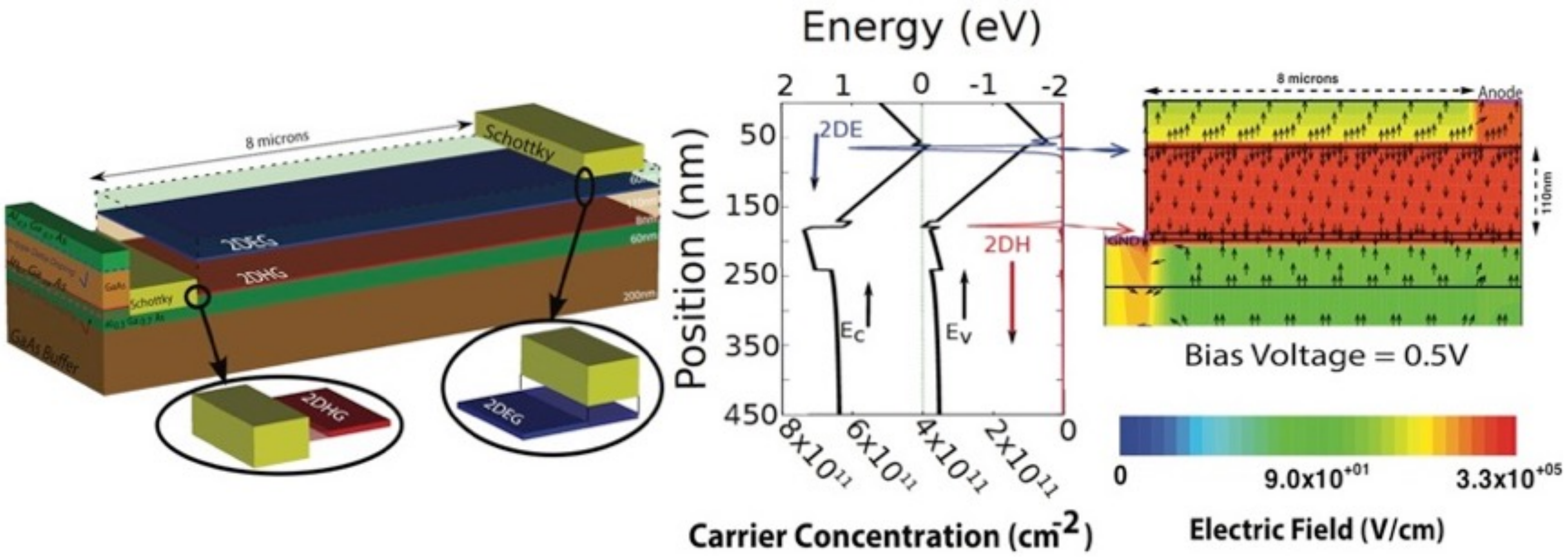
without

moving electrons from A to B

with photons we can perturb charge fields effecting oscillations

Courtesy Bahram Nabet, Drexel University

A thin film Opto-Plasmonic Device:



Nabet et al, ACS Photonics, 2014

Energy consumption

- $C_{dark\ @\ 1V}$ = 80fF & Capacitance Area = 30x50μm^2
- Therefore:

