TCP ex Machina: Computer-Generated Congestion Control

Keith Winstein

MIT Computer Science and Artificial Intelligence Laboratory

http://mit.edu/remy

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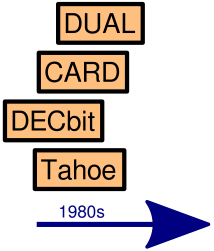
Joint work with Anirudh Sivaraman, Pratiksha Thaker, and Hari Balakrishnan

The march of congestion-control protocols



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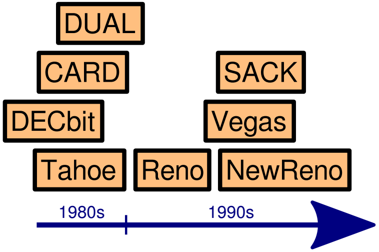

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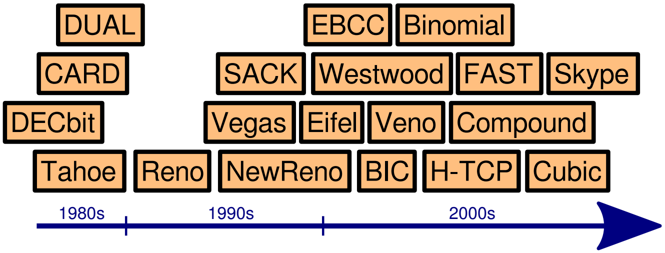

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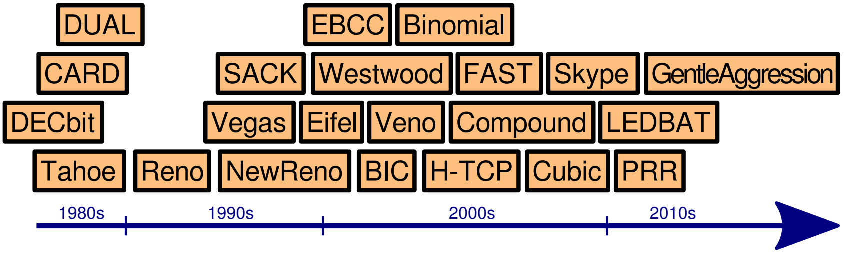

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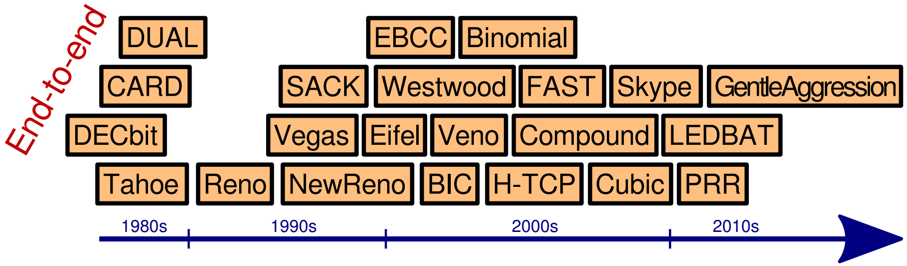

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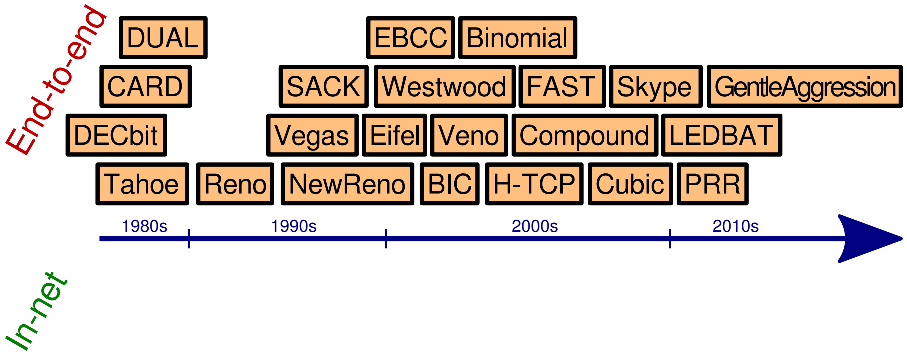

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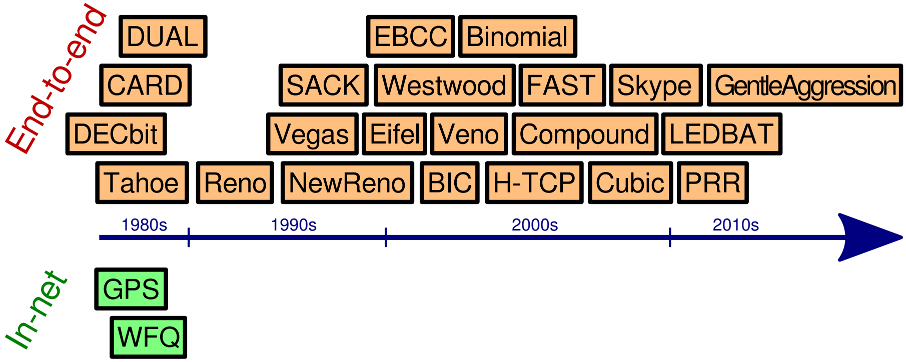

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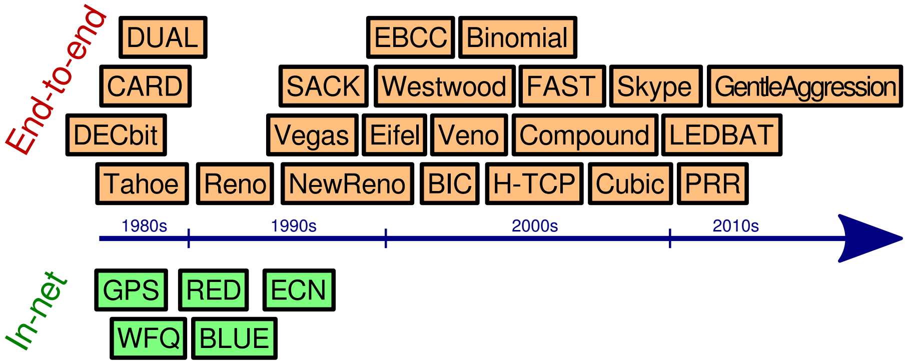

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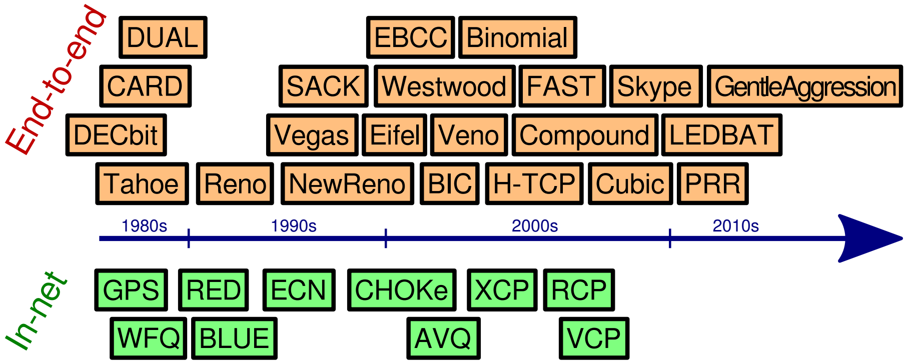

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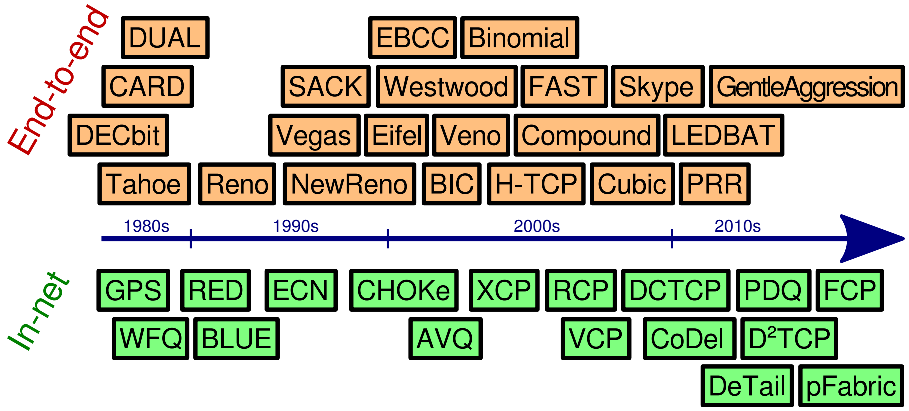

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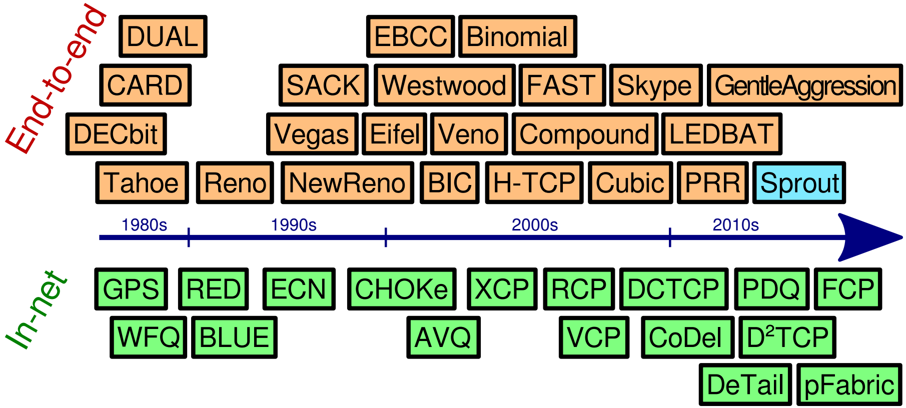

Rational choice of scheme is challenging

Cubic vs. Compound

- Different missions?
- Different assumptions about network?
- One scheme just plain better?

Networks constrained by a fuzzy idea of TCP's assumptions

- Mask stochastic loss
- Bufferbloat
- Mask out-of-order delivery
- No parallel/multipath routing

Advice for Internet Subnetwork Designers (RFC 3819) is 21,000 words!

Apps hack around TCP

- Open lots of flows
- Goose slow start
- Add pacing
- Give up and do it yourself

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Chrome (QUIC)
BitTorrent (μTP)
Mosh (SSP)
IBM Aspera (fasp)

Idea: computer-generated protocols

Transport layer should adapt to **whatever**:

- network does
- application wants

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Transport layer should adapt to **whatever**:

- network does (**model**)
- application wants (**mission**)

What we built

Remy: a program that generates congestion-control schemes offline

Input:

- Assumptions about network and workload (**model**)
- Application's objective (**mission**)

Output: CC algorithm for a TCP sender (RemyCC)

Time: hours to days

The basic question of congestion control

At this moment, do I:

- send a packet
- not send a packet?

Missions of congestion control

Maximize

- $\sum_i \log[\text{throughput}_i]$ (proportionally fair throughput)

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- $\min_i \text{throughput}_i$ (max-min throughput)

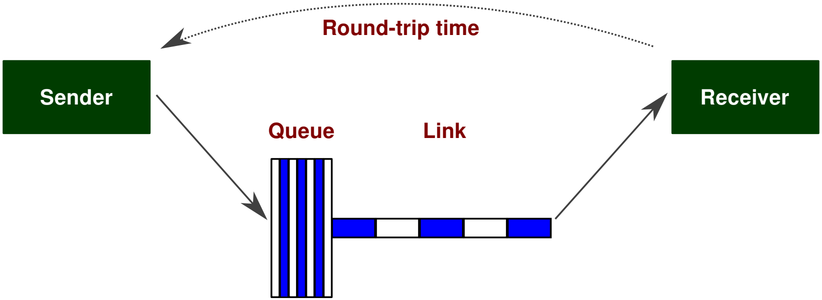
Minimize

- average flow completion time
- page load time
- tail completion time

Encoding the designer's prior assumptions

- **Model** of network uncertainty
  - Link speed distribution
  - Delay distribution
  - Topology distribution
- **Model** of workload
  - Web browsing
  - MapReduce
  - videoconferencing
  - streaming video (YouTube/Netflix)

Dumbbell network



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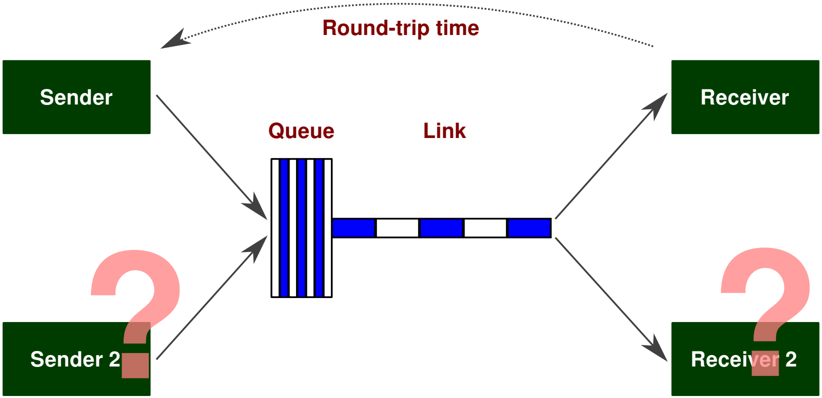

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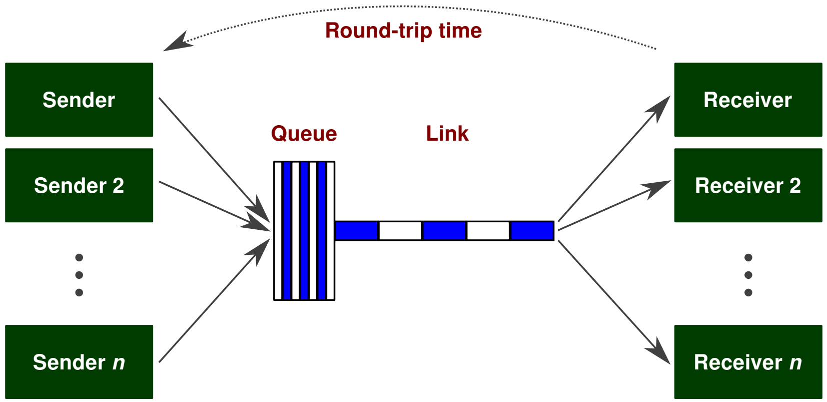

Superrational congestion control

At this moment,* do I:

- send a packet
- not send a packet?

Superrational congestion control

At this moment,* do I:

- send a packet
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* Assuming every node is running the same algorithm.

Internet congestion control as a Dec-POMDP

I: independent endpoint computers

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S:	packets in net + whether each computer has data to send now

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Internet congestion control as a Dec-POMDP

- I: independent endpoint computers
- S: packets in net + whether each computer has data to send now
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- T: simple networks are deterministic, with parameters drawn from a distribution. Flows arrive per a random process.

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- O: deterministic

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O:	deterministic

Complexity in general: $\mathcal{O}(2^{2^n})$ (NEXP-hard)

Remy: tractable search for best policy

- Best decision given all history: not tractable
- Instead, remember only **a summary of history**

A RemyCC tracks four congestion signals

r_ewma_{α}:	**short-term** moving average of interval between acks *"How fast are packets arriving (now)?"*
r_ewma_{β}:	**long-term** moving average of same *"How fast are packets arriving (smoothed)?"*
s_ewma:	moving average of interval between acked timestamps *"How fast was I sending?"*
rtt_ratio:	ratio of last RTT to smallest RTT so far *"How long is the queue?"*

Why these congestion signals?

- Removing any of the four hurts
  - r_ewma_α hurts the most
- More signals increase search time
- Other signals might help on other networks

A RemyCC maps each state to an action

$$\text{RemyCC}(r\_ewma_{\alpha\beta}, s\_ewma, rtt\_ratio) \rightarrow \langle m, b, \tau \rangle$$

m	Multiple to congestion window
b	Increment to congestion window
τ	Minimum interval between two outgoing packets

Runtime for a RemyCC

On ack:

- $\langle m, b, \tau \rangle \leftarrow \textsc{RemyCC}(r\_ewma_{\alpha\beta}, s\_ewma, rtt\_ratio)$
- $\texttt{cwnd} \leftarrow m \cdot \texttt{cwnd} + b$

Send packet if:

- $\texttt{cwnd} > \texttt{FlightSize}$, and
- last packet sent $> \tau$ ago

Remy's job

Find piecewise-continuous $\textsc{RemyCC}()$ that optimizes expected value of objective function

Remy example: 2D state space

On ack:

$$\langle m, b, \tau \rangle \leftarrow \textsc{RemyCC}(\mathit{s\_ewma}, \mathit{r\_ewma}_\alpha, \quad \mathit{r\_ewma}_\beta, \mathit{rtt\_ratio} \quad)$$

Remy example: 2D state space

On ack:

$\langle m, b, \tau \rangle \leftarrow \textsc{RemyCC}(s\_ewma, r\_ewma_{\alpha},$ [redacted] $)$

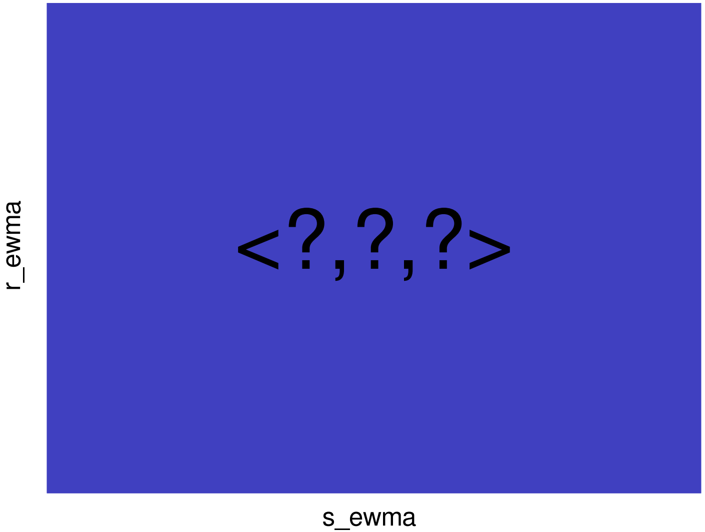
Remy example: **model**

Quantity	**Distribution**	**Units**
Link speed	Uniform(10, 20)	Mbps
RTT	Uniform(100, 200)	ms
n	Uniform(1, 16)	
"On" process	$\exp[\mu = 5]$	seconds
"Off" process	same	

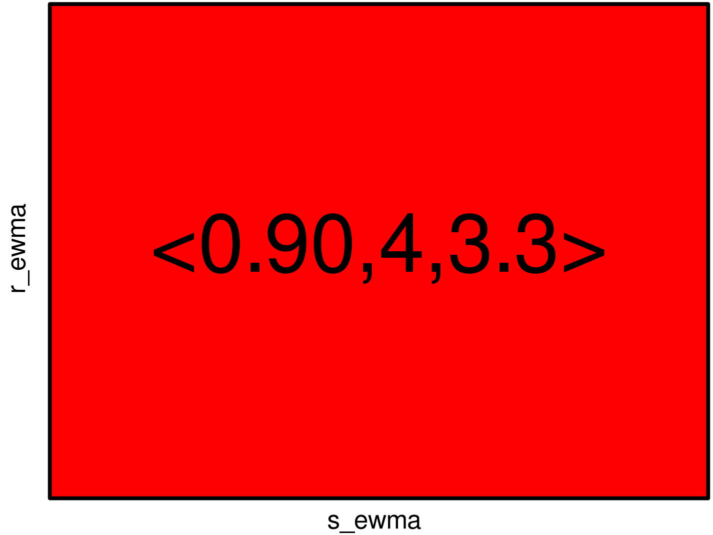
Remy example: **mission**

$$\sum_i \log \left[\frac{\text{throughput}_i}{\text{delay}_i} \right]$$

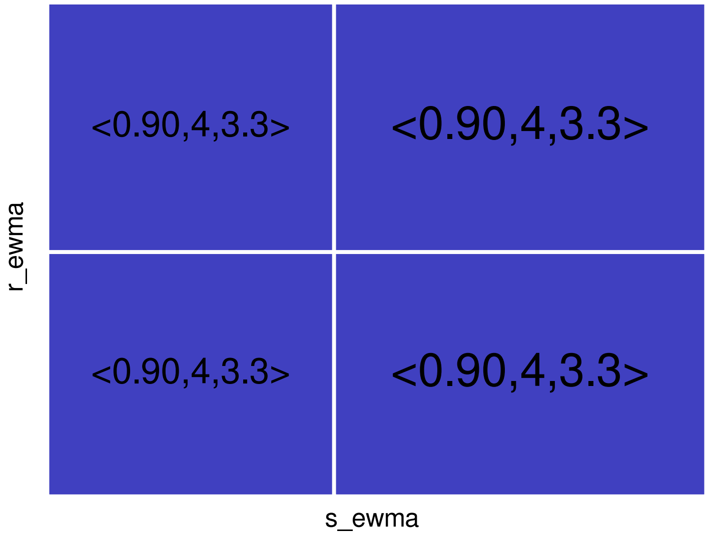
One action for all states. Find the best value.



