Washington University in St. Louis

Engineering

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

Roch Guérin

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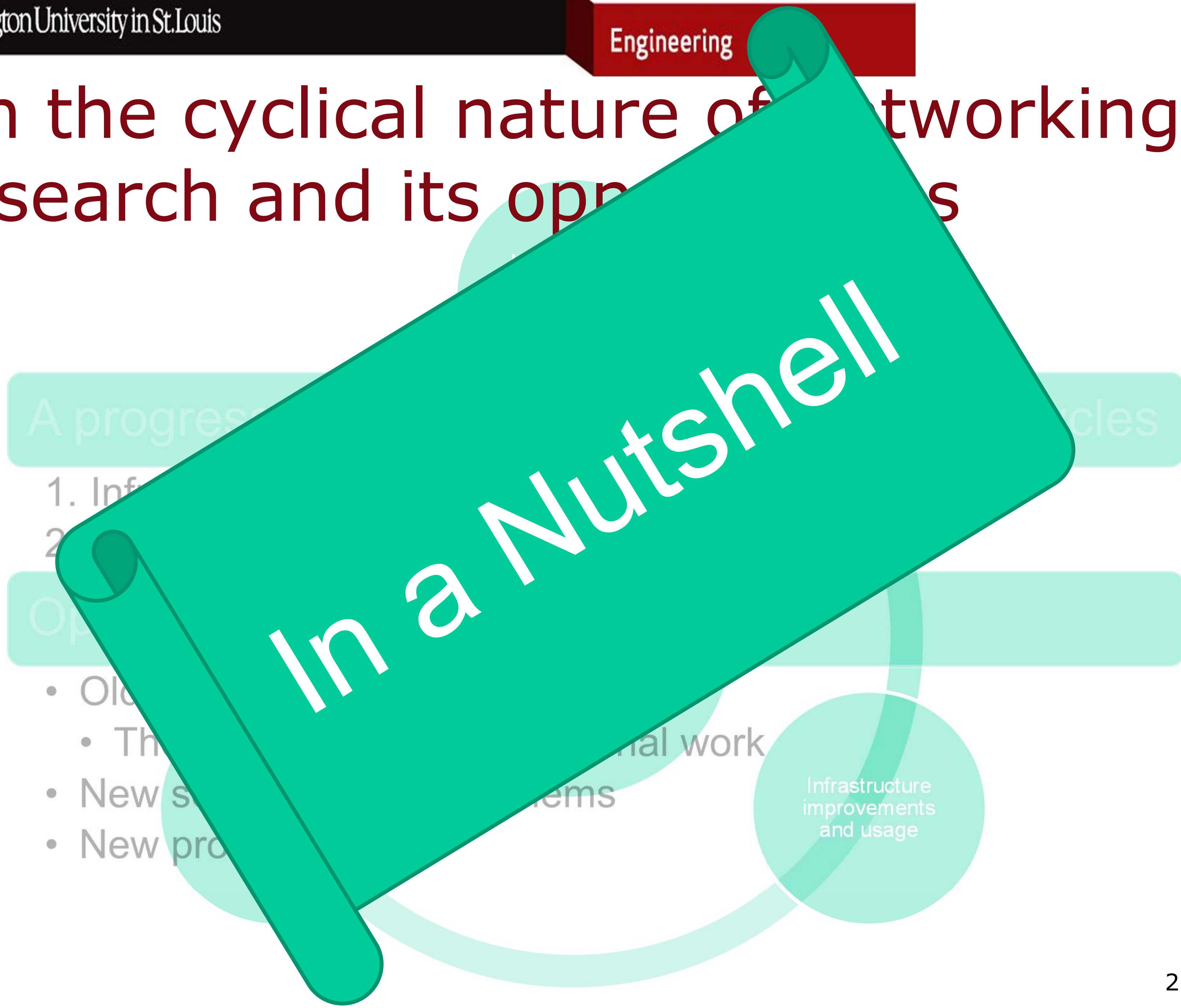
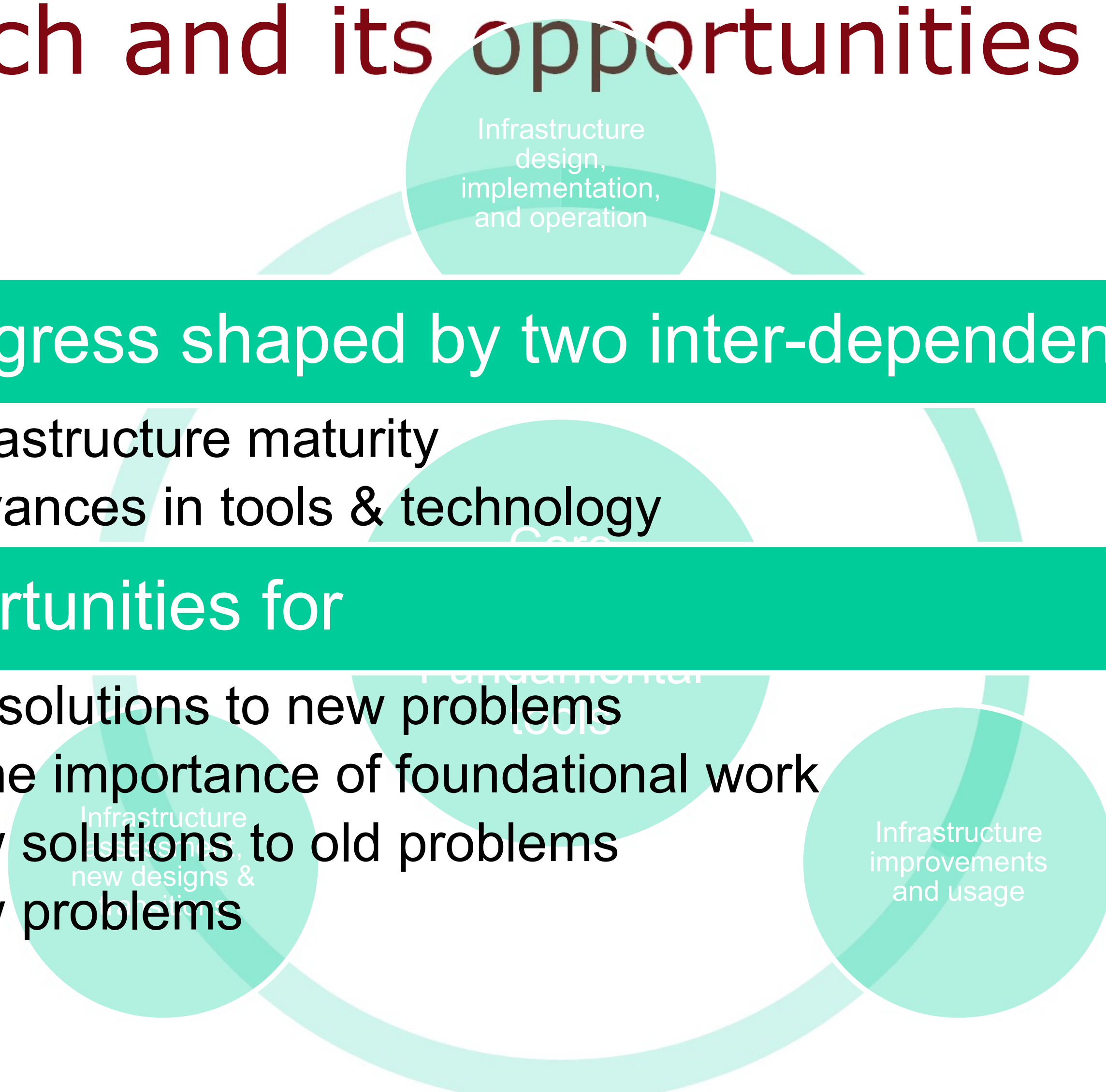
On the cyclical nature of ... tworking research and its opp... s



On the cyclical nature of networking research and its opportunities



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

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

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
1	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**
2	computer	System	local	packet	protocol	protocol	performance	system	performance	performance	atm	atm	atm	atm	atm	atm	atm	control	control
3	local	distributed	control	radio	radio	performance	system	packet	analysis	analysis	Analysis	analysis	traffic	traffic	traffic	control	control	multicast	multicast
4	protocol	protocol	protocol	protocol	access	analysis	protocol	performance	packet	packet	Performance	routing	control	performance	protocol	performance	performance	routing	algorithm
5	system	local	packet	analysis	analysis	distributed	analysis	analysis	atm	protocol	Traffic	performance	performance	control	system	analysis	wireless	internet	tcp
6	communication	packet	distributed	mobile	packet	system	packet	protocol	protocol	routing	Control	protocol	routing	analysis	performance	multicast	multicast	performance	traffic
7	distributed	analysis	integrated	performance	system	access	communication	Algorithm	communication	atm	high-speed	traffic	analysis	routing	control	protocol	routing	Service	internet
8	experimental	communication	performance	multihop	local	area	distributed	control	ring	control	Packet	control	bandwidth	video	analysis	routing	algorithm	Qos	performance
9	performance	integrated	access	access	performance	local	access	isdn	control	switch	Routing	application	protocol	packet	algorithm	service	packet	Traffic	routing
10	access	algorithm	analysis	channel	area	algorithm	routing	area	switch	systems	Switch	delay	management	optical	service	traffic	traffic	mobile	wireless
11	addressing	application	data	ring	control	channel	switching	distributed	access	algorithm	Bandwidth	buffer	dynamic	protocol	delay	design	analysis	wireless	admission
12	allocation	area	area	algorithm	distributed	communication	algorithm	architecture	systems	distributed	Buffer	communication	cell	communication	switch	abr	distributed	flow	packet
13	analysis	broadcast	adaptive	allocation	link	aloha	computer	communication	token	traffic	Flow	queueing	communication	virtual	multicast	algorithm	service	bandwidth	service
14	architecture	computer	architecture	bandwidth	channel	integrated	control	data	evaluation	communication	Queue	service	congestion	admission	routing	dynamic	adaptive	ip	analysis
15	area	control	buffer	computer	lan	ring	integrated	radio	service	design	Queueing	speed	optical	multimedia	model	rate	internet	tcp	fair
16	bases	experiences	flow	control	algorithm	token	load	access	switching	access	Switching	integrated	switch	wavelength	scheduling	multimedia	tcp	access	qos
17	bus	file	high	csma	allocation	allocation	architecture	high	traffic	buffer	protocol	access	algorithm	allocation	allocation	optical	channel	atm	application
18	cma/cd	implementation	systems.	data	approximation	architecture	design	lan	distributed	integrated	application	multiplexing	application	design	bandwidth	admission	queueing	protocol	bandwidth
19	data	multihop	virtual	design	mobile	control	application	traffic	routing	switching	broadband	optical	lan	multicast	video	application	scheduling	allocation	protocol
20	database	performance	algorithm	distributed	routing	lan	area	channel	area	channel	video	priority	lightwave	switch	communication	flow	video	analysis	congestion

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**	**network**
2	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	data	data	wireless	data	learning
3	routing	wavelength	ad hoc	routing	sensor	sensor	sensor	sensor	sensor	sensor	sensor	sensor	data	data	data	wireless	mobile	data	wireless	edge
4	multicast	routing	routing	ad-hoc	routing	routing	routing	routing	routing	system	data	data	mobile	system	mobile	mobile	cloud	mobile	learning	data
5	control	multicast	control	sensor	control	distributed	scheduling	data	scheduling	routing	scheduling	scheduling	energy	cloud	system	cloud	crowd	system	scheduling	distributed
6	ad hoc	tcp	algorithm	control	ad hoc	control	ad-hoc	distributed	algorithm	scheduling	delay	distributed	sensor	mobile	cloud	scheduling	wireless	learning	mobile	mobile
7	network	control	packet	tcp	distributed	scheduling	protocol	protocol	distributed	access	radio	mobile	scheduling	scheduling	distributed	system	social	online	edge	scheduling
8	analysis	scheduling	analysis	wavelength	algorithm	algorithm	algorithm	coding	control	delay	system	control	cloud	traffic	dynamic	energy	communication	scheduling	service	deep
9	packet	traffic	performance	algorithms	protocol	ad hoc	control	mesh	system	coding	cognitive	cloud	system	cooperative	heterogeneous	communication	device	communication	system	system
10	protocol	ad hoc	tcp	performance	internet	data	distributed	scheduling	delay	data	mobile	cognitive	distributed	distributed	radio	dynamic	system	crowd	computing	wireless
11	traffic	allocation	internet	power	tcp	design	channel	traffic	peer-to-peer	distributed	energy	radio	privacy	user	crowd	sensor	traffic	service	distributed	online
12	internet	packet	scheduling	system	packet	service	mesh	access	coding	mobile	access	traffic	cognitive	privacy	sensor	wi-fi	analysis	device	cloud	service
13	service	energy	service	traffic	analysis	traffic	power	ad hoc	mobile	ad hoc	routing	channel	radio	sensor	spectrum	algorithm	online	access	communication	adaptive
14	dynamic	internet	traffic	scheduling	peer-to-peer	analysis	analysis	delay	protocol	control	spectrum	delay	spectrum	service	device	sdn	application	distributed	online	computing
15	tcp	management	ip	service	power	peer-to-peer	detection	energy	analysis	multi-hop	traffic	routing	algorithm	delay	scheduling	service	scheduling	application	placement	energy
16	scheduling	protocol	multicast	internet	energy	mobile	multicast	packet	capacity	analysis	allocation	spectrum	analysis	social	algorithm	channel	service	cloud	deep	optimization
17	algorithms	switch	systems	mobile	scheduling	overlay	performance	mobile	packet	model	analysis	energy	traffic	cognitive	applications	content	energy	edge	resource	channel
18	ip	analysis	optical	analysis	throughput	802.11	delay	throughput	model	traffic	social	analysis	channel	protocol	channel	optimization	privacy	privacy	sensor	sdn
19	web	bandwidth	sensor	bandwidth	traffic	delay	mobile	analysis	traffic	mesh	control	location	dynamic	video	content	routing	sdn	video	traffic	security
20	management	performance	wavelength	application	ip	internet	multi-hop	capacity	mesh	peer-to-peer	multicast	system	communication	applications	online	video	dynamic	iot	iot	video

- Unsurprisingly, ***"network"*** (or *networks*) emerges as the most frequent word across titles every single year
- But there are a few other interesting findings

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40 Years of INFOCOM Top-20

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1	network	network	networks	networks	networks	network	network	network	network	network	network	network	network	network	network	network	network	network	network	networks
2	computer	system	local	packet	**Protocol**	**protocol**	performance	system	performance	performance	atm	atm	atm	atm	atm	atm	atm	control	control	wireless
3	local	packet	control	radio	Radio	Performance	system	packet	analysis	analysis	analysis	analysis	traffic	traffic	traffic	control	control	multicast	multicast	routing
4	**protocol**	distributed	**protocol**	**protocol**	Access	analysis	**protocol**	performance	packet	Packet	performance	routing	control	performance	**protocol**	Performance	performance	routing	algorithm	multicast
5	system	**Protocol**	packet	analysis	analysis	distributed	Analysis	analysis	Atm	**Protocol**	traffic	performance	performance	control	system	Analysis	wireless	internet	tcp	control
6	communication	local	distributed	mobile	packet	system	packet	**protocol**	**Protocol**	routing	control	**Protocol**	routing	analysis	performance	Multicast	multicast	performance	traffic	ad hoc
7	distributed	analysis	integrated	performance	system	access	communication	algorithm	communication	atm	high-speed	Traffic	analysis	routing	control	**Protocol**	routing	service	internet	network
8	experimental	communication	performance	multihop	local	area	distributed	control	ring	control	packet	Control	bandwidth	video	analysis	routing	algorithm	qos	performance	analysis
9	performance	control	access	access	performance	local	access	isdn	control	switch	routing	Application	**protocol**	Packet	algorithm	service	packet	traffic	routing	packet
10	access	integrated	analysis	channel	area	algorithm	routing	area	switch	systems	switch	Delay	management	Optical	service	traffic	traffic	mobile	wireless	**protocol**
11	addressing	performance	data	ring	control	channel	switching	distributed	access	algorithm	bandwidth	Buffer	dynamic	**protocol**	delay	design	analysis	wireless	admission	traffic
12	allocation	algorithm	area	algorithm	distributed	communication	algorithm	architecture	systems	distributed	buffer	Communication	cell	communication	switch	abr	distributed	flow	packet	internet
13	analysis	application	adaptive	allocation	link	aloha	computer	communication	token	traffic	flow	Queueing	communication	virtual	multicast	algorithm	service	bandwidth	service	service
14	architecture	area	architecture	bandwidth	channel	integrated	control	data	evaluation	communication	queue	Service	congestion	admission	routing	dynamic	adaptive	ip	analysis	dynamic
15	area	broadcast	buffer	computer	lan	ring	integrated	radio	service	design	queueing	Speed	optical	multimedia	model	rate	internet	tcp	fair	tcp
16	bases	computer	flow	control	algorithm	token	load	access	switching	access	switching	Integrated	switch	wavelength	scheduling	multimedia	tcp	access	qos	scheduling
17	bus	file	high	csma	allocation	allocation	architecture	high	traffic	buffer	**protocol**	Access	algorithm	allocation	allocation	optical	channel	atm	application	algorithms
18	csma-cd	implementation	systems.	data	approximation	architecture	design	lan	distributed	integrated	application	multiplexing	application	design	bandwidth	admission	queueing	**protocol**	bandwidth	ip
19	data	information	virtual	design	mobile	control	application	traffic	routing	switching	broadband	optical	lan	multicast	video	application	scheduling	allocation	**protocol**	web
20	database	multihop	algorithm	distributed	routing	lan	area	channel	area	channel	video	priority	lightwave	switch	communication	flow	video	analysis	congestion	management

