OIST Quantum Communications Summer School

Rodney Van Meter
Keio University
2025/09/22

https://forms.gle/KZAp1C1uvUacAtzQ6

Icebreaker questionnaire

The Next Four (Working) Hours (give or take)

- Discuss questionnaire / these slides / introduction to networks
- QCE25 keynote speech reprise:
  QCE Keynote Modular Quantum Multicomputers 2509
- Hands-on: **teleportation, entanglement swapping,** and **purification** (in Qiskit)
  - content: sfc-aqua/wqrn-tutorial
  - progress tracker: teleportation-QiskitWS-progress-worksheet-E
- Toward Standardized Quantum Internet Protocols
- Putting it all together: hands-on with QuISP
  https://github.com/sfc-aqua/quisp

progress worksheet

Qiskit notebook

From *Experiment* Toward *Systems*

I showed Dave Farber (grandfather of the Internet) some Qiskit code, complete with job management and data post-processing. He responded (paraphrasing),

> **This isn't an application, it's an experiment.**

So how do we get to *applications* and *systems* that people can use?

Quick Advertisement: IEEE QCE

世界最大の量子情報工学の国際会議である IEEE Quantum Week (QCE) 2025 において、アドバイザー Van Meter が Keynote Speakerを務めました。

IEEE Quantum Week (QCE) 2025 において永山・Van Meterらが Best Paper Award を受賞しました。

世界最大の量子情報工学の国際会議である IEEE Quantum Week (QCE) 2025 において、 代表 永山・アドバイザー Van Meterらが Best Paper Award 2nd place を受賞しました。 IEEE Quantum Week (QCE) 2025 について

2025/09/10

SEE MORE →


IEEE
QUANTUM
WEEK


Q-CTRL
Qunnect

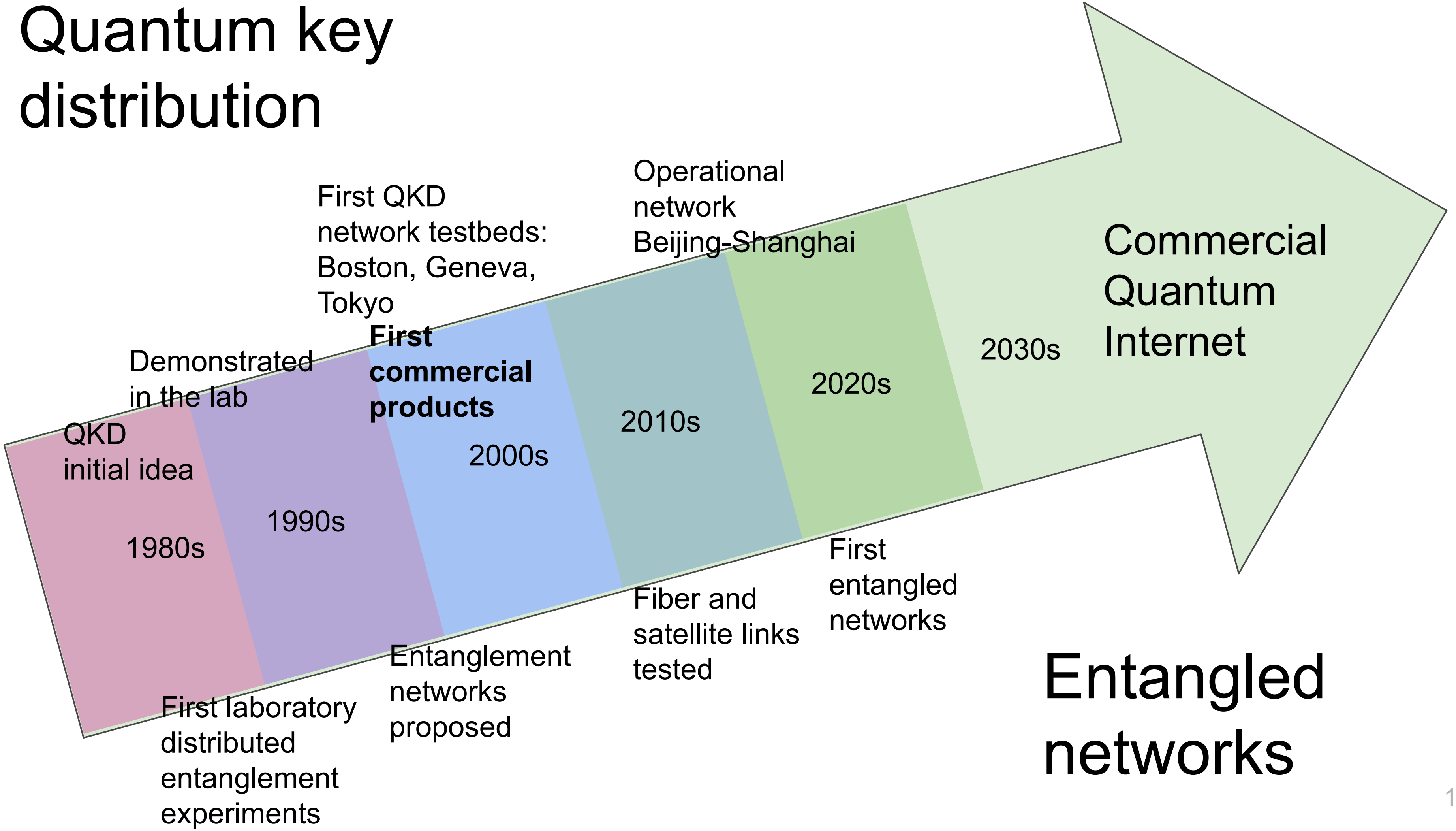

POWERFORD
Where the Fun Begins!
NQC
Albuquerque
ISOTOPES

QCE 2026

- Toronto, Sept. 13-18 → you should come! You should organize (or help us organize) workshops!
- Paper submission deadline ~April 1?

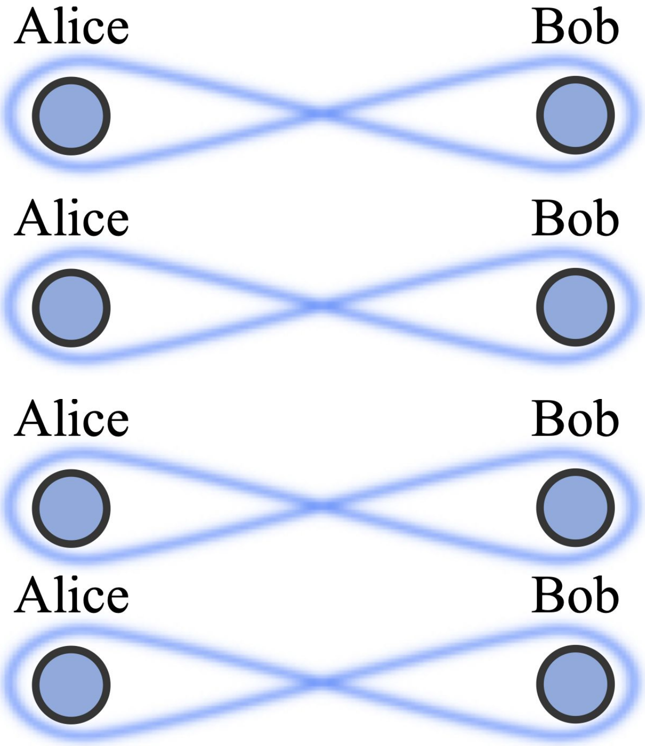
Quantum Repeater Networks

Quantum key distribution



The job of a quantum repeater network is…

- …to make end-to-end entanglement (modulo some arguments about temporal matters).
- And, entanglement is a consumable resource, so we have to make lots of it.



