CausalSim: A Causal Framework for Unbiased Trace-Driven Simulation

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*Equal Contribution

Massachusetts
Institute of
Technology

Trace-driven simulation

✓ Use traces to capture **real** system behavior

✓ **Less complex** than full-system simulation

Biased outcomes

Trace-driven simulation

- ✓ Use traces to capture **real** system behavior
- ✓ **Less complex** than full-system simulation
- **Biased** outcomes

Promise

- ➢ Key source of bias in trace-driven simulation

Trace-driven simulation

✓ Use traces to capture **real** system behavior

✓ **Less complex** than full-system simulation

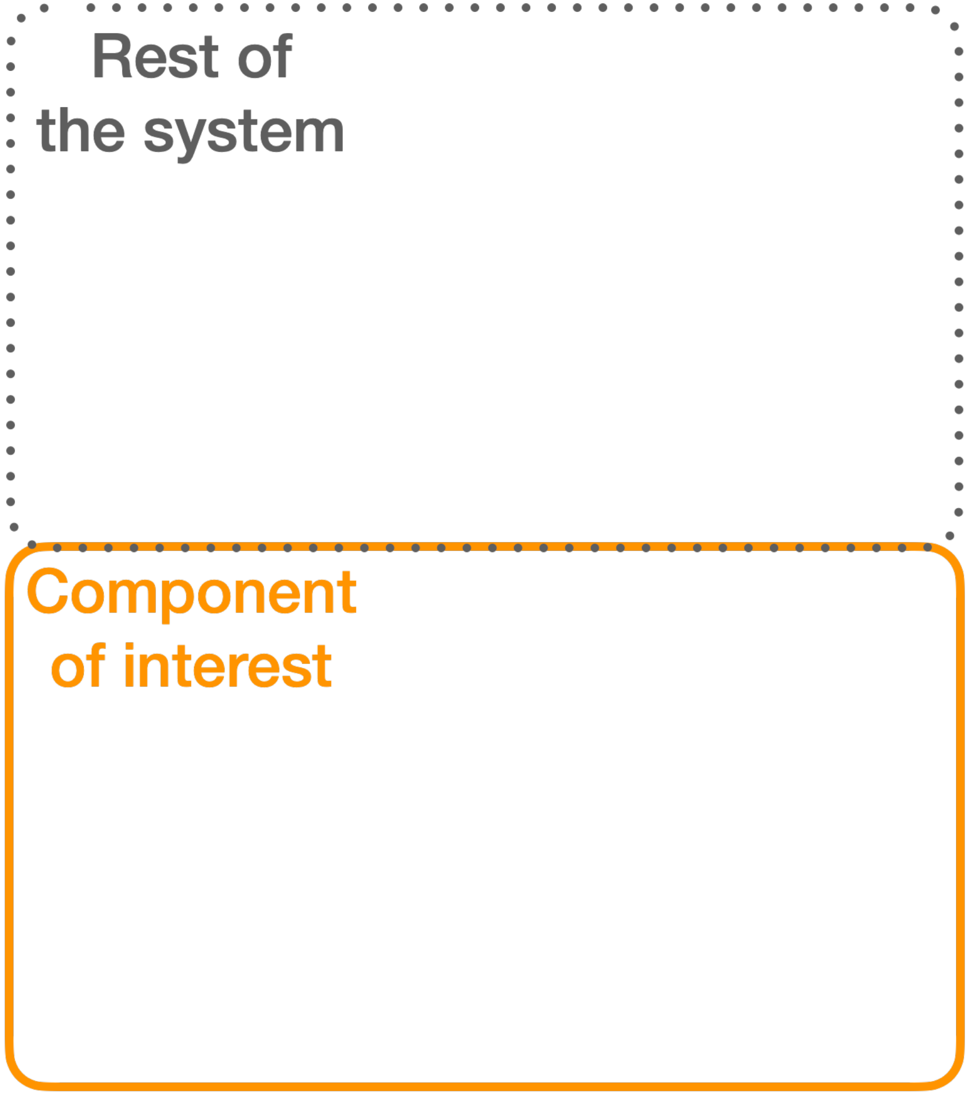
Biased outcomes

Promise

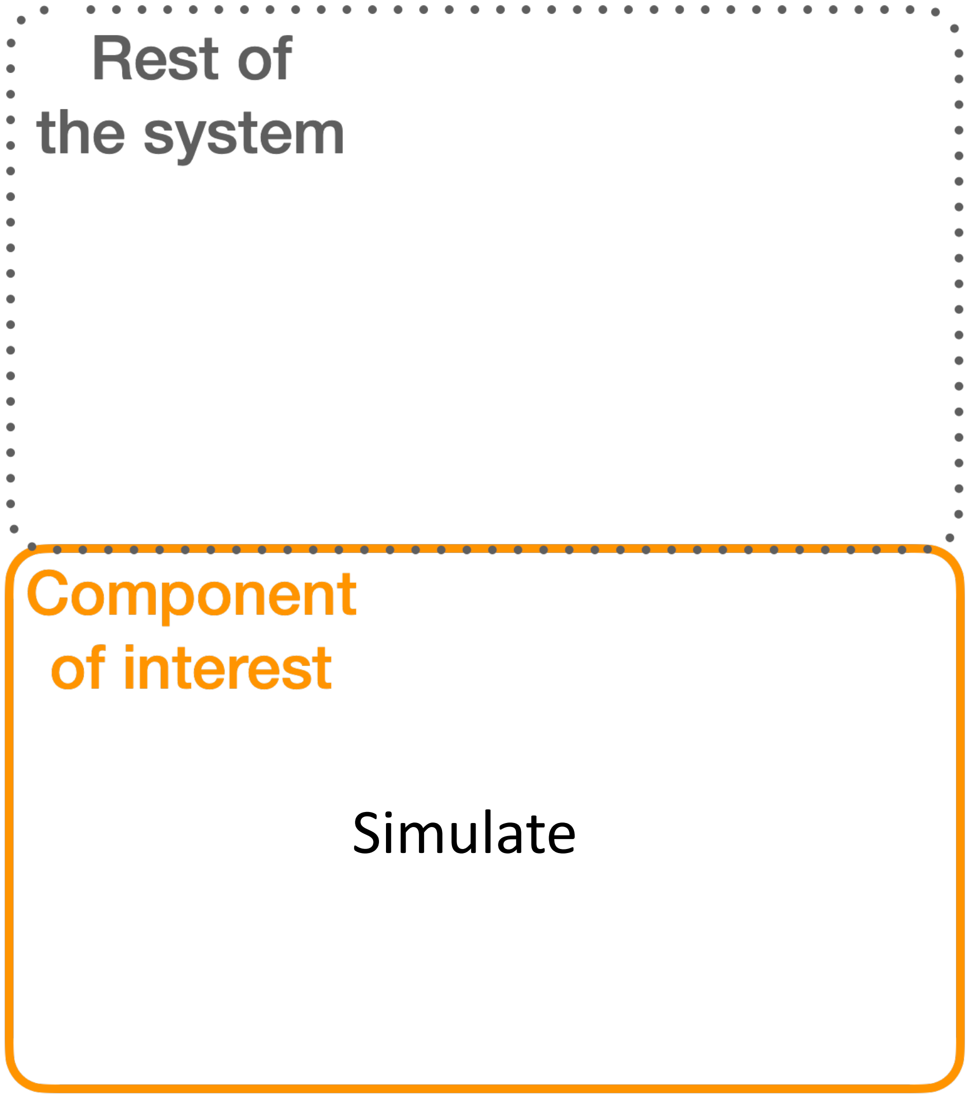
➢ Key source of bias in trace-driven simulation