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	network	network	network	network	network	network	network	network	network	network	network	network	network	network	network	network	network	network	network
2	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	data	data	wireless	data	learning
3	wavelength	ad hoc	routing	sensor	sensor	sensor	sensor	sensor	sensor	sensor	sensor	data	data	data	wireless	mobile	data	wireless	edge
4	routing	routing	ad-hoc	routing	routing	routing	routing	routing	system	data	data	mobile	system	mobile	mobile	cloud	mobile	learning	data
5	multicast	control	sensor	control	distributed	scheduling	data	scheduling	routing	scheduling	scheduling	energy	cloud	system	cloud	crowd	system	scheduling	distributed
6	tcp	algorithm	control	ad hoc	control	ad-hoc	distributed	algorithm	scheduling	delay	distributed	sensor	mobile	cloud	scheduling	wireless	learning	mobile	mobile
7	control	packet	tcp	distributed	scheduling	**protocol**	**protocol**	distributed	access	radio	mobile	scheduling	scheduling	distributed	system	social	online	edge	scheduling
8	scheduling	analysis	wavelength	algorithm	algorithm	algorithm	coding	control	delay	system	control	cloud	traffic	dynamic	energy	communication	scheduling	service	deep
9	traffic	performance	algorithms	**protocol**	ad hoc	control	mesh	system	coding	cognitive	cloud	system	cooperative	heterogeneous	communication	device	communication	system	system
10	ad hoc	tcp	performance	internet	data	distributed	scheduling	delay	data	mobile	cognitive	distributed	distributed	radio	dynamic	system	crowd	computing	wireless
11	allocation	internet	power	tcp	design	channel	traffic	peer-to-peer	distributed	energy	radio	privacy	user	crowd	sensor	traffic	service	distributed	online
12	packet	scheduling	system	packet	service	mesh	access	coding	mobile	access	traffic	cognitive	privacy	sensor	wi-fi	analysis	device	cloud	service
13	energy	service	traffic	analysis	traffic	power	ad hoc	mobile	ad hoc	routing	channel	radio	sensor	spectrum	algorithm	online	access	communication	adaptive
14	internet	traffic	scheduling	peer-to-peer	analysis	analysis	delay	**protocol**	control	spectrum	delay	spectrum	service	device	sdn	application	distributed	online	computing
15	management	ip	service	power	peer-to-peer	detection	energy	analysis	multi-hop	traffic	routing	algorithm	delay	scheduling	service	scheduling	application	placement	energy
16	**protocol**	multicast	internet	energy	mobile	multicast	packet	capacity	analysis	allocation	spectrum	analysis	social	algorithm	channel	service	cloud	deep	optimization
17	switch	systems	mobile	scheduling	overlay	performance	mobile	packet	model	analysis	energy	traffic	cognitive	applications	content	energy	edge	resource	channel
18	analysis	optical	analysis	throughput	802.11	delay	throughput	model	traffic	social	analysis	channel	protocol	channel	optimization	privacy	privacy	sensor	sdn
19	bandwidth	sensor	bandwidth	traffic	delay	mobile	analysis	traffic	mesh	control	location	dynamic	video	content	routing	sdn	video	traffic	security
20	performance	wavelength	application	ip	internet	multi-hop	capacity	mesh	peer-to-peer	multicast	system	communication	applications	online	video	dynamic	iot	iot	video

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2	computer	system	local	packet	protocol	protocol	performance	system	performance	performance	atm	atm	atm
3	local	packet	control	radio	radio	performance	system	packet	analysis	analysis	analysis	analysis	traffic
4	protocol	distributed	protocol	protocol	access	analysis	protocol	performance	packet	packet	performance	routing	control
5	system	protocol	packet	analysis	analysis	distributed	analysis	analysis	atm	protocol	traffic	performance	performance
6	communication	local	distributed	mobile	packet	system	packet	protocol	protocol	routing	control	protocol	routing
7	distributed	analysis	integrated	performance	system	access	communication	algorithm	communication	atm	high-speed	traffic	analysis
8	experimental	communication	performance	multihop	local	area	distributed	control	ring	control	packet	control	bandwidth
9	performance	control	access	access	performance	local	access	isdn	control	switch	routing	application	protocol
10	access	integrated	analysis	channel	area	algorithm	routing	area	switch	systems	switch	delay	management
11	addressing	performance	data	ring	control	channel	switching	distributed	access	algorithm	bandwidth	buffer	dynamic
12	allocation	algorithm	area	algorithm	distributed	communication	algorithm	architecture	systems	distributed	buffer	communication	cell
13	analysis	application	adaptive	allocation	link	aloha	computer	communication	token	traffic	flow	queueing	communication
14	architecture	area	architecture	bandwidth	channel	integrated	control	data	evaluation	communication	queue	service	congestion
15	area	broadcast	buffer	computer	lan	ring	integrated	radio	service	design	queueing	speed	optical
16	bases	computer	flow	control	algorithm	token	load	access	switching	access	switching	integrated	switch
17	bus	file	high	csma	allocation	allocation	architecture	high	traffic	buffer	protocol	access	algorithm
18	csma-cd	implementation	systems.	data	approximation	architecture	design	lan	distributed	integrated	application	multiplexing	application
19	data	information	virtual	design	mobile	control	application	traffic	routing	switching	broadband	optical	lan
20	database	multihop	algorithm	distributed	routing	lan	area	channel	area	channel	video	priority	lightwave

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1	network	network	network	network	network	network	networks	network	network	network	network	network	network
2	atm	atm	atm	atm	control	control	wireless	Wireless	wireless	wireless	wireless	wireless	wireless
3	traffic	traffic	control	control	multicast	multicast	routing	Wavelength	ad hoc	routing	sensor	sensor	sensor
4	performance	protocol	performance	performance	routing	algorithm	multicast	Routing	routing	ad-hoc	routing	routing	routing
5	control	system	analysis	wireless	internet	tcp	control	Multicast	control	sensor	control	distributed	scheduling
6	analysis	performance	multicast	multicast	performance	traffic	ad hoc	Tcp	algorithm	control	ad hoc	control	ad-hoc
7	routing	control	protocol	routing	service	internet	network	Control	packet	tcp	distributed	scheduling	protocol
8	video	analysis	routing	algorithm	qos	performance	analysis	Scheduling	analysis	wavelength	algorithm	algorithm	algorithm
9	packet	algorithm	service	packet	traffic	routing	packet	Traffic	performance	algorithms	protocol	ad hoc	control
10	optical	service	traffic	traffic	mobile	wireless	protocol	ad hoc	tcp	Performance	internet	data	distributed
11	protocol	delay	design	analysis	wireless	admission	traffic	Allocation	internet	**Power**	tcp	design	channel
12	communication	switch	abr	distributed	flow	packet	internet	Packet	scheduling	System	packet	service	mesh
13	virtual	multicast	algorithm	service	bandwidth	service	service	**Energy**	service	Traffic	analysis	traffic	**power**
14	admission	routing	dynamic	adaptive	ip	analysis	dynamic	Internet	traffic	scheduling	peer-to-peer	analysis	analysis
15	multimedia	model	rate	internet	tcp	fair	tcp	management	ip	service	**power**	peer-to-peer	detection
16	wavelength	scheduling	multimedia	tcp	access	qos	scheduling	protocol	multicast	internet	**energy**	mobile	multicast
17	allocation	allocation	optical	channel	atm	application	algorithms	switch	systems	mobile	scheduling	overlay	performance
18	design	bandwidth	admission	queueing	protocol	bandwidth	ip	analysis	optical	analysis	throughput	802.11	delay
19	multicast	video	application	scheduling	allocation	protocol	web	bandwidth	sensor	bandwidth	traffic	delay	mobile
20	switch	communication	flow	video	analysis	congestion	management	performance	wavelength	application	ip	internet	multi-hop

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	network	network	network	network	network	network	network	network	network	network	network	network	network
2	wireless	wireless	wireless	wireless	wireless	wireless	wireless	wireless	data	data	wireless	data	learning
3	sensor	sensor	sensor	sensor	sensor	data	data	data	wireless	mobile	data	wireless	edge
4	routing	routing	system	data	data	mobile	system	mobile	mobile	cloud	mobile	learning	data
5	data	scheduling	routing	scheduling	scheduling	**energy**	cloud	system	cloud	crowd	system	scheduling	distributed
6	distributed	algorithm	scheduling	delay	distributed	sensor	mobile	cloud	scheduling	wireless	learning	mobile	mobile
7	protocol	distributed	access	radio	mobile	scheduling	scheduling	distributed	system	social	online	edge	scheduling
8	coding	control	delay	system	control	cloud	traffic	dynamic	**energy**	communication	scheduling	service	deep
9	mesh	system	coding	cognitive	cloud	system	cooperative	heterogeneous	communication	device	communication	system	system
10	scheduling	delay	data	mobile	cognitive	distributed	distributed	radio	dynamic	system	crowd	computing	wireless
11	traffic	peer-to-peer	distributed	**energy**	Radio	privacy	user	crowd	sensor	traffic	service	distributed	online
12	access	coding	mobile	access	Traffic	cognitive	privacy	sensor	wi-fi	analysis	device	cloud	service
13	ad hoc	mobile	ad hoc	routing	Channel	radio	sensor	spectrum	algorithm	online	access	communication	adaptive
14	delay	protocol	control	spectrum	Delay	spectrum	service	device	sdn	application	distributed	online	computing
15	**energy**	analysis	multi-hop	traffic	Routing	algorithm	delay	scheduling	service	scheduling	application	placement	**energy**
16	packet	capacity	analysis	allocation	Spectrum	analysis	social	algorithm	channel	service	cloud	deep	optimization
17	mobile	packet	model	analysis	**Energy**	traffic	cognitive	applications	content	**energy**	edge	resource	channel
18	throughput	model	traffic	social	Analysis	channel	protocol	channel	optimization	privacy	privacy	sensor	sdn
19	analysis	traffic	mesh	control	location	dynamic	video	content	routing	sdn	video	traffic	security
20	capacity	mesh	peer-to-peer	multicast	system	communication	applications	online	video	dynamic	iot	iot	video

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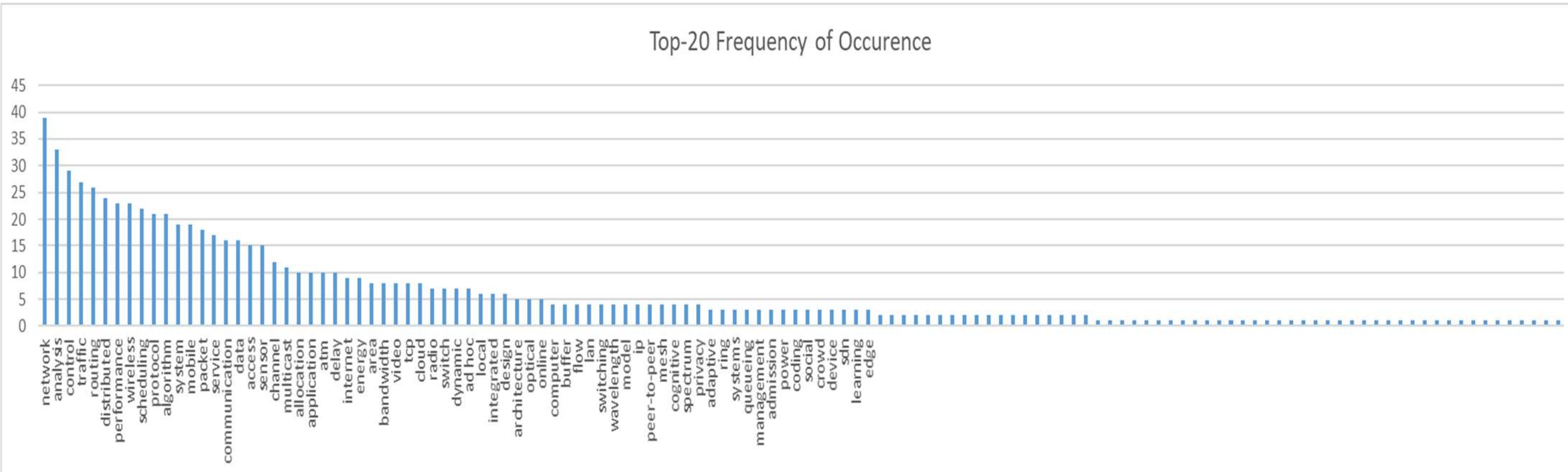
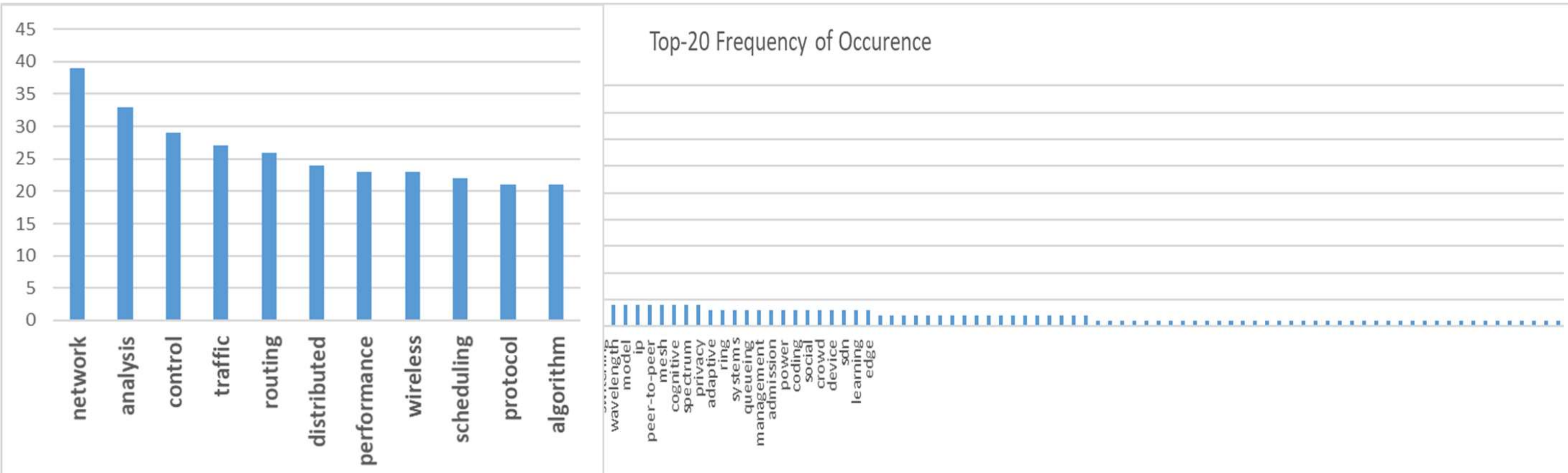
- But there are a few other interesting findings