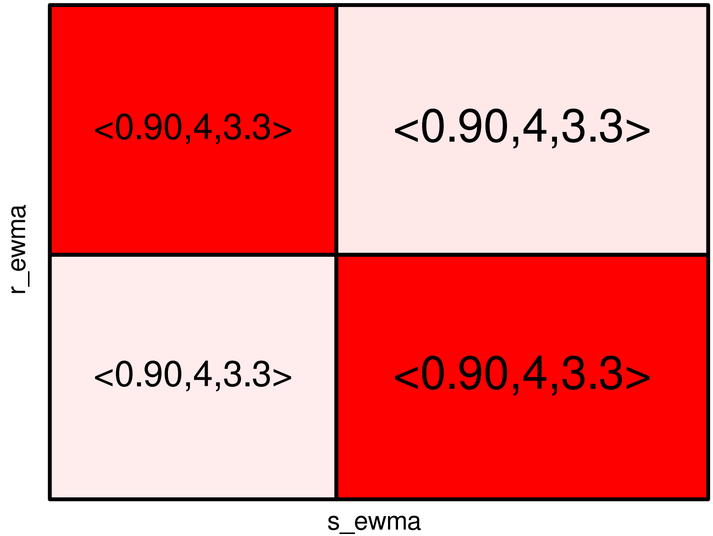
The best (single) action. Now split it on median.



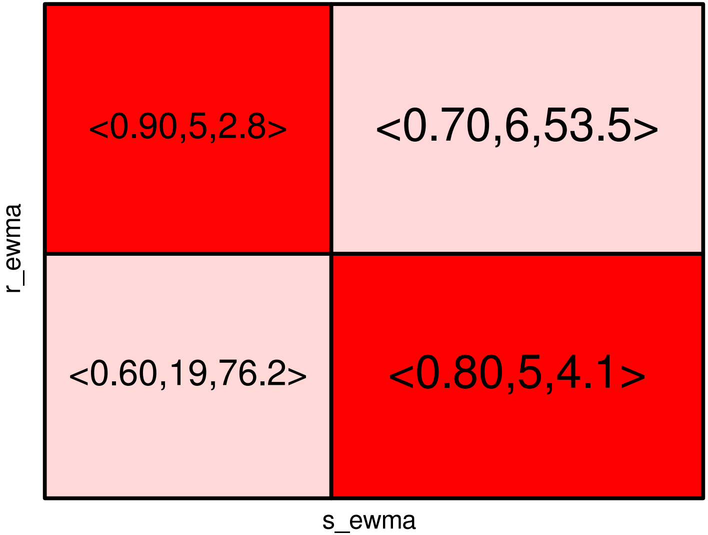
Simulate



Optimize each of the new actions



Now split the most-used rule



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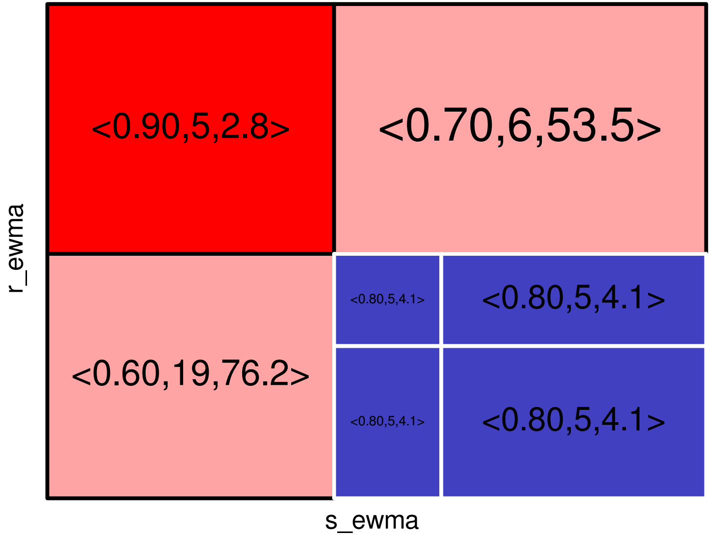

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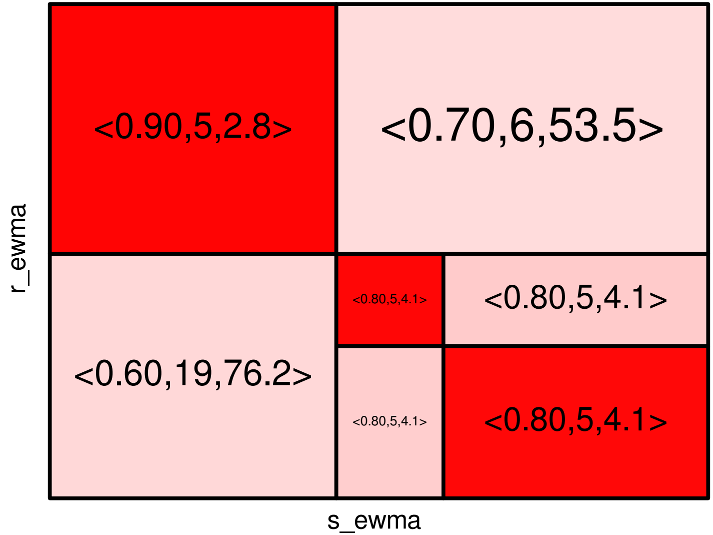
r_ewma
s_ewma

Optimize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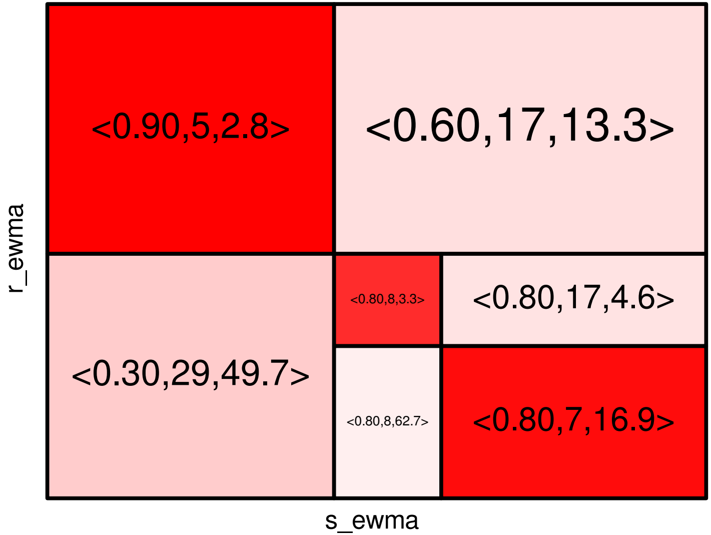

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s_ewma

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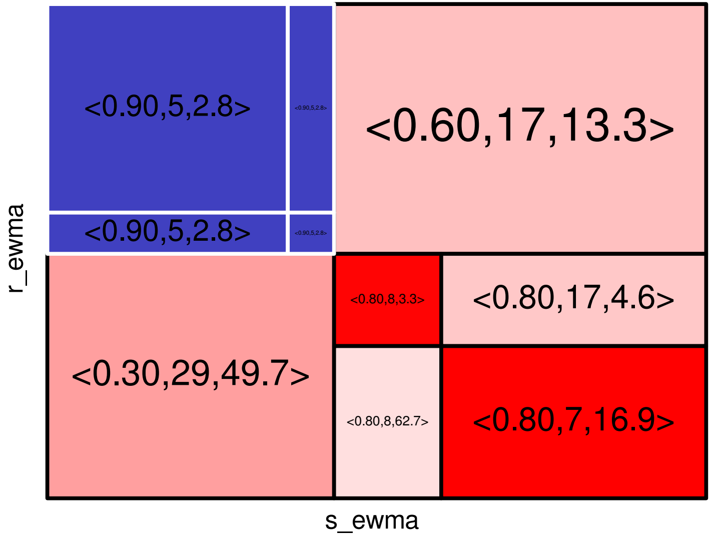
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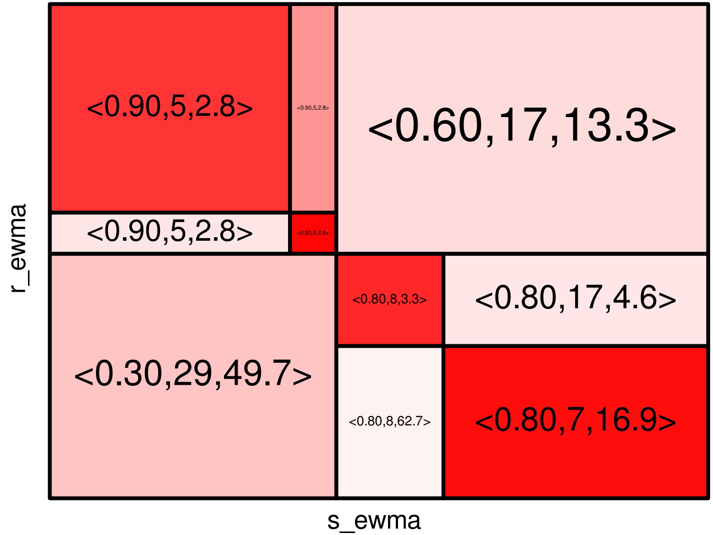

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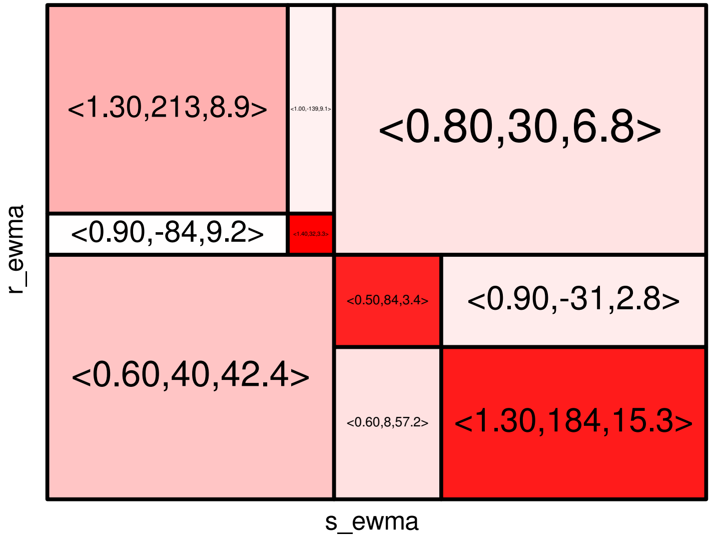

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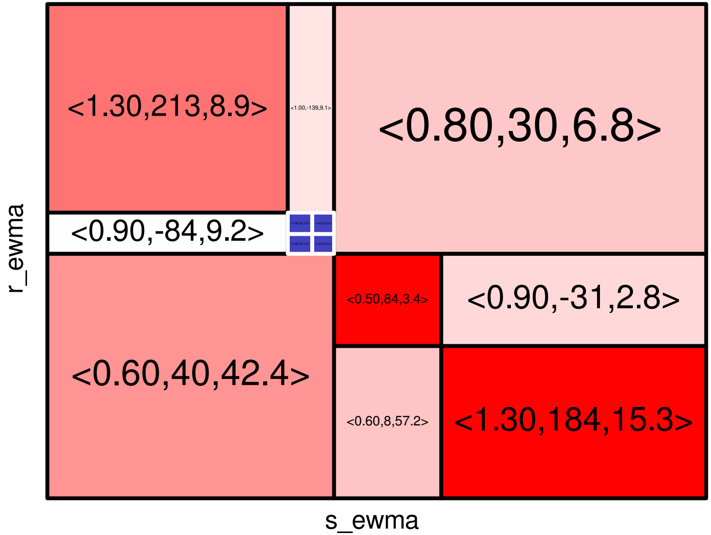

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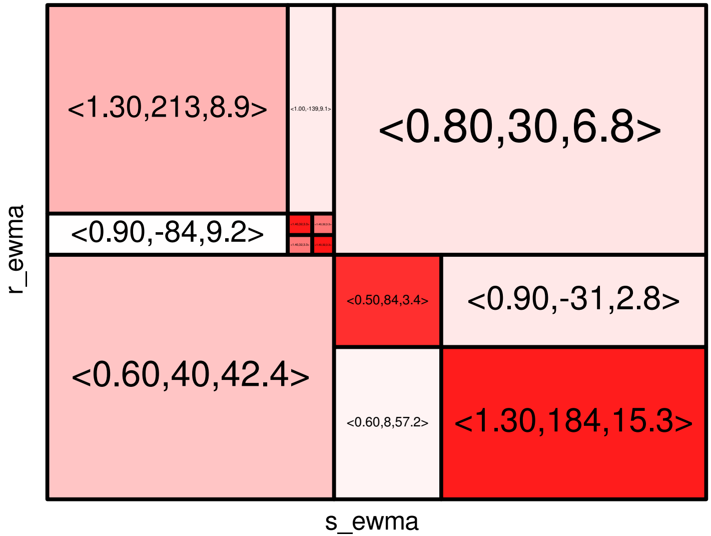

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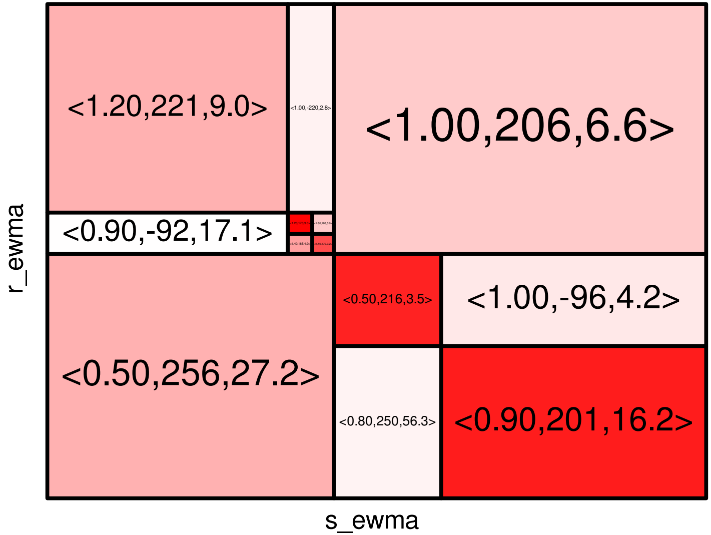

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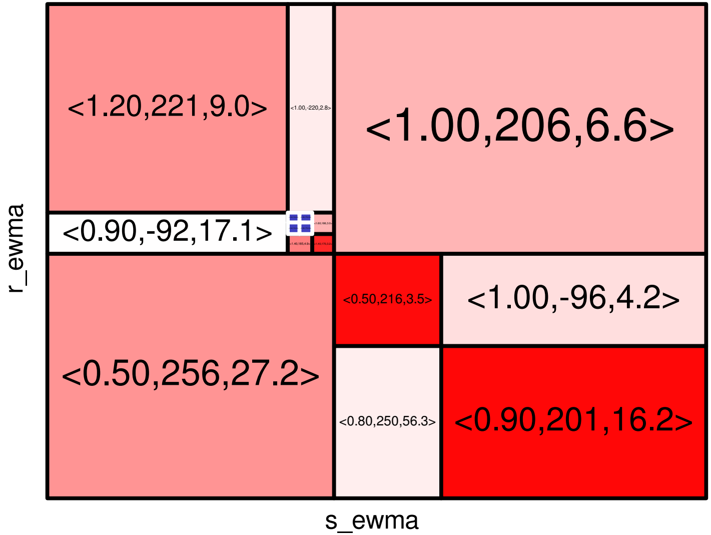

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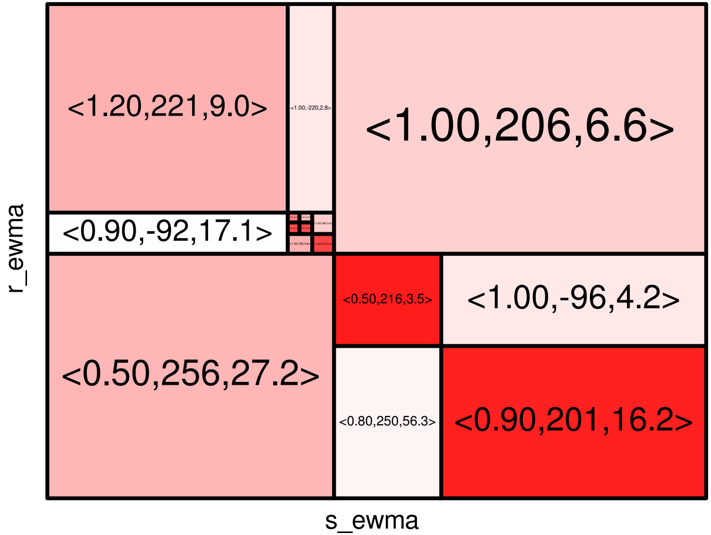

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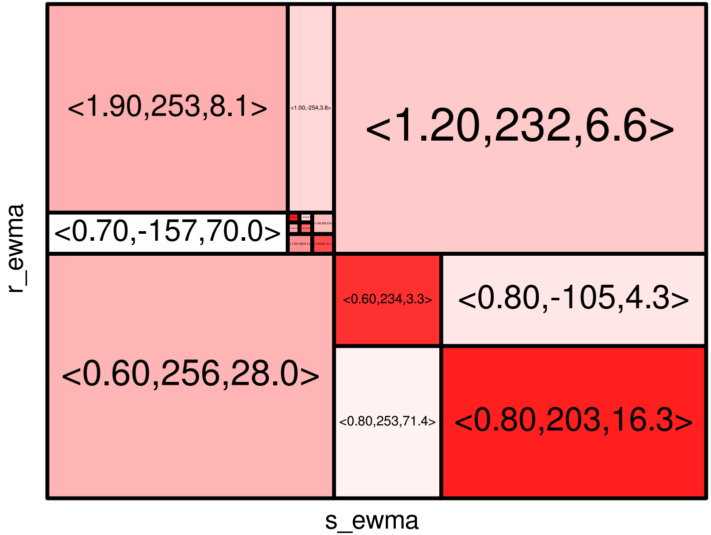

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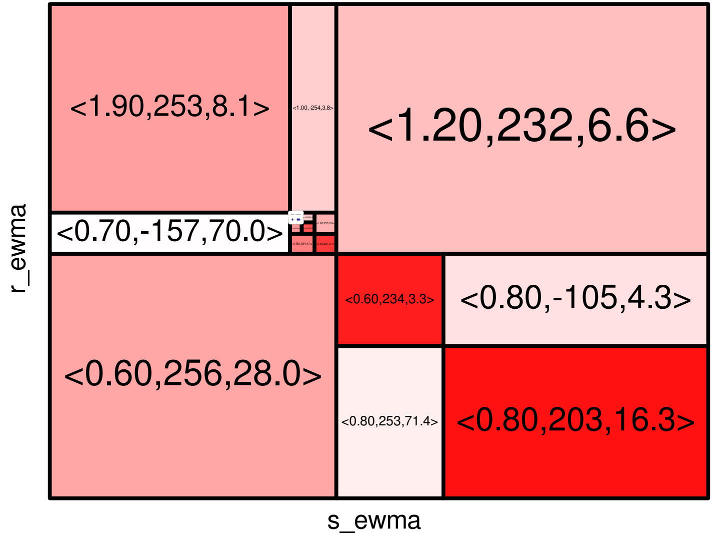

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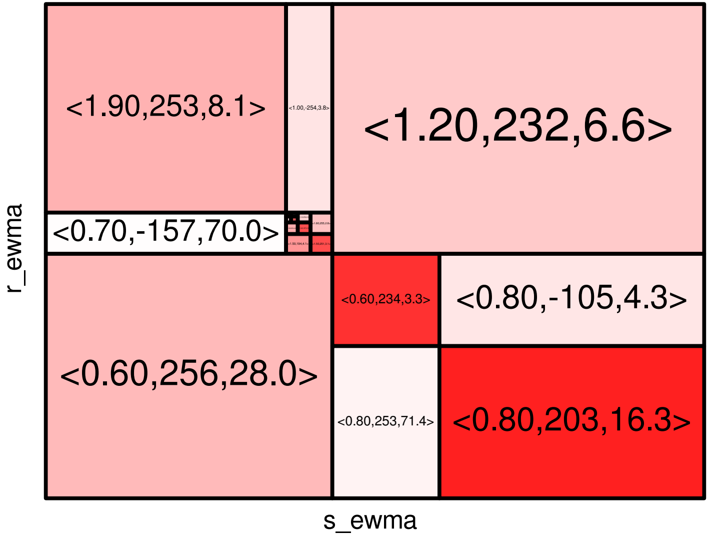

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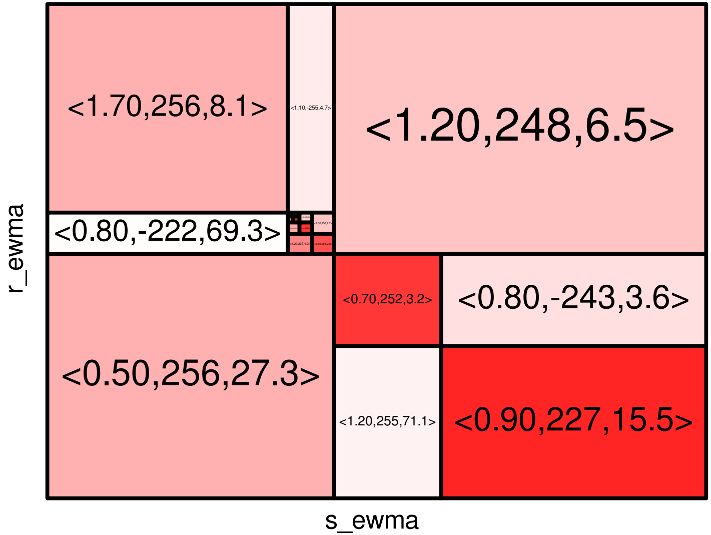
s_ewma