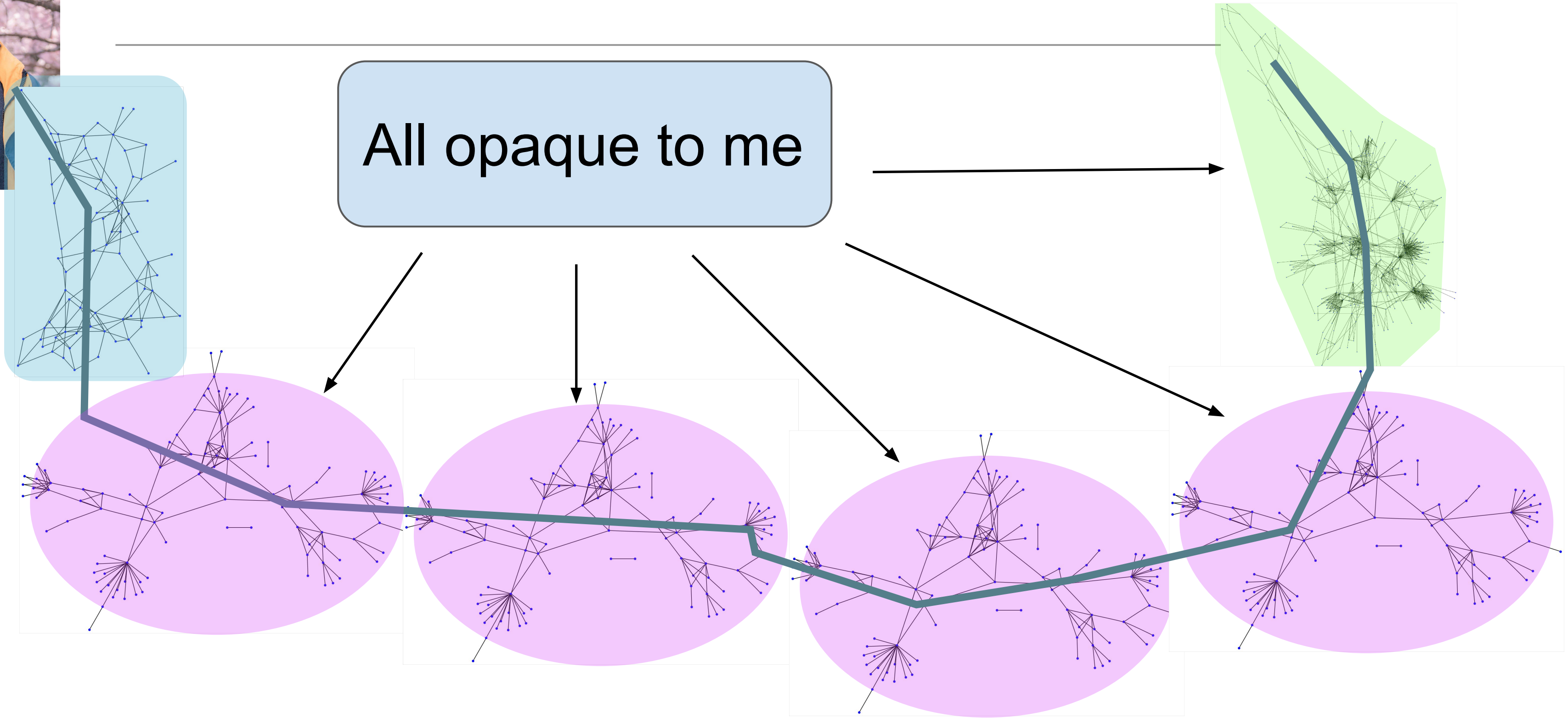
So the job of a quantum repeater is…

- 1) to make base-level entanglement over a link
- 2) to couple entangled links along an end-to-end path to meet the applications' needs
- 3) to monitor and manage errors (purification, QEC, or both)
- 4) to participate in the management of the network

And the job of a Quantum *Internet* is…

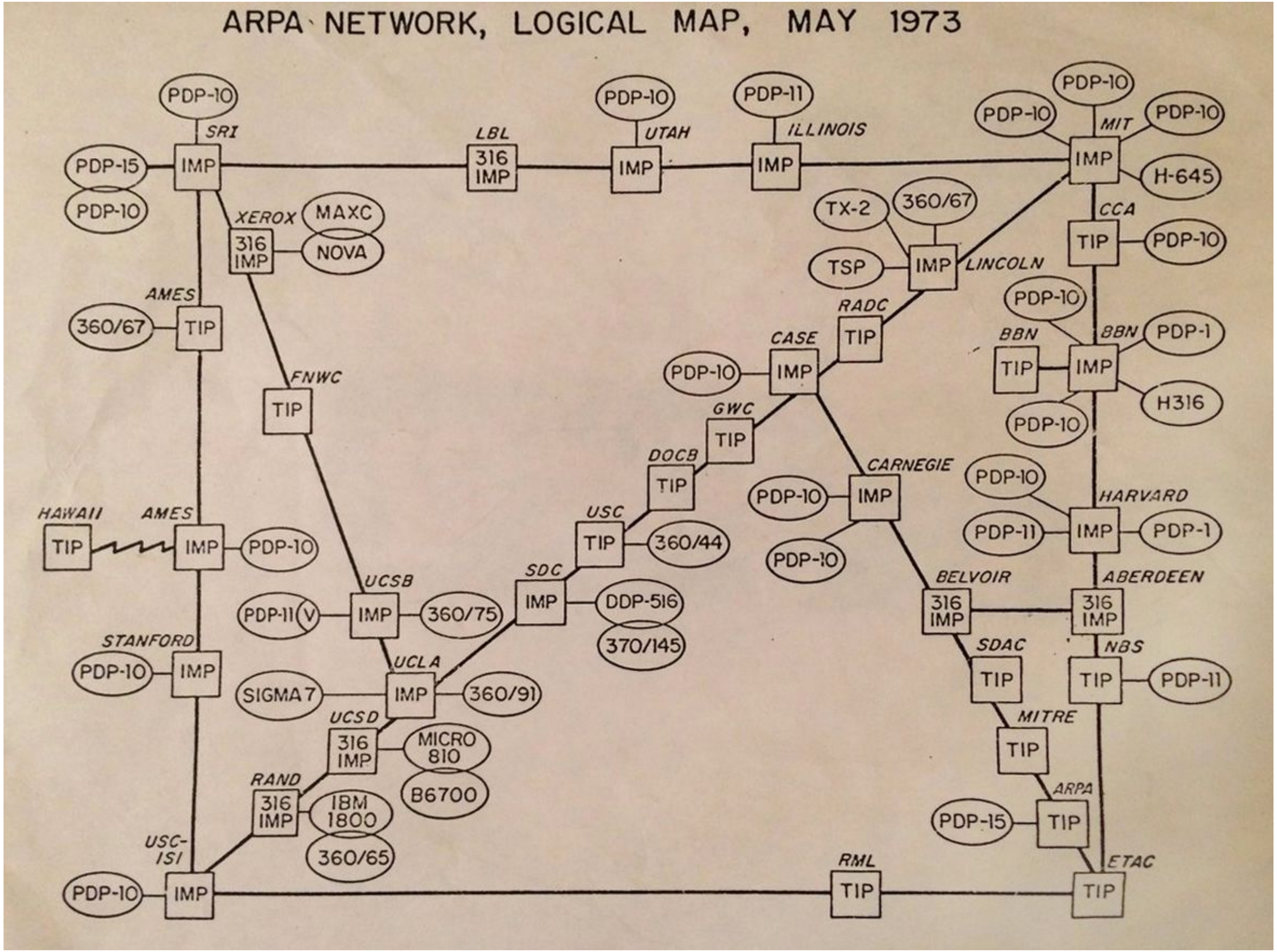
To do all of this:

- across *heterogeneous* networks
  (both physically and logically hetero)
- in an environment with *minimal trust* between networks
  - no knowledge of the internals of autonomous networks
  - possible presence of malicious nodes


All opaque to me

Networks

https://rarehistoricalphotos.com/the-stockholm-telephone-tower-1890/


ARPA NETWORK, LOGICAL MAP, MAY 1973
PDP-10
SRI
PDP-15
IMP
PDP-10
LBL
316 IMP
PDP-10
UTAH
IMP
PDP-11
ILLINOIS
IMP
PDP-10
PDP-10
MIT
PDP-10
IMP
H-645
XEROX
316 IMP
MAXC
NOVA
TX-2
360/67
TSP
IMP
LINCOLN
CCA
TIP
PDP-10
AMES
360/67
TIP
RADC
TIP
CASE
PDP-10
IMP
PDP-10
BBN
TIP
BBN
IMP
PDP-1
H316
PDP-10
FNWC
TIP
GWC
TIP
DOCB
TIP
CARNEGIE
PDP-10
IMP
PDP-10
PDP-10
HARVARD
PDP-11
IMP
PDP-1
HAWAII
TIP
AMES
IMP
PDP-10
USC
TIP
360/44
SDC
IMP
DDP-516
370/145
UCSB
PDP-11
V
IMP
360/75
BELVOIR
316 IMP
ABERDEEN
316 IMP
STANFORD
PDP-10
IMP
UCLA
SIGMA 7
IMP
360/91
SDAC
TIP
NBS
TIP
PDP-11
UCSD
316 IMP
MICRO 810
B6700
MITRE
TIP
RAND
316 IMP
IBM 1800
360/65
ARPA
PDP-15
TIP
USC-ISI
PDP-10
IMP
RML
TIP
ETAC
TIP