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

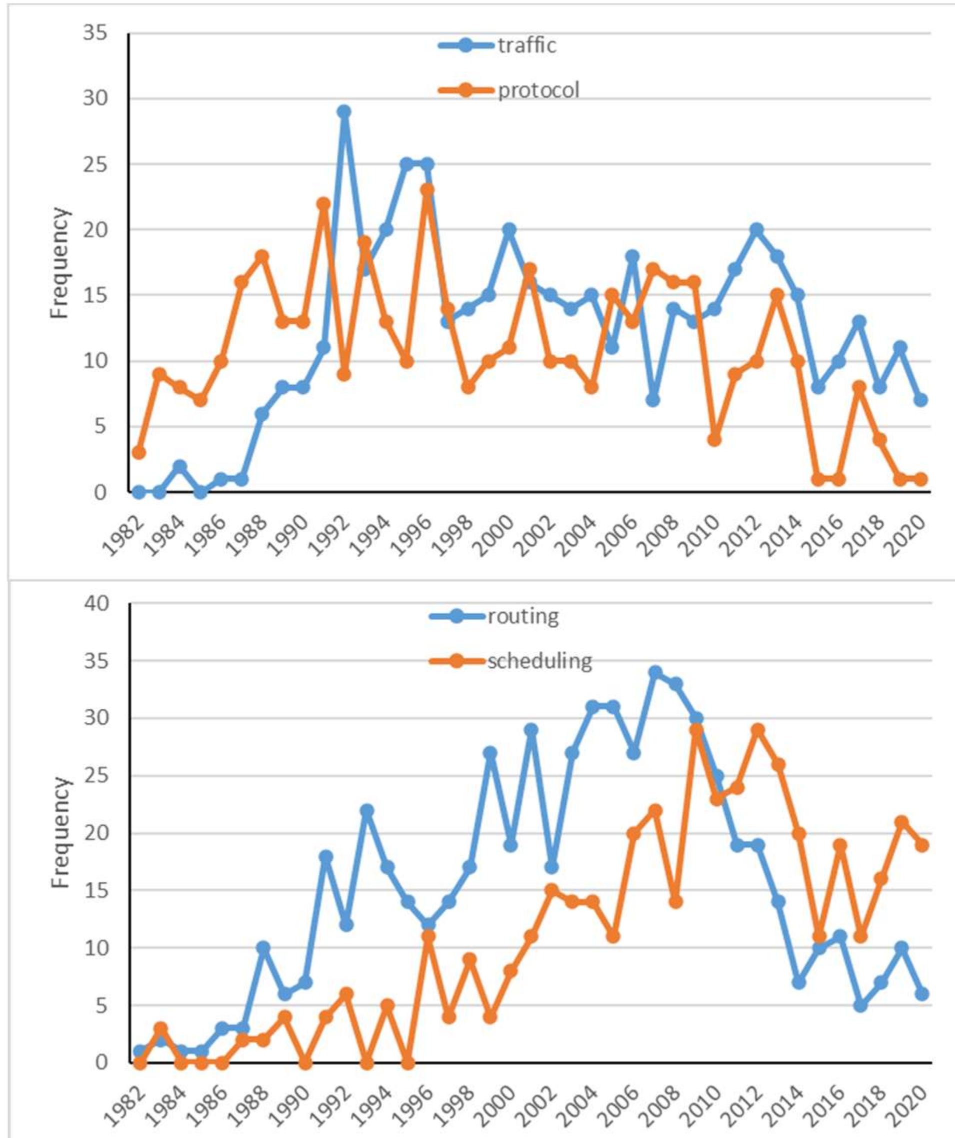
Terms in Top-20 List Over 40 Years



- With a prevalence of foundational themes in the top ranks

Tracking a Few Key Terms Over the Years

- Foundational themes
    - traffic & protocol
    - routing & scheduling



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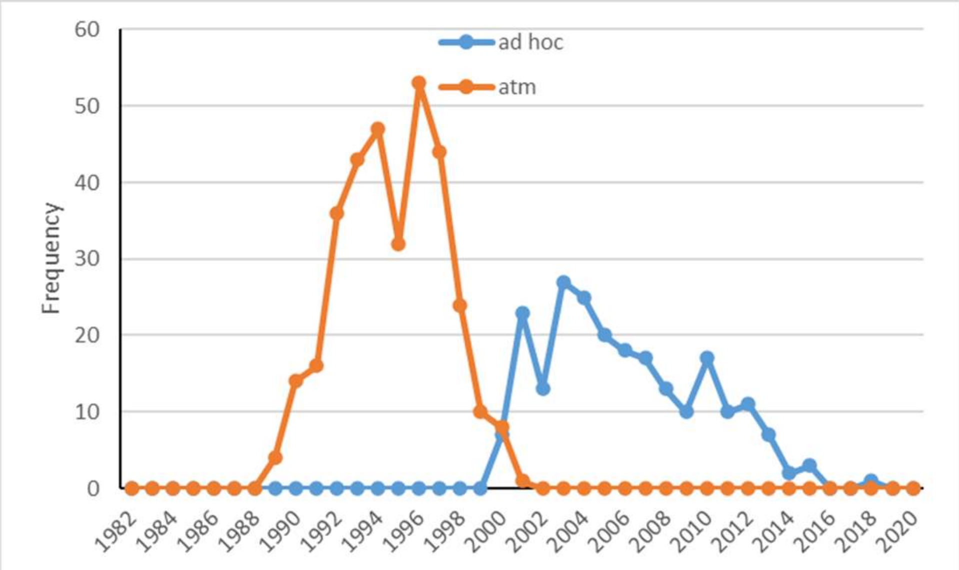
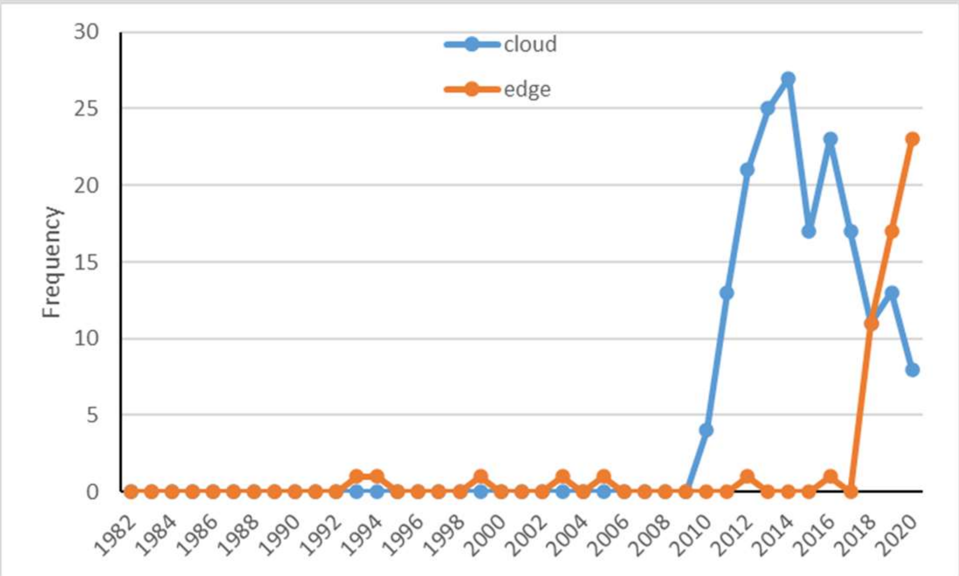
Tracking a Few Key Terms Over the Years

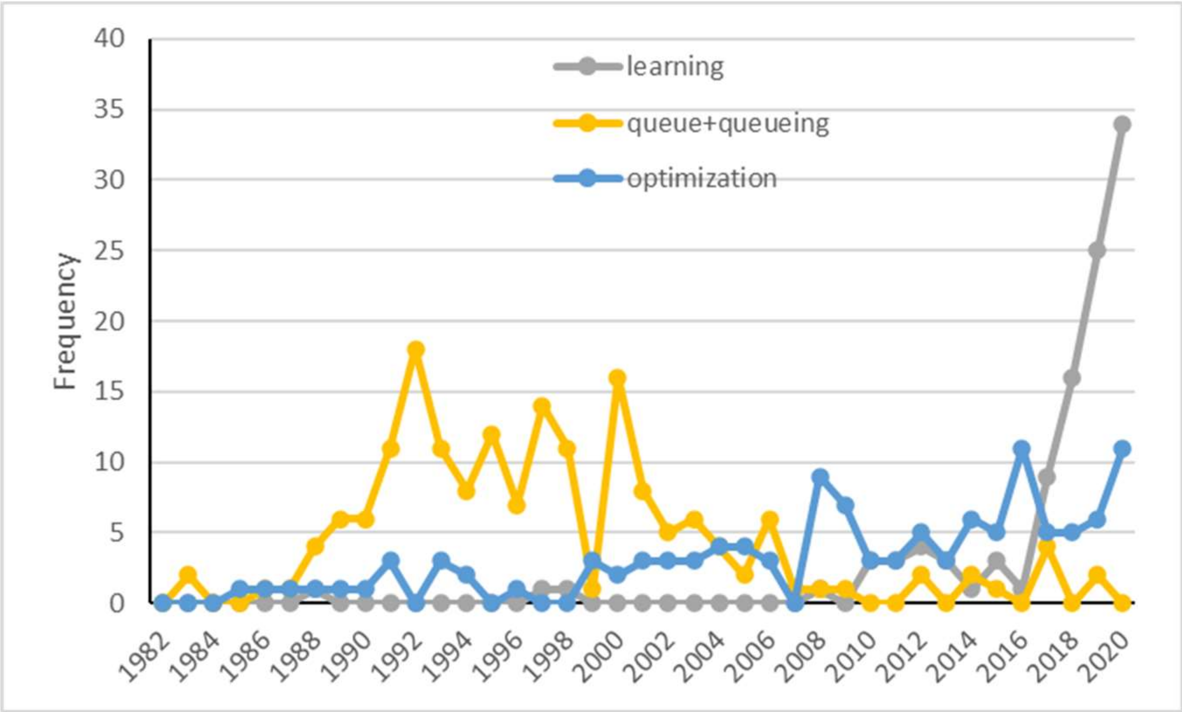
- More topical themes
  - ad hoc & atm
  - cloud & edge





