Performance-oriented Congestion Control

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TCP
Est. 1988

High BDP	Wireless	Satellite	Inter-DC	Intra-DC
BIC				
H-TCP	Westwood	Hybla	Illinois	ICTCP
Compound	Vegas	STAR	SABUL	DCTCP
CUBIC	Veno			
FAST TCP				

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•••

High BDP	Wireless	Satellite	Inter-DC	Intra-DC
BIC H-TCP Compound CUBIC FAST TCP	Westwood Vegas Veno	Hybla STAR	Illinois SABUL	ICTCP DCTCP

...

Who can be not happy with TCP ?


are
can be not happy with TCP ?

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Point Solutions

High BDP	Wireless	Satellite	Inter-DC	Intra-DC
BIC H-TCP Compound CUBIC FAST TCP	Westwood Vegas Veno	Hybla STAR	Illinois SABUL	ICTCP DCTCP
10X	10X	17X	4X	

Unstable, RTT Unfair, Bufferbloat, Crash on Changing Networks, ……..

Point Solutions

+

Performance

Far from Optimal

TCP fails to achieve consistent high performance

Why is it so hard?

Reno	1 pkt loss	cwnd/2
Scalable	ACK	cwnd+1
CUBIC	Time pass 1ms	cwnd+f(t,cwn,rtt)
FAST	RTT increase x%	Reduce cwnd to f(x)%
HTCP	100 ACK	cwnd+f(cwnd)/cwnd

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Hardwired Mapping

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Hardwired Mapping

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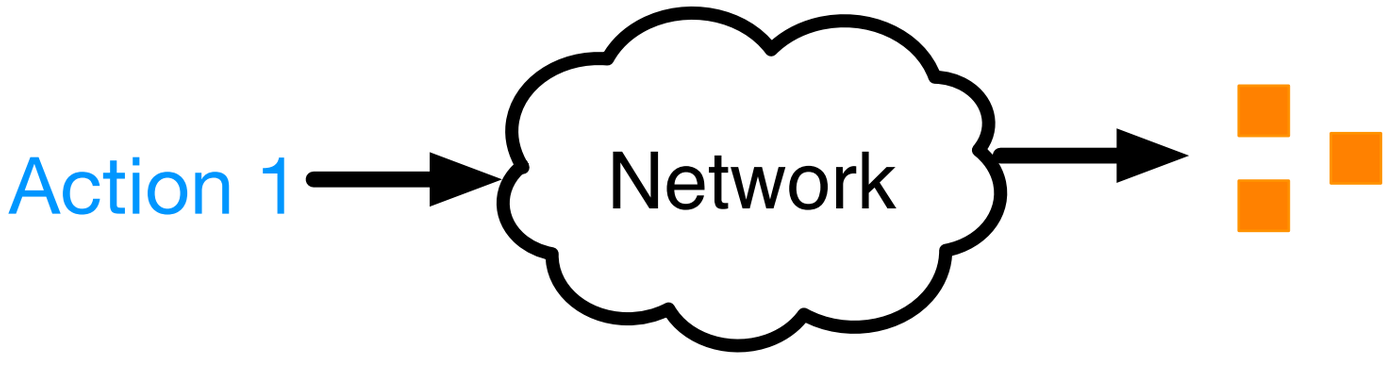
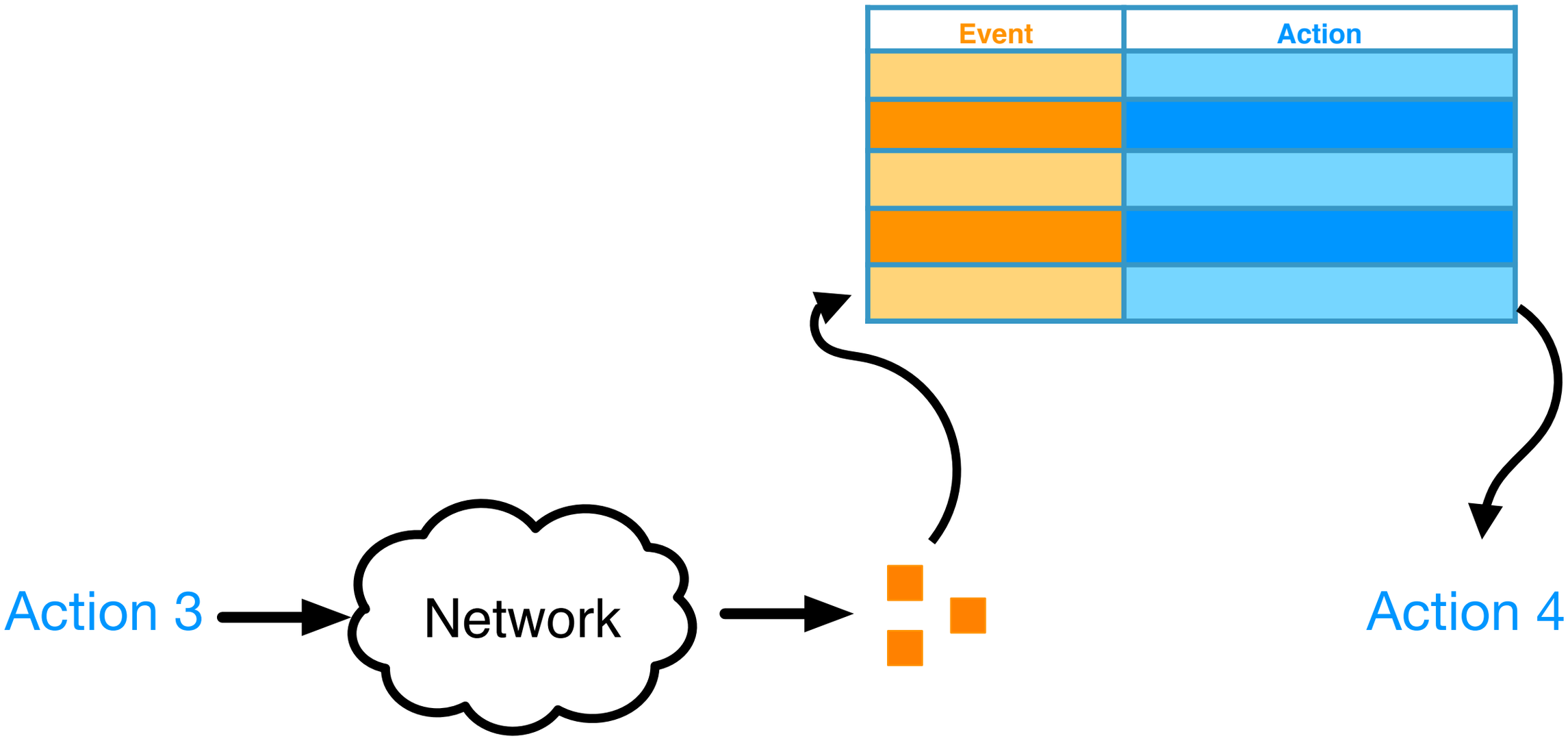
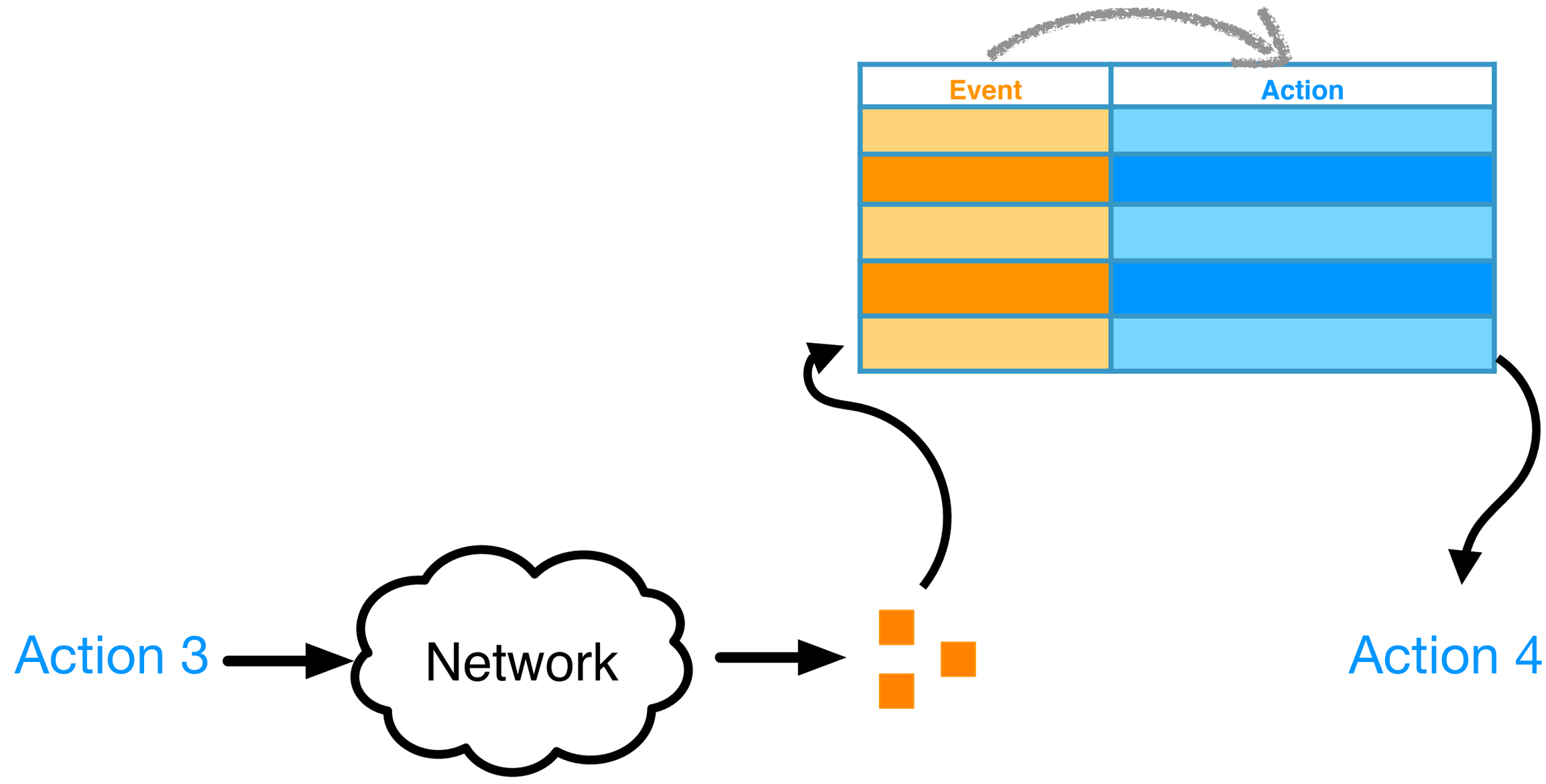



Event
Action
Action 3
Network
Action 4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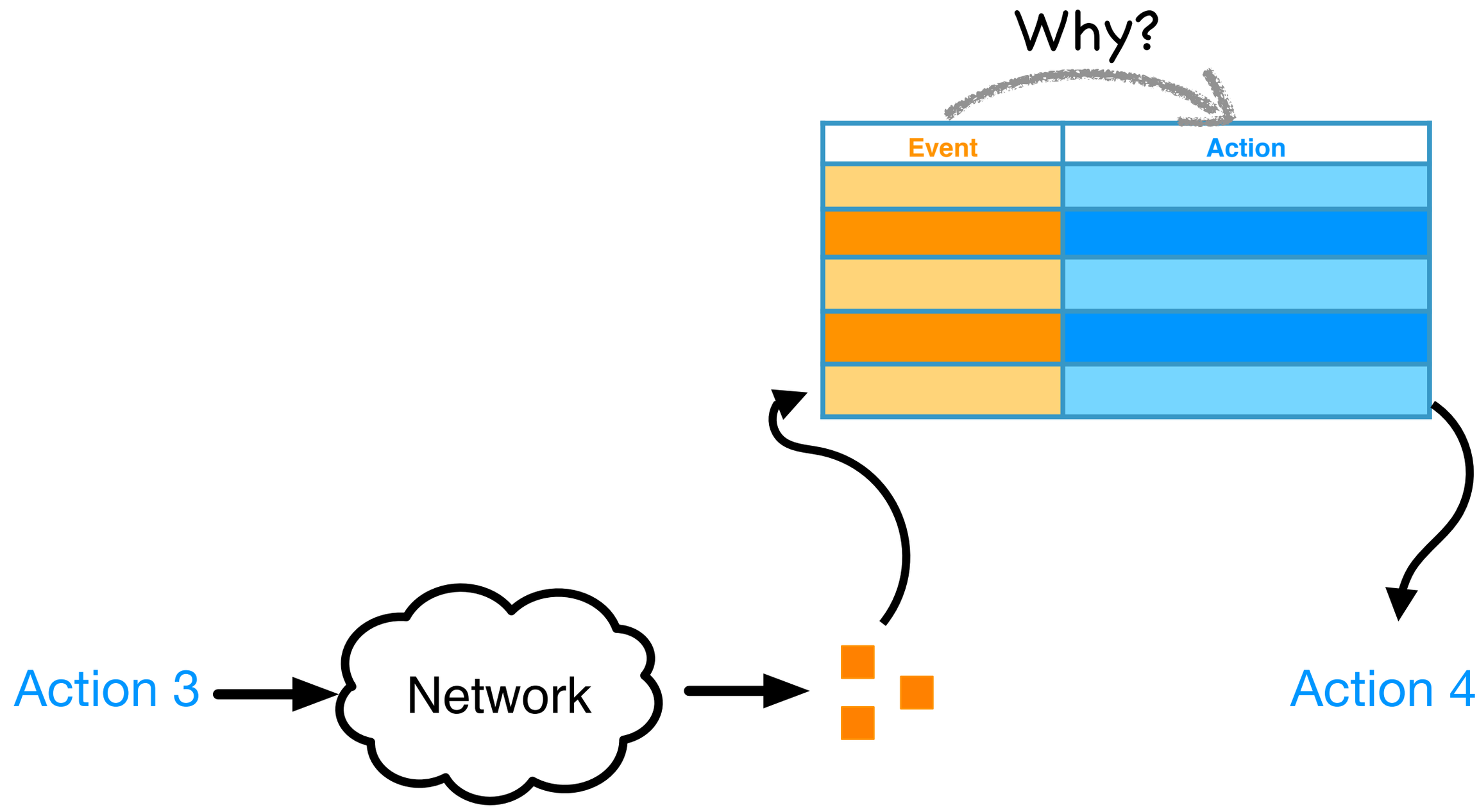
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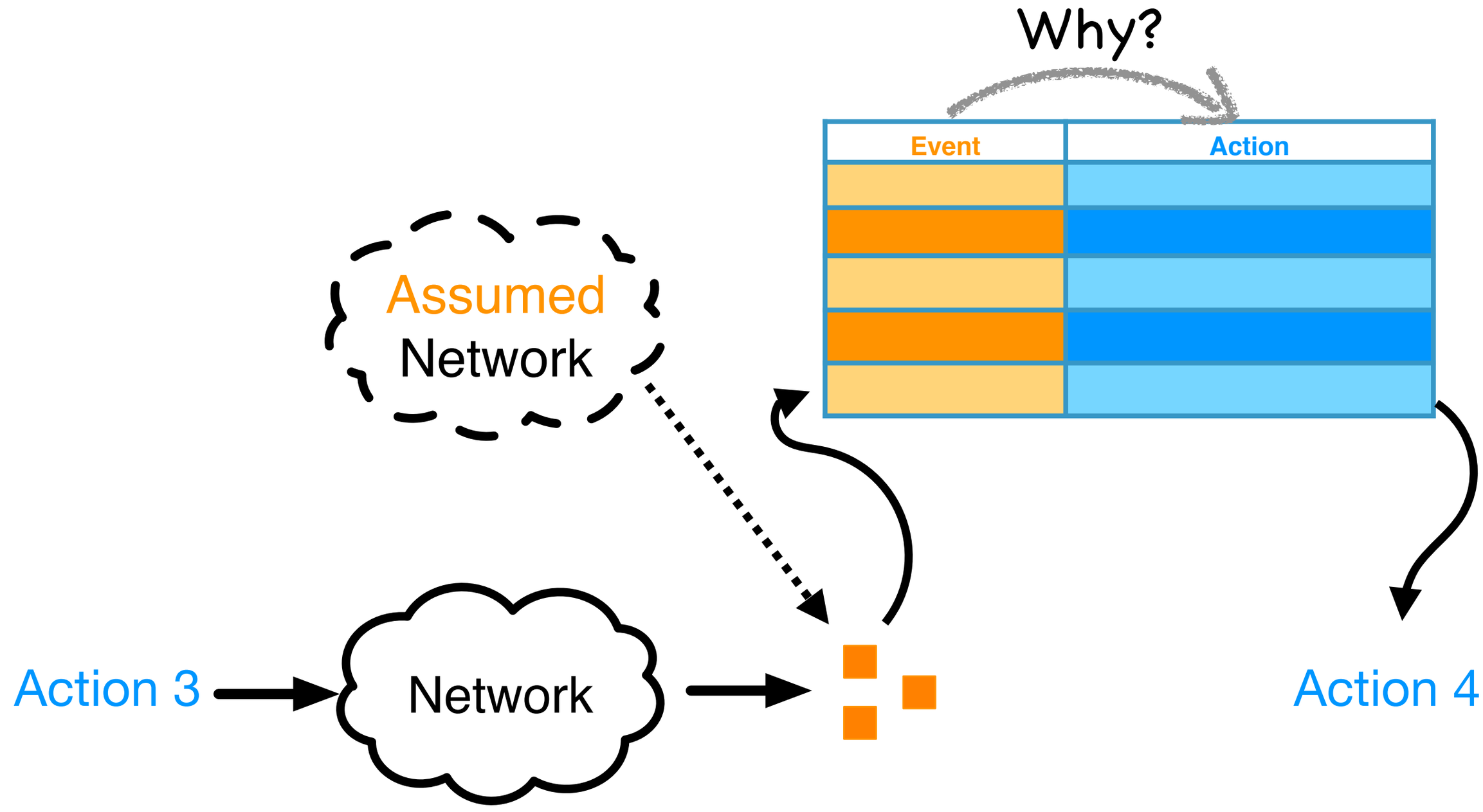
Why?
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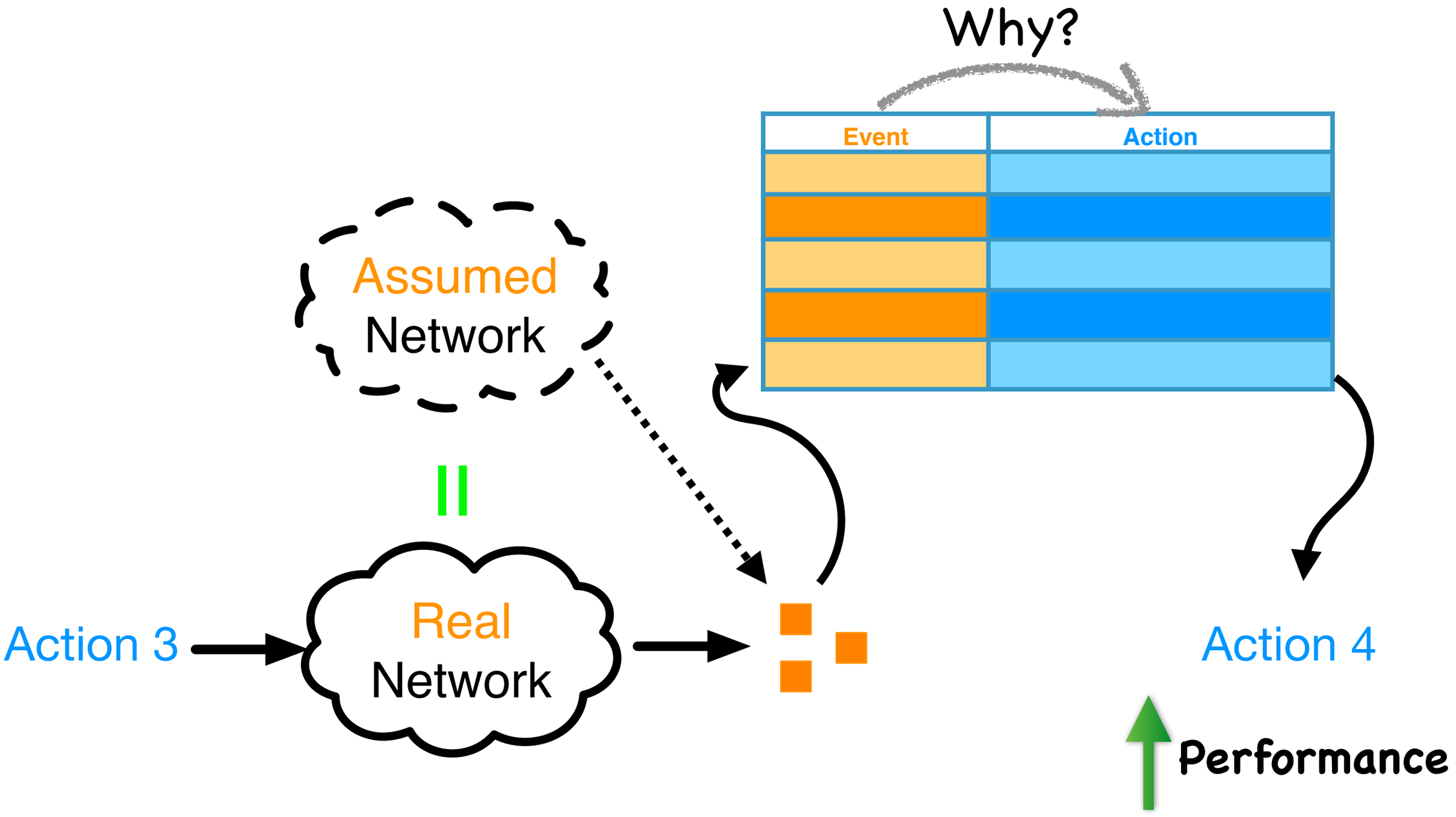
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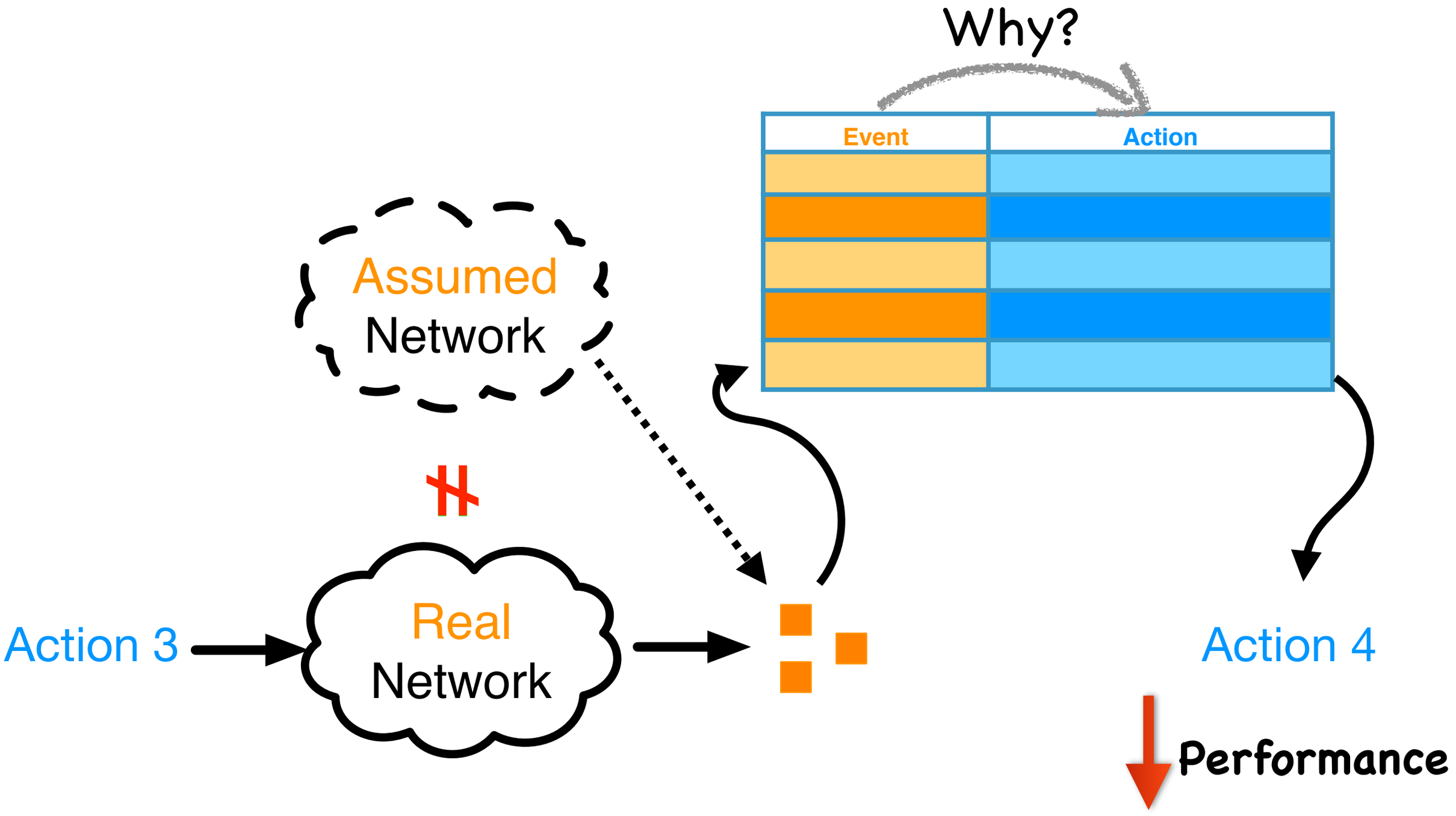
Performance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Performance

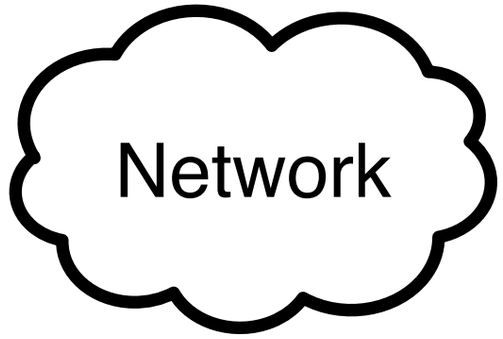
Flow f sends at R

Event	Action

Flow f sends at R

Event	Action
Packet Loss	

Flow f sends at R



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Packet Loss	

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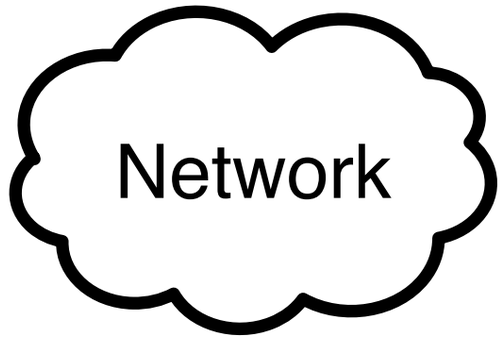
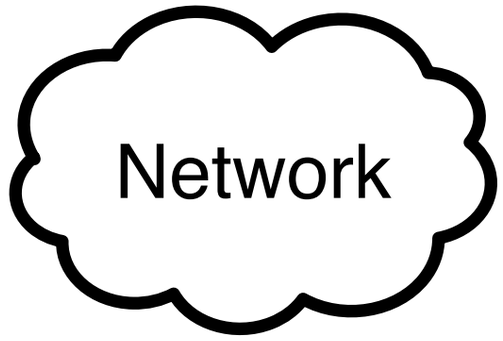


f causes
most congestion

Flow f sends at R

Event	Action
Packet Loss	Dec R a lot



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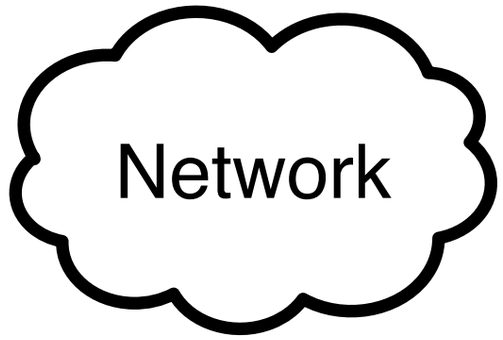
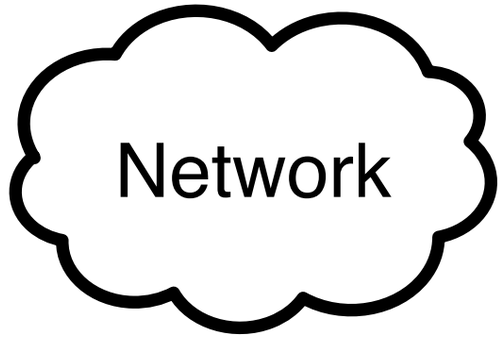


shallow buffer overflow

Flow f sends at R

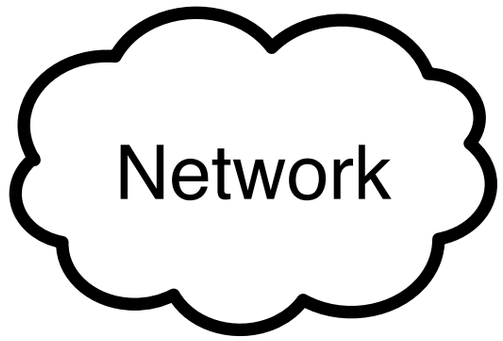


Event	Action
Packet Loss	~~Dec R a lot~~

shallow buffer overflow

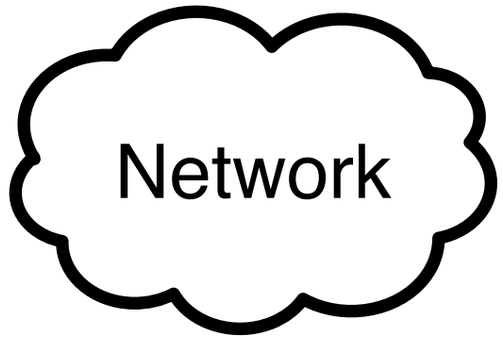
Flow f sends at R

Event	Action
Packet Loss	~~Dec R a lot~~ Dec R a little



shallow buffer overflow

Flow f sends at R



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other high rate flow causing congestion

Flow f sends at R

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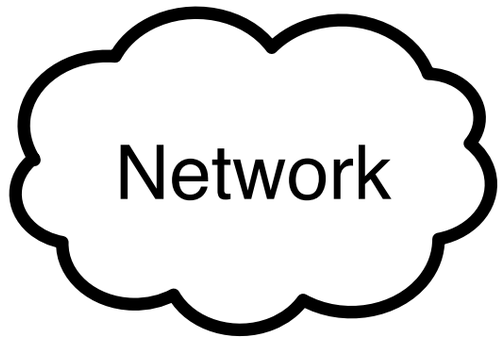

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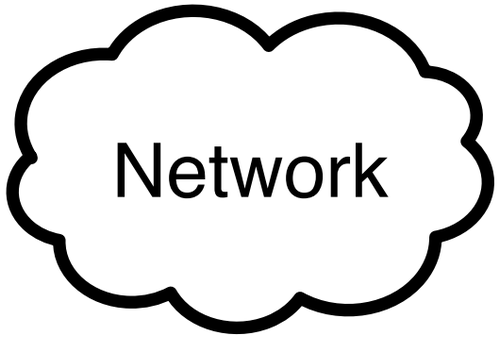

Event	Action
Packet Loss	~~Dec R a lot~~ ~~Dec R a little~~ Maintain R

other high rate flow causing congestion

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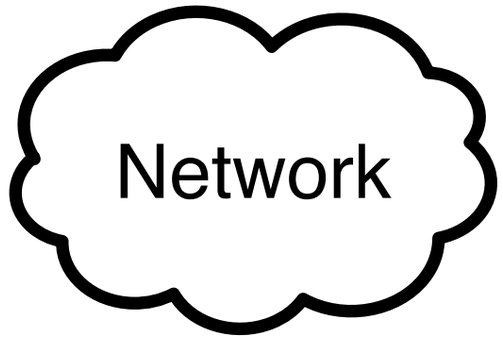

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loss is random

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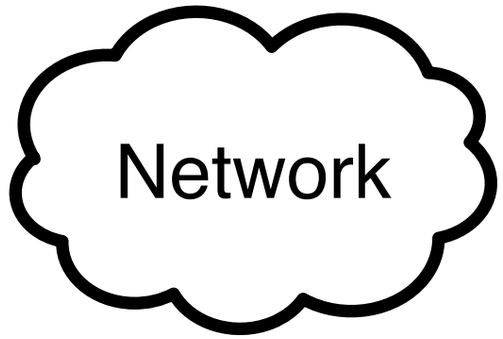

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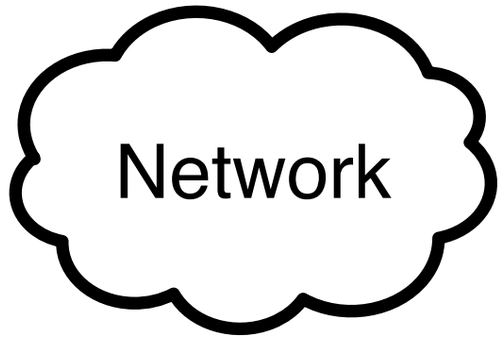
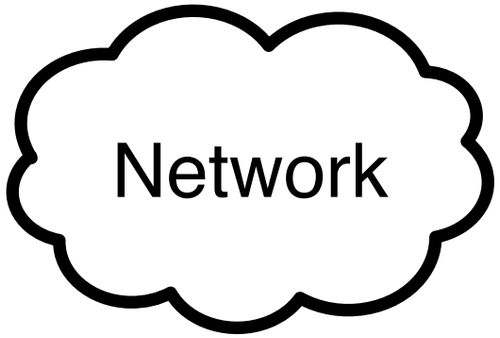


Event	Action
Packet Loss	~~Dec R a lot~~ ~~Dec R a little~~ ~~Maintain R~~ Increase R

loss is random

Flow f sends at R



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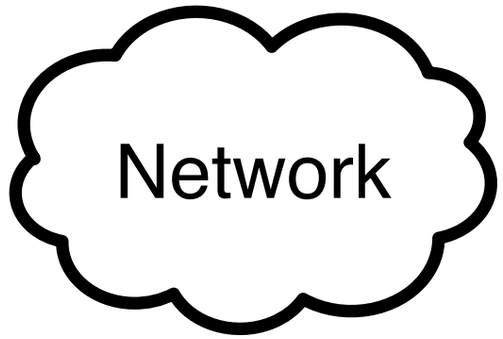

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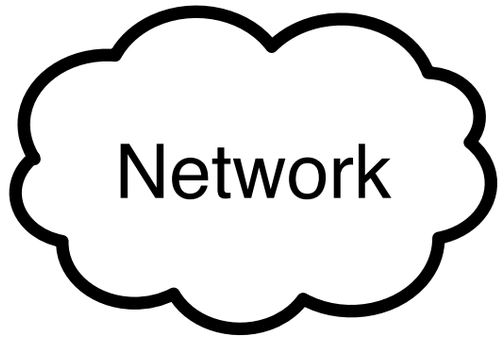

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No event-control mapping optimal for all network scenarios

What is the right rate to send?

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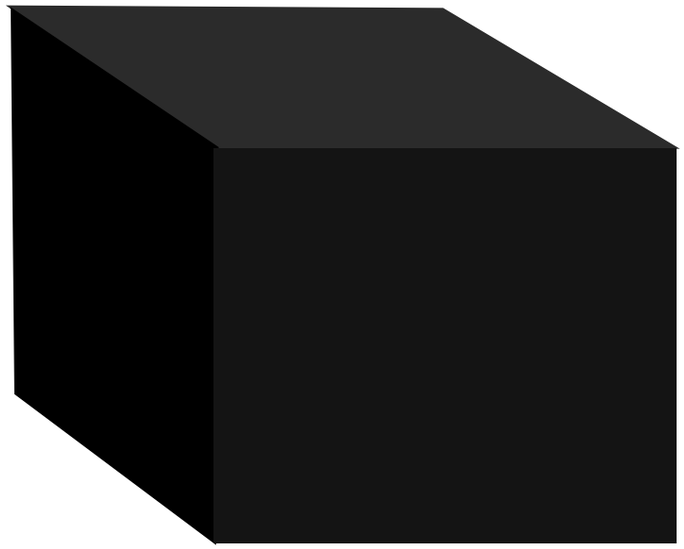

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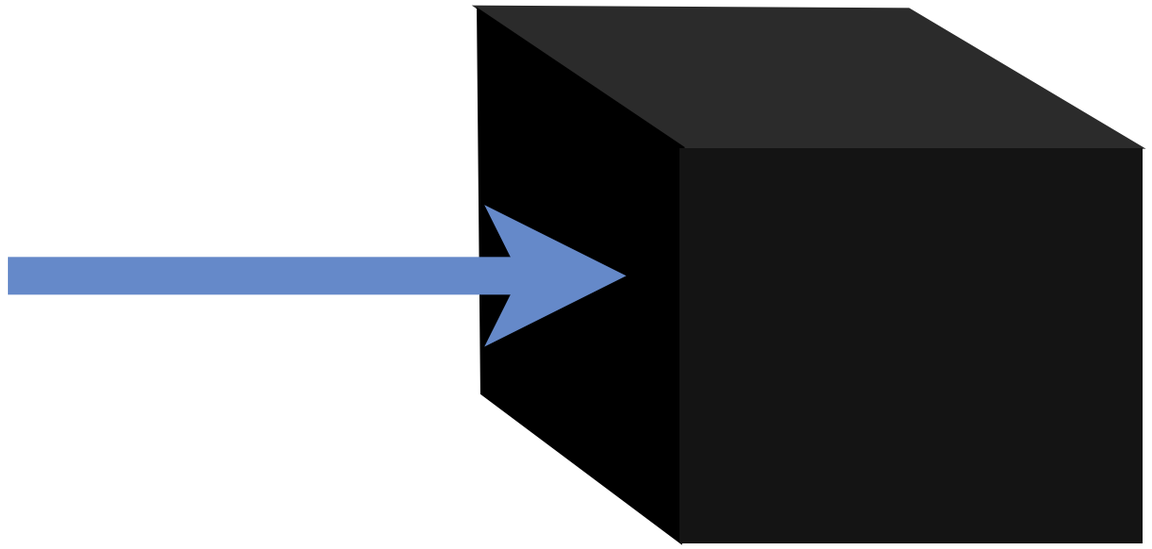

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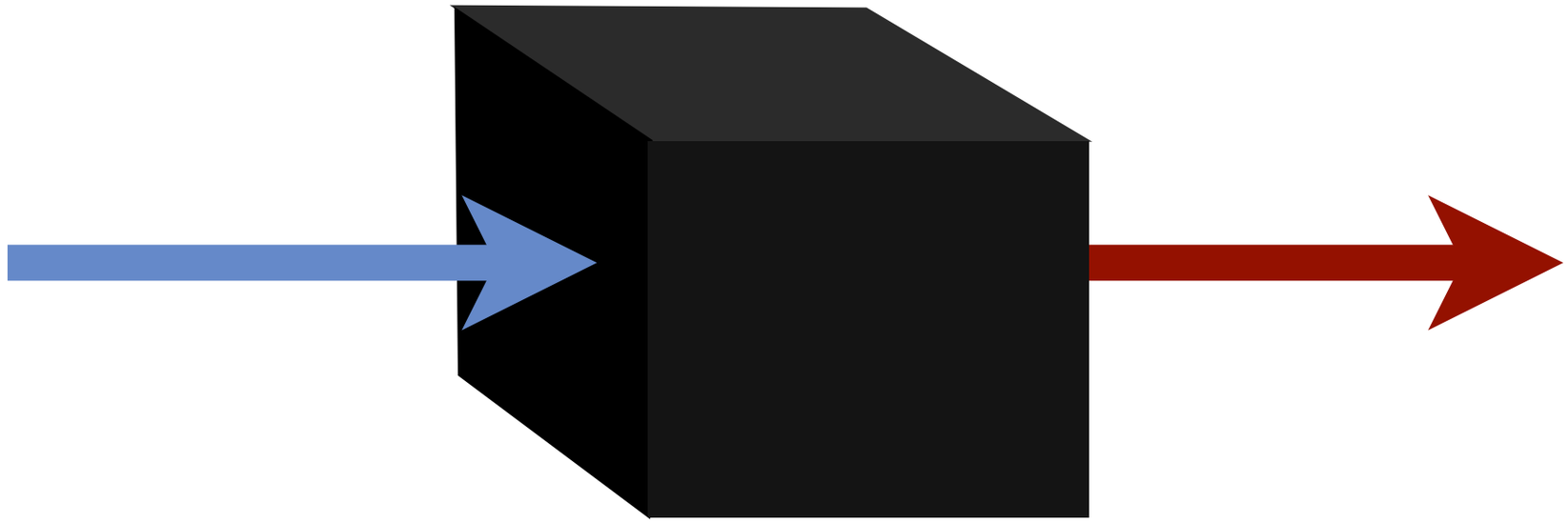

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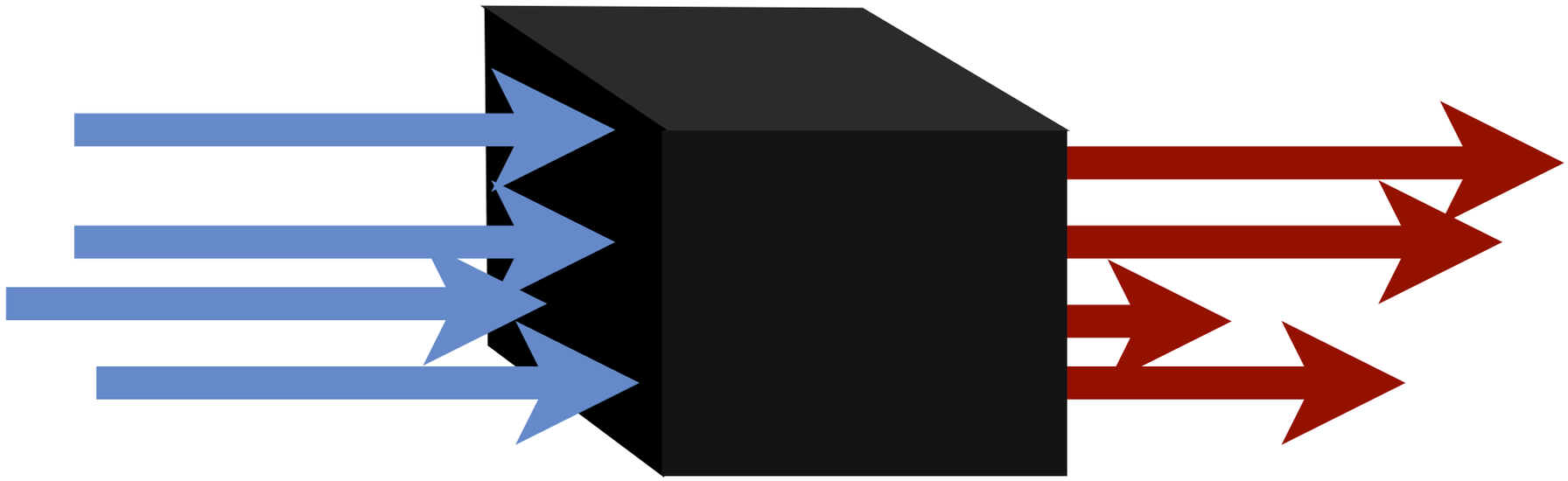

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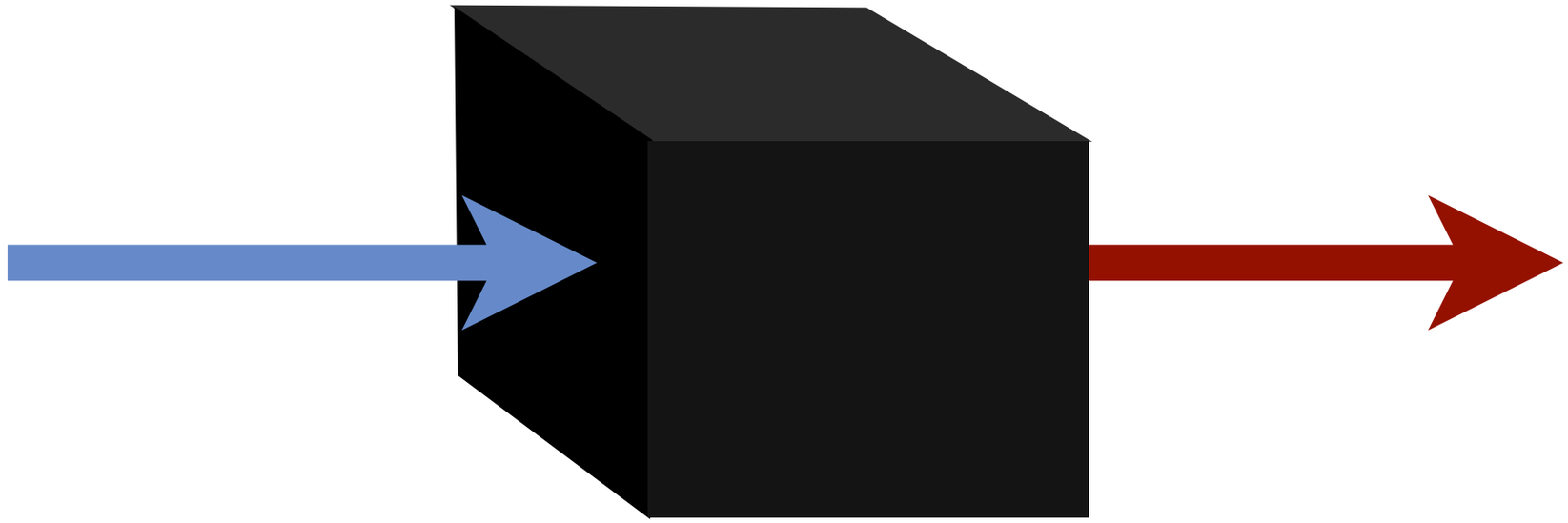

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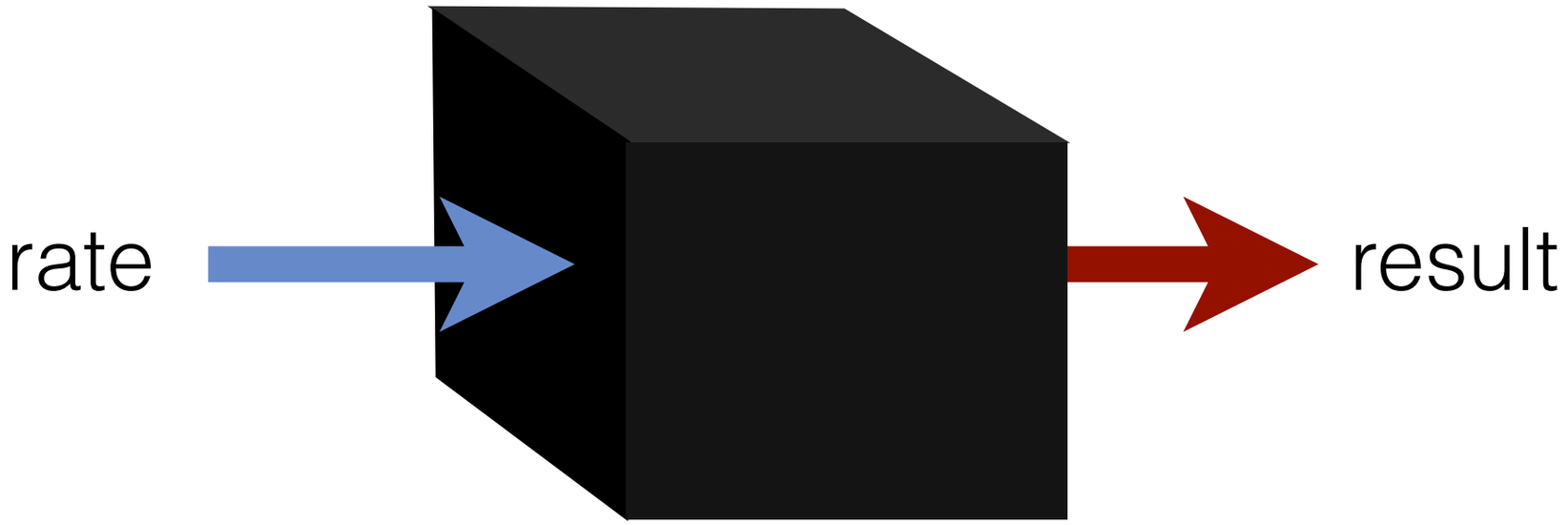