➢ How to do unbiased trace-driven simulation?

Exogenous trace assumption in trace-driven simulation



Exogenous trace assumption in trace-driven simulation



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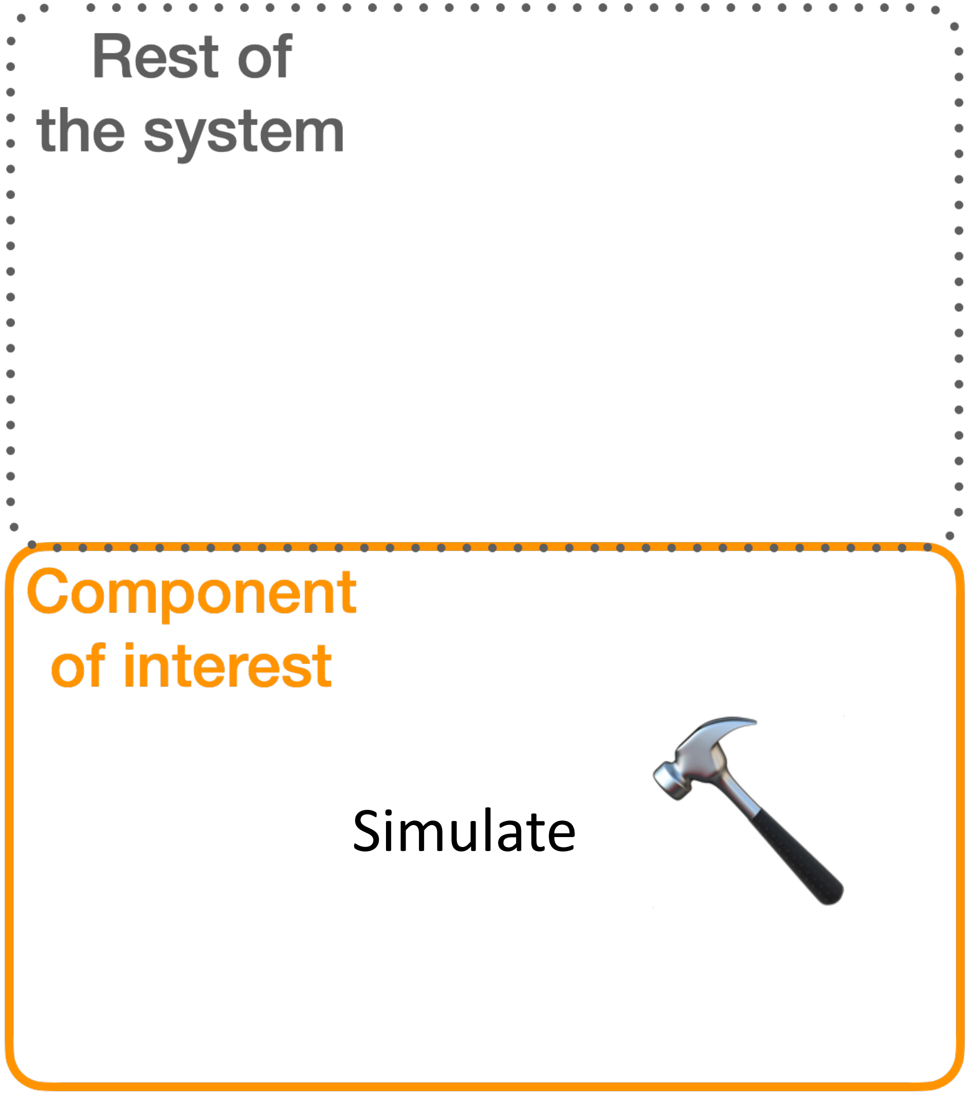