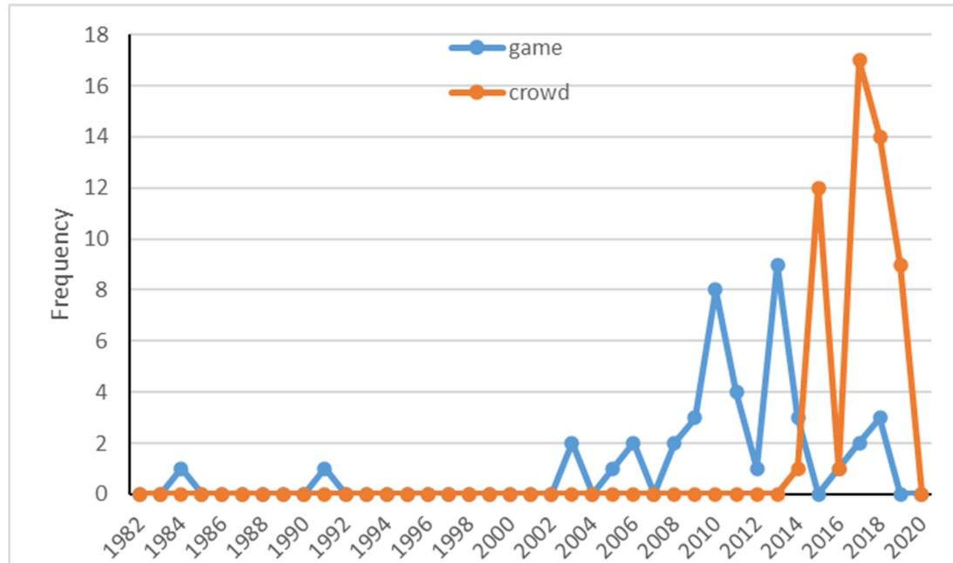
Tracking a Few Key Terms Over the Years

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

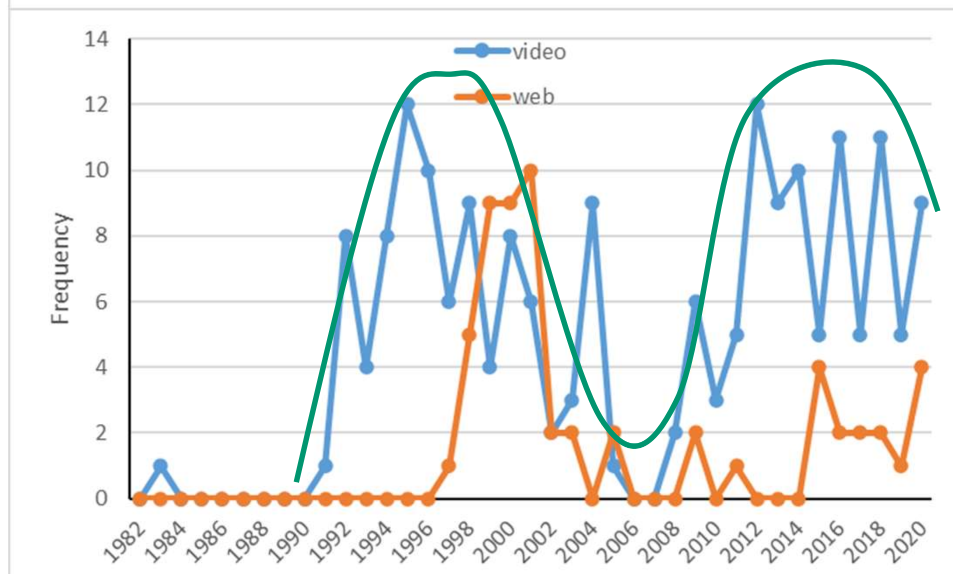


Tracking a Few Key Terms Over the Years

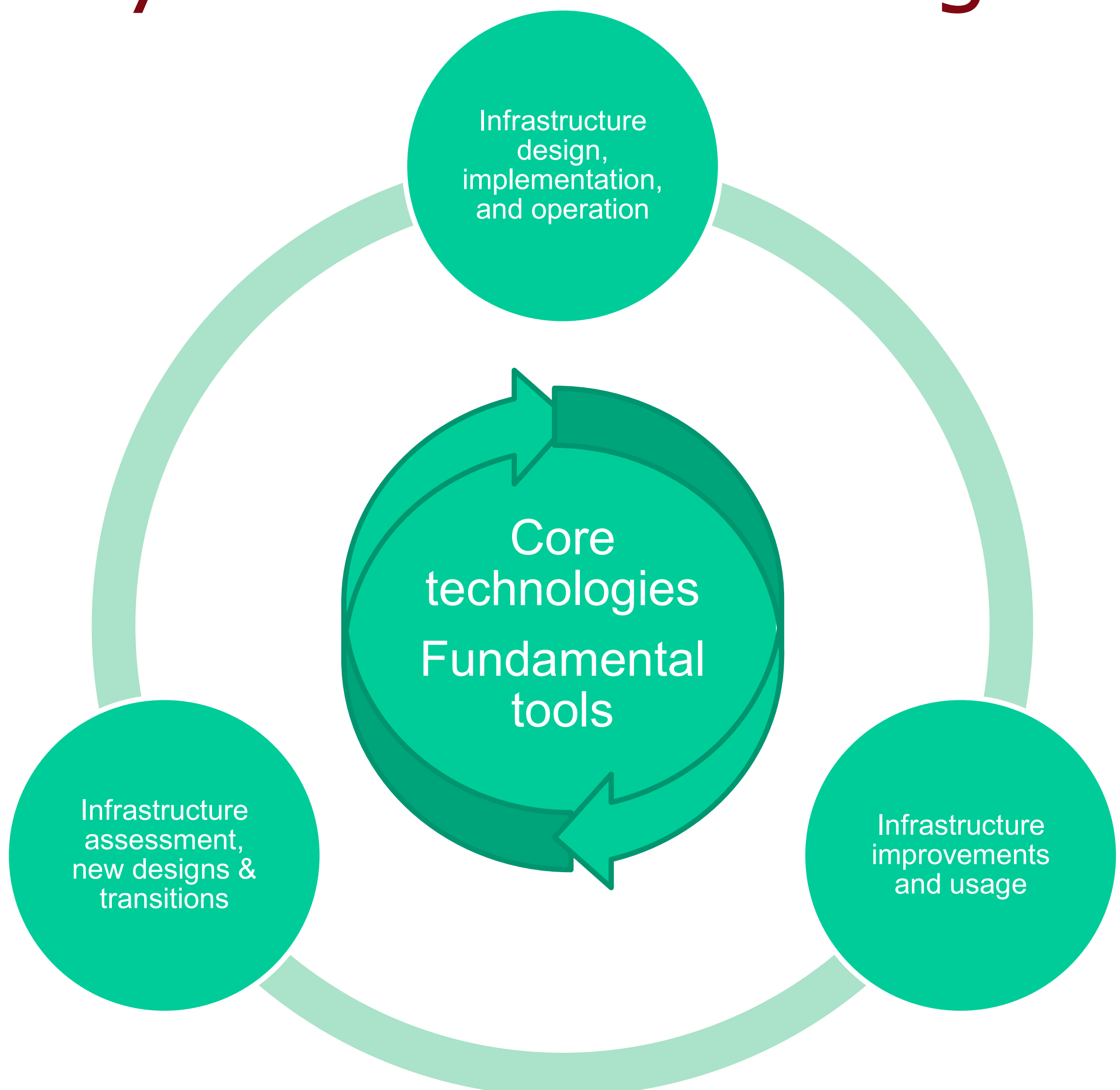
- And applications
  - game & crowd



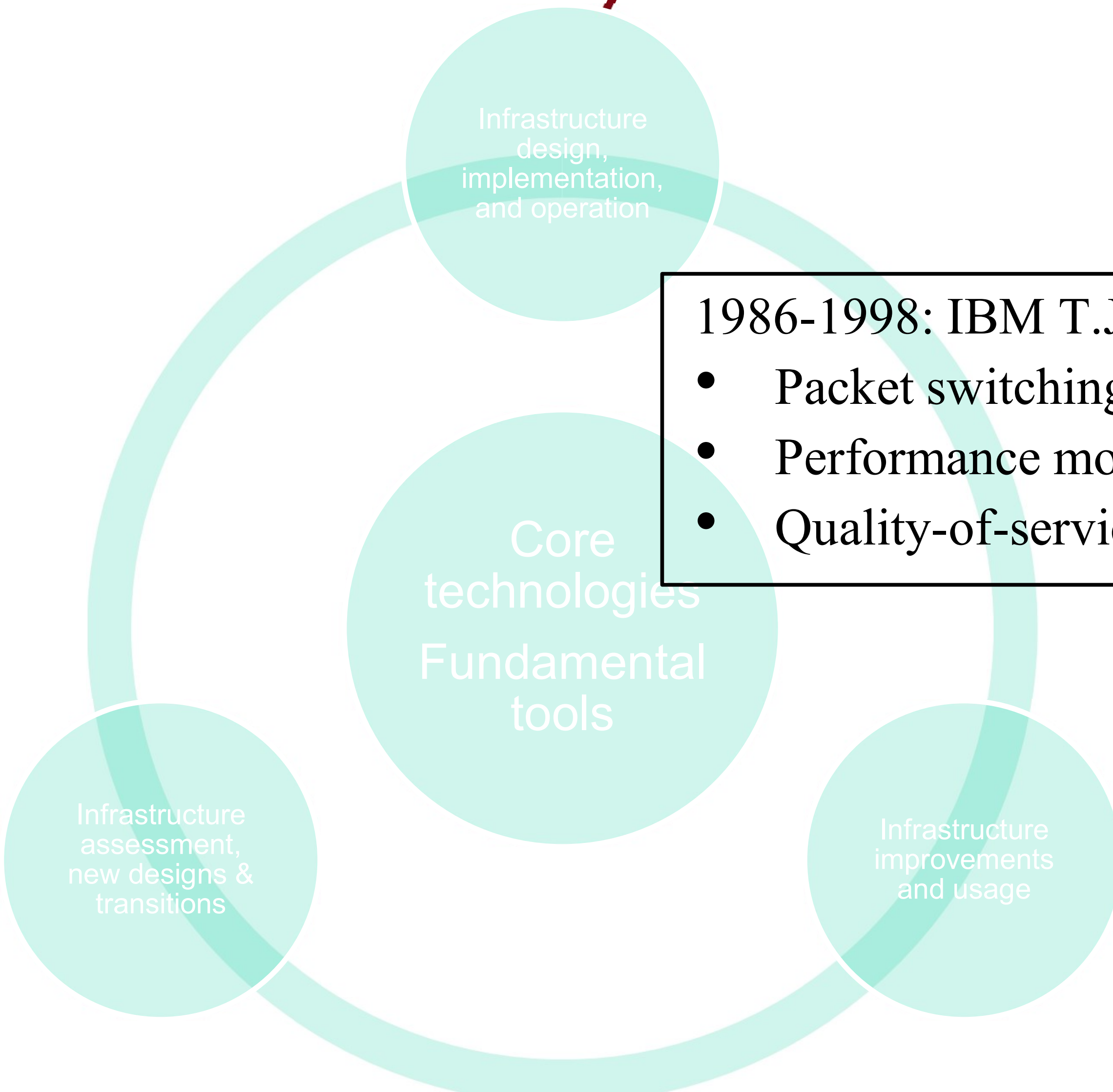
  - video & web



A Basic Cycle of Networking Research



My Own Personal Cycle



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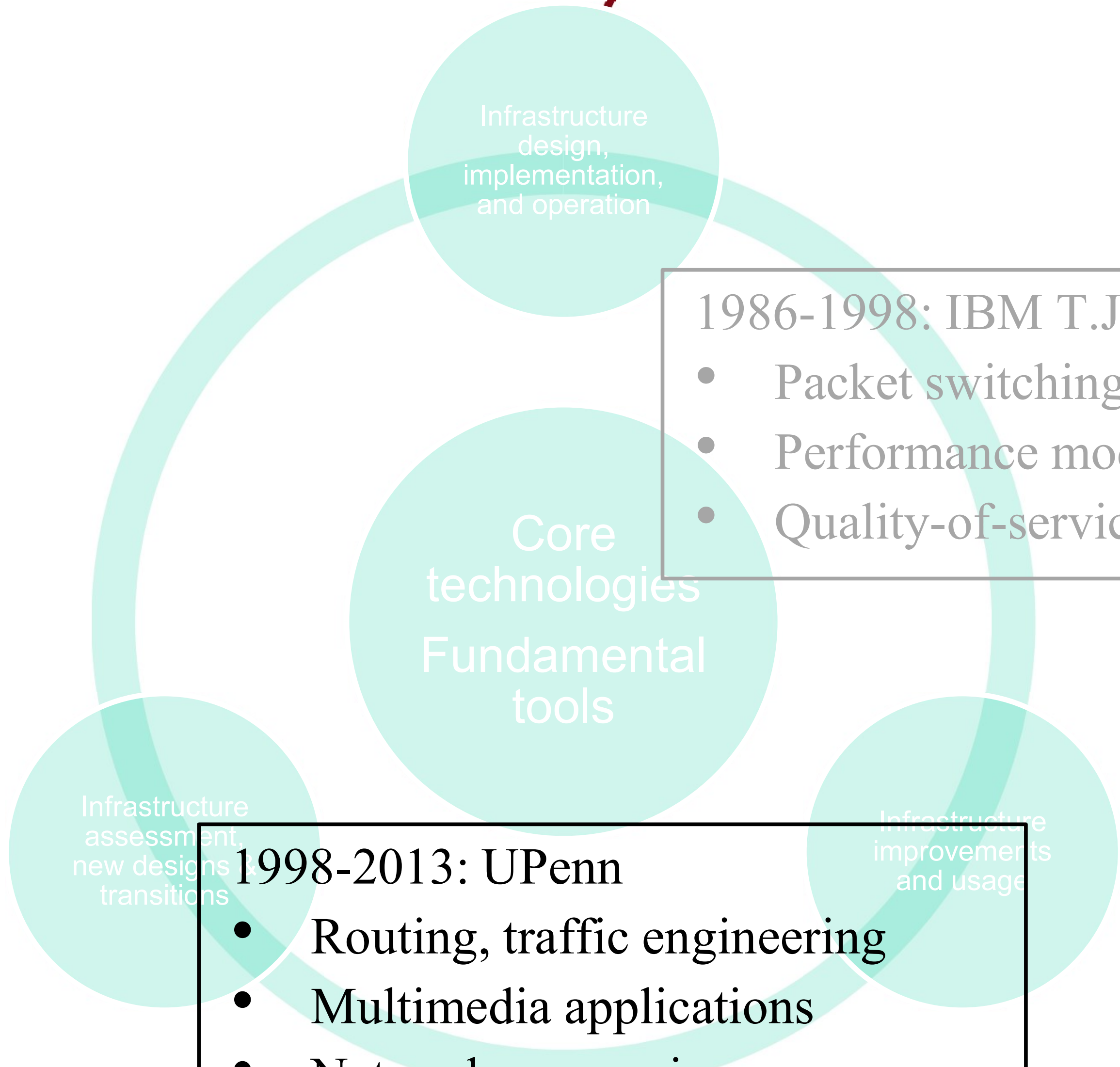

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- Routing, traffic engineering
- Multimedia applications
- Network economics

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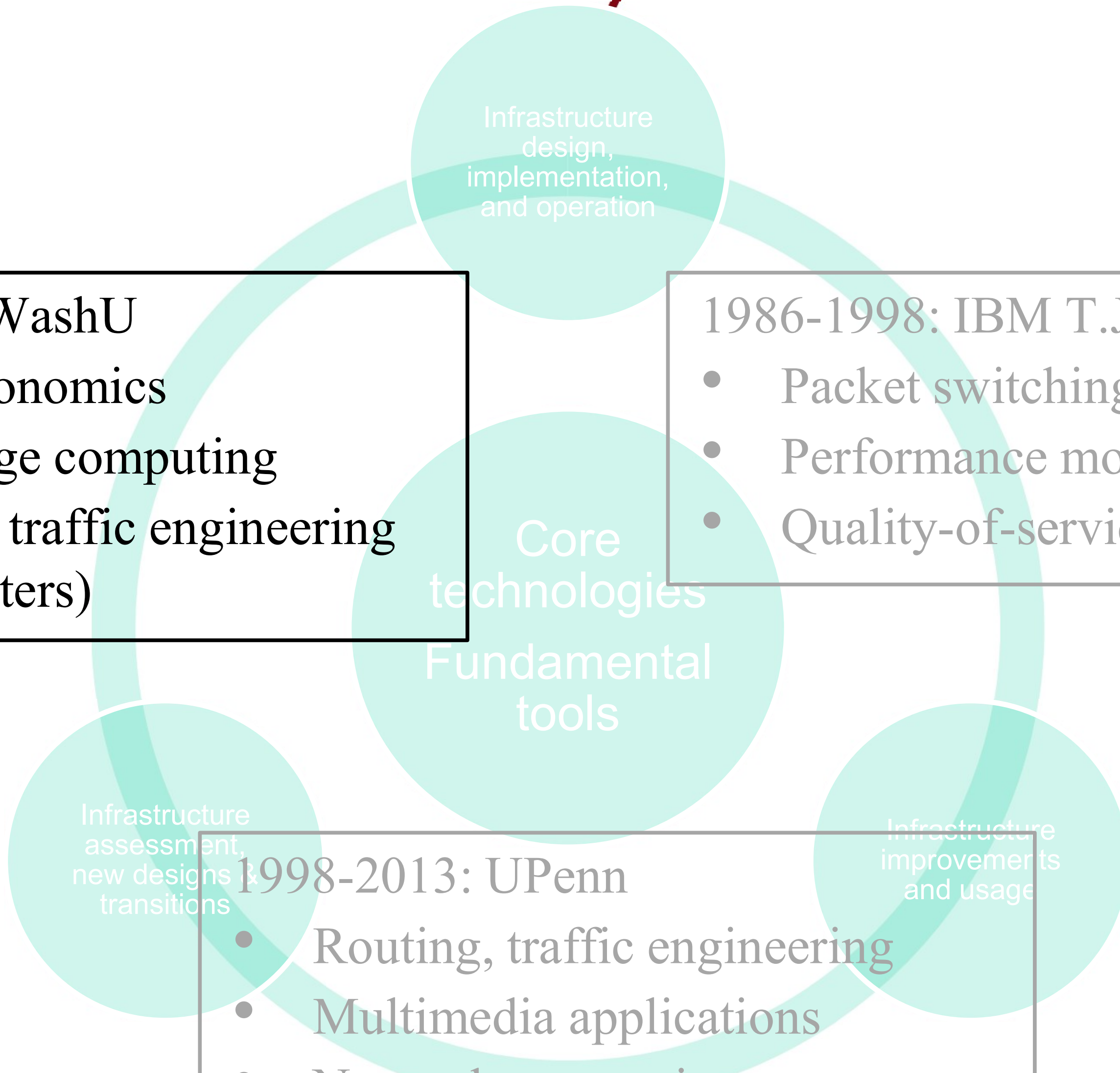

2013-present: WashU
- Network economics
- Cloud & edge computing
- Scheduling, traffic engineering (for datacenters)

1986-1998: IBM T.J. Watson
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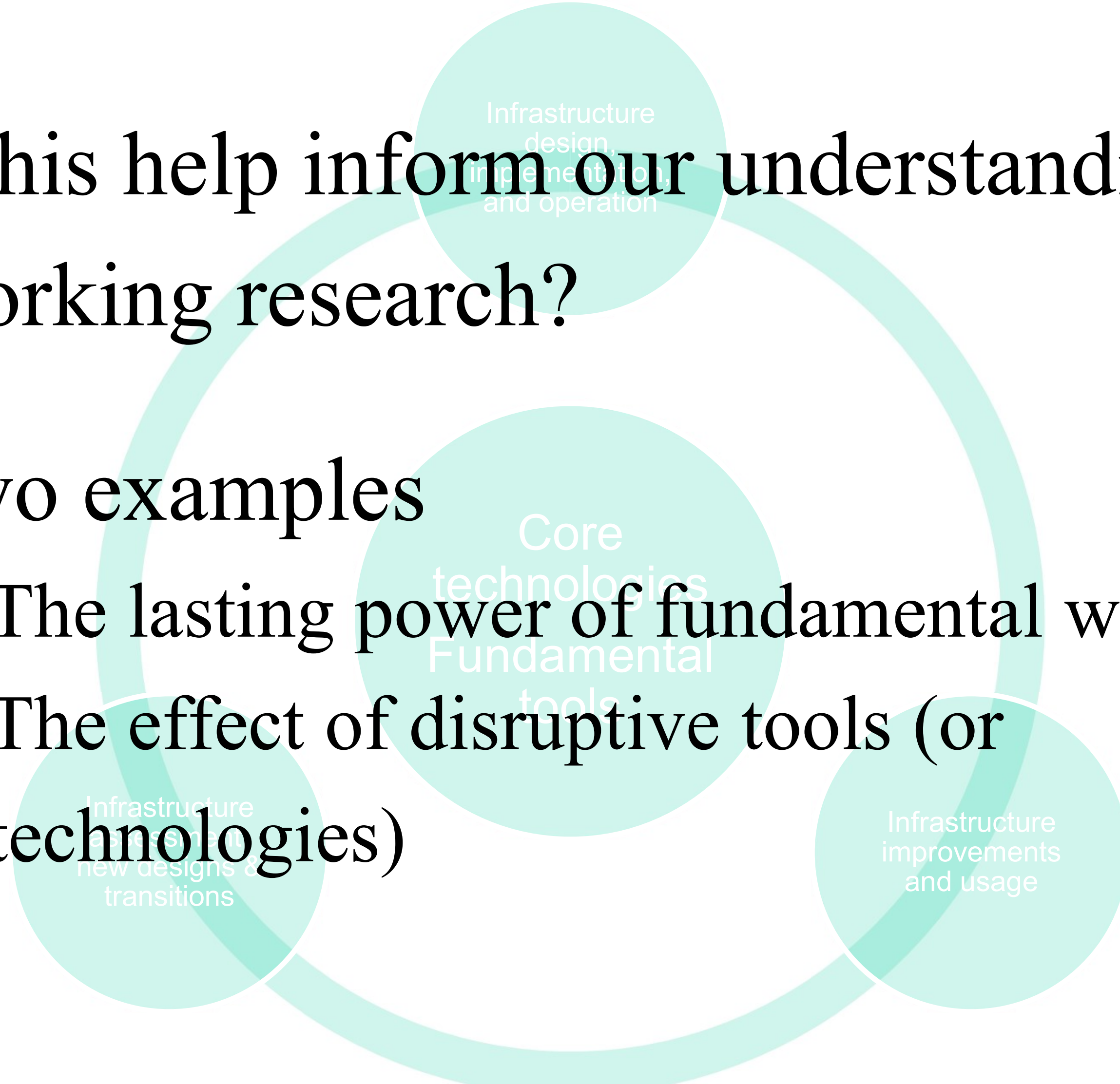
Taking stock

Can this help inform our understanding of networking research?