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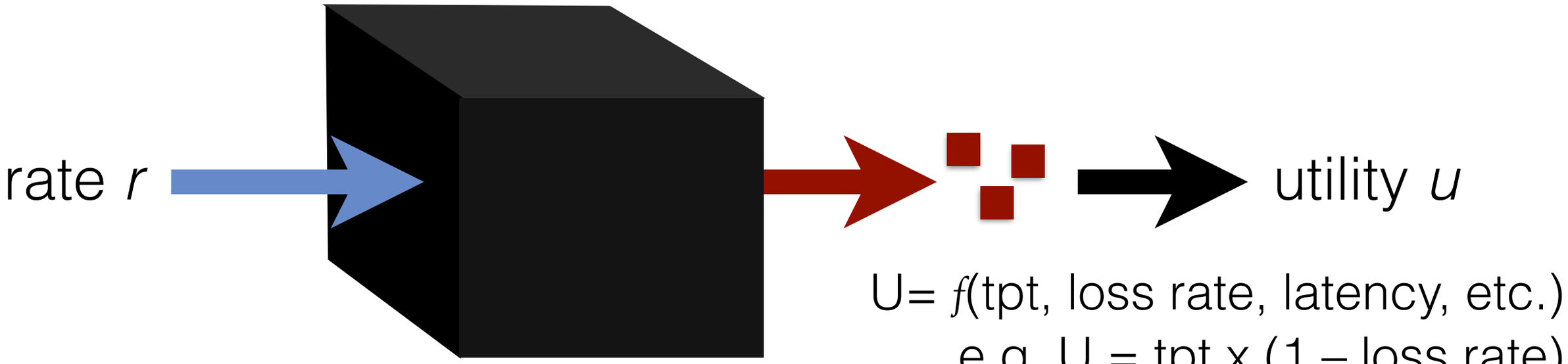

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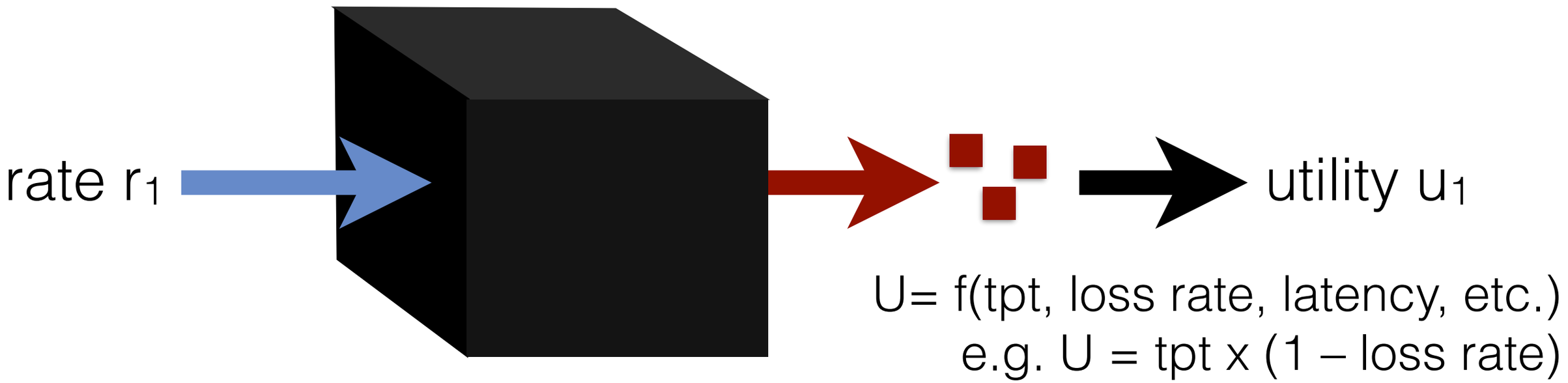
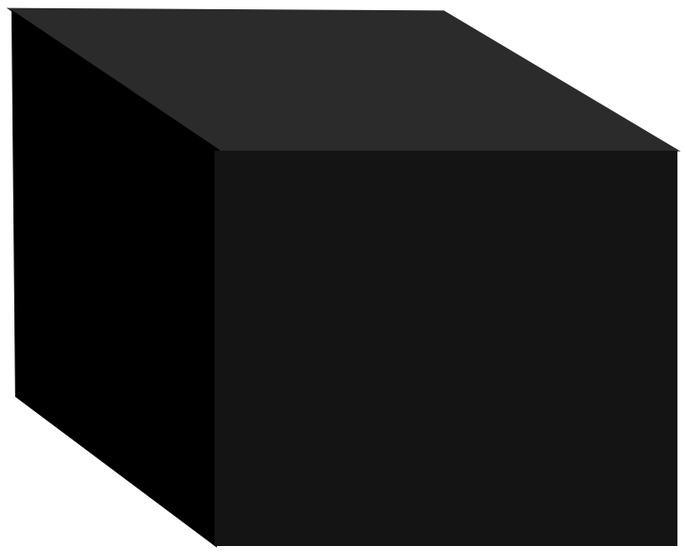
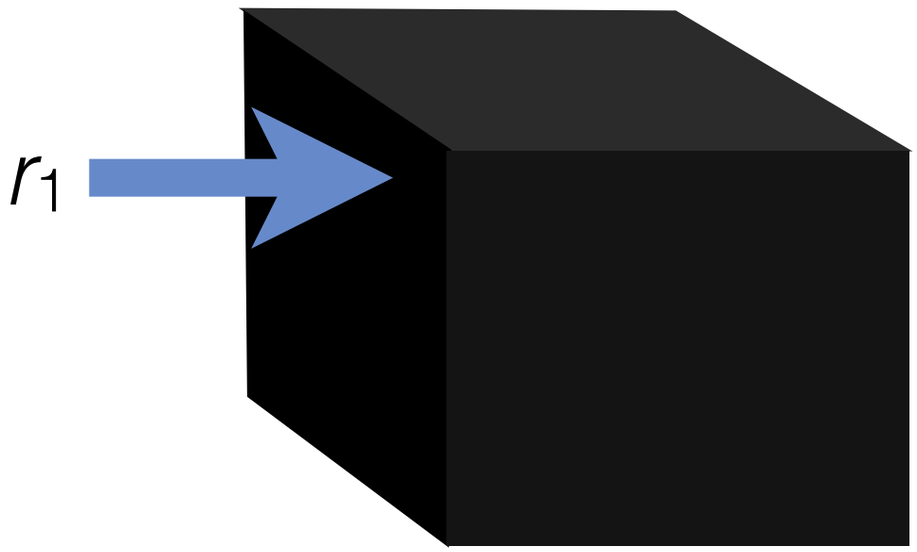
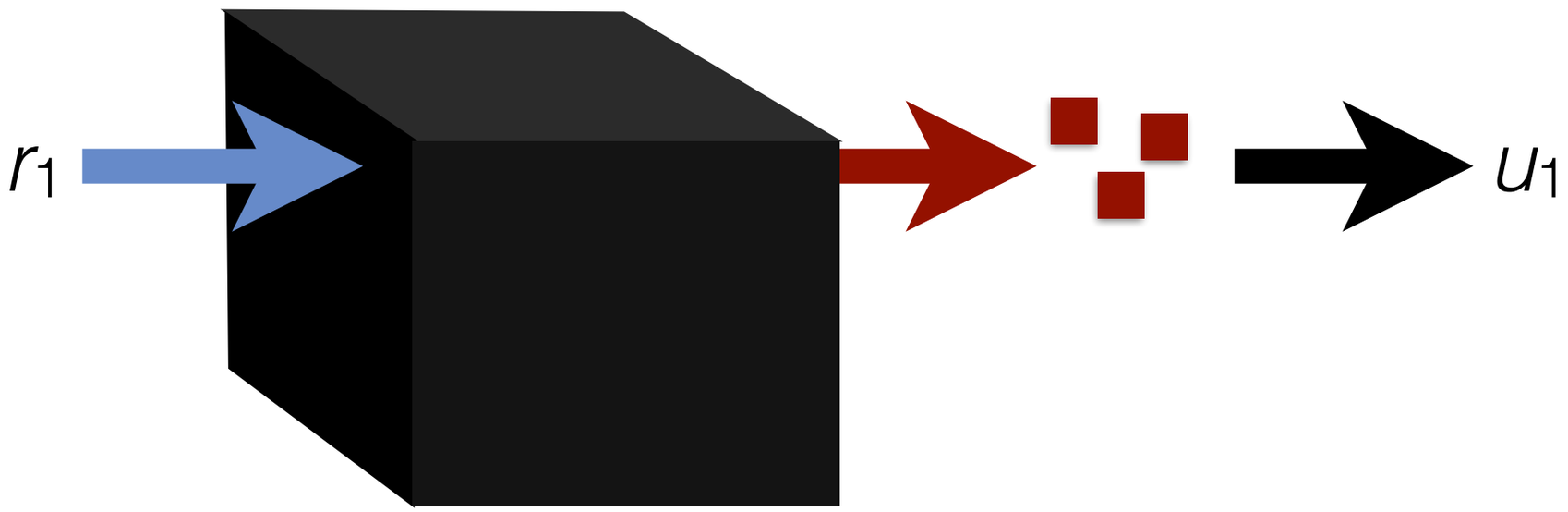
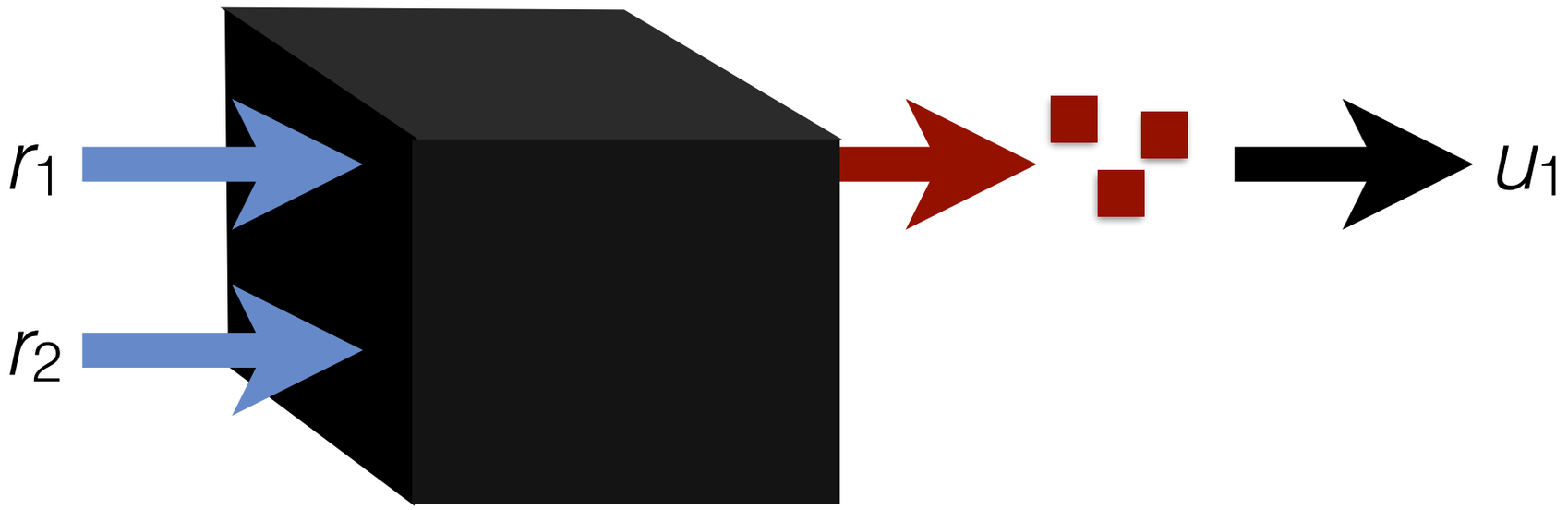


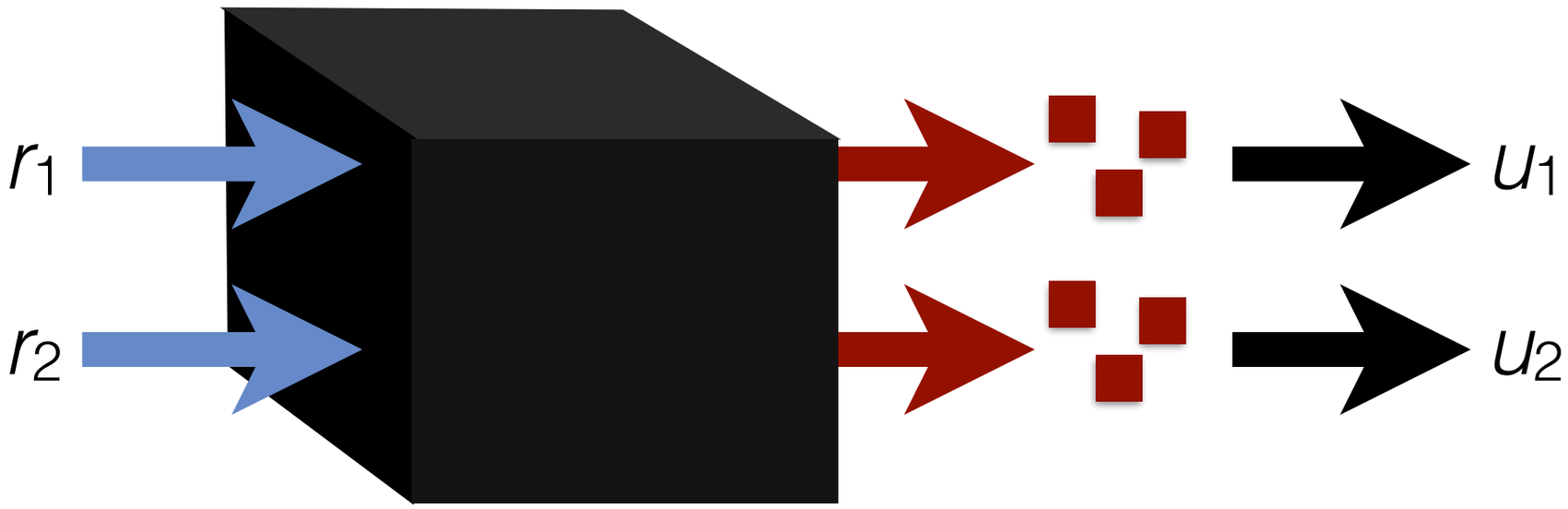
No matter how complex the network,
rate r —> utility u

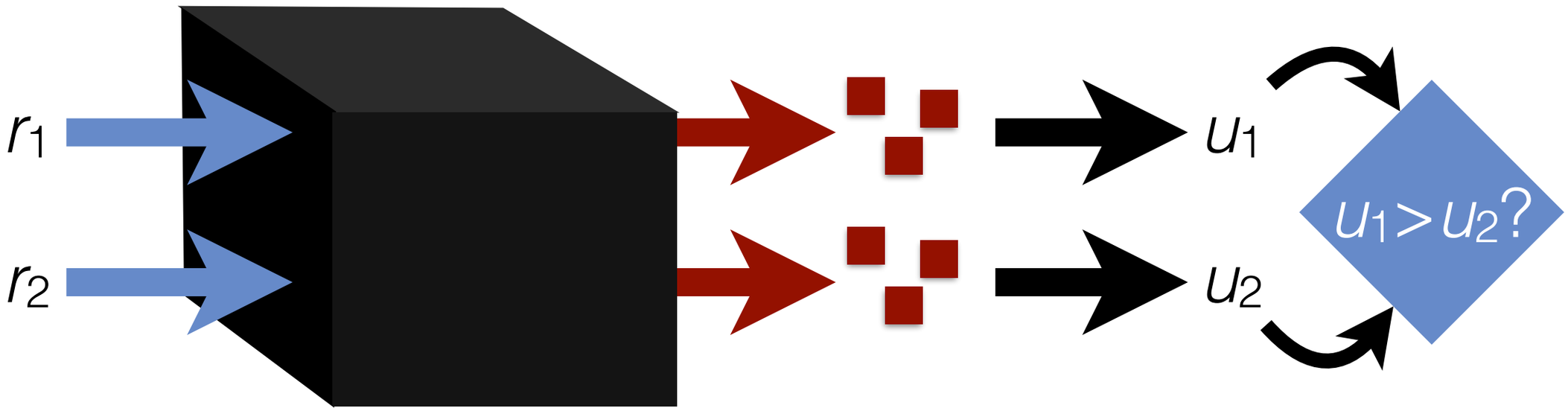


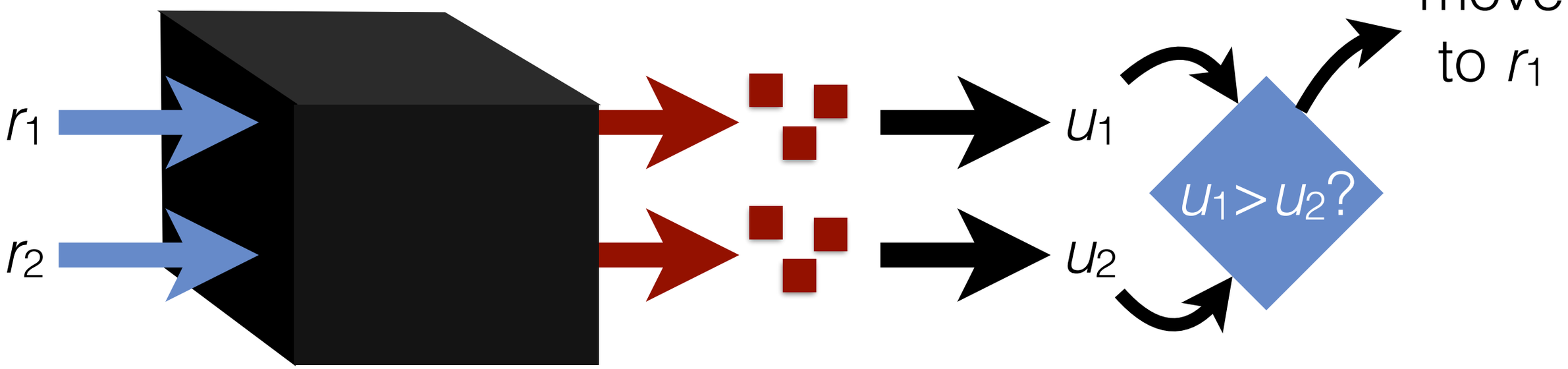

r_1

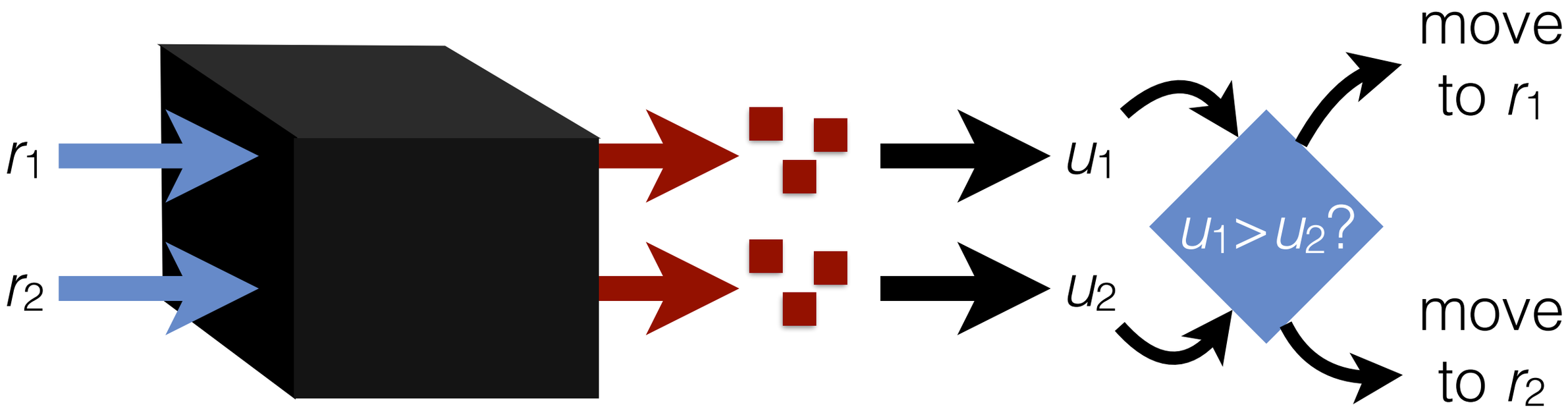

r_1
u_1


r_1
r_2
u_1

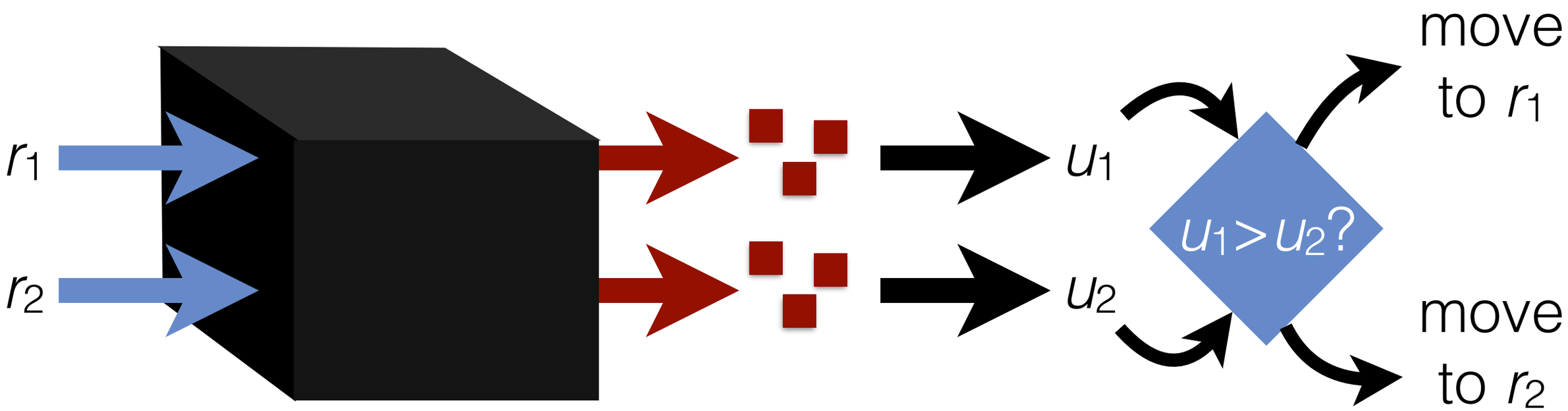

r_1
r_2
u_1
u_2


r_1
r_2
u_1
u_2
$u_1 > u_2$?

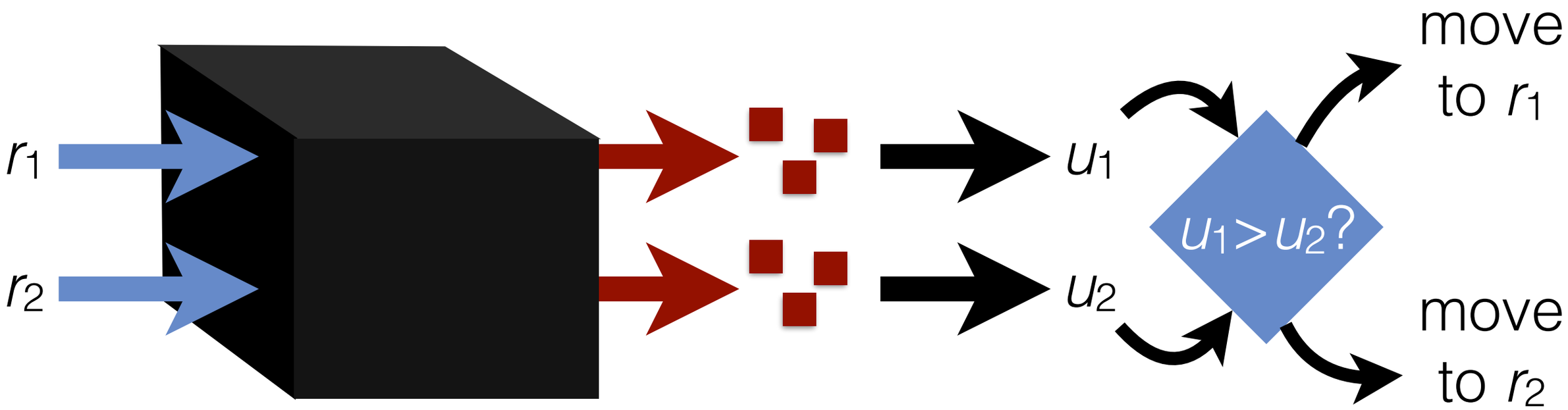

r_1
r_2
u_1
u_2
$u_1 > u_2$?
move to r_1


r_1
r_2
u_1
u_2
$u_1 > u_2$?
move to r_1
move to r_2

Performance-oriented Congestion Control

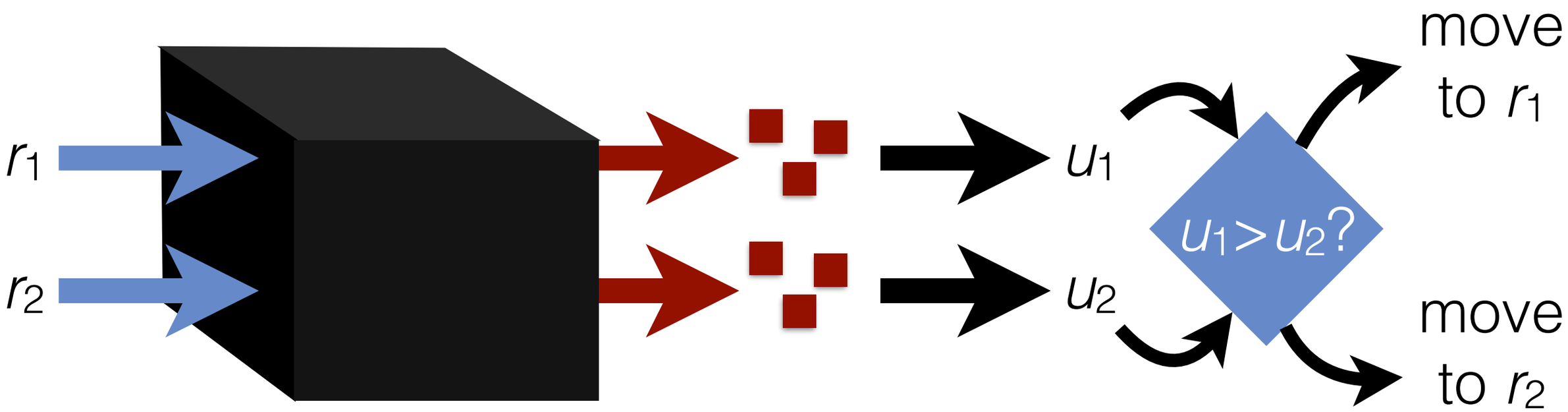


Performance-oriented Congestion Control



Observe real performance

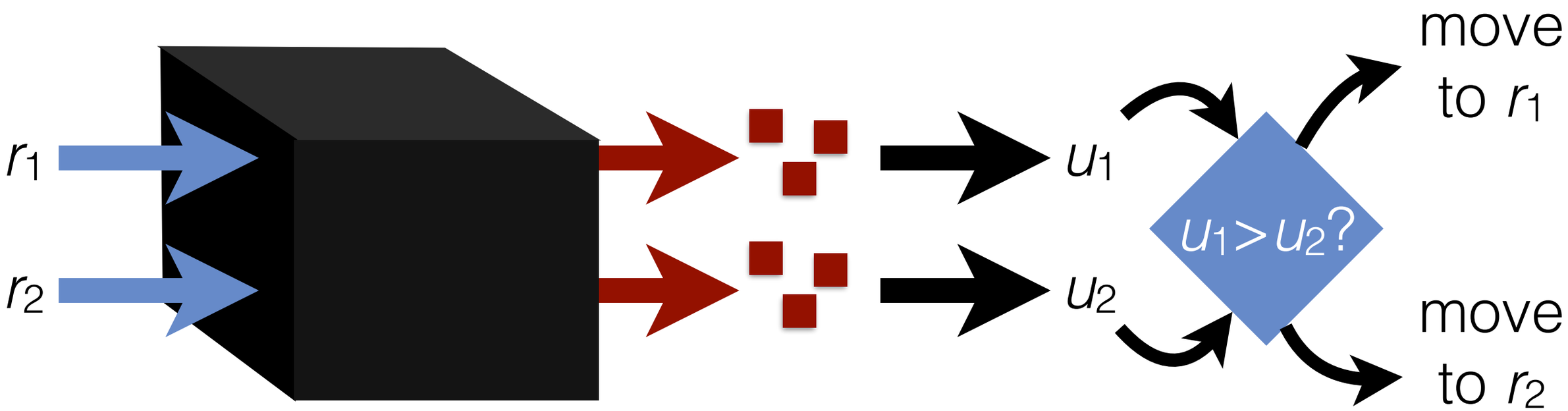
Performance-oriented Congestion Control



Observe real performance

Control based on empirical evidence

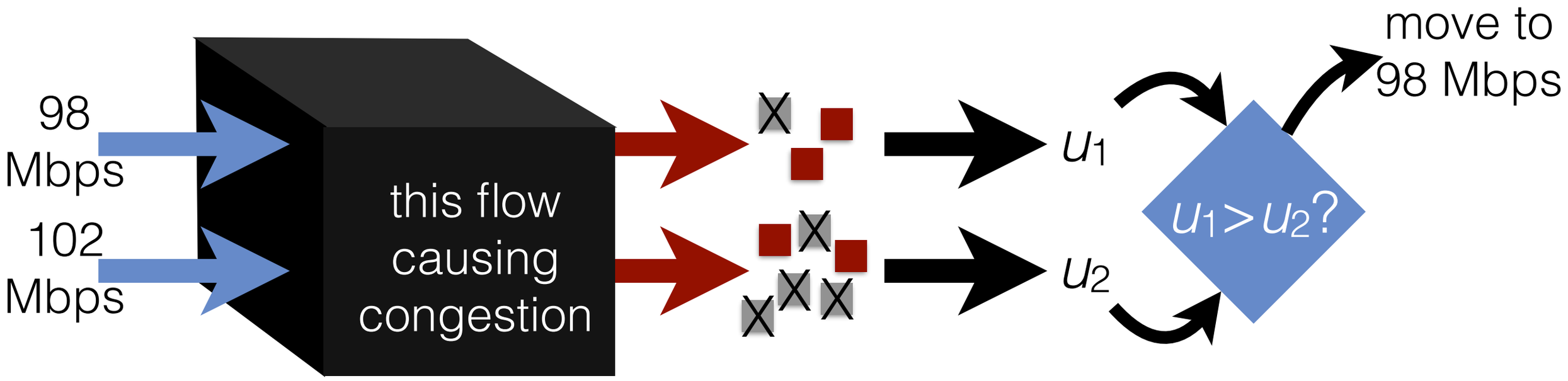
Performance-oriented Congestion Control

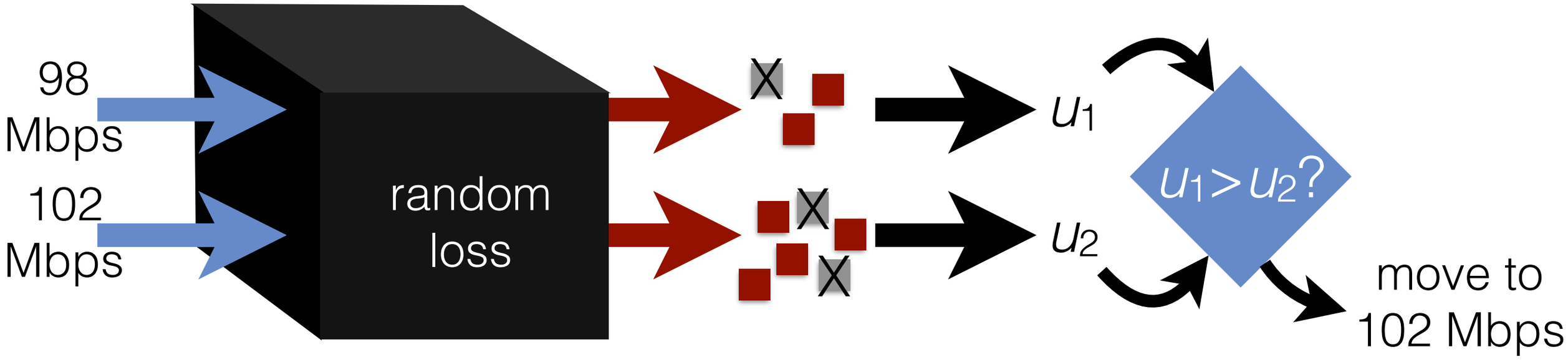


Observe real performance

Control based on empirical evidence

yields **Consistent high performance**


98
Mbps
102
Mbps
this flow
causing
congestion
u_1
u_2
$u_1 > u_2$?
move to
98 Mbps


98
Mbps
102
Mbps
random
loss
u_1
u_2
$u_1 > u_2$?
move to
102 Mbps

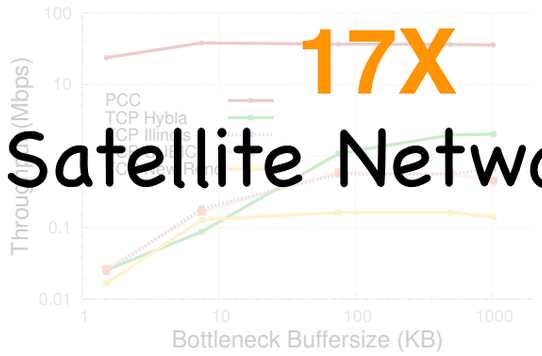
Consistent High Performance

4X
InterDC

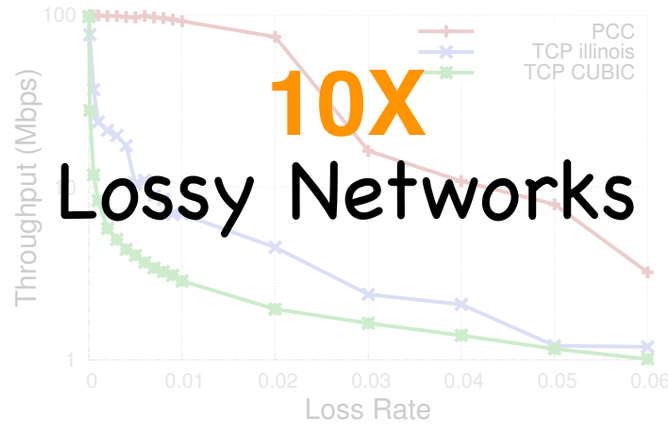
Table 1: PCC significantly outperforms TCP in inter-data center environments. RTT in msec; throughput in Mbps.

Transmission Pair	RTT	PCC	SABUL	CUBIC	Illinois
GPO → NYSERNet	12.1	791	674	129	326
GPO → Missouri	47.4	808	661	80.7	90.1
GPO → Illinois	35.4	766	664	84.5	102
NYSERNet → Missouri	47.4	816	662	108	109
Wisconsin → Illinois	9.01	801	700	547	562
GPO → Wisc.	38.0	783	487	79.3	120
NYSERNet → Wisc.	38.3	791	673	134	134
Missouri → Wisc.	20.9	807	698	259	262
NYSERNet → Illinois	36.1	808	674	141	141

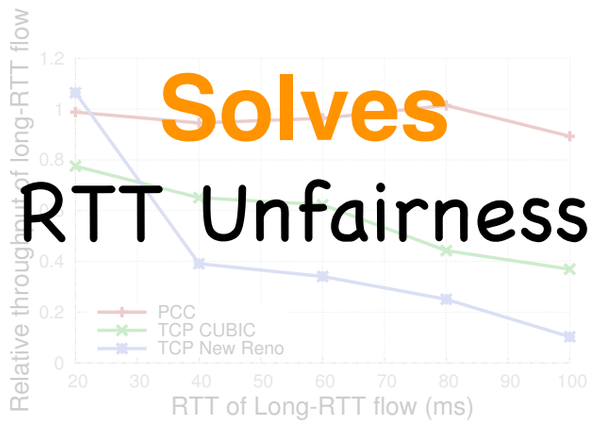
17X
Satellite Networks



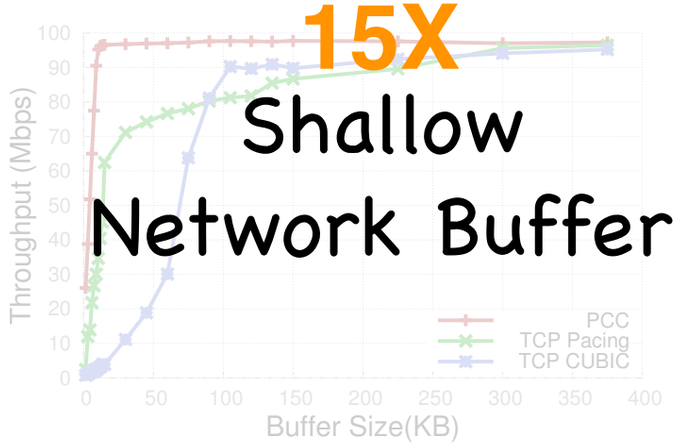
10X
Lossy Networks



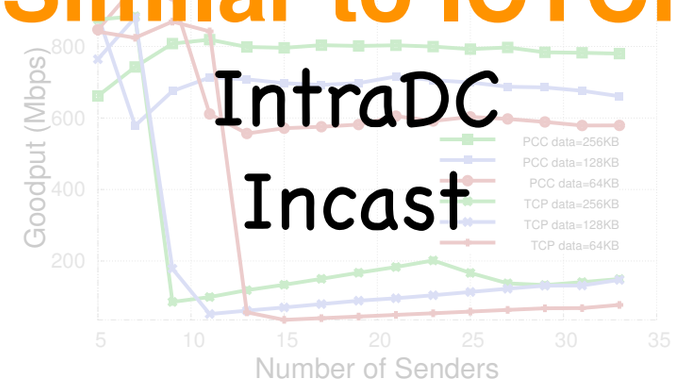
Solves
RTT Unfairness



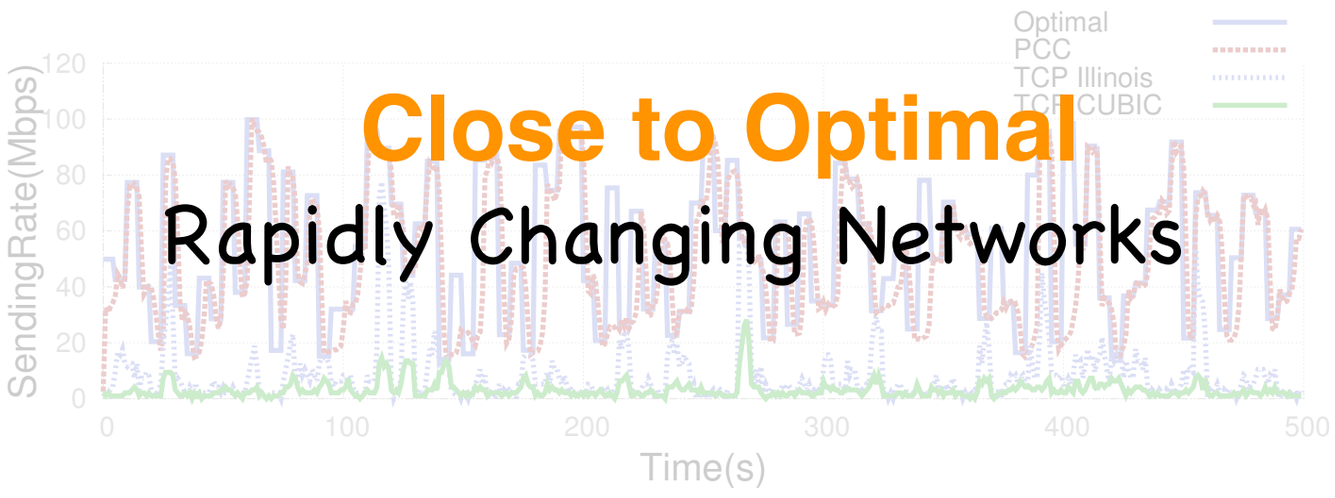
15X
Shallow
Network Buffer



Similar to ICTCP
IntraDC
Incast

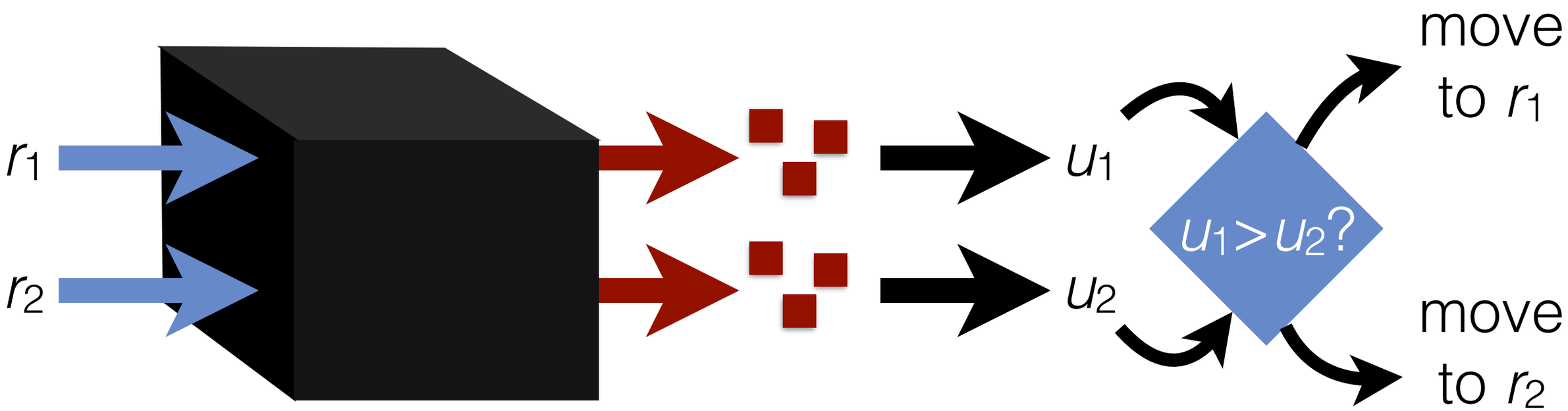


Close to Optimal
Rapidly Changing Networks

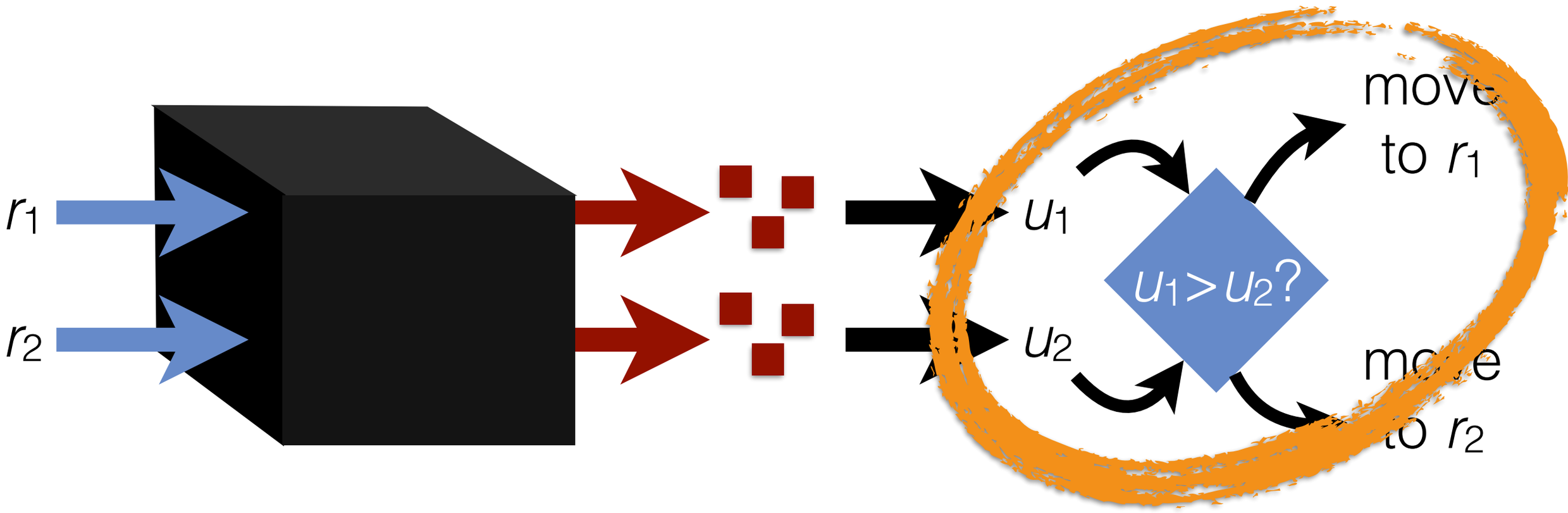


5X in median
Global Commercial
Internet

Where is Congestion Control?

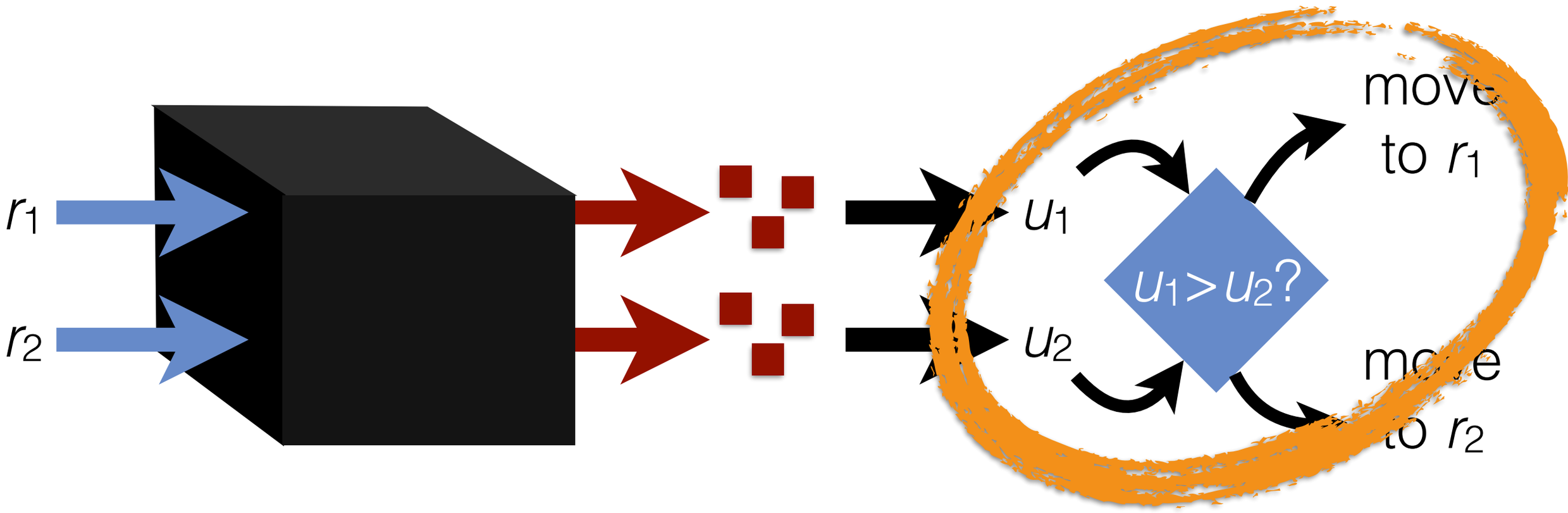


Where is Congestion Control?