Split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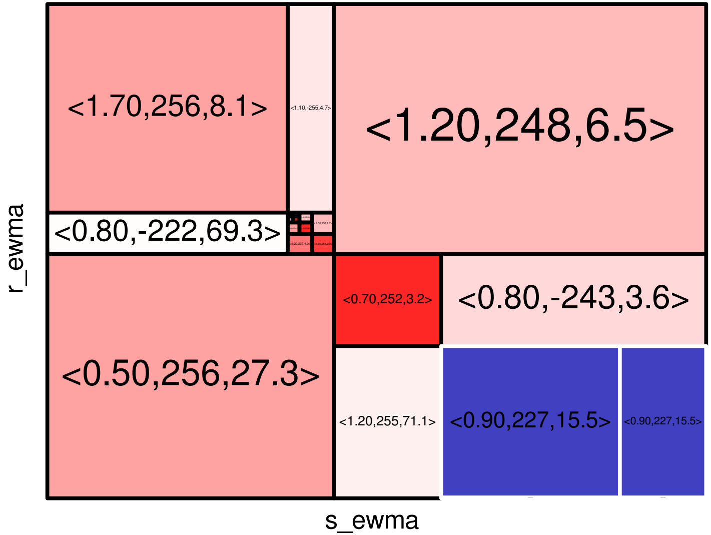
Simulate



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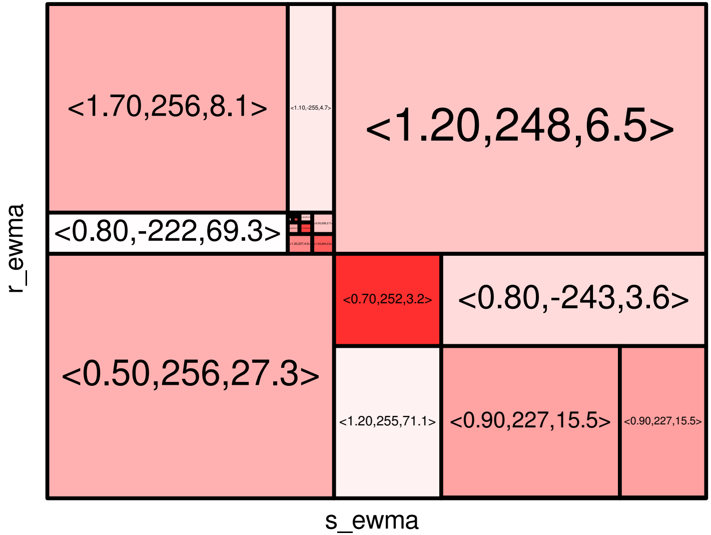
r_ewma
s_ewma

Optimize



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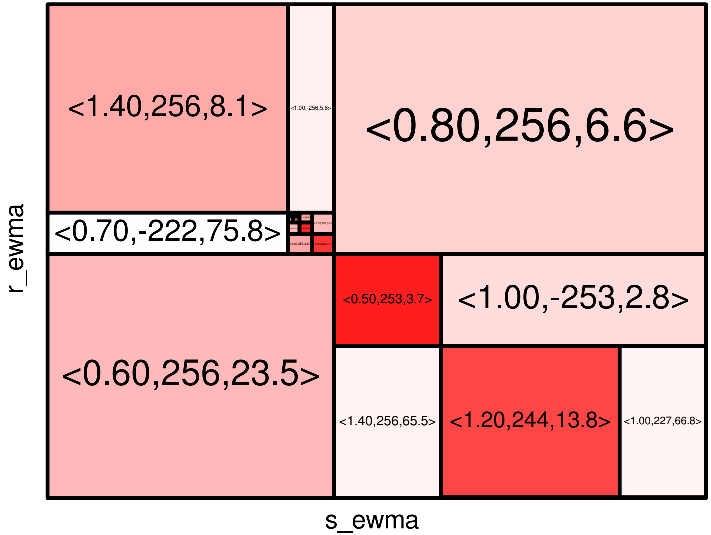
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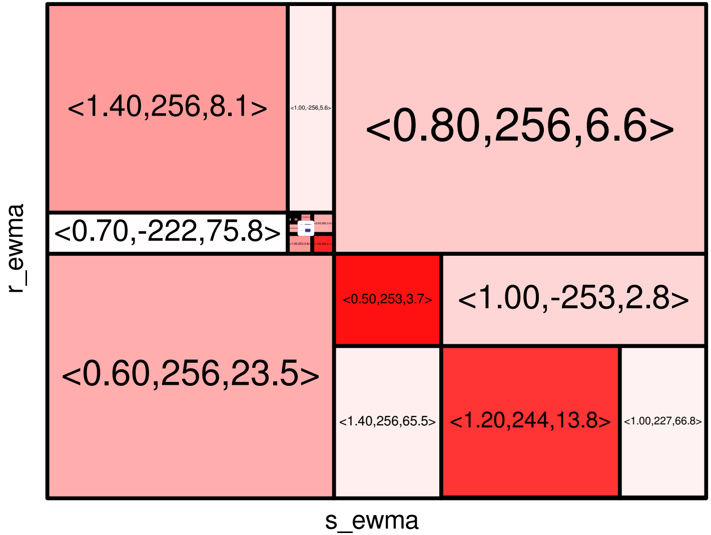
Simulate



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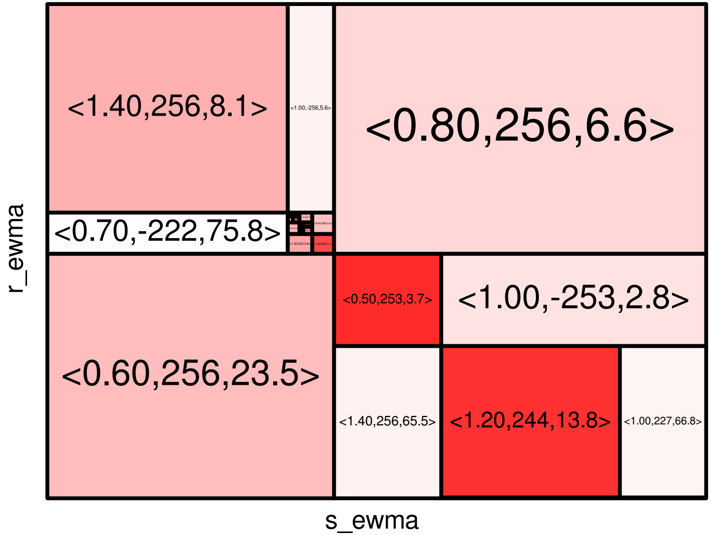
Optimize



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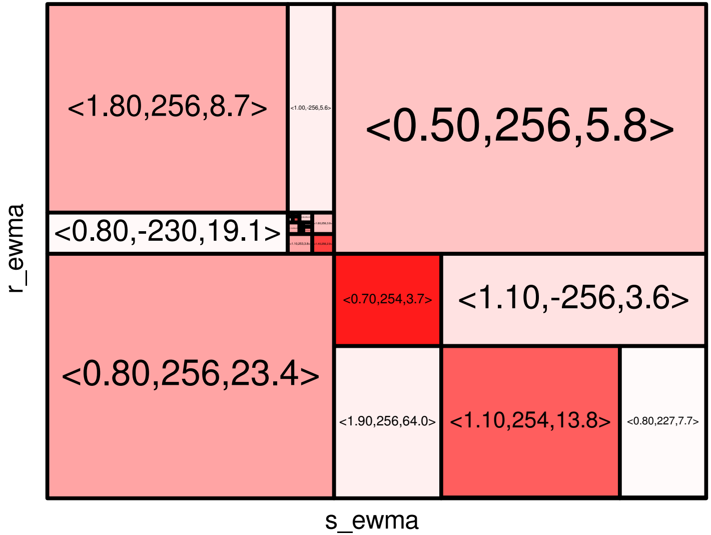

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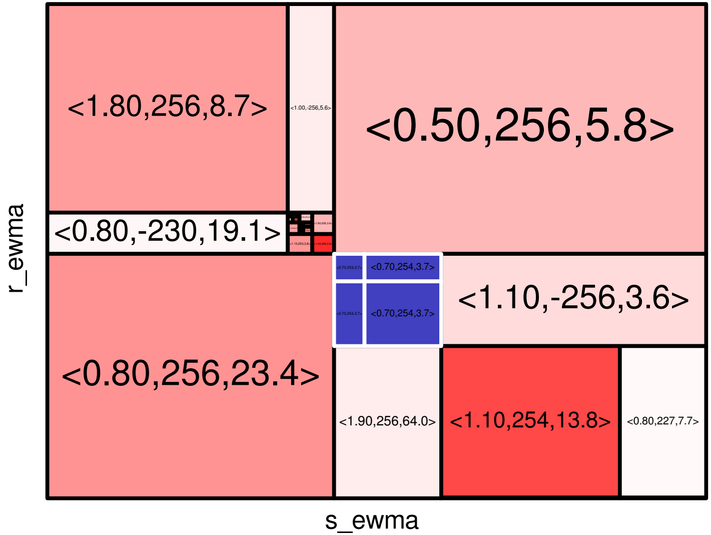
Simulate



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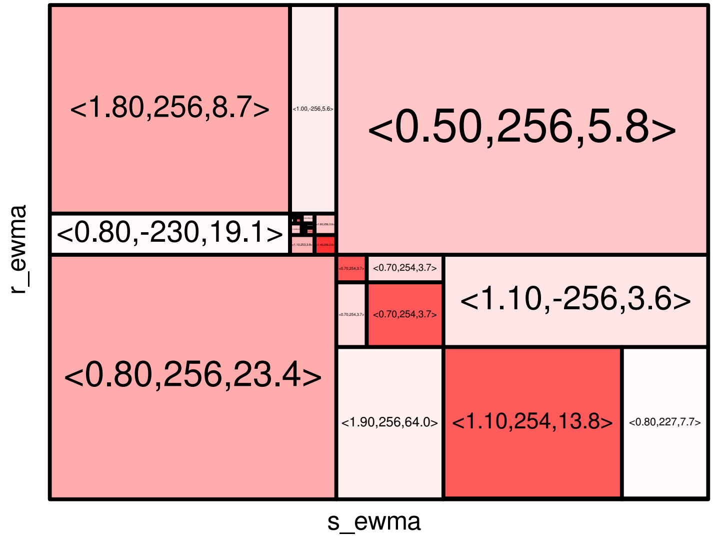
Optimize



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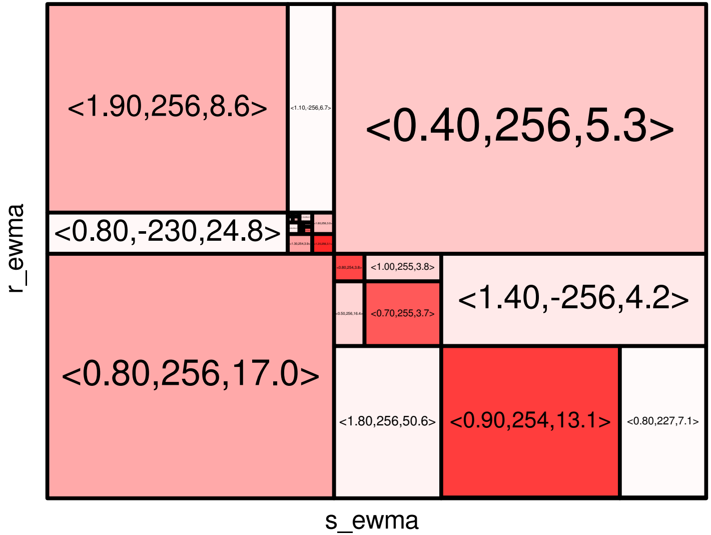
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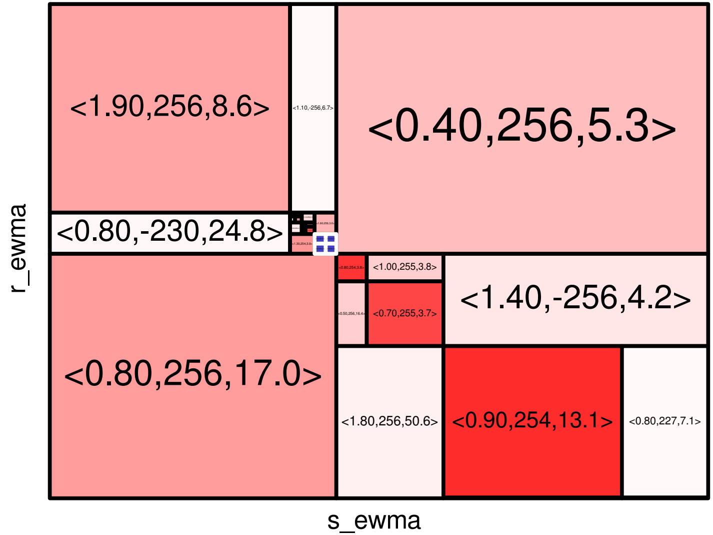
Simulate



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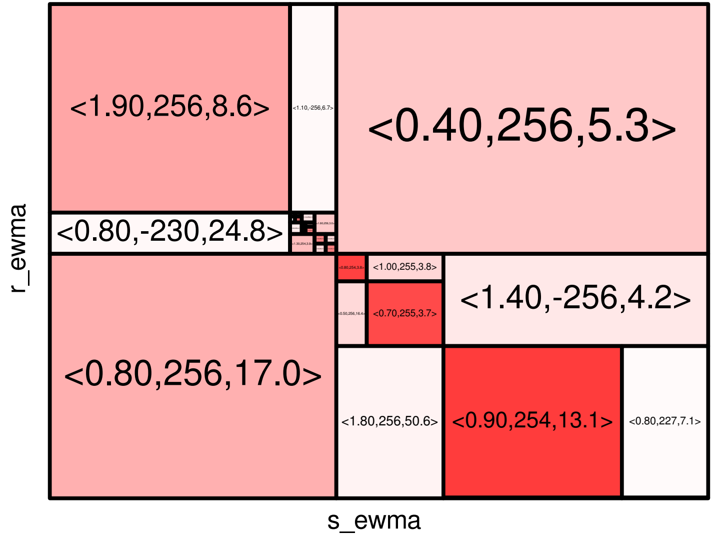
r_ewma
s_ewma

Optimize



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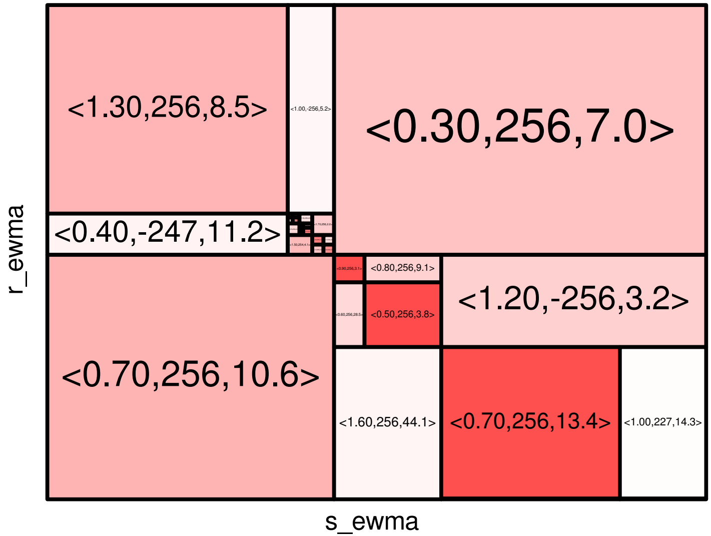

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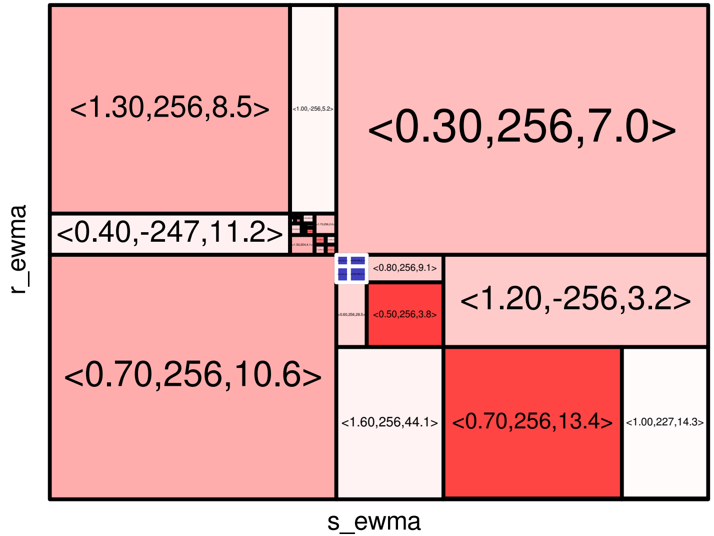
Simulate



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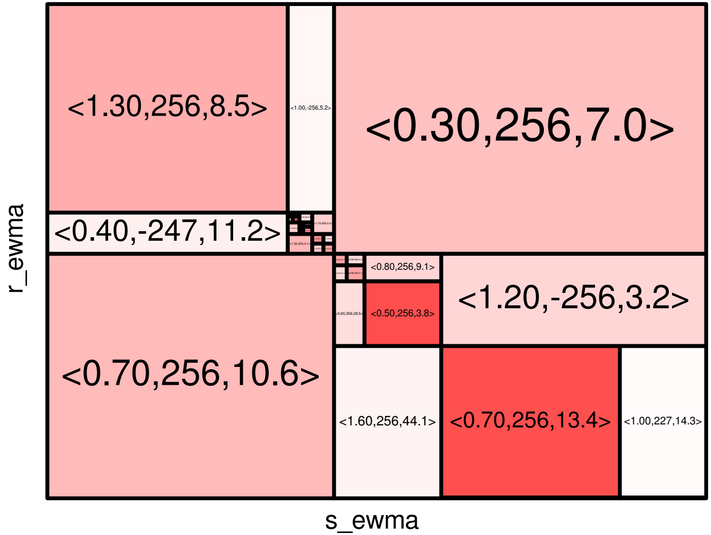
Optimize



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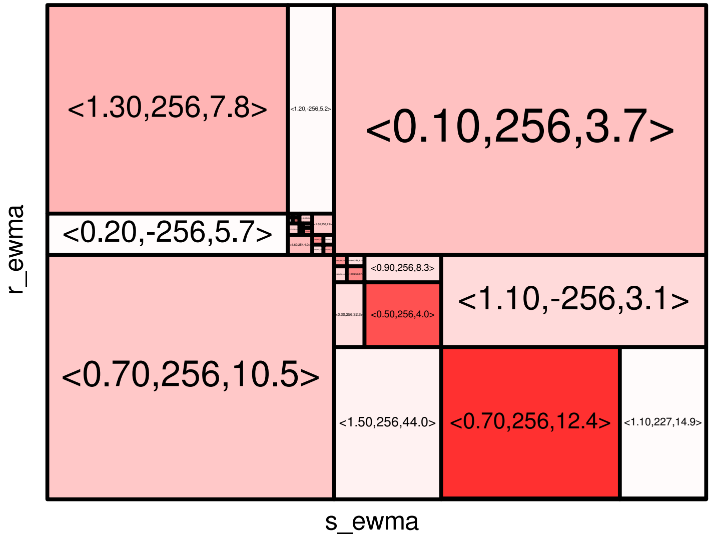
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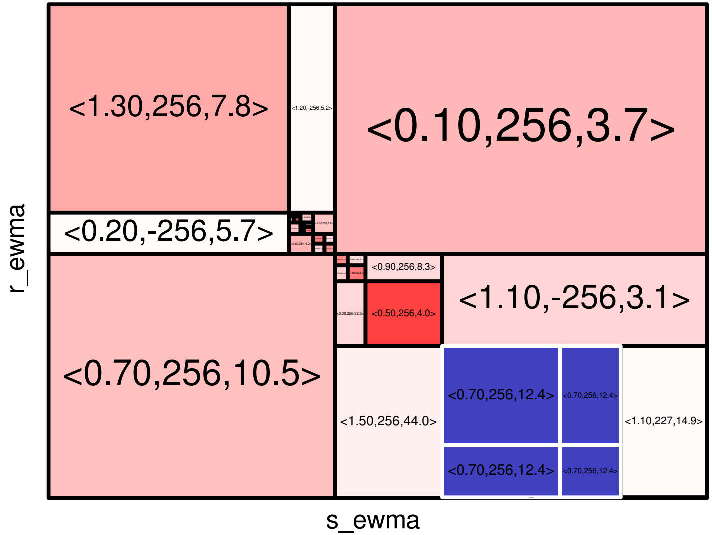
Simulate