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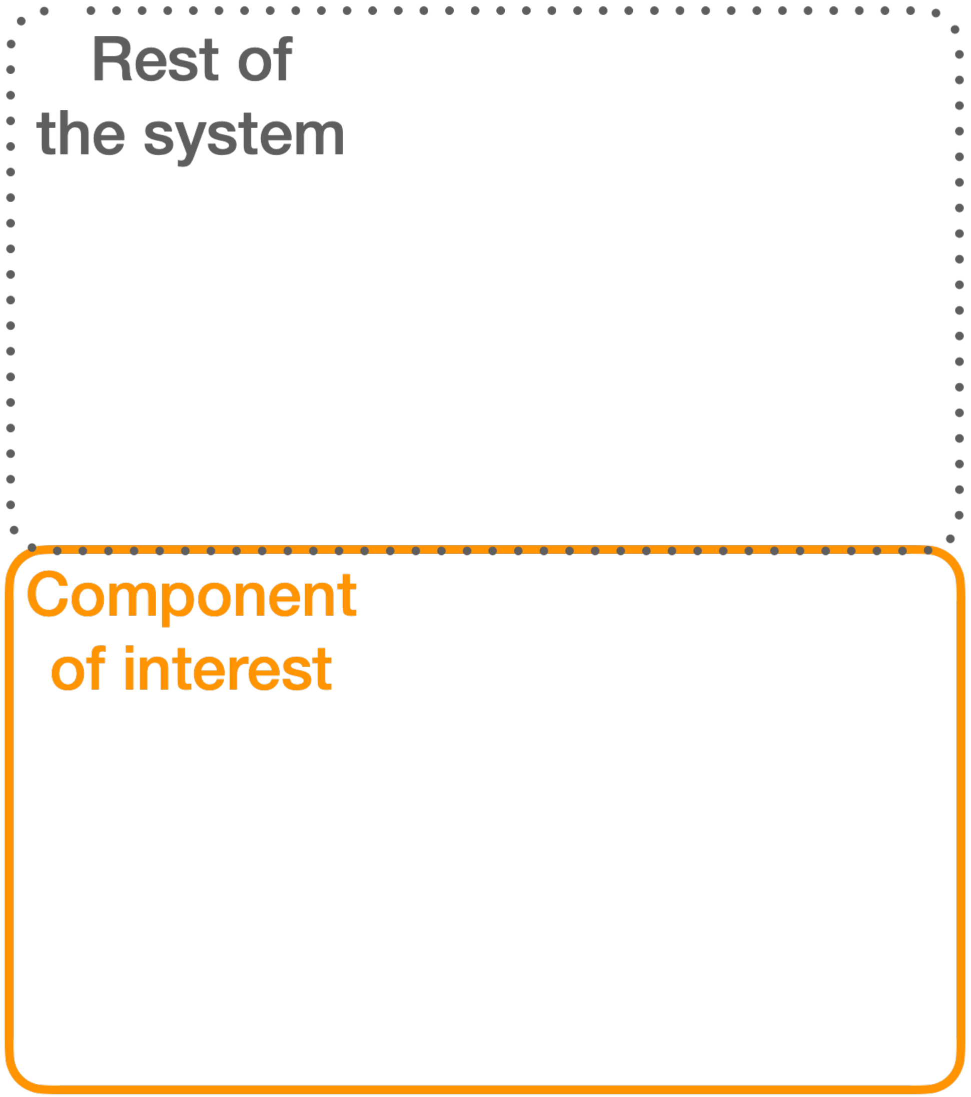

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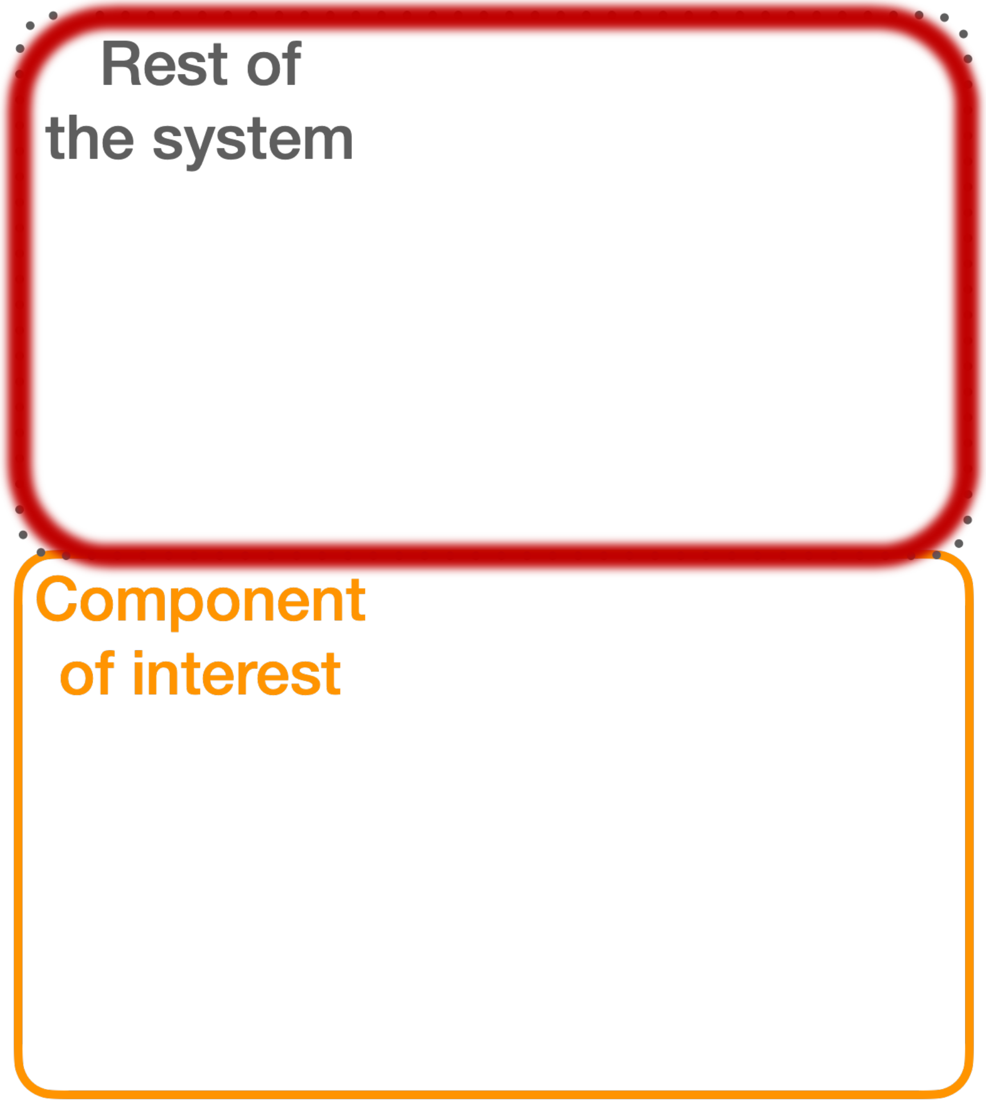

