Our Research on Quantum, AI, and Network Security


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These slides are available at:
http://www.cse.wustl.edu/~jain/talks/cs59124.htm

1. Trends in:
   - Cybersecurity
   - Quantum
   - AI
2. Our Research in these areas
3. Key distinctions of our research

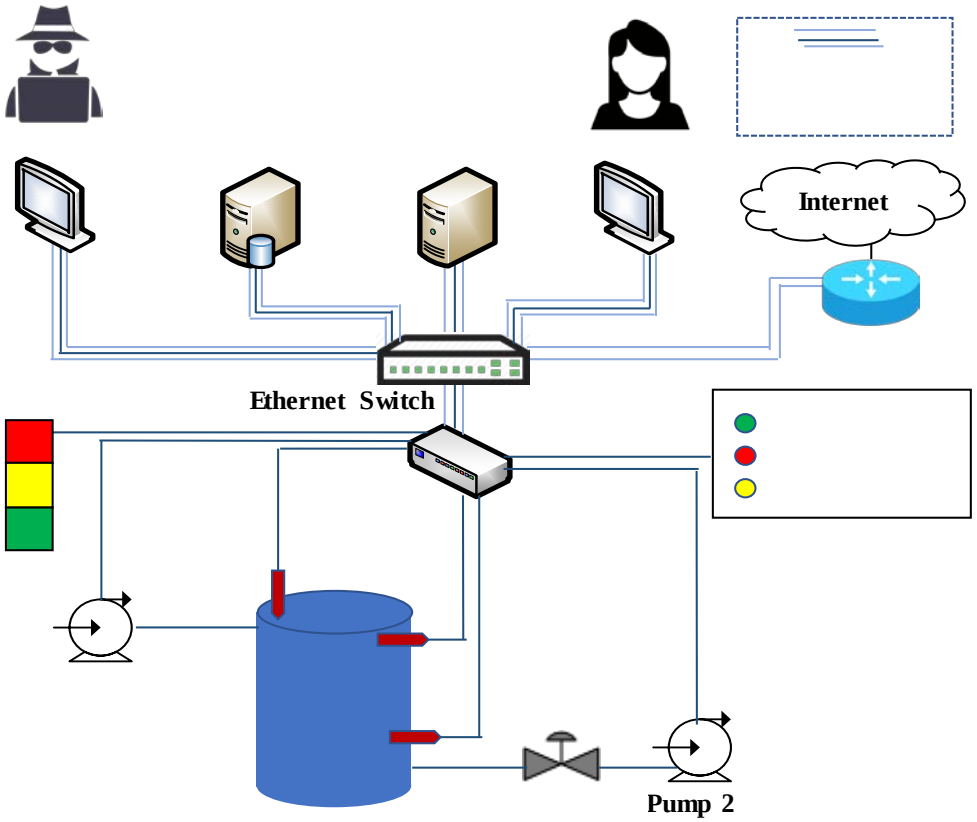
AI-Based Security of IoT: Our Research

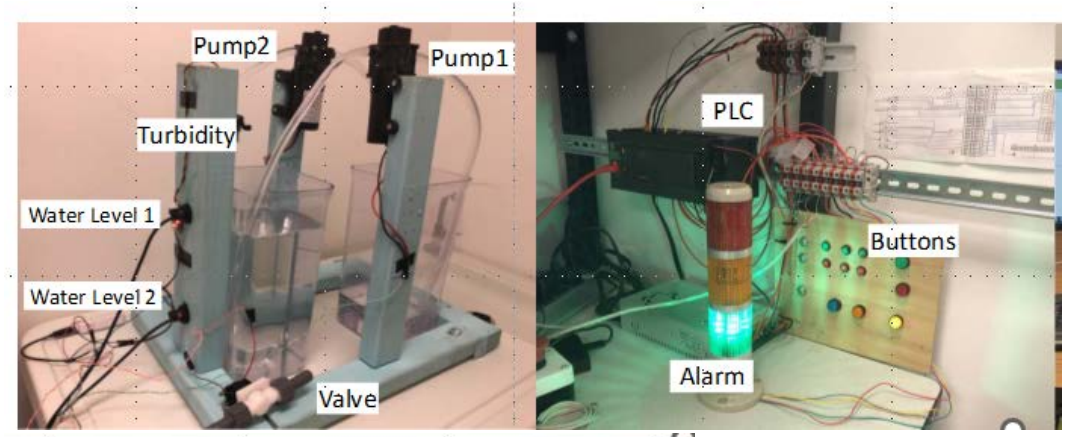
- Security research since 2009
- AI research since 2017
- Security of Industrial Internet of Things (IIoT)