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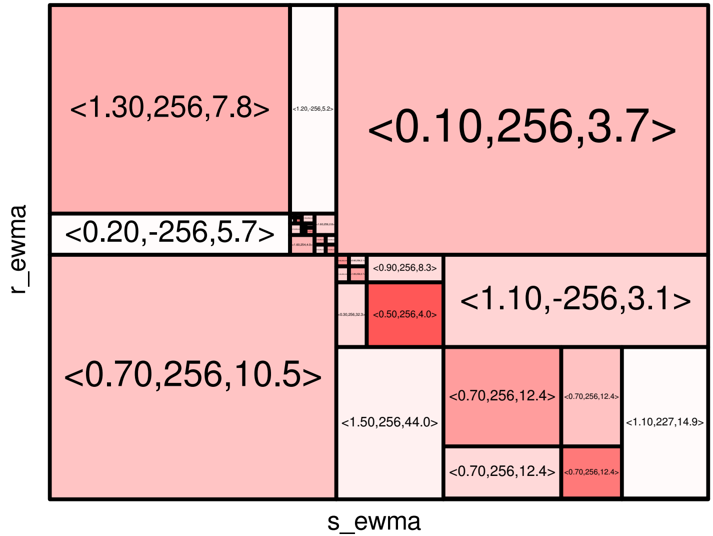
Optimize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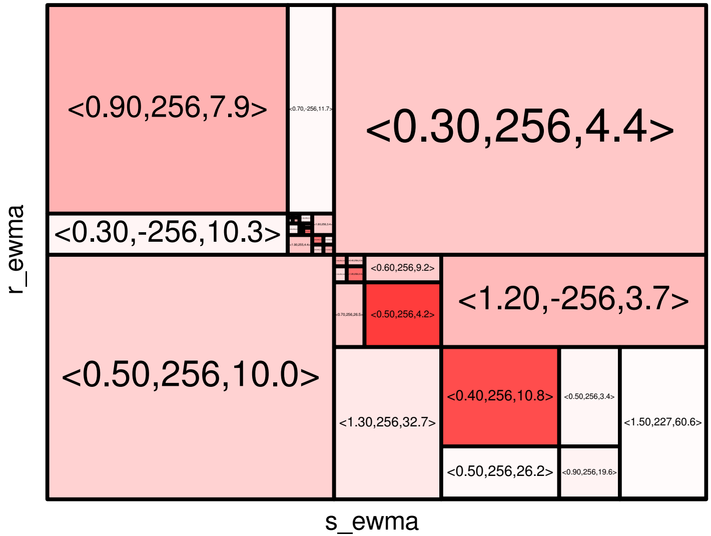

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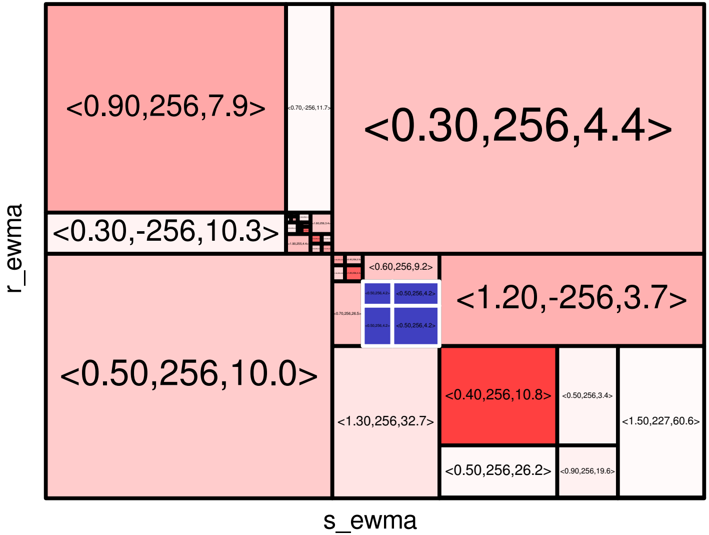
s_ewma

Simulate



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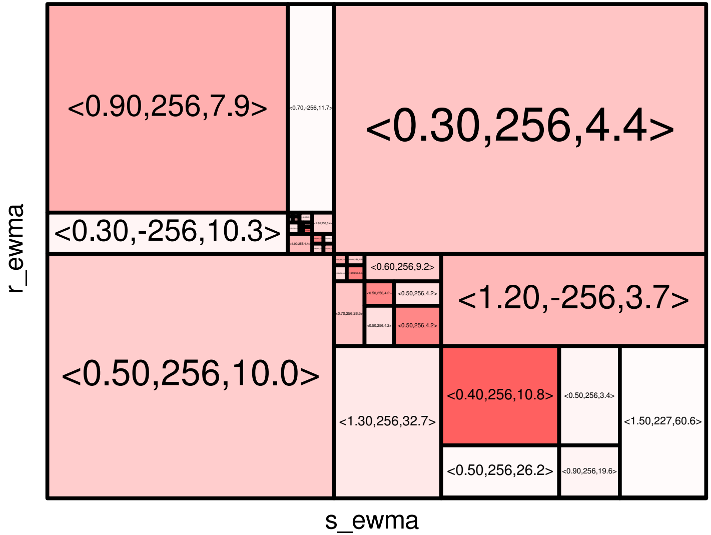
Optimize



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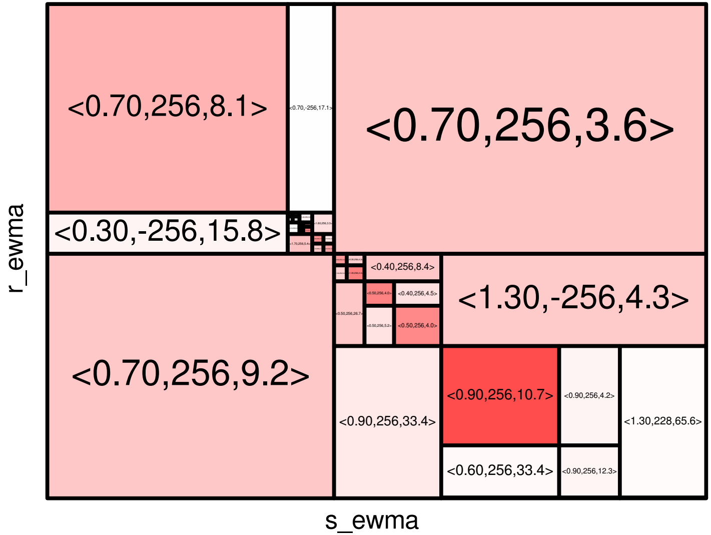

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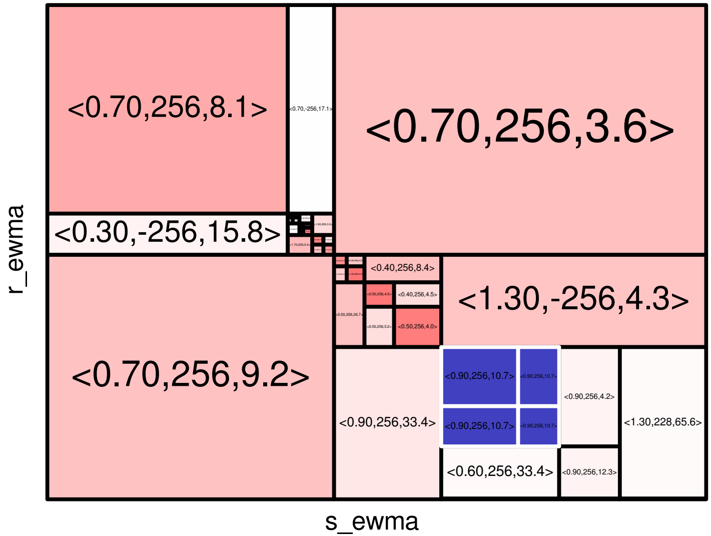
Simulate



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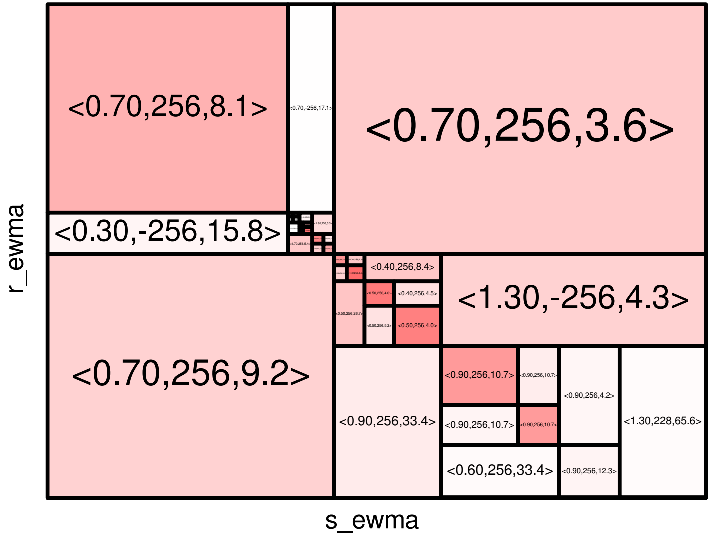
s_ewma

Optimize



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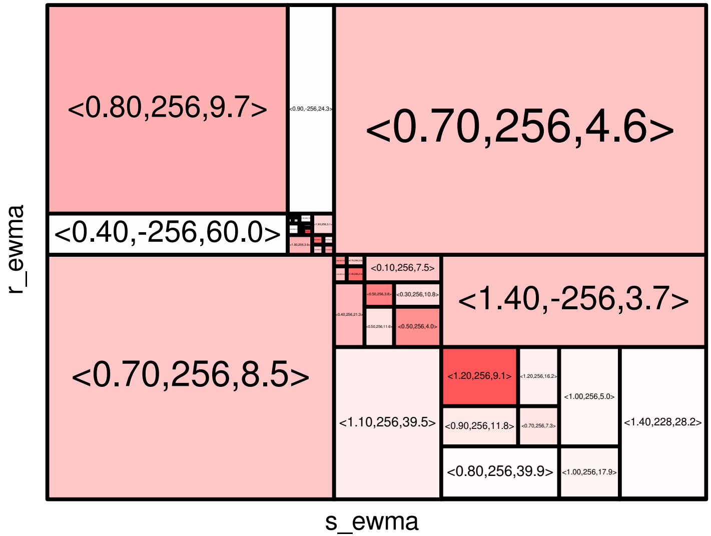
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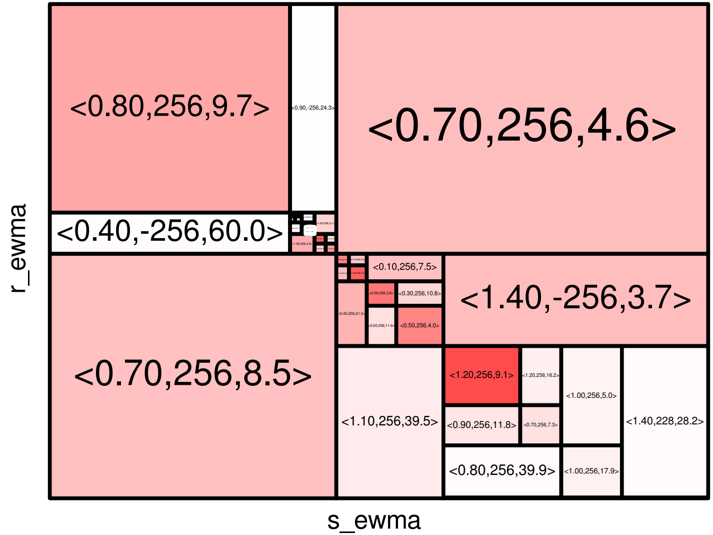

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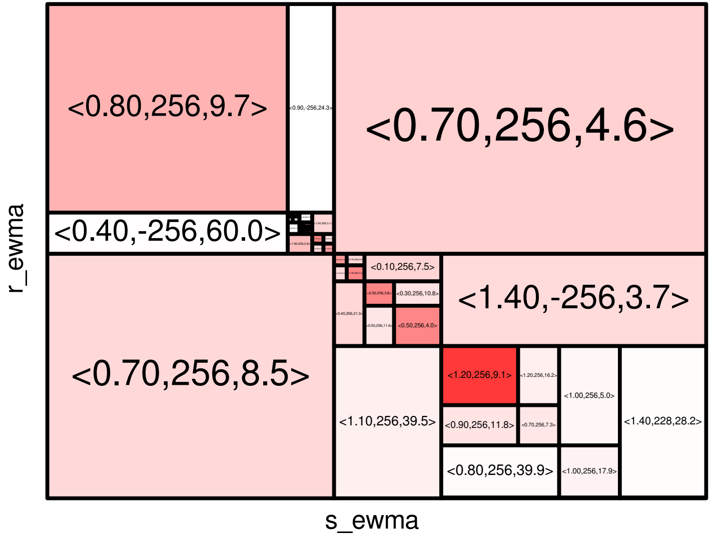
s_ewma

Optimize



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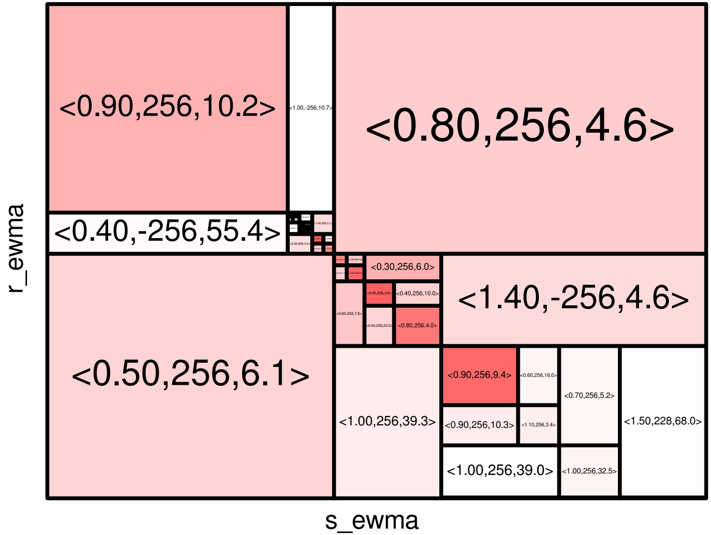

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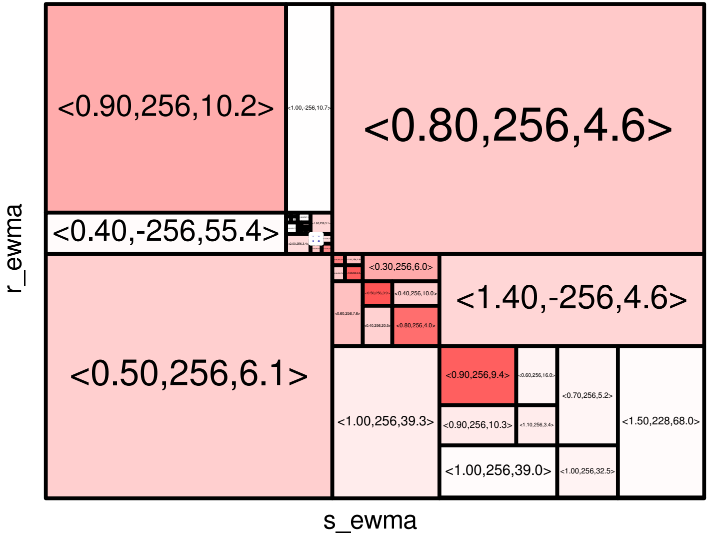
Simulate



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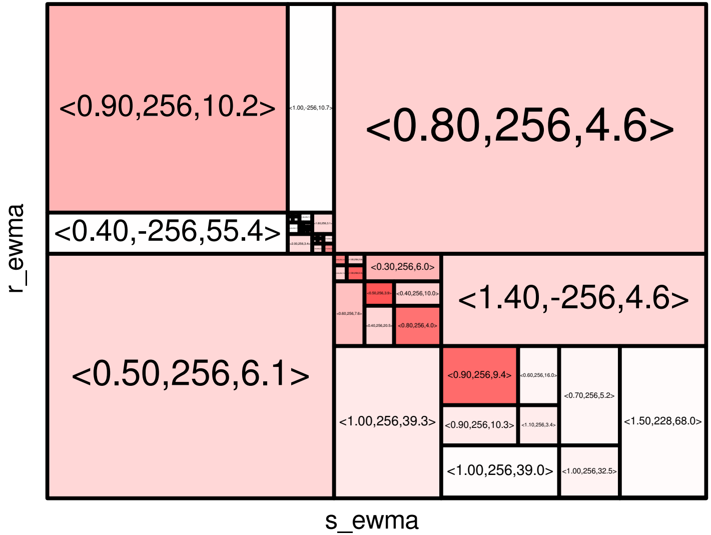
Optimize



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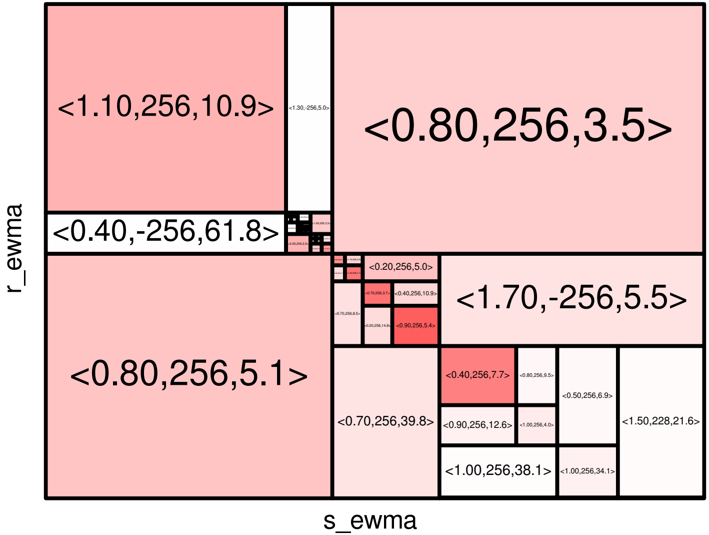
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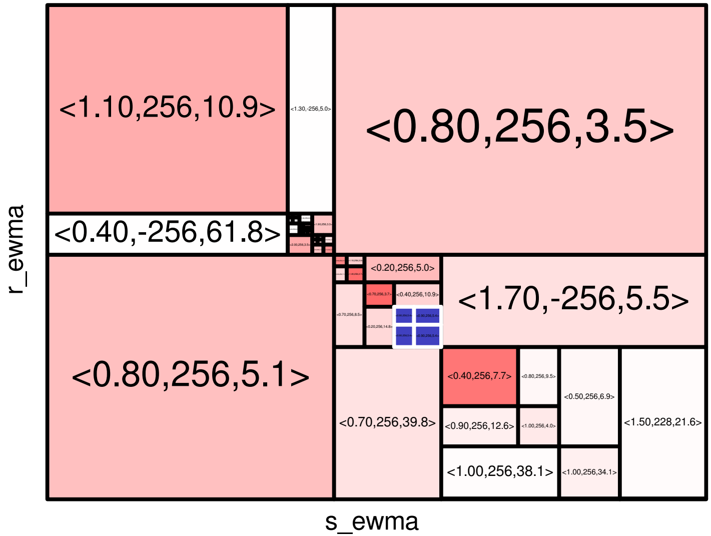
Simulate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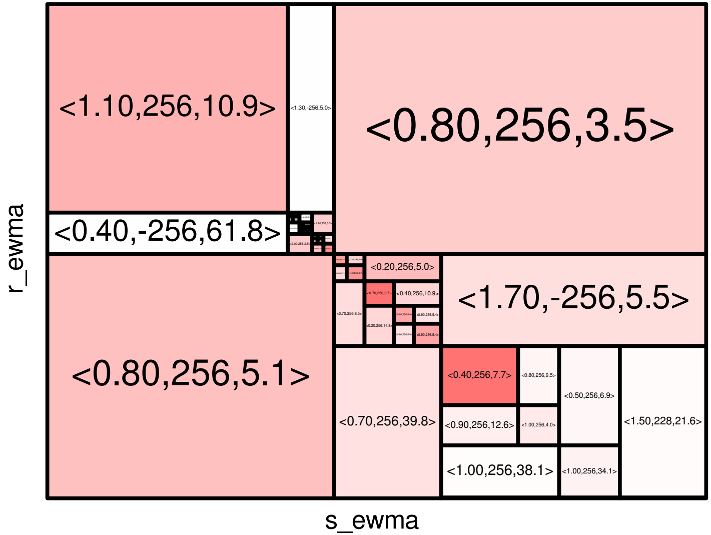
r_ewma
s_ewma

Optimize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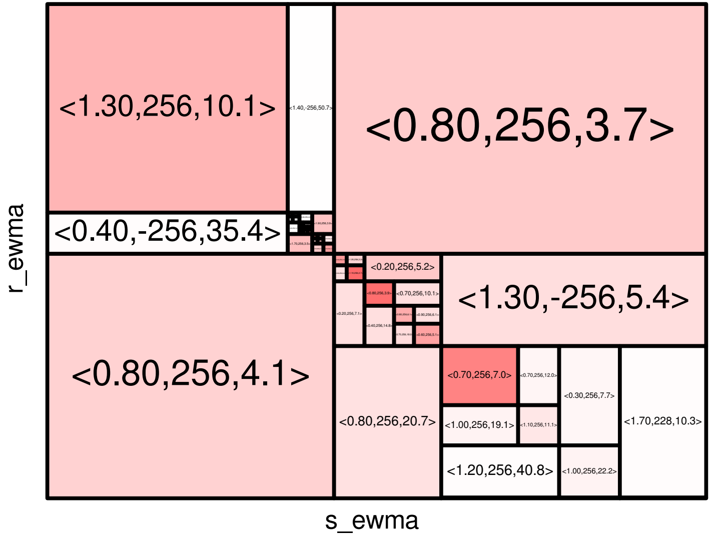

