Back to the Future Can lessons from networking's past help inform its future?

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On the cyclical nature of networking research and its opportunities

Infrastructure design, implementation, and operation

A progress shaped by two inter-dependent cycles

- 1. Infrastructure maturity
- 2. Advances in tools & technology

Opportunities for

- Old solutions to new problems
 - The importance of foundational work
- New solutions to old problems
- New problems

Infrastructure improvements and usage

Outline

The cycle of networking research: A "historical" perspective intertwined with own trajectory through networking research

Two representative examples:

- Network calculus
- The dual role of ML

First, a Little Bit of (INFOCOM) History

- First INFOCOM held in Las Vegas, Nevada in 1982
 2021 is 40th Anniversary!
- Held in North America until 1992 when it went to Florence, Italy (rotating across the world since then)
- Lots of papers published over those 40 years from across the networking community
- Can we use this data to get a sense for the evolution of networking research over that period?
- Basic approach: Parse proceedings and analyze frequency of terms in papers' titles

40 Years of INFOCOM Top-20

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19	data	information	virtual	design	mobile	control	application	traffic	routing	switching	broadband	optical	lan	multicast	video	application	scheduling	allocation	protocol	web	bandwidth	sensor	bandwidth	traffic	delay	mobile	analysis	traffic	mesh	control	location	dynamic	video	content	routing	sdn	video	traffic	security
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- Unsurprisingly, *"network"* (or *networks*) emerges as the most frequent word across titles every single year
- But there are a few other interesting findings

Terms in Top-20 List Over 40 Years



- 25 terms with 10 or more occurrences in top-20 list, but a relatively long tail (126 unique terms)
- A mixture of foundational themes combined with the emergence of some "hot topics" of varied lasting power

Terms in Top-20 List Over 40 Years



• With a prevalence of foundational themes in the top ranks

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Engineering

Tracking a Few Key Terms Over the Years

- Foundational themes
 - traffic & protocol

routing & scheduling



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Engineering

Tracking a Few Key Terms Over the Years

60

50

- More topical themes
 - \circ ad hoc & atm

----ad hoc

cloud & edge

Tracking a Few Key Terms Over the Years

- And let's not forget tools?
 - queue+queueing
 - \circ optimization
 - o learning



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Engineering

Tracking a Few Key Terms Over the Years

- And applications
 - o game & crowd



o video & web

A Basic Cycle of Networking Research



My Own Personal Cycle



My Own Personal Cycle



My Own Personal Cycle



Taking stock

Can this help inform our understanding of networking research?

- Two examples
 - The lasting power of fundamental work

• The effect of disruptive tools (or

technologies)

Infrastructure improvements and usage

The **Network Calculus** Example

۲ 1991: Rene Cruz seminal work 1997: RFC 2212 on ۲ 1990-2000: An explosion of results on **Guaranteed Service** scheduling disciplines and end-to-end delay bounds 1999: RFC 2598 on ۲ 2001: Le Boudec & Thiran Network ۲ Expedited Forwarding Calculus book ۲ Early 2000: Stochastic network calculus extensions 2010 onward: A new round of ۲ 2010-2020 extensions motivated by a range of specialized applications targeting better DetNet (RF) \bigcirc bounds (algebraic and optimization-IEEE TSN (802.1**) based), optimized shapers (interleaved shapers), etc.

A VERY Short Network Calculus Primer

- *Deterministic* arrival and service curves
 - Upper bound on arrivals
 - \circ Lower bound on service
- Three main results
 - Delay bound
 - Backlog bound
 - Departure curve bound
- A general "algebra" for deriving end-to-end bounds from concatenation of service elements



The Network Calculus Example

- 1991: Rene Cruz seminal work
- 1990-2000: An explosion of results on scheduling disciplines and end-to-end delay bounds
- 2001: Le Boudec & Thiran Network Calculus book
- 1997: RFC 2212 on Guaranteed Service
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 2010-201
 DetNet 4C 8578)

• IEEE TSN (802.1**)

2010 onward: A new round of extensions motivated by a range of specialized applications targeting better bounds (algebraic and optimizationbased), optimized shapers (interleaved shapers), etc.