A Protocol for Packet Network Intercommunication

VINTON G. CERF AND ROBERT E. KAHN,

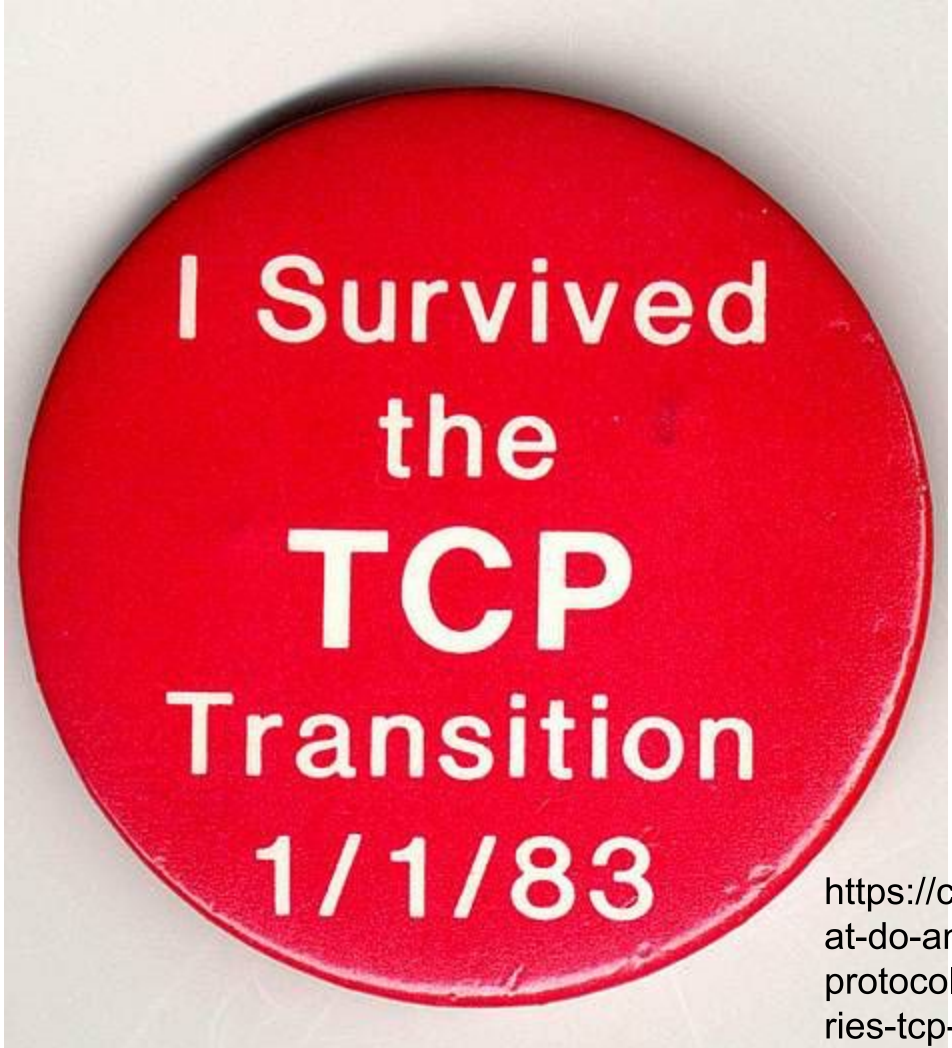
MEMBER, IEEE

Abstract — A protocol that supports the sharing of resources that exist in different packet switching networks is presented. The protocol provides for variation in individual network packet sizes, transmission failures, sequencing, flow control, end-to-end error checking, and the creation and destruction of logical process-to-process connections. Some implementation issues are considered, and problems such as internetwork routing, accounting, and timeouts are exposed.

INTRODUCTION

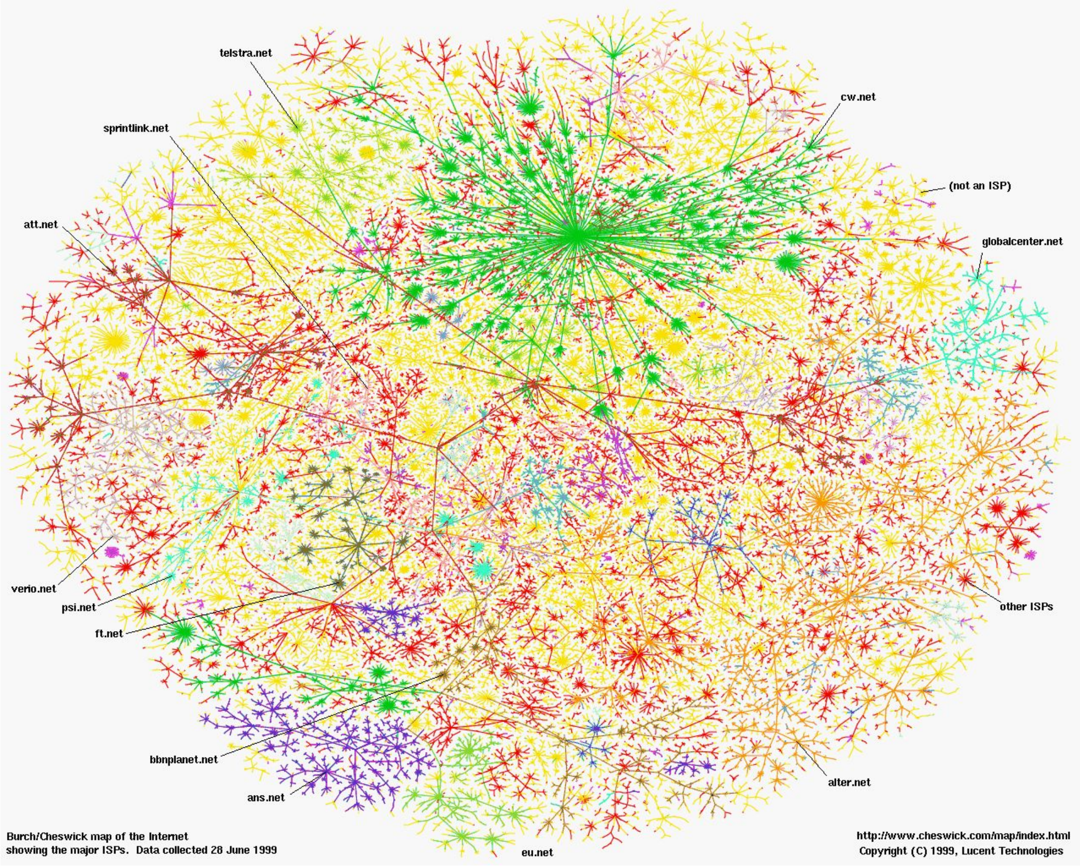
IN THE LAST few years considerable effort has been expended on the design and implementation of packet switching networks [1]-[7],[14],[17]. A principle reason for developing such networks has been to facilitate the sharing of computer resources. A packet communication network includes a transportation mechanism for delivering data between computers or between computers and terminals. To make the data meaningful, computer and terminals share a common protocol (i.e, a set of agreed upon conventions). Several protocols have already been

of one or more *packet switches*, and a collection of communication media that interconnect the packet switches. Within each HOST, we assume that there exist *processes* which must communicate with processes in their own or other HOSTS. Any current definition of a process will be adequate for our purposes [13]. These processes are generally the ultimate source and destination of data in the network. Typically, within an individual network, there exists a protocol for communication between any source and destination process. Only the source and destination processes require knowledge of this convention for communication to take place. Processes in two distinct networks would ordinarily use different protocols for this purpose. The ensemble of packet switches and communication media is called the *packet switching subnet*. Fig. 1 illustrates these ideas.



https://computerhistory.org/blog/what-do-anniversaries-mean-internet-protocols-at-40/protocals-anniversaries-tcp-transition-button/

Map of the Internet (1999)



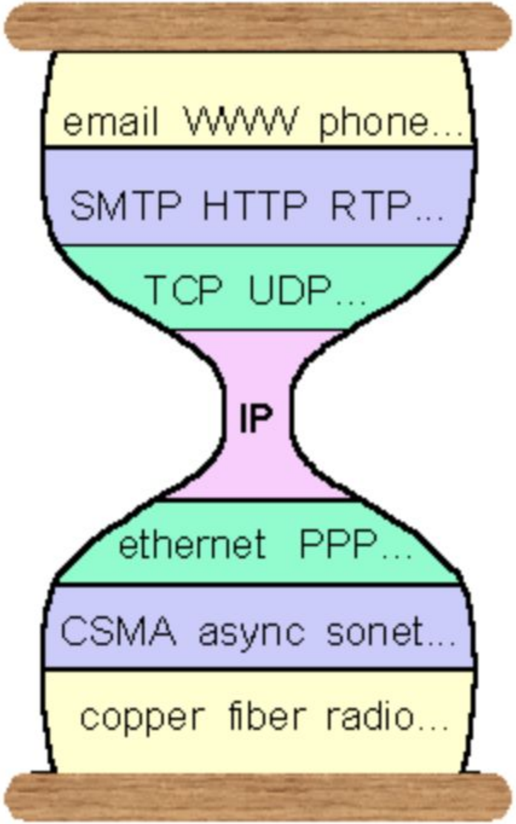
https://www.ietf.org/proceedings/51/slides/plenary-1/