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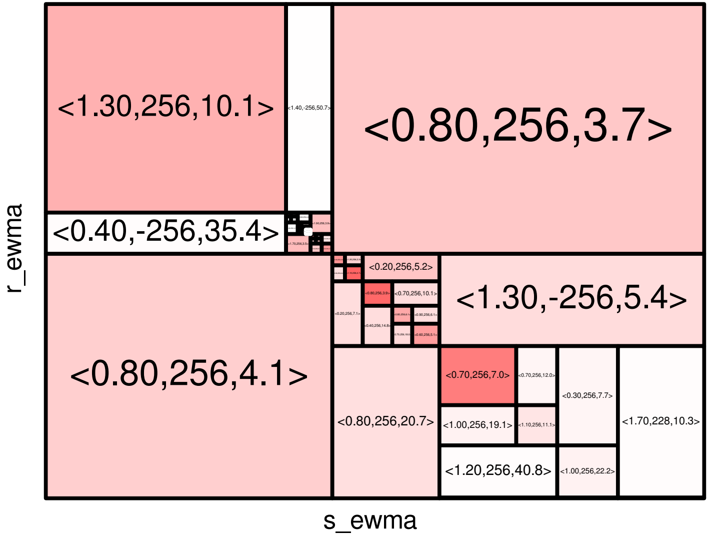
Simulate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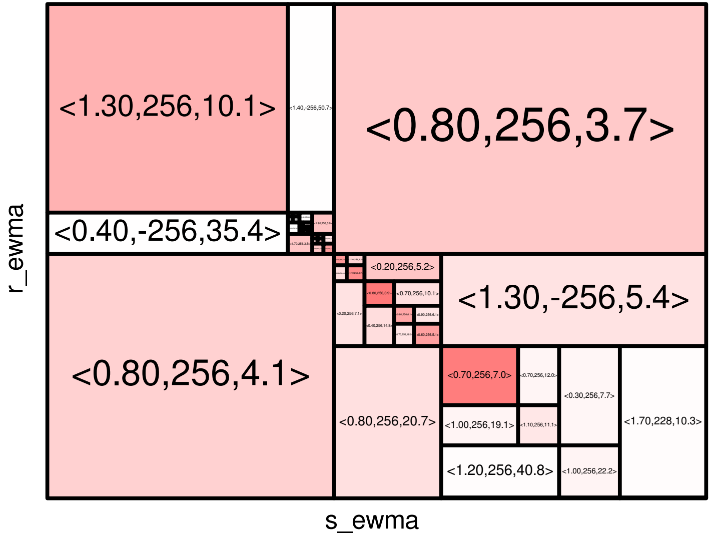
Optimize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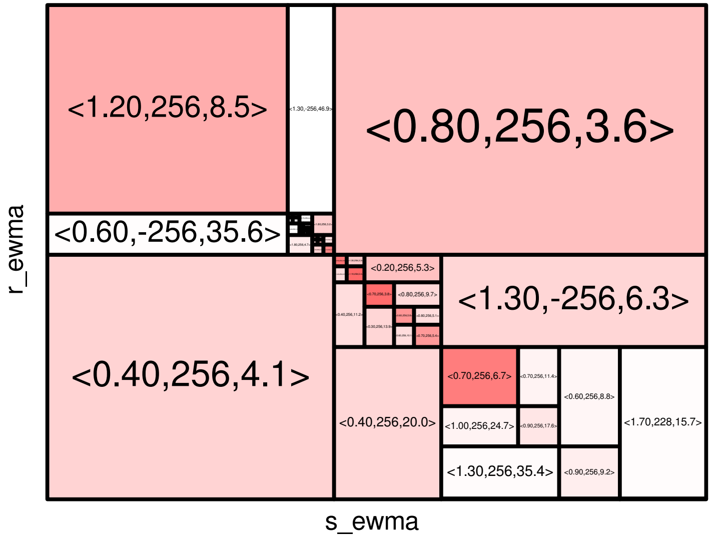

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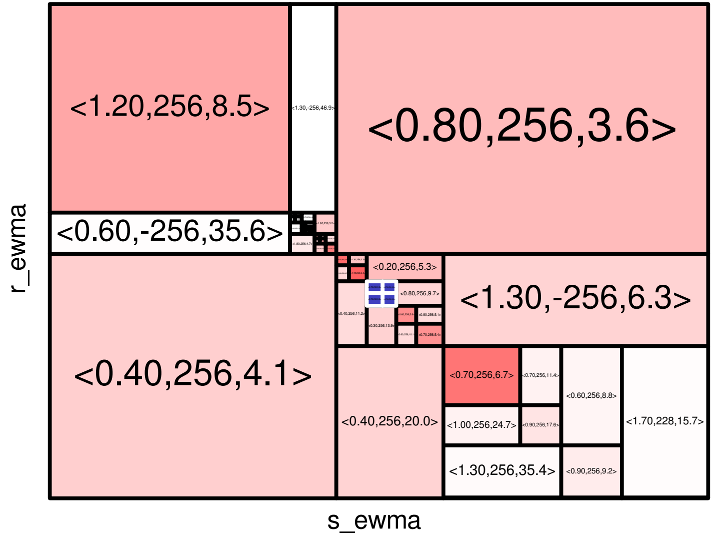
Simulate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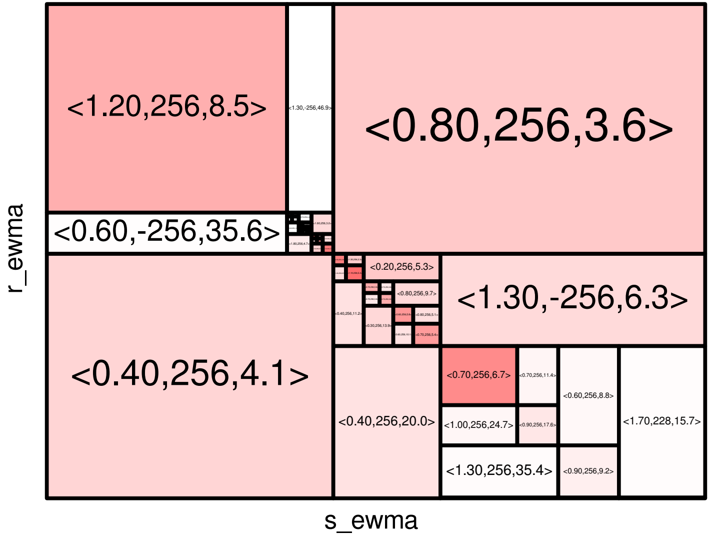
Optimize



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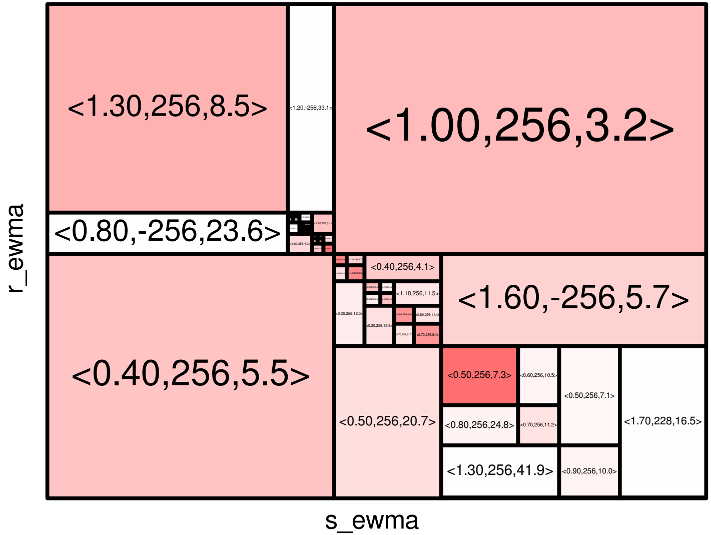

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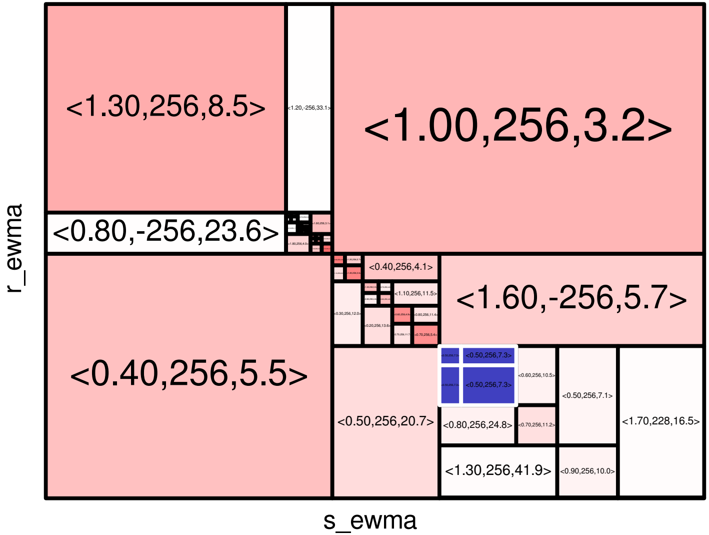
Simulate



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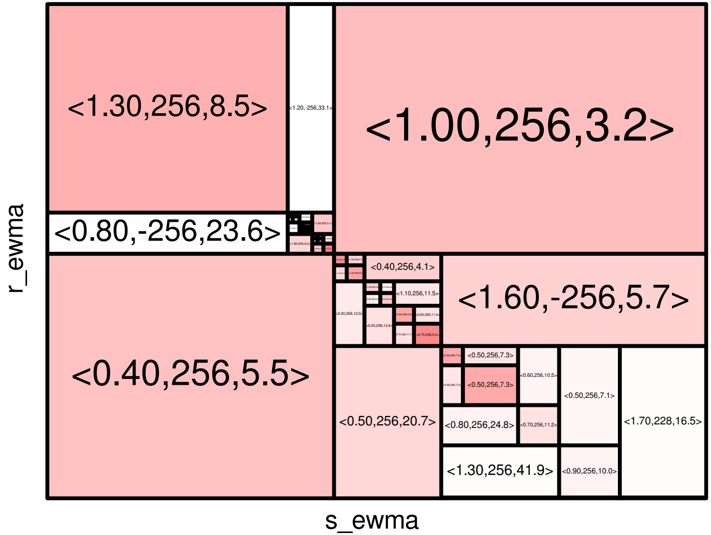
Optimize



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s_ewma
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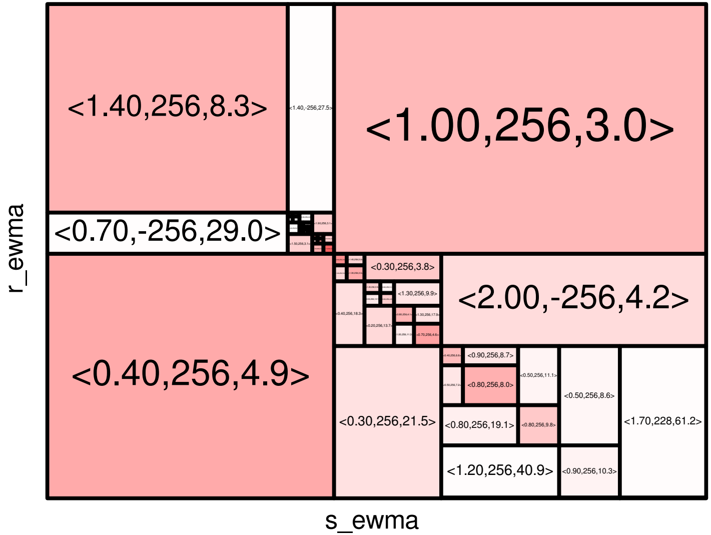
Split



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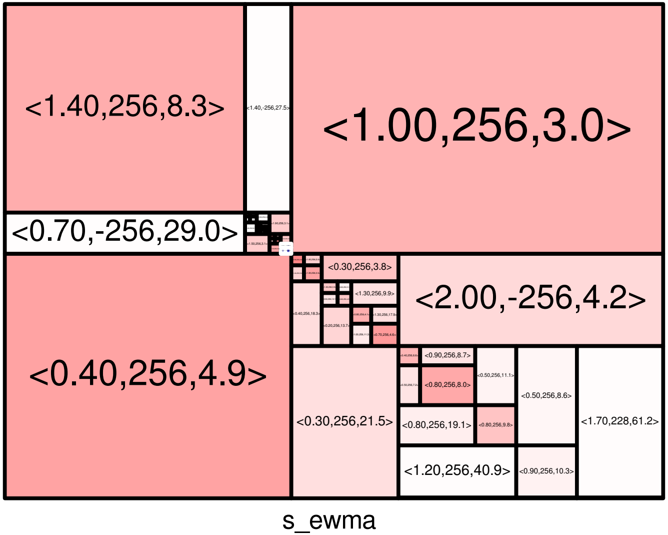
r_ewma
s_ewma

Simulate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s_ewma
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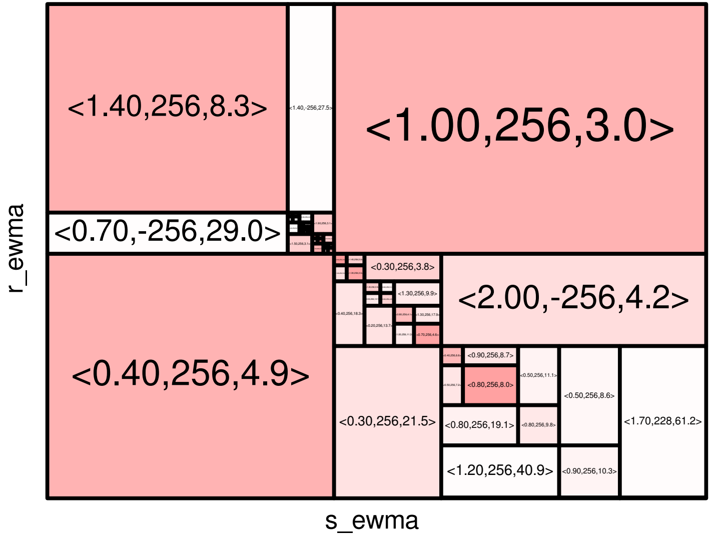
Optimize



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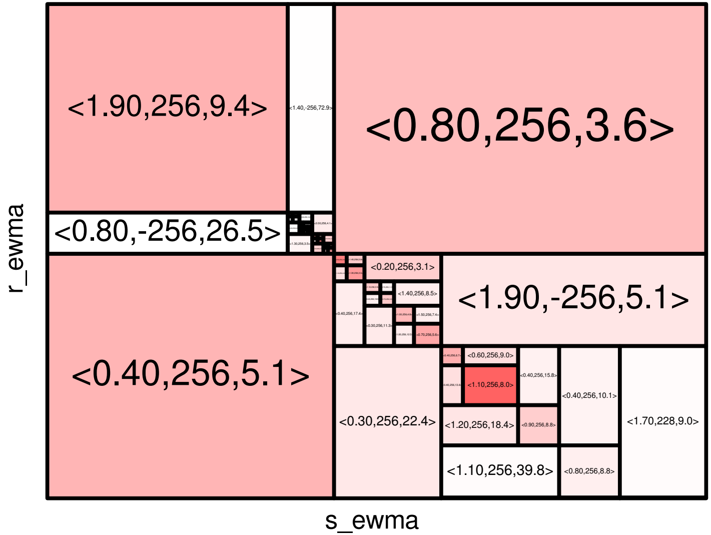
r_ewma
s_ewma

Split



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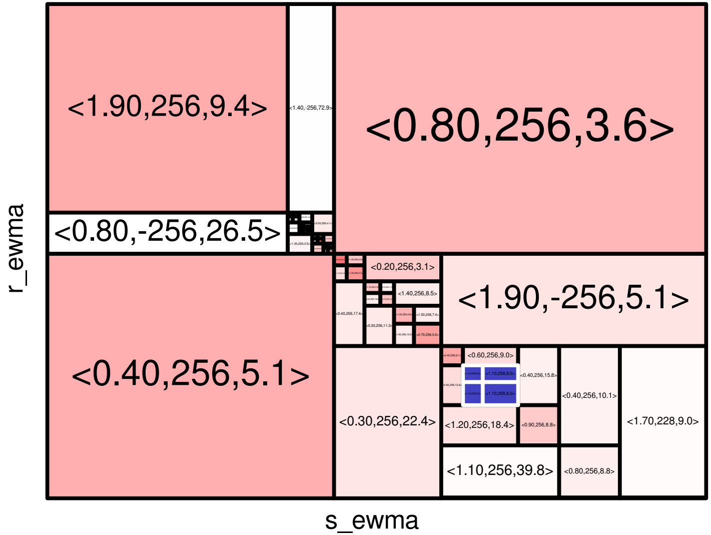
Simulate



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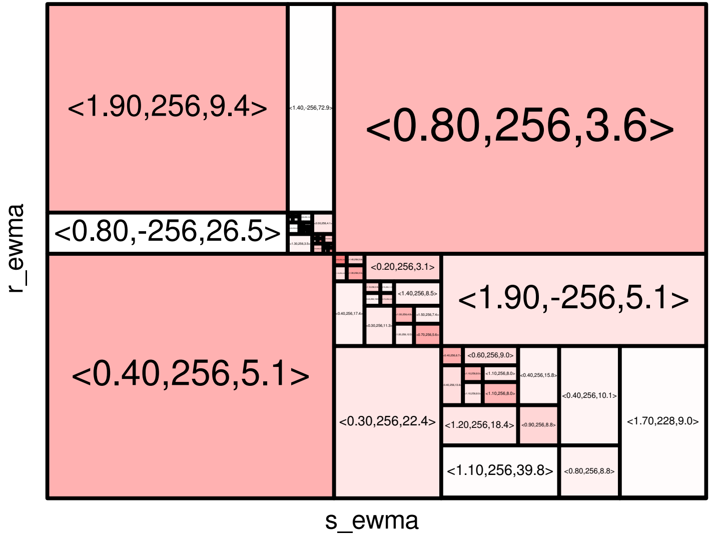
r_ewma
s_ewma

Optimize



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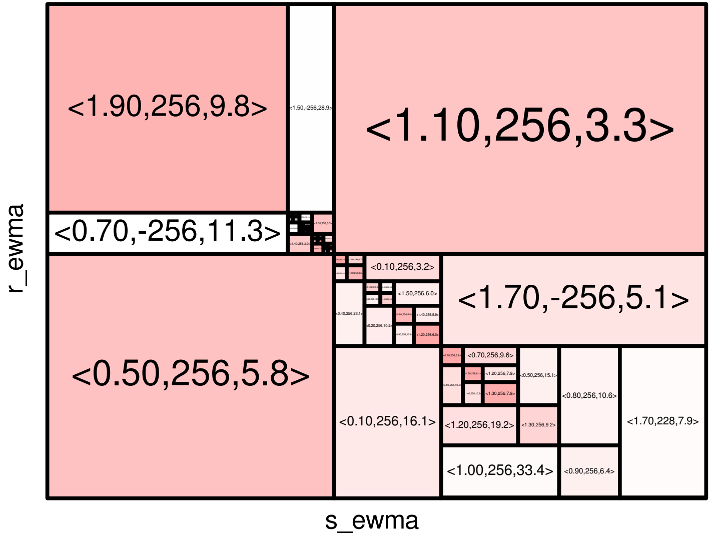
Split



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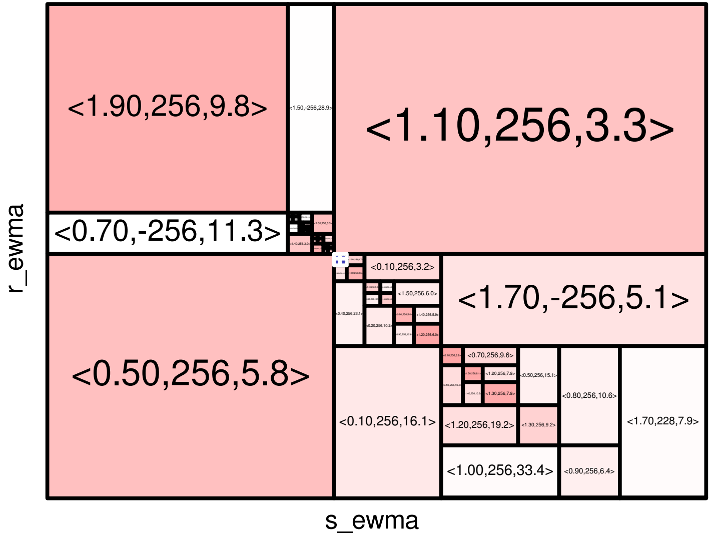
r_ewma
s_ewma