- Two examples
  - The lasting power of fundamental work
  - The effect of disruptive tools (or technologies)



The **Network Calculus** Example

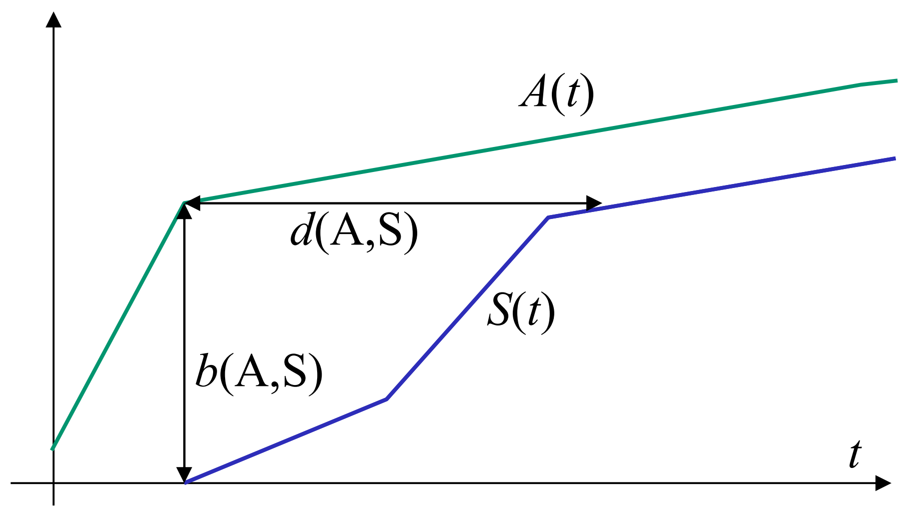
- 1991: Rene Cruz seminal work
- 1990-2000: An explosion of results on scheduling disciplines and end-to-end delay bounds
- 2001: Le Boudec & Thiran Network Calculus book
- Early 2000: Stochastic network calculus extensions
- 2010 onward: A new round of extensions motivated by a range of specialized applications targeting better bounds (algebraic and optimization-based), optimized shapers (interleaved shapers), etc.

- 1997: RFC 2212 on Guaranteed Service
- 1999: RFC 2598 on Expedited Forwarding
- 2010-2020
  - DetNet (RFC 8578)
  - IEEE TSN (802.1**)

Technology evolution
SDN, emerging demand

A VERY Short Network Calculus Primer

- ***Deterministic*** arrival and service curves
  - Upper bound on arrivals
  - 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



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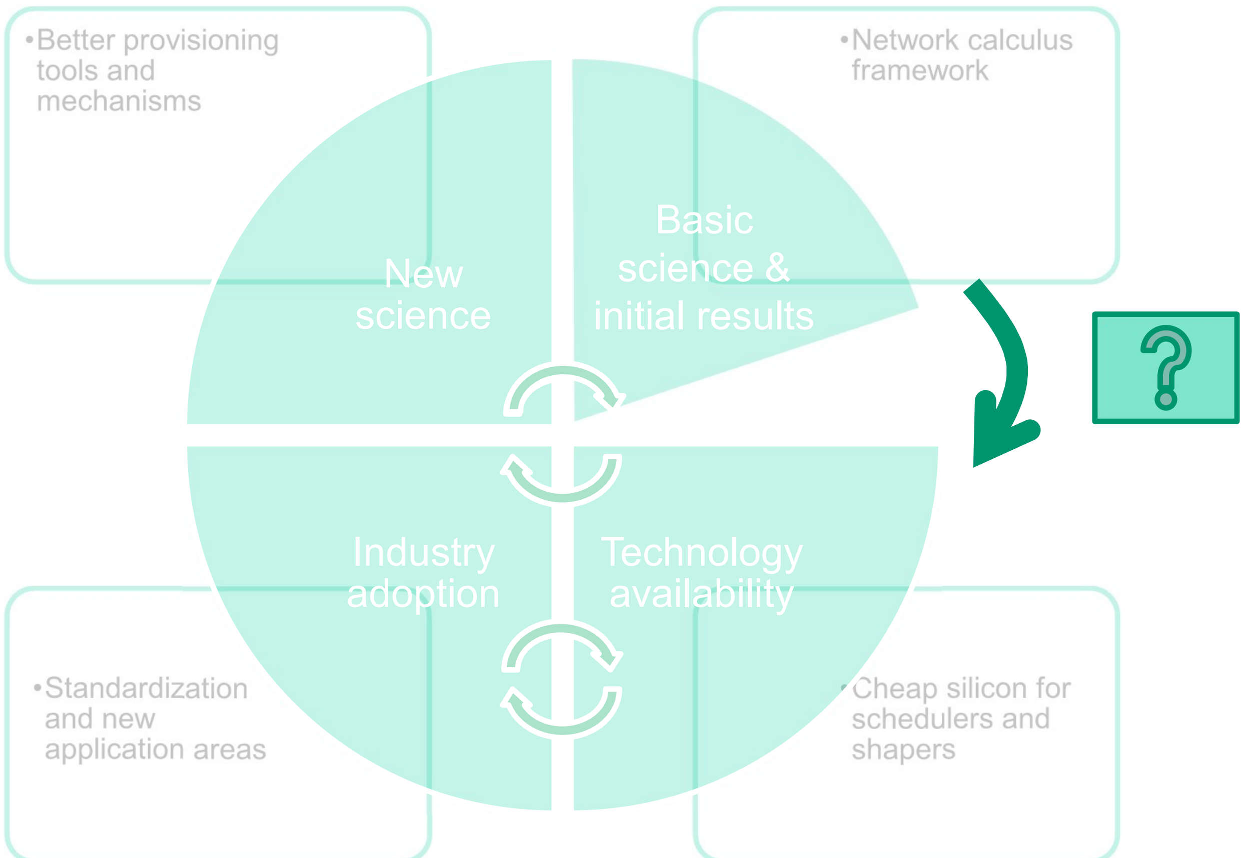
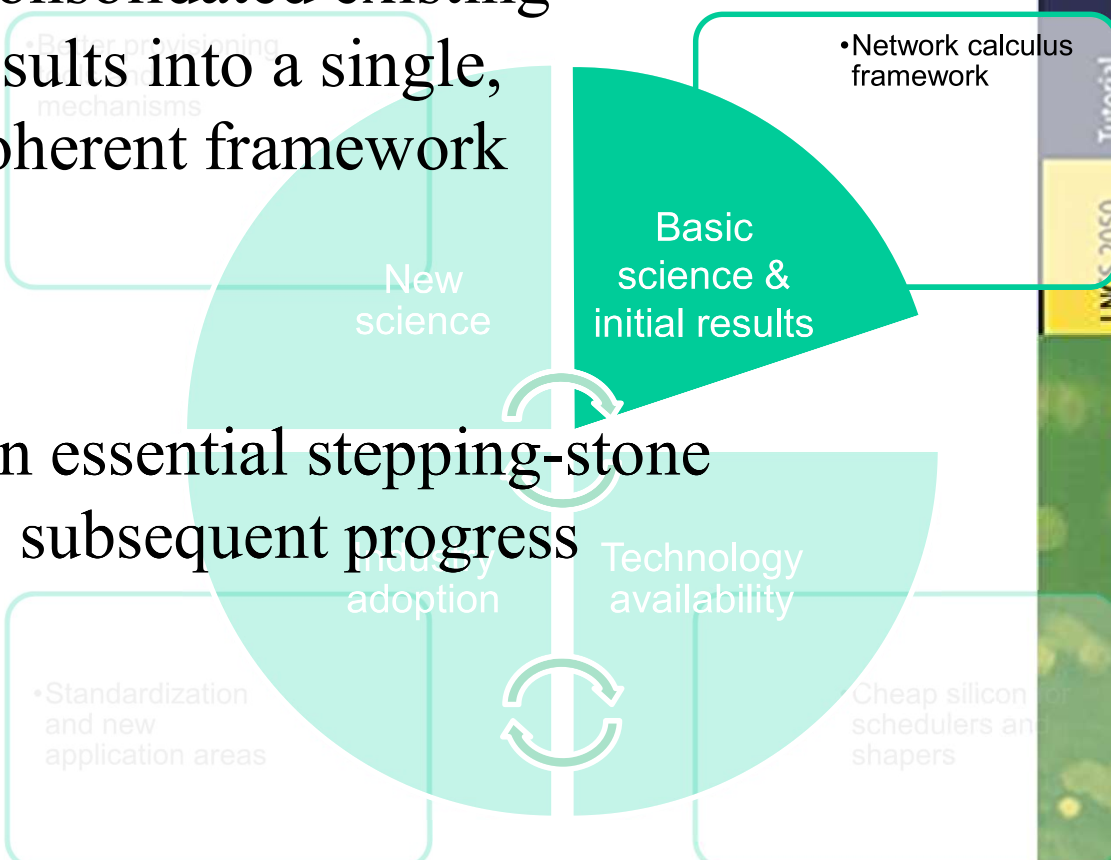
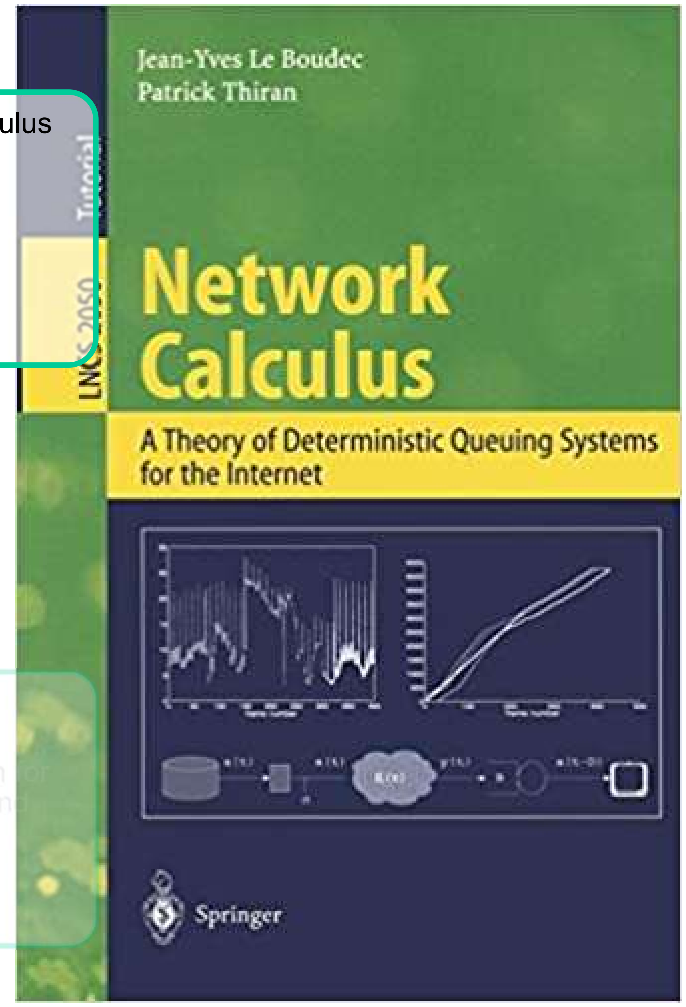
A Case of Technology Catching Up With Science **and** triggering New Science



Scientific Foundation

- Consolidated existing results into a single, coherent framework
- An essential stepping-stone to subsequent progress

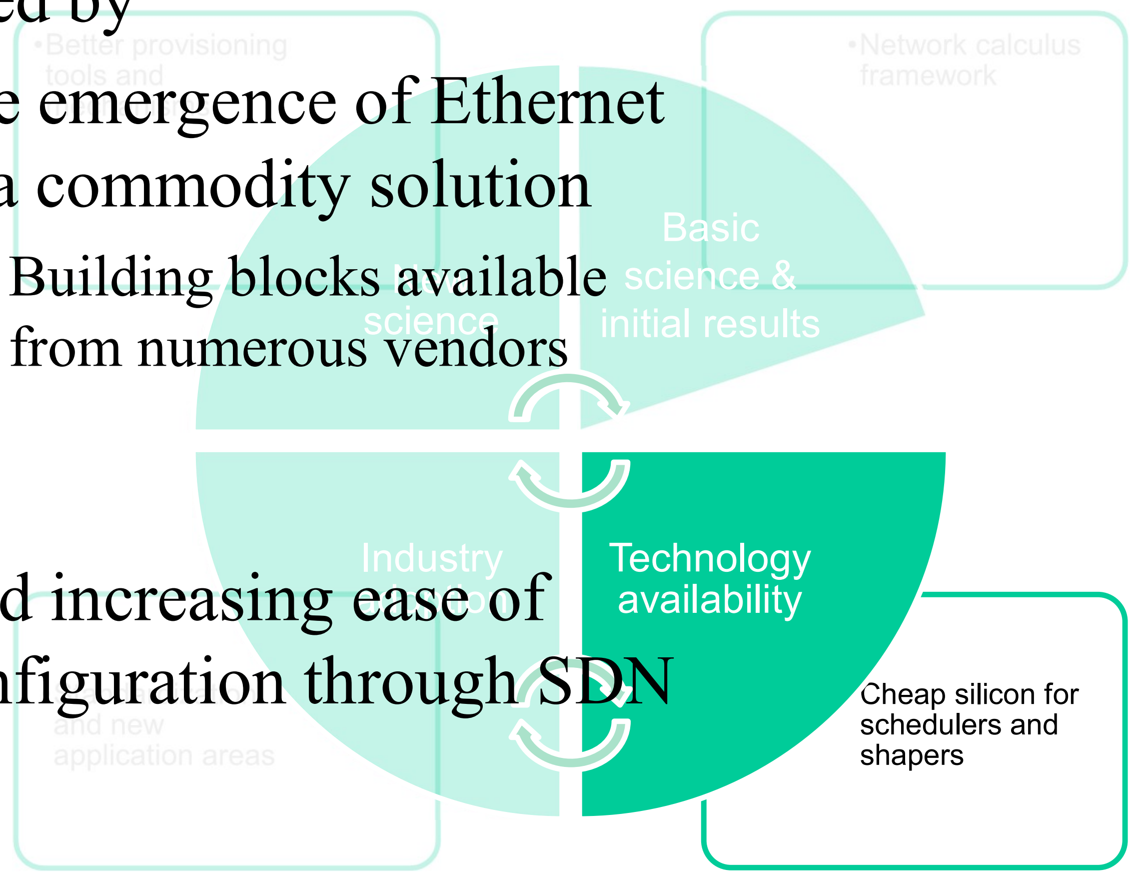




Technology Availability

Spurred by

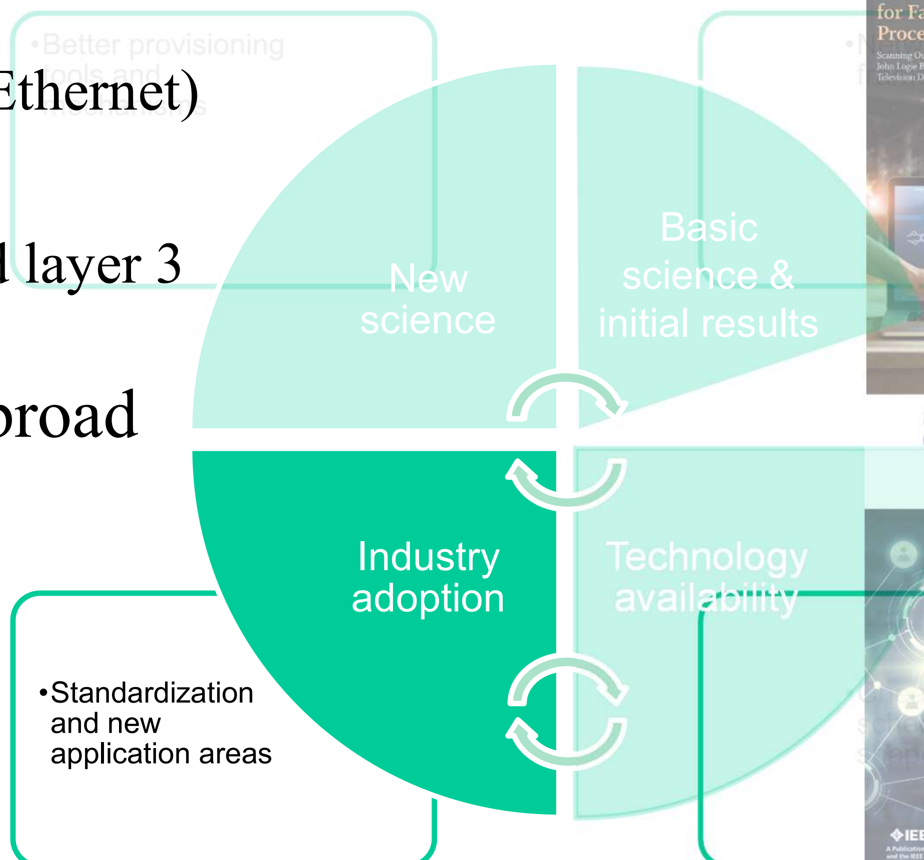
- The emergence of Ethernet as a commodity solution
  - Building blocks available from numerous vendors
- And increasing ease of configuration through SDN