Steve Deering's Waist

Watching the Waist of the Protocol Hourglass

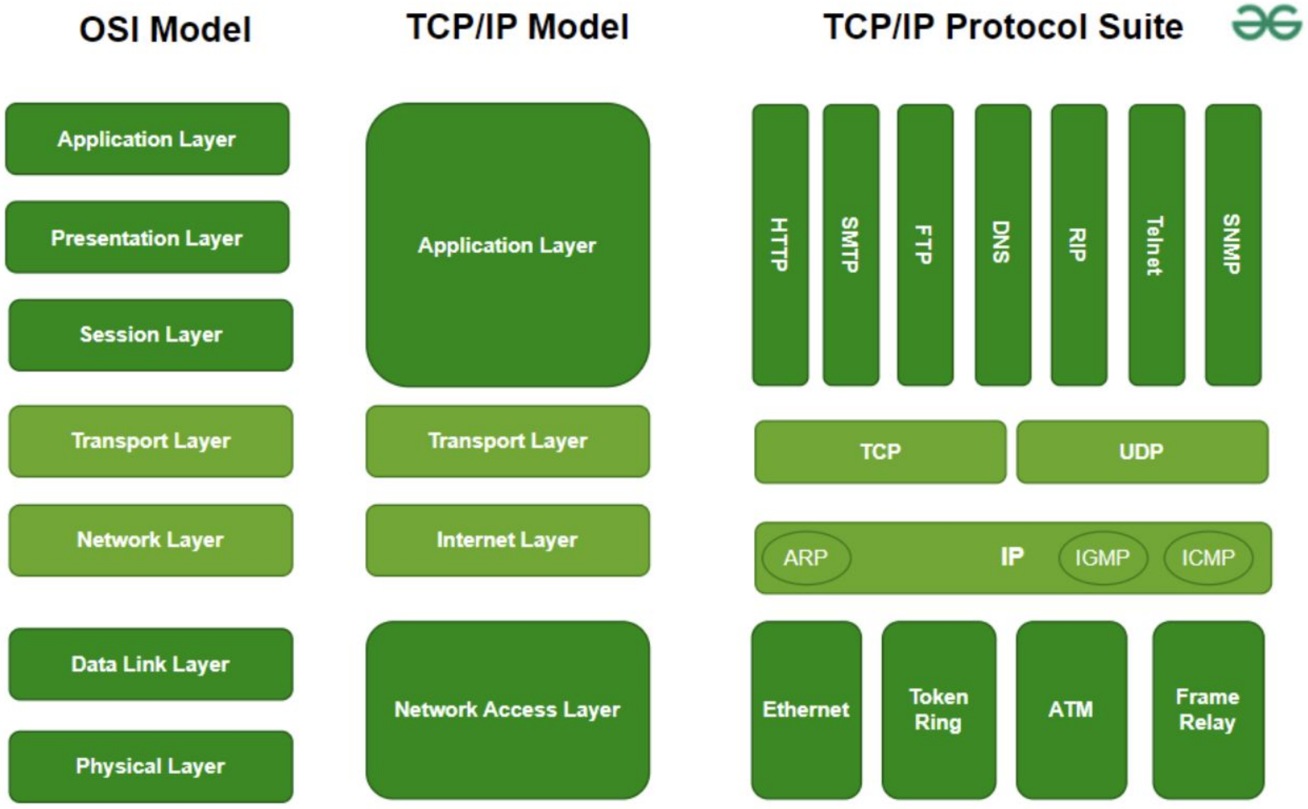
IETF 51, London, Plenary session

August 2001



https://www.geeksforgeeks.org/computer-networks/difference-between-osi-model-and-tcp-ip-model/

OSI Model v. TCP/IP Stack



OSI vs TCP/IP

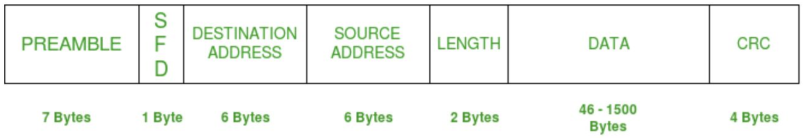
https://www.potaroo.net/ispcol/2004-07/tcp1.html

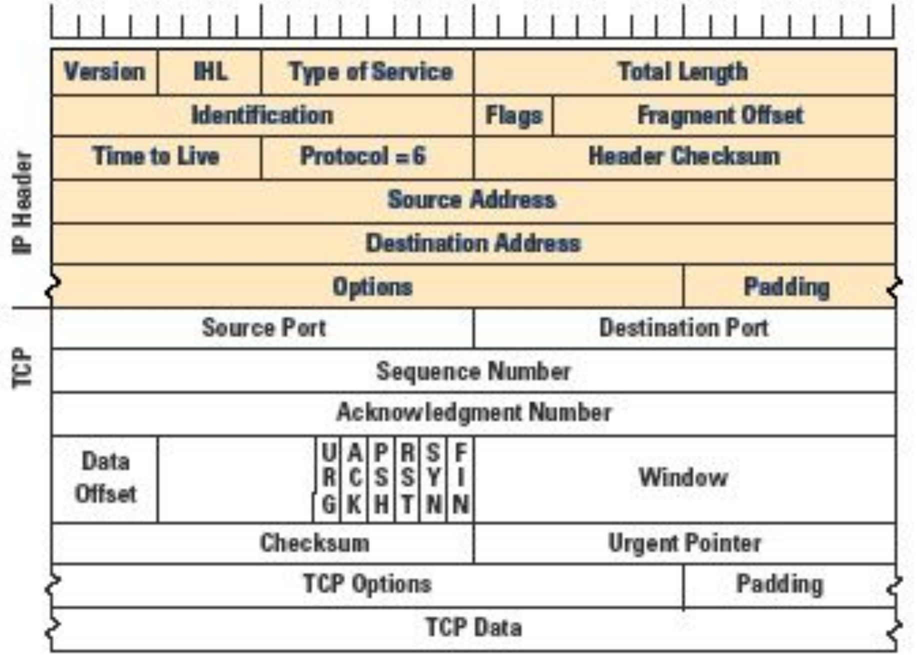
Packet Headers

This will be preceded by the link layer header (e.g. Ethernet) and the payload data may include additional headers for e.g. HTTPS

- Ethernet frame header: 14 bytes
- IPv4 header: 20 bytes
- IPv6 header: 40 bytes
- TCP header: 20+ bytes
- Ethernet trailer (checksum): 4 bytes

Ethernet (IEEE 802.3) Frame Format





https://www.geeksforgeeks.org/computer-networks/ethernet-frame-format/

Issues in Network Design

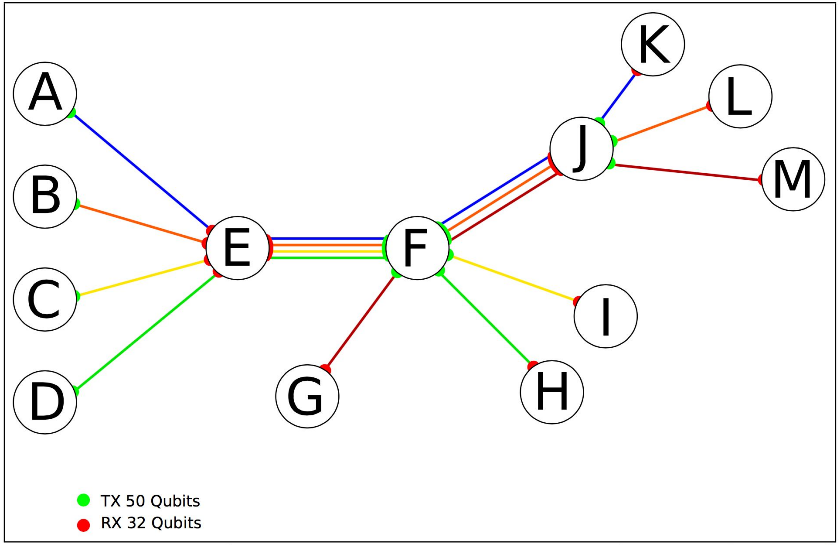
- Communication model
- Resource allocation method
- Naming & Addressing
- Routing
- Scaling & Heterogeneity: Internetworking
- Security
- Network management

Communication Model

- Circuit switching (old school, original telephone network)
- Virtual circuit (see multiplexing)
- Datagram (the Internet)

n.b.: Dave Farber is fond of saying (paraphrasing), “The principles remain the same, but the technology changes, the economic, business and political environments change; so it’s wise to revisit this decision every couple of decades.”