Simulate



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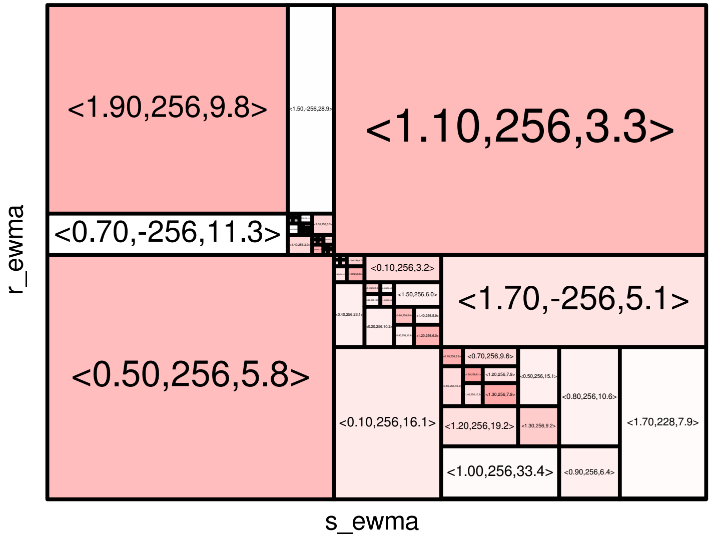
r_ewma
s_ewma

Optimize



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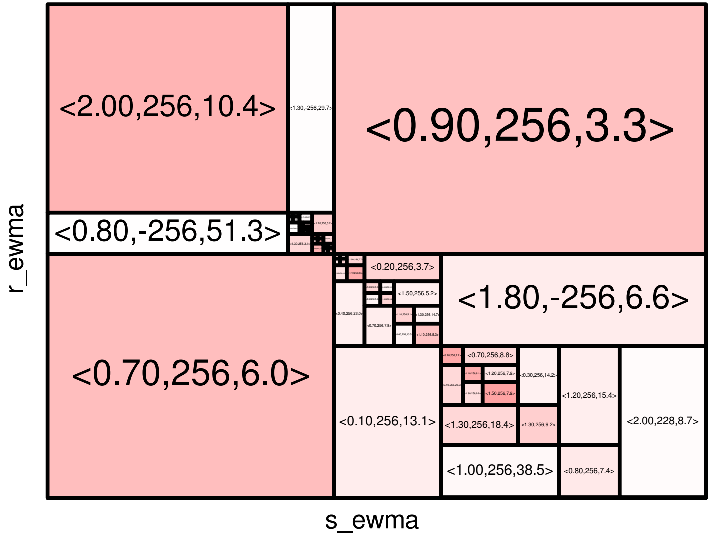
Split



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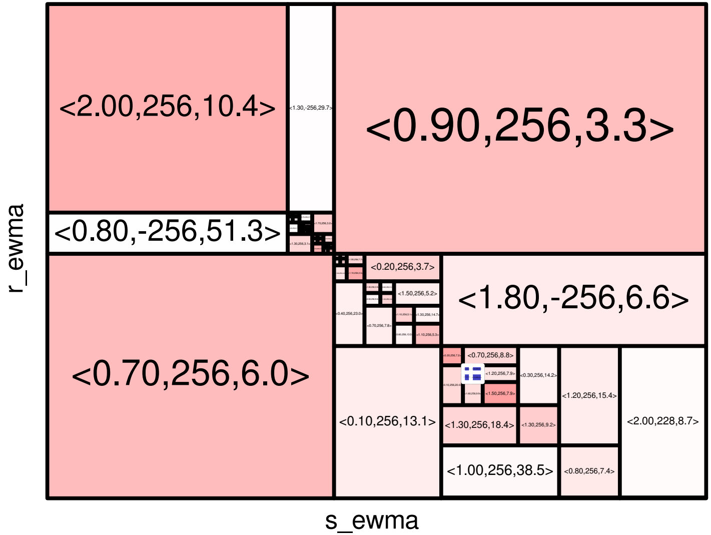
r_ewma
s_ewma

Simulate



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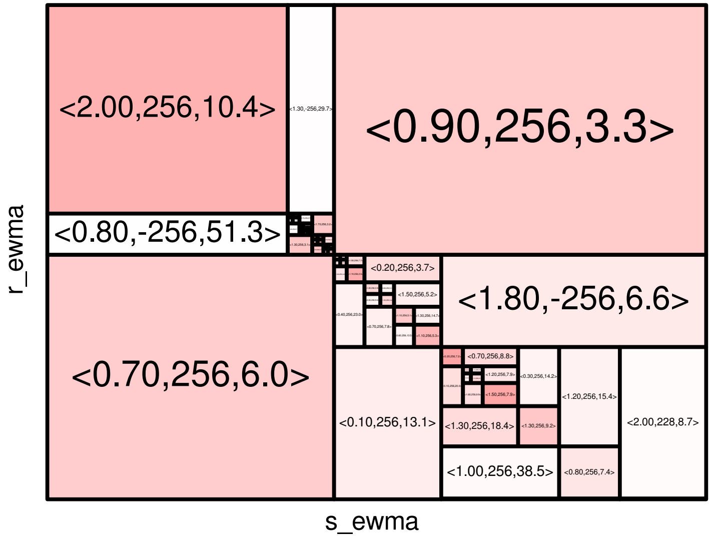
r_ewma
s_ewma

Optimize



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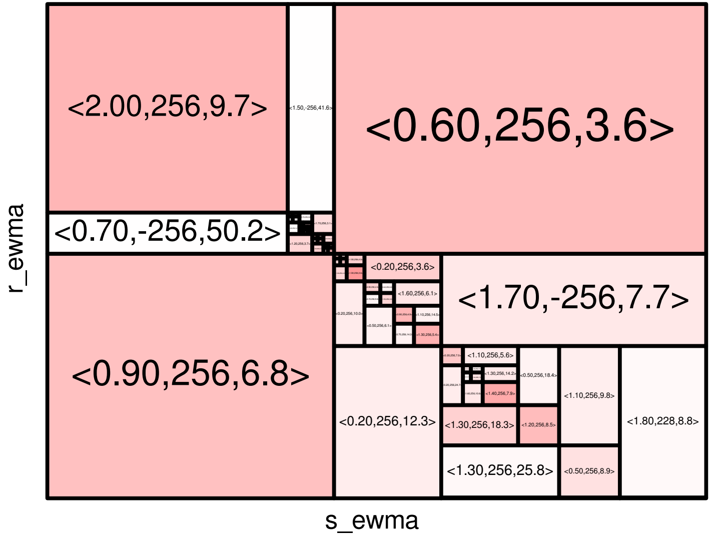
s_ewma

Split



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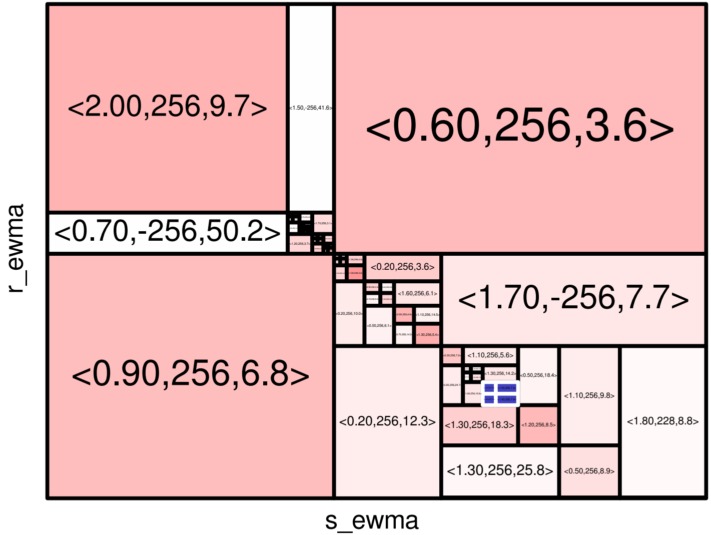
r_ewma
s_ewma

Simulate



r_ewma
s_ewma
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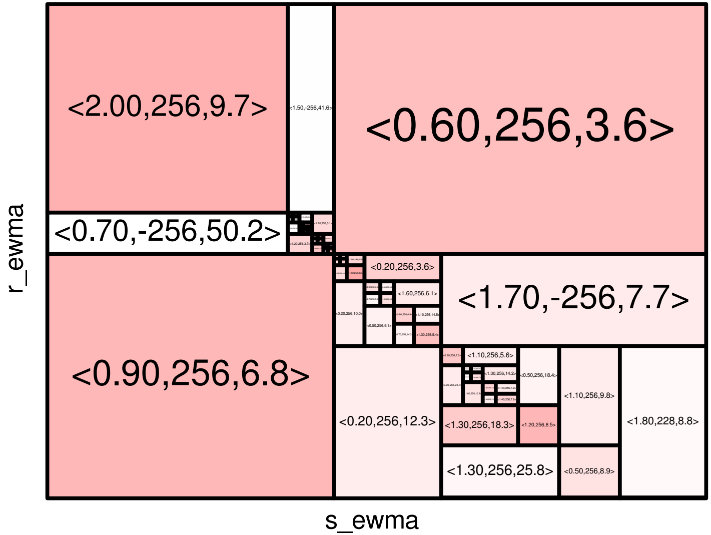

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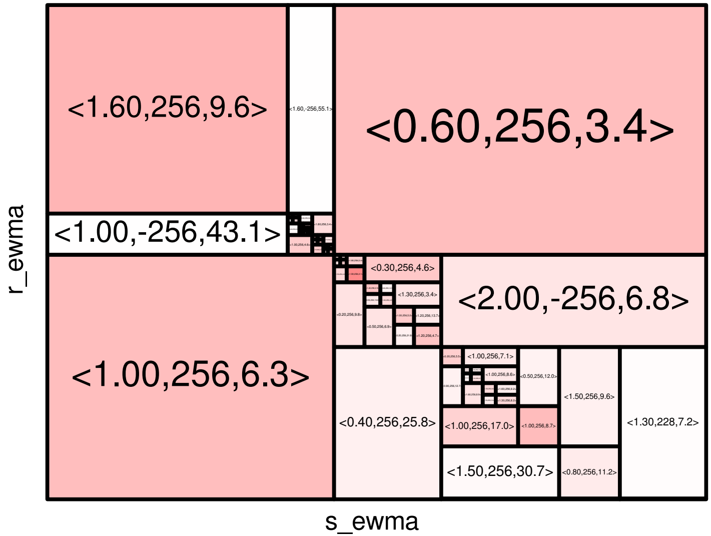
s_ewma
r_ewma

RemyCC



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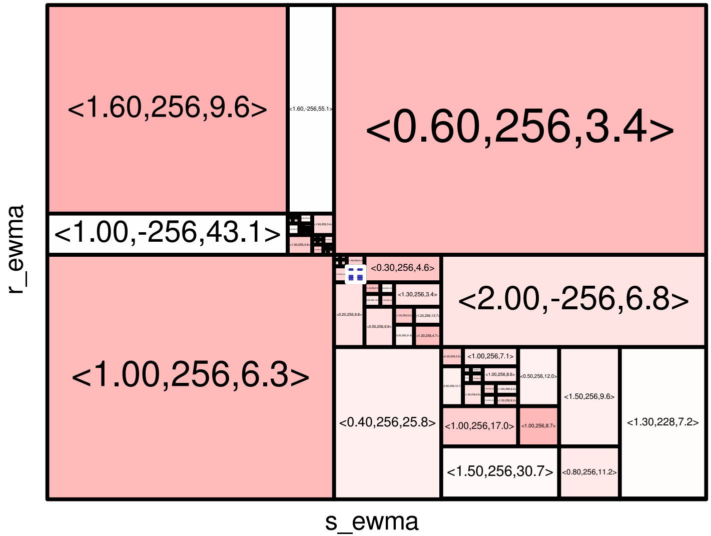

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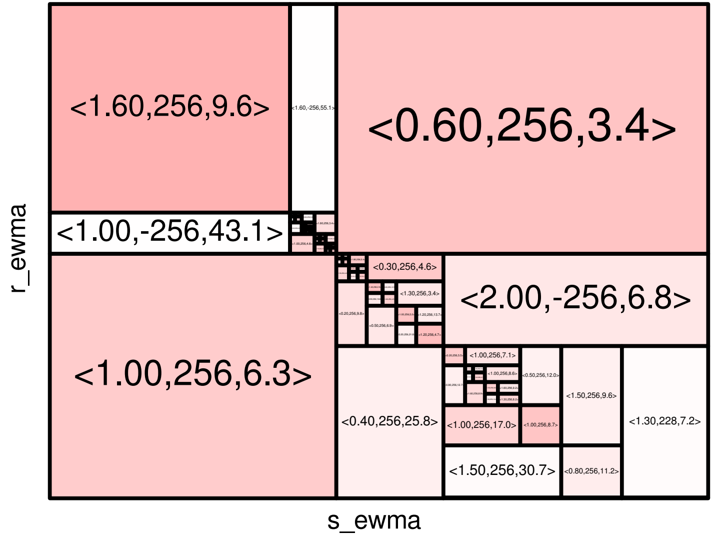
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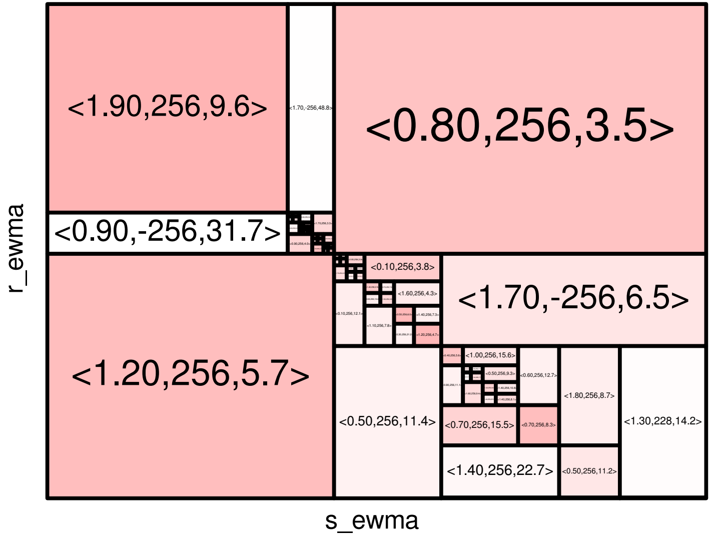

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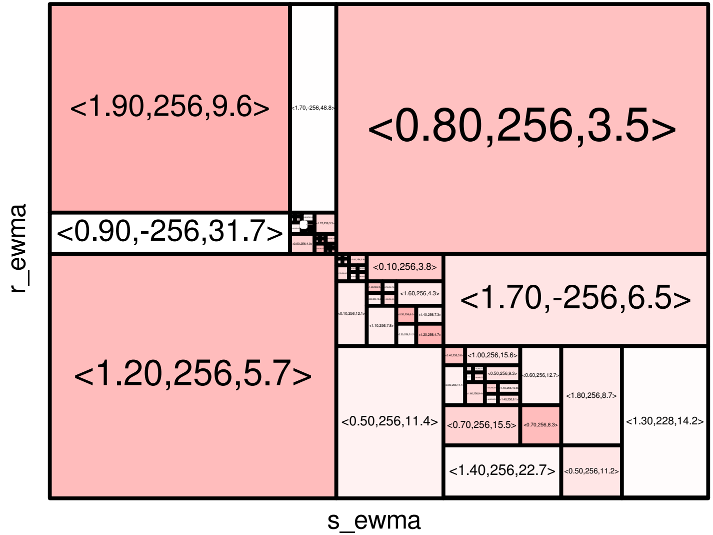
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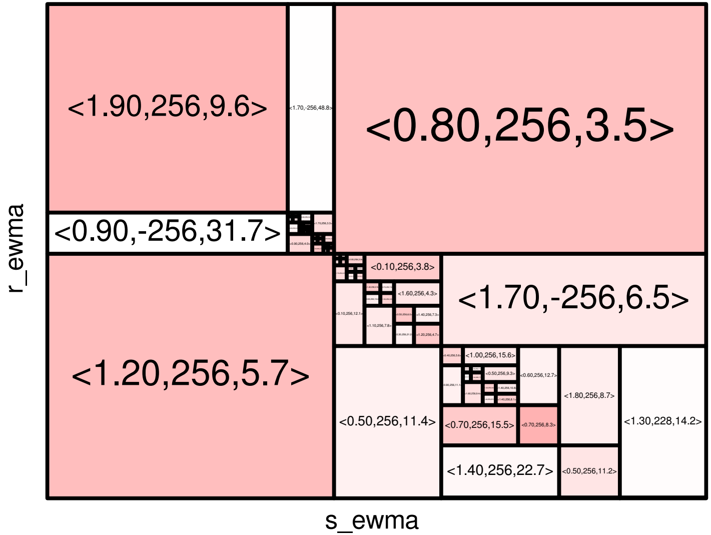
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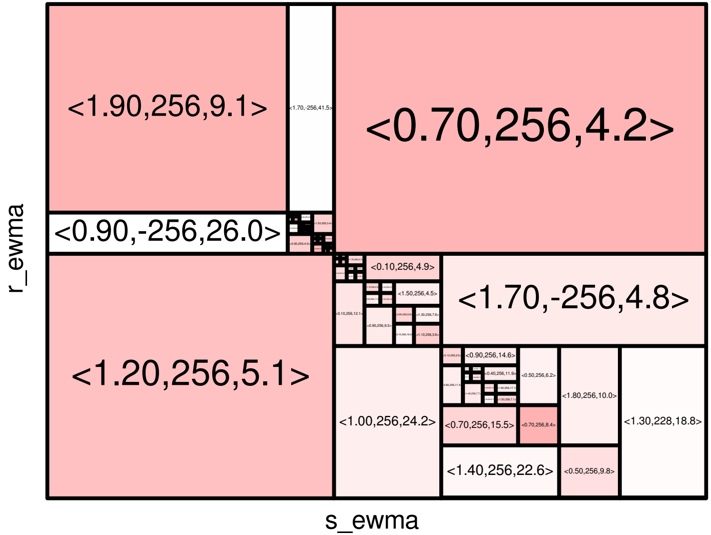

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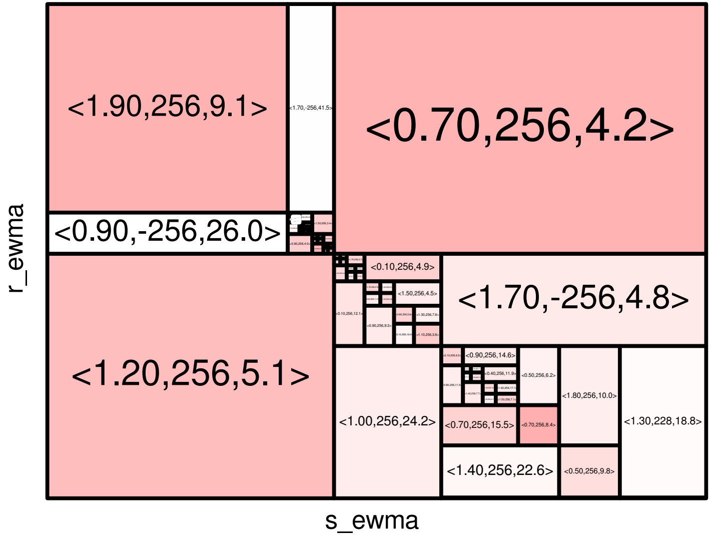

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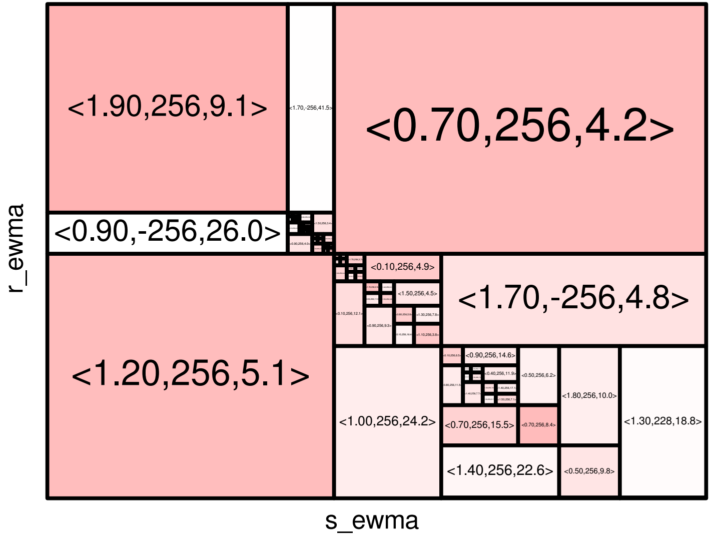