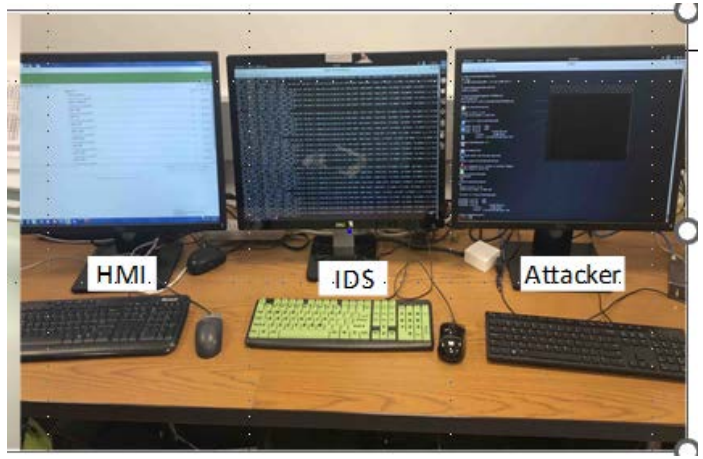
- Security of Internet of Medical Things (IoMT)

- Security using blockchains
- 24+ papers
- AI = Pattern recognition, probabilistic reasoning, machine learning, deep learning, …
- Everything we say applies to all of these variations.

Industrial Control Systems Security Using AI

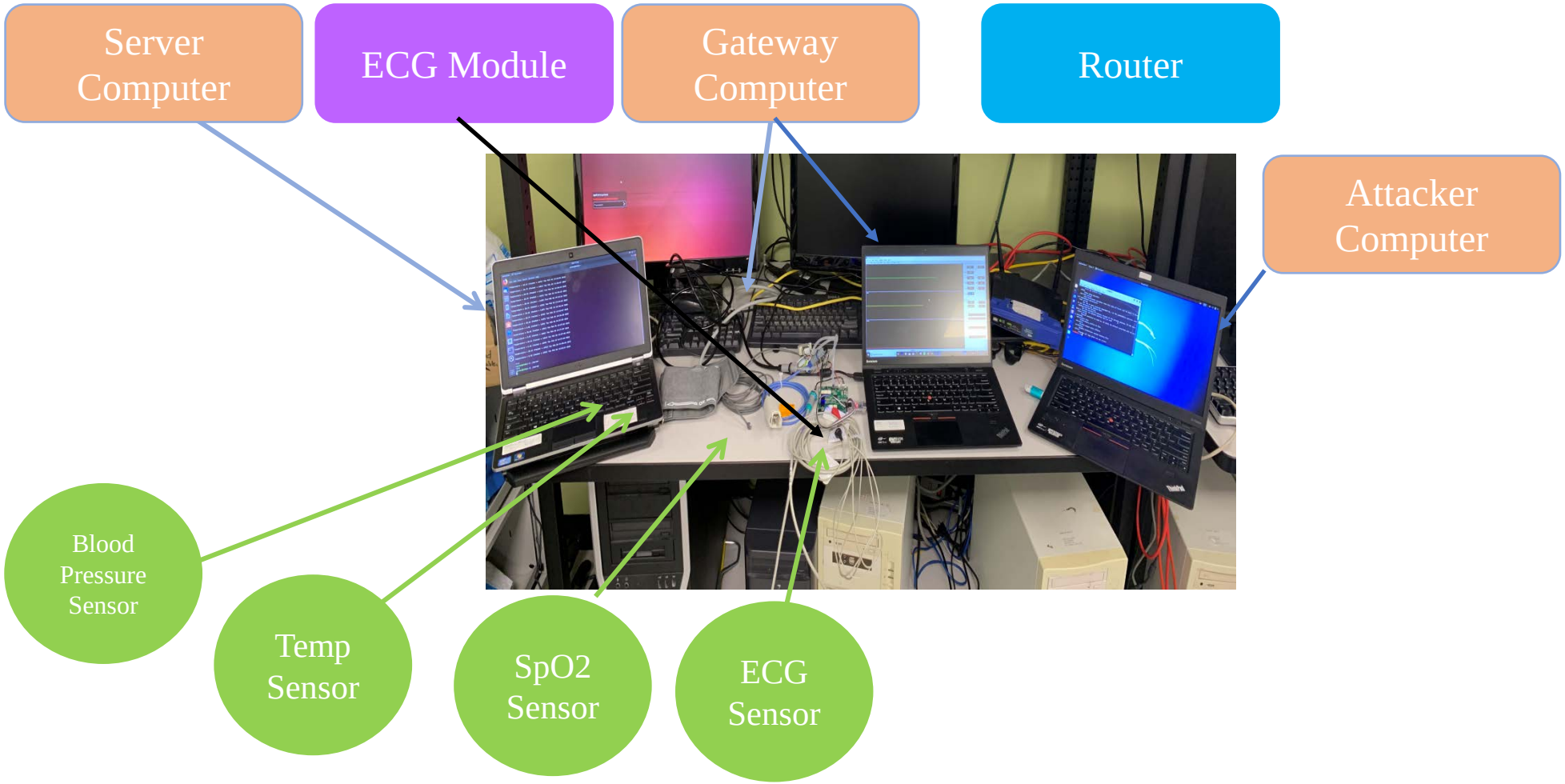






WUSTL-IIOT-2024 Dataset for IIoT Cybersecurity Research, http://www.cse.wustl.edu/~jain/iiot2/index.html