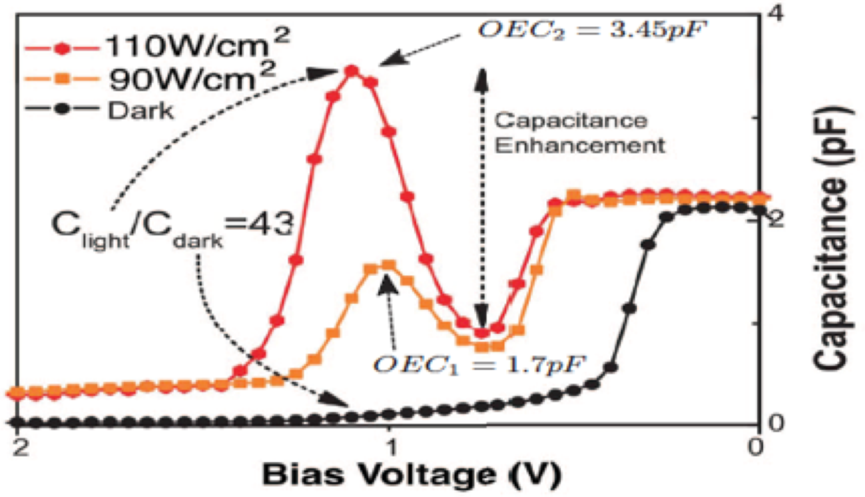
  $C_{@1V\ bias}$= 530fF/cm²

- In 22 nanometer node, gate capacitance in an integrated circuit:

Gate Capacitor Area ~ 0.1μm^2 → C = 5.3aF

Energy-per-bit = 0.5xCV² = 2.5 aJ

10Gbs Opto Plasmonic ➔ 0.00014 mW versus 350 mW 56Gbs PAM4 SerDes



http://www.ieee802.org/3/ck/public/adhoc/aug29_18/sun_3ck_adhoc_01_082918.pdf

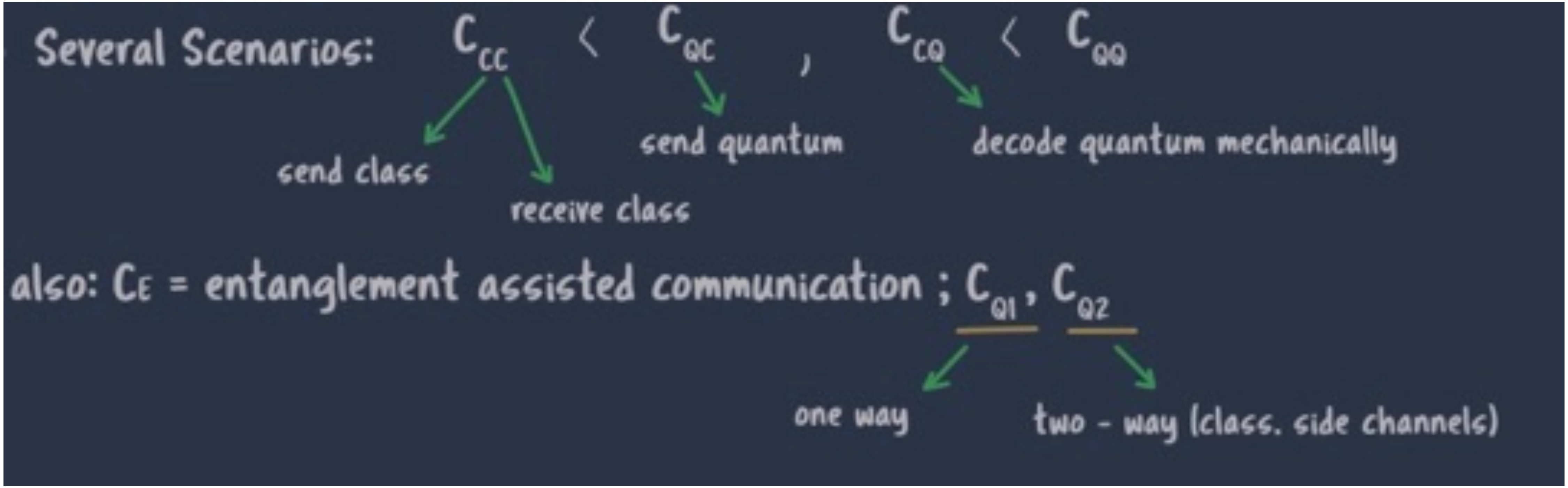
Nabet et al, ACS Photonics, 2014

Quantum error codes

This scheme is a step toward the quantum analog of channel coding in classical information theory. Whereas the quantum analog of Shannon's source coding theorem is already known [4,13], it is not even clear how a noisy quantum channel should properly be defined. Other steps in this direction have also recently been taken in [14,15], which deal with transmitting classical information over a quantum channel, and in [16], which deals with transmitting quantum information over a quantum channel, given an auxiliary two-way classical channel. The ultimate goal would be to define the quantum analog of the Shannon capacity for a quantum channel, and find encoding schemes which approach this capacity. An intermediate goal would be to find schemes for faithfully encoding k qubits that use $k + \epsilon k$ qubits, where ϵ approaches 0 as the channel's error rate goes to 0, as in classical information theory.

https://doi.org/10.1103/PhysRevA.52.R2493

Shannon Meets Quantum



Quantum Worldwide

(not an exhaustive list)

D-Wave The Quantum Computing Company

1QBit

Microsoft

intel

Google

KEYSIGHT TECHNOLOGIES

rigetti

Raytheon BBN Technologies

NORTHROP GRUMMAN

LOCKHEED MARTIN

Honeywell

IBM

qci

Labber QUANTUM

IONQ

AOSense

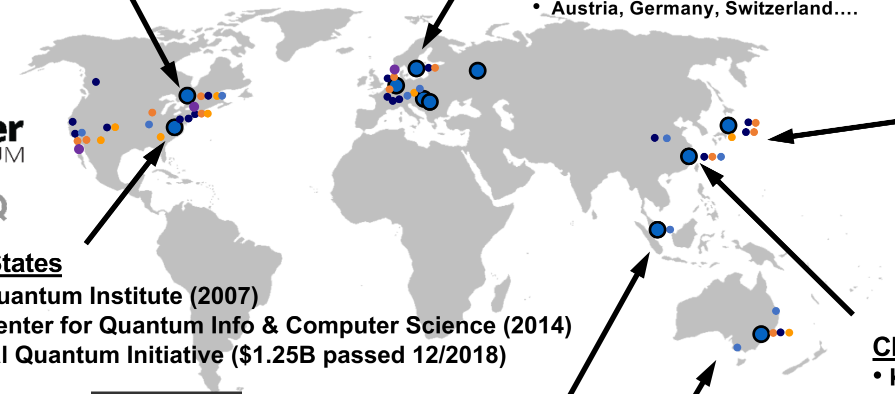
Twinleaf

ColdQuanta

HARRIS

Canada
- Inst. for Quantum Computing (2002)
- Inst. Quantique (2015)

Europe
- Netherlands: QuTech (2014)
- United Kingdom: National Quantum Technologies Program, $0.5B (2014)
- EU: Quantum Flagship, $1B (2016)
- Sweden: Wallenberg Center for Quantum Technology, $0.2B (2017)
- Austria, Germany, Switzerland….



United States
- Joint Quantum Institute (2007)
- Joint Center for Quantum Info & Computer Science (2014)
- National Quantum Initiative ($1.25B passed 12/2018)

Japan
- Gate-model and QA programs
- JST ImPACT program (2014)
  - Quantum artificial brain
  - Quantum secure network
  - Quantum simulation

China
- Key Lab, Quantum Information, CAS (2001)
- Satellite quantum communication (2016)
- Alibaba – CAS cloud computer - $15B (2018)

Singapore
- Research Center on Quantum Information Science and Technology (2007)

Australia
- ARC Centers of Excellence
  - Center for Quantum Computing Technology (2000)
  - Engineered Quantum Systems (2011)
- CommBank – Telstra – UNSW (2015)

element six a De Beers Group Company

IDQ

Zurich Instruments

BlueFors CRYOGENICS

HITACHI

FUJITSU

NEC

Baidu

Alibaba.com

Q-CTRL

Tencent 腾讯

Potential value of quantum computing for economic and information security is driving significant worldwide investment – estimated at $6 billion / year by 2020*.

• Superconducting qubits • Ion trap qubits • Semiconducting qubits • Quantum optics • NV centers

* European Commission