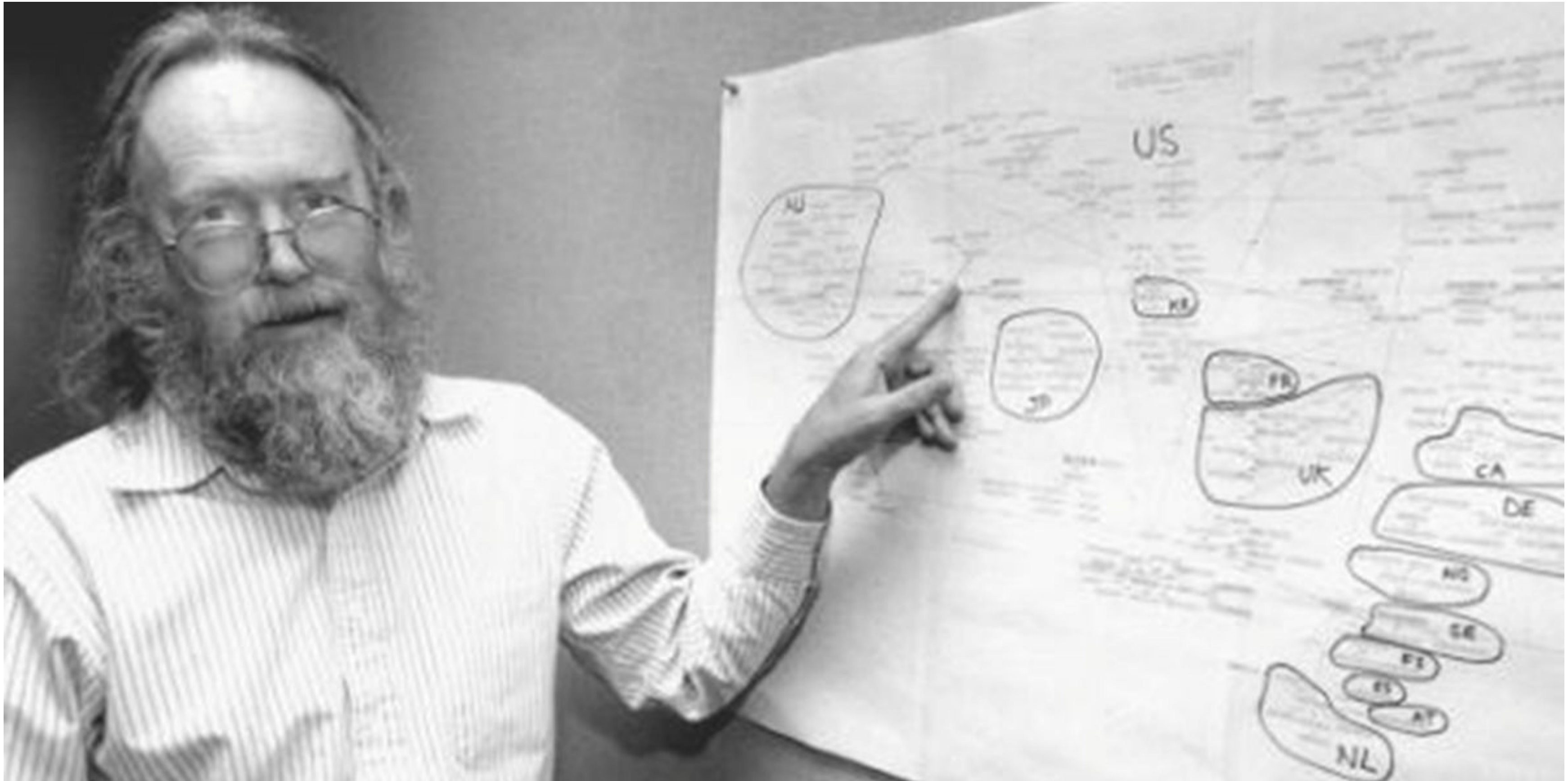
Multiplexing



- Spatial (cellular)
- Temporal (fixed time division)
- Statistical (datagram)
- Frequency (wave division)
- Mathematical (code division)

Aparicio & rdv
Proc. SPIE, 2011

Naming & Addressing (Jon Postel, IANA, USC/ISI 1943-1998)

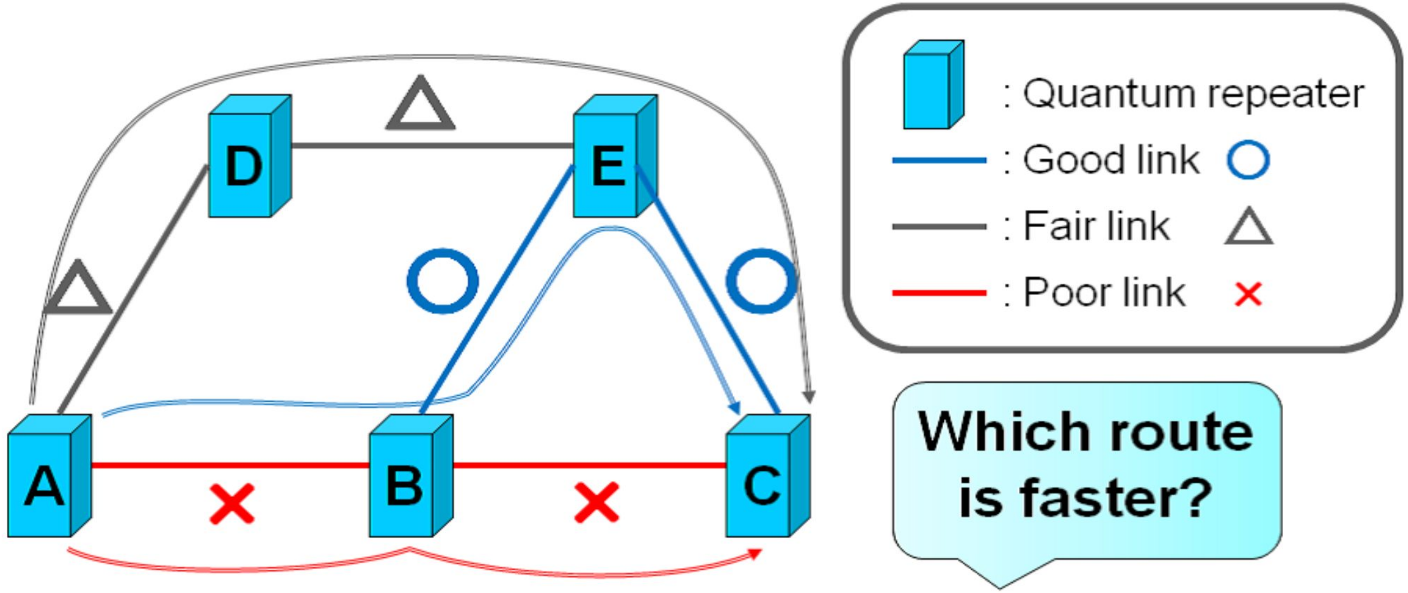


Domain Name System

Translates one type of name to another type of name

Generally a human-readable text string, an **FQDN** (fully qualified domain name) to an IP address (IPv4 or IPv6)

Routing



α route: A ⇒ D ⇒ E ⇒ C △△○

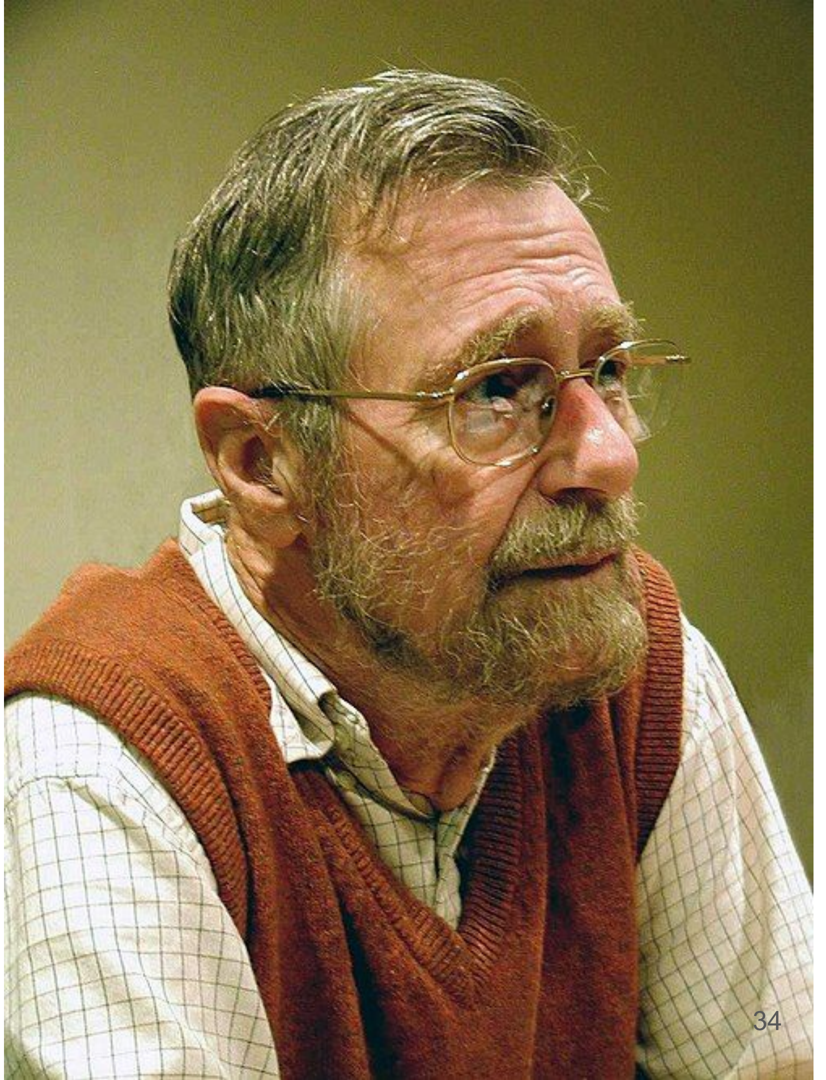
β route: A ⇒ B ⇒ E ⇒ C ×○○

γ route: A ⇒ B ⇒ C ××

rdv et al.,
Net. Sci. 2013
arXiv: 1206.5655

Dijkstra’s Algorithm, 1959

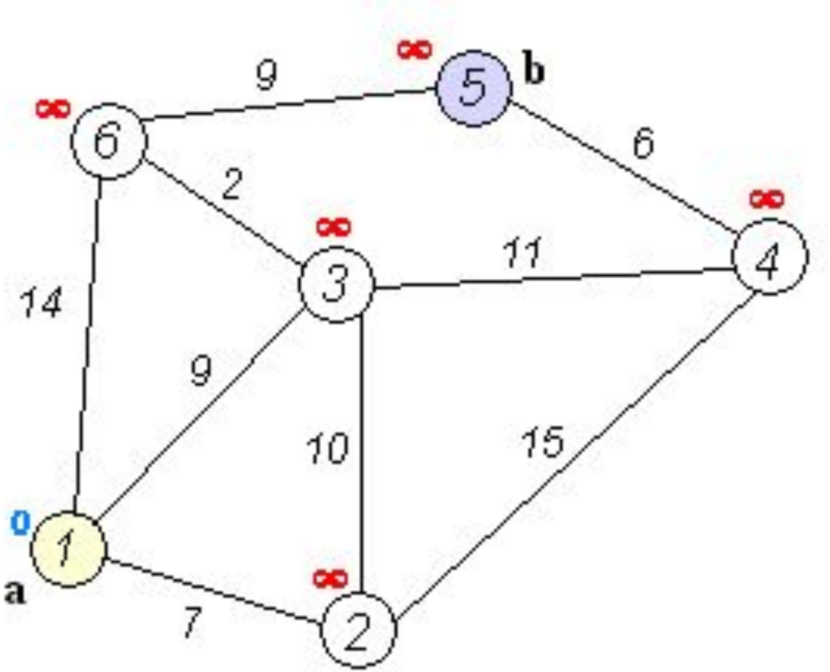
- …is just a graph theory problem
- solvable in polynomial time
- builds a *spanning tree* from some root



https://en.wikipedia.org/wiki/Dijkstra%27s_algorithm

Dijkstra's Algorithm

Interestingly, if every node builds a spanning tree using the same information, *those trees will be different but mutually consistent* (no routing loops!)