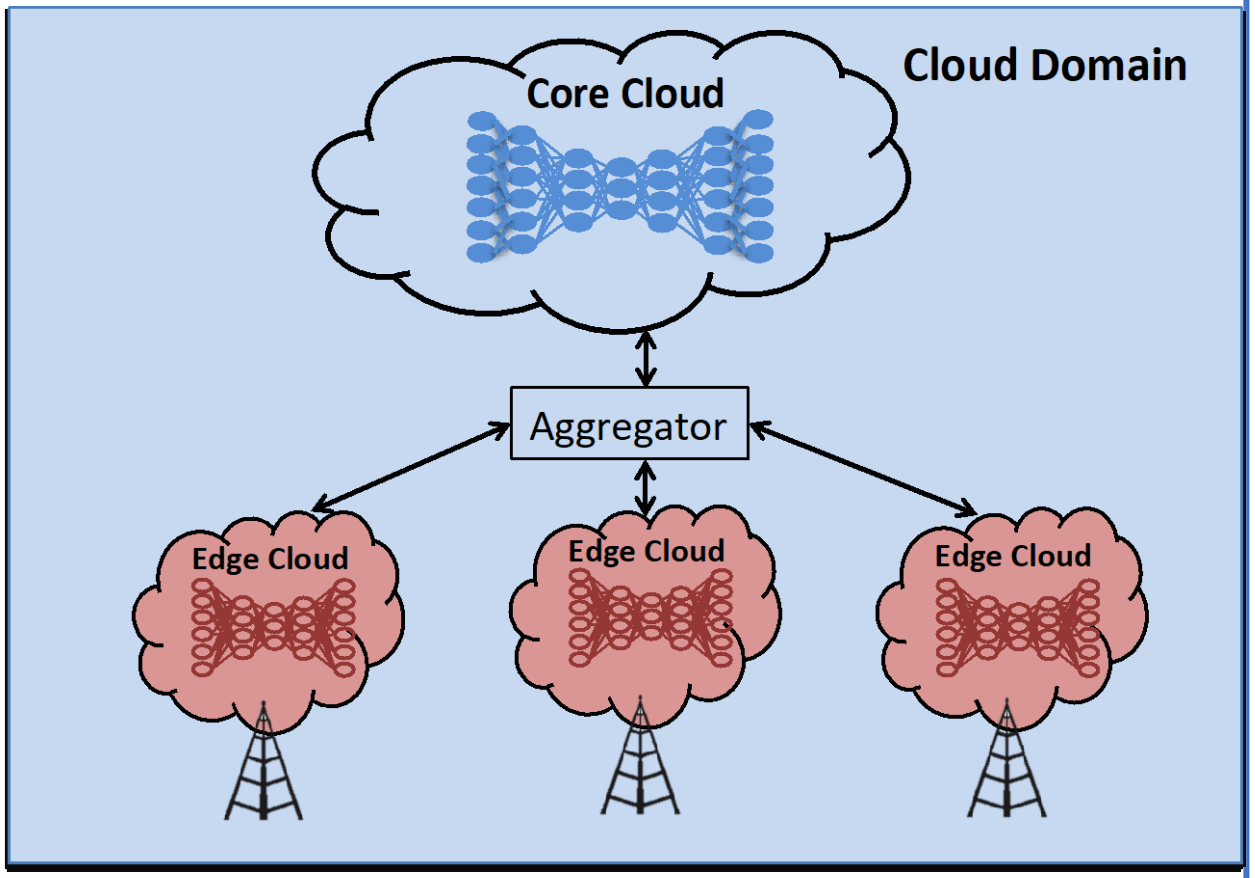
Internet of Medical Things Security Using AI



WUSTL EHMS 2020 Dataset for Internet of Medical Things (IoMT) Cybersecurity Research, http://www.cse.wustl.edu/~jain/ehms/index.html

Edge AI: Hierarchical Deep Learning

- No need to send data to the core cloud
- Edge clouds send a preliminary model to the core
- Also known as “Federated Learning”



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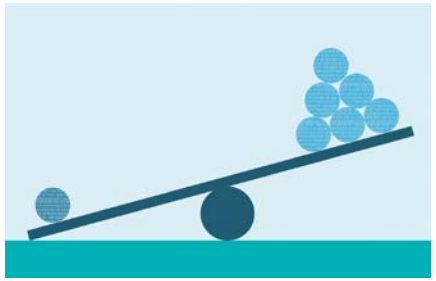
Imbalance of Security Data

- AI started with image analysis but needs to be extended for security
- Security data is very different from image data
  - Most security datasets are not representative of the real world.
  - In most papers, 10-15% of the packets are attack packets
- In the real world, 1 in several billion packets is an attack packet. Mis-classify the attack packet ⇒ 99.9999% accuracy
- **Extreme Data imbalance** is a critical issue in security