The Network Calculus Example



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Engineering

A Case of Technology Catching Up With Science **and** triggering New Science



Scientific Foundation



Technology Availability



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Engineering

Relevant Standards



New Science



My Own Network Calculus Journey

- 1996
 - O Efficient network QoS provisioning based on per node traffic shaping
 - O Efficient support of delay and rate guarantees in an internet
- 1997
 - O Optimal multiplexing on a single link: Delay and buffer requirements
 - O Specification of Guaranteed Quality of Service
- 1998
 - O Scalable QoS provision through buffer management
- 1999
 - O Quality-of-service in packet networks: basic mechanisms and directions

- 2021
 - Minimizing network cost under latency constraints

- Scheduling and resource allocation in packet networks
 - O Basic questions of efficiency vs. complexity
 - O Guaranteed Service specifications



• A new application domain (datacenters) with new relevance and questions

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Infrastructure improvements and usage

A new application domain (datacenters) with new relevance and questions

Fast Forward 20 Years The Internet is still there

But so are many other "specialized" networks

1. Manufacturing

2. Avionics

- 3. Power plants
- 4. datacenters



- 1. Photo by <u>Science in HD</u> on <u>Unsplash</u>
- 2. Photo by Mike Petrucci on Unsplash
- 3. Photo by Tim Mossholder on Unsplash
- 4. Photo by Massimo Botturi on Unsplash

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Engineering

Fast Forward 20 Years The Internet is still there

- But so are many other "specialized" networks
 - Manufacturing
 - Avionics
 - Power plants



- The datacenter world
 - SLAs/SLOs with latency guarantees
 - A network under (mostly) single ownership
 - Controlled flow profiles

My Own Network Calculus Journey

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- Basic questions of efficiency vs. complexity \bigcirc ga years ntal 20 \checkmark
- A new application domain (datacenters) with new relevance and questions

A (Basic) Representative Problem



Scheduler & bandwidth costs

A Representative Problem

The answer varies across schedulers (from dynamic priority to simple FIFO) Unsurprisingly, an EDF scheduler needs the least bandwidth More interestingly is what to do when using simple schedulers (static priority & FIFO) On the benefits of "pre-processing" flows (reshaping) Ο $d_1 - \delta$ Flow 1 (r'_{1},b'_{1}) (r_1, b_1)

Quantifying the Cost of Simplicity



The benefits of "smart" shaping for static priority (left) and FIFO (right)





Taking Stock

Old problems become interesting again

 As the technology cycle evolves, new application areas open-up and impractical or expensive solutions become feasible often with a new interesting twist

Foundational work never grows old

 Deterministic networking and network calculus as a case in point

What About Technology Disruption





Top 10 INFOCOM'21 terms

Term	Occurrences
network	69
learning	52
edge	23
system	19
wireless	18
reinforcement	16
reinforcement deep	16 14
reinforcement deep distributed	16 14 14
reinforcementdeepdistributedfederated	16 14 14 13
reinforcementdeepdistributedfederatedmobile	16 14 14 13 12

A Dual Role for ML/DL

As a source of new problems

As a source of new solutions

A New (Old) Problem

Latency-sensitive edge detection/classification

Weak (device) vs. strong (edge) classifier





A Basic Question

To offload or not to offload?

A statistical optimization problem under constraints



A Basic Solution

An MDP formulation for threshold policies and iid inputs

A traditional approach with a twist to account for the statistical behavior of the classifier when defining the offloading metric

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ML/DL as a Source of New Solutions

Networks as a data-driven problem space

• A combination of scale and a move to more systematic instrumentation

Numerous application areas with abundant data available, *e.g.*,

- Network management & troubleshooting
- Network security & monitoring
- Congestion control

Multiple recent surveys on applying ML to networking problems (and its pitfalls)

Clearly a new arrow in our quiver

ML/DL as a Source of New Solutions

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Multiple recent surveys on applying ML to networking problems (and its pitfalls)

Clearly a new arrow in our quiver

A Representative Example (again)

Weak (device) vs. strong (edge) classifier

But now w/ a more complex, *e.g.*, correlated input process



The MDP formulation of the base problem points to DQN (Deep Q-Learning) as a possible approach to tackling correlated inputs

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We are in a networked world and Sun's old slogan **"The network is the computer"** is today's reality

• But this does not mean there are no networking problems left to solve. To the contrary.

What is old can be new again

• Technology evolution can make *foundational* work relevant again, *e.g.*, the network calculus example

What is new can create new problems

• Technology disruption creates *new versions* of traditional problems, *e.g.,* incorporating *learning* components into distributed computations

What is new teatingsolve old problems

• Technology disruption creates *new solutions* to traditional problems, *e.g.*, incorporating learning components into distributed computations

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What is new can create new problements

• Technology disruption creates *new versions* of traditional problems, *e.g.*, incorporating *learning* components into distributed computations

What is new carries olve old problems

• The network as a source of data from which we can *learn* to make it better

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Acknowledgments

Throughout my career, I have benefited from collaborating with many great students and colleagues. They deserve much, if not most of the credit for the technical contributions I have been referring to in this talk.

Any insight this talk may have imparted likely comes from those contributors, while errors are all mine.

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Thank You!

QUESTIONS?