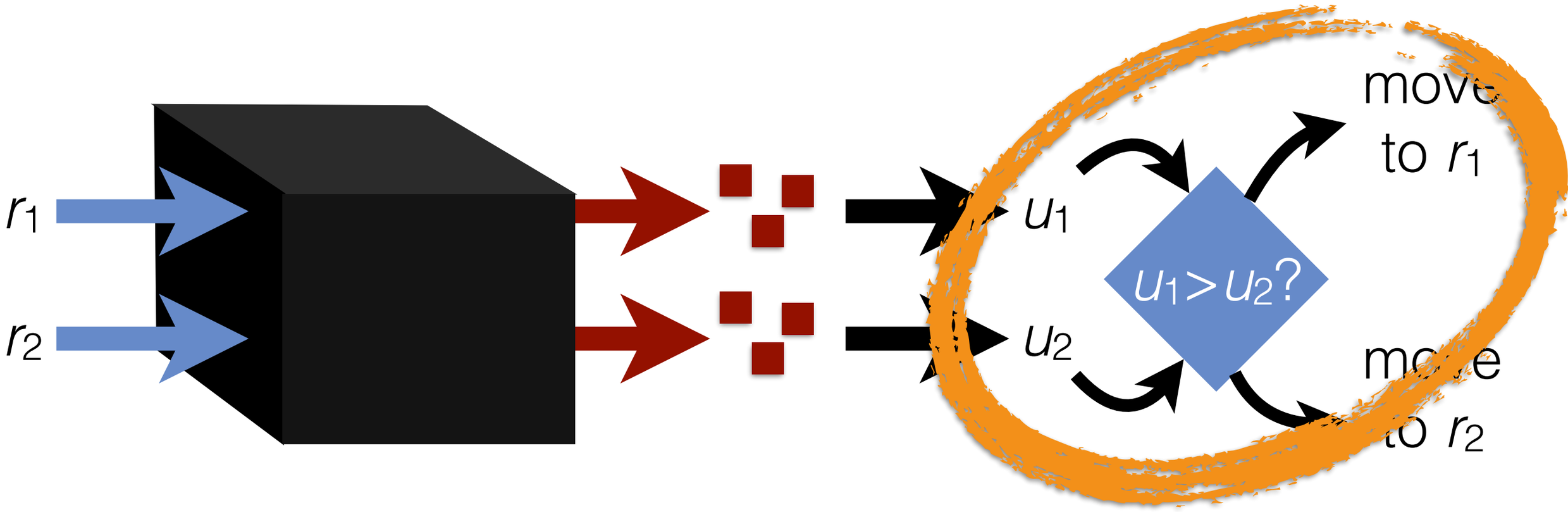
Selfishly maximizing utility

Where is Congestion Control?



Selfishly maximizing utility
=> non-cooperative game

Where is Congestion Control?



Selfishly maximizing utility
=> non-cooperative game

Do we converge to a fair Nash equilibrium?

A class of utility functions converge to a fair and efficient Nash Equilibrium

A class of utility functions converge to a fair and efficient Nash Equilibrium

$$u_i(x) = T_i \qquad - x_i * L_i$$

A class of utility functions converge to a fair and efficient Nash Equilibrium

$$u_i(x) = T_i - x_i * L_i$$

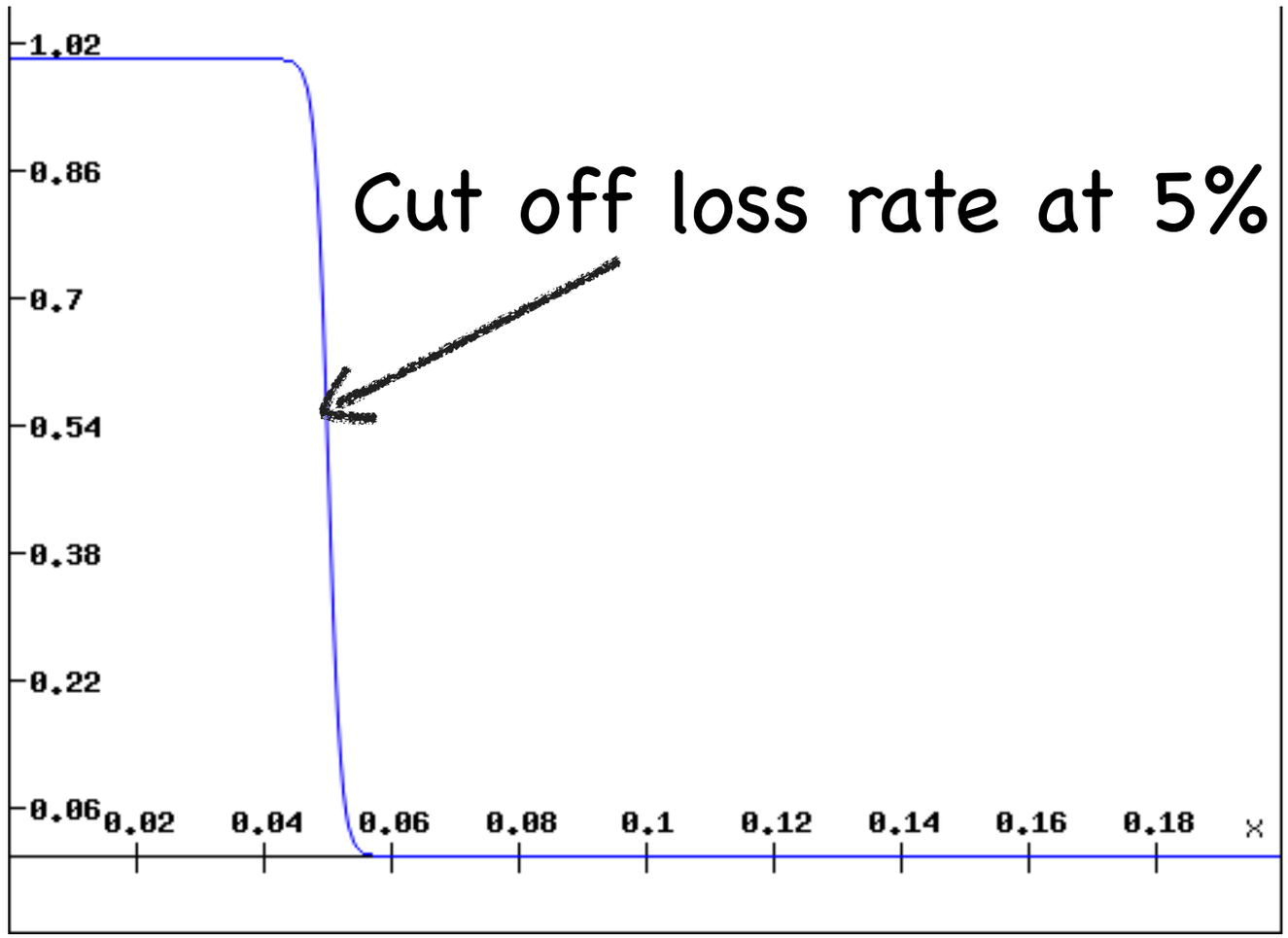
throughput

sending rate

observed loss rate

A class of utility functions converge to a fair and efficient Nash Equilibrium

$$u_i(x) = T_i * sigmoid(L_i - 0.05) - x_i * L_i$$



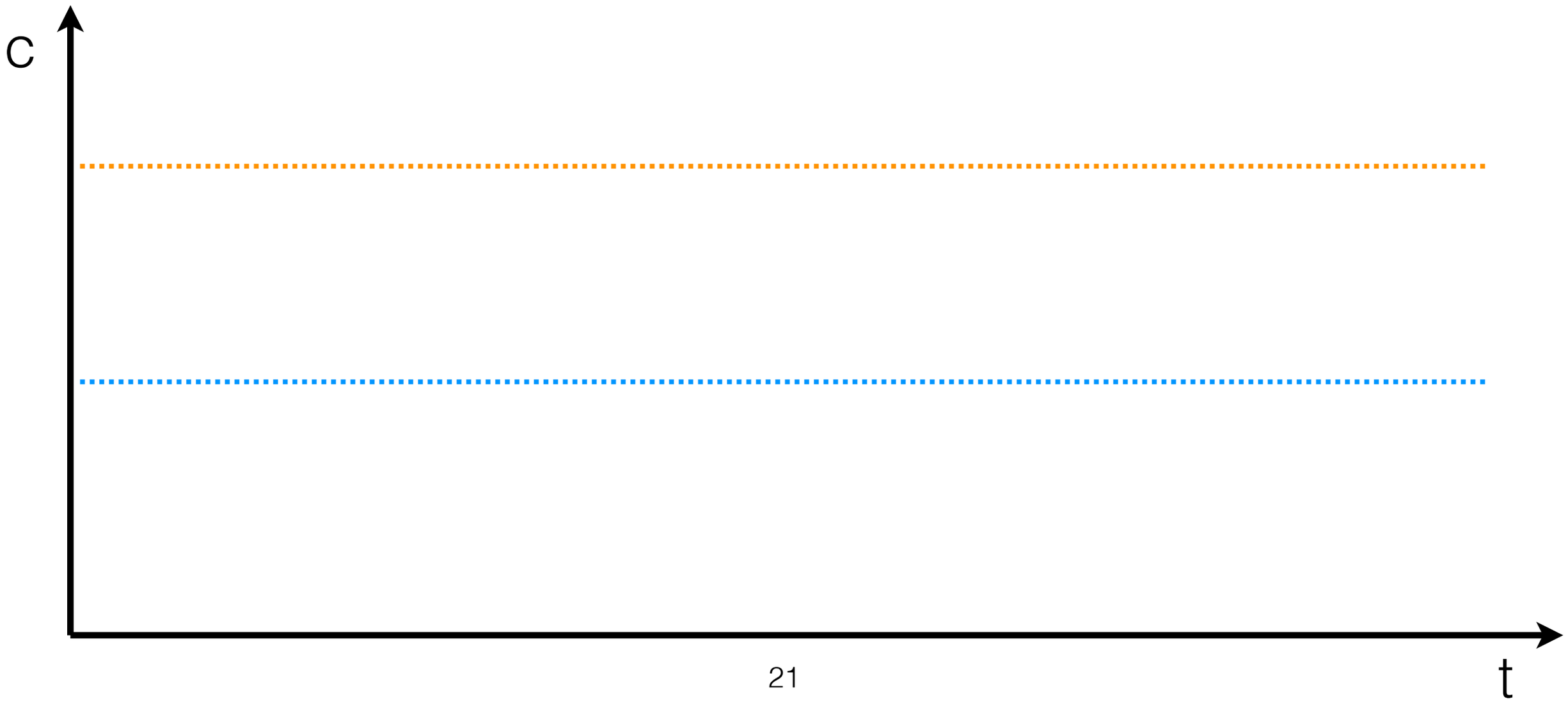
TCP Dynamics

TCP Dynamics

AIMD as a "hack" to asymptotic fairness

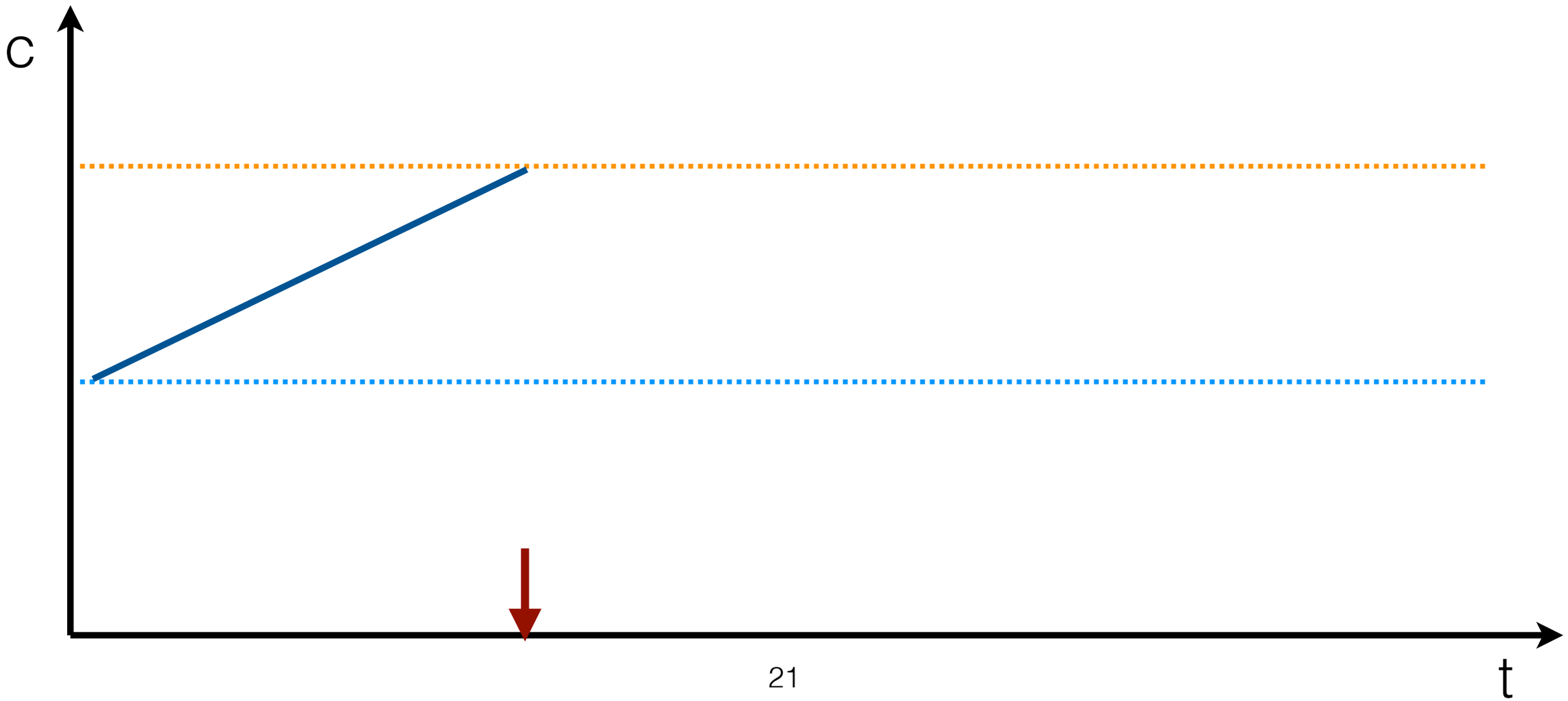
TCP Dynamics

AIMD as a "hack" to asymptotic fairness



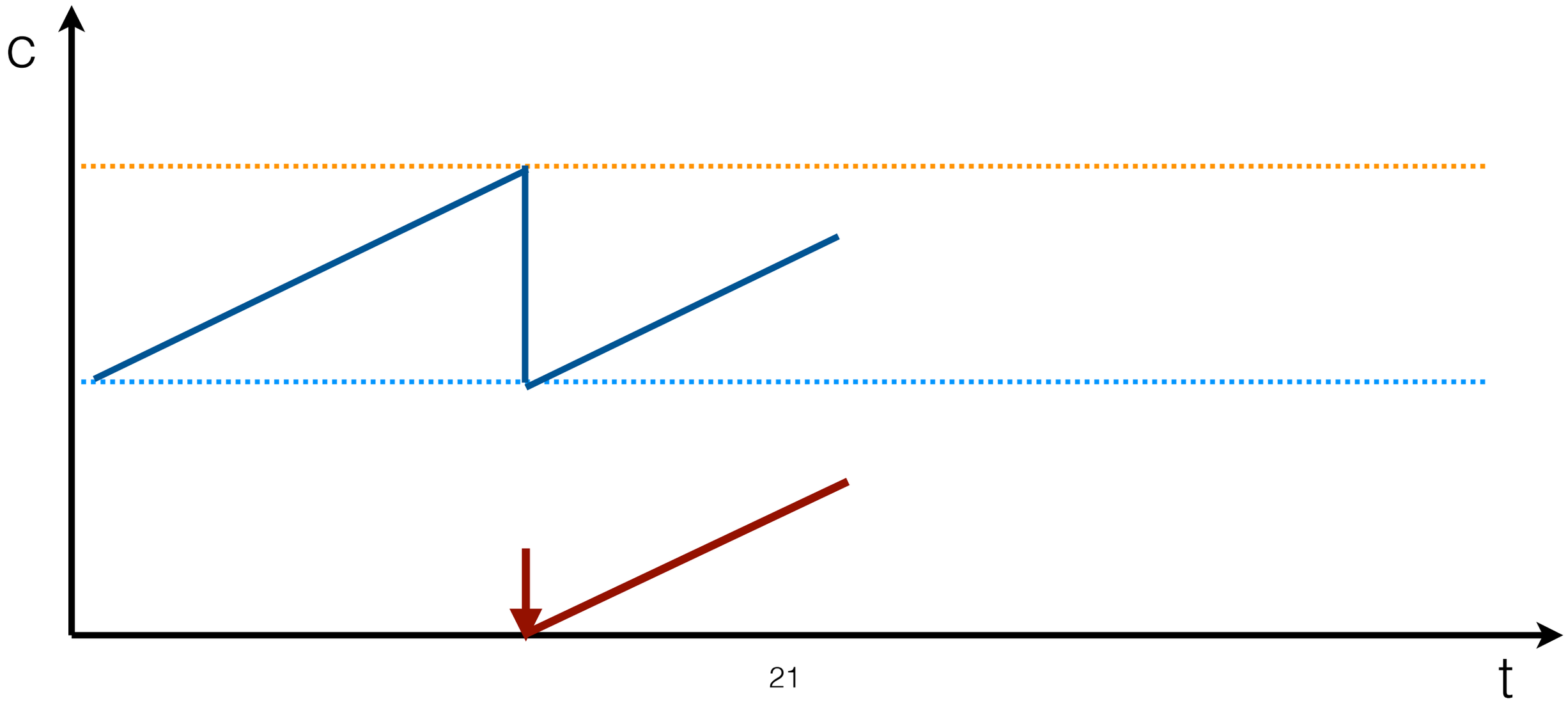
TCP Dynamics

AIMD as a "hack" to asymptotic fairness



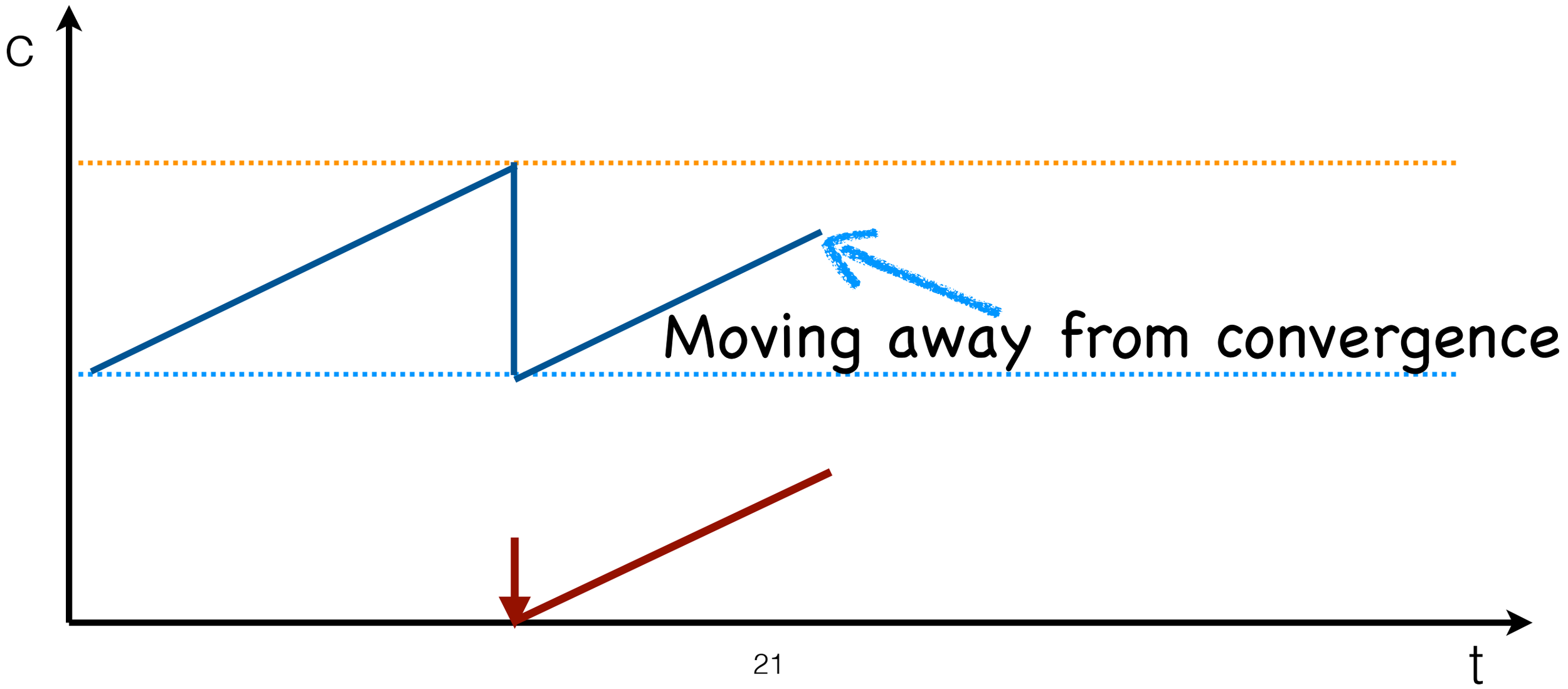
TCP Dynamics

AIMD as a "hack" to asymptotic fairness

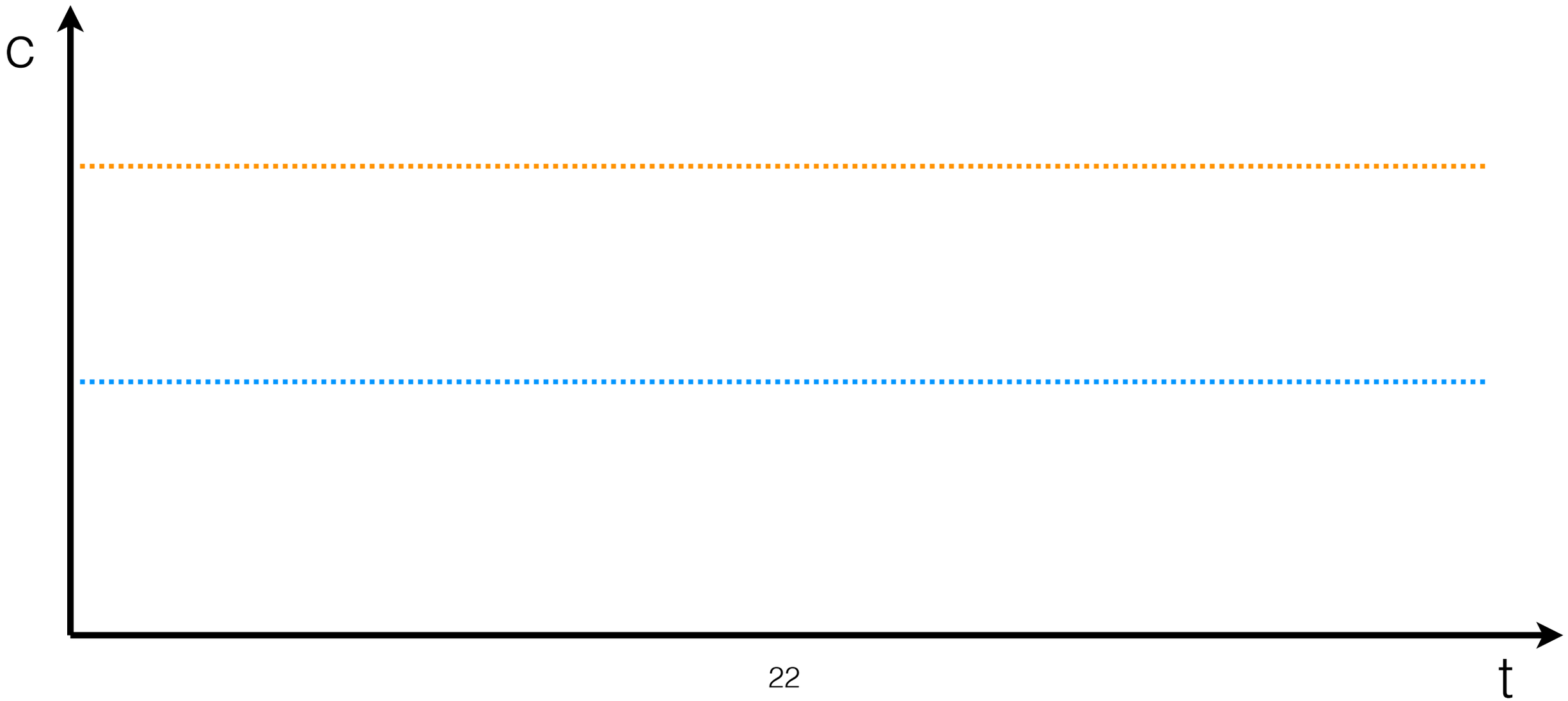


TCP Dynamics

AIMD as a "hack" to asymptotic fairness

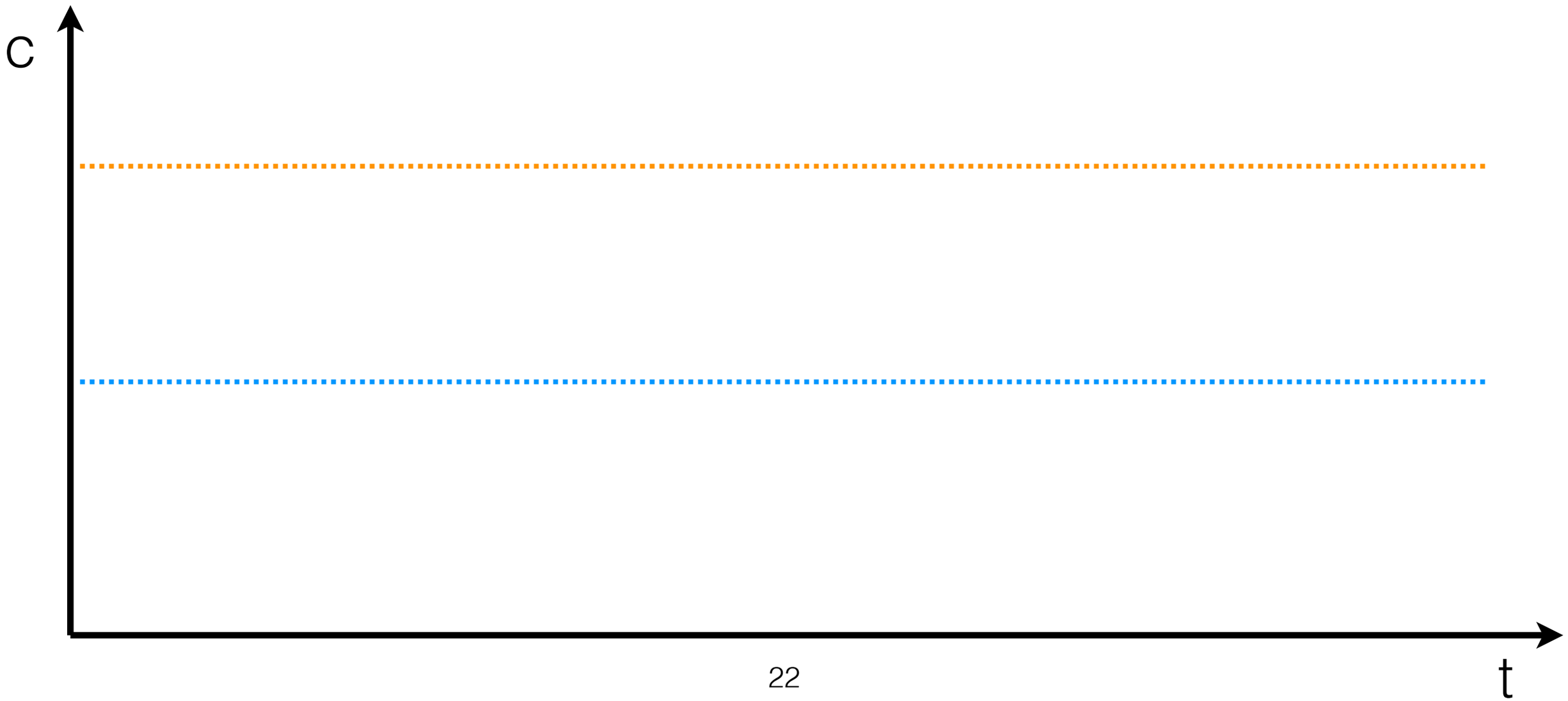


PCC Dynamics



PCC Dynamics

PCC does not need AIMD because it looks at real performance



PCC Dynamics

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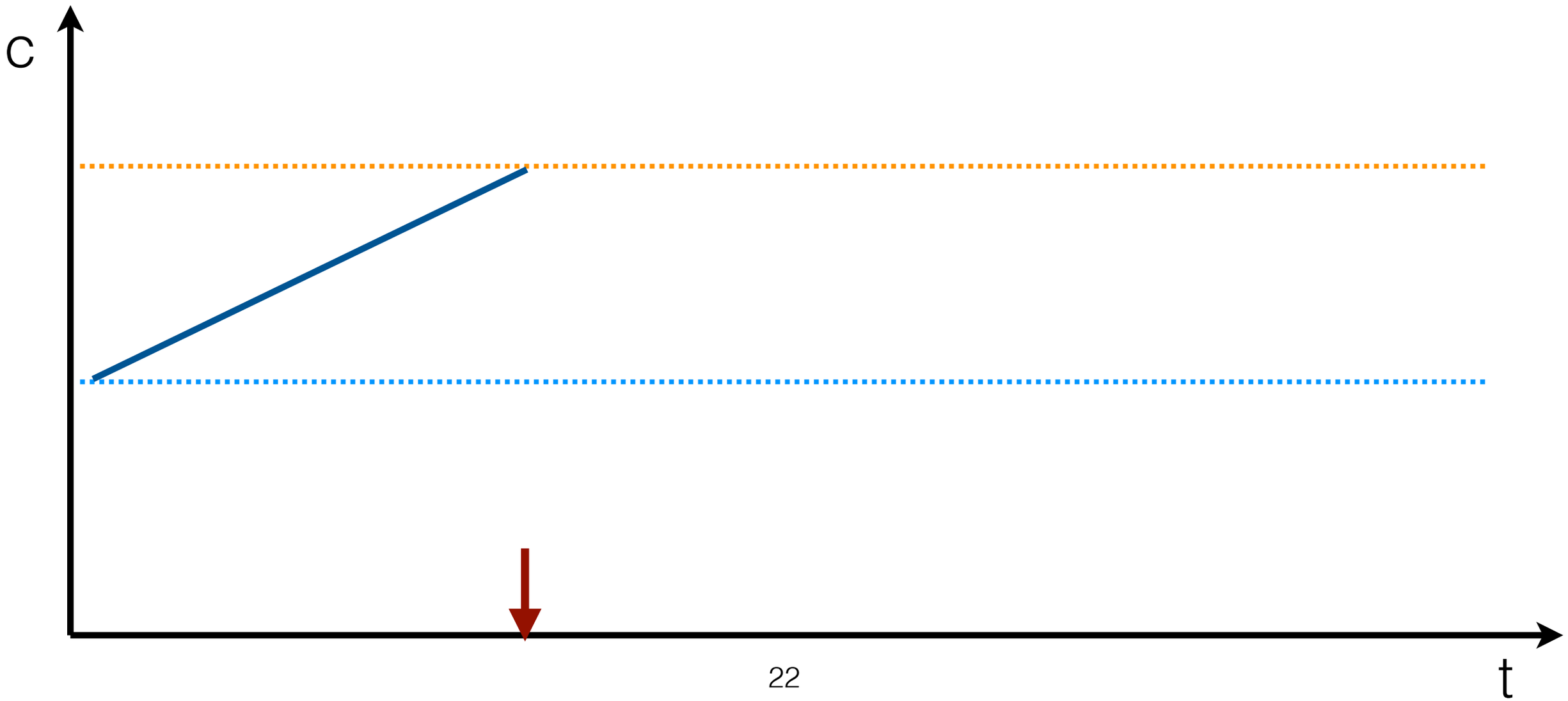

PCC Dynamics

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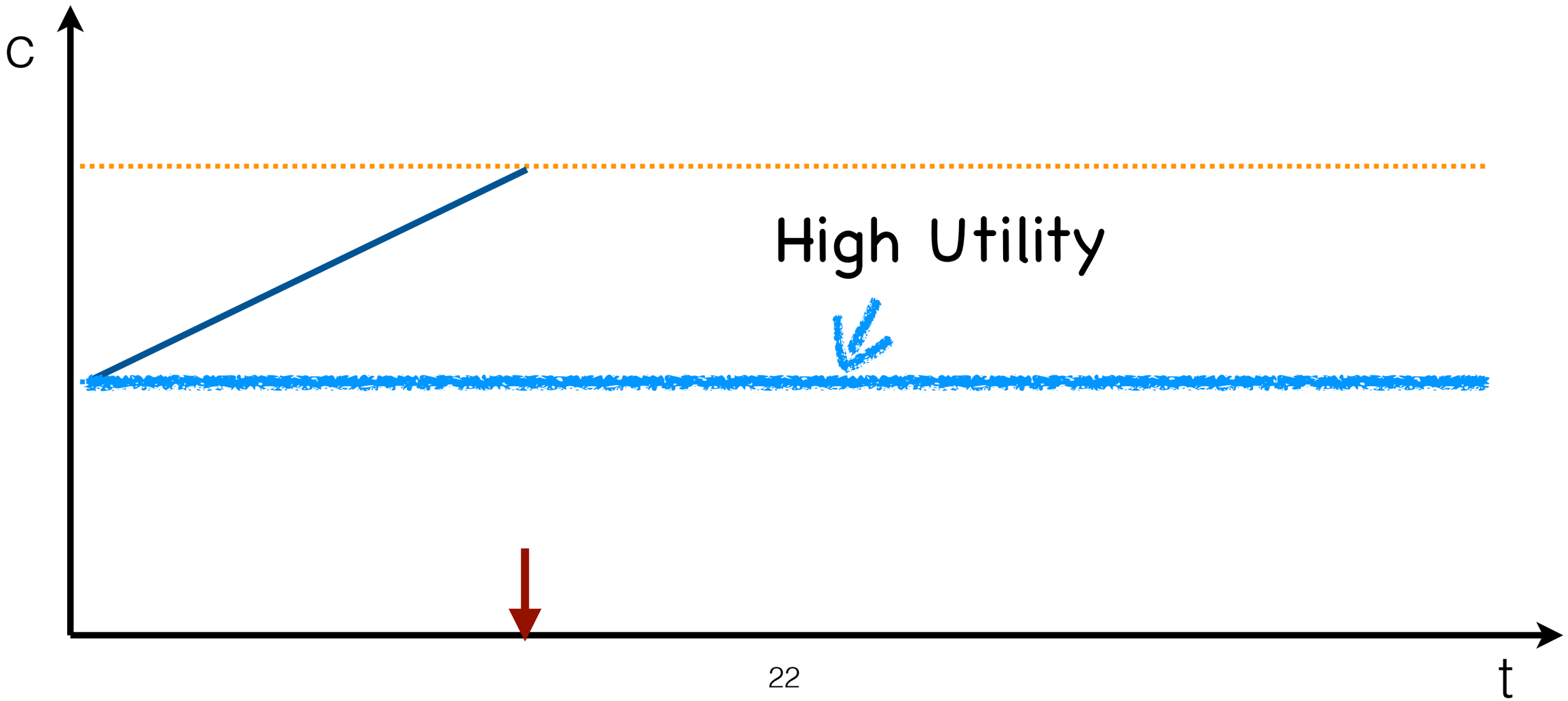

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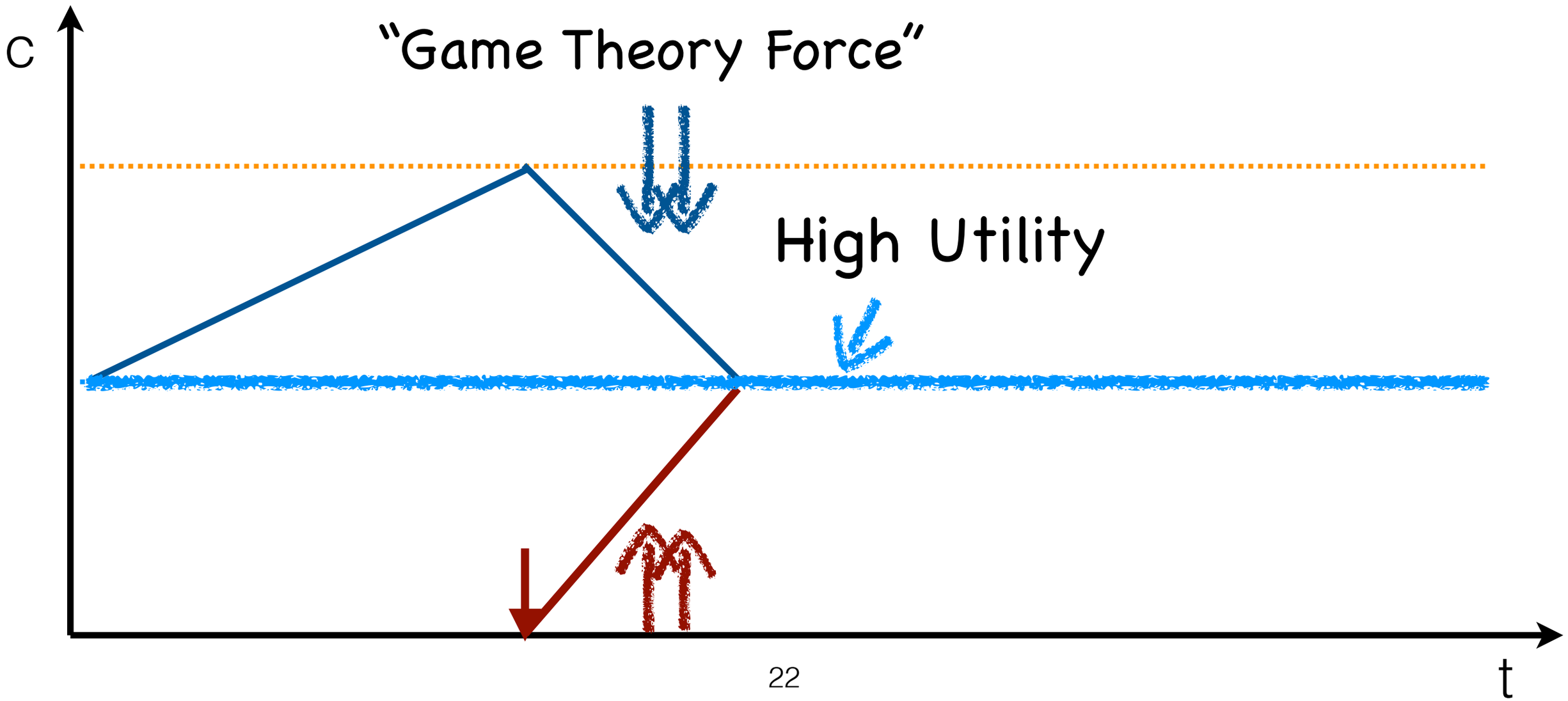
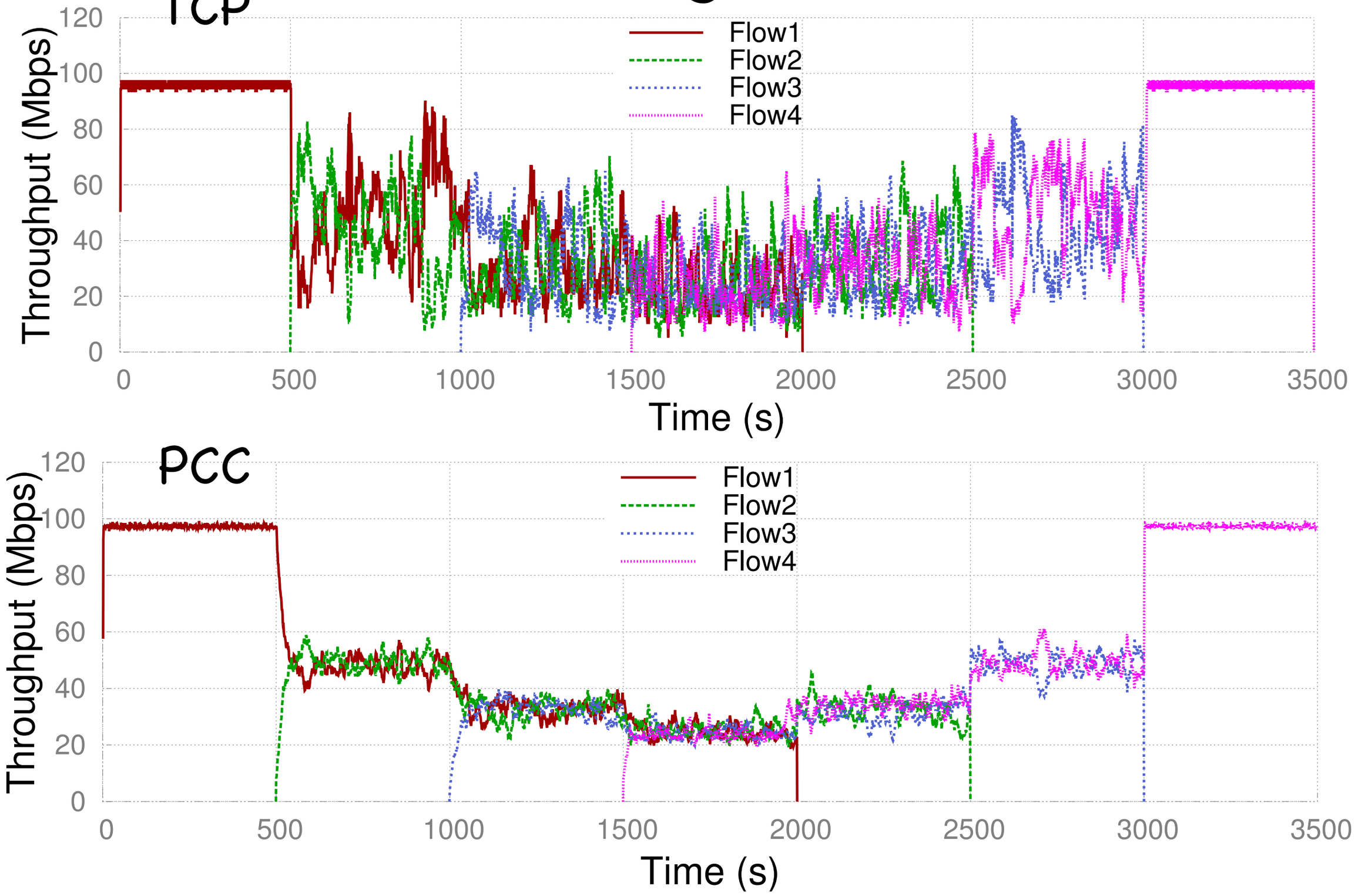