1% attack

Ref: Maede Zolanvari, Marcio A. Teixeira, Raj Jain, "**Effect of Imbalanced Datasets on Security of Industrial IoT Using Machine Learning**," 2018 IEEE International Conference on Intelligence and Security Informatics (ISI), Miami FL, Nov. 9 - 11, 2018, 6 pp., http://www.cse.wustl.edu/~jain/papers/imb_isi.htm

Wrong Metrics

- In Image analysis:
  Cost of predicting "0" when it is "1" = Cost of predicting "1" when it is "0."
  $\Rightarrow$ Cost of errors is symmetric $\Rightarrow$. Almost all metrics are symmetric.
- In Cyber Security:
  - Cost of missing an attack = $10^6 \times$ Cost of false attack prediction
  - Washington Post (5/30/22): 5 missiles hit Iraqi base hosting US troops
  - Would you live at the base protected with 90% accuracy?
- Need new metric to find the best algorithm $\Rightarrow$ Use **Safety Score**

Ref: Tara Salman, Ali Ghubaish, Devrim Unal, Raj Jain, "**Safety Score as an Evaluation Metric for Machine Learning Models of Security Applications**," IEEE Networking Letters, Vol. 2, Issue 4, December 2020, pp. 207-211, http://www.cse.wustl.edu/~jain/papers/safety.htm

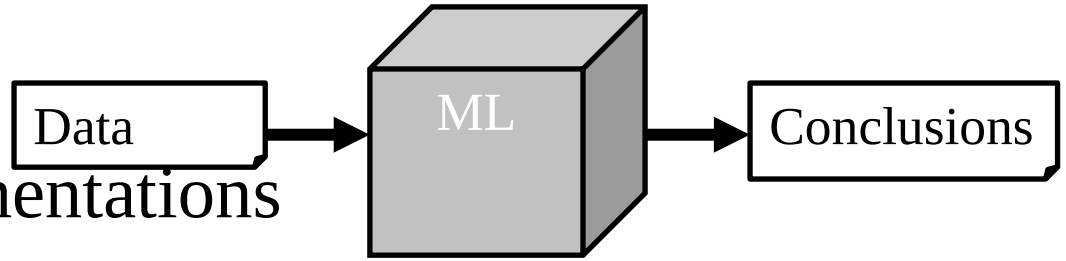
Results Not Explainable

- Would you trust AI to diagnose your disease?
- No, because you have no idea why the results are what they are

Machine Learning is what only machines can do, but human cannot do and cannot explain

- AI is a black box
- Can't discover bugs in ML model implementations
- Need Trustable AI = Explainable AI

  ⇒ Models to explain the AI predictions so that humans can understand



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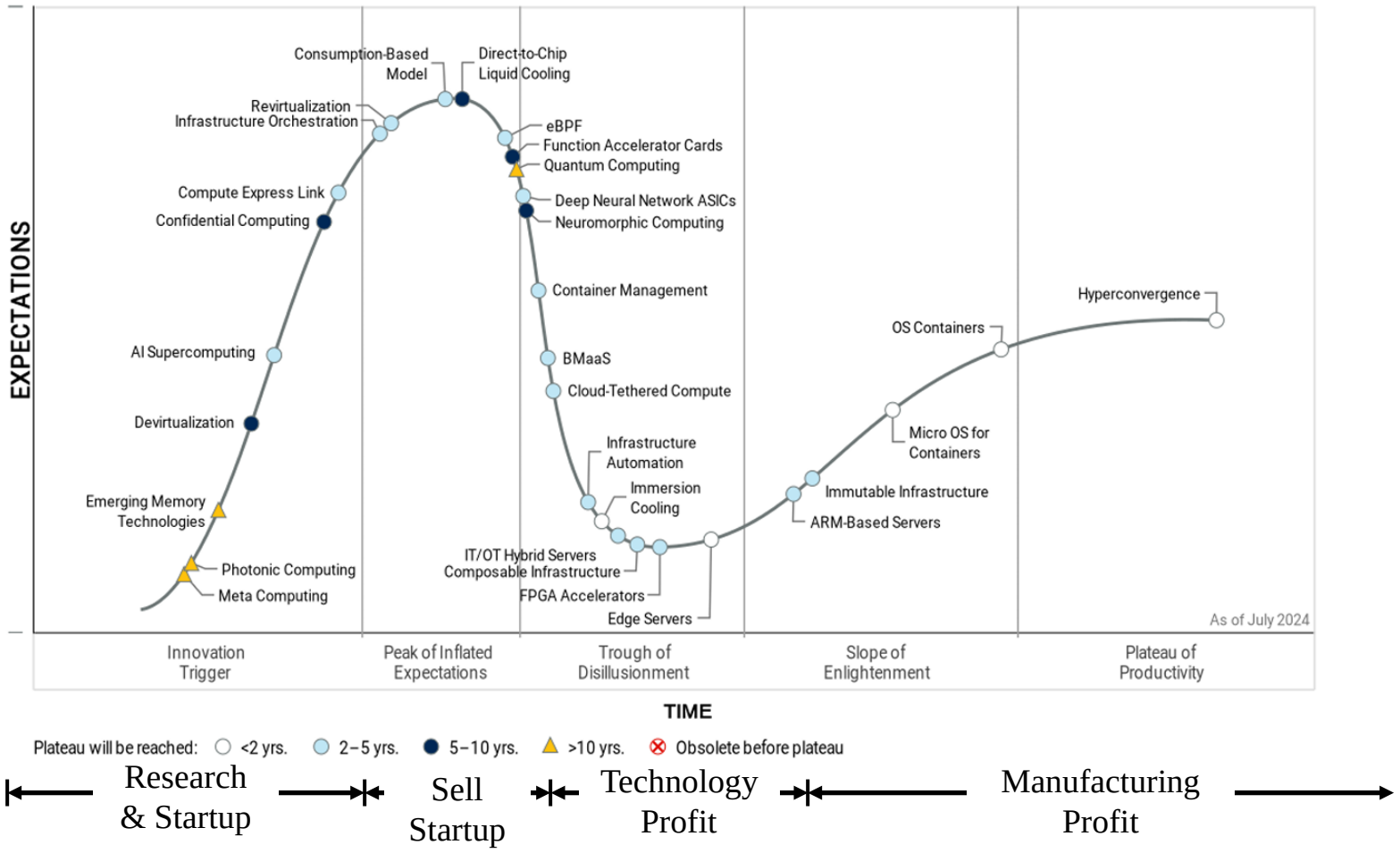
Gartner's Hype Cycle for Compute, 2024