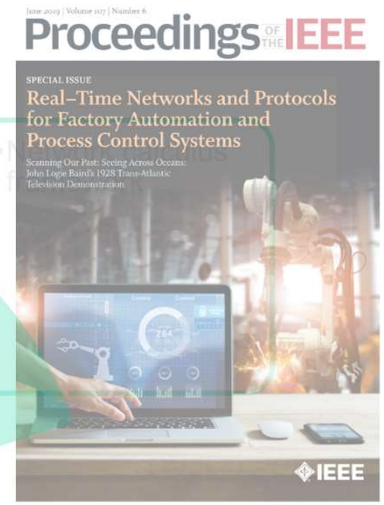


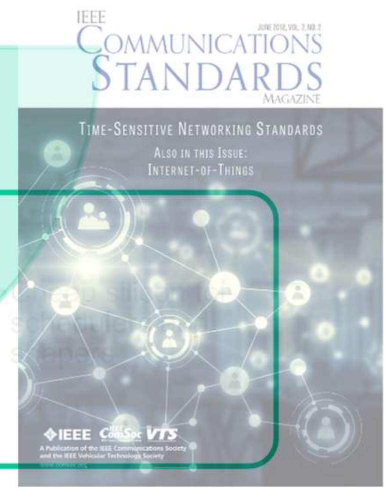
ANALOG DEVICES
BROADCOM
intel
MICROCHIP
NXP
SoCe
TEXAS INSTRUMENTS

Relevant Standards

- IEEE TSN
  - Focus on layer 2 (Ethernet)
- IETF DetNet
  - Targets layer 2 and layer 3 solutions
- Adoption across a broad range of industries
  - Automotive
  - Avionics
  - Manufacturing
  - Transportation
  - Power & energy

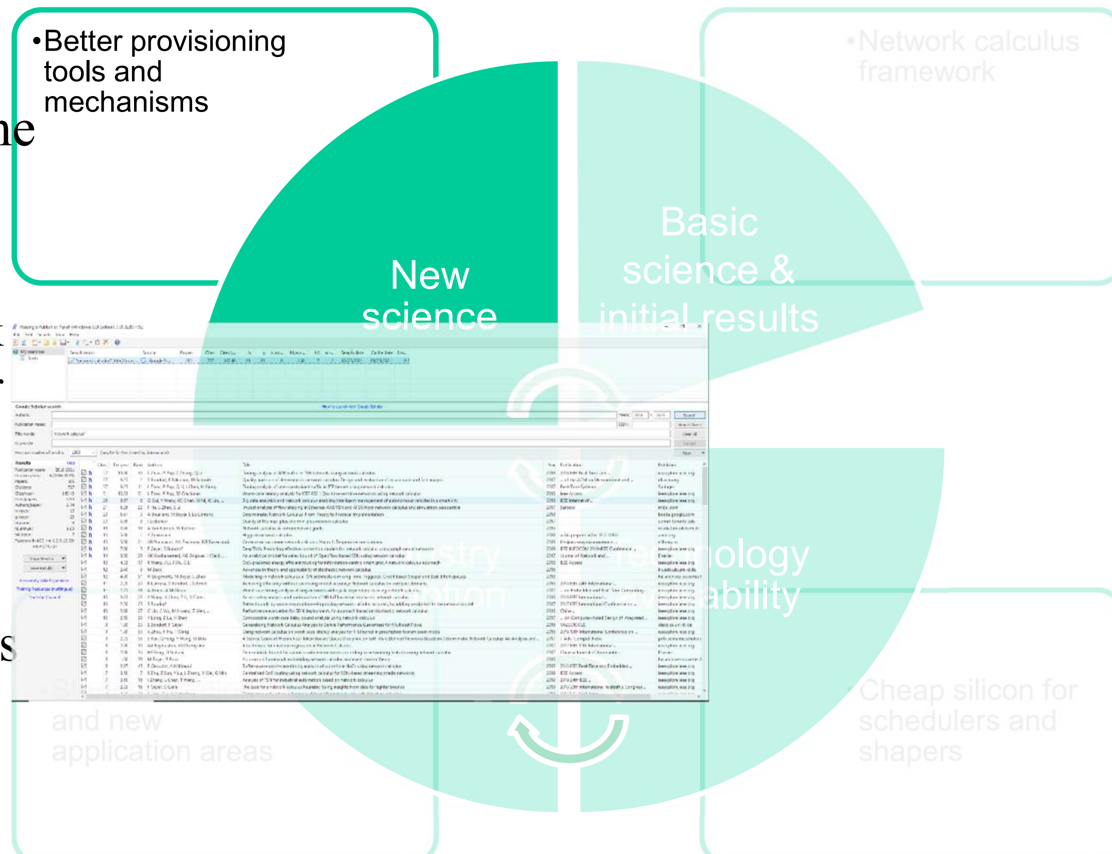






New Science

- An explosion of new results, (~200 papers with "network calculus" in their title over the past 5 years – though few at INFOCOM)
  - Optimization-based network calculus (LP formulation for tighter bounds)
  - New bounds for a range of schedulers and shapers
- And numerous software tools realizing them
  - See [1] for a recent list

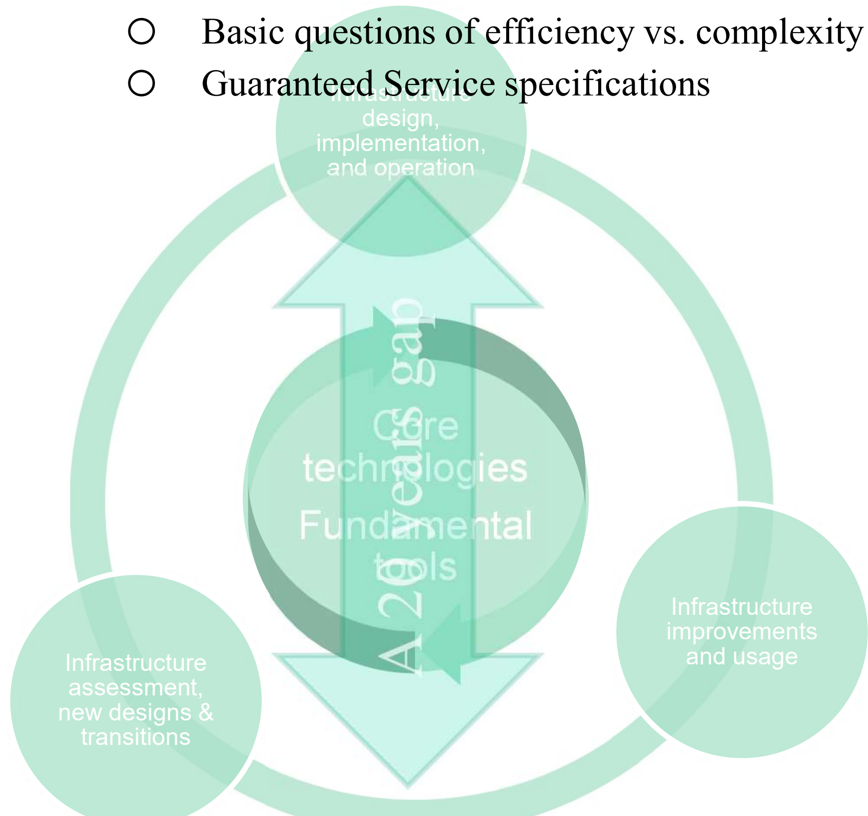


[1] B. Zhou et al., "Survey on Network Calculus Tools for Network Infrastructure in Real-Time Systems." IEEE Access, Vol. 8, 2020

My Own Network Calculus Journey

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

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



- 2021
  - Minimizing network cost under latency constraints

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

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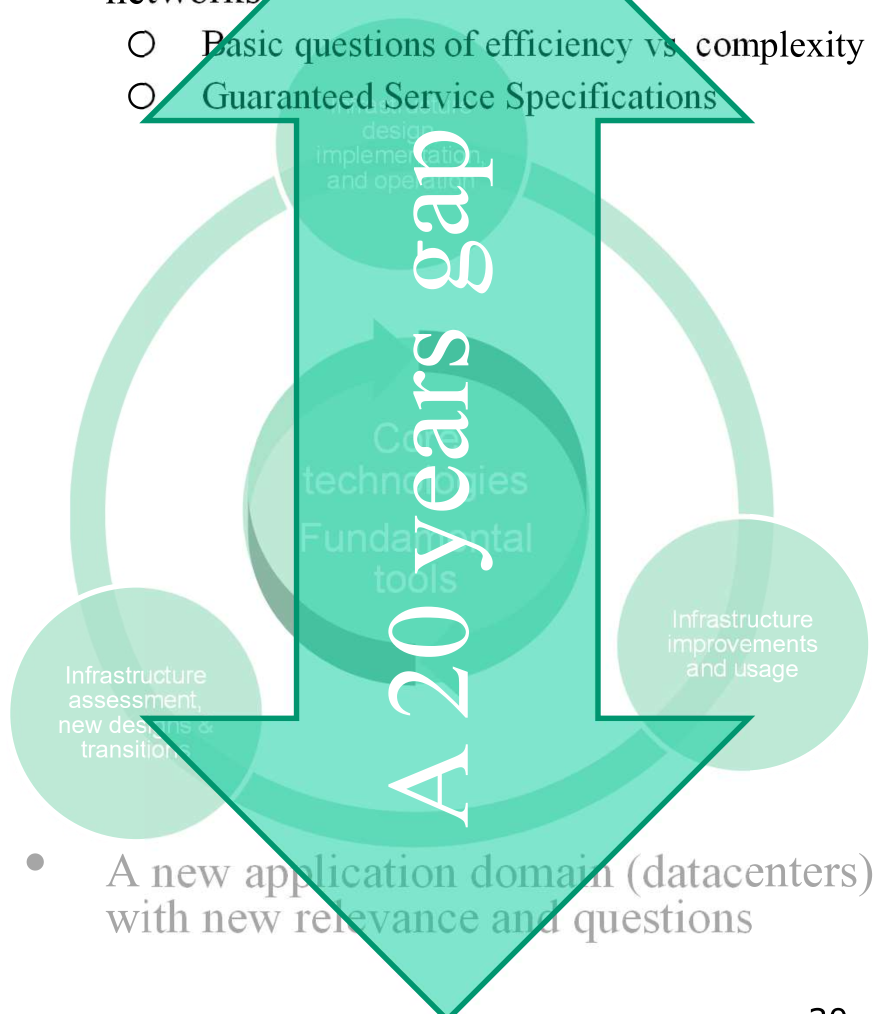

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Fast Forward 20 Years
The Internet is still there

But so are many other “specialized” networks

1. Manufacturing
2. Avionics
3. Power plants
4. datacenters

1. Photo by Science in HD on Unsplash
2. Photo by Mike Petrucci on Unsplash
3. Photo by Tim Mossholder on Unsplash
4. Photo by Massimo Botturi on Unsplash

Fast Forward 20 Years
The Internet is still there

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

- 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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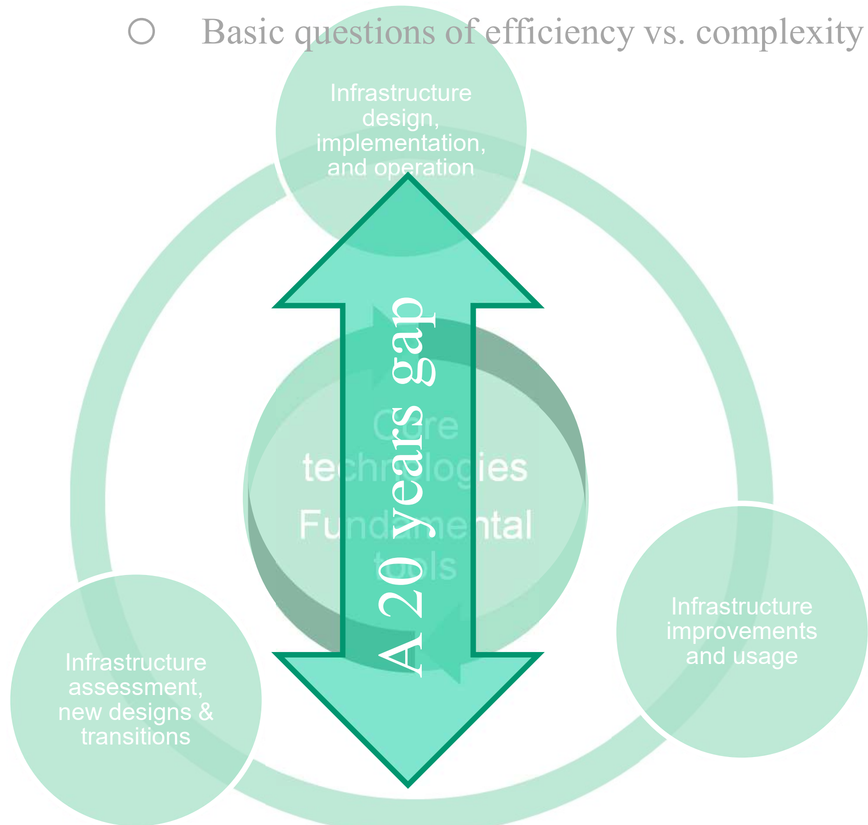