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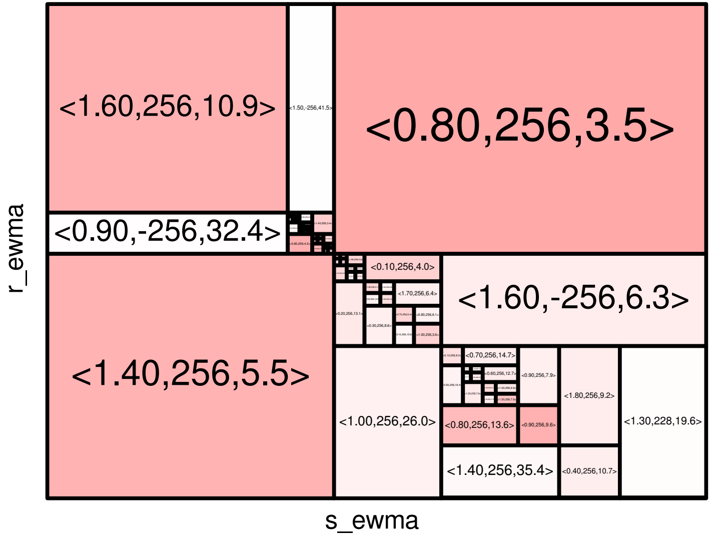
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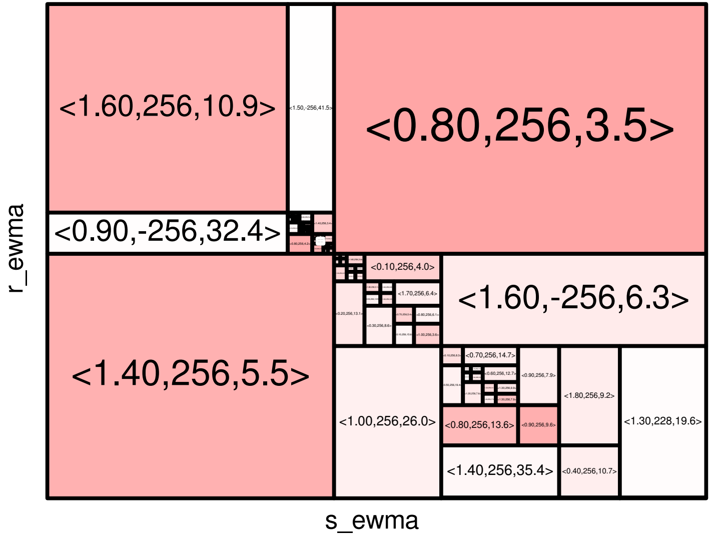

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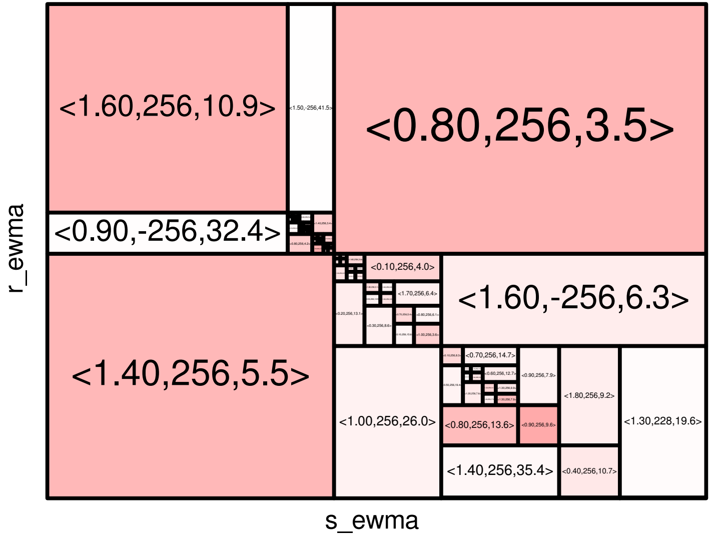

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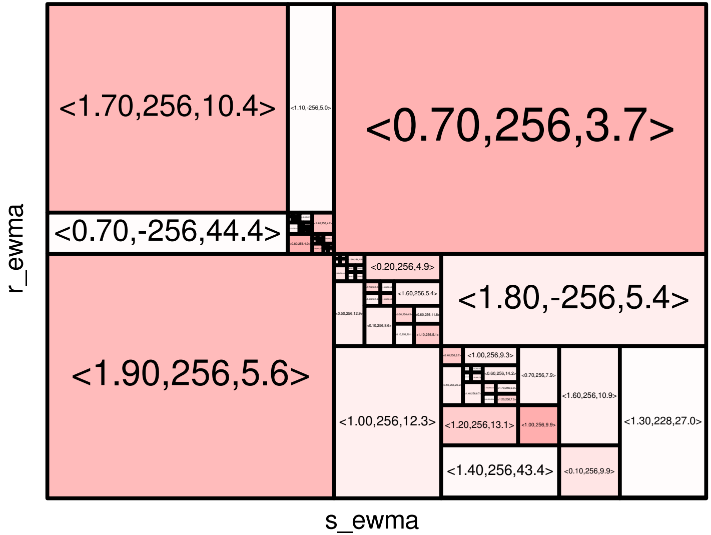

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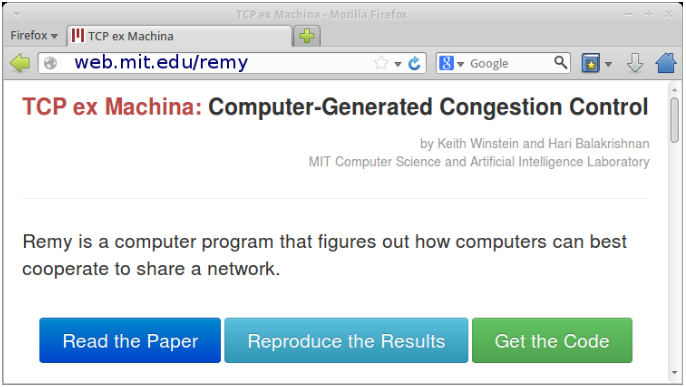
Evaluation in ns-2

- End-to-end comparators: NewReno, Cubic, Compound, Vegas
- In-net comparators: Cubic-over-sfqCoDel, XCP
- Simulation setup published for replication

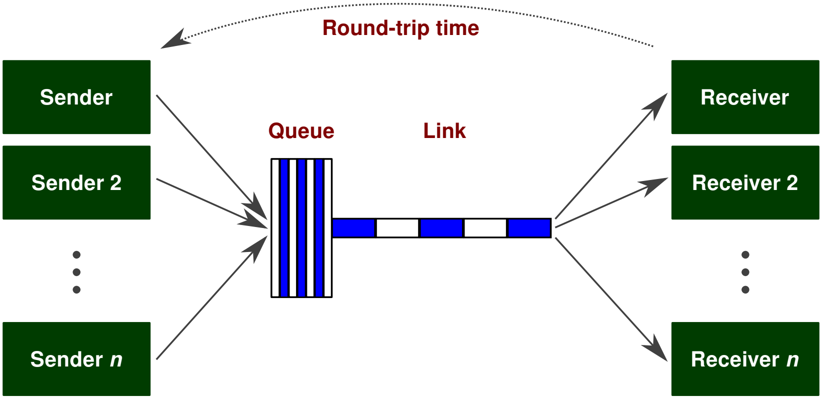


TCP ex Machina: Computer-Generated Congestion Control

by Keith Winstein and Hari Balakrishnan
MIT Computer Science and Artificial Intelligence Laboratory

Remy is a computer program that figures out how computers can best cooperate to share a network.

Scenario 1: fixed-rate network, homogenous senders



Scenario 1: details

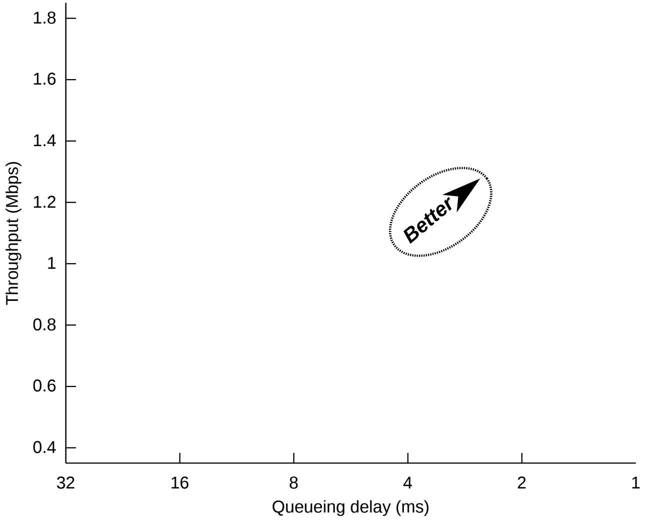
Quantity	**Simulation parameter**	**Remy assumptions**
Link speed	15 Mbps	Uniform(10, 20) Mbps
RTT	150 ms	Uniform(100, 200) ms
n	8	Uniform(1, 16)
"On" process	$\exp[\mu = 100]$ **kB**	$\exp[\mu = 5]$ **s**
"Off" process	$\exp\left[\mu = \frac{1}{2}\right]$ s	$\exp[\mu = \mathbf{5}]$ s

Remy objective:

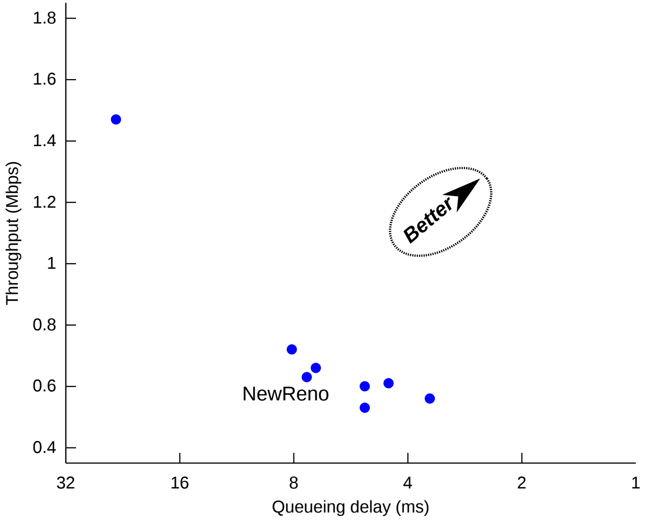
$$\sum_i \log\left[\frac{\text{throughput}_i}{(\text{delay}_i)^{\delta}}\right]$$

$$\delta \in \left\{\frac{1}{10}, 1, 10\right\}$$

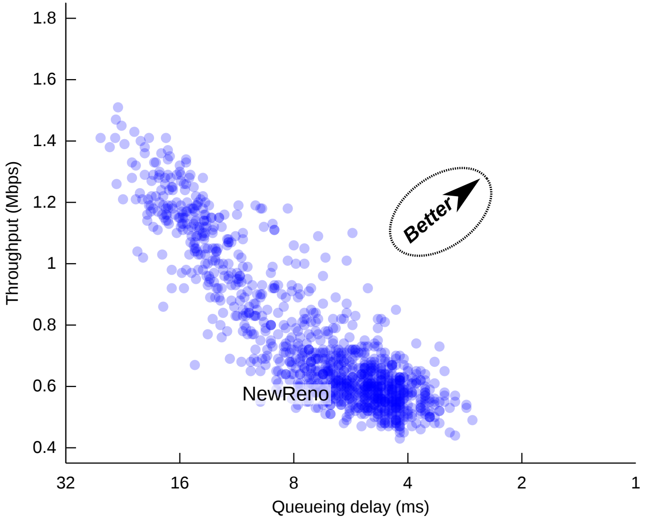
Scenario 1: throughput-delay plot



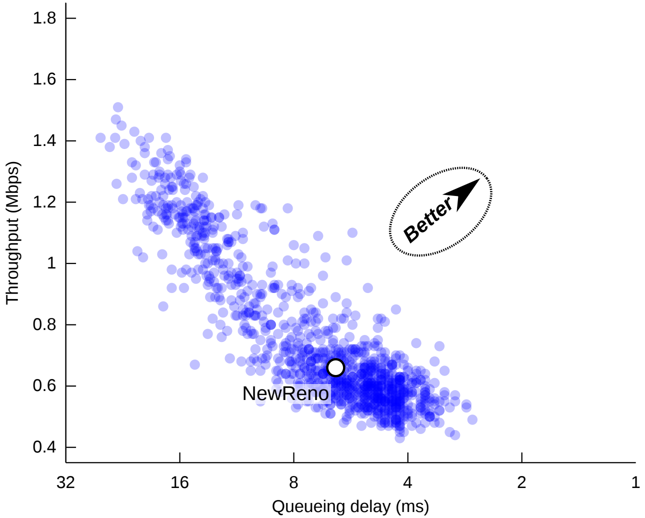
Scenario 1: throughput-delay plot



Scenario 1: throughput-delay plot



Scenario 1: throughput-delay plot



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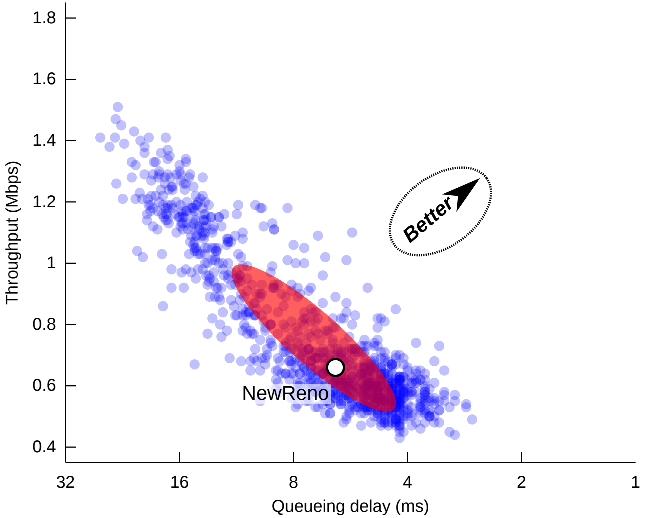

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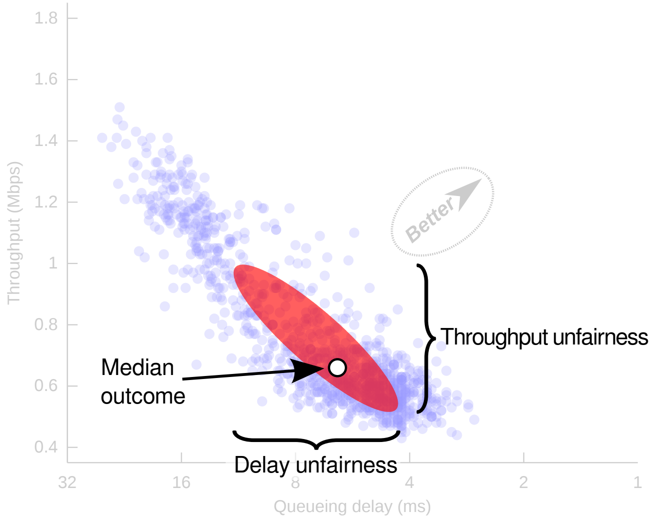

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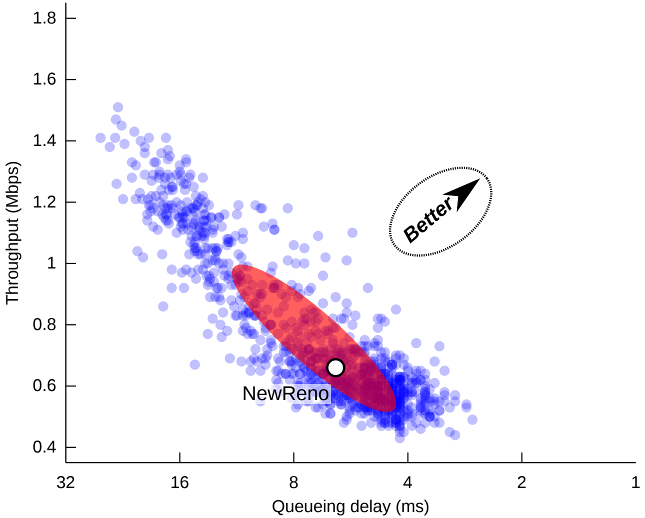

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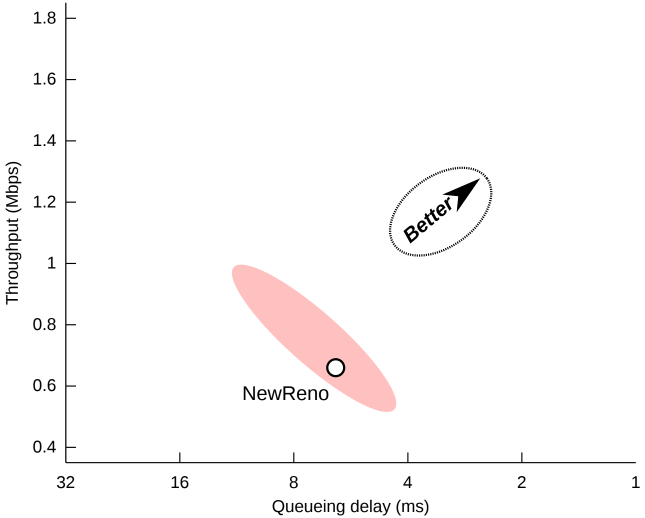

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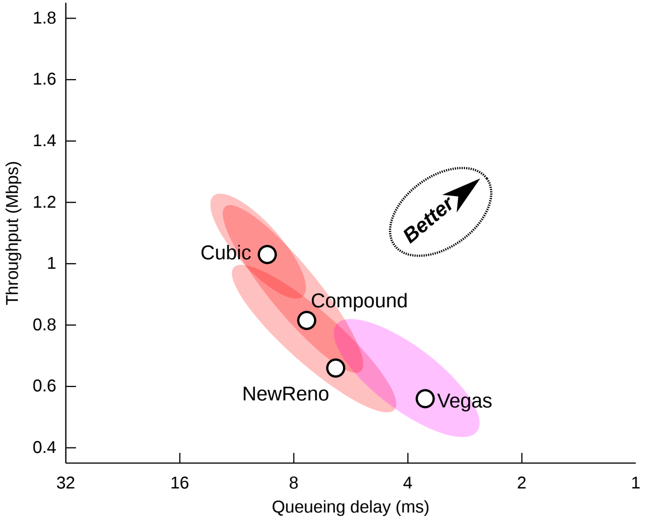

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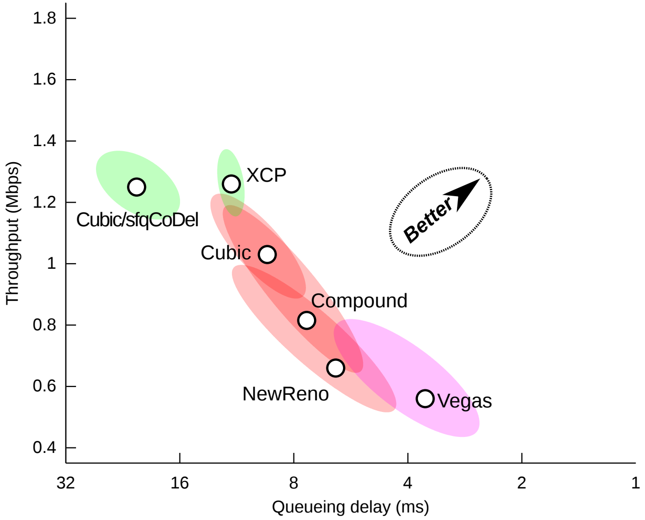
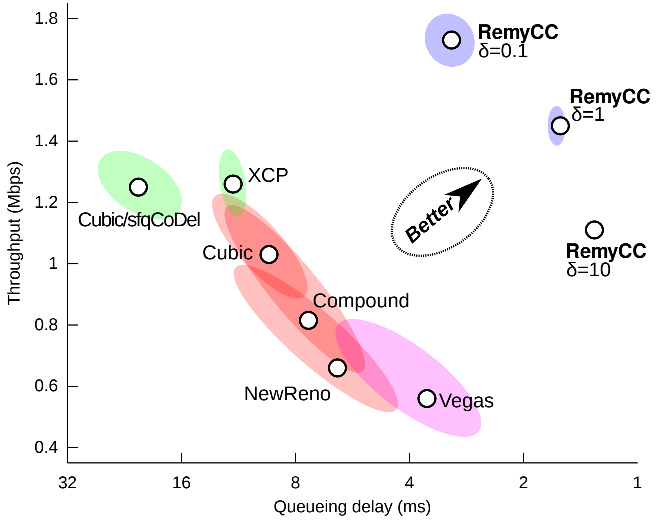
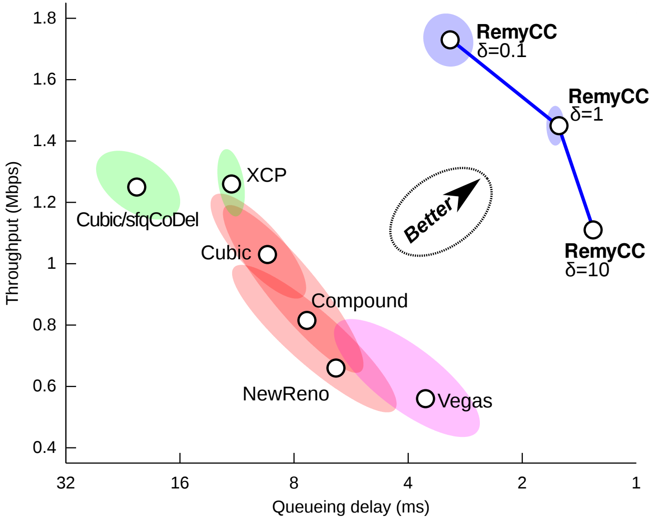