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How Quantum Threatens Cybersecurity?

1. Easy to factorize large numbers

- Easy to find the private key given the public key
- Anyone with your private key can sign your contracts ⇒ ID theft
- They can empty your wallet by giving away your cryptocurrencies

2. Easy to invert one-way hash functions

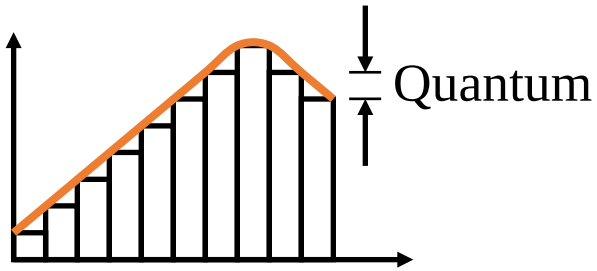
Proof-of-Work uses a puzzle to find the number that hashes below a threshold ⇒ Trivial to win Proof-of-Work puzzles

3. Easily find hash collisions: Two numbers with the same hash

- Hash is used in Merkle tree ⇒ Can change a transaction with no change in hash
- Hash of a block is used as a pointer by the next block
  ⇒ Can change a block such that the hash does not change.

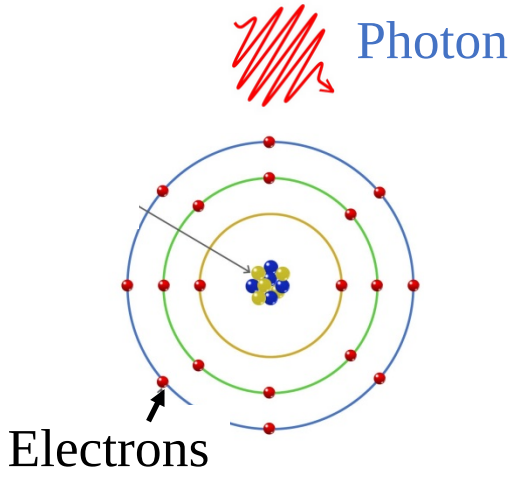
What is a Quantum?

- Quantization: Analog to digital conversion
  - **Quantum** = Smallest discrete unit



Wave Theory: Light is a continuous wave. It has a frequency, phase, amplitude

- **Quantum Mechanics**: Light behaves like discrete packets of energy that can be absorbed and released
- **Photon** = One quantum of light energy
- Photons can move an electron from one energy level to the next higher level
- Photons are released when an electron moves from one level to a lower energy level



How to Protect Security?

A. **Quantum-Resistant Blockchains**
   1. **Post-Quantum Cryptography**: Does not use factoring. NIST recommends:
      - ✓ CRYSTALS-KYBER for public-key encryption and key-establishment
      - ✓ CRYSTALS-DILITHIUM, FALCON, and SPHINCS+ for Digital signature
   2. **Secret-Key Cryptography**: With sufficiently large keys
   3. **Larger Hashes**: SHA-512

B. **Quantum Native Cryptography**: Hybrid of classical computing and quantum computing. Most quantum circuits require classical communication lines after measurement.