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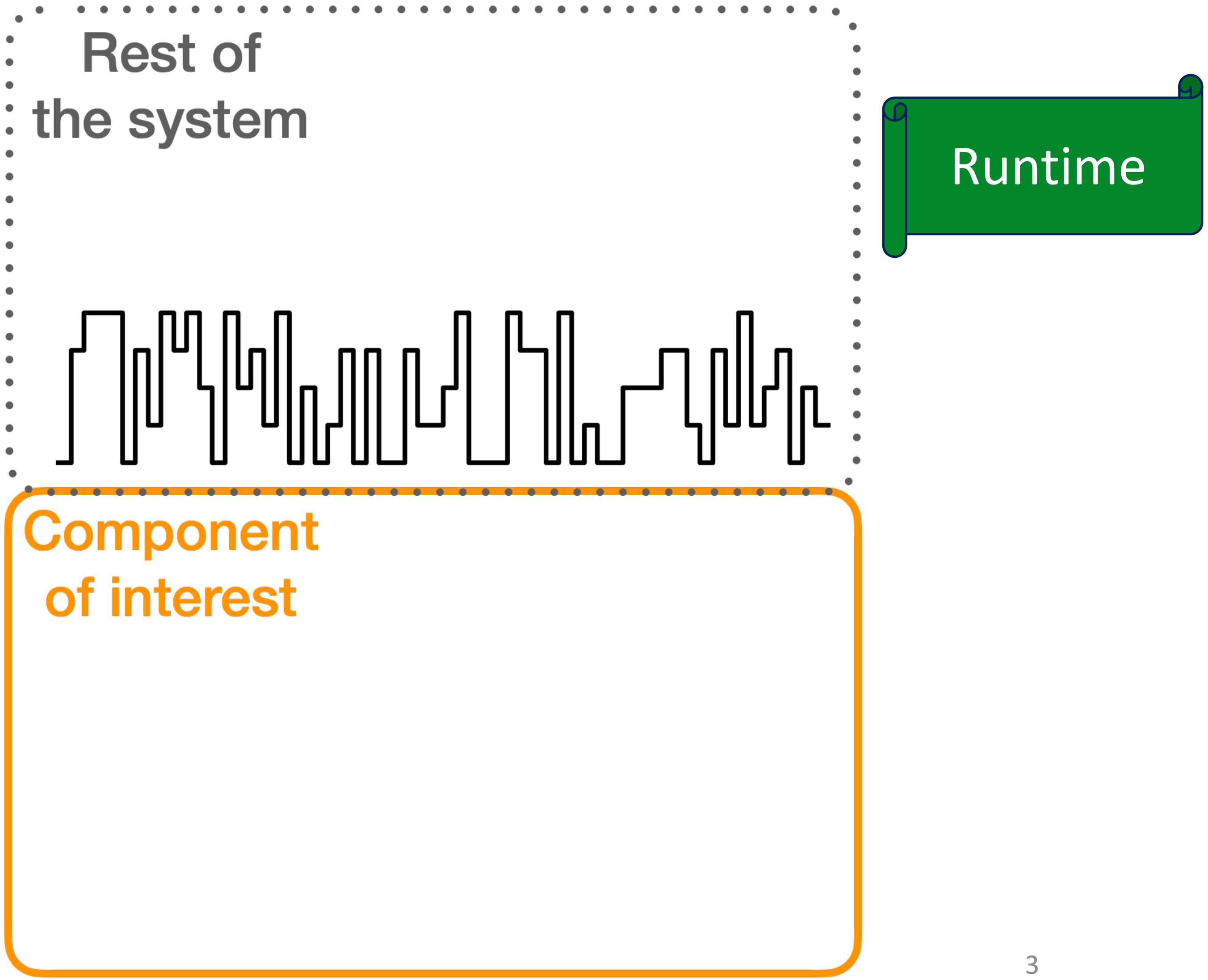

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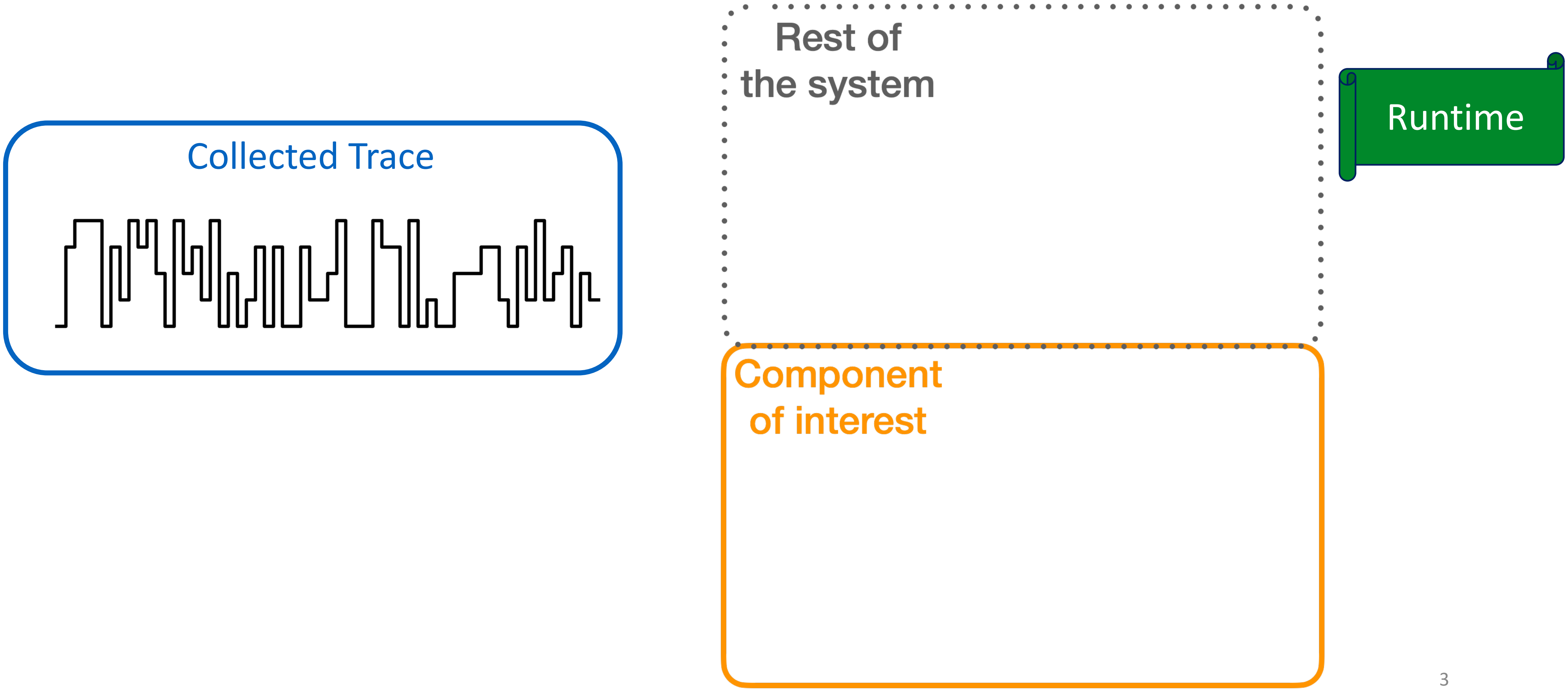