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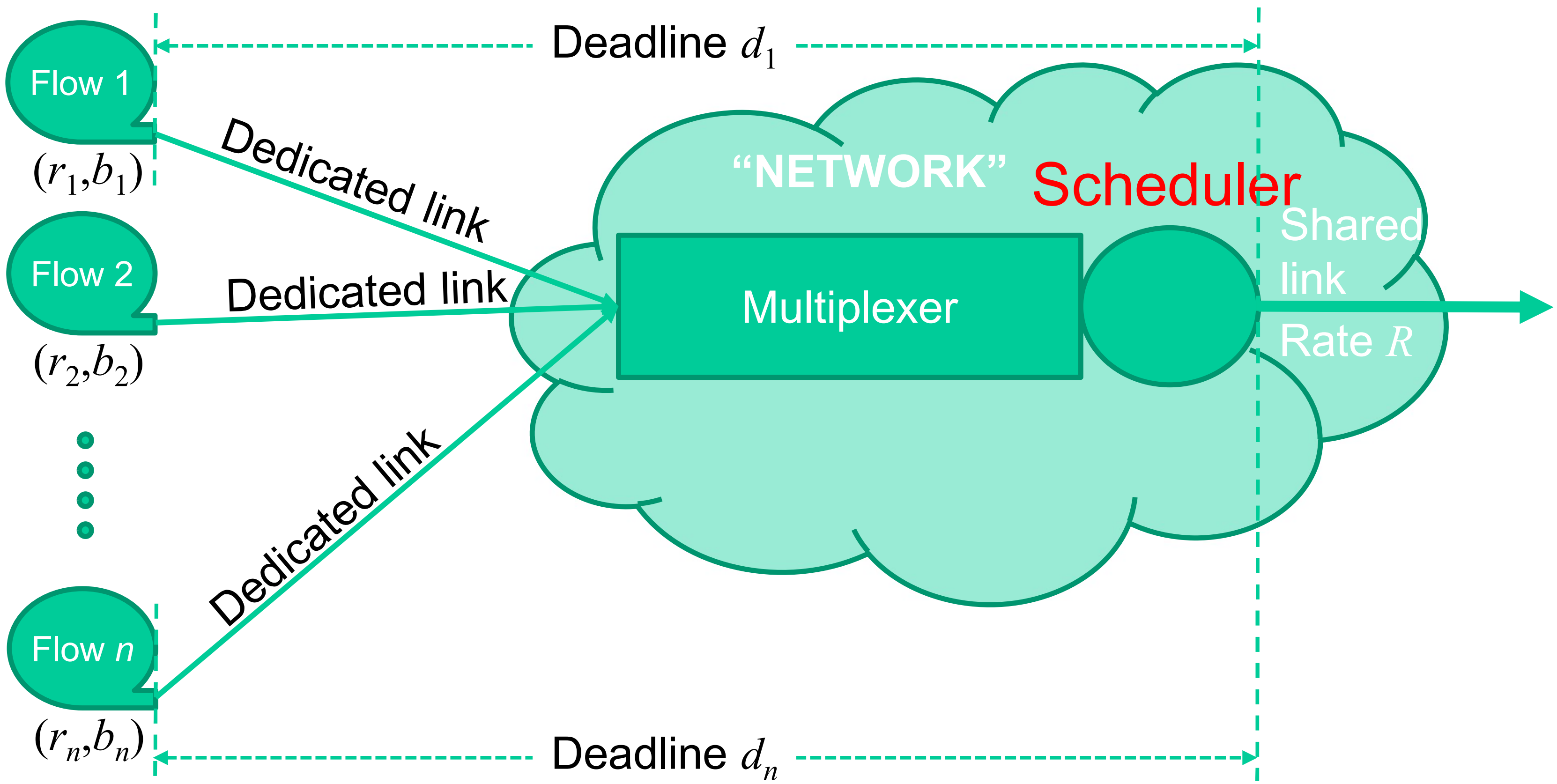
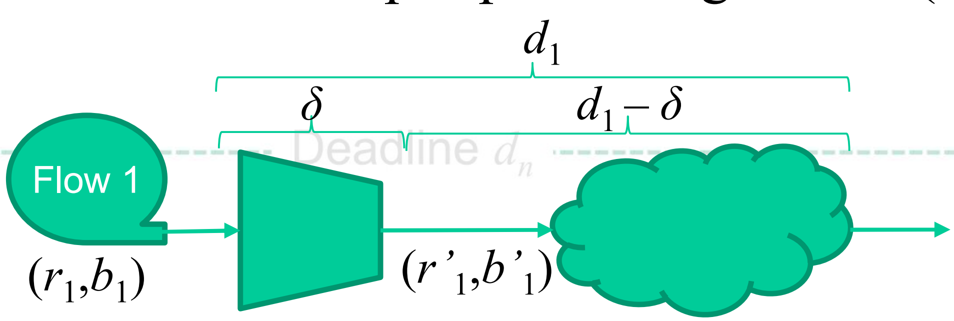
A (Basic) Representative Problem



Finding the cheapest solution?
Scheduler & bandwidth costs

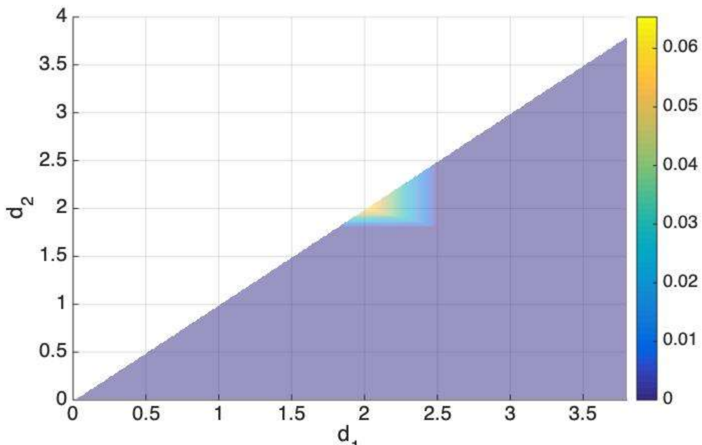
A Representative Problem

- 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)

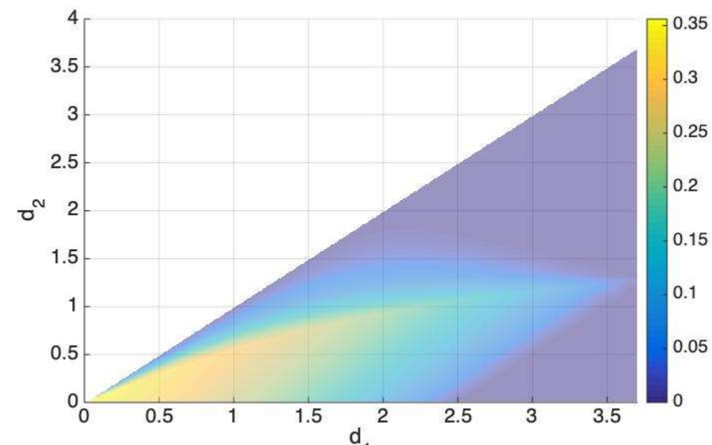


Quantifying the Cost of Simplicity

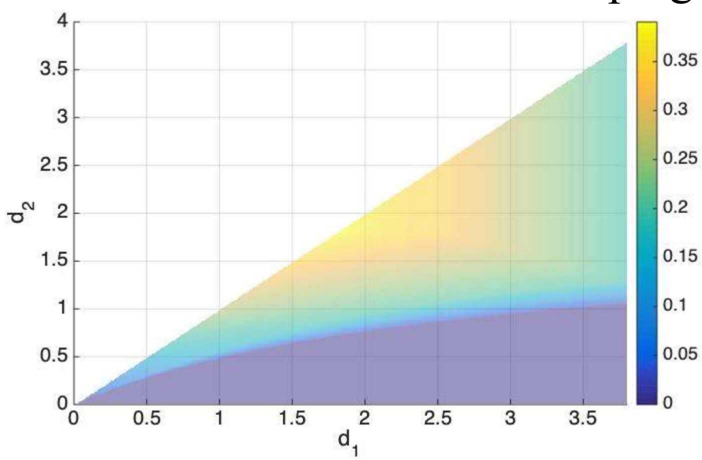
Static priority + shaping vs. optimal

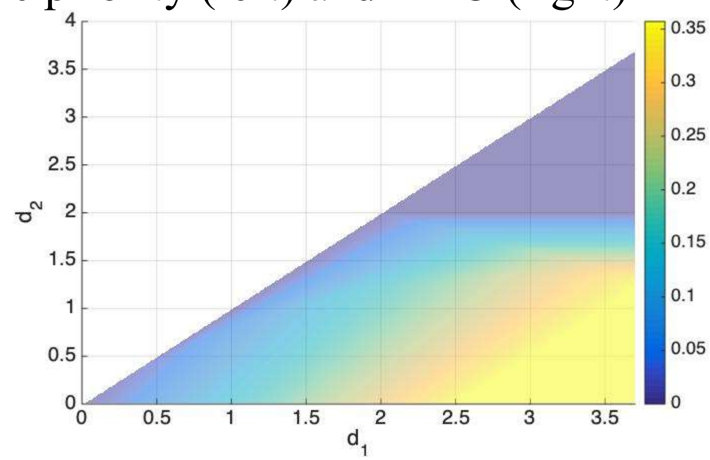


Basic FIFO + shaping vs. optimal



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





Taking Stock

Old problems become interesting again

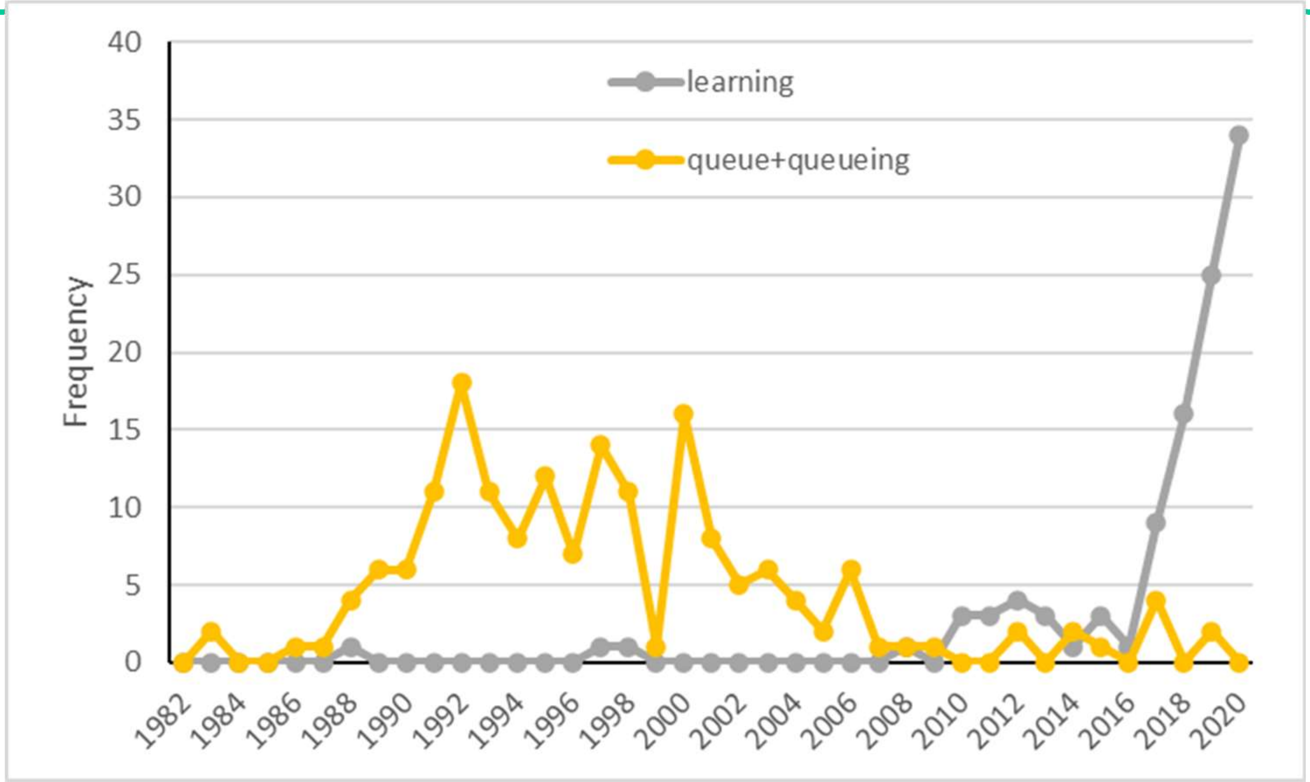
- As the technology cycle evolves, new application areas open-up and impractical or expensive solutions become feasible often with a new interesting twist

Foundational work never grows old

- Deterministic networking and network calculus as a case in point

What About Technology Disruption

machine/deep learning?



Top 10 INFOCOM'21 terms

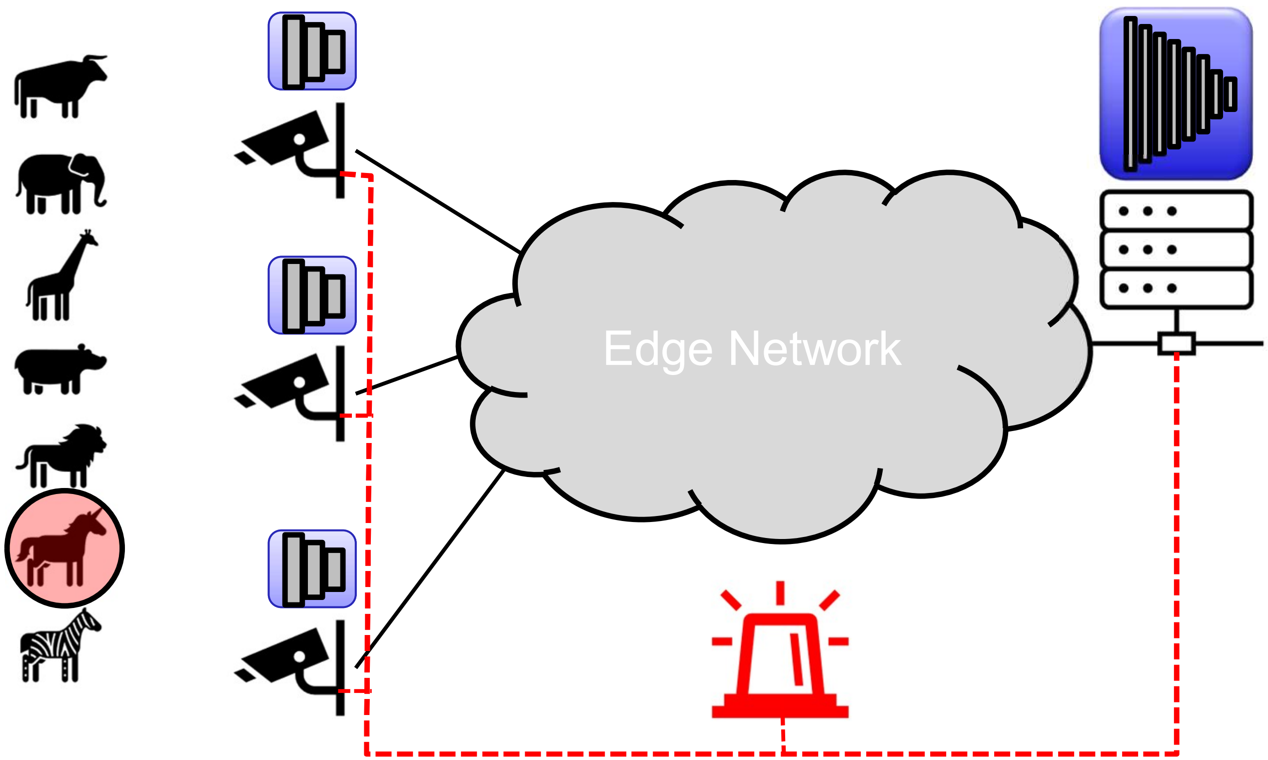
Term	Occurrences
network	69
learning	52
edge	23
system	19
wireless	18
reinforcement	16
deep	14
distributed	14
federated	13
mobile	12
scheduling	12