Ref: https://csrc.nist.gov/Projects/post-quantum-cryptography/selected-algorithms-2024

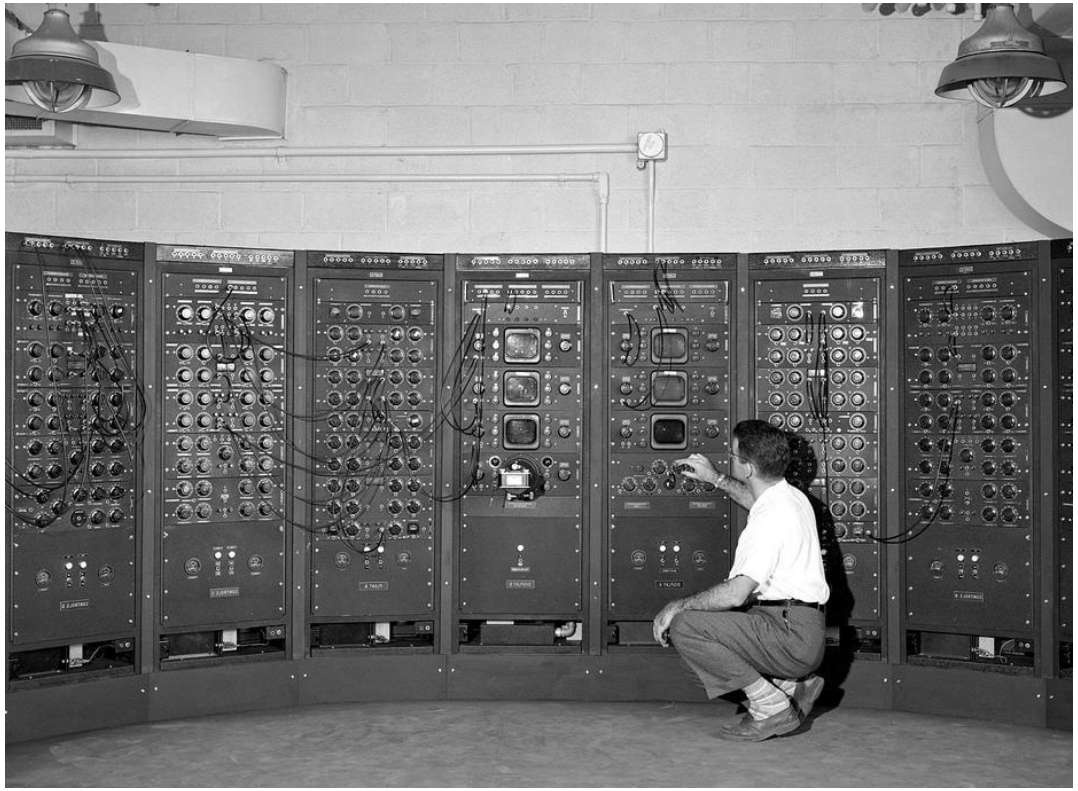
Challenges for Quantum

- **Decoherence**: Qubits lose their state over time.
  In nanoseconds to seconds, depending upon the temperature.
  - Need near zero-kelvin (10 milli Kelvin) temperature ⇒ Large cooling equipment.
  - Need extra qubits for quantum error correction to overcome decoherence
- Errors in quantum computers accumulate fast and require a thousand times more qubits to take care of errors
- Most of the research is theoretical.
  Practical experiments are limited to a tiny number of qubits.

Ref: M. Dyaknov, "The case against Quantum Computing," IEEE Spectrum, Nov 15, 2018, https://spectrum.ieee.org/the-case-against-quantum-computing#toggle-gdpr
D. Monroe, "Quantum Computers and the Universe," Communications of the ACM, December 2024, p10-11, https://dl.acm.org/doi/pdf/10.1145/3565977