Collected Trace

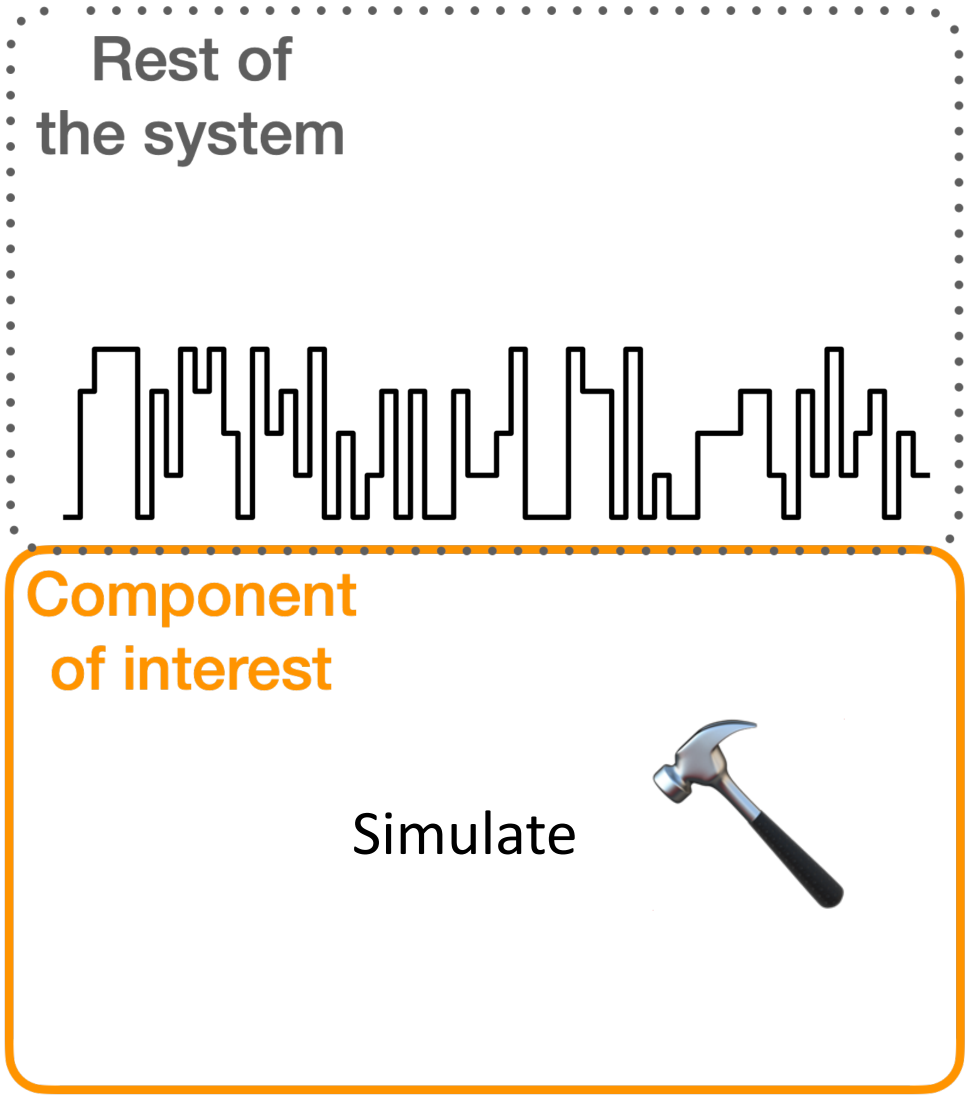
Rest of the system

Runtime

Component of interest

Exogenous trace assumption in trace-driven simulation

Collected Trace



Rest of the system

Component of interest

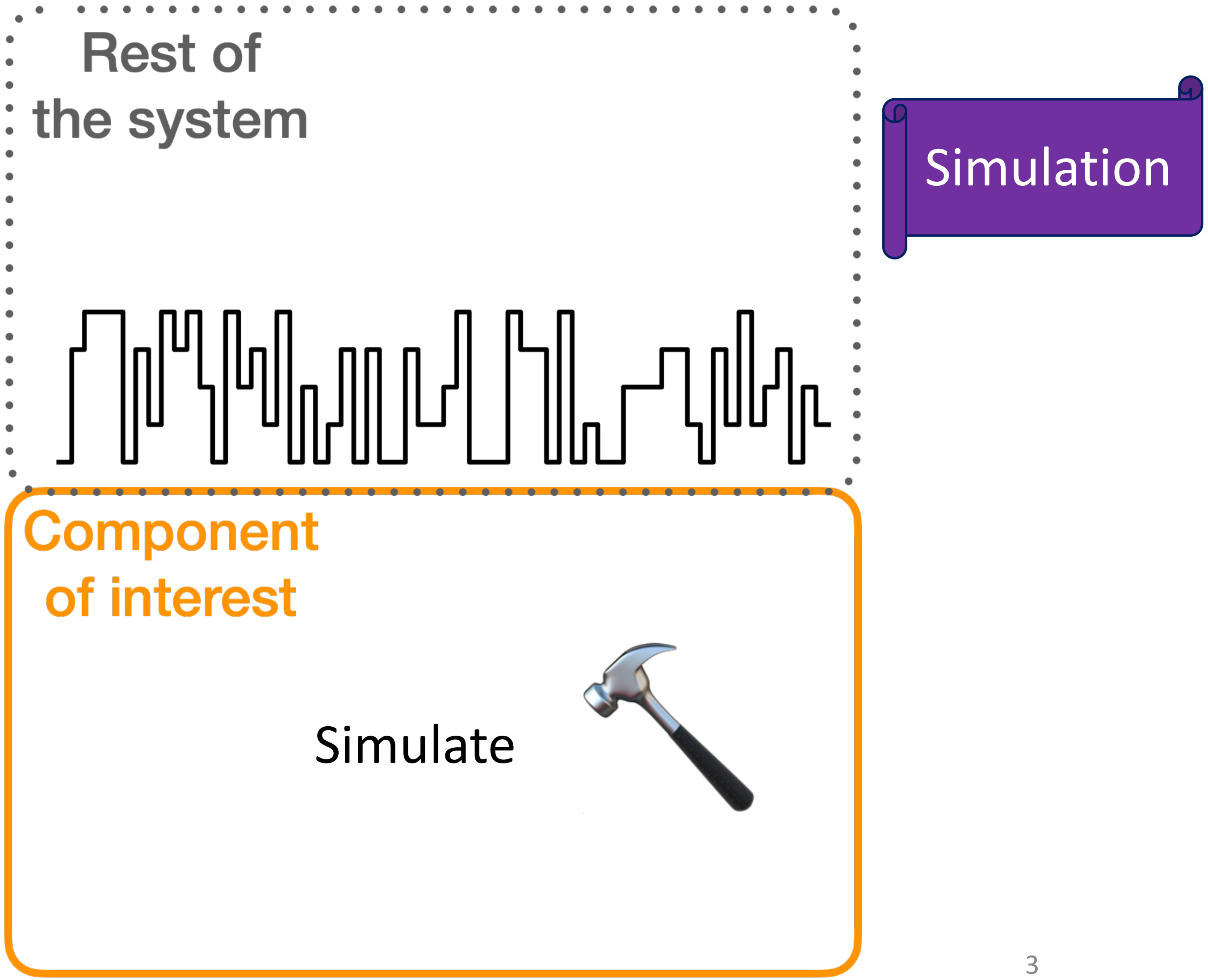
Simulate

Simulation

Exogenous trace assumption in trace-driven simulation

Collected Trace