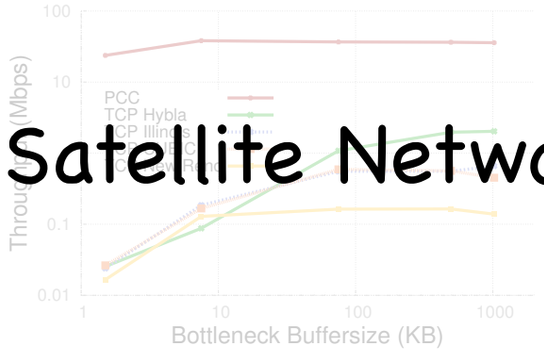
Convergence



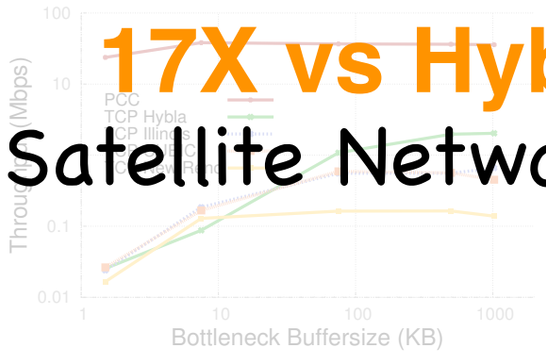
Consistent High Performance

Consistent High Performance

Satellite Networks



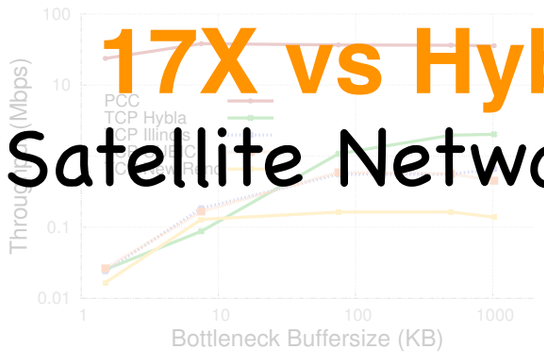
Consistent High Performance



17X vs Hybla

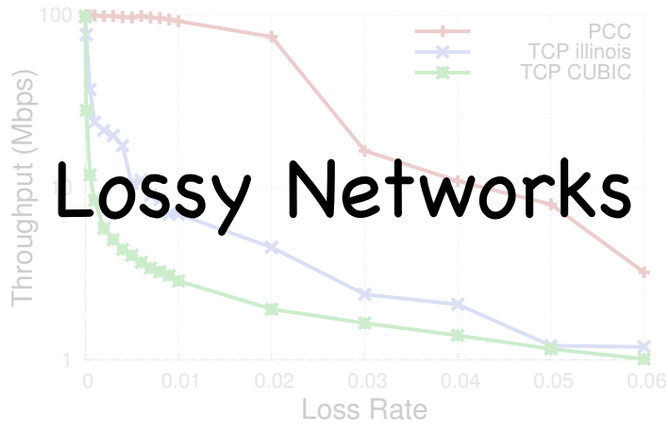
Satellite Networks

Consistent High Performance



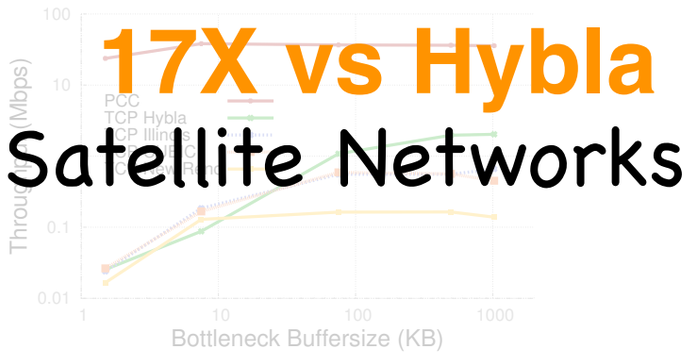
17X vs Hybla

Satellite Networks



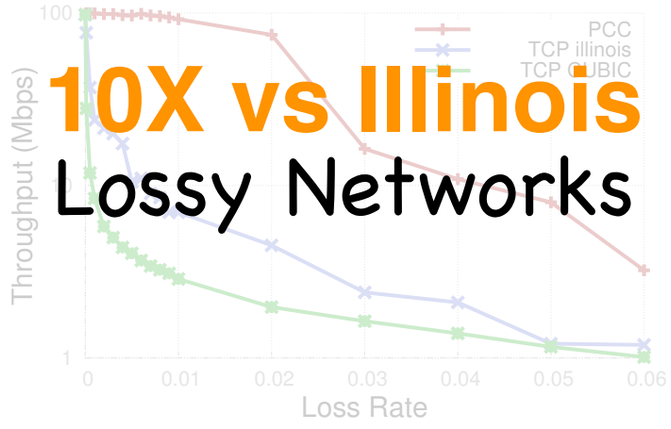
Lossy Networks

Consistent High Performance



17X vs Hybla

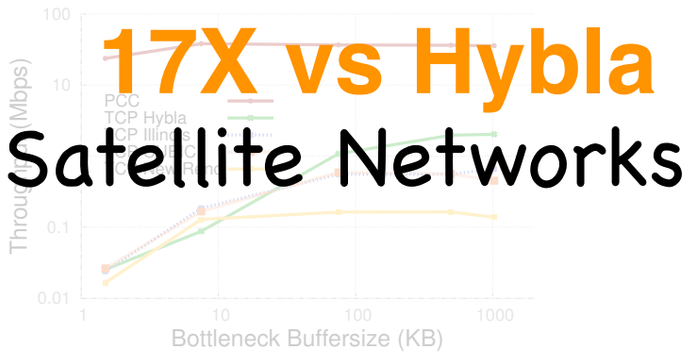
Satellite Networks



10X vs Illinois

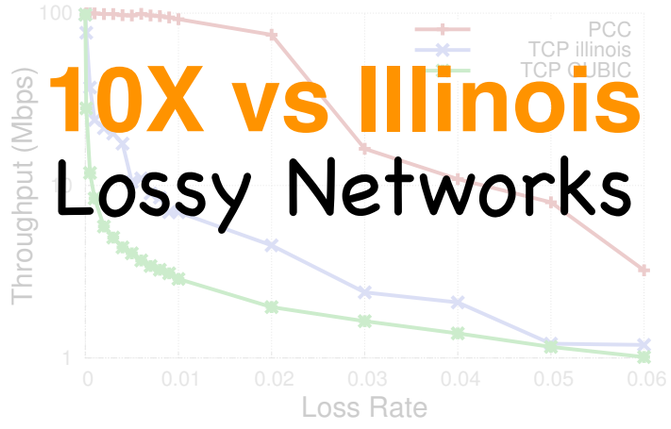
Lossy Networks

Consistent High Performance



17X vs Hybla

Satellite Networks



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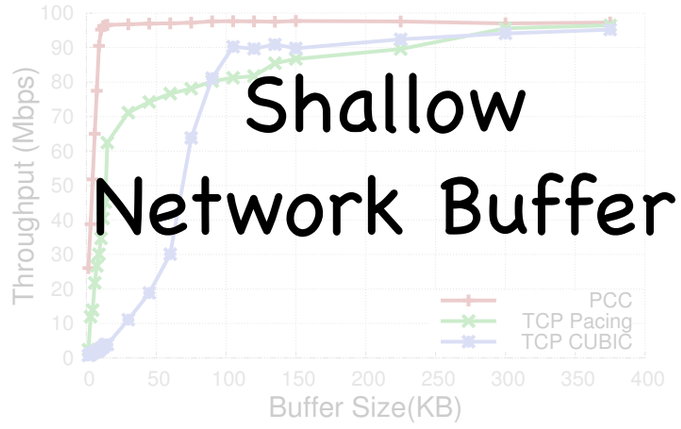
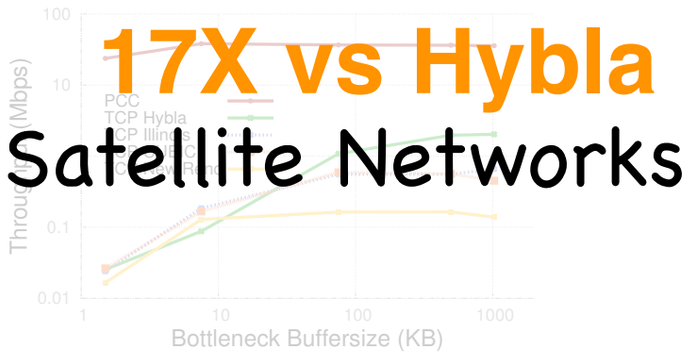
Lossy Networks



Shallow

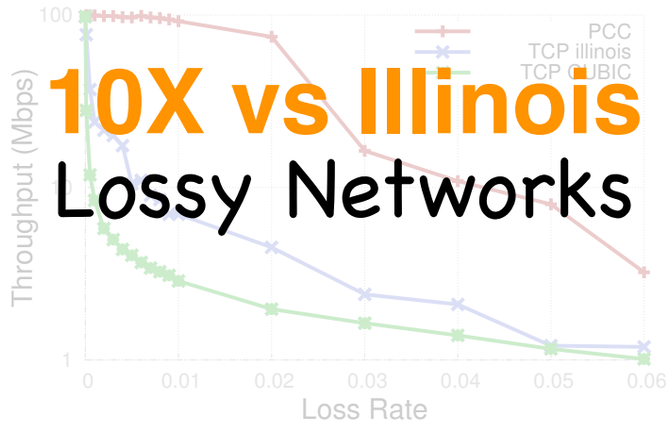
Network Buffer

Consistent High Performance



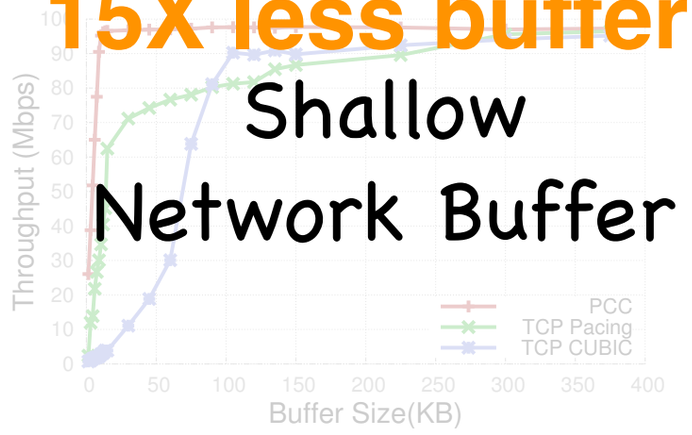
17X vs Hybla

Satellite Networks



10X vs Illinois

Lossy Networks



15X less buffer

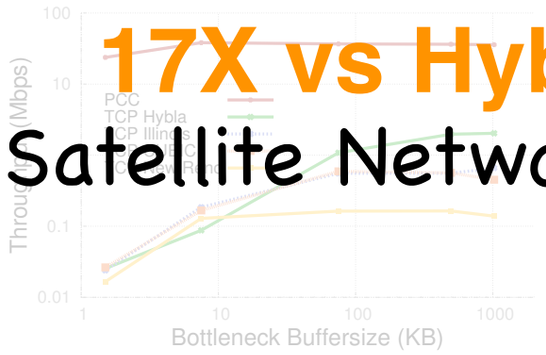
Shallow

Network Buffer

Consistent High Performance

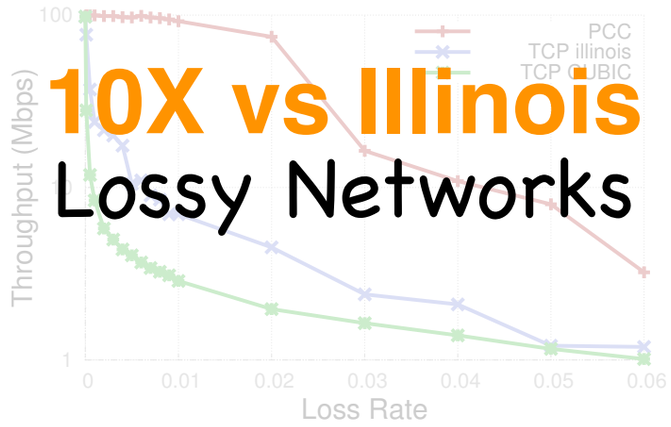
17X vs Hybla

Satellite Networks



10X vs Illinois

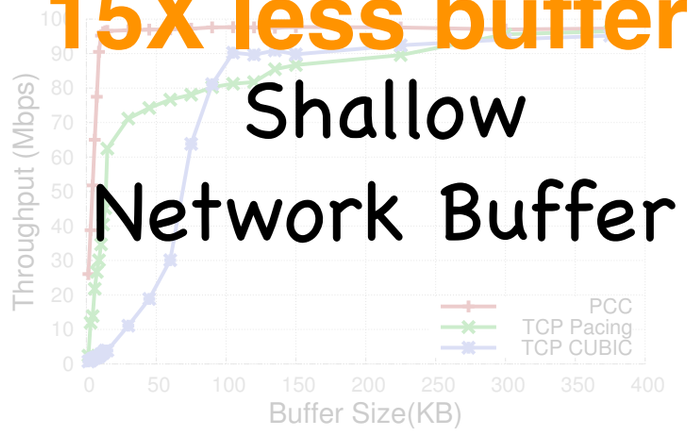
Lossy Networks



15X less buffer

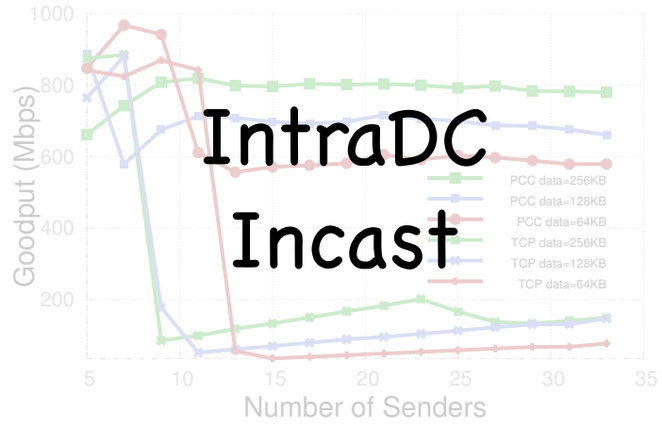
Shallow

Network Buffer



IntraDC

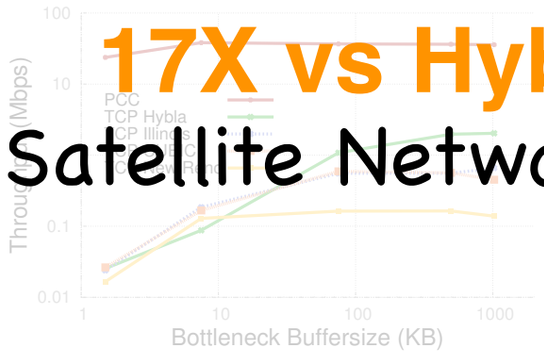
Incast



Consistent High Performance

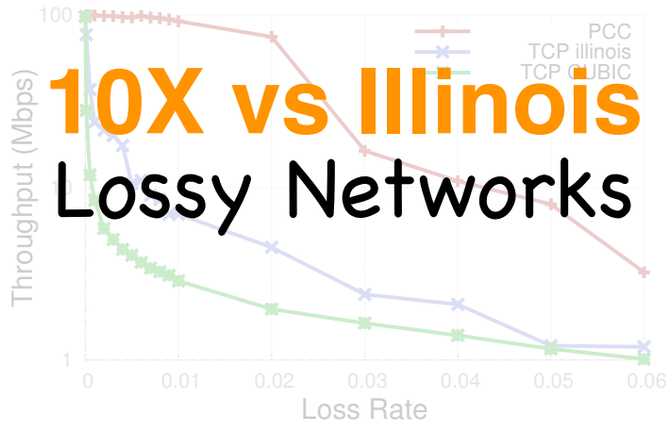
17X vs Hybla

Satellite Networks



10X vs Illinois

Lossy Networks



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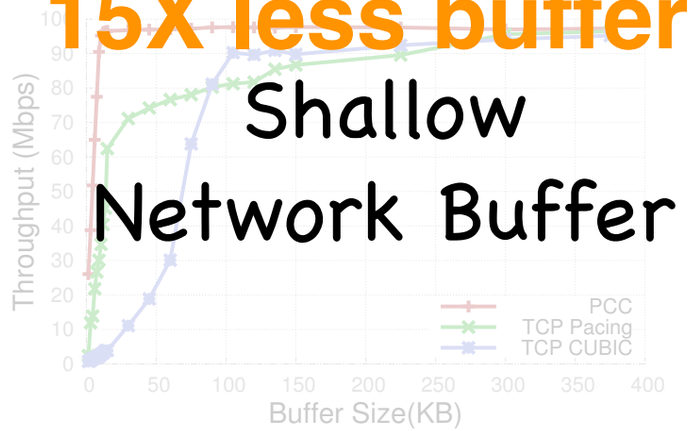
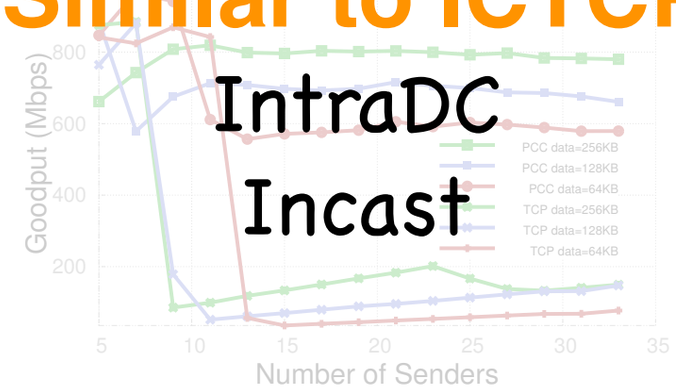


Similar to ICTCP

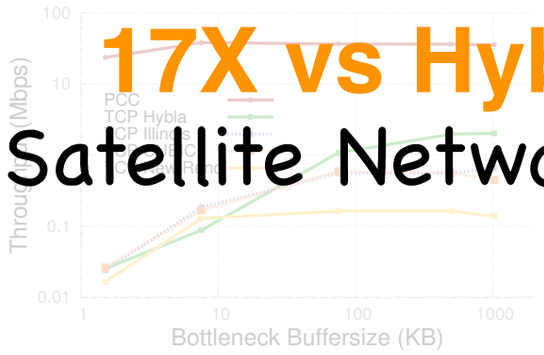
IntraDC

Incast

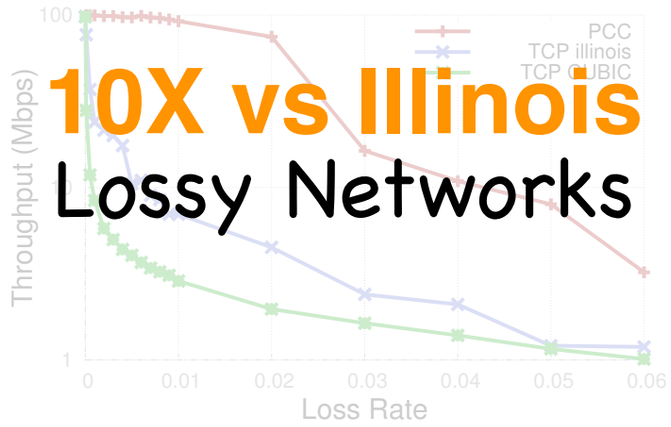


Consistent High Performance

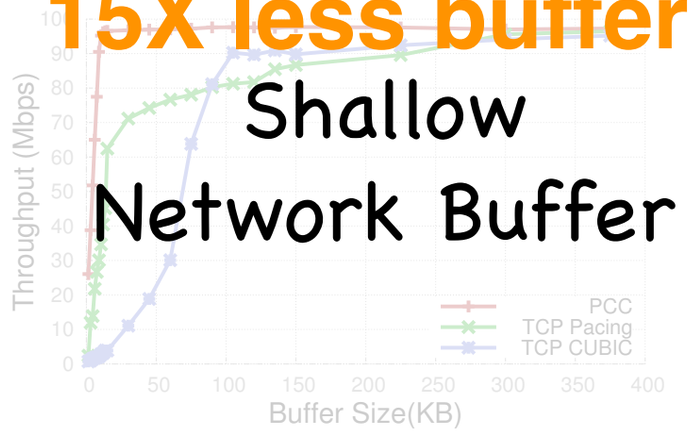
17X vs Hybla
Satellite Networks



10X vs Illinois
Lossy Networks



15X less buffer
Shallow
Network Buffer



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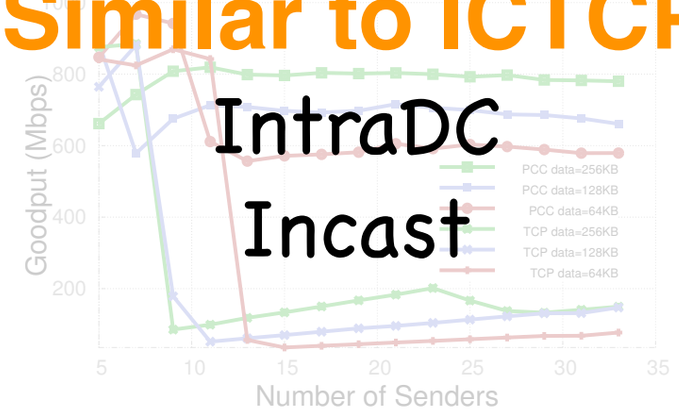
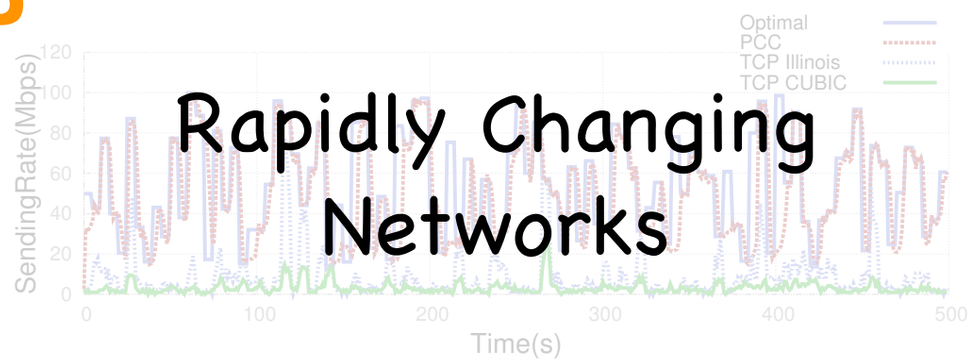
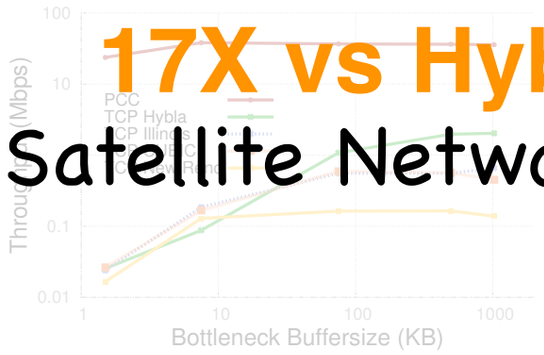


Rapidly Changing
Networks



Consistent High Performance

17X vs Hybla
Satellite Networks



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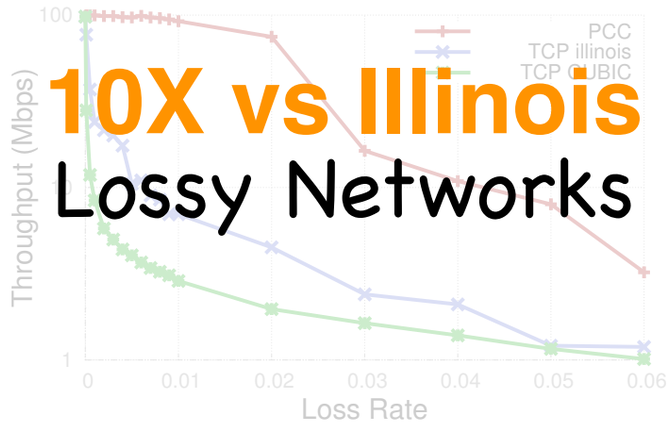
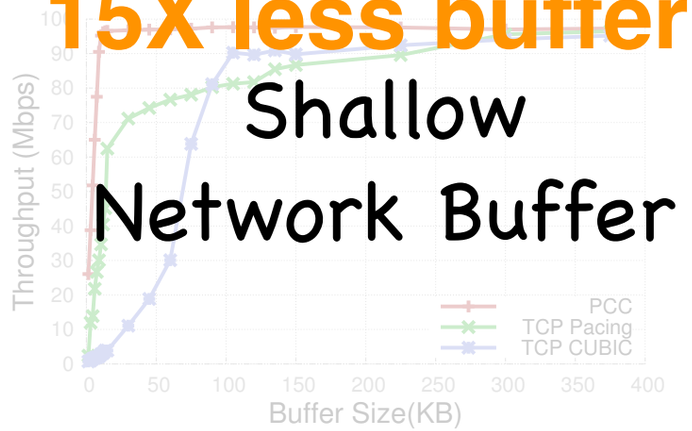
Lossy Networks



15X less buffer
Shallow
Network Buffer



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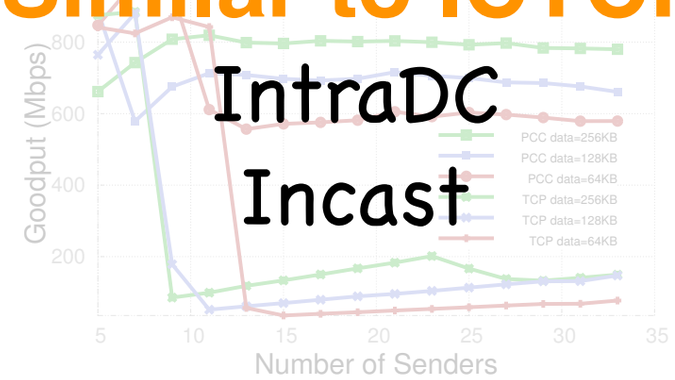
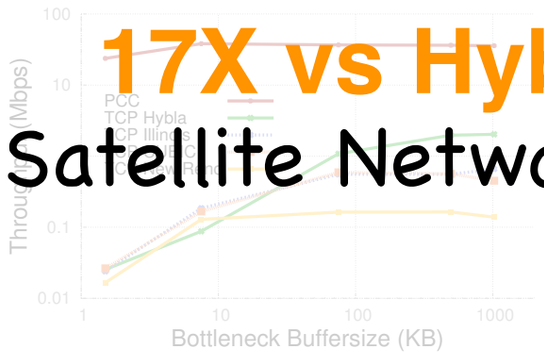
Incast



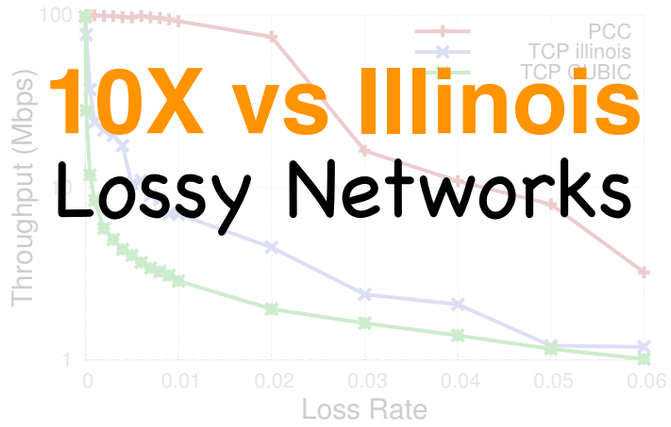
Close to Optimal
Rapidly Changing
Networks

Consistent High Performance

17X vs Hybla
Satellite Networks



10X vs Illinois
Lossy Networks



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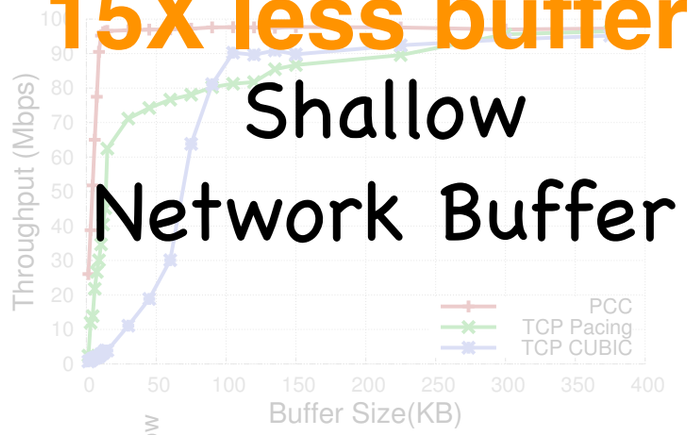
Shallow
Network Buffer



Similar to ICTCP
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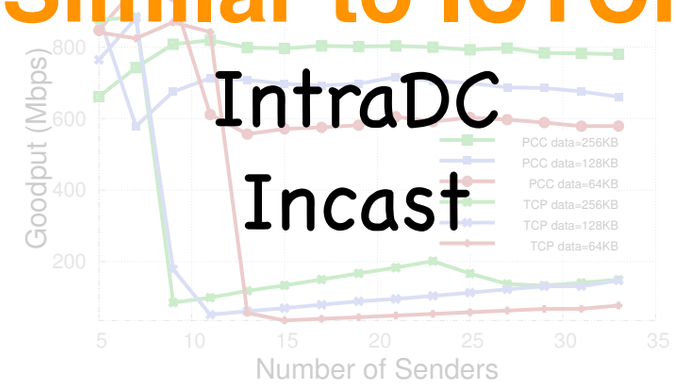
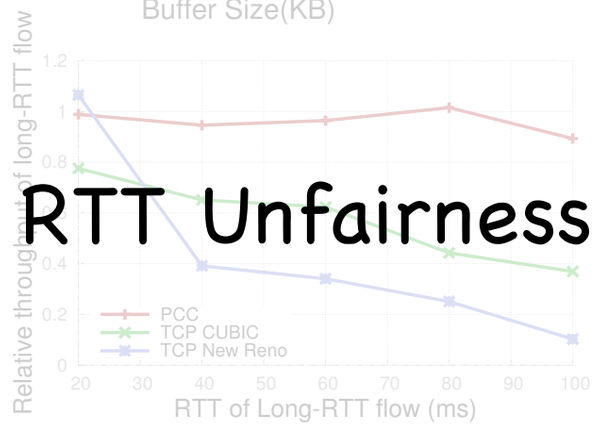


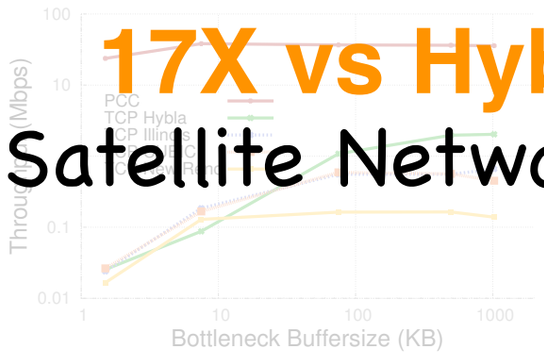
Close to Optimal
Rapidly Changing
Networks

RTT Unfairness

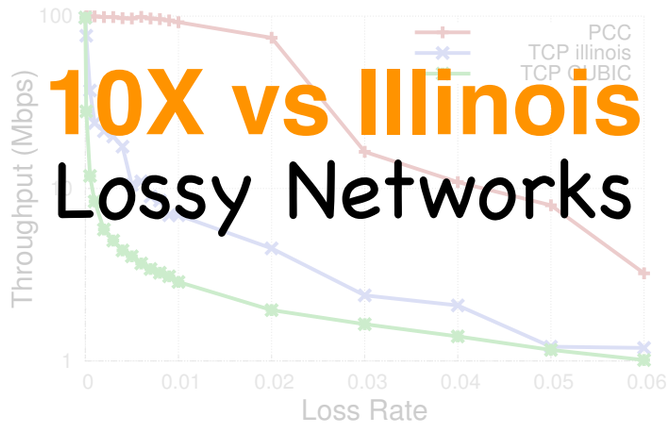


Consistent High Performance

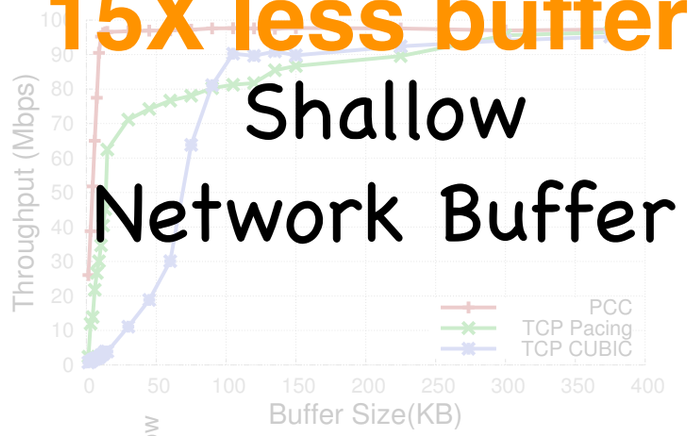
17X vs Hybla
Satellite Networks



10X vs Illinois
Lossy Networks



15X less buffer
Shallow
Network Buffer



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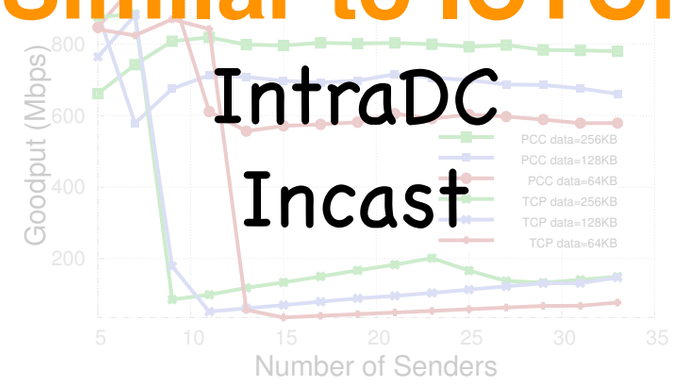

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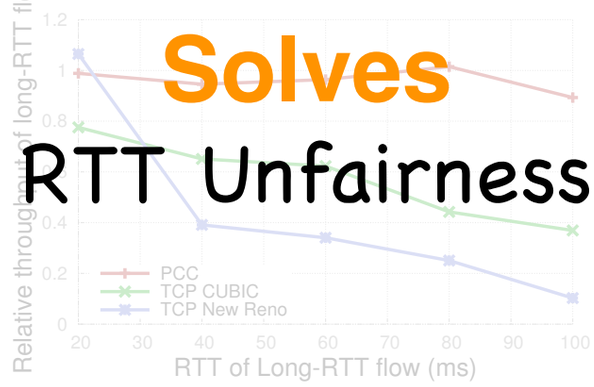
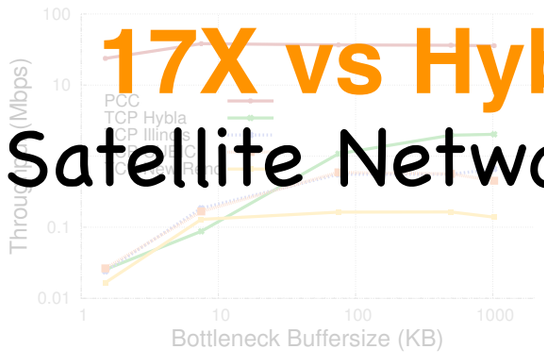
Rapidly Changing
Networks

Solves
RTT Unfairness

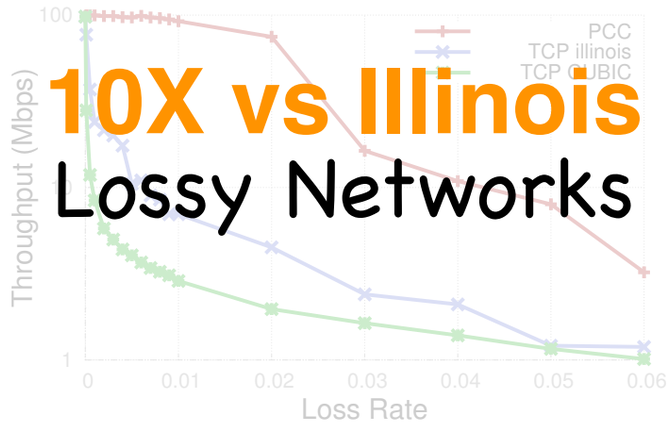


Consistent High Performance



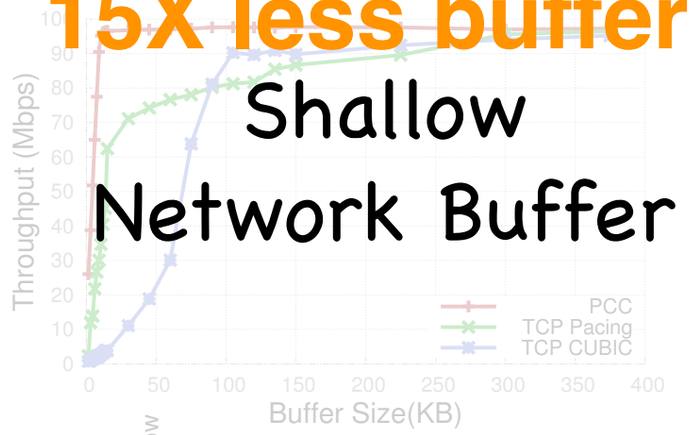
17X vs Hybla

Satellite Networks



10X vs Illinois

Lossy Networks



15X less buffer

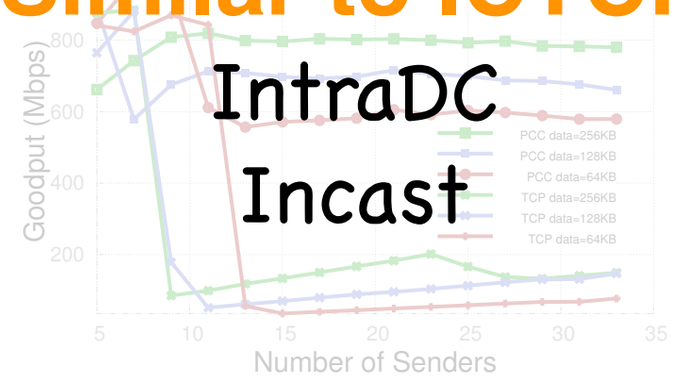
Shallow

Network Buffer

Similar to ICTCP

IntraDC

Incast



Close to Optimal

Rapidly Changing

Networks

Solves

RTT Unfairness

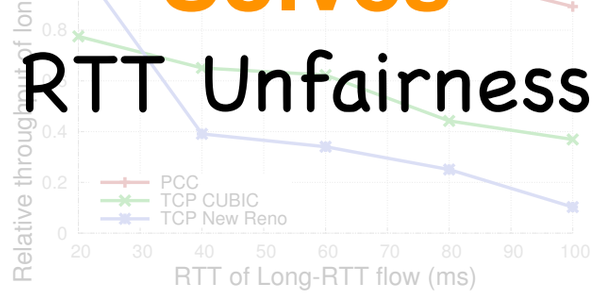


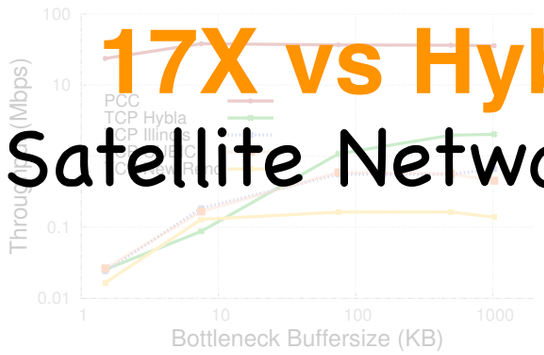
Table 1: PCC significantly outperforms TCP in inter-data center environments. RTT is in msec; throughput in Mbps.

InterDC

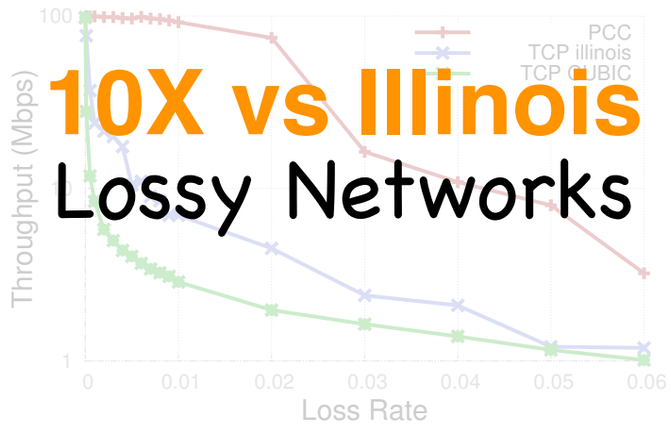
Transmission Pair	RTT	PCC	SABUL	CUBIC	Illinois
GPO → NYSERNet	12.1	791	674	129	326
GPO → Missouri	47.4	808	664	80.7	90.1
GPO → Illinois	35.4	766	664	84.5	102
NYSERNet → Missouri	47.4	816	662	108	109
Wisconsin → Illinois	9.01	801	700	547	562
GPO → Wisc.	38.0	783	487	79.3	120
NYSERNet → Wisc.	38.3	791	673	134	134
Missouri → Wisc.	20.9	807	698	259	262
NYSERNet → Illinois	36.1	808	674	141	141

Consistent High Performance

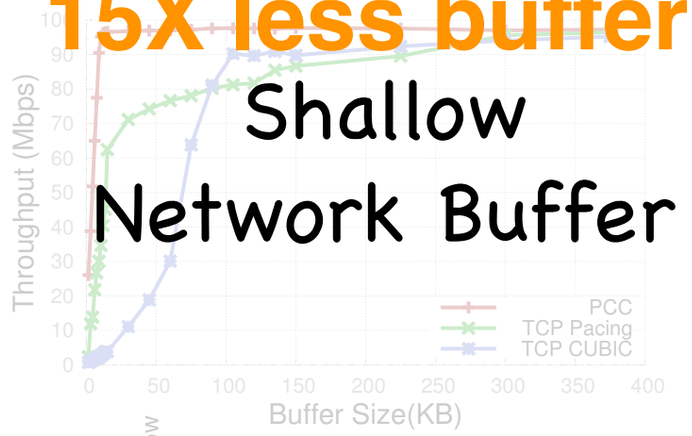
17X vs Hybla
Satellite Networks



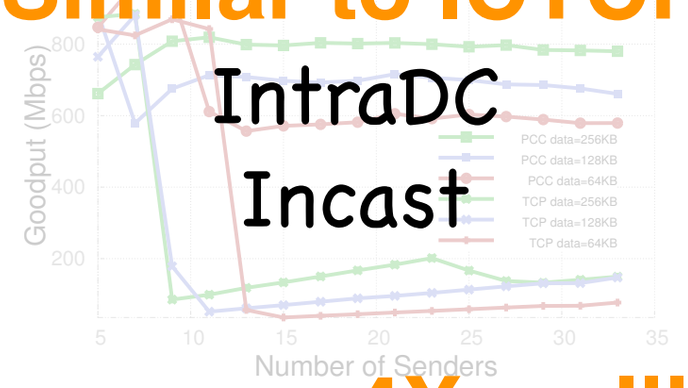
10X vs Illinois
Lossy Networks



15X less buffer
Shallow
Network Buffer

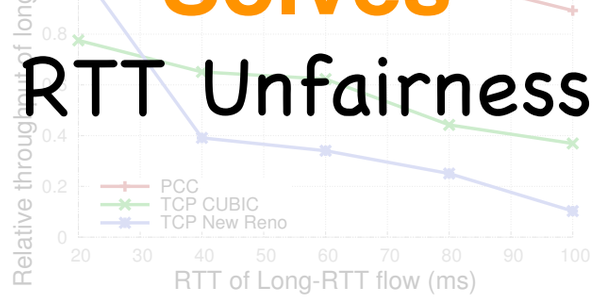


Similar to ICTCP
IntraDC
Incast



Close to Optimal
Rapidly Changing
Networks

Solves
RTT Unfairness

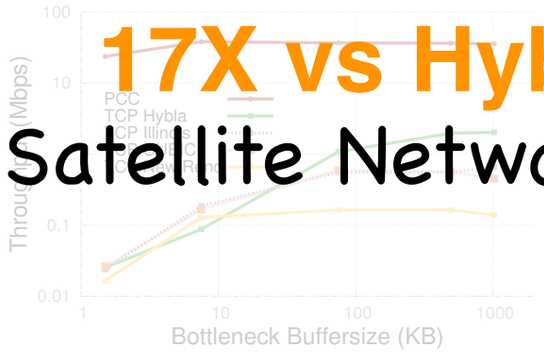


4X vs Illinois
1.23X vs UDT
InterDC

Table 1: PCC significantly outperforms TCP in inter-data center environments. RTT is in msec; throughput in Mbps.

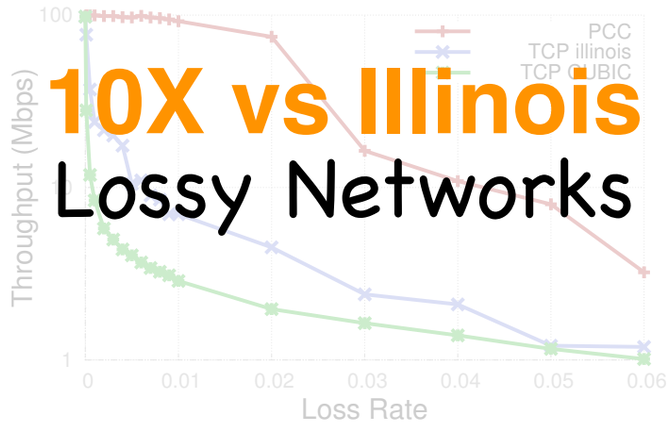
GPO → NYSERNet			129	326
GPO → Missouri			80.7	90.1
GPO → Illinois	35.4	766	664	84.5	102
NYSERNet → Missouri	47.4	816	662	108	109
Wisconsin → Illinois	9.01	801	700	547	562
GPO → Wisc.	38.0	783	487	79.3	120
NYSERNet → Wisc.	38.3	791	673	134	134
Missouri → Wisc.	20.9	807	698	259	262
NYSERNet → Illinois	36.1	808	674	141	141

Consistent High Performance



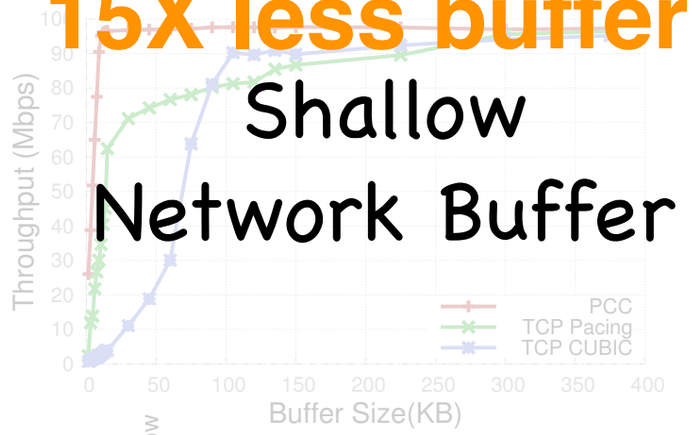
17X vs Hybla

Satellite Networks



10X vs Illinois

Lossy Networks



15X less buffer

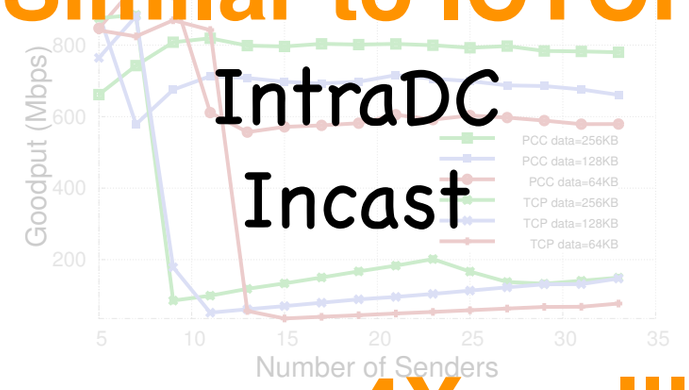
Shallow

Network Buffer

Similar to ICTCP

IntraDC

Incast



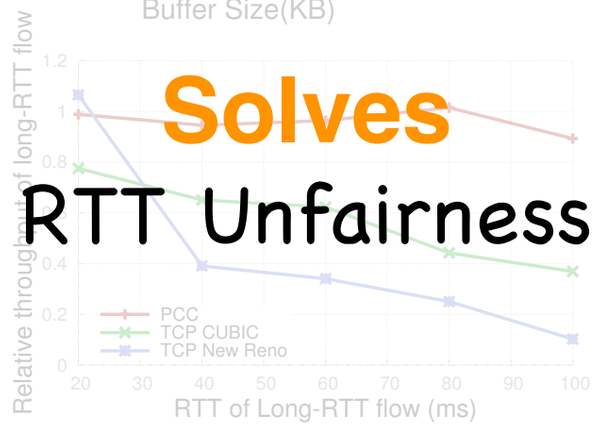
Close to Optimal

Rapidly Changing

Networks

Solves

RTT Unfairness



4X vs Illinois

1.23X vs UDT

InterDC

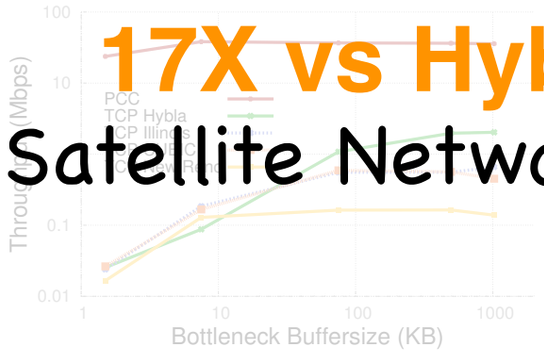
Table 1: PCC significantly outperforms TCP in inter-data center environments. RTT is in msec; throughput in Mbps.