Quantum Hardware

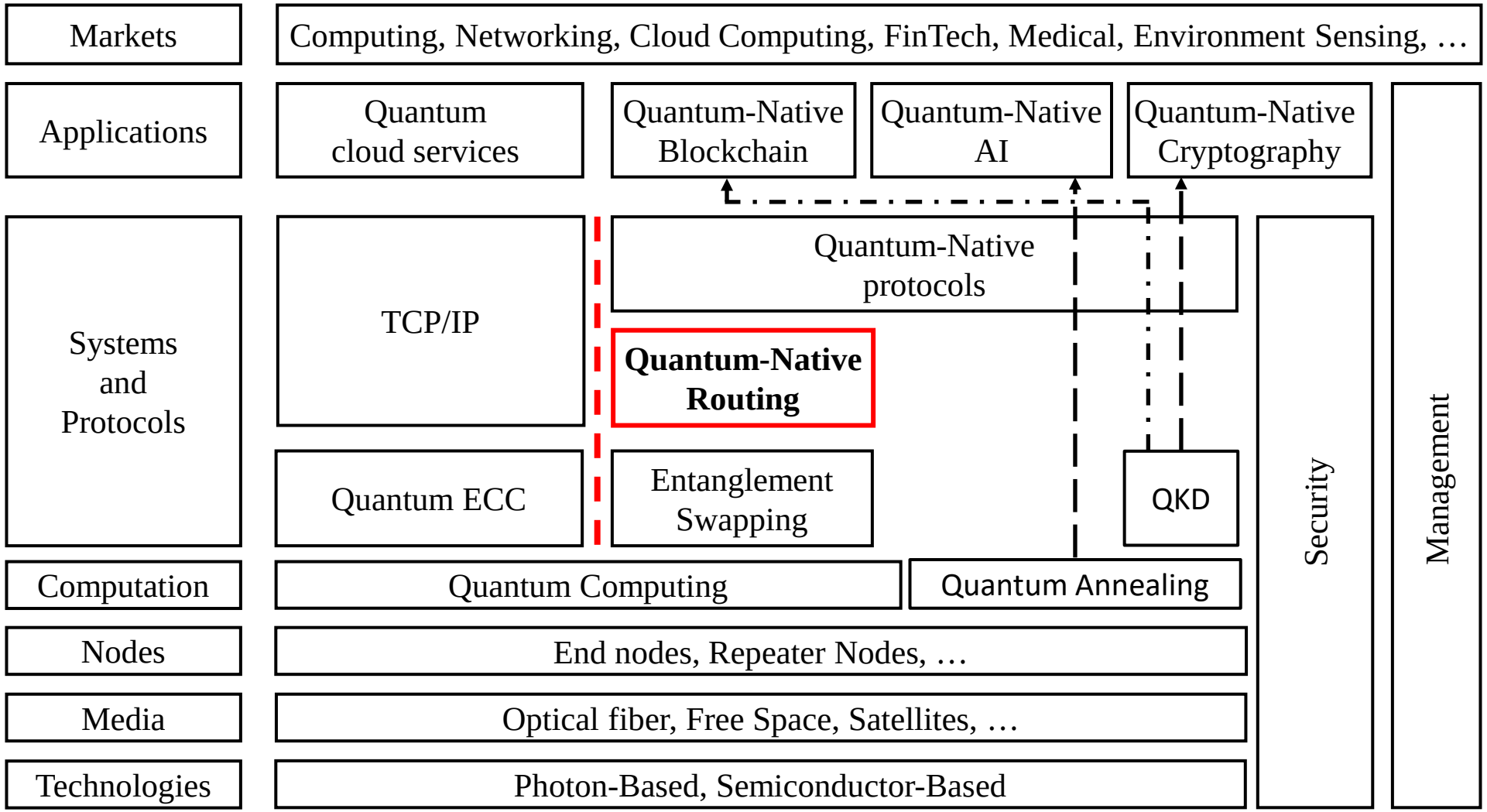
IBM's Quantum System One (2019) 20-qubit in a 9 ft cube



ENIAC (1943) 20 accumulators (10 decimal digits each)

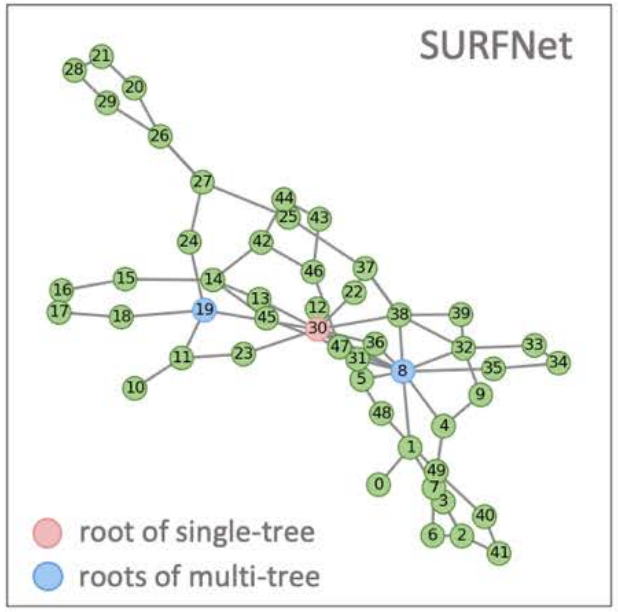
Ref: https://www.datacenterdynamics.com/en/news/ces-ibm-announces-q-system-one-quantum-computer-9ft-cube/