- ***Exogenous trace*** assumption: Simulated interventions would not affect the replayed trace.



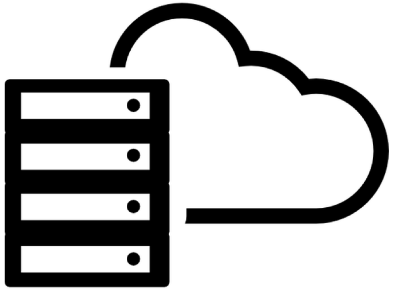
Exogenous trace assumption does not hold for many real-world traces

Exogenous trace assumption does not hold for many real-world traces

… hurts accuracy, can lead to completely wrong conclusions

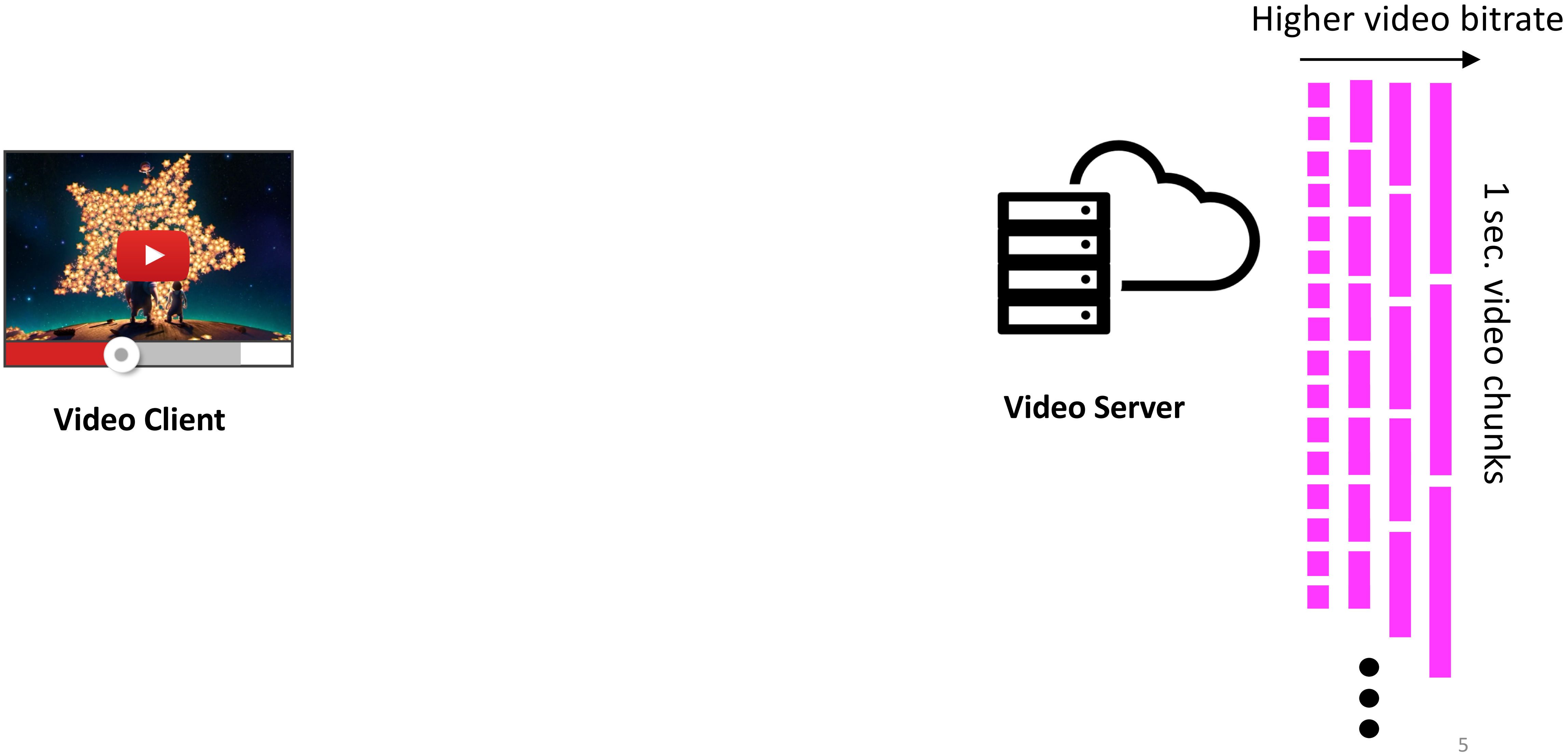
Example: Adaptive Bitrate Video Streaming (ABR)