Numerische Mathematik 1, 269—271 (1959)

A Note on Two Problems in Connexion with Graphs

By

E. W. DIJKSTRA

We consider n points (nodes), some or all pairs of which are connected by a branch; the length of each branch is given. We restrict ourselves to the case where at least one path exists between any two nodes. We now consider two problems.

Problem 1. Construct the tree of minimum total length between the n nodes. (A tree is a graph with one and only one path between every two nodes.)

In the course of the construction that we present here, the branches are subdivided into three sets:

I. the branches definitely assigned to the tree under construction (they will form a subtree);

II. the branches from which the next branch to be added to set I, will be selected;

III. the remaining branches (rejected or not yet considered).

The nodes are subdivided into two sets:

A. the nodes connected by the branches of set I,

B. the remaining nodes (one and only one branch of set II will lead to each of these nodes).

We start the construction by choosing an arbitrary node as the only member of set A, and by placing all branches that end in this node in set II. To start with, set I is empty. From then onwards we perform the following two steps repeatedly.

Step 1. The shortest branch of set II is removed from this set and added to set I. As a result one node is transferred from set B to set A.

Step 2. Consider the branches leading from the node, that has just been transferred to set A, to the nodes that are still in set B. If the branch under consideration is longer than the corresponding branch in set II, it is rejected; if it is shorter, it replaces the corresponding branch in set II, and the latter is rejected.

We then return to step 1 and repeat the process until sets II and B are empty. The branches in set I form the tree required.

The solution given here is to be preferred to the solution given by J. B. KRUSKAL [*1*] and those given by H. LOBERMAN and A. WEINBERGER [*2*]. In their solutions all the — possibly $\frac{1}{2}n(n-1)$ — branches are first of all sorted according to length. Even if the length of the branches is a computable function of the node coordinates, their methods demand that data for all branches are stored simultaneously. Our method only requires the simultaneous storing of

the data for at most n branches, viz. the branches in sets I and II and the branch under consideration in step 2.

Problem 2. Find the path of minimum total length between two given nodes P and Q.

We use the fact that, if R is a node on the minimal path from P to Q, knowledge of the latter implies the knowledge of the minimal path from P to R. In the solution presented, the minimal paths from P to the other nodes are constructed in order of increasing length until Q is reached.

In the course of the solution the nodes are subdivided into three sets:

A. the nodes for which the path of minimum length from P is known; nodes will be added to this set in order of increasing minimum path length from node P;

B. the nodes from which the next node to be added to set A will be selected; this set comprises all those nodes that are connected to at least one node of set A but do not yet belong to A themselves;

C. the remaining nodes.

The branches are also subdivided into three sets:

I. the branches occurring in the minimal paths from node P to the nodes in set A;

II. the branches from which the next branch to be placed in set I will be selected; one and only one branch of this set will lead to each node in set B;

III. the remaining branches (rejected or not yet considered).

To start with, all nodes are in set C and all branches are in set III. We now transfer node P to set A and from then onwards repeatedly perform the following steps.

Step 1. Consider all branches r connecting the node just transferred to set A with nodes R in sets B or C. If node R belongs to set B, we investigate whether the use of branch r gives rise to a shorter path from P to R than the known path that uses the corresponding branch in set II. If this is not so, branch r is rejected; if, however, use of branch r results in a shorter connexion between P and R than hitherto obtained, it replaces the corresponding branch in set II and the latter is rejected. If the node R belongs to set C, it is added to set B and branch r is added to set II.

Step 2. Every node in set B can be connected to node P in only one way if we restrict ourselves to branches from set I and one from set II. In this sense each node in set B has a distance from node P: the node with minimum distance from P is transferred from set B to set A, and the corresponding branch is transferred from set II to set I. We then return to step 1 and repeat the process until node Q is transferred to set A. Then the solution has been found.

Remark 1. The above process can also be applied in the case where the length of a branch depends on the direction in which it is traversed.

Remark 2. For each branch in sets I and II it is advisable to record its two nodes (in order of increasing distance from P), and the distance between P and that node of the branch that is furthest from P. For the branches of set I this

is the actual minimum distance, for the branches of set II it is only the minimum thus far obtained.

The solution given above is to be preferred to the solution by L. R. FORD [*3*] as described by C. BERGE [*4*], for, irrespective of the number of branches, we need not store the data for all branches simultaneously but only those for the branches in sets I and II, and this number is always less than n. Furthermore, the amount of work to be done seems to be considerably less.

References

[*1*] KRUSKAL jr., J. B.: On the Shortest Spanning Subtree of a Graph and the Travelling Salesman Problem. Proc. Amer. Math. Soc. 7, 48—50 (1956).

[*2*] LOBERMAN, H., and A. WEINBERGER: Formal Procedures for Connecting Terminals with a Minimum Total Wire Length. J. Ass. Comp. Mach. 4, 428—437 (1957).

[*3*] FORD, L. R.: Network flow theory. Rand Corp. Paper, P-923, 1956.

[*4*] BERGE, C.: Théorie des graphes et ses applications, pp. 68—69. Paris: Dunod 1958.

Mathematisch Centrum
2e Boerhaavestraat 49
Amsterdam-O

(*Received June 11, 1959*)

Druck der Universitätsdruckerei H. Stürtz AG., Würzburg

RFC Editor

https://www.rfc-editor.org/info/rfc2328

Search RFCs
number, title, ke
Advanced Sear

STD 54
RFC 2328

OSPF Version 2, APRIL 1998

File formats:

TEXT PDF HTML HTML

Status:
INTERNET STANDARD

244 pages!

Obsoletes:
RFC 2178

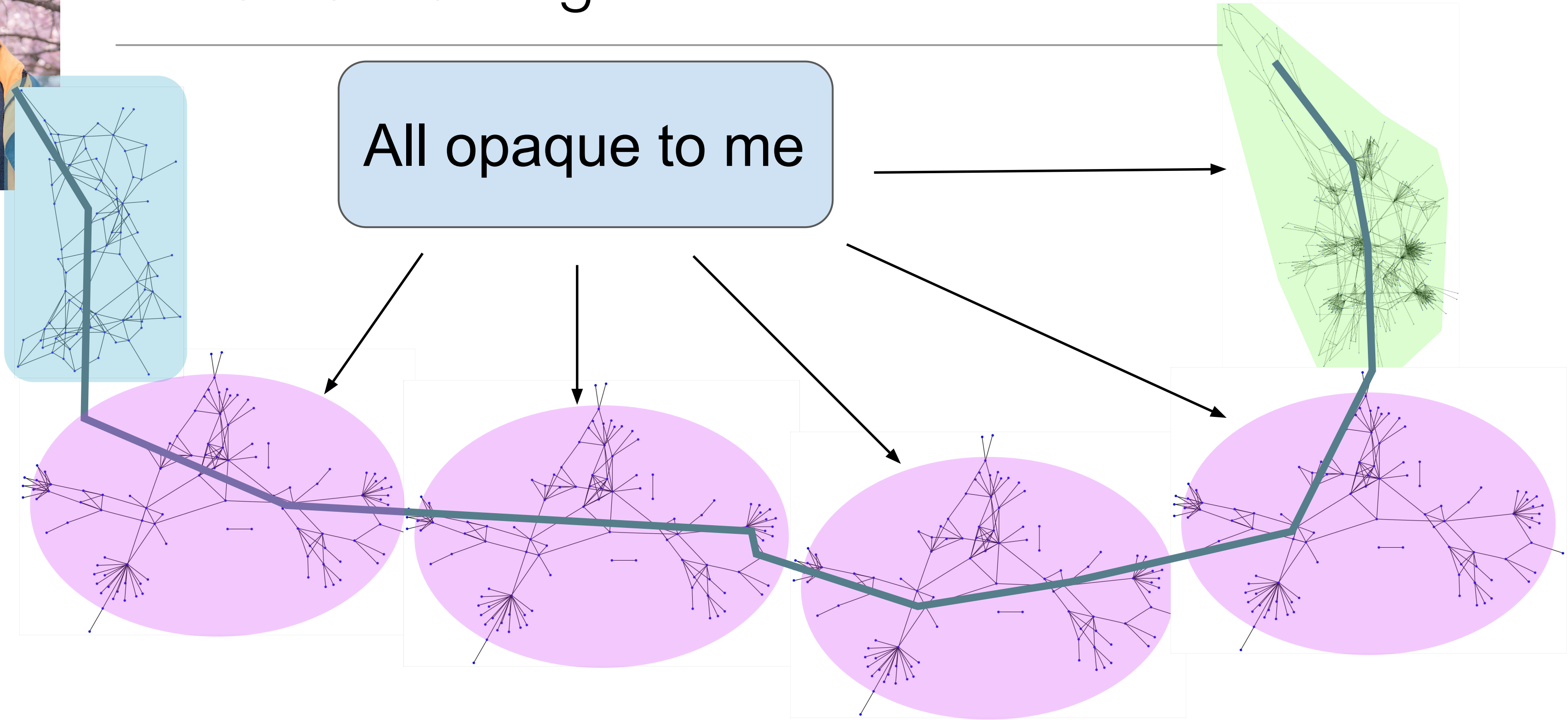
Updated by:
RFC 5709, RFC 6549, RFC 6845, RFC 6860, RFC 7474, RFC 8042, RFC 9355, RFC 9454