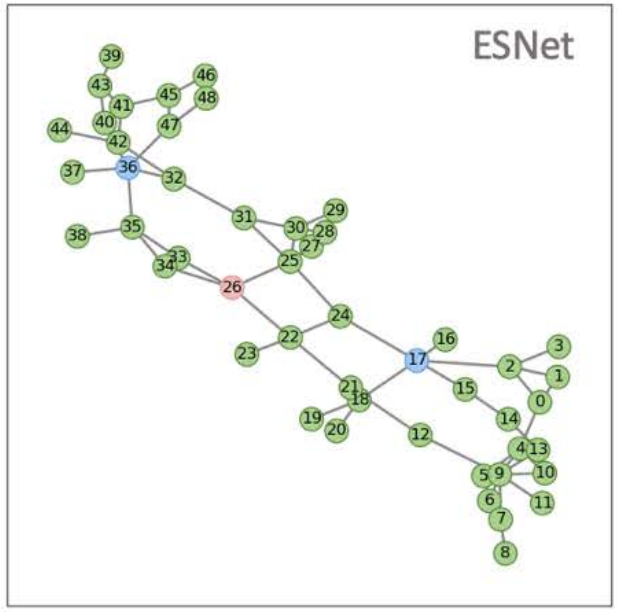
7-Layers Stack of Quantum Research

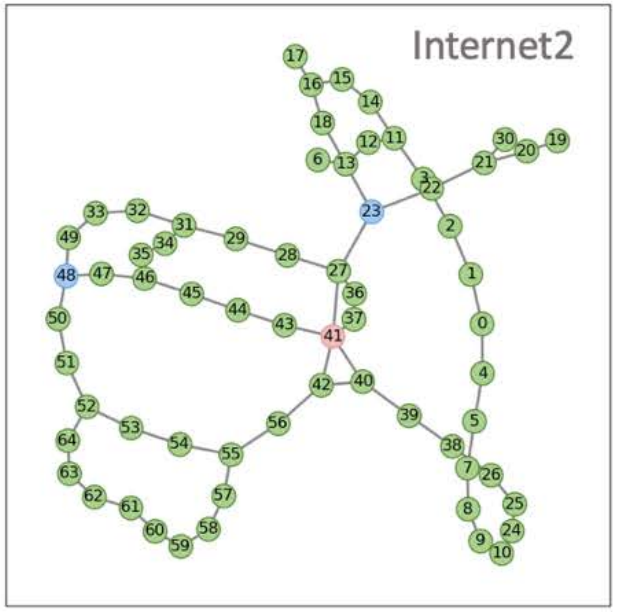


- A Lot of work in the lower layers
- Due to high error rates, we need large number of ECC Qubits
- Two camps for upper layers: Classical vs Quantum-native
- Significant Quantum Specific developments by experts in respective layers
  ⇒ Quantum-native protocols and systems
- Quantum-Native Routing

Realistic Topology Experiments







Dense Grid

Less-Dense Grid

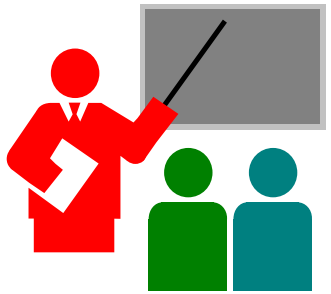
Linear Chains

Ref: Zebo Yang, Ali Ghubaish, Raj Jain, Ramana Kompella, and Hassan Shapourian, "Multi-Tree Quantum Routing in Realistic Topologies," IEEE Communications Magazine, Special Issue on Integrated Non-Terrestrial and Terrestrial (NTN/TN) Quantum Networks, Accepted August 2024.

Key Distinction of Our Research

- Goal: Impact to the real-world
  DECbit congestion indication in almost all networking architectures since its invention
- Funded by industry partners:
  Intel, Cisco, Broadcom, Boeing, …
- Impact real-world by participating in standards organizations and industry forums:
  ATM Forum, IEEE Standards, American National Standards Institute (ANSI), Internet Engineering Task Force (IETF), WiMAX Forum
- Work on long term as well as short term research

Summary



1. AI → Explainable AI → Federated AI
2. IoT Intelligent IoT Secure and Intelligent IoT
   - Industrial systems
   - Medical systems
3. Shor's factorization algorithm allows the factorization of integers in less time on quantum computers than in classical computing
4. Quantum-Safe Crypto is in standardization
5. Research for Impact

References: Class Recordings

- Recordings of all of my classes and talks are available on YouTube and on my website:

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3. CSE 574S: Wireless Networks, http://www.cse.wustl.edu/~jain/cse574-22/index.html
4. CSE 567: Computer Systems Analysis http://www.cse.wustl.edu/~jain/cse567-17/index.html
5. CSE 571S: Network Security, http://www.cse.wustl.edu/~jain/cse571-17/index.html

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Acronyms

- 3GPP Third Generation Partnership Project
- AI Artificial Intelligence
- ANSI American National Standards Institute
- AT&T American Telephone and Telegraph
- BSS Business Support Services
- CA California
- CGNAT Carrier Grade Network Address Translator
- CSE Computer Science and Engineering
- DECbit Digital Equipment Corporation Bit
- IEEE Institution of Electrical and Electronic Engineering
- IoT Internet of Things
- ML Machine Learning
- MO Missouri
- MS Master of Science
- NFV Network Function Virtualization
- NTT Nippon Telephone and Telegraph

Acronyms (Cont)

- OpenADN Open Application Delivery Networking
- OSS Operations Support Services
- SON Self-Organizing Networks
- TV Television
- UK United Kingdom
- US United States
- VC Venture Capital
- WAN Wide Area Network
- WiMAX Worldwide Interoperability for Microwave Access
- WUSTL Washington University in St. Louis

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