Video Client



Video Server

Example: Adaptive Bitrate Video Streaming (ABR)



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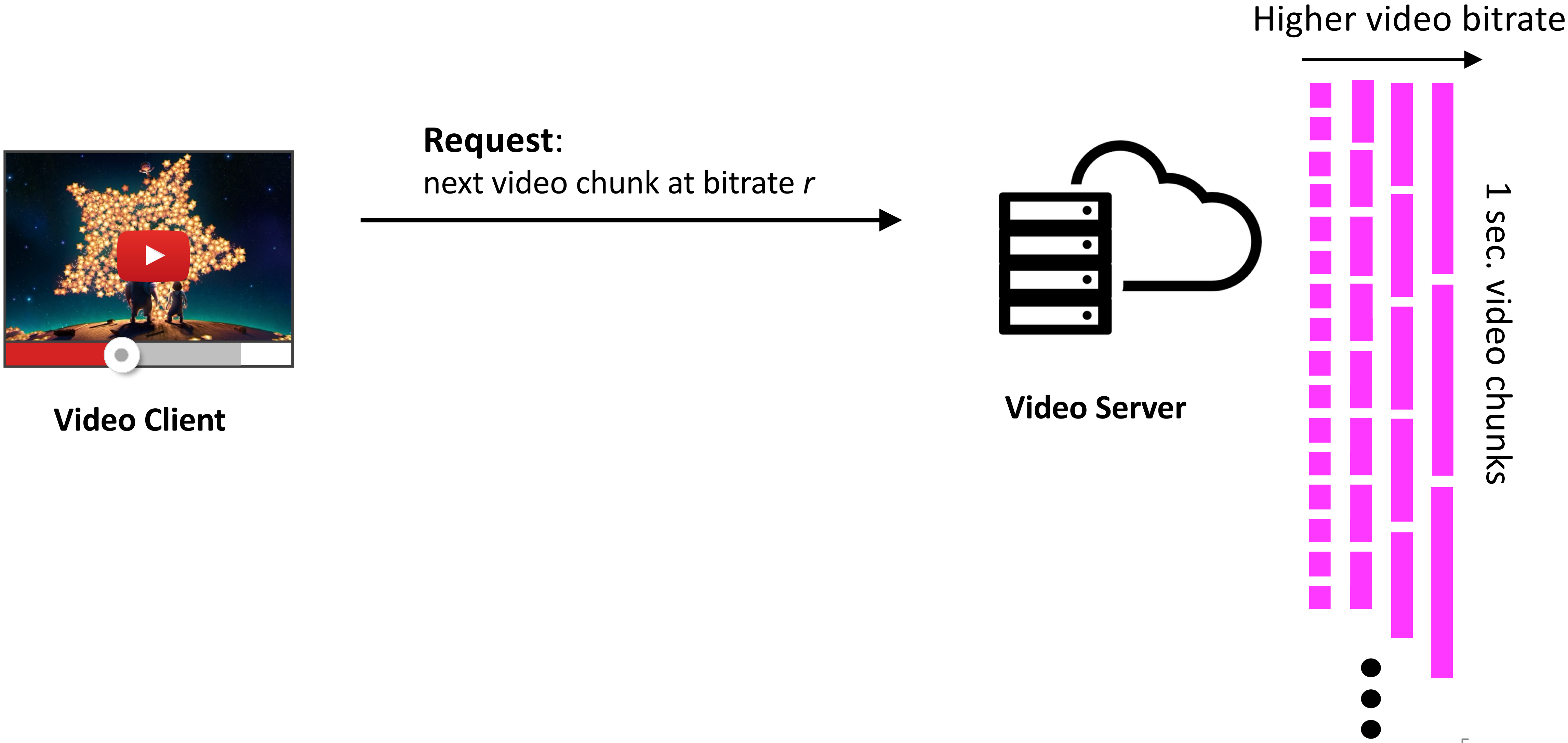
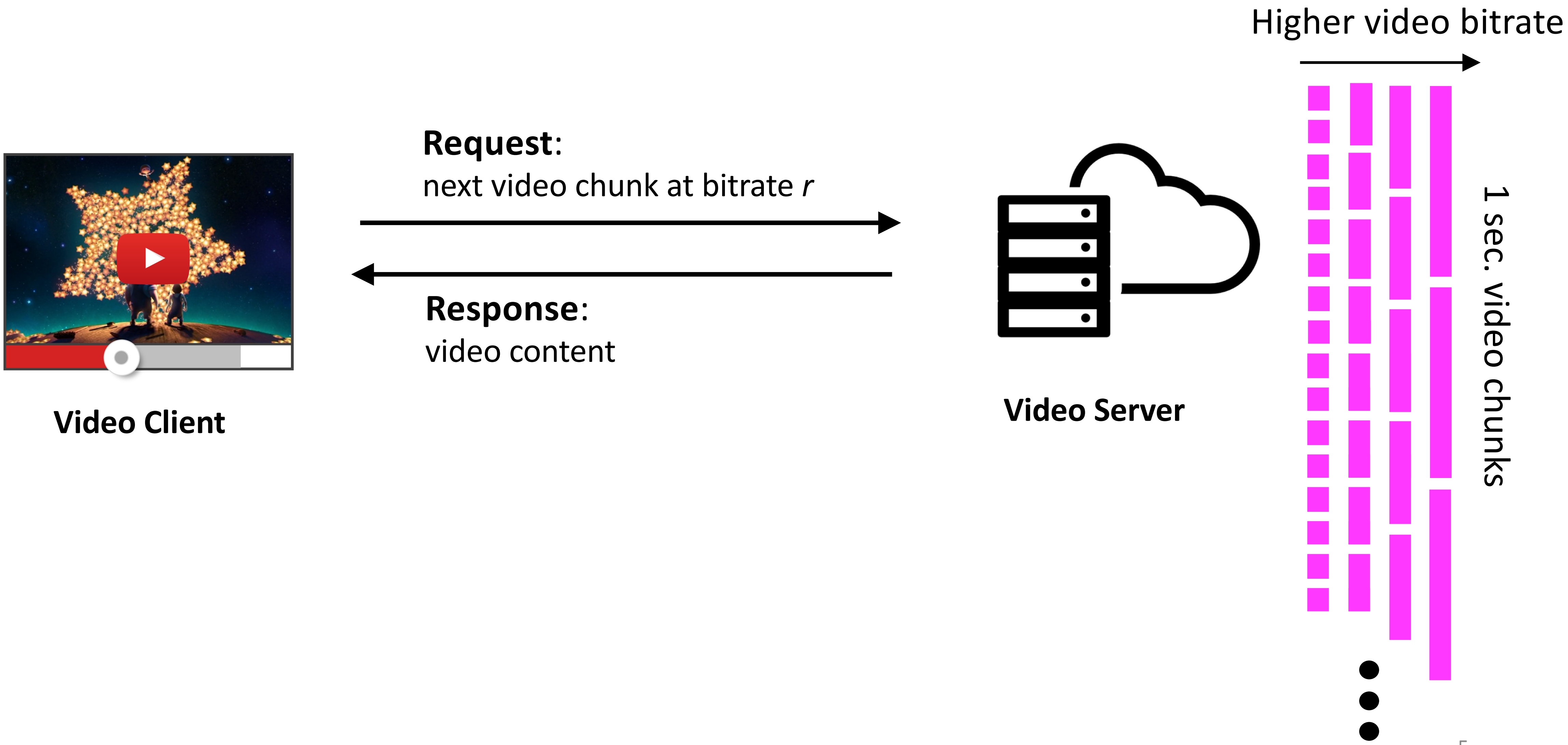