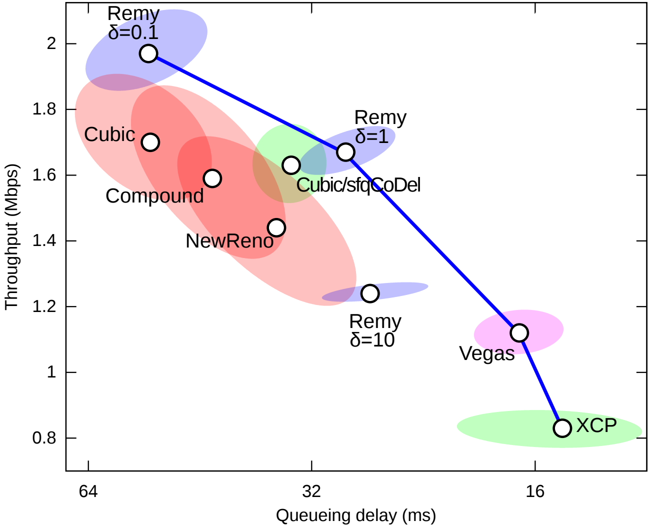
Scenario 1: throughput-delay plot



Scenario 1: throughput-delay plot



Scenario 2: Verizon LTE, $n = 8$

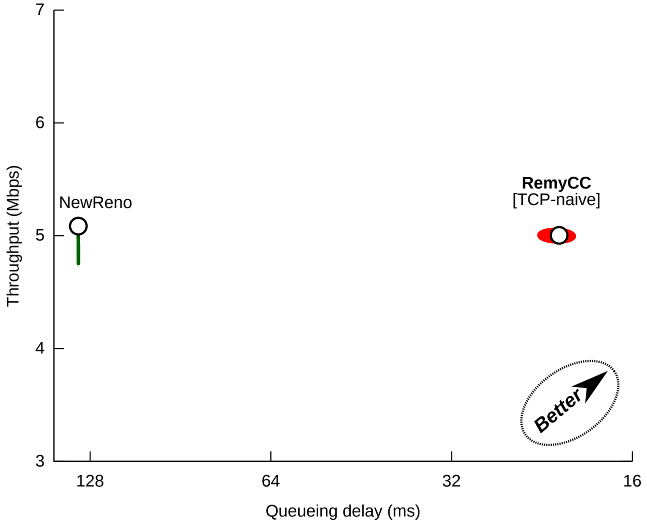


Remy as an instrument to study network science

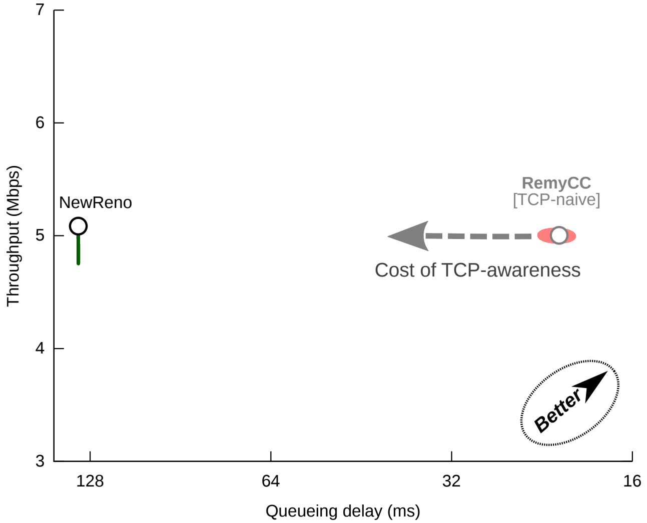
From the perspective of a network endpoint, **what matters?**

How difficult is it to learn a good protocol, given an **imperfect** *model of the network?*

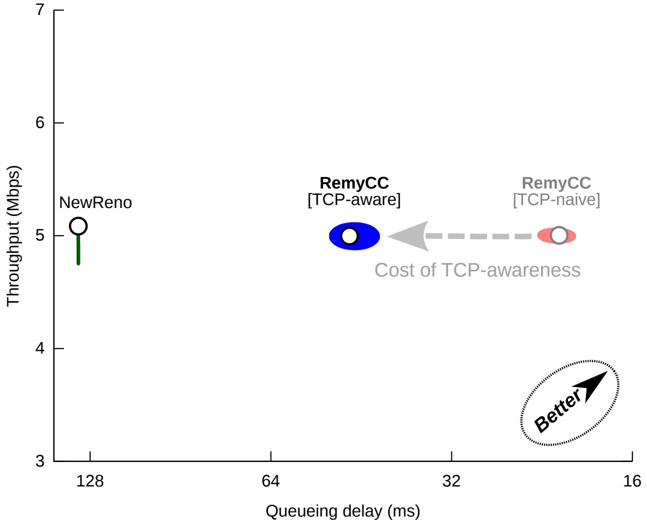
RemyCC competing against itself



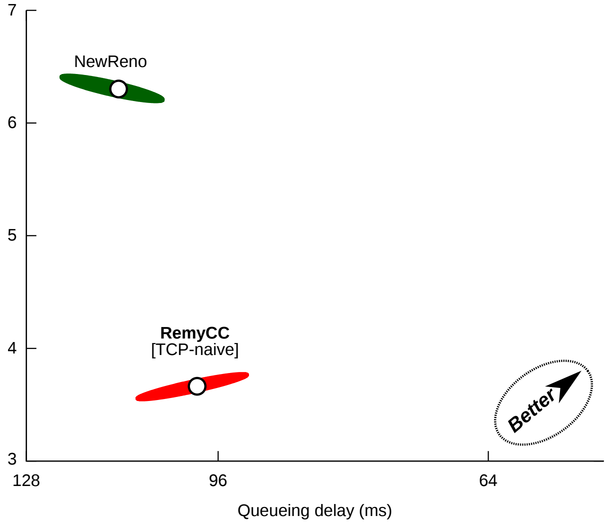
RemyCC competing against itself



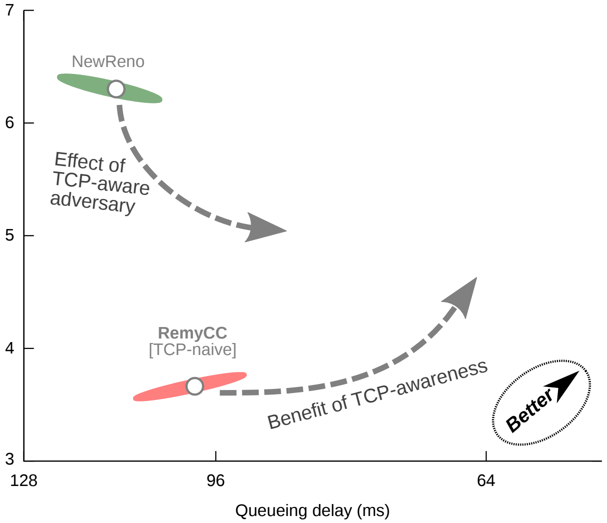
RemyCC competing against itself



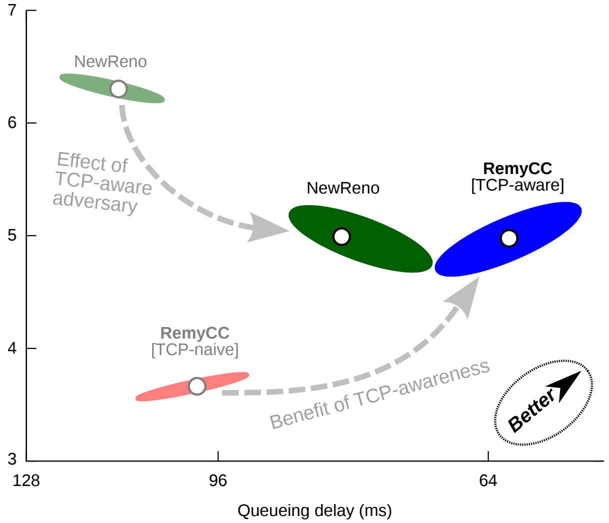
RemyCC competing against TCP NewReno



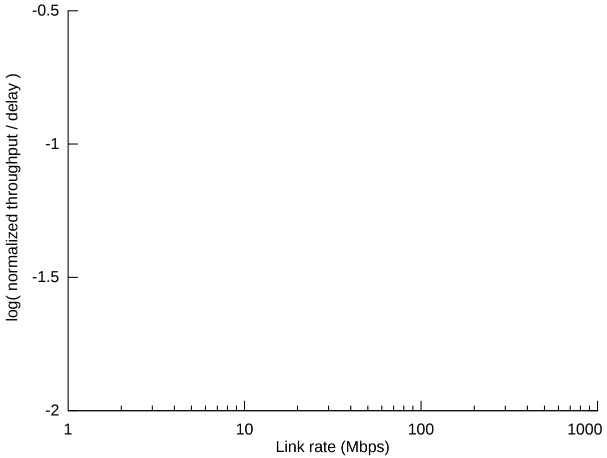
RemyCC competing against TCP NewReno



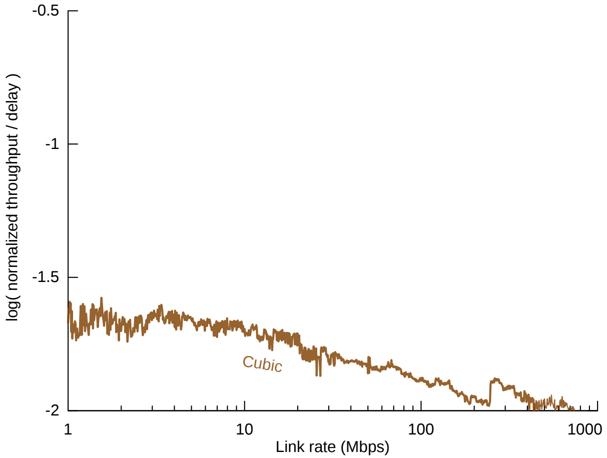
RemyCC competing against TCP NewReno



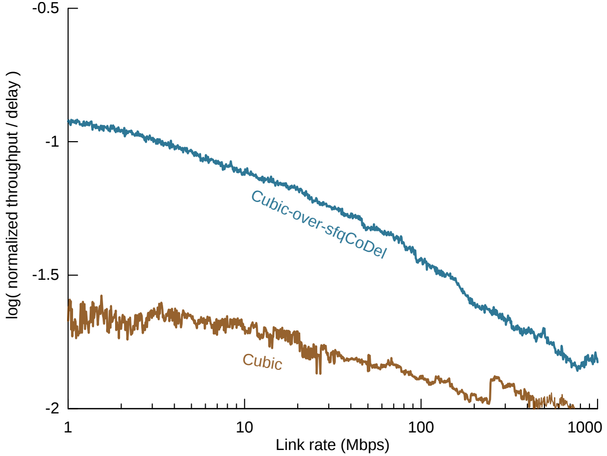
The cost of generality



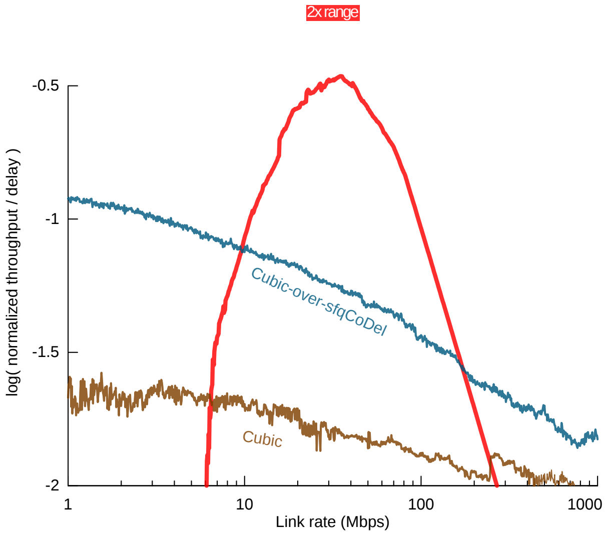
The cost of generality



The cost of generality



The cost of generality



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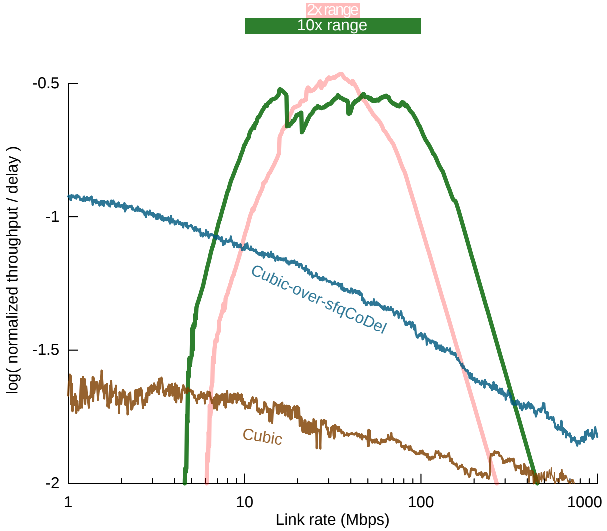
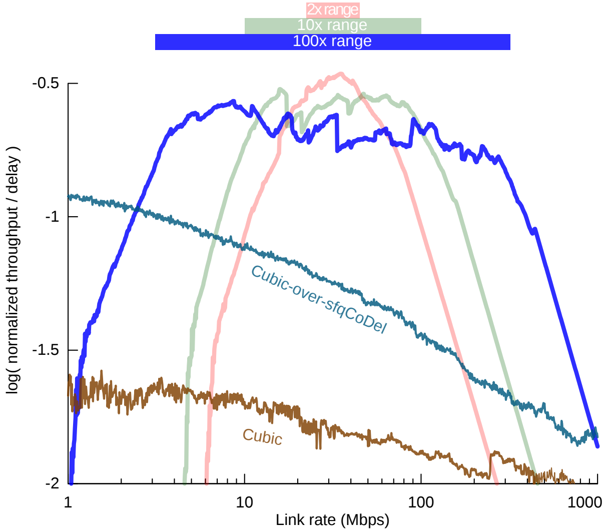
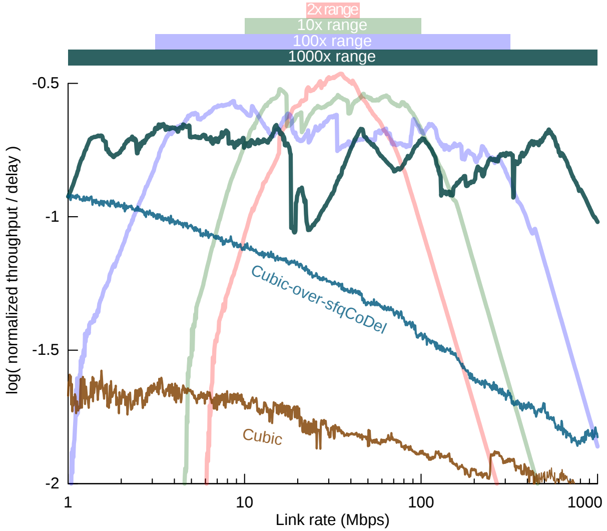


The cost of generality

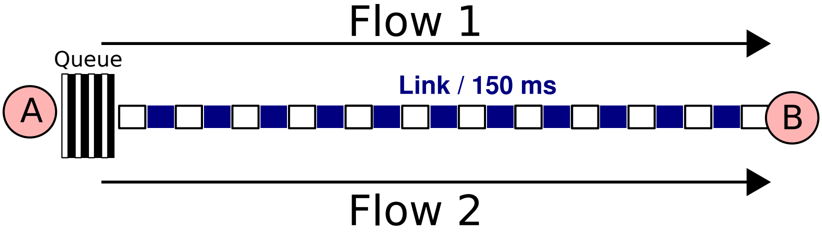


The cost of generality



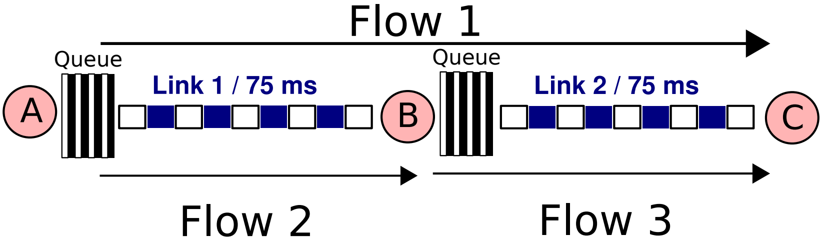
When the model is wrong about the topology

One bottleneck

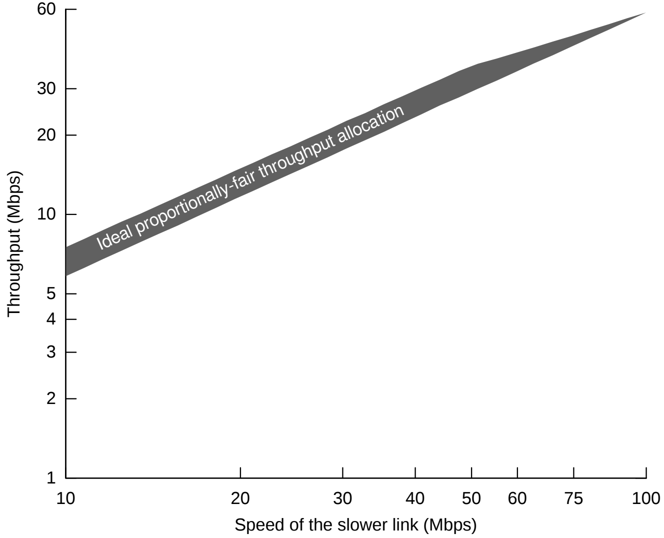


When the model is wrong about the topology

Two bottlenecks



When the model is wrong about the topology



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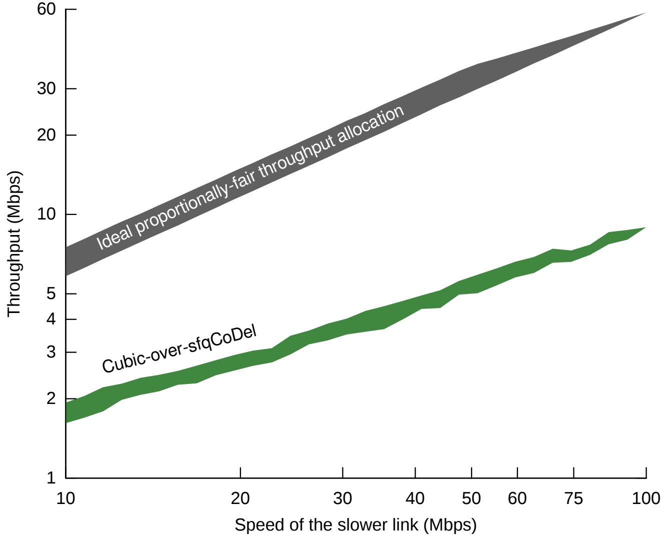

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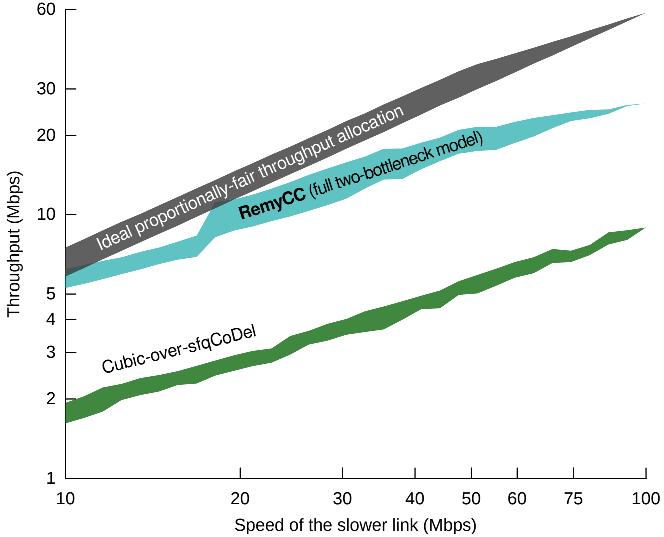
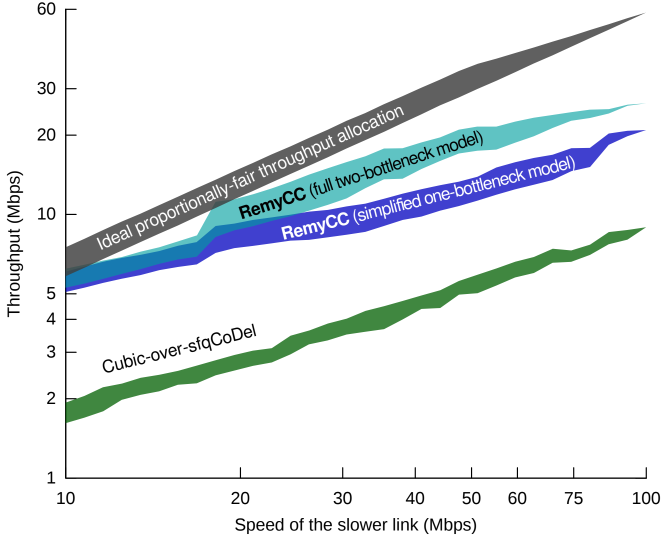


When the model is wrong about the topology



Systems ex Machina

- Explicit design considerations → **freedom to innovate**
- "If this protocol is the answer, what's the question?"

keithw@mit.edu

http://mit.edu/remy