A Dual Role for ML/DL

- As a source of new problems
- As a source of new solutions

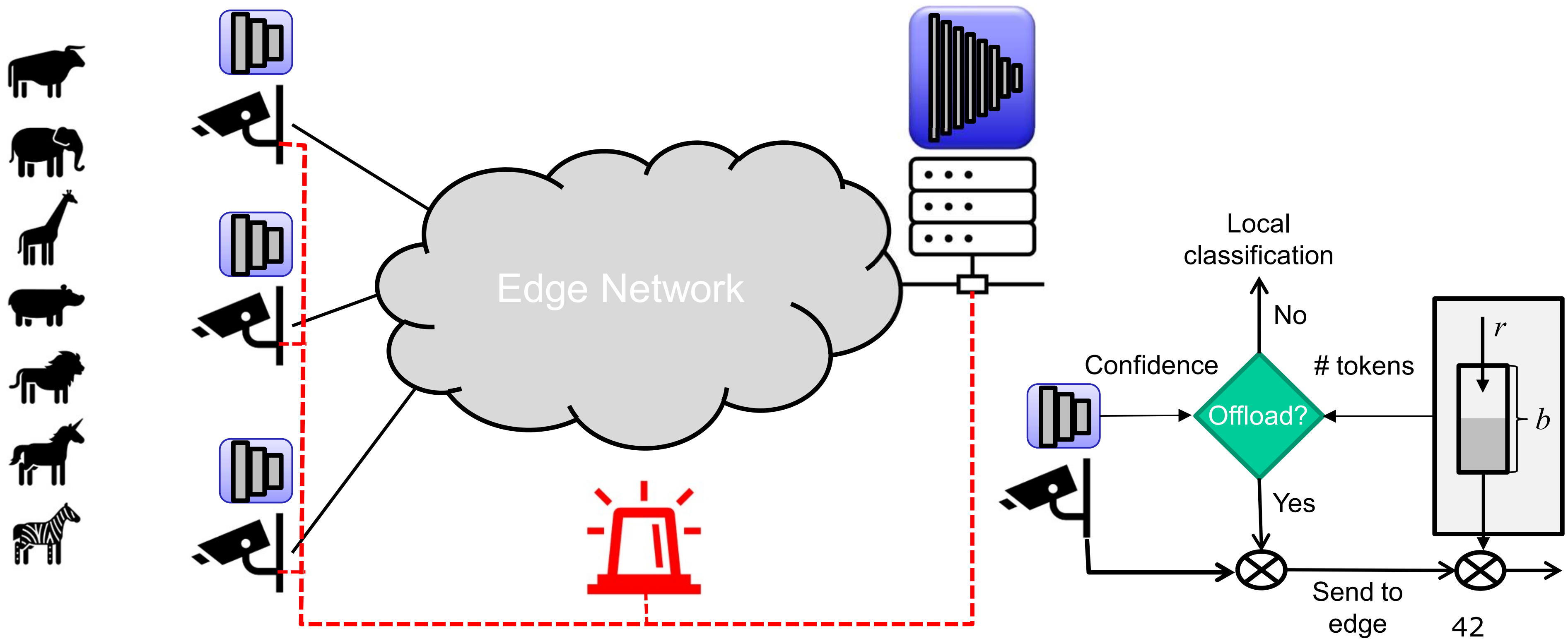
A New (Old) Problem

- 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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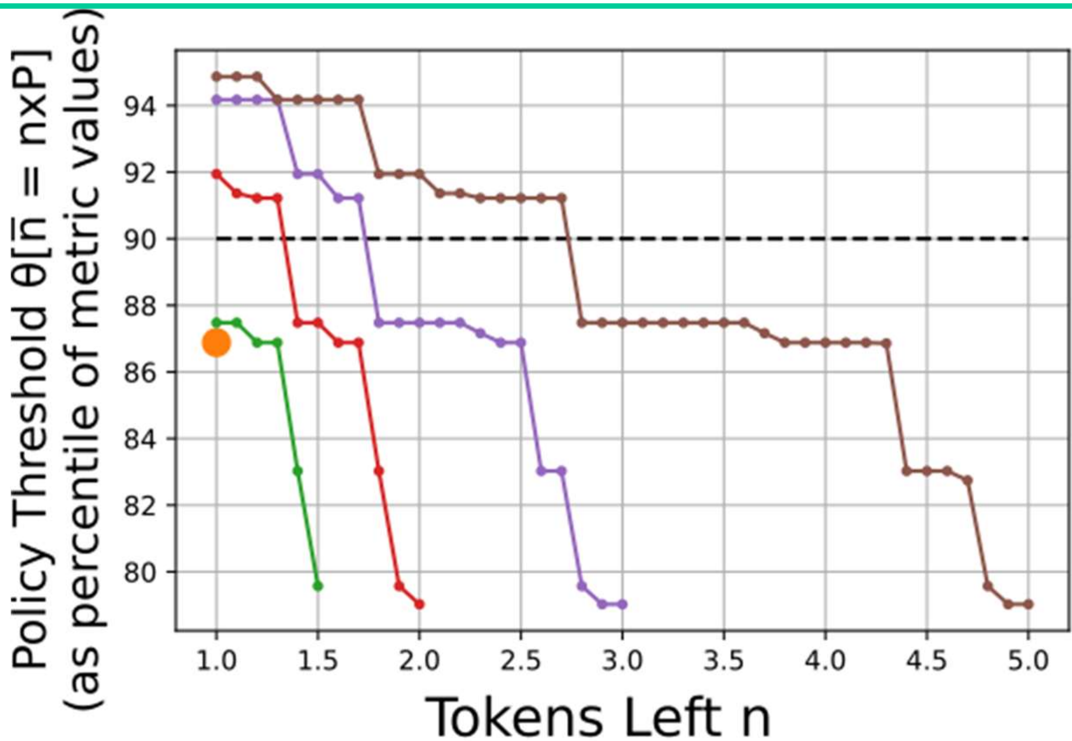
$r = 0.1$



$b = 1.0$ $b = 1.5$ $b = 2.0$ $b = 3.0$ $b = 5.0$

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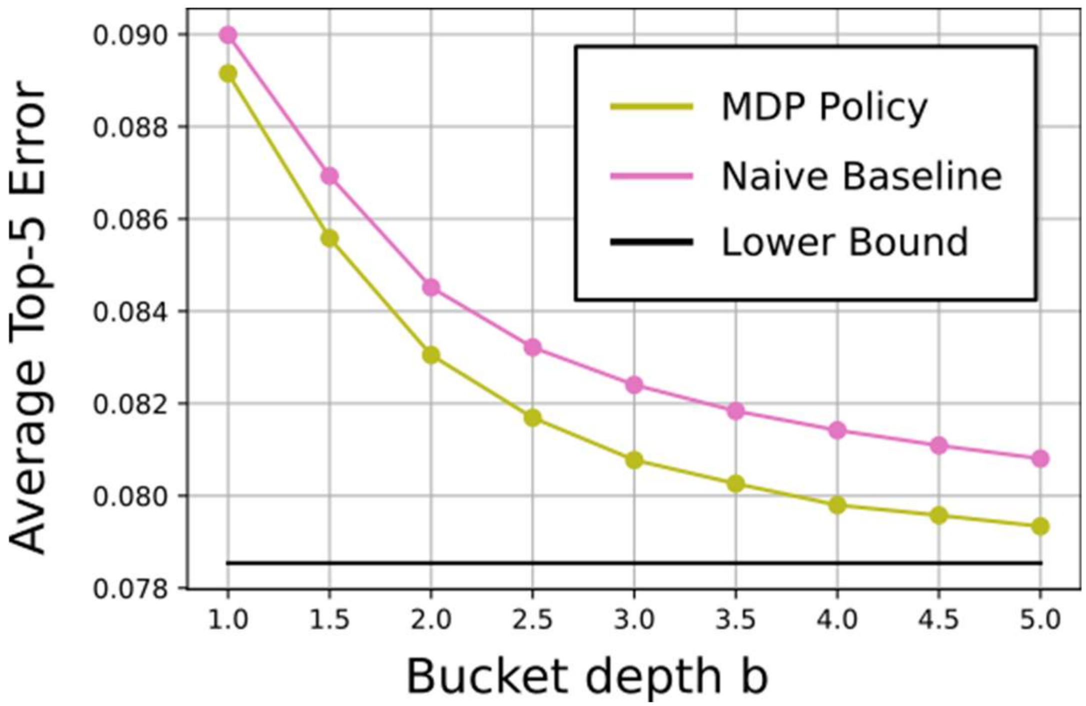

ML/DL as a Source of New Solutions

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

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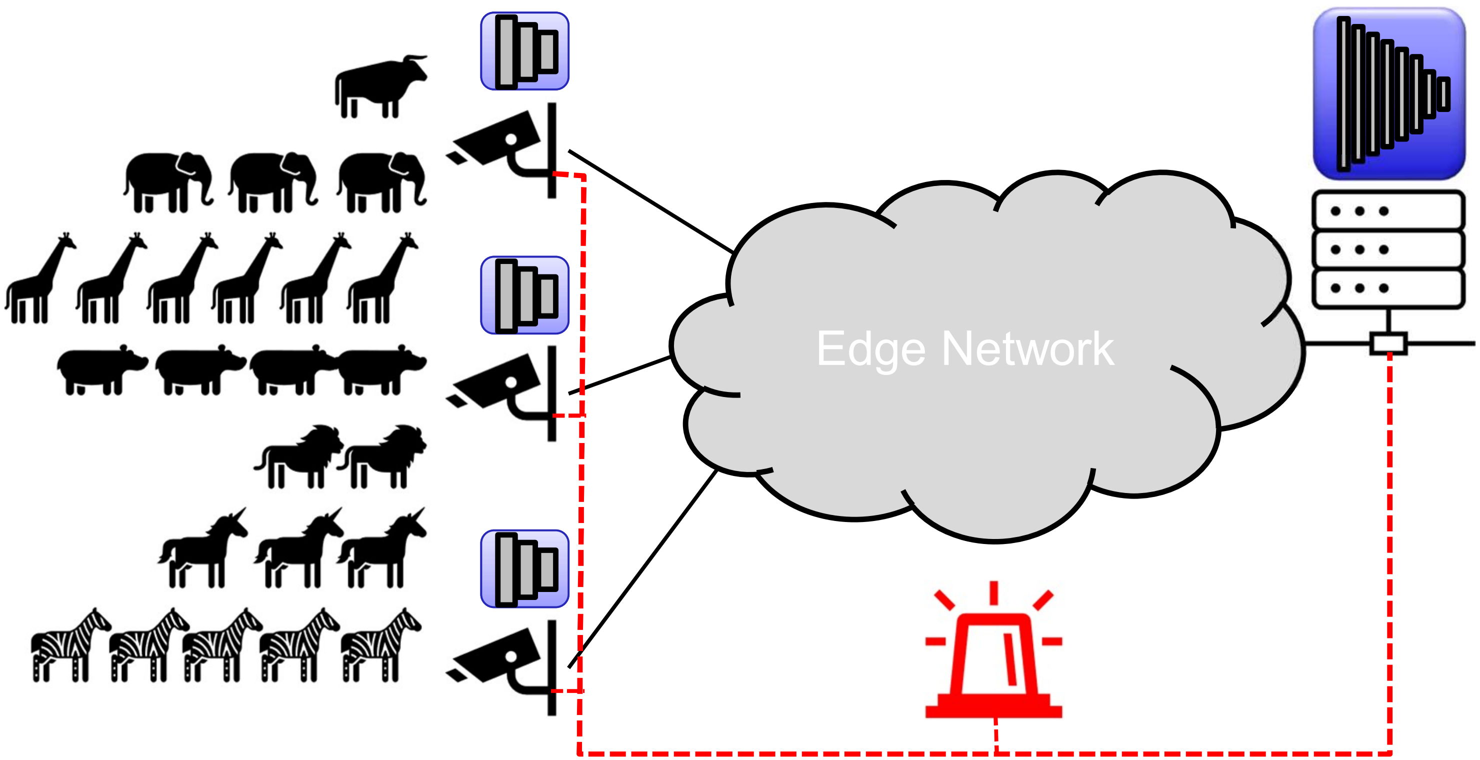
A Representative Example (again)

- Weak (device) vs. strong (edge) classifier
- But now w/ a more complex, *e.g.*, correlated input process



A Possible Solution

- The MDP formulation of the base problem points to DQN (Deep Q-Learning) as a possible approach to tackling correlated inputs
- We can use Q-learning with a Q-function based on a neural network using standard stochastic gradient descent to learn how to solve our optimization

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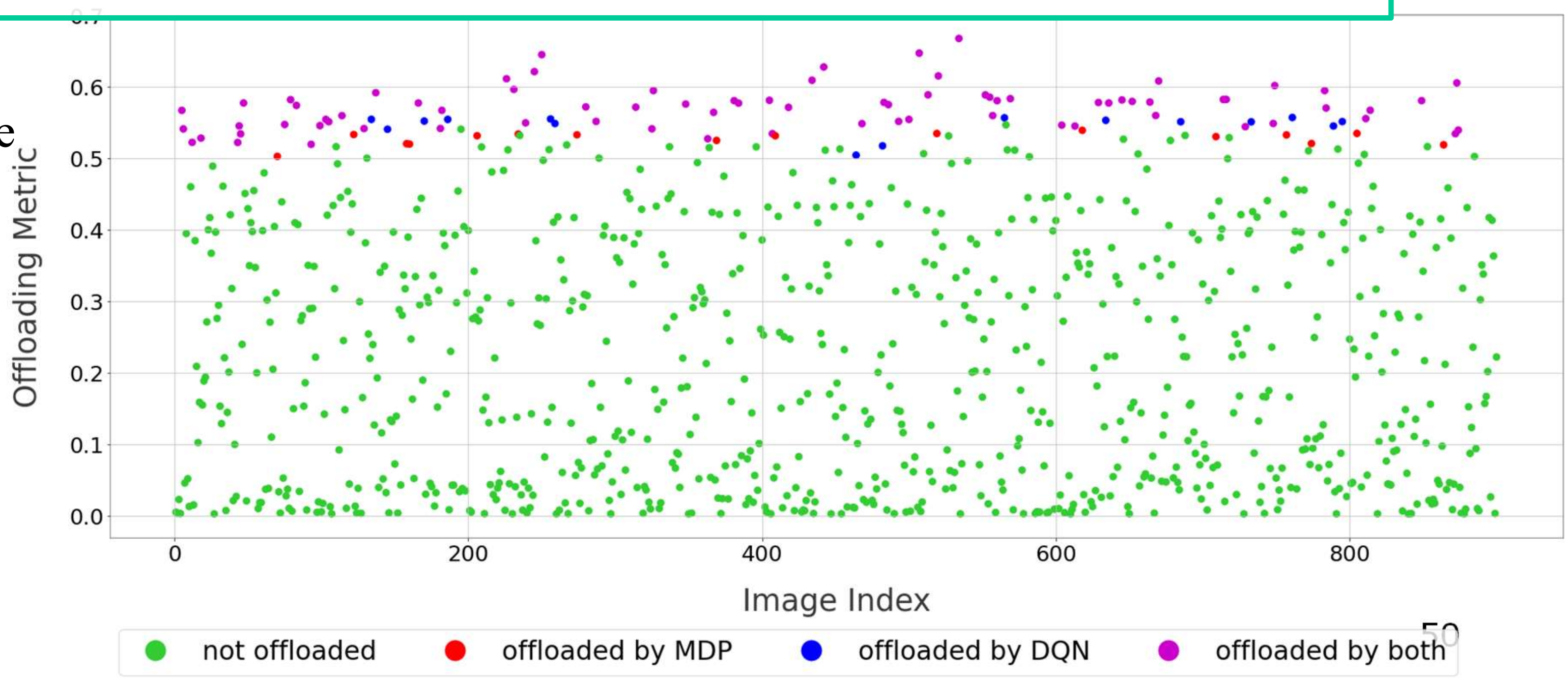
DQN *learns* the MDP solution for i.i.d. inputs

Token bucket $(r,b)=(0.1,10)$



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DQN also *learns* the presence of correlation

Token bucket (r,b)=(0.1,10)

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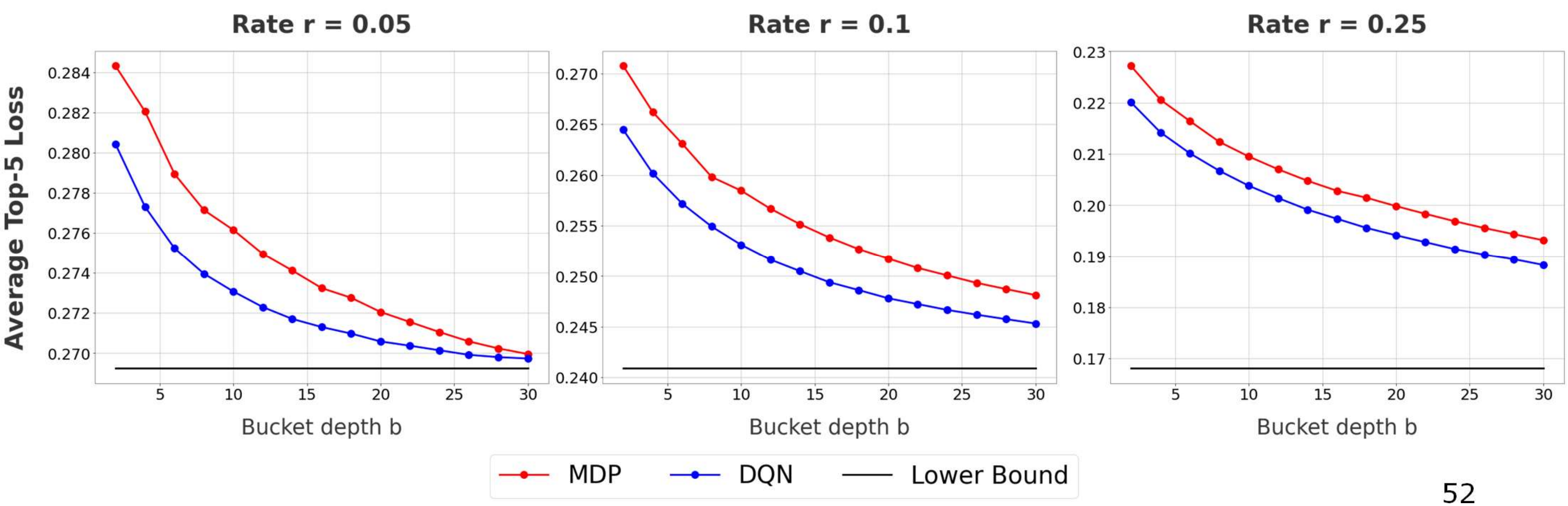

Back to the Future?

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 can solve old problems

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

Core technologies

Fundamental tools

Infrastructure assessment, new designs & transitions

Infrastructure improvements and usage

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- 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.

Finally, I want to acknowledge the support provided over the years by NSF and a number of companies, without whom none of the work would have been possible. I am very grateful for that support.

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Thank You!

Questions?