GPO → NYSERNet	12.1	792	339	129	326
GPO → Missouri	47.4	816	662	80.7	90.1
GPO → Illinois	35.4	766	664	84.5	102
NYSERNet → Missouri	47.4	816	662	108	109
Wisconsin → Illinois	9.01	801	700	547	562
GPO → Wisc.	38.0	783	487	79.3	120
NYSERNet → Wisc.	38.3	791	673	134	134
Missouri → Wisc.	20.9	807	698	259	262
NYSERNet → Illinois	36.1	808	674	141	141

Global Commercial

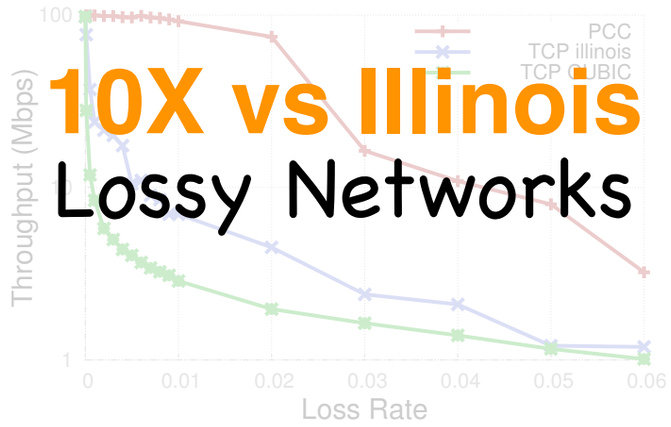
Internet

Consistent High Performance



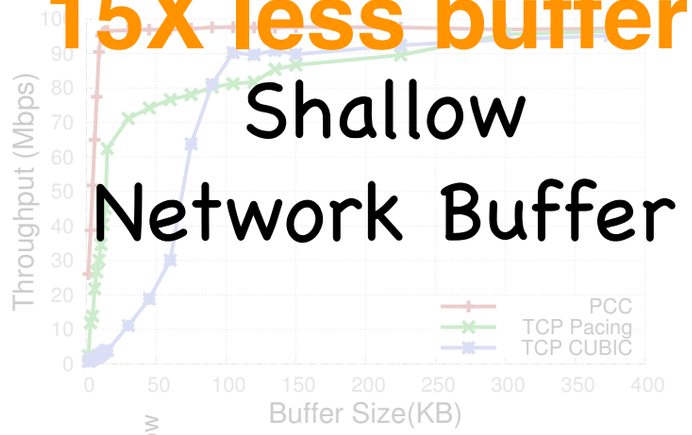
17X vs Hybla

Satellite Networks



10X vs Illinois

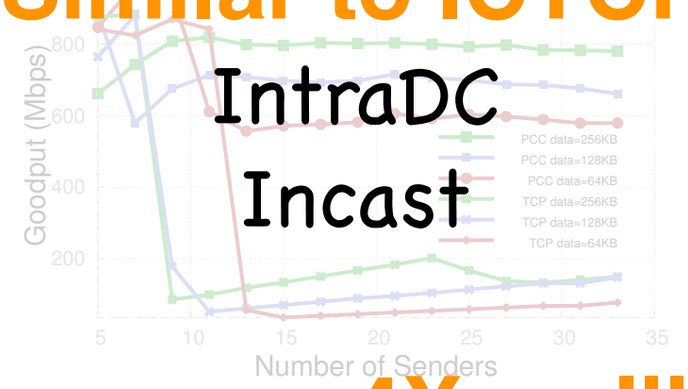
Lossy Networks



15X less buffer

Shallow

Network Buffer



Similar to ICTCP

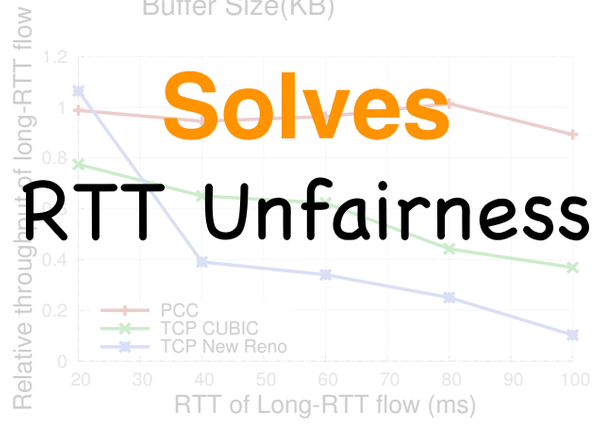
IntraDC

Incast

Close to Optimal

Rapidly Changing

Networks



Solves

RTT Unfairness

4X vs Illinois

1.23X vs UDT

InterDC

Table 1: PCC significantly outperforms TCP in inter-data center environments. RTT is in msec; throughput in Mbps.

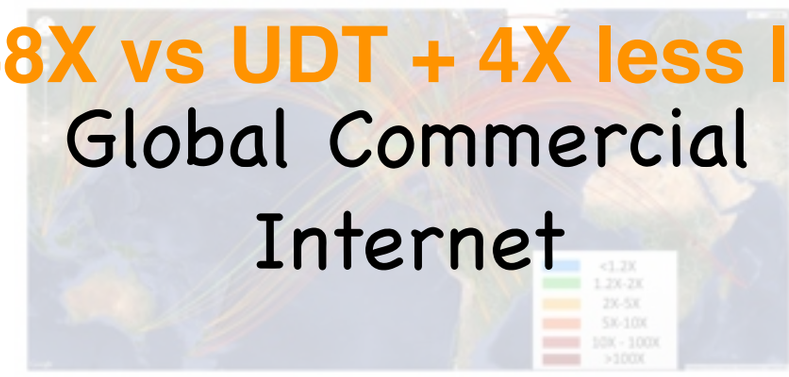
Pair	RTT	PCC	TABULA	CUBIC	Illinois
GPO → NYSERNet	12.1	791	661	129	326
GPO → Missouri	46.5	808	674	80.7	90.1
GPO → Illinois	35.4	766	664	84.5	102
NYSERNet → Missouri	47.4	816	662	108	109
Wisconsin → Illinois	9.01	801	700	547	562
GPO → Wisc.	38.0	783	487	79.3	120
NYSERNet → Wisc.	38.3	791	673	134	134
Missouri → Wisc.	20.9	807	698	259	262
NYSERNet → Illinois	36.1	808	674	141	141

4X median vs CUBIC

1.48X vs UDT + 4X less loss

Global Commercial

Internet

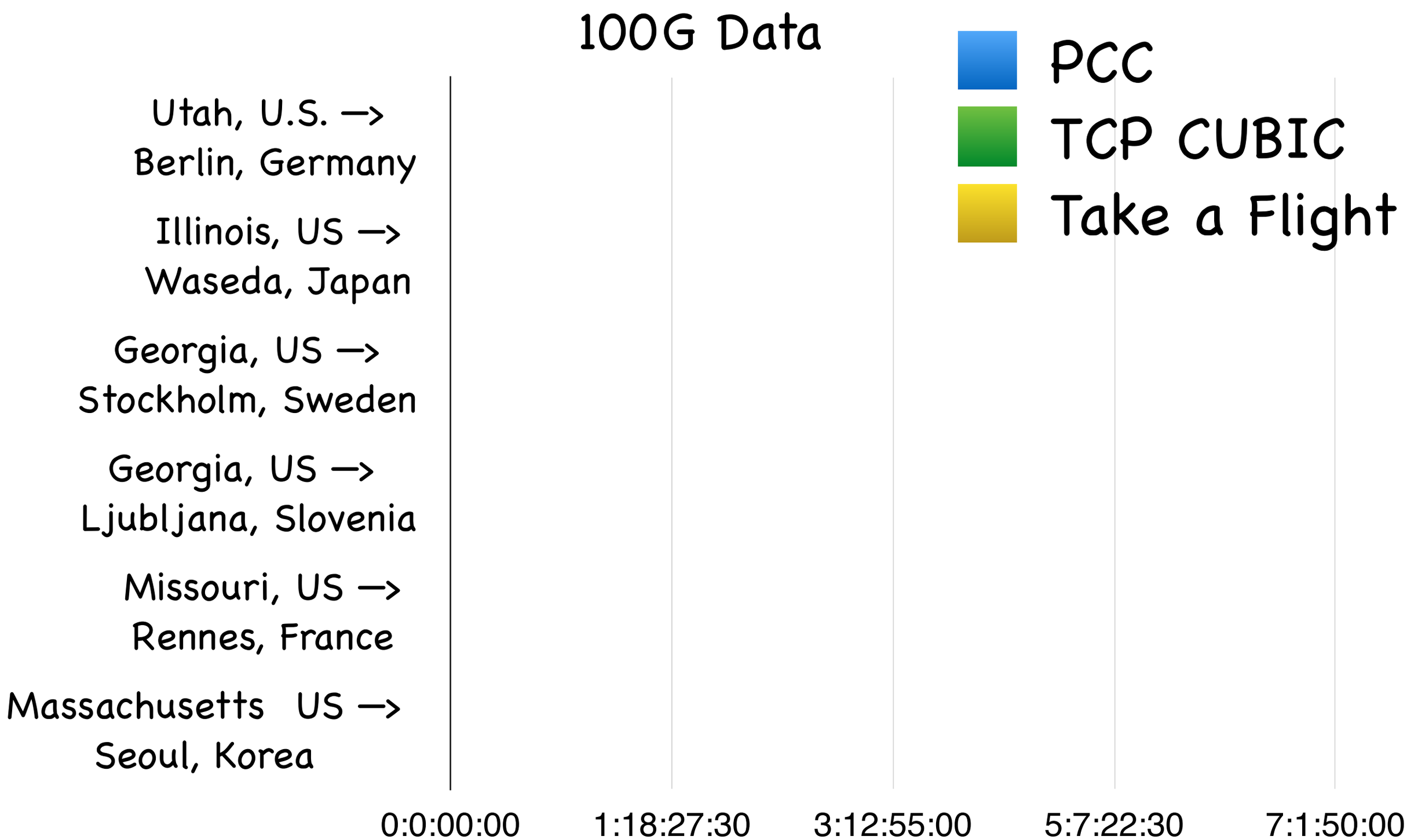


Global Commercial Internet

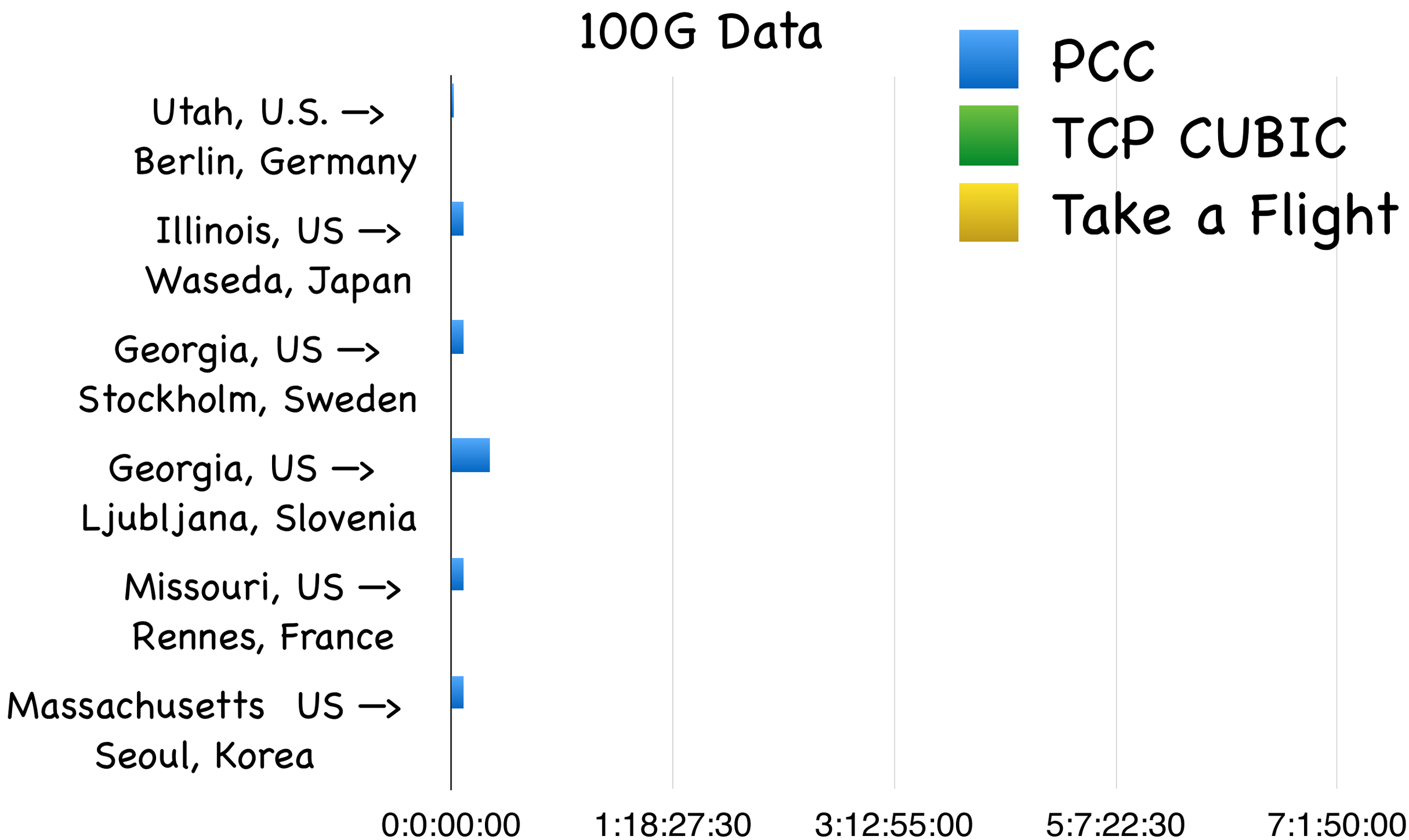
PCC vs TCP vs Take a Flight

100G Data

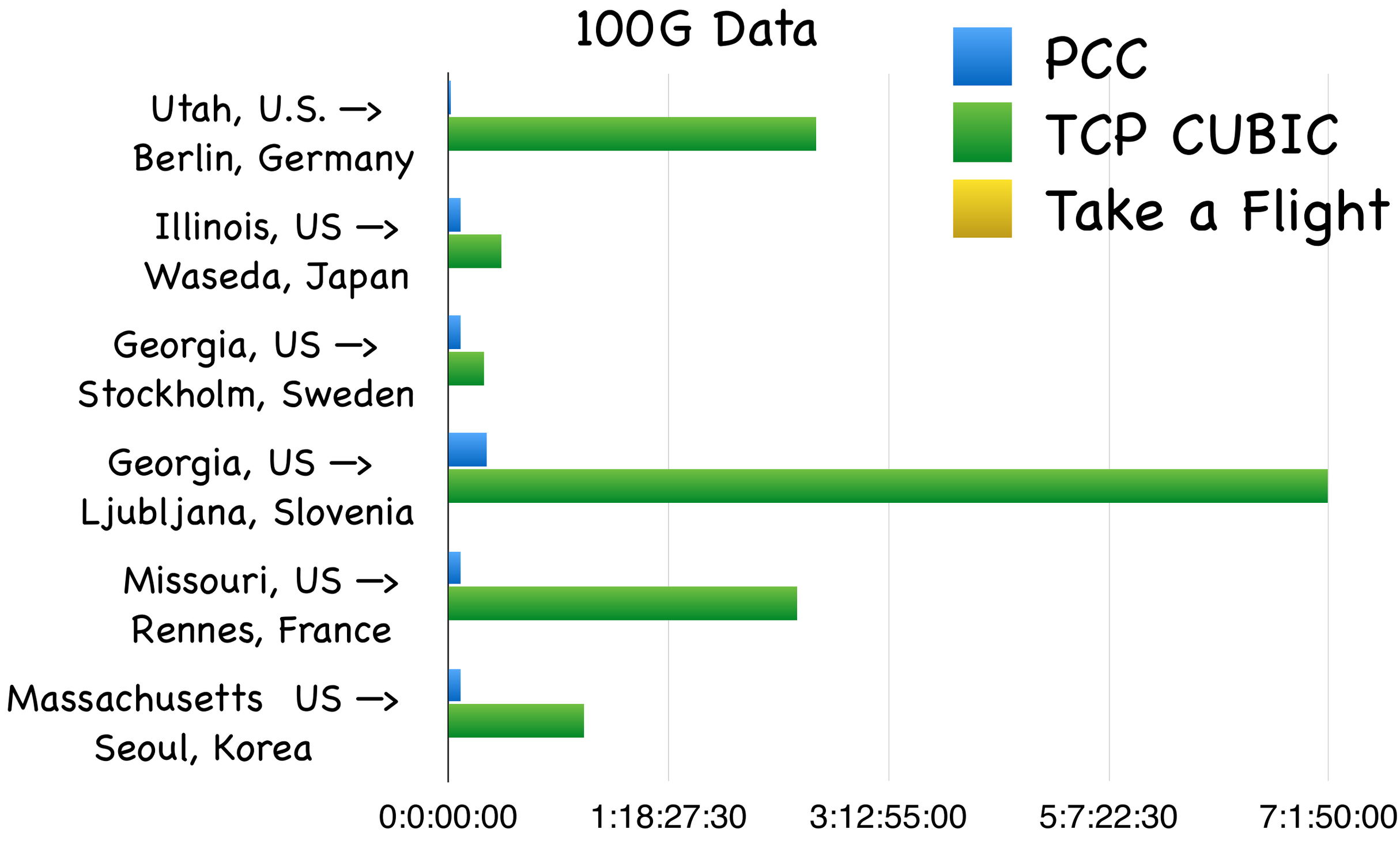
PCC vs TCP vs Take a Flight



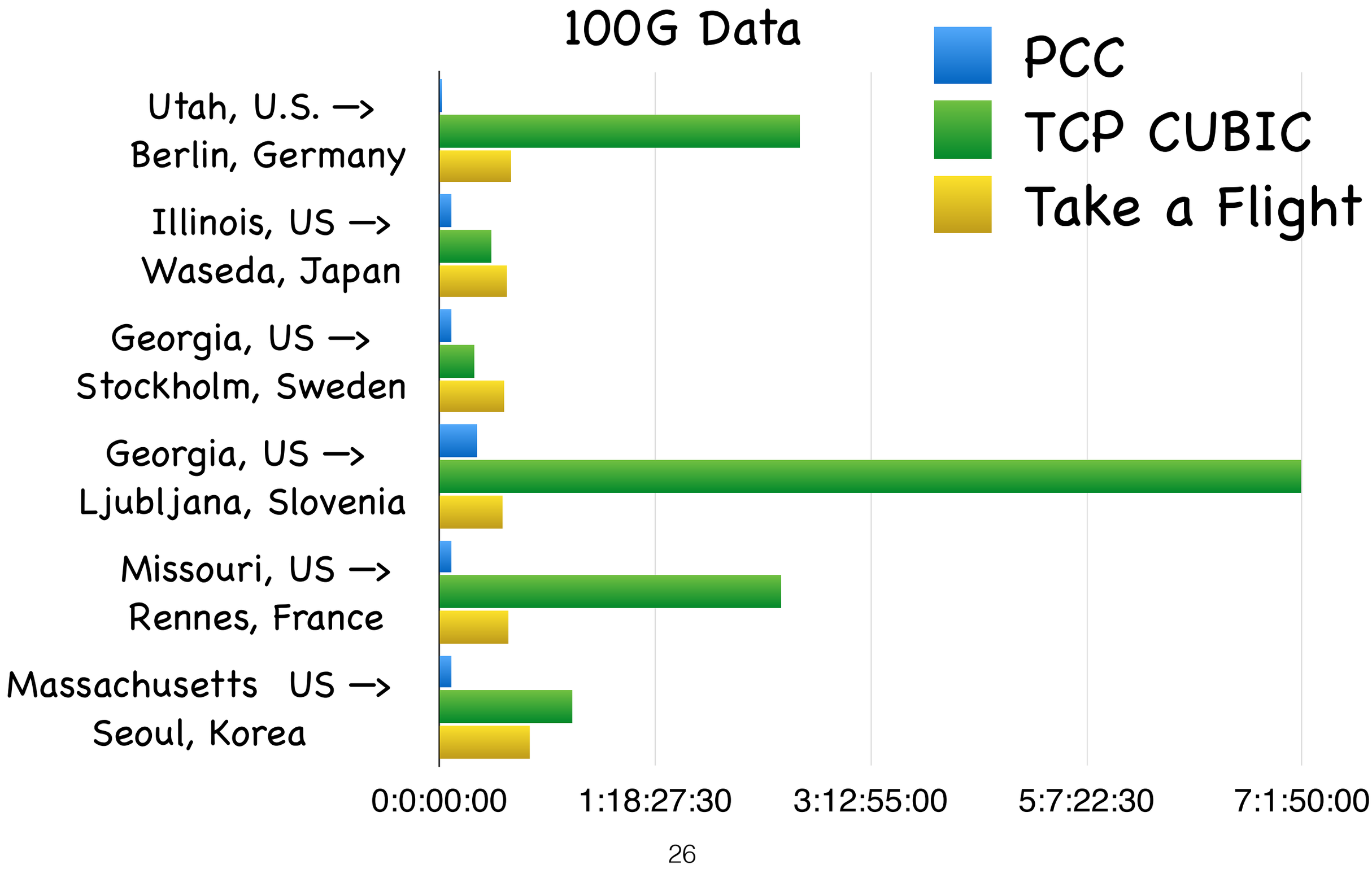
PCC vs TCP vs Take a Flight



PCC vs TCP vs Take a Flight



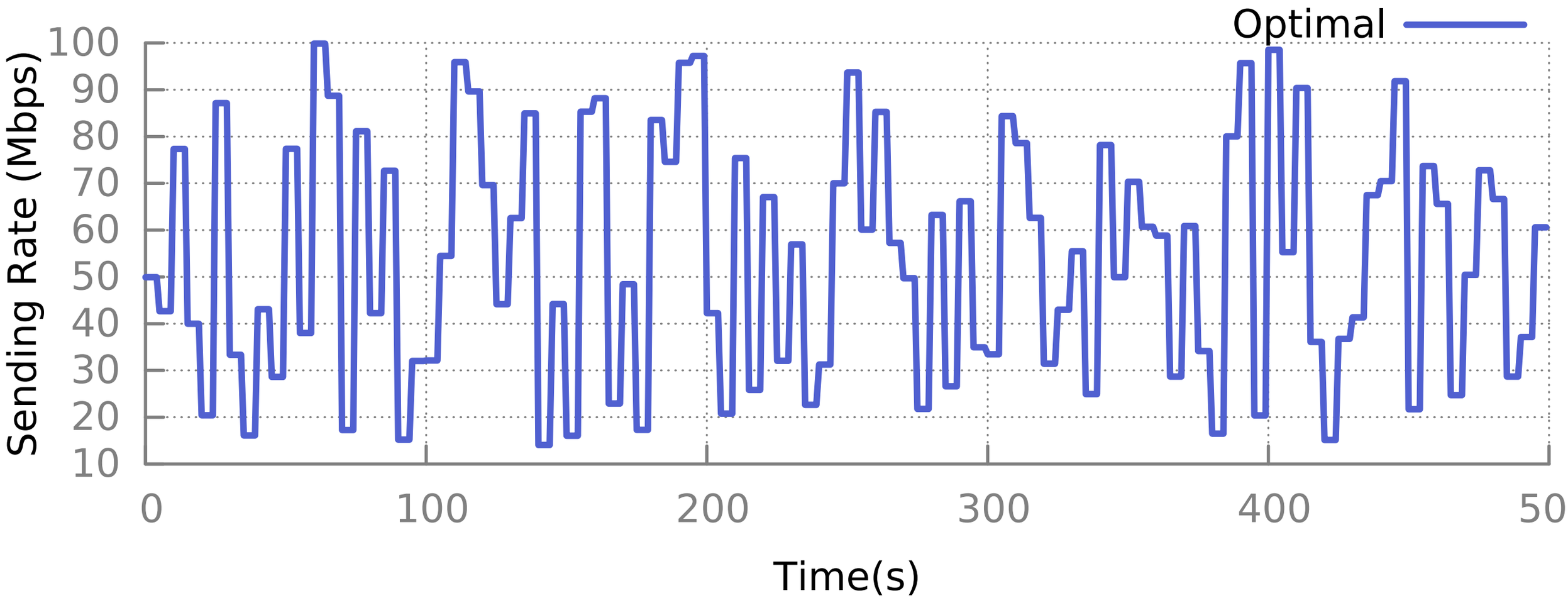
PCC vs TCP vs Take a Flight



Consistent High Performance

Rapidly Changing Networks

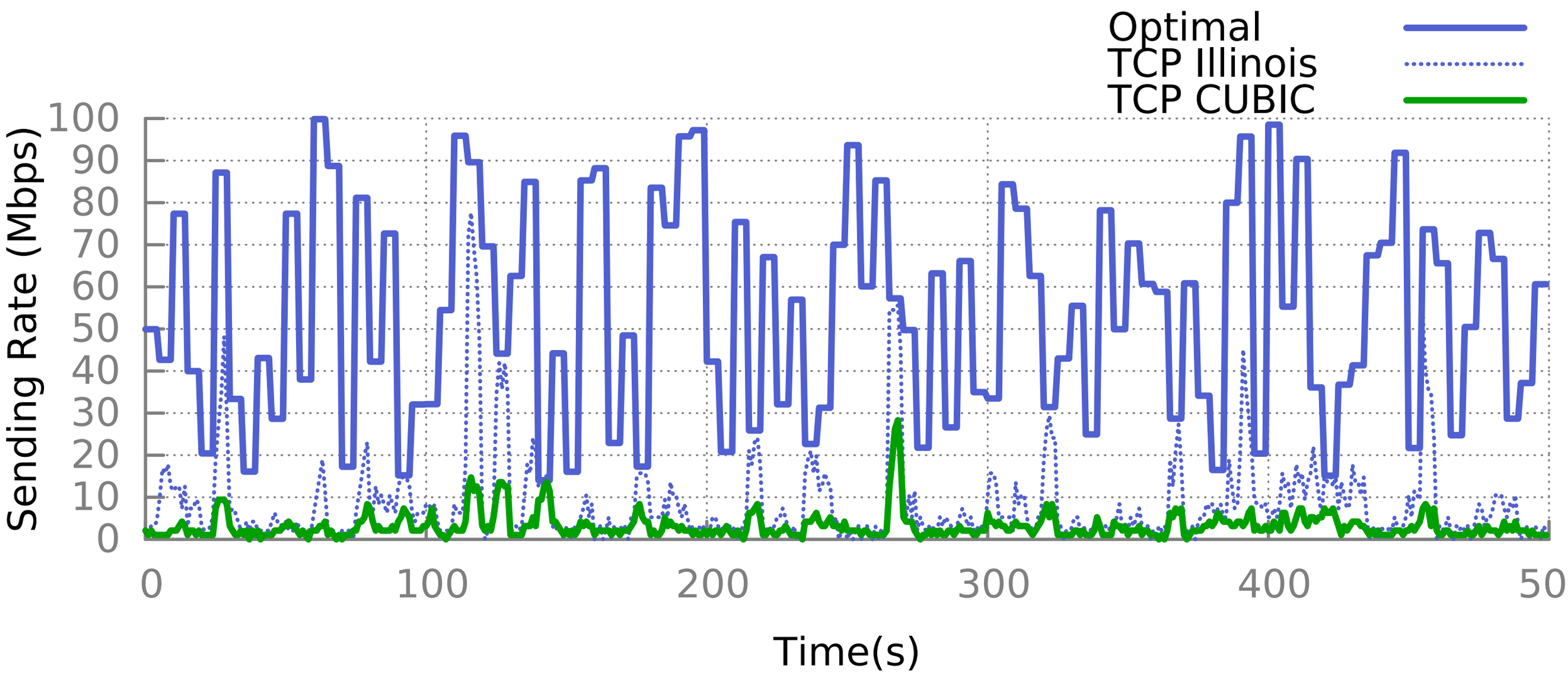
BW: 10-100Mbps; RTT: 10-100ms; Loss Rate: 0-1%
Change every 5 seconds



Consistent High Performance

Rapidly Changing Networks

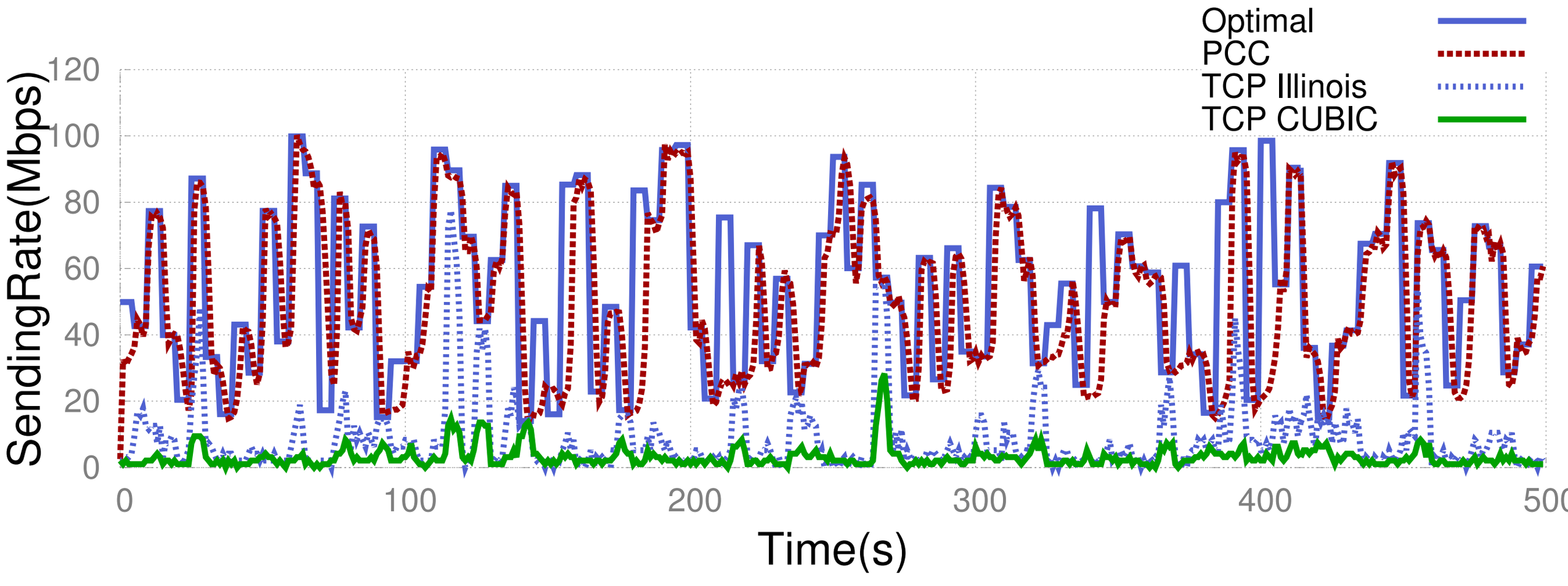
BW: 10-100Mbps; RTT: 10-100ms; Loss Rate: 0-1%
Change every 5 seconds



Consistent High Performance

Rapidly Changing Networks

BW: 10-100Mbps; RTT: 10-100ms; Loss Rate: 0-1%
Change every 5 seconds



Long list of things we have done but don't have time to talk about

- More stories about the fact that TCP is broken
- Proof of Nash Equilibrium and Convergence
- Concrete Implementation of PCC
    - Performance monitoring
    - Details of learning control algorithm
    - Implementation designs and optimizations
- Performance Evaluation
    - Plaenetlab detailed explanation
    - Satellite like network
    - Lossy Links
    - TCP friendliness
    - RTT fairness
    - Shallow buffer networks
    - Inter data center networks
    - small buffer networks
    - Reactiveness and stability tradeoff
    - Jain index fairness
    - Benefit of Randomized Control Trials
    - Details of TCP friendliness evaluation
    - Emulated satellite networks
    - Emulated datacenter networks
    - Cure RTT unfairness
    - Does not fundamentally harm short flow FCT
    - Evaluation in the wild vs non-TCP protocols
- Flexibility by pluggable utility function

Cellular Networks

- Deep queue and bufferbloat
- Highly dynamic available bandwidth

PCC

- Flexible (latency sensitive) utility function
- Handling small causality window

Flexible Utility Function

Flexible Utility Function

Same Rate Control Algorithm

Flexible Utility Function

Same Rate Control Algorithm

+

Flexible Utility Function

Same Rate Control Algorithm

+

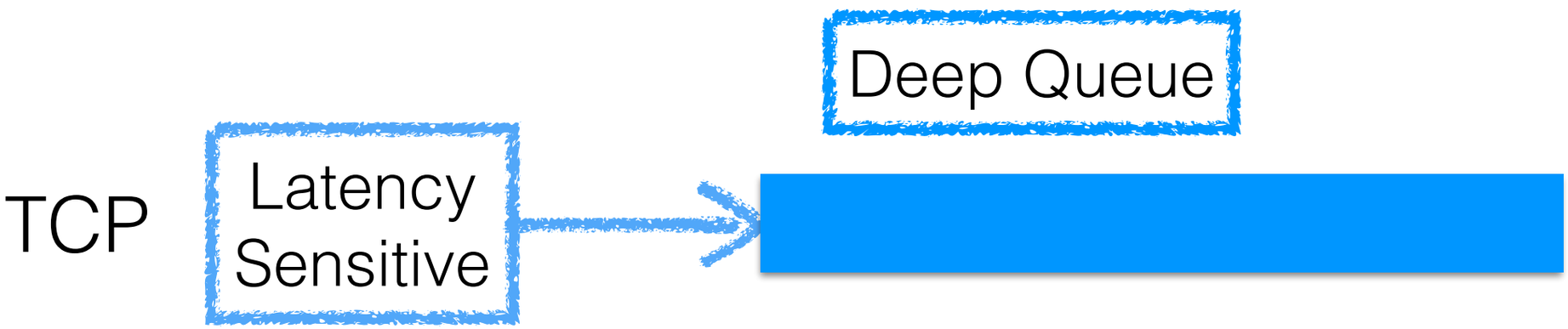
Different Utility Function

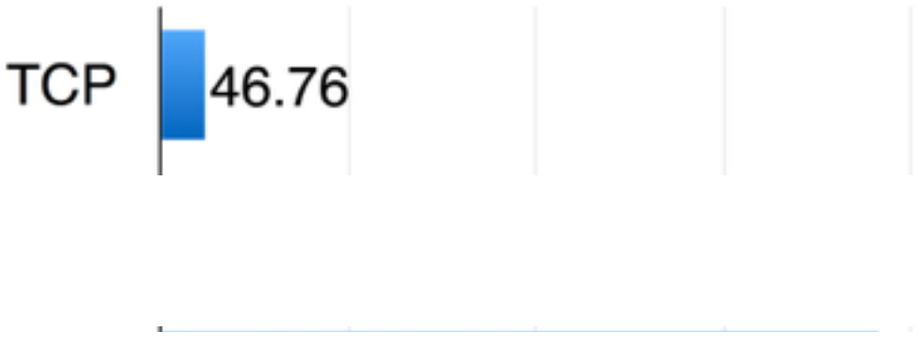
=

Flexibility

Latency Sensitive Utility Function

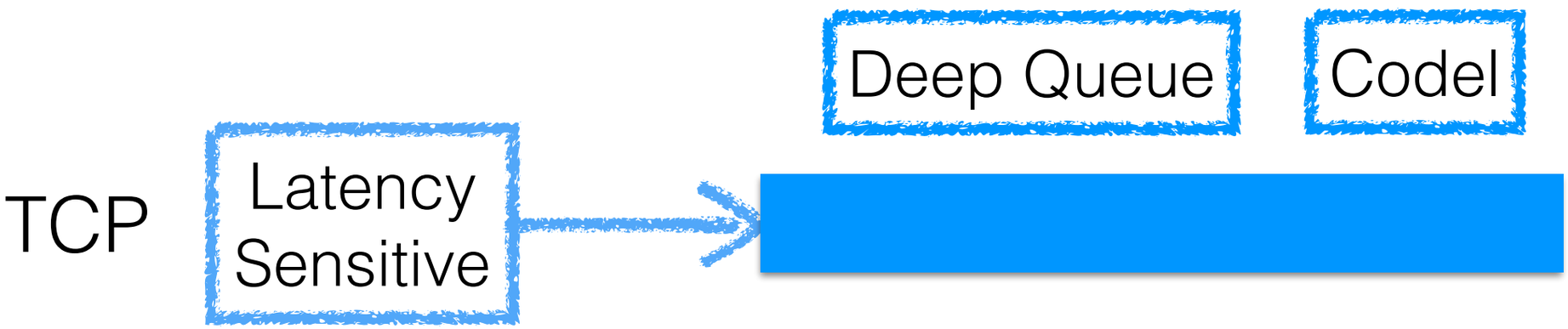
Power = Tpt/RTT

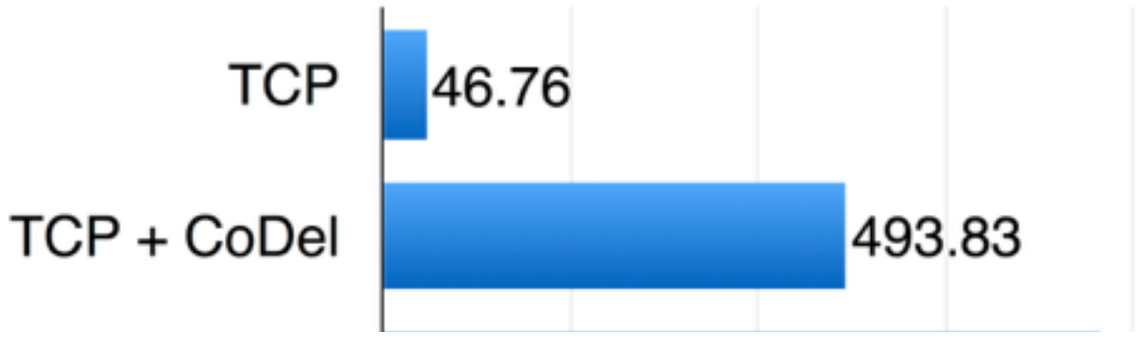




Latency Sensitive Utility Function

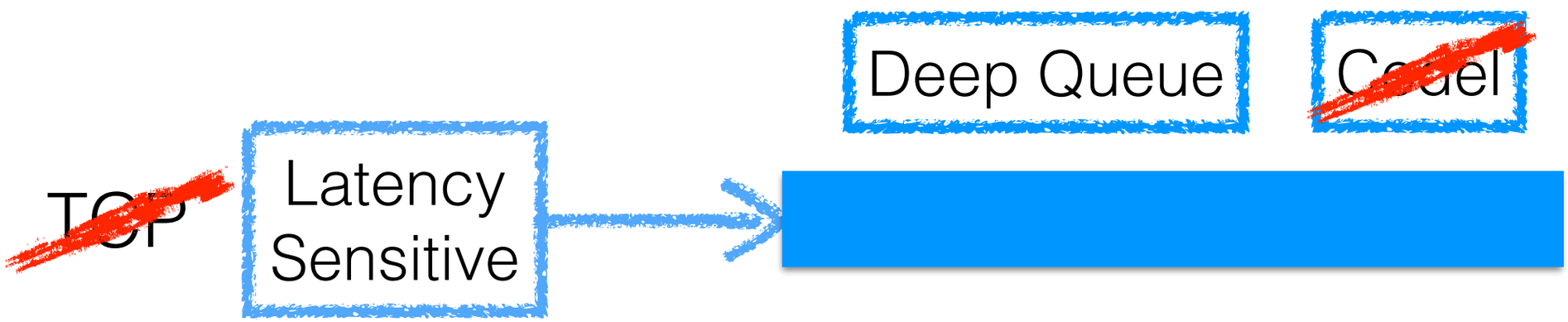
Power = Tpt/RTT

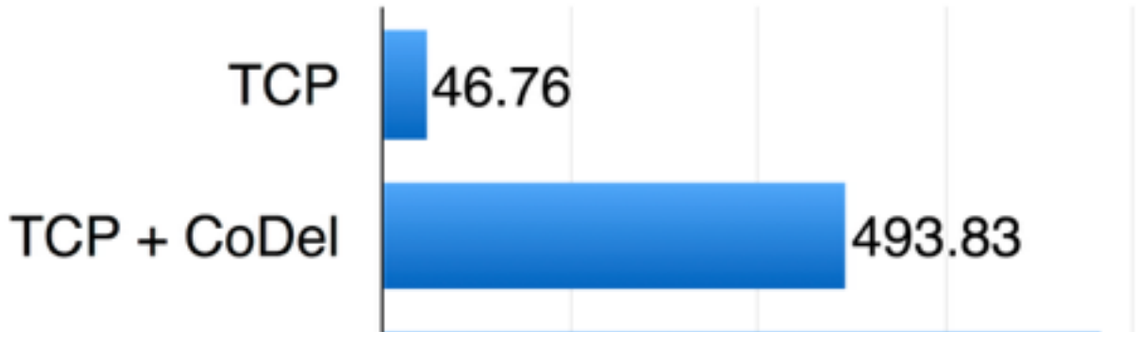




Latency Sensitive Utility Function

Power = Tpt/RTT





Latency Sensitive Utility Function

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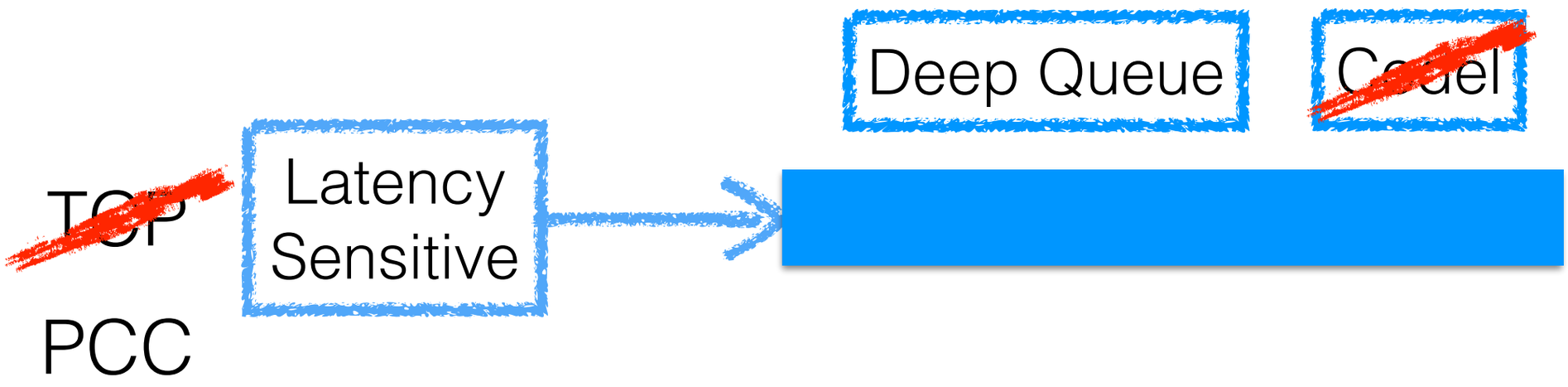
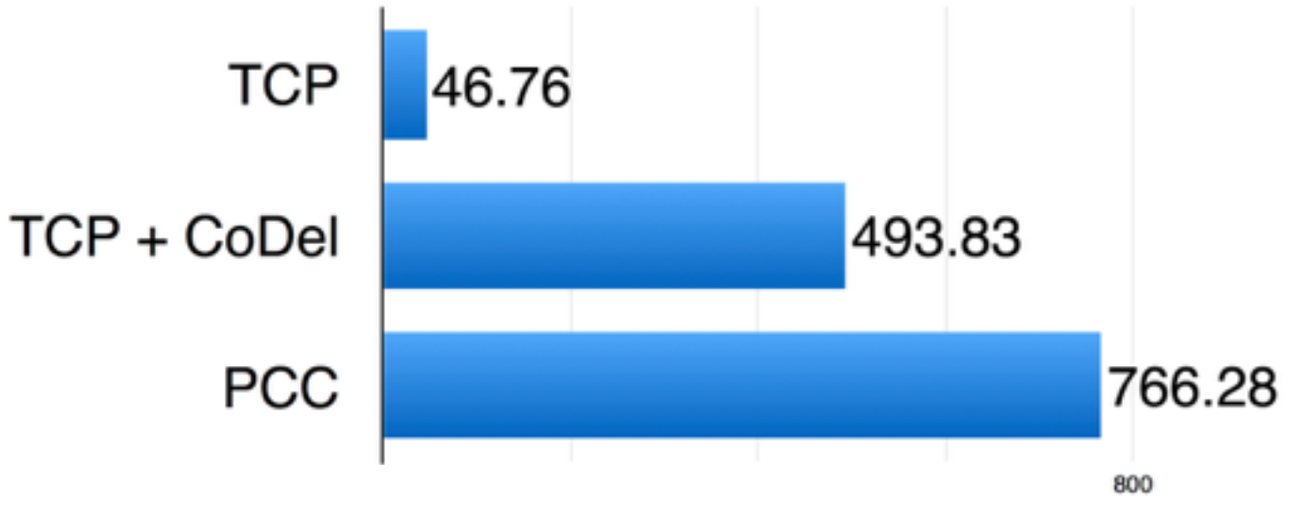
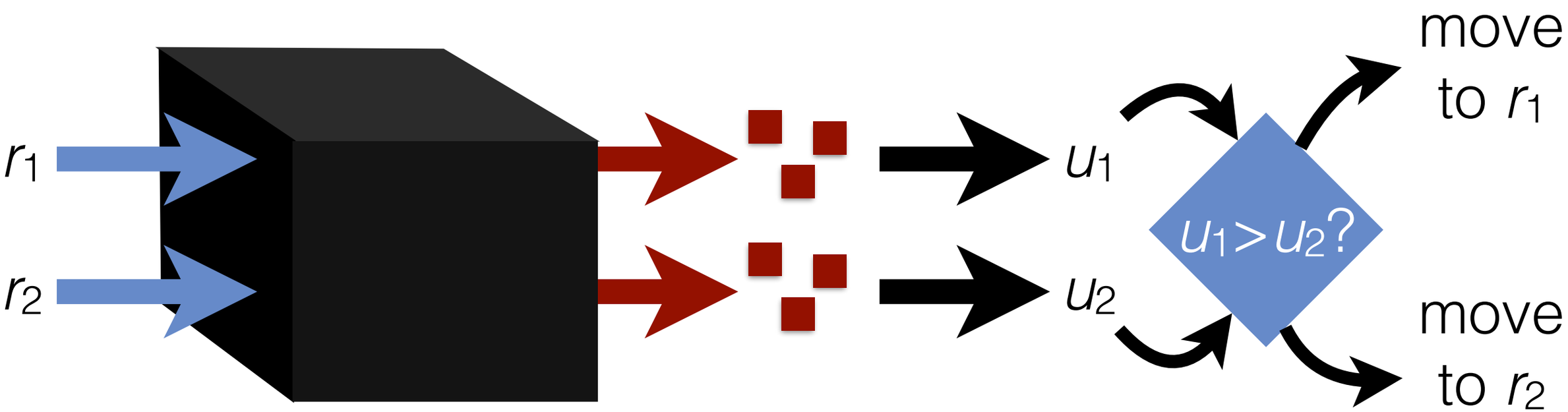