Author:
J. Moy

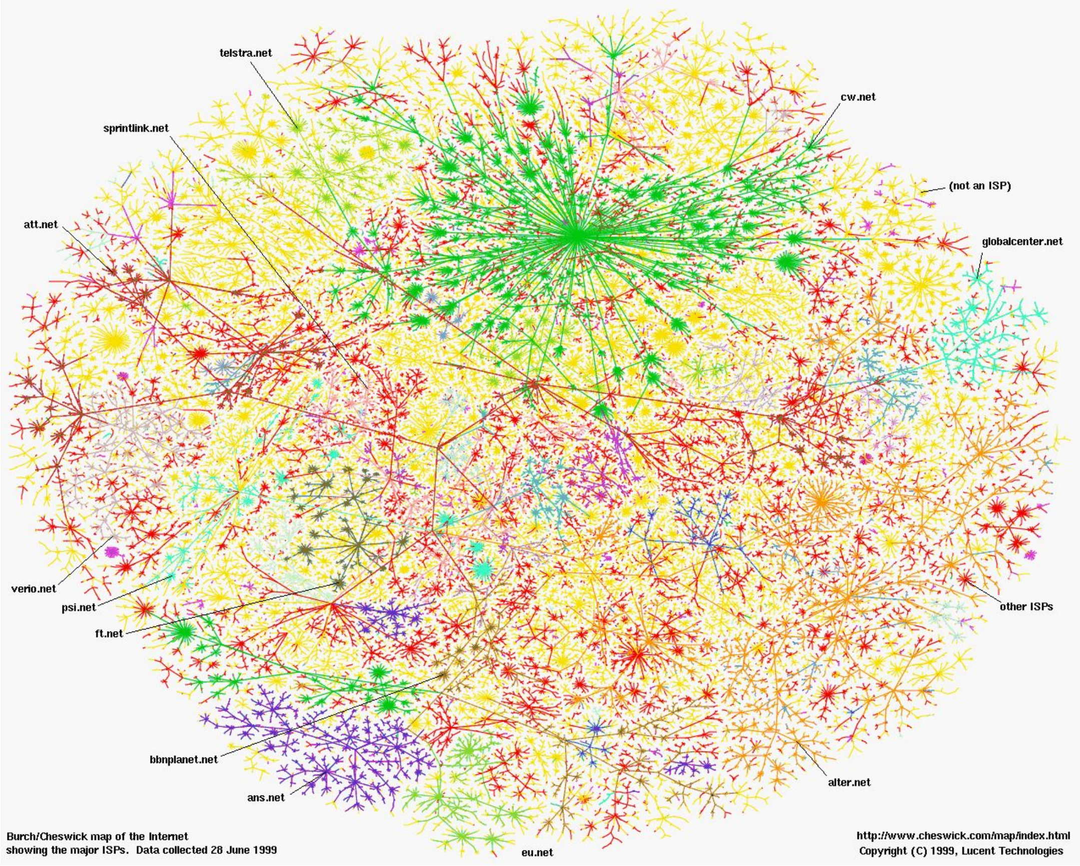
Stream:
IETF

Source:
ospf (rtg)

Internetworking



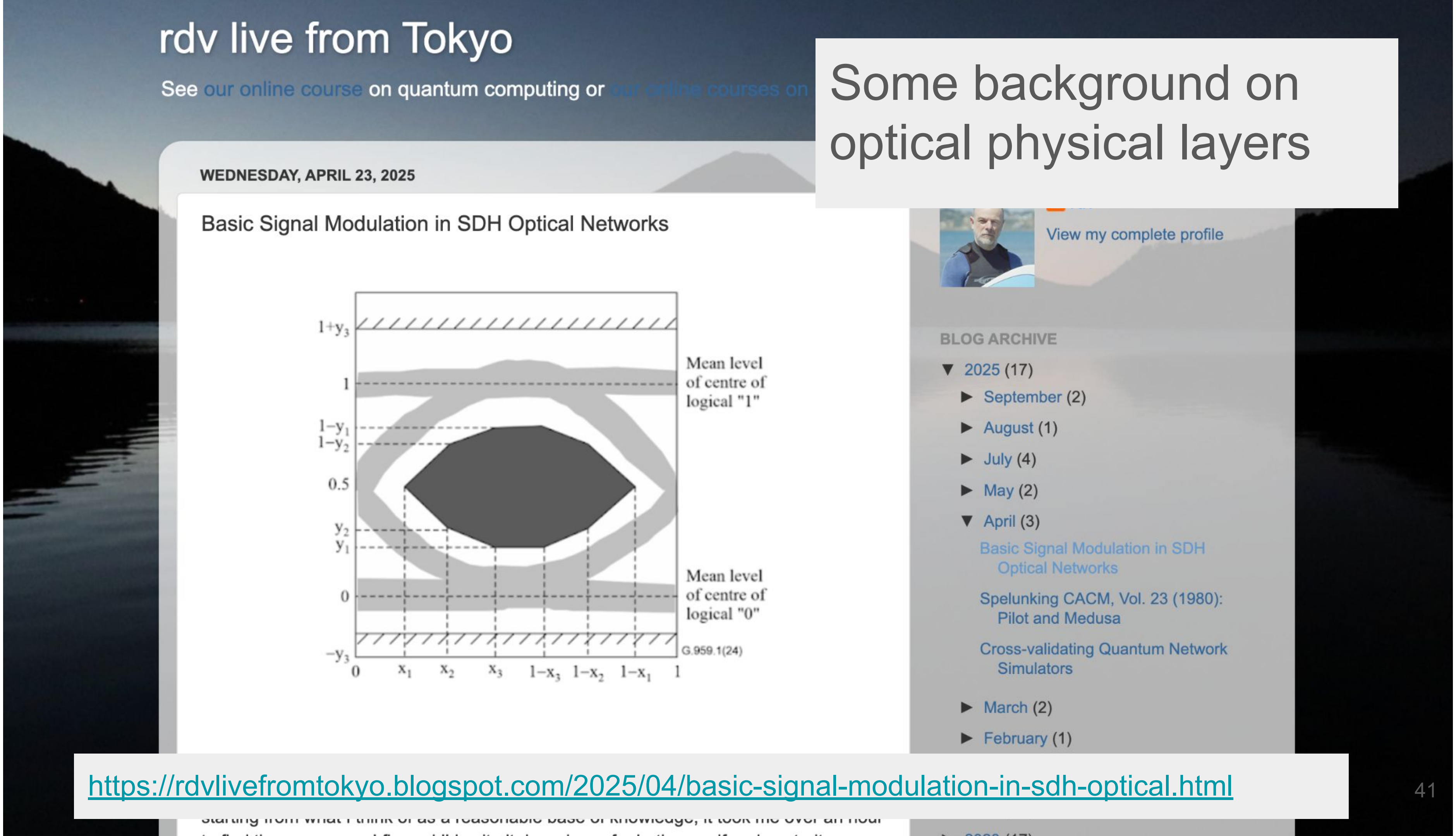
Internetworking: Map of the Internet (1999)



Internet Routing

- IGP: Interior Gateway Protocol
  - OSPF
  - IS-IS
  - RIP (long since outdated)
- EGP: Exterior Gateway Protocol
  - global choice: BGP, Border Gateway Protocol
- Also, LANs have their own routing protocol
  - e.g., switched Ethernet's spanning tree (Radja Perlman)
- (and then there are tunnels, VPNs, overlay networks, network slicing…)

Some background on optical physical layers



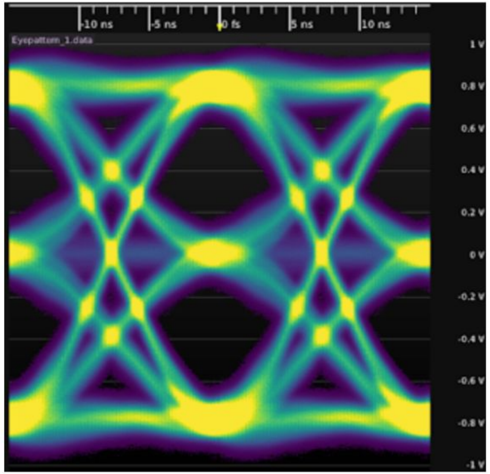
https://rdvlivefromtokyo.blogspot.com/2025/04/basic-signal-modulation-in-sdh-optical.html

rdv live from Tokyo

See our online course on quantum computing or our online courses on quantum communication.