Small Causality Window



Small Causality Window

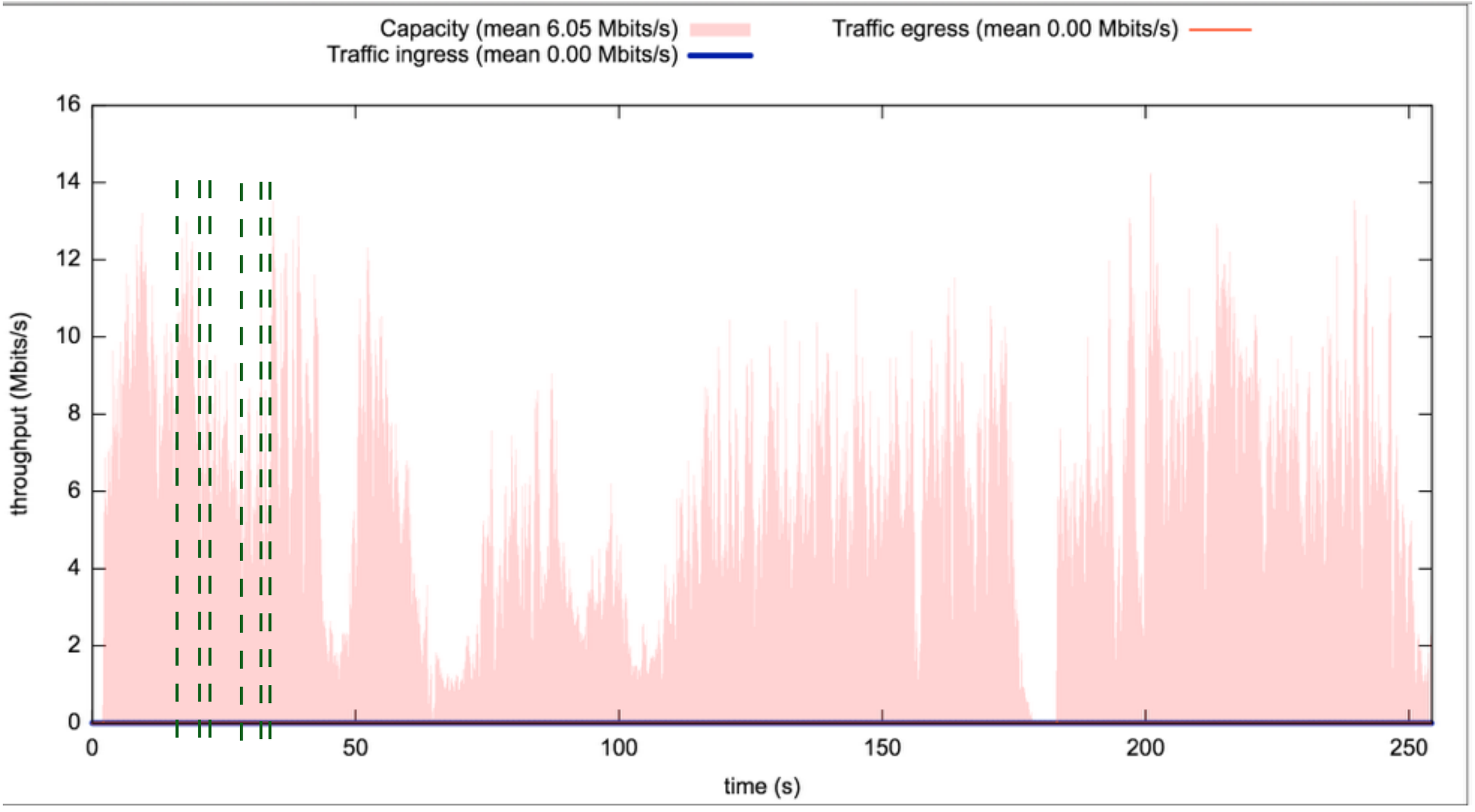


Figure drawn using Mahimahi by K. Winstein et. al. (http://mahimahi.mit.edu/)

Small Causality Window

PCC V2

- Fast convergence to optimal in tiny causality window
- Fast reaction to causality disruption
- Handling noisy measurement

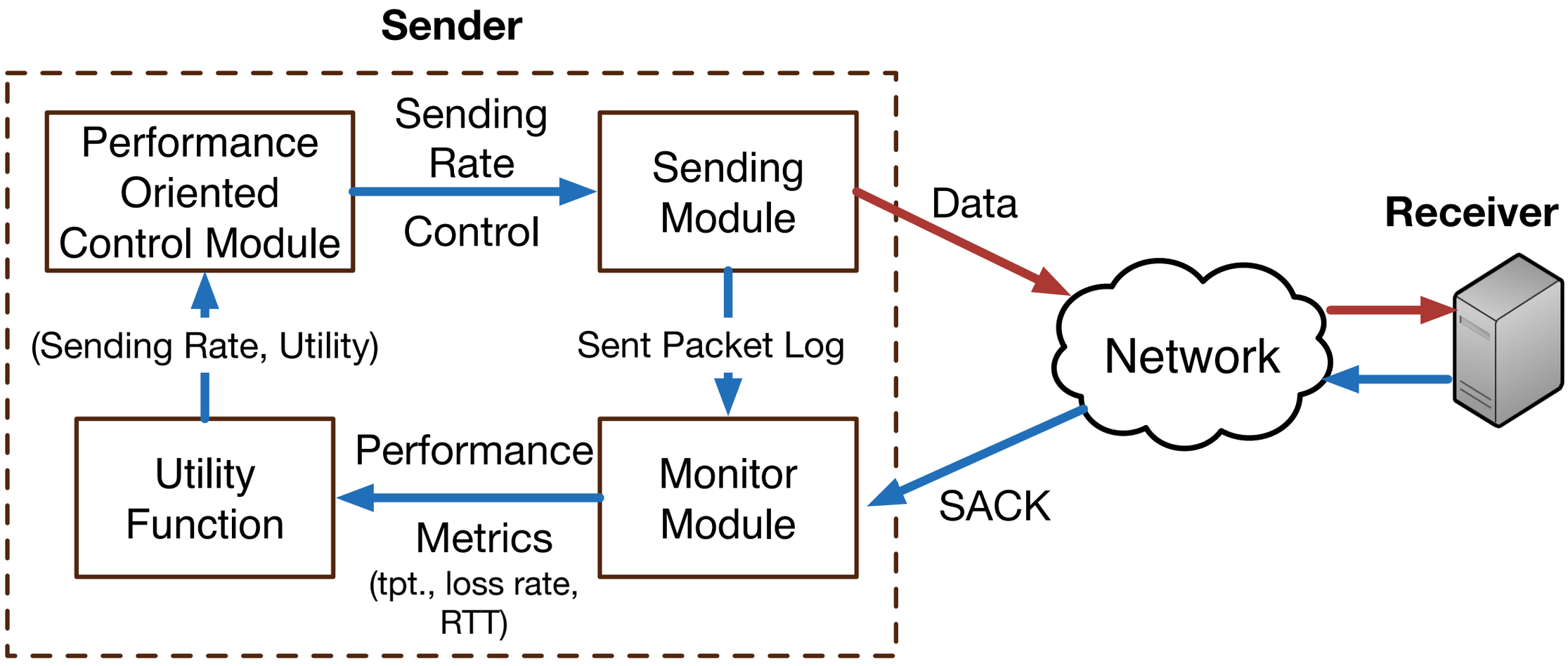
- Rate control based on empirically observed performance yields
  - Consistent high performance
  - Better stability than TCP
  - Flexible performance objectives
  - PCC V2 is coming

speedier.net

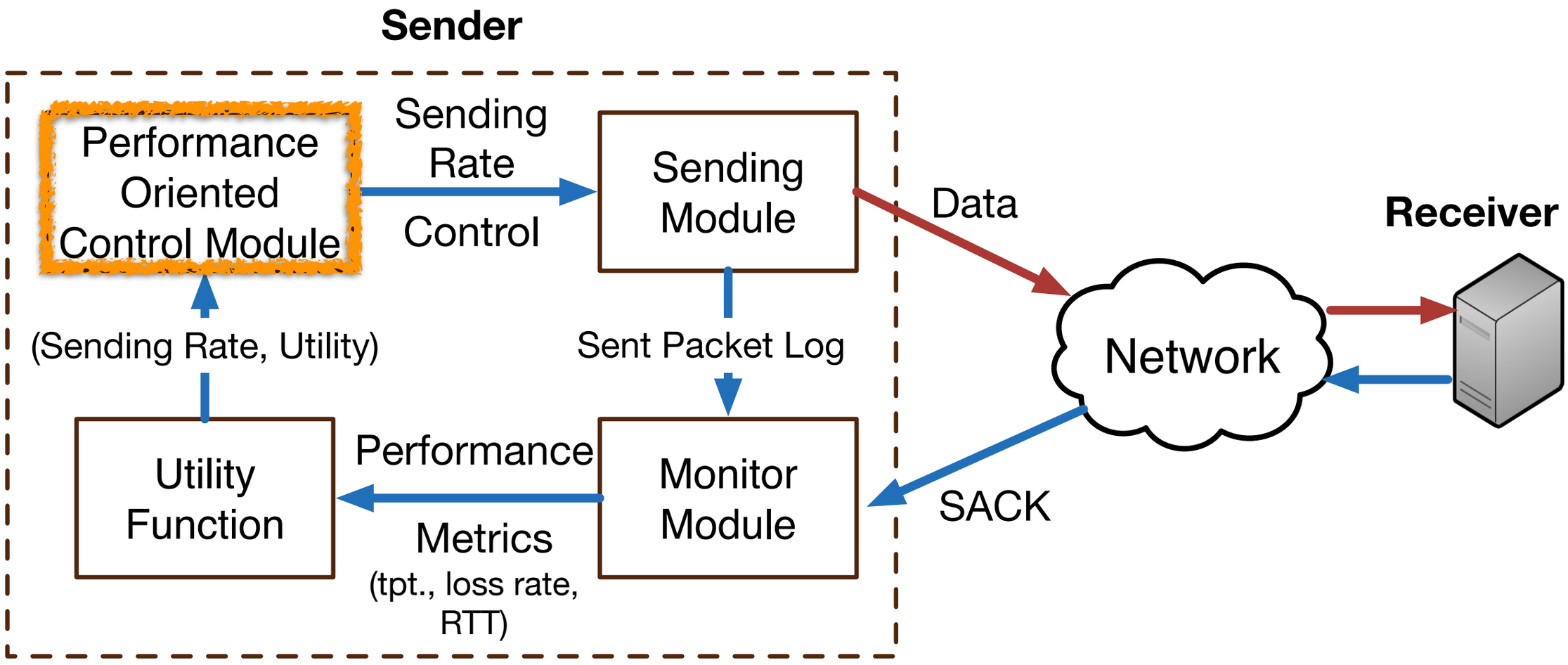
speedier.net/pcc

Backup Slides

Software Components

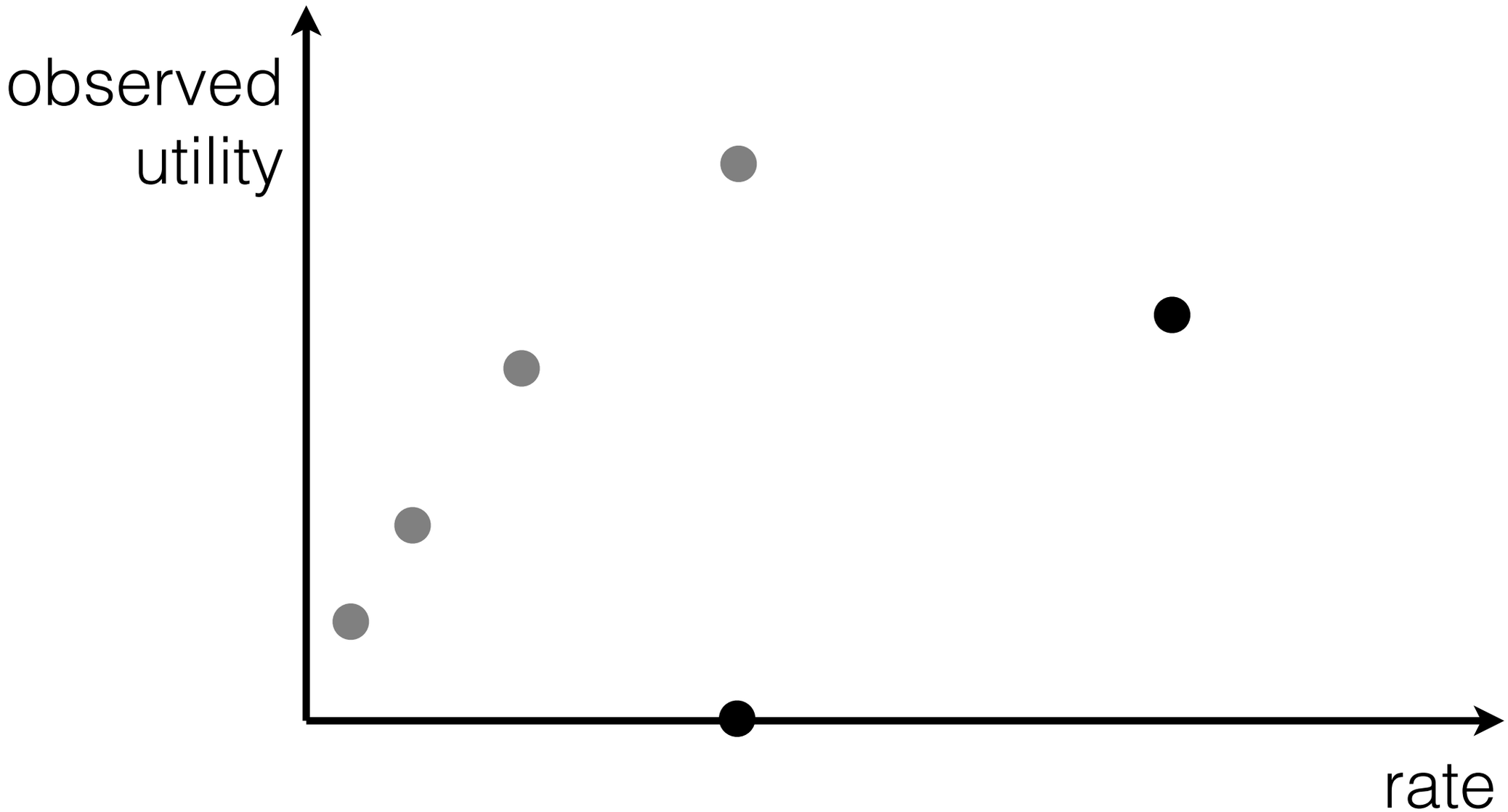


Software Components

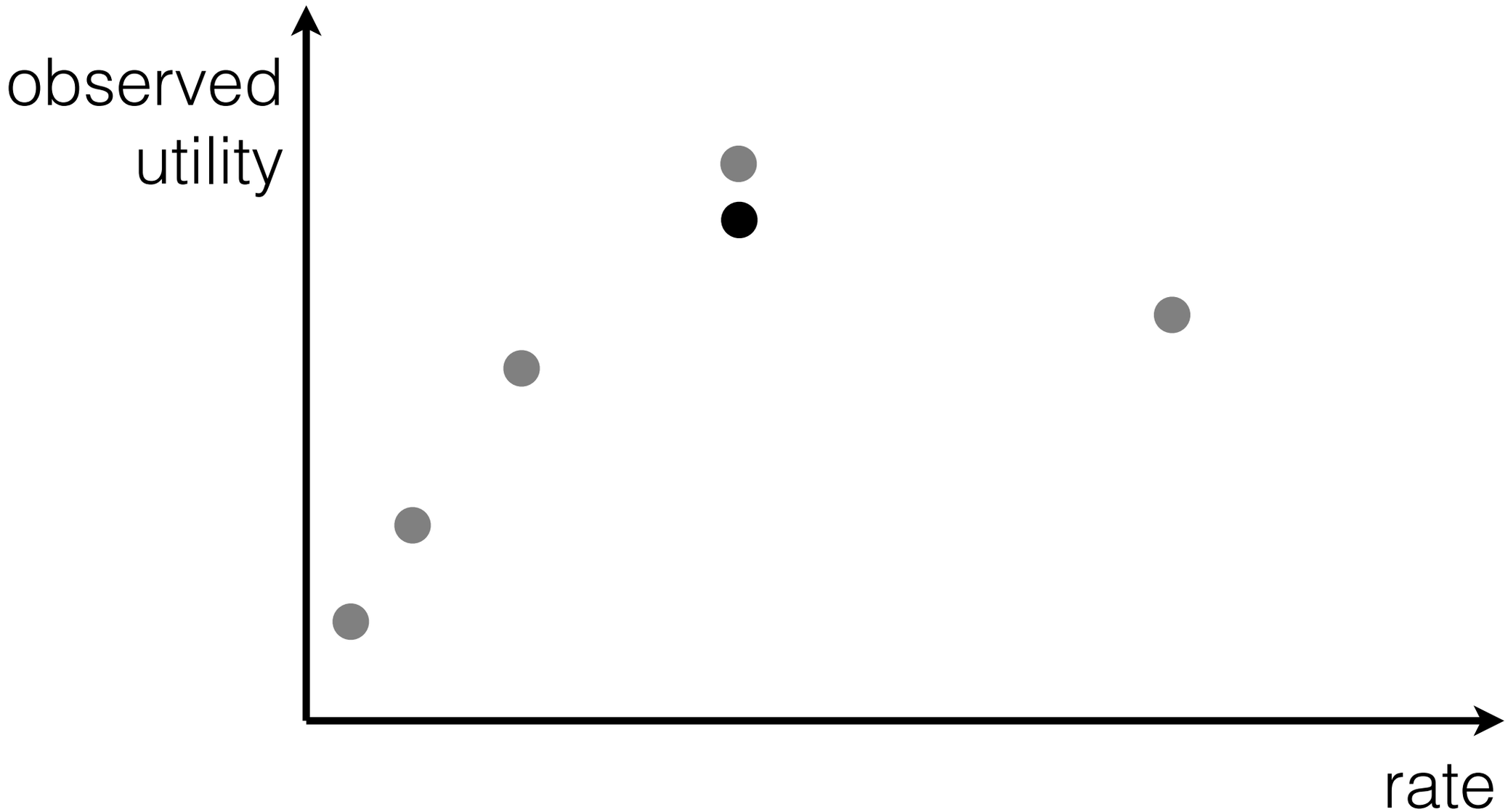


Performance Oriented Control

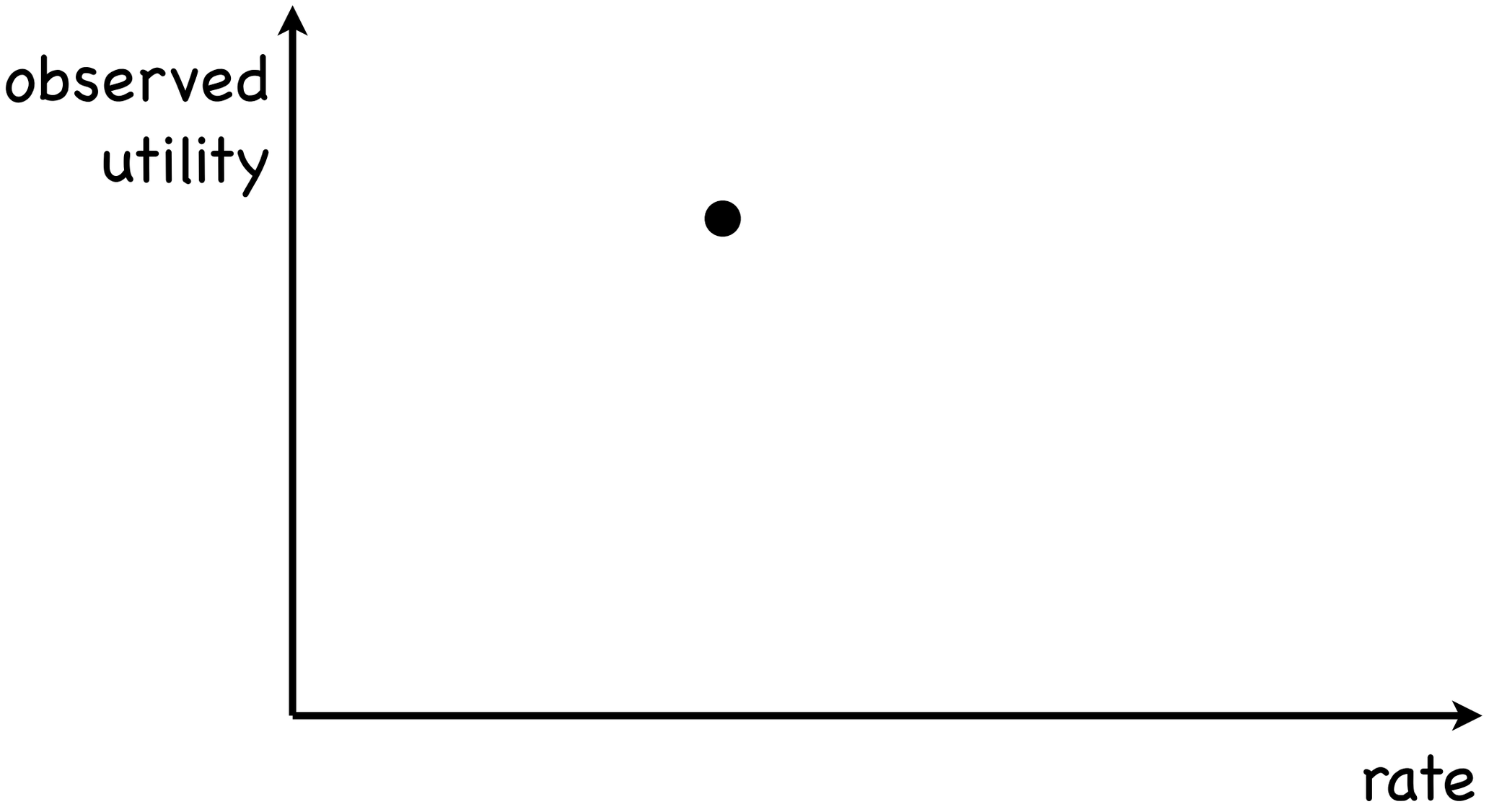
Performance Oriented Control



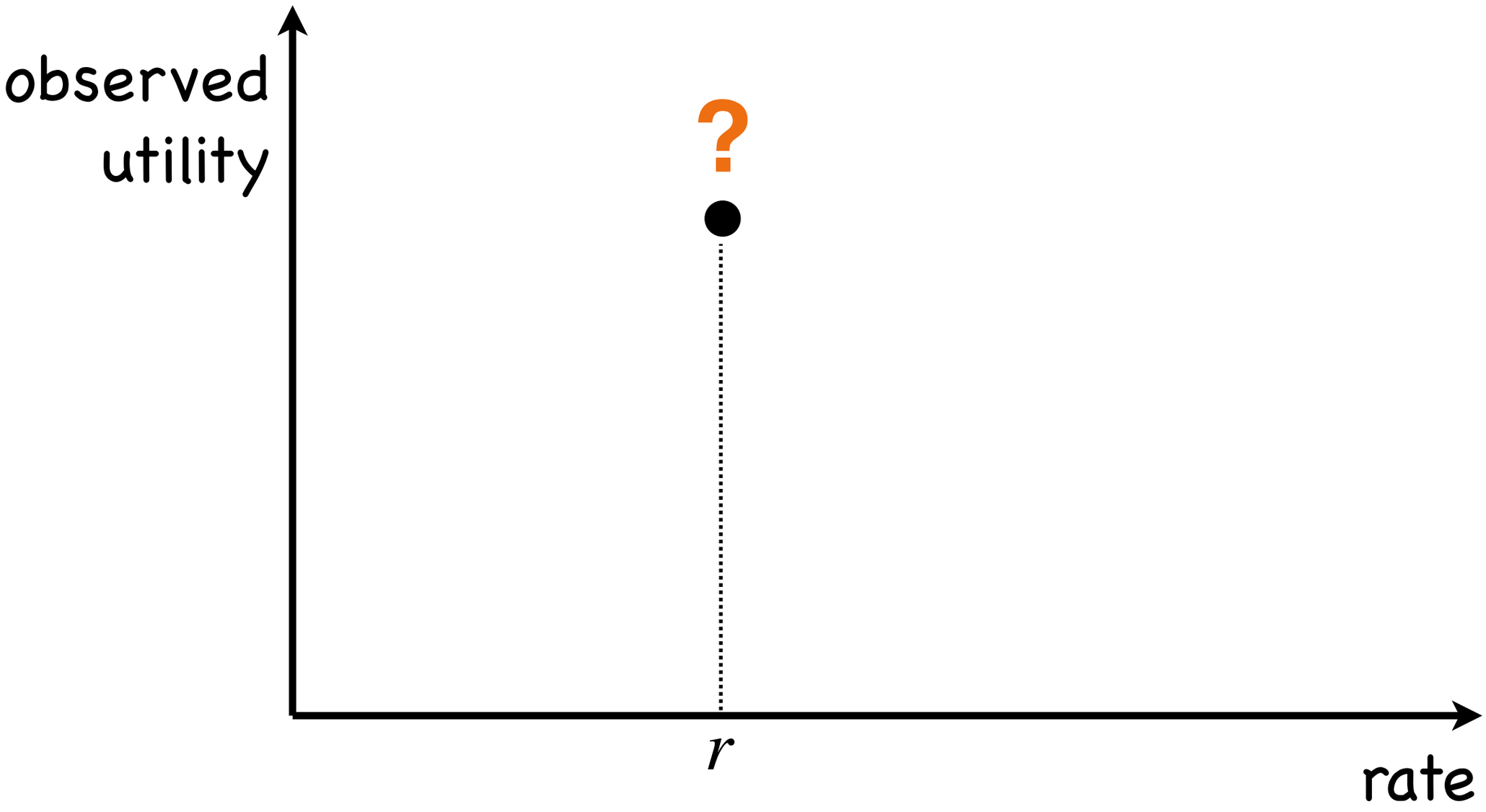
Performance Oriented Control



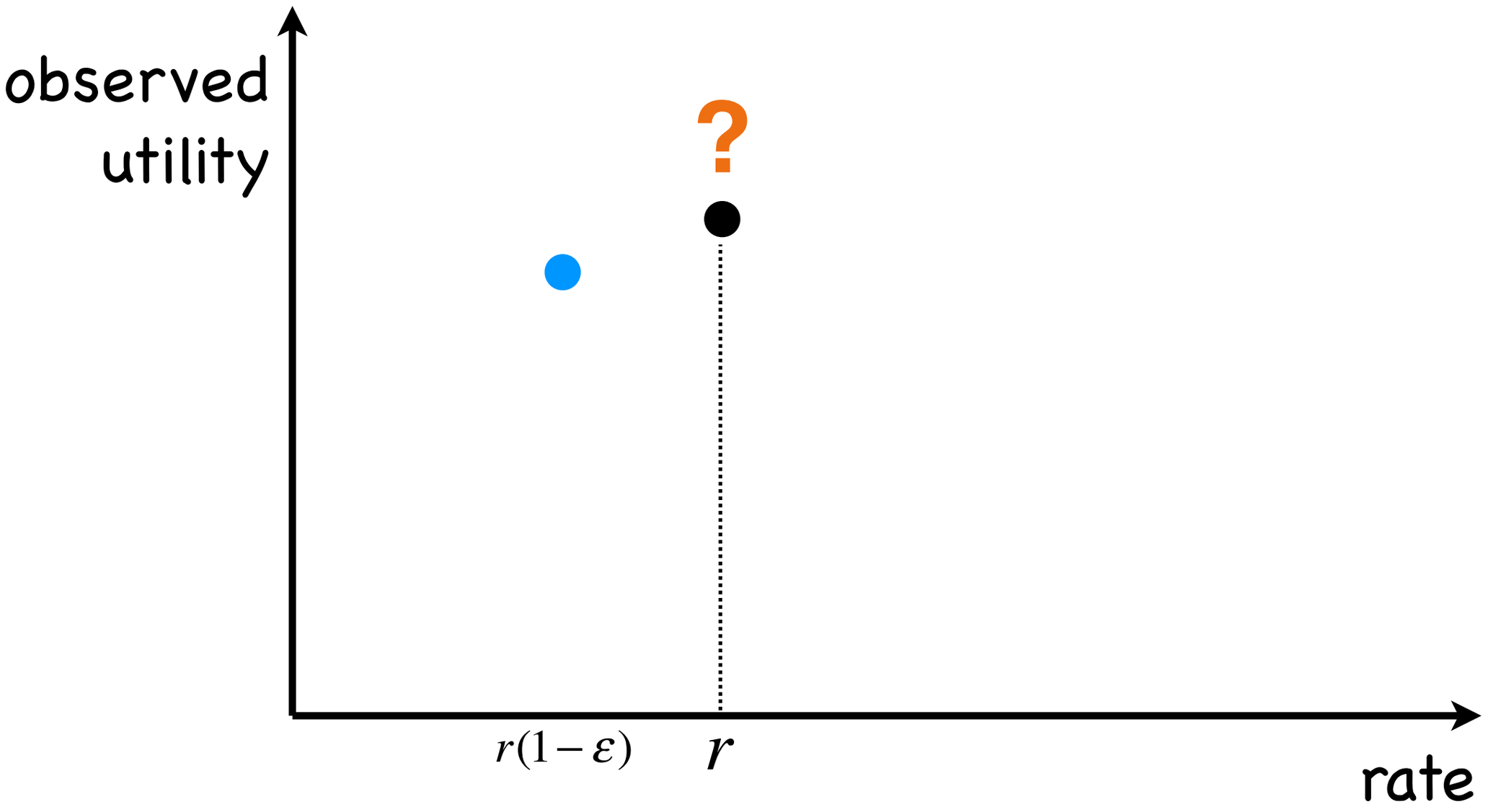
Performance Oriented Control



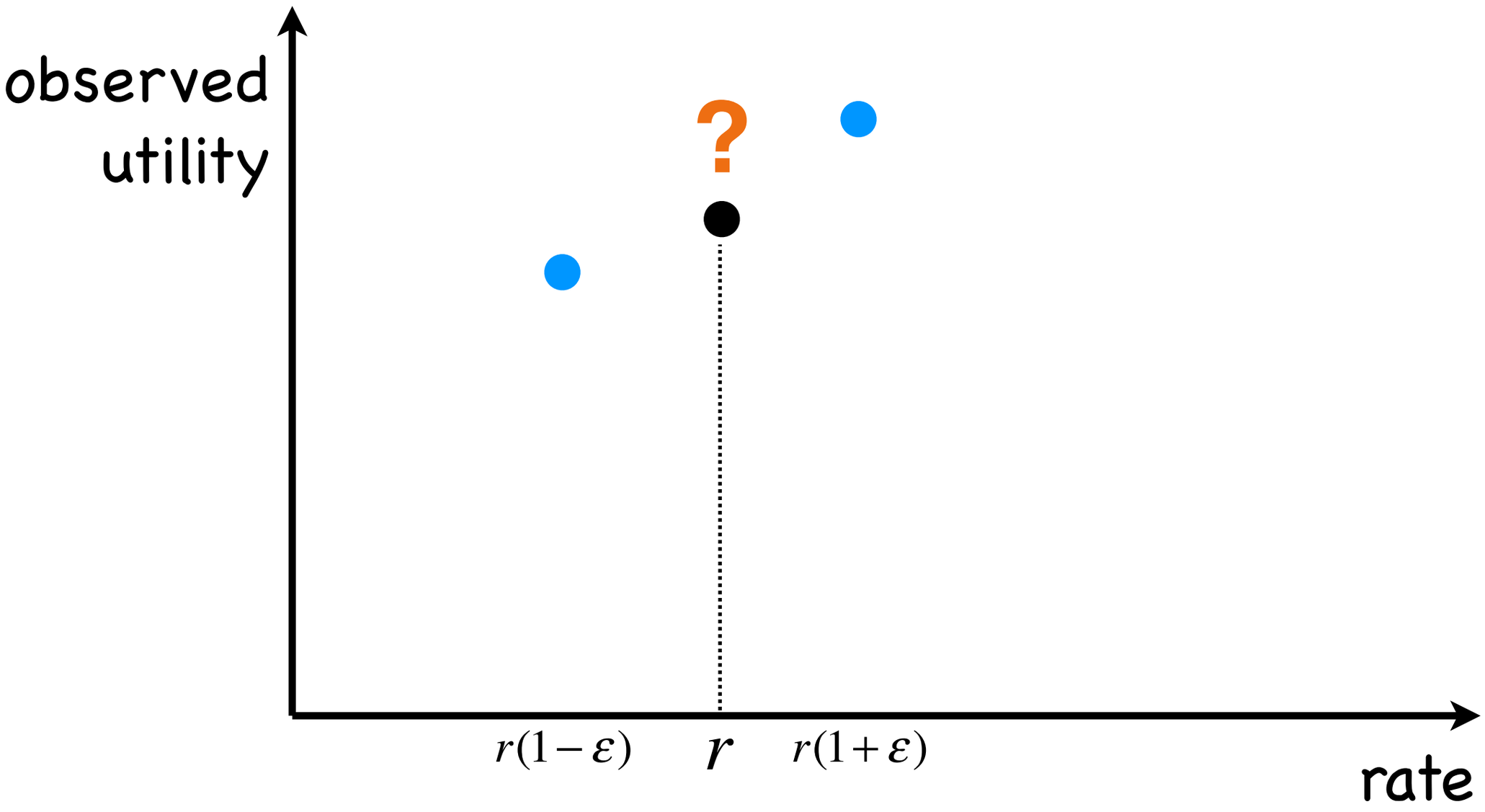
Performance Oriented Control



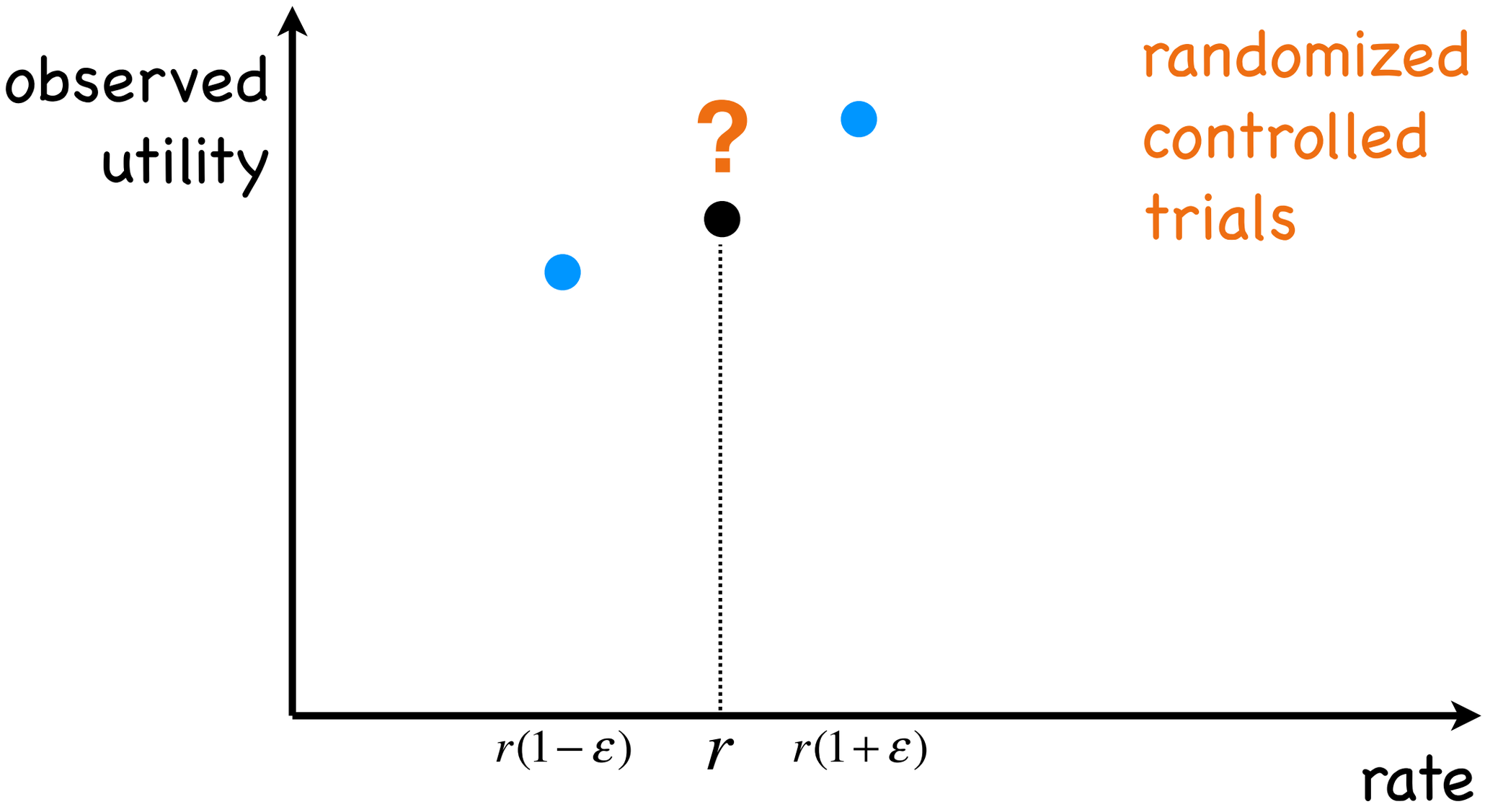
Performance Oriented Control



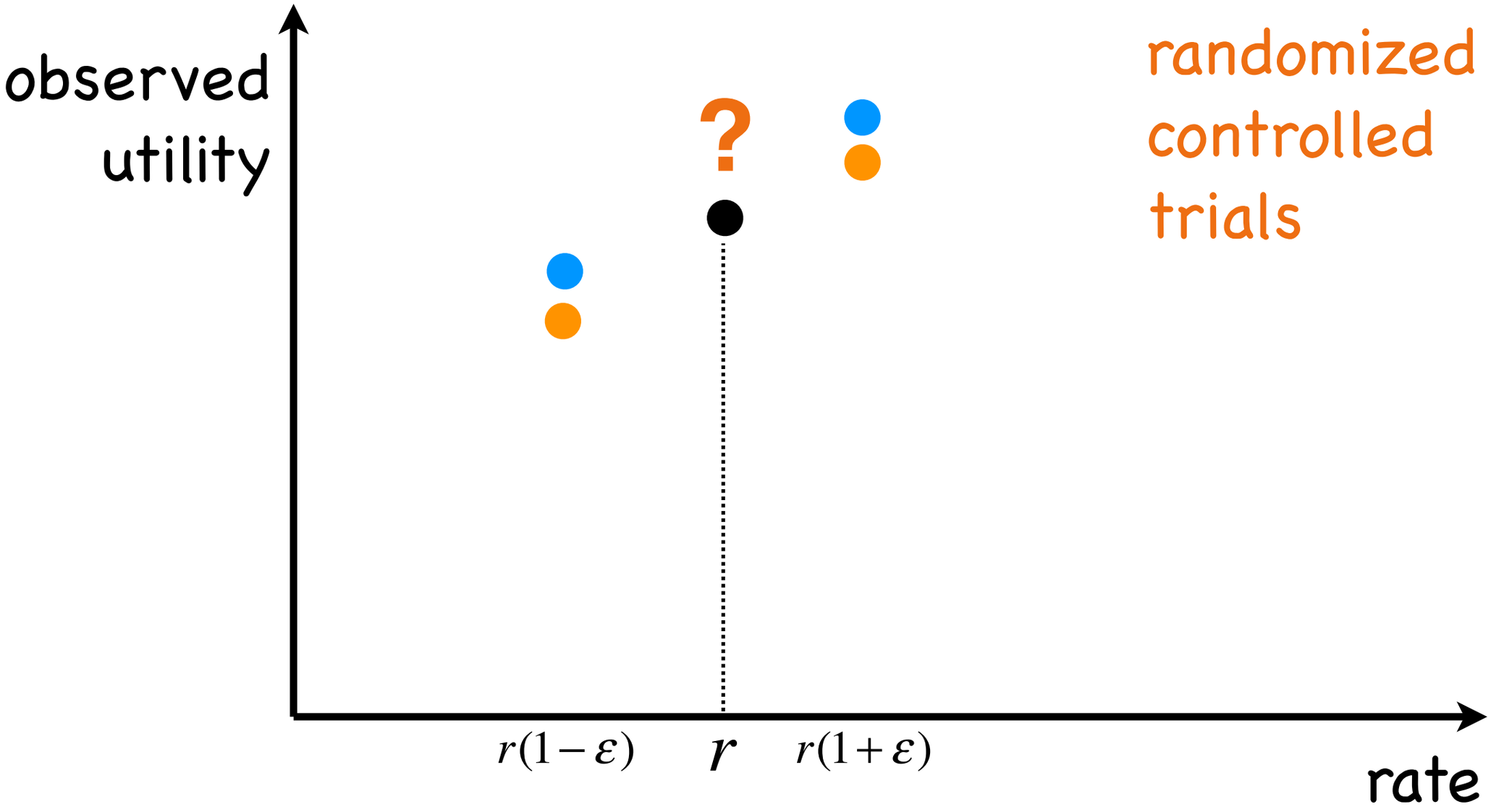
Performance Oriented Control



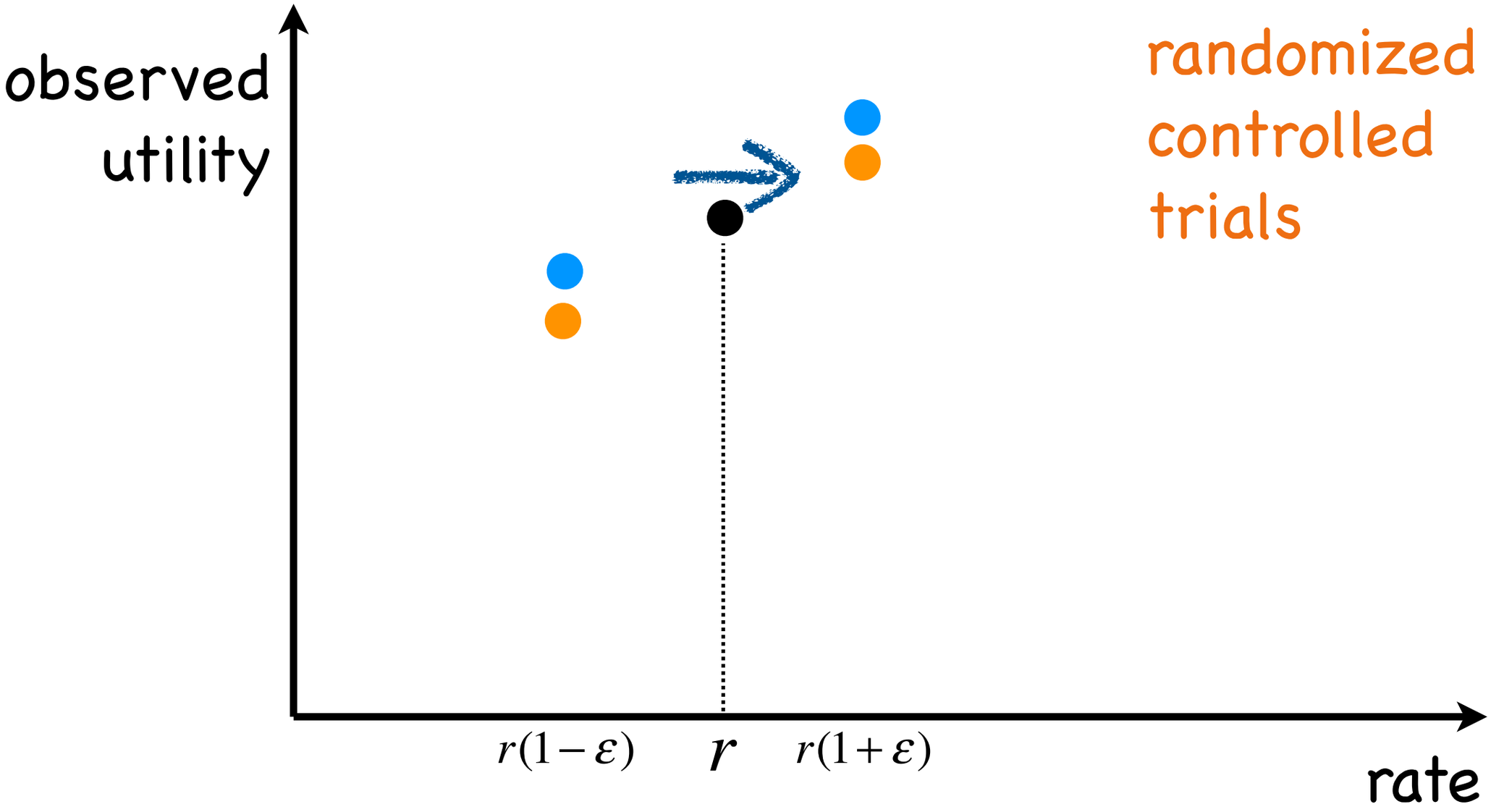
Performance Oriented Control



Performance Oriented Control

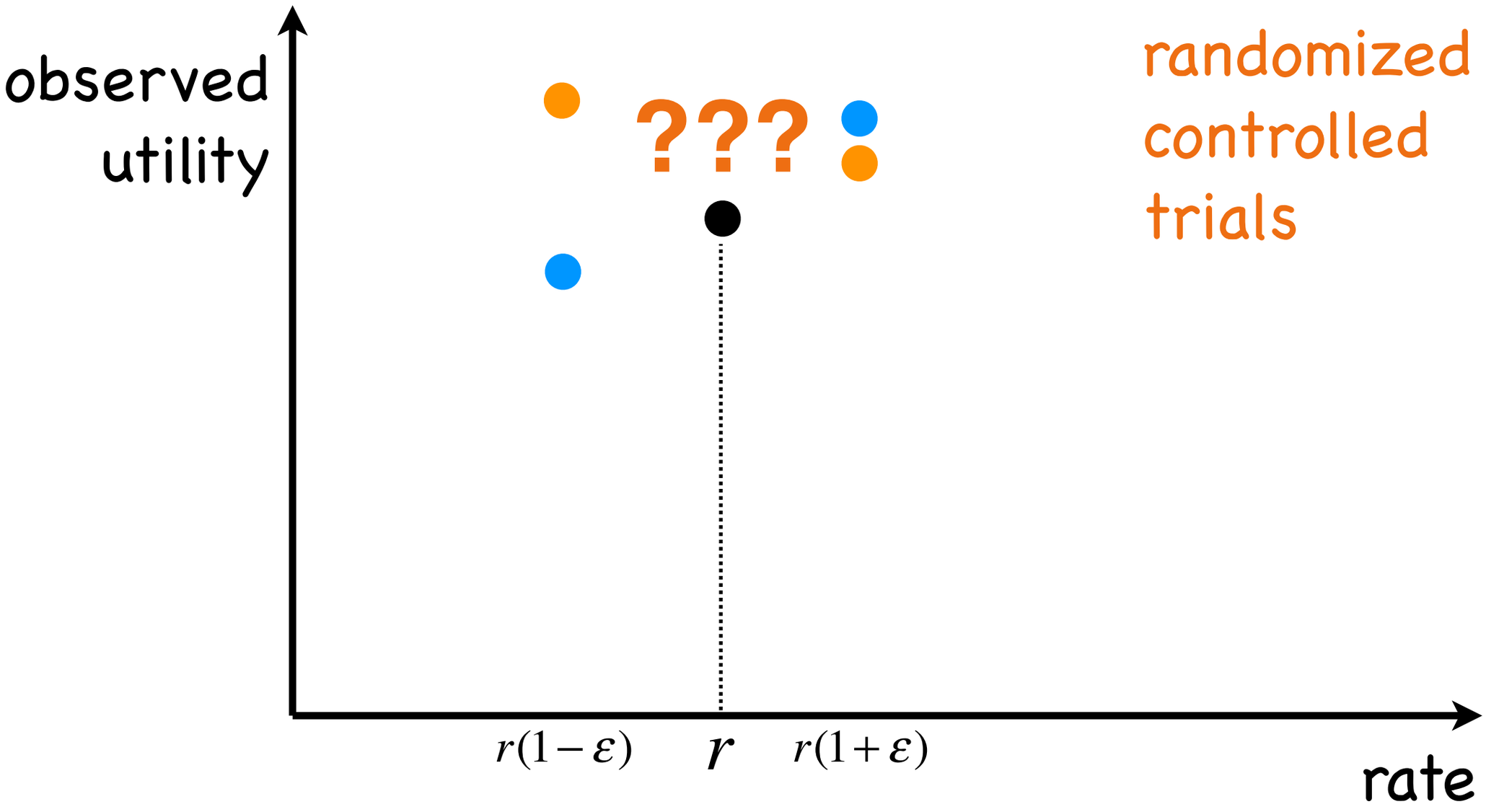


Performance Oriented Control

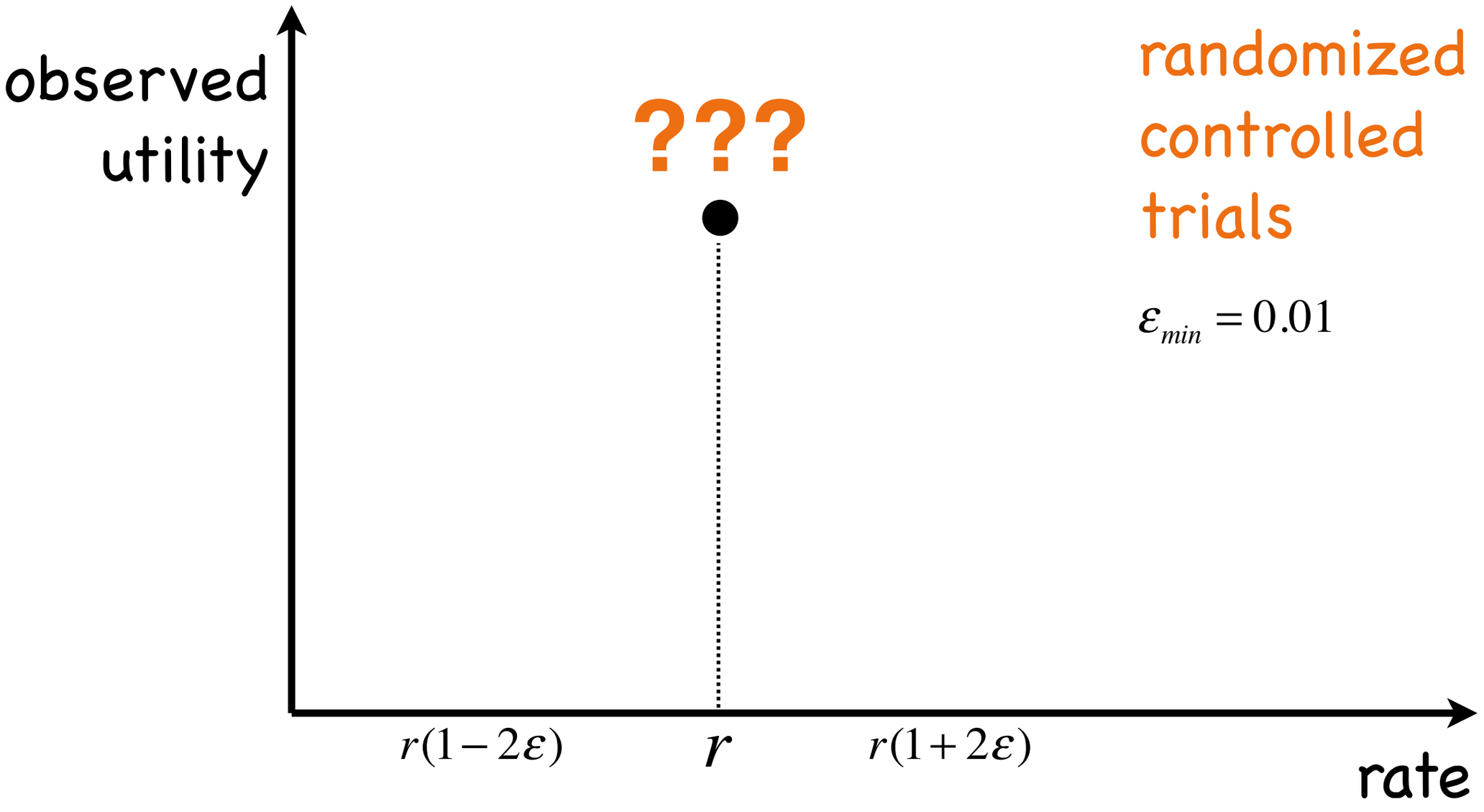


randomized
controlled
trials

Performance Oriented Control



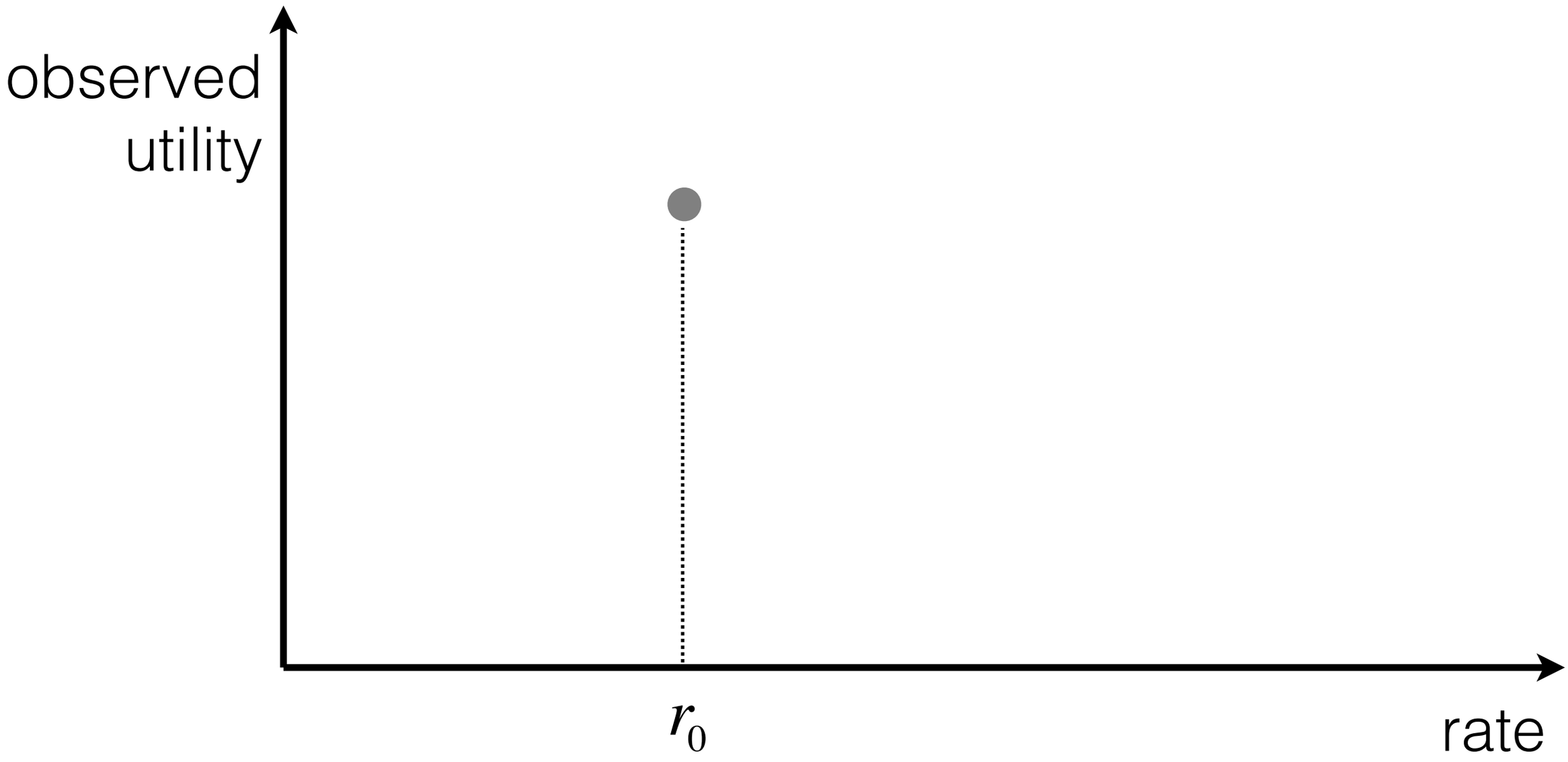
Performance Oriented Control



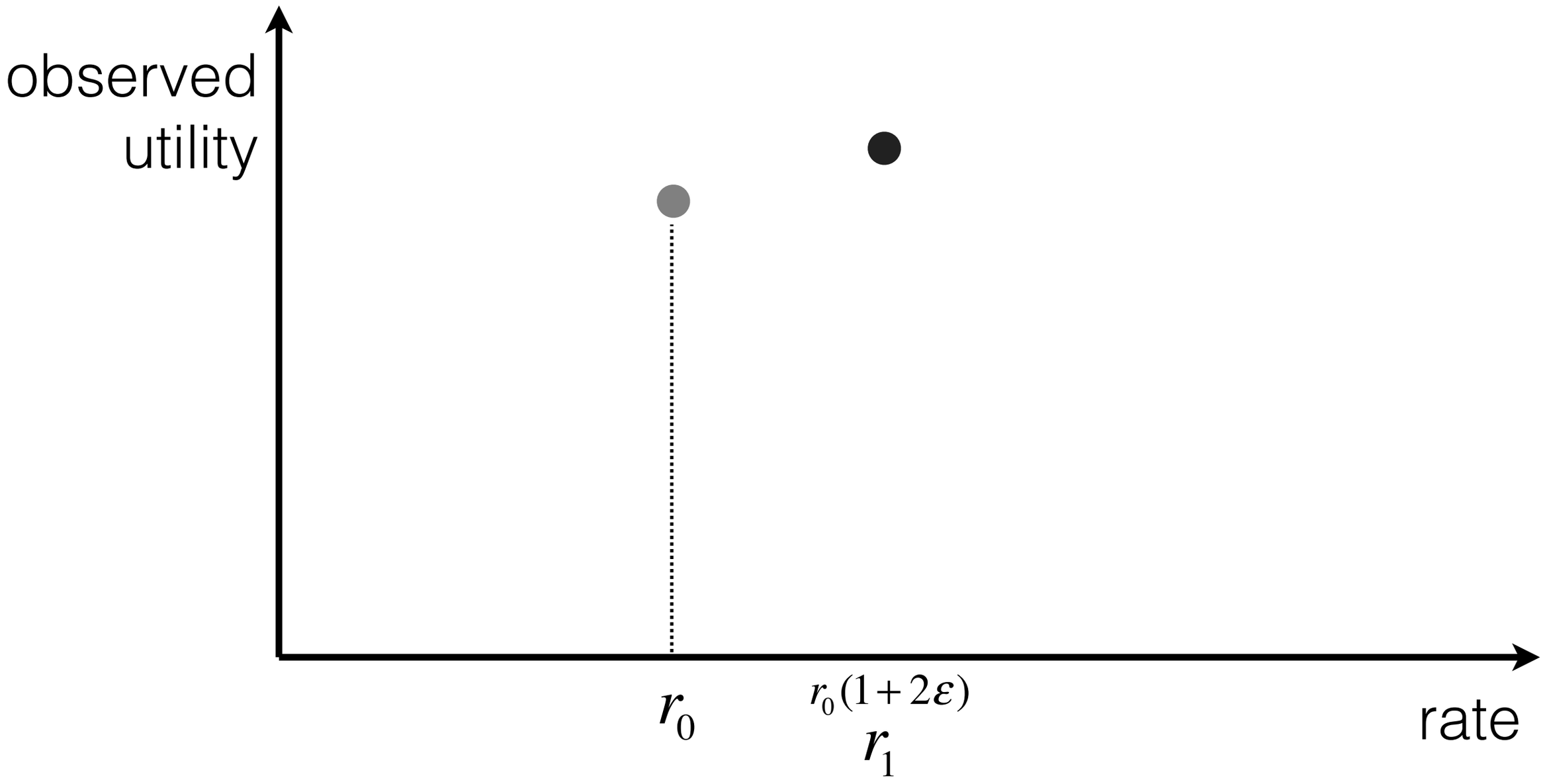
randomized
controlled
trials

$\varepsilon_{min} = 0.01$

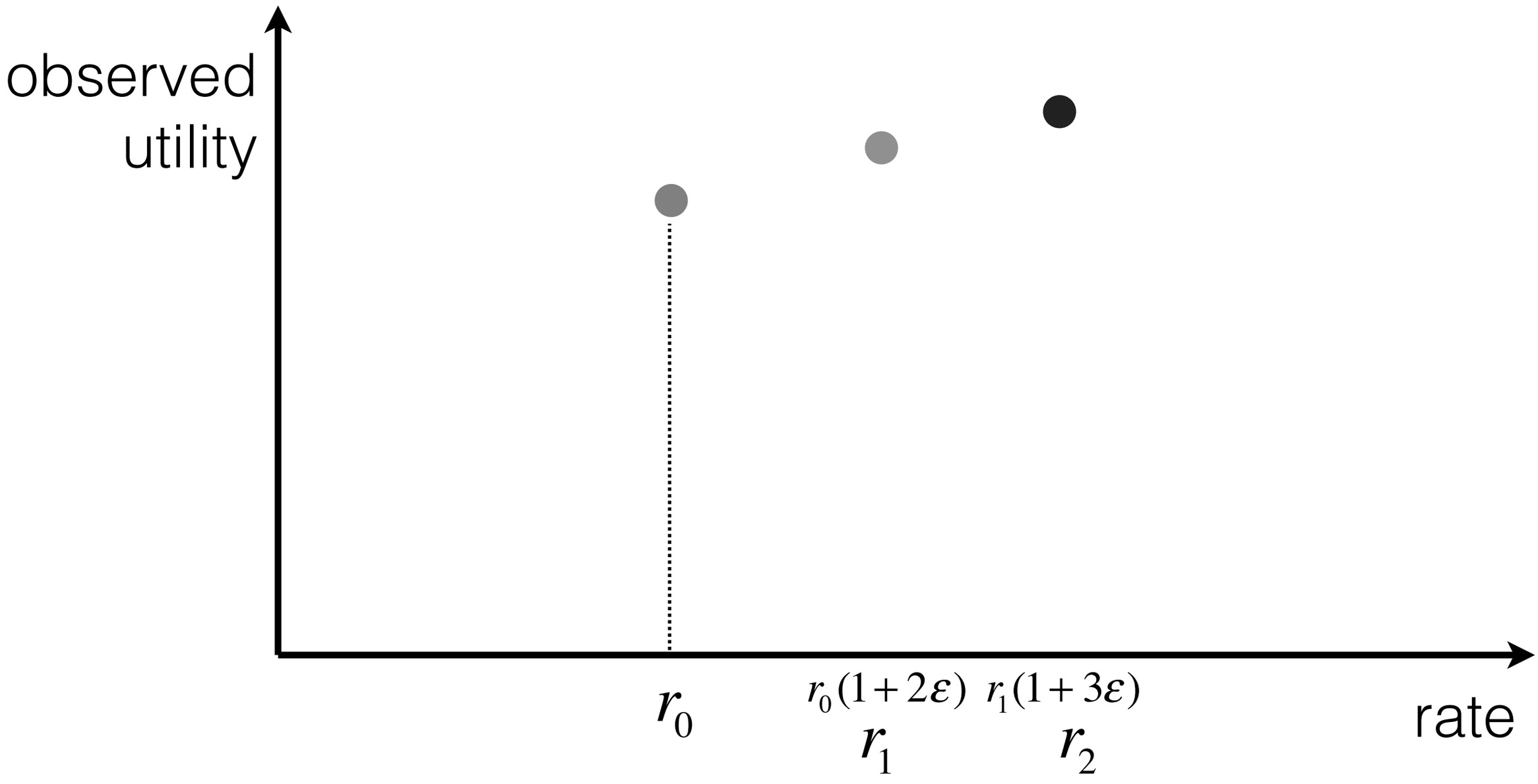
Online Learning Control



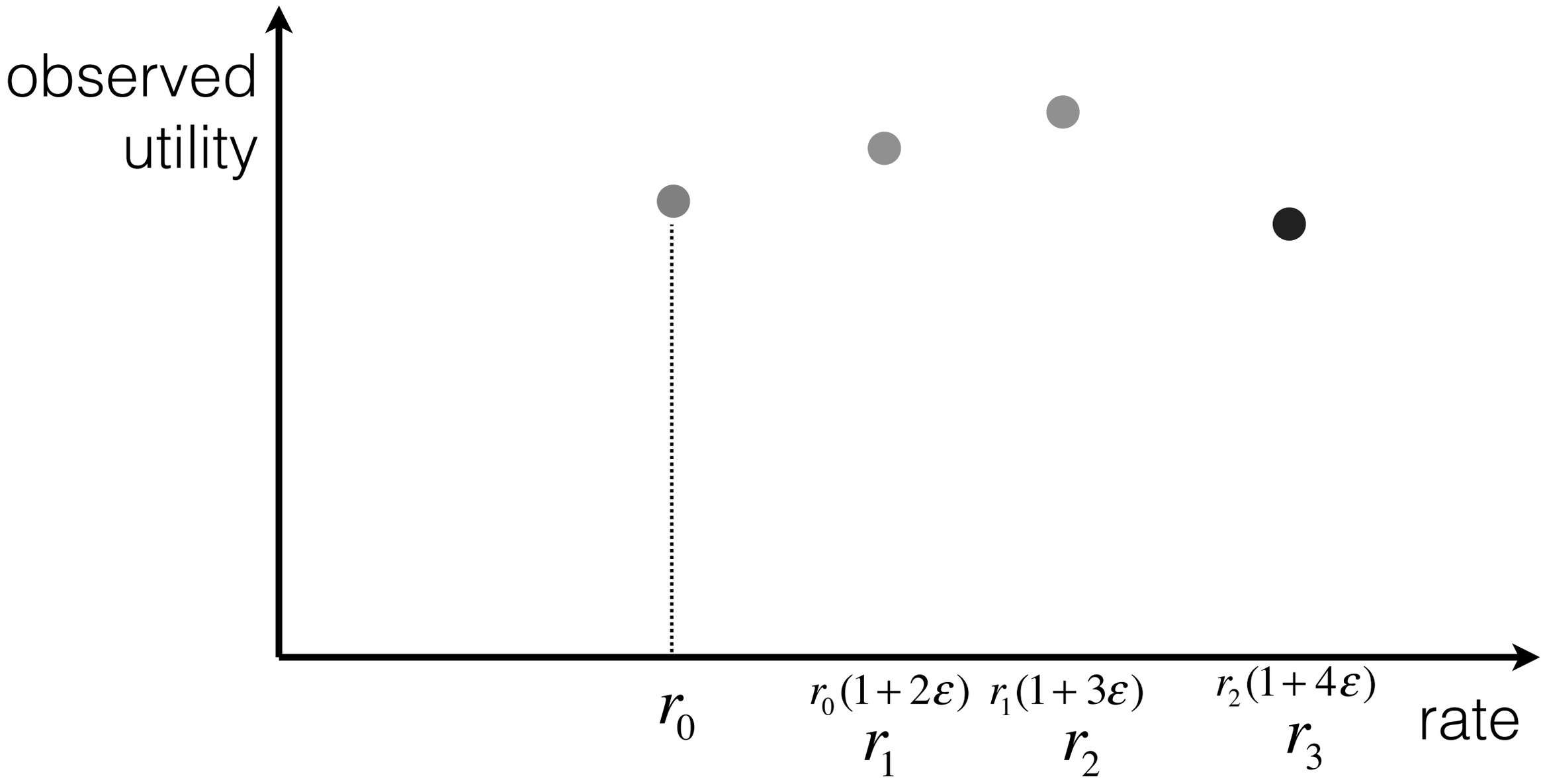
Online Learning Control



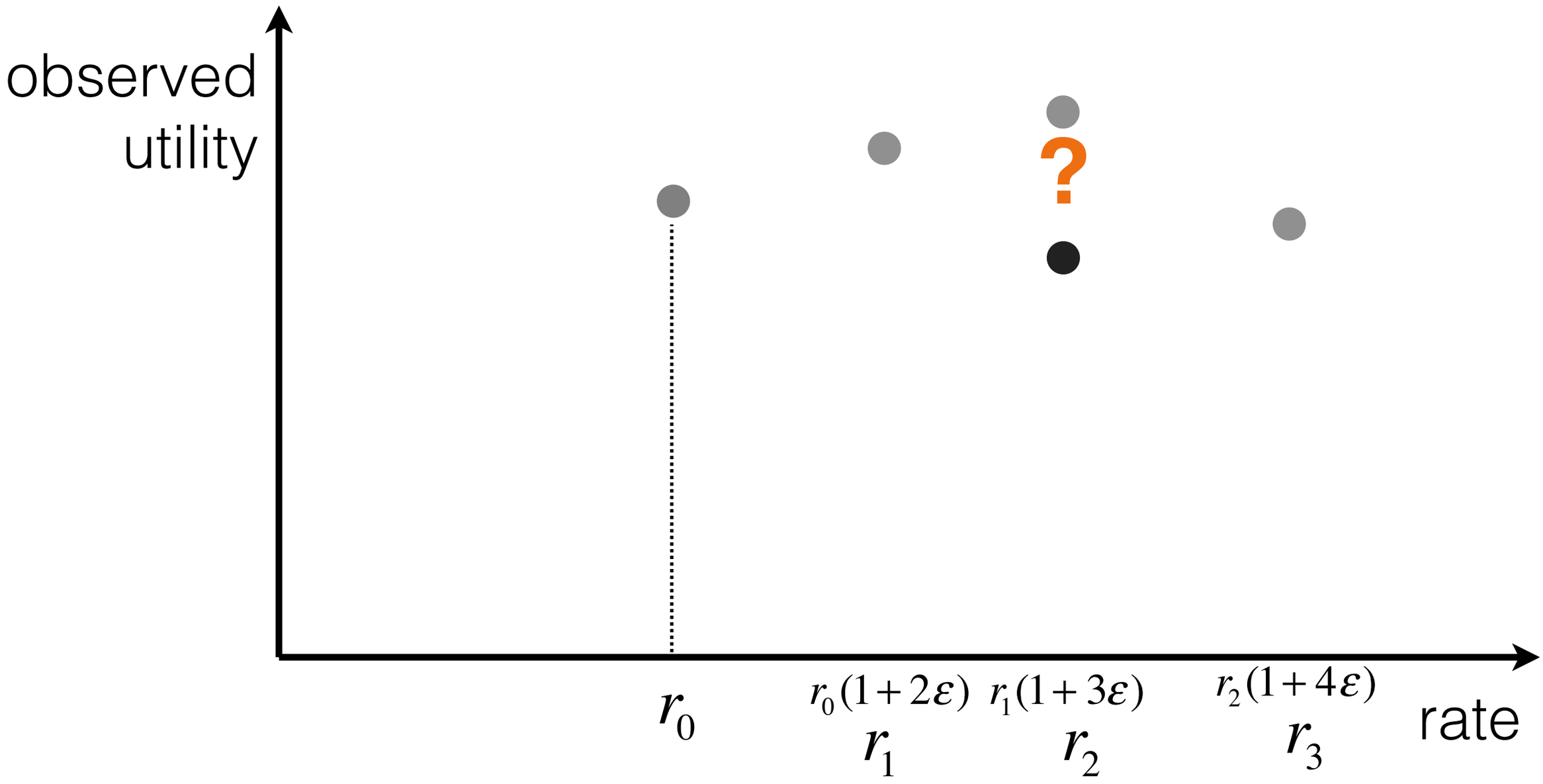
Online Learning Control



Online Learning Control



Online Learning Control



Deployment

- No hardwired support, packet header, protocol change needed
- Where to deploy
  - CDN backbone, Inter-data center, dedicated scientific nw
  - "In the Wild"?

TCP Friendliness

TCP Friendliness

- Is PCC TCP-friendly?

TCP Friendliness

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TCP Friendliness

TCP Friendliness

- PCC's default utility function is not TCP Friendly

TCP Friendliness

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But not **that** bad

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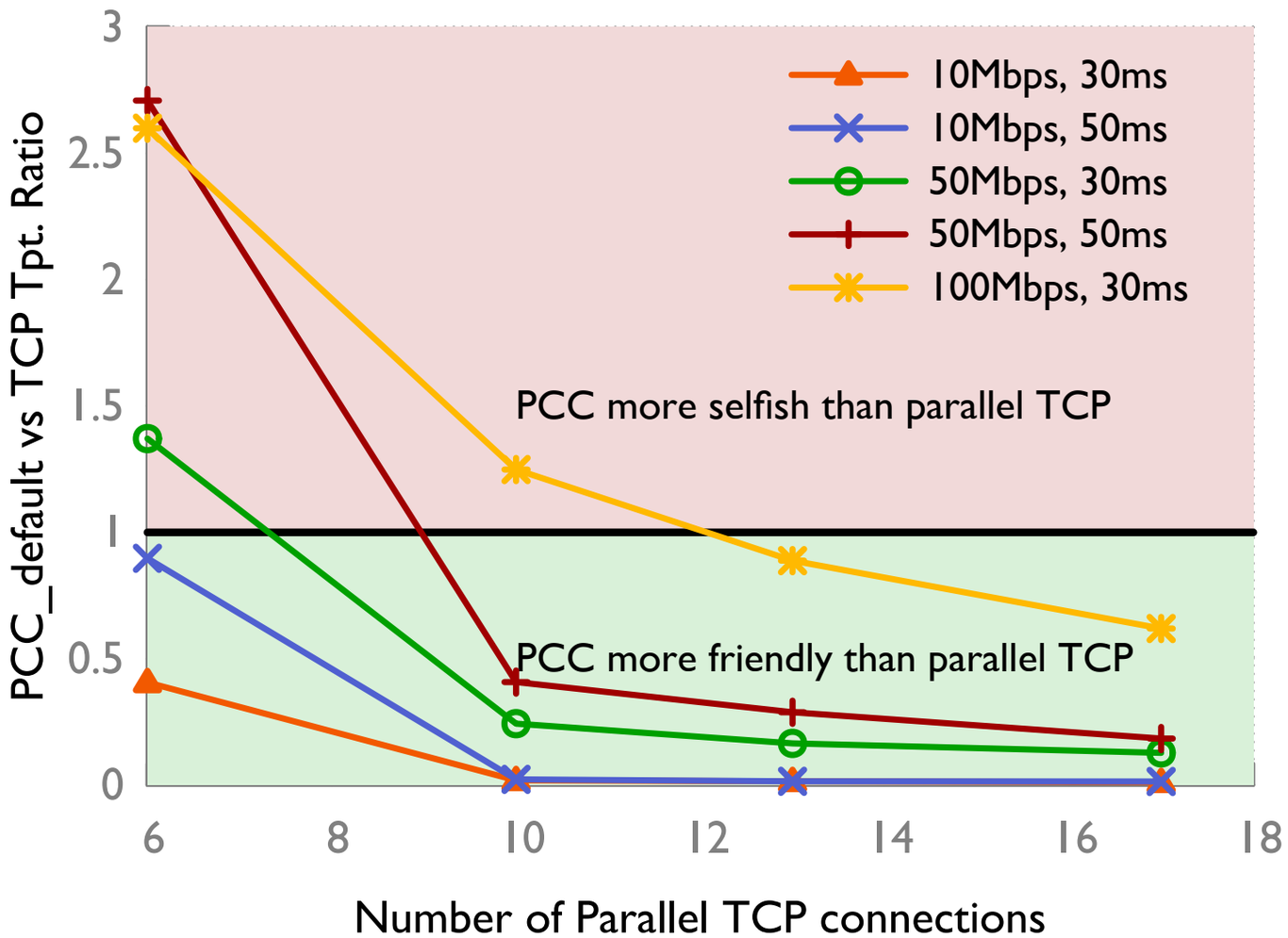
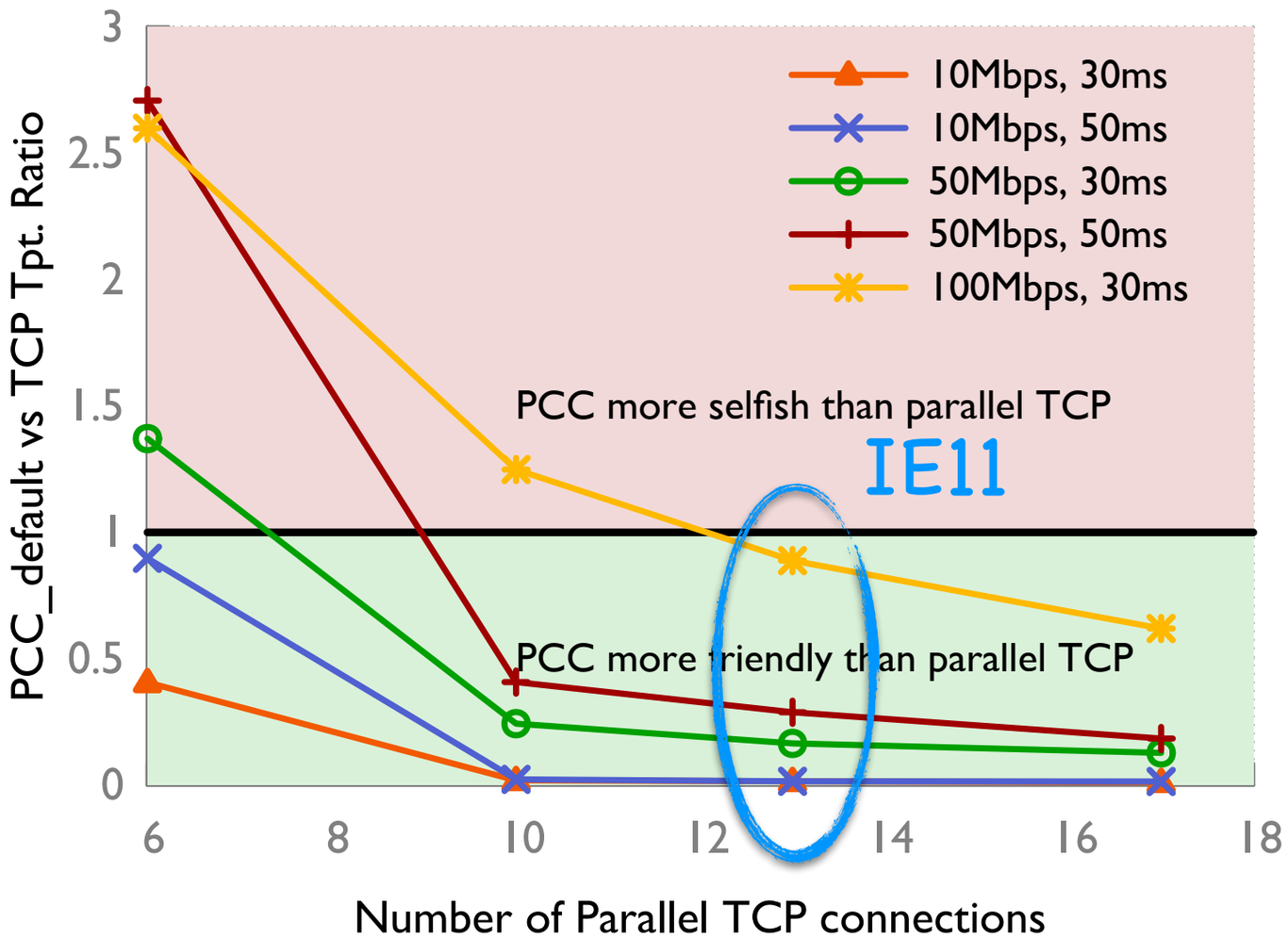


TCP Friendliness

- PCC's default utility function is not TCP Friendly

But not **that** bad



TCP Friendliness

- PCC's default utility function is not TCP Friendly
- Different utility functions can be a solution

TCP Friendliness

- PCC's default utility function is not TCP Friendly
- Different utility functions can be a solution

$$u_i(x) = \frac{T_i * sigmoid_\alpha(L_i - 0.05) * sigmoid_\beta(\frac{rtt_n}{rtt_{n-1}} - 1) - x_i * L_i}{rtt_n}$$

TCP Friendliness

- PCC's default utility function is not TCP Friendly
- Different utility functions can be a solution

TCP Friendliness

- PCC's default utility function is not TCP Friendly
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TCP vs TCP TCP vs PCC

TCP Friendliness

- PCC's default utility function is not TCP Friendly
- Different utility functions can be a solution

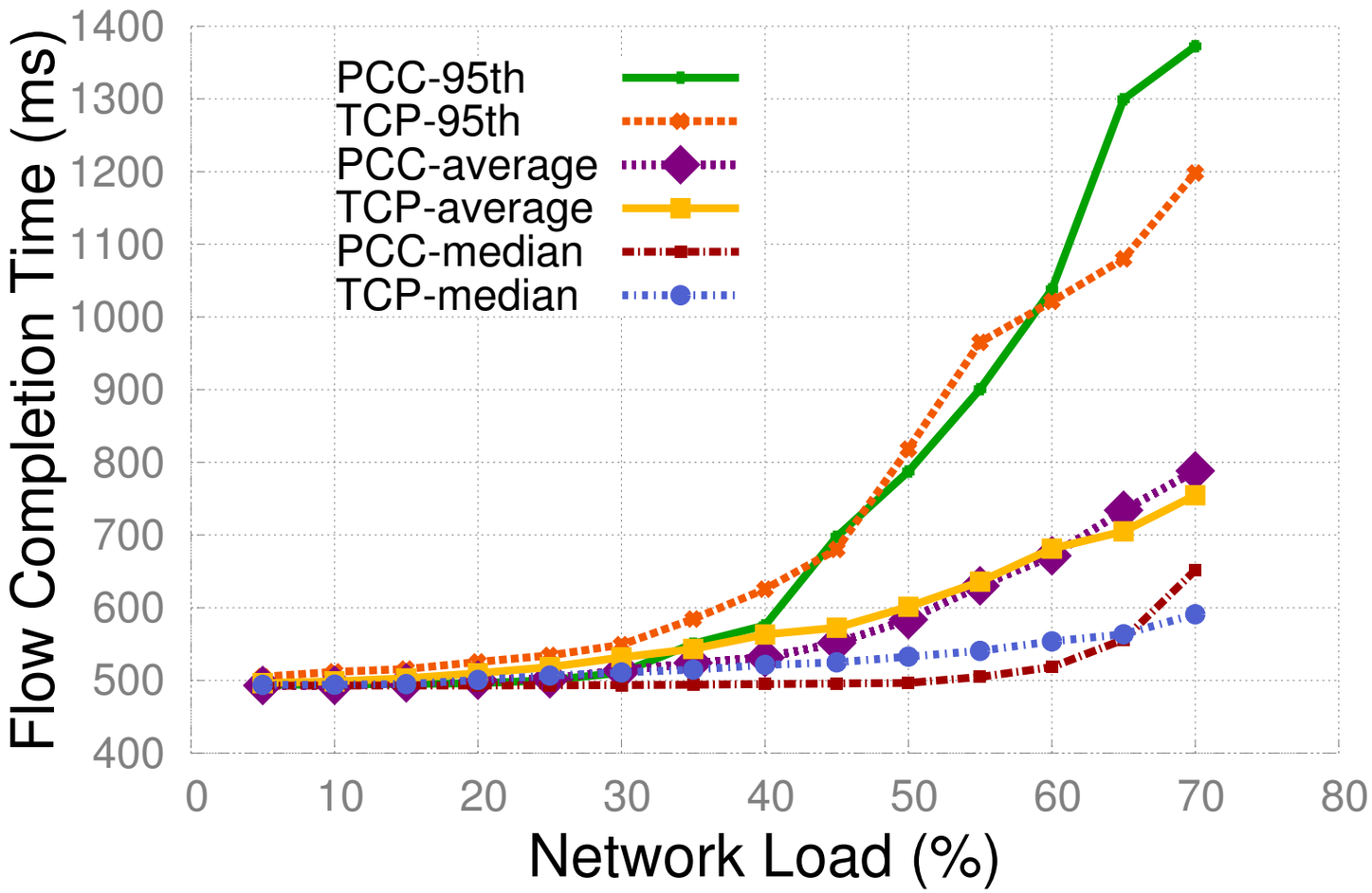
TCP Friendliness

- PCC's default utility function is not TCP Friendly
- Different utility functions can be a solution

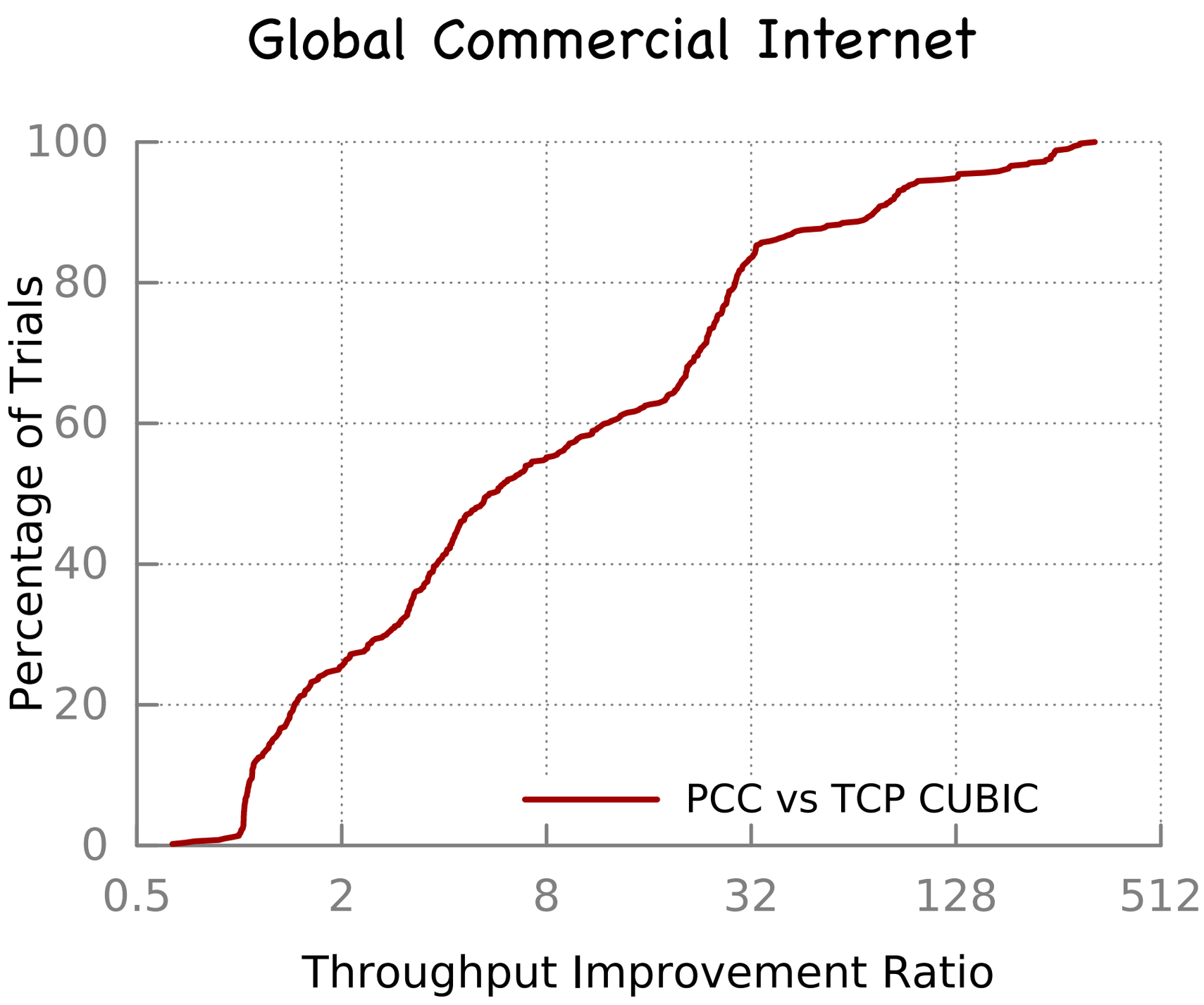
		30ms	60ms	90ms
$\beta = 10$	10Mbit/s	0.94	0.75	0.67
	50Mbit/s	0.74	0.73	0.81
	90Mbit/s	0.89	0.91	1.01
$\beta = 100$	10Mbit/s	0.71	0.58	0.63
	50Mbit/s	0.56	0.58	0.54
	90Mbit/s	0.63	0.62	0.88