THURSDAY, MAY 15, 2025

Modern-Day Optical Network Physical Signal Encoding



(PAM-3 eye pattern; image from Wikipedia)

This blog posting is still in editing, and is posted just so I could talk to some students about elements of the contents.

quantum information on different channels/wavelengths, and part of that involves a

ABOUT ME

rdv

View my complete profile

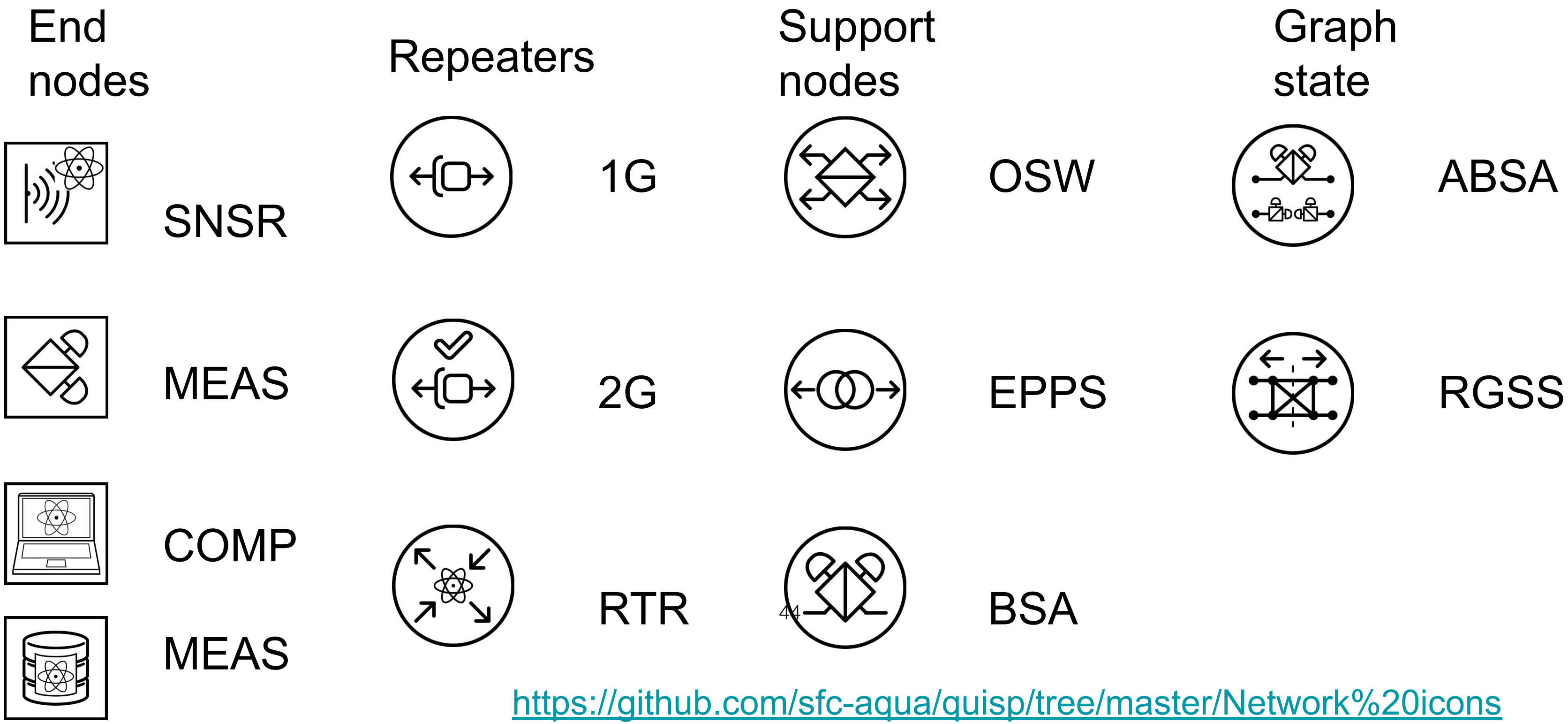
BLOG ARCHIVE

- ▼ 2025 (17)
  - ► September (2)
  - ► August (1)
  - ► July (4)
  - ▼ May (2)
    - Modern-Day Optical Network Physical Signal Encoding
    - Julia Parsons, "Code Girl", 1921-2025
  - ► April (3)
  - ► March (2)
  - ► February (1)
  - ► January (2)
- ► 2024 (28)
- ► 2021 (12)

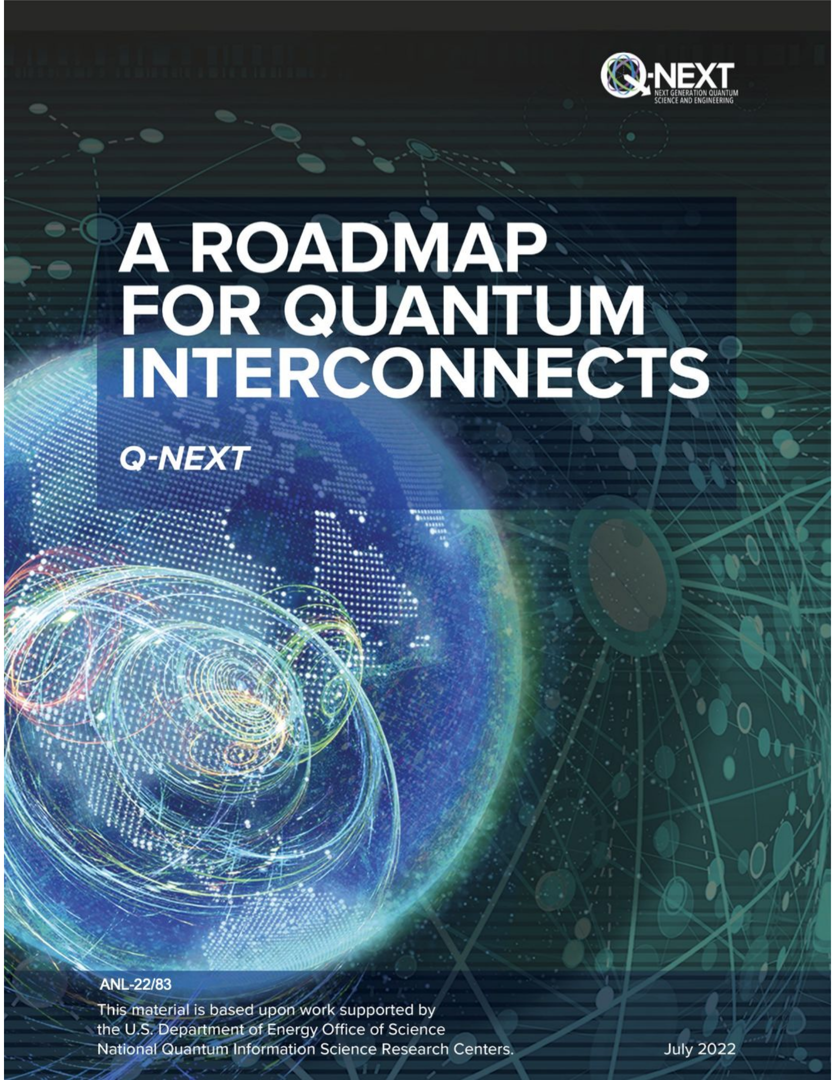
https://rdvlivefromtokyo.blogspot.com/2025/05/modern-day-optical-network-physical.html

Back to Quantum Networks, Briefly

Icon set for network diagrams



https://github.com/sfc-aqua/quisp/tree/master/Network%20icons



Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

A ROADMAP FOR QUANTUM INTERCONNECTS

Q-NEXT

ANL-22/83

This material is based upon work supported by the U.S. Department of Energy Office of Science National Quantum Information Science Research Centers.

July 2022

Table 1: Networks and Node Types (R: rare; C: common)

NODE	MI	DCN	LAN	MOB	MAN	WAN	SAT
Full computational end (COMP)	C	C	C	R	C	C	C
Memory end (MEM)	R	R	C	C	C	C	C
Sensor end (SNSR)	R	R	R	C	R	R	R
Measurement end (MEAS)	R	R	C	C	C	C	C
Repeater 1G (REP 1)	R	R	R	C	C	C	R
Repeater 2/3G (REP 2)	R	R	R	C	C	C	R
Router (RTR)	R	C	C	C	C	C	R
Bell state analyzer (BSA)	C	C	C	C	C	C	R
Entangled photon pair source (EPPS)	R	R	C	C	C	C	C
Optical switch (OSW)	C	C	C	C	C	R	R

Additional References

- Siam keynote Modular Quantum Multicomputers 2411
- van-meter-timing-regimes-seefeld-2406
- Timing regime in Quantum networks (IETF 119, Mar. 2024)
- van-meter-engineering-quantum-internet-seefeld-2206
- Naphan Benchasattabuse, PhD dissertation, Sept. 2025 https://aqua.sfc.wide.ad.jp/publications/whit3z-thesis-local-compiled.pdf
- A #QuantumComputerArchitecture Tweetstorm https://zenodo.org/records/3496597


学位記
ペンジャサッタブット，ナパン
本大学大学院政策・メディア研究科政策・メディア専攻の博士課程所定の単位を修得し学位論文の審査ならびに最終試験に合格したことを証し博士(学術)の学位を授与する
2025年9月5日
慶應義塾大学長 伊藤公平
The President of Keio University
BENCHASATTABUSE, NAPHAN
Doctor of Philosophy