Deployability: Short Flow FCT

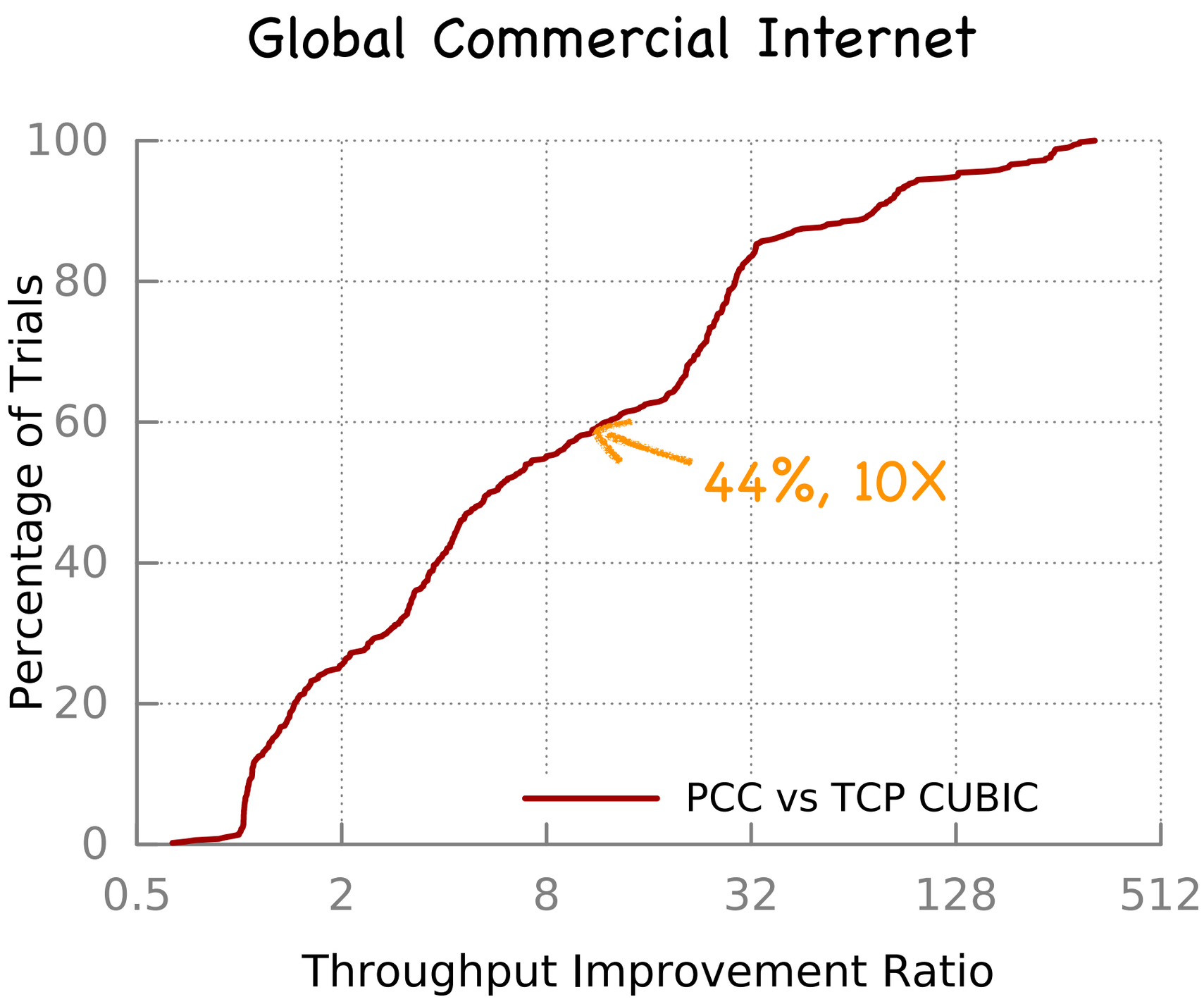
PCC does not fundamentally harm FCT



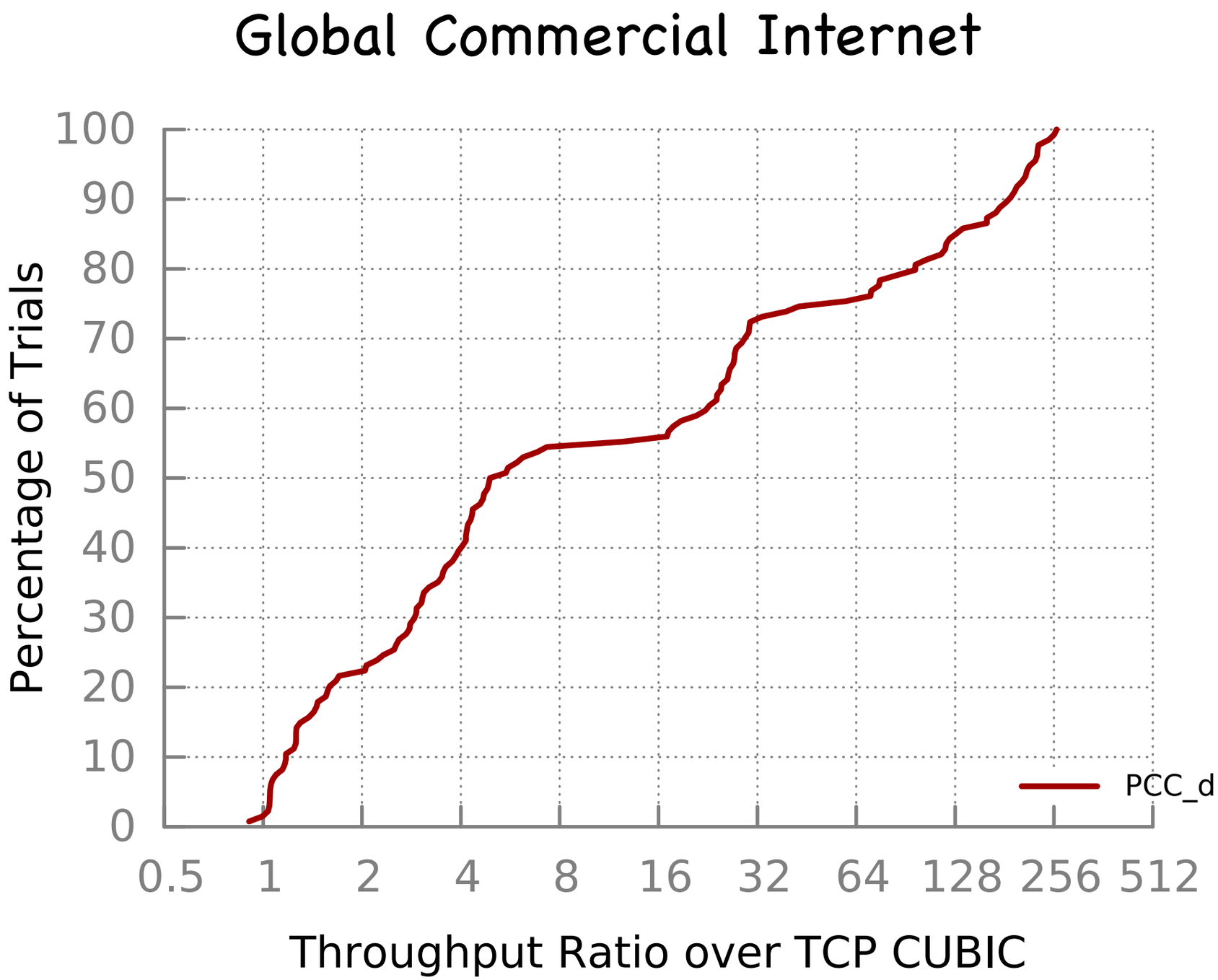
Consistent High Performance



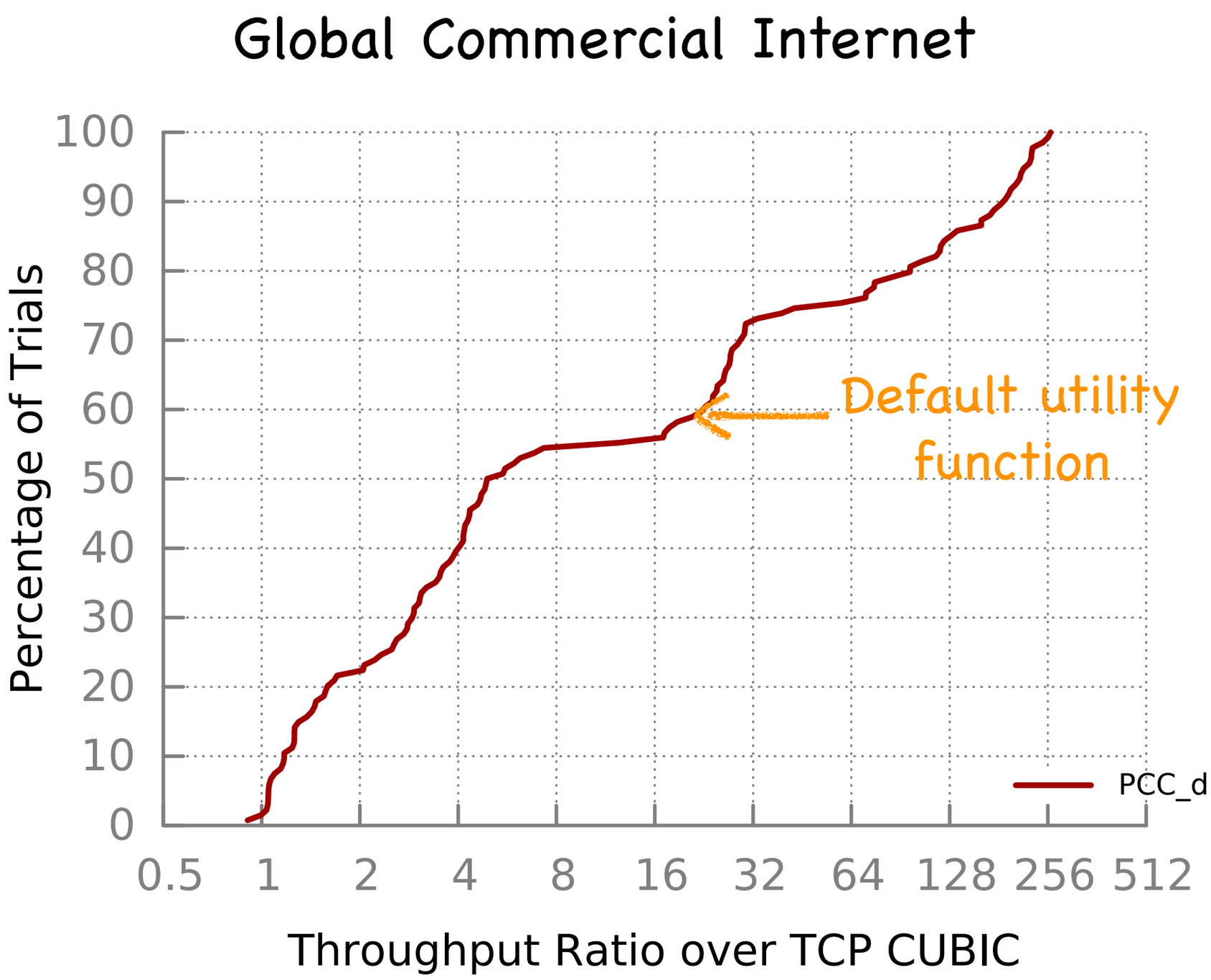
Consistent High Performance



Consistent High Performance



Consistent High Performance



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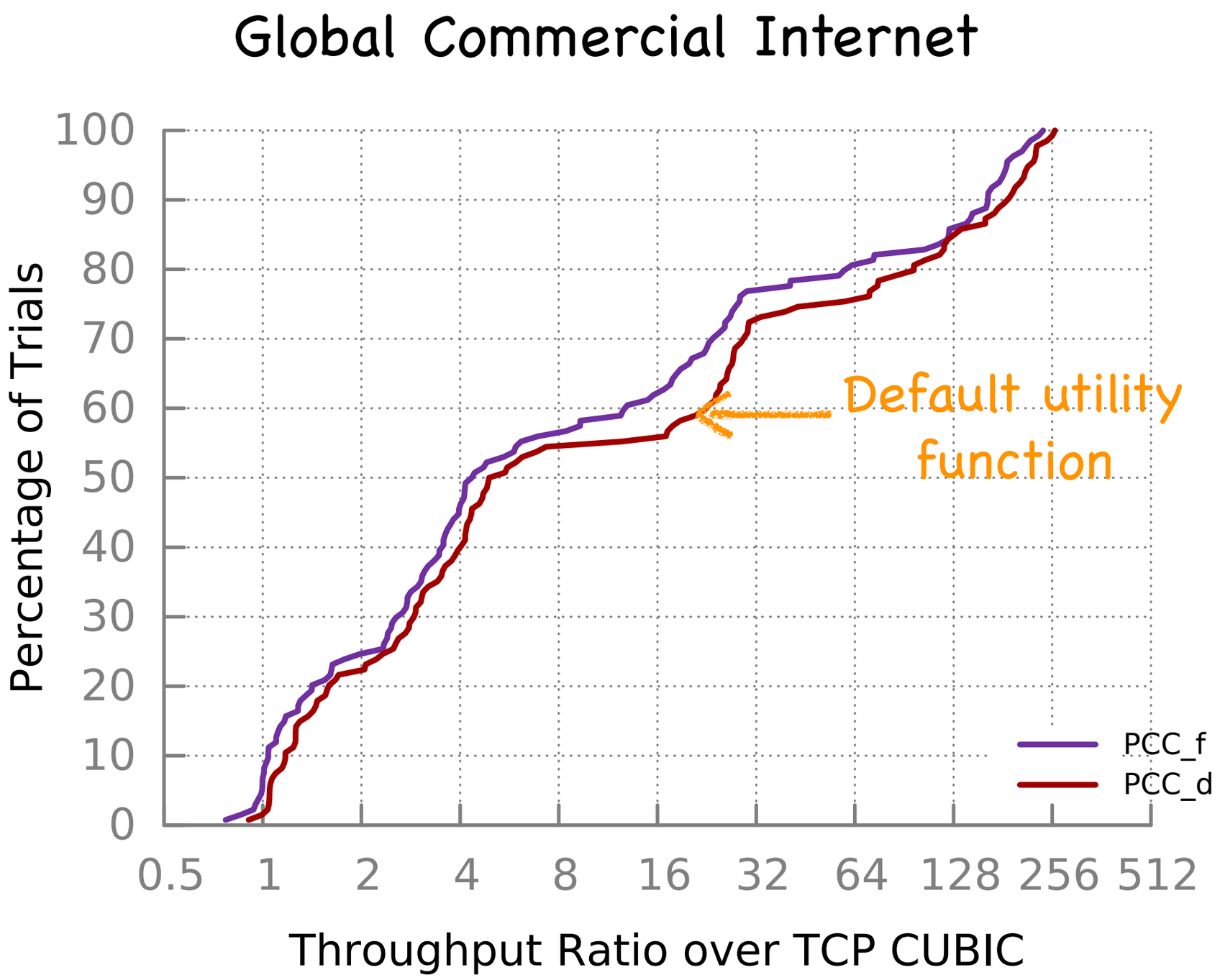

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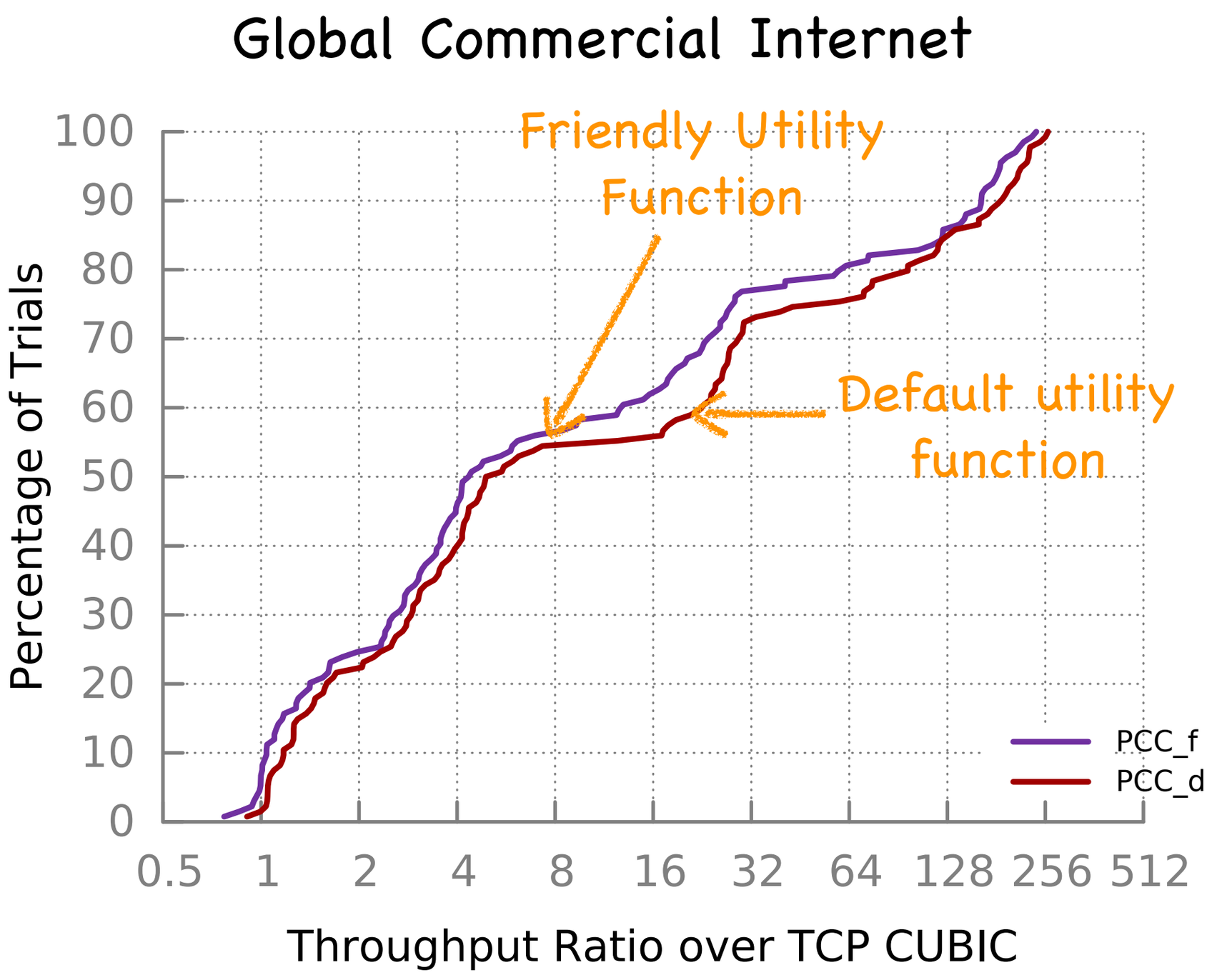

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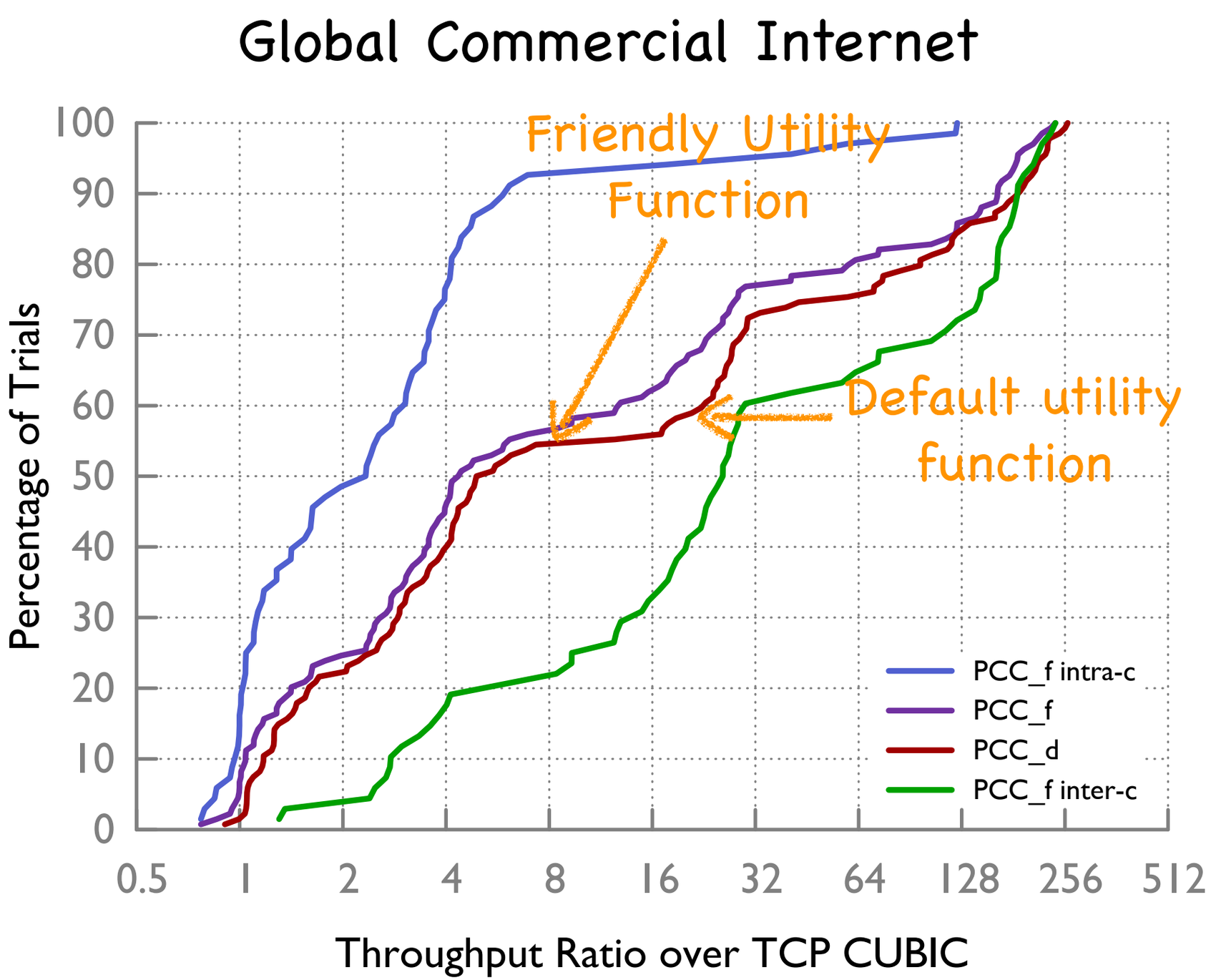
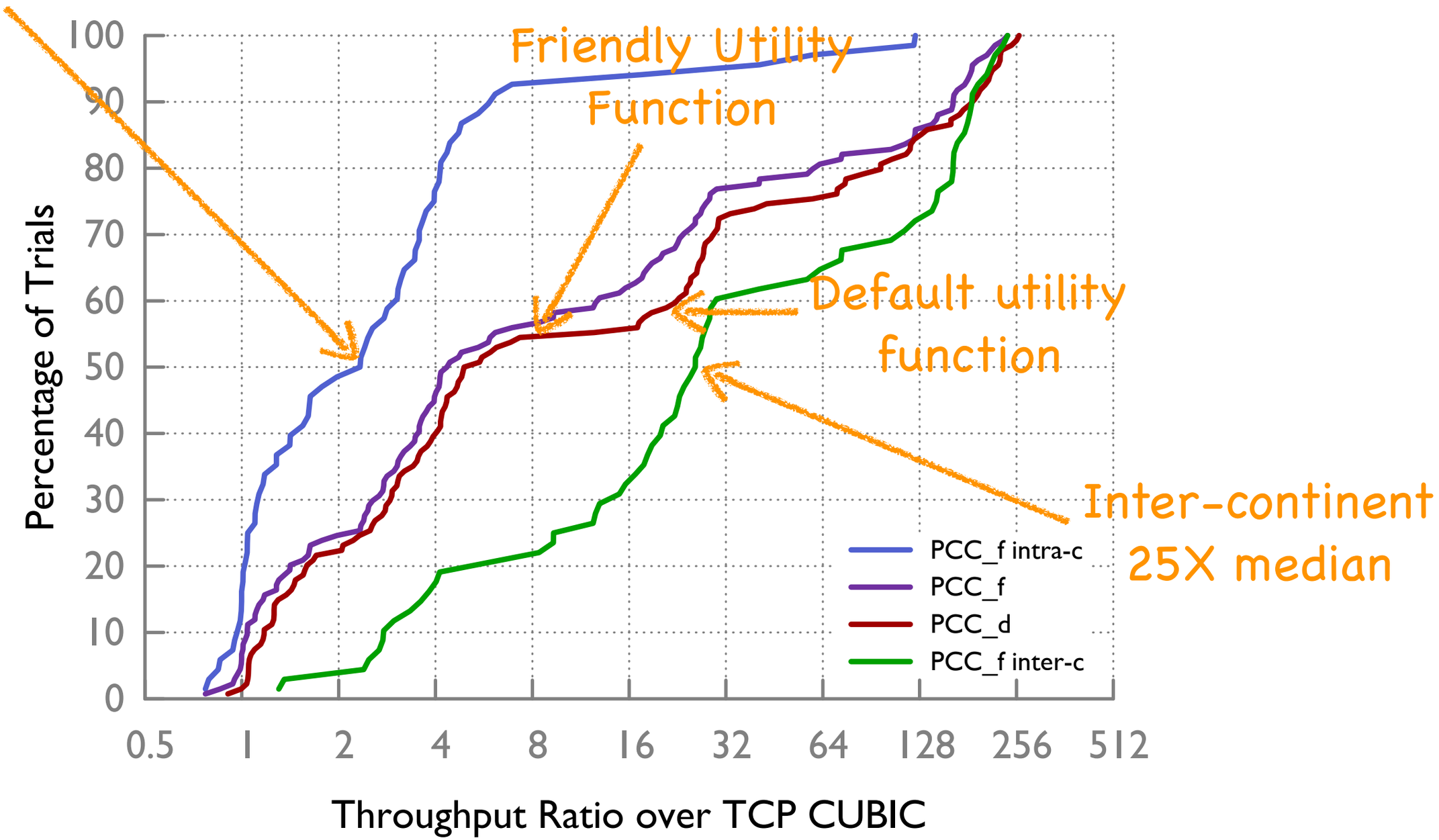


Consistent High Performance

Intra-continent
2.33X median



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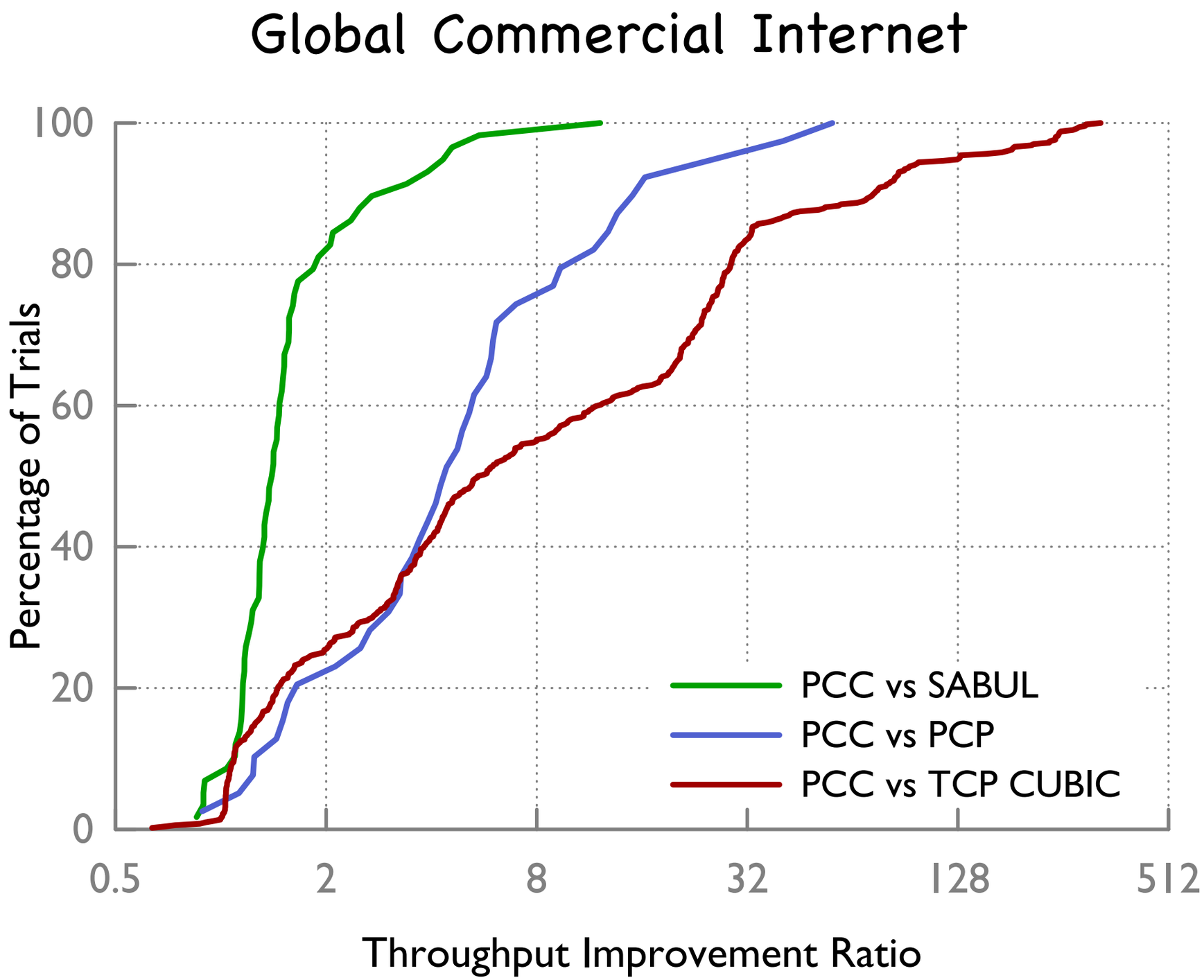
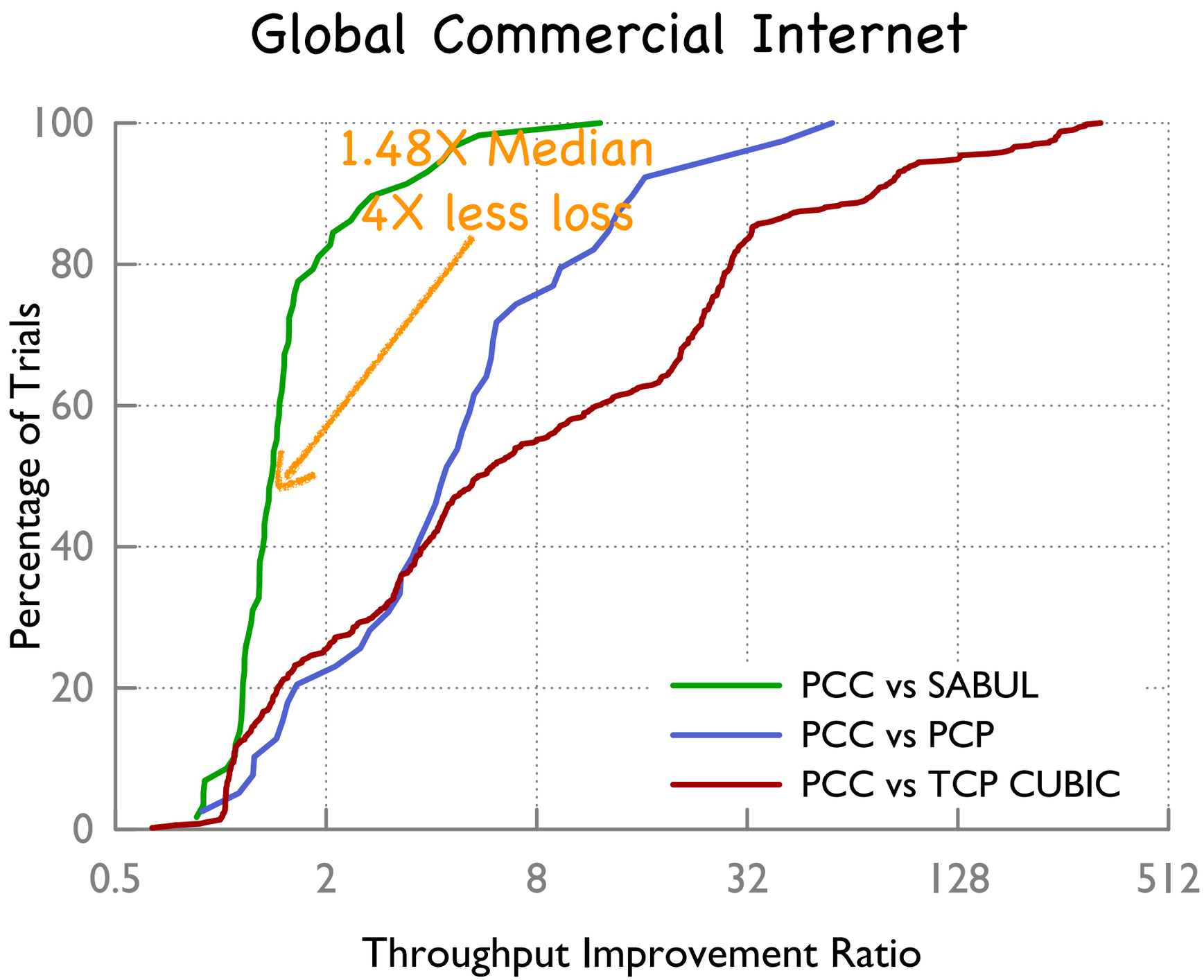
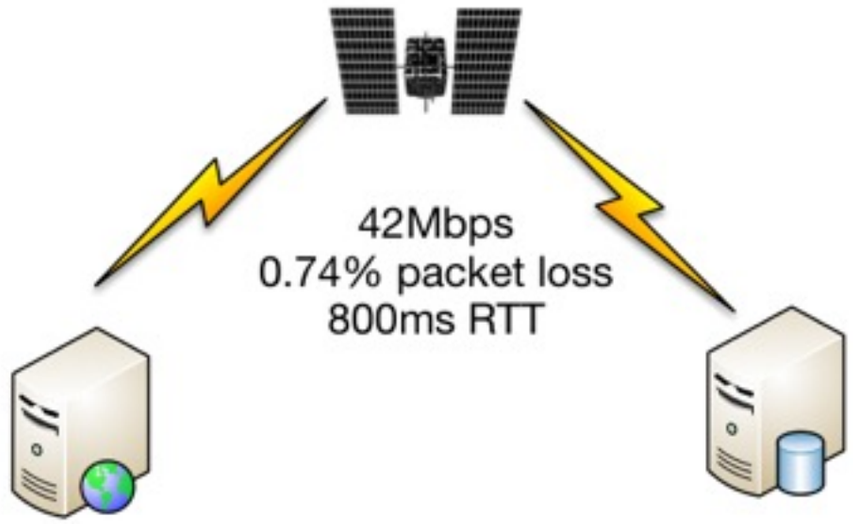


Consistent High Performance

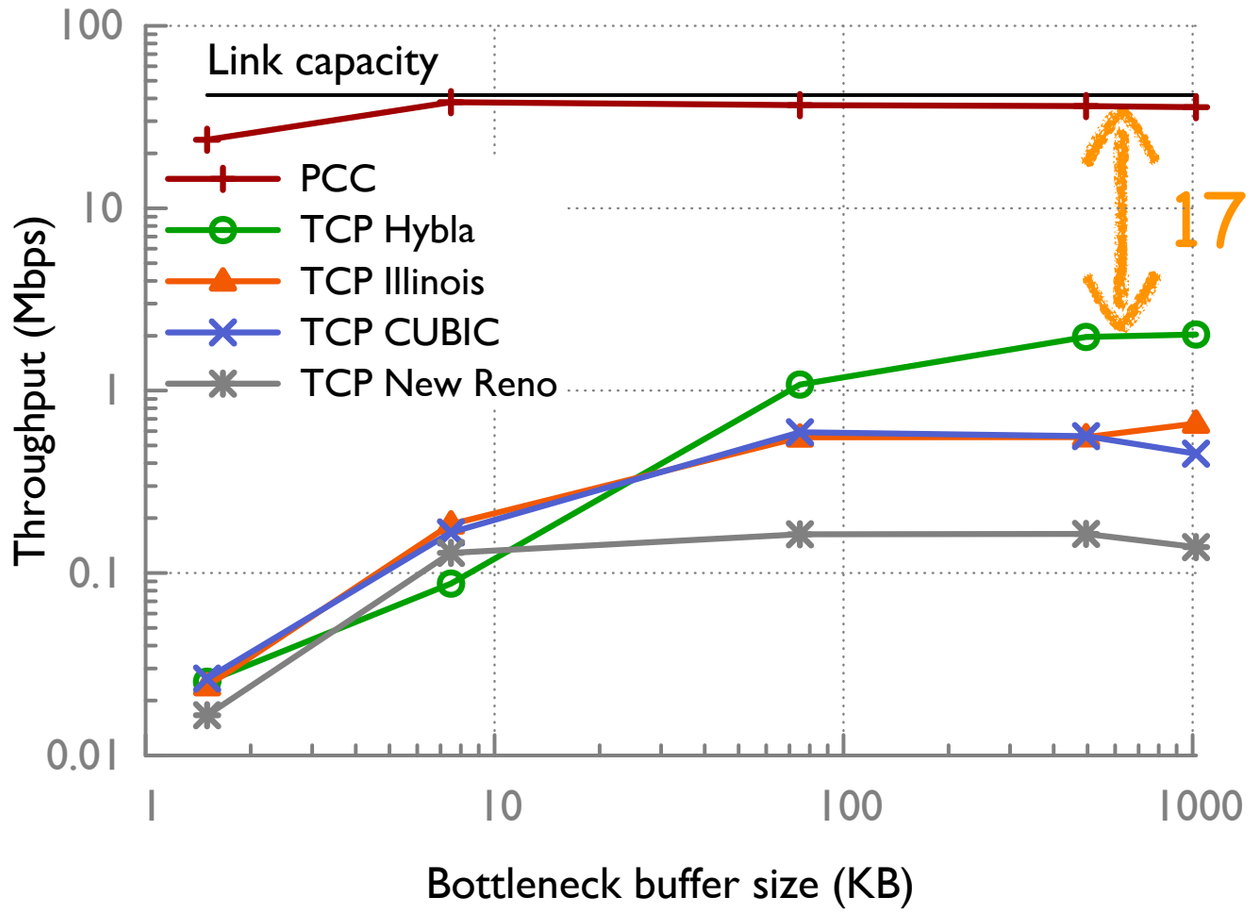


Consistent High Performance

Satellite Network



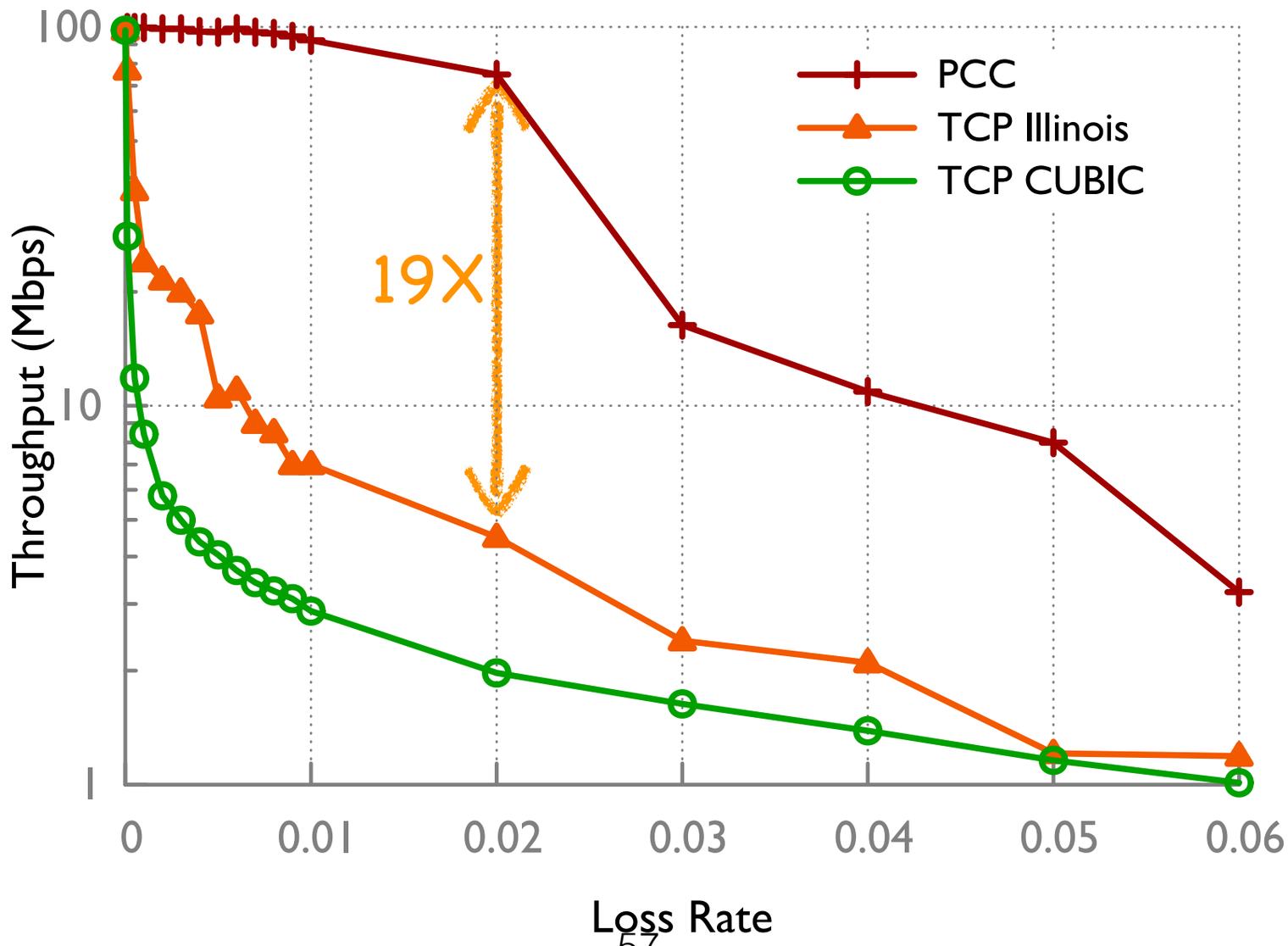
WINDS System



Consistent High Performance

Lossy Networks

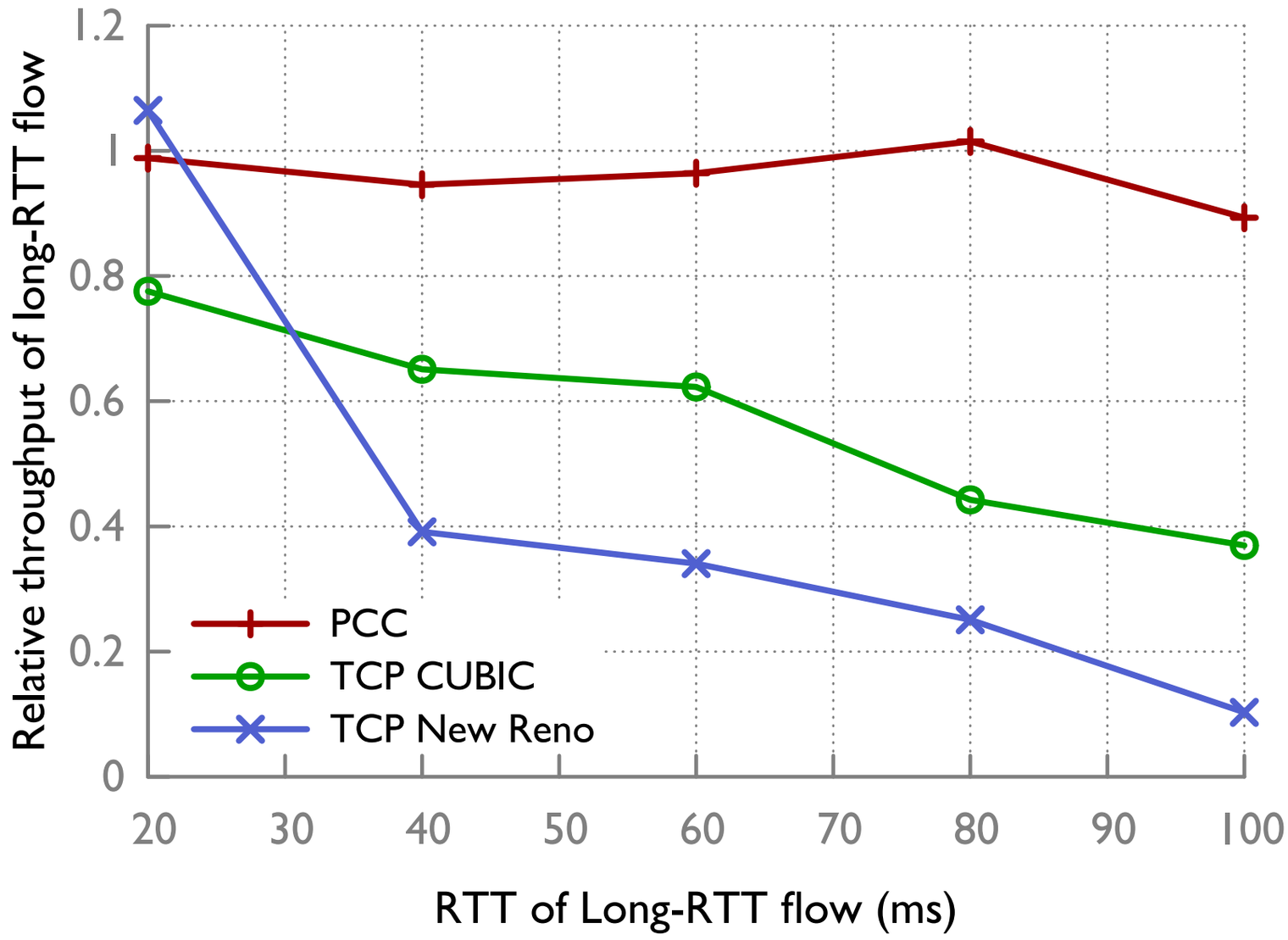
100Mbps, 30ms, varying loss rate
TCP's throughput collapse 10X with 0.5% loss



Consistent High Performance

Treat RTT Unfairness

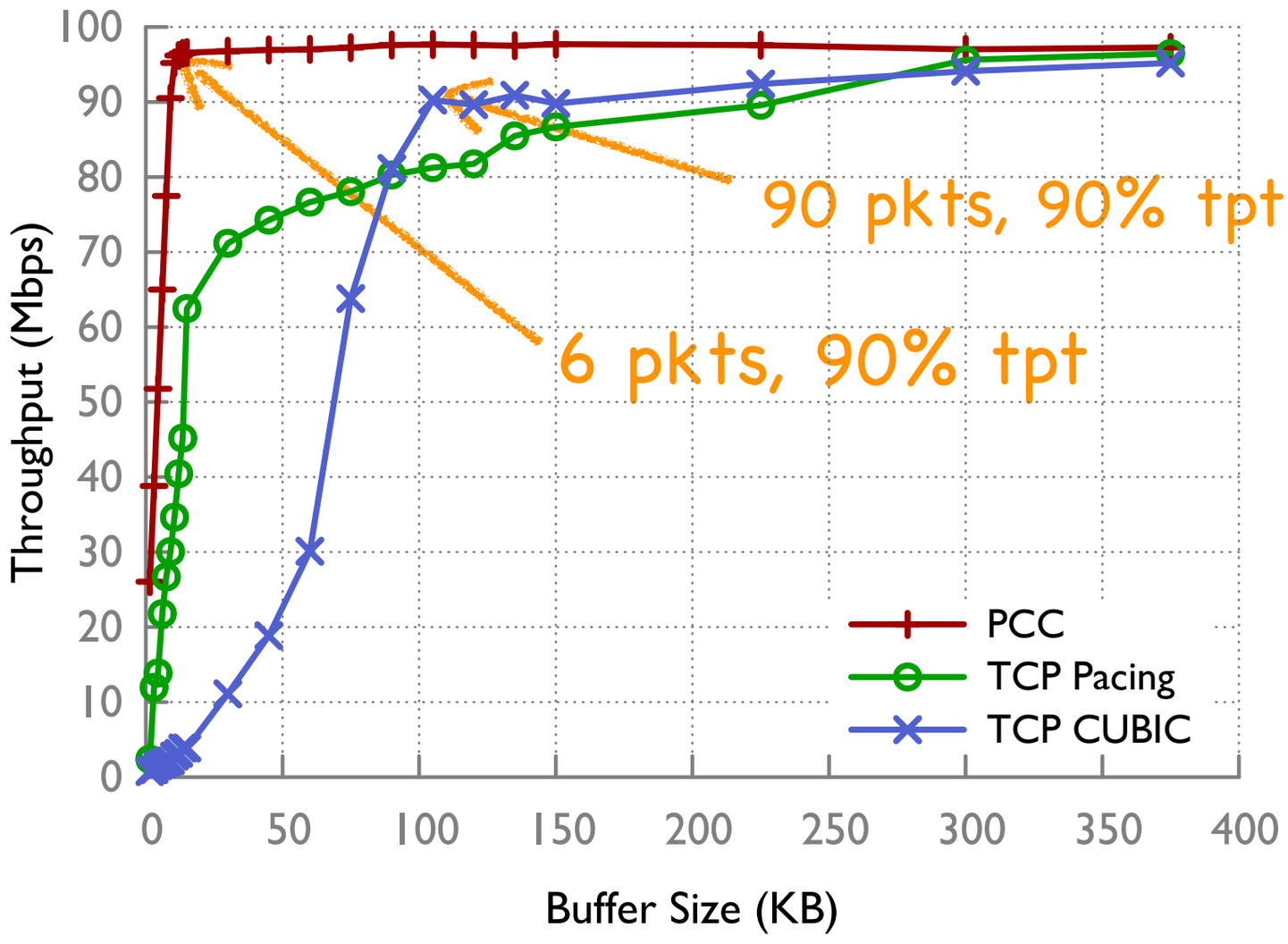
100Mbps, 10ms short RTT flow
Varying RTT of long RTT one



Consistent High Performance

A possible solution to the bufferbloat problem

100Mbps, 30ms Link



Consistent High Performance

Inter Datacenter and Dedicated High Speed Network

Transmission Pair	RTT	PCC	SABUL	CUBIC	Illinois
GPO → NYSERNet	12.1	818	563	129	326
GPO → Missouri	46.5	624	531	80.7	90.1
GPO → Illinois	35.4	766	664	84.5	102
NYSERNet → Missouri	47.4	816	662	108	109
Wisconsin → Illinois	9.01	801	700	547	562
GPO → Wisc.	38.0	783	487	79.3	120
NYSERNet → Wisc.	38.3	791	673	134	134
Missouri → Wisc.	20.9	807	698	259	262
NYSERNet → Illinois	36.1	808	674	141	141

Consistent High Performance

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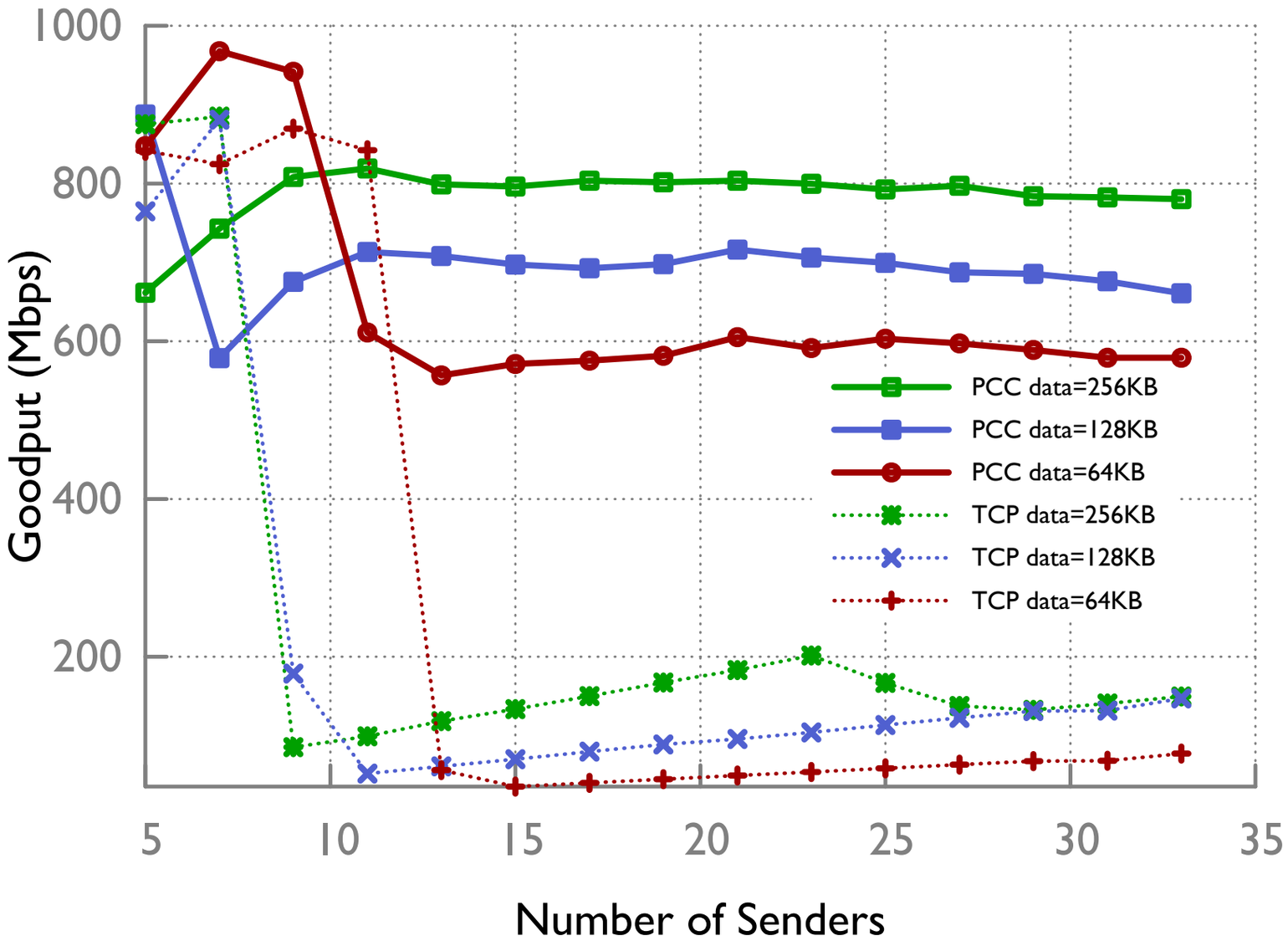
123%

Consistent High Performance

Mitigate Incast



Long list of things we have done but don't have time to talk about