Request:
next video chunk at bitrate *r*

Example: Adaptive Bitrate Video Streaming (ABR)



Request:
next video chunk at bitrate *r*

Response:
video content

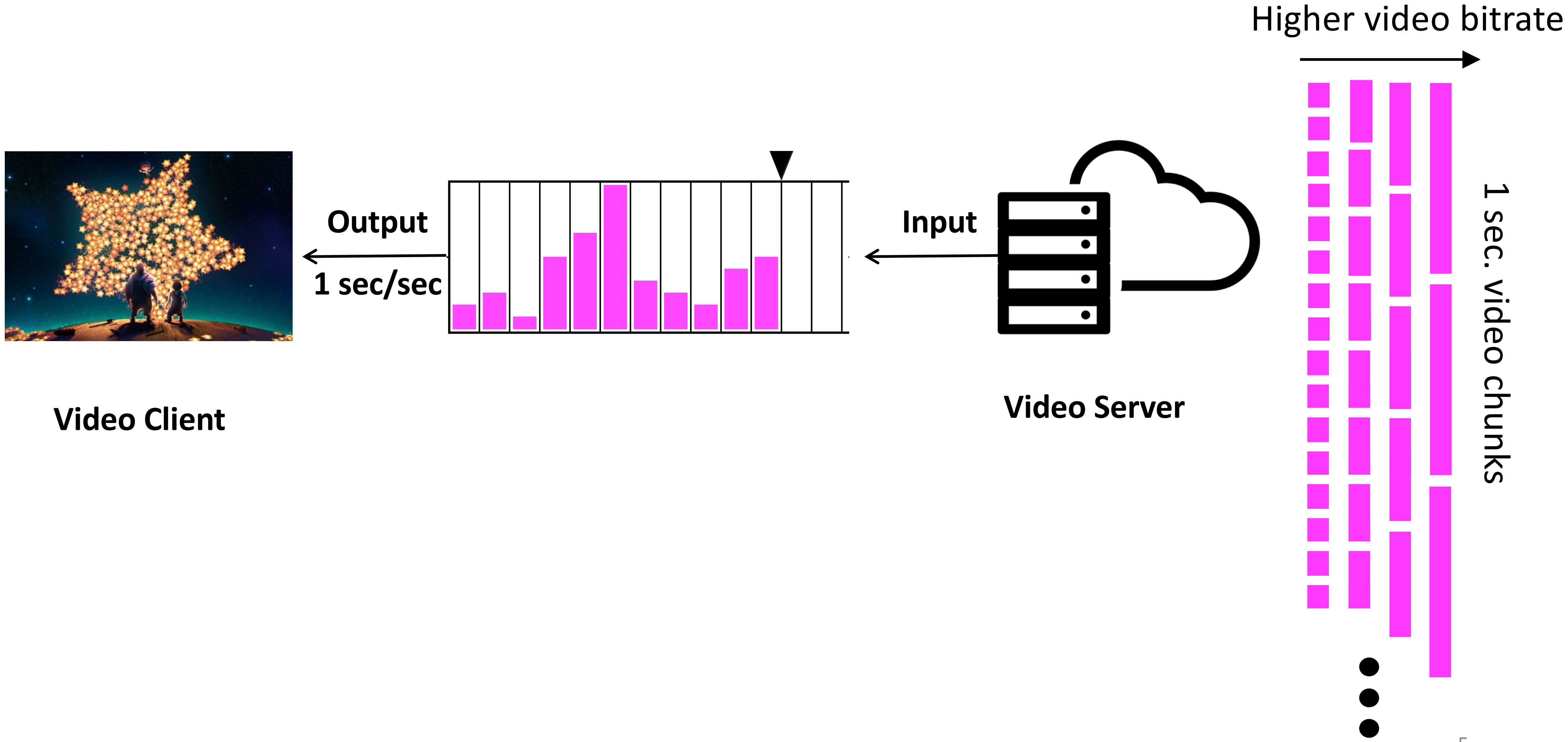
Video Client

Video Server

Higher video bitrate

1 sec. video chunks

Example: Adaptive Bitrate Video Streaming (ABR)



Higher video bitrate

Output

1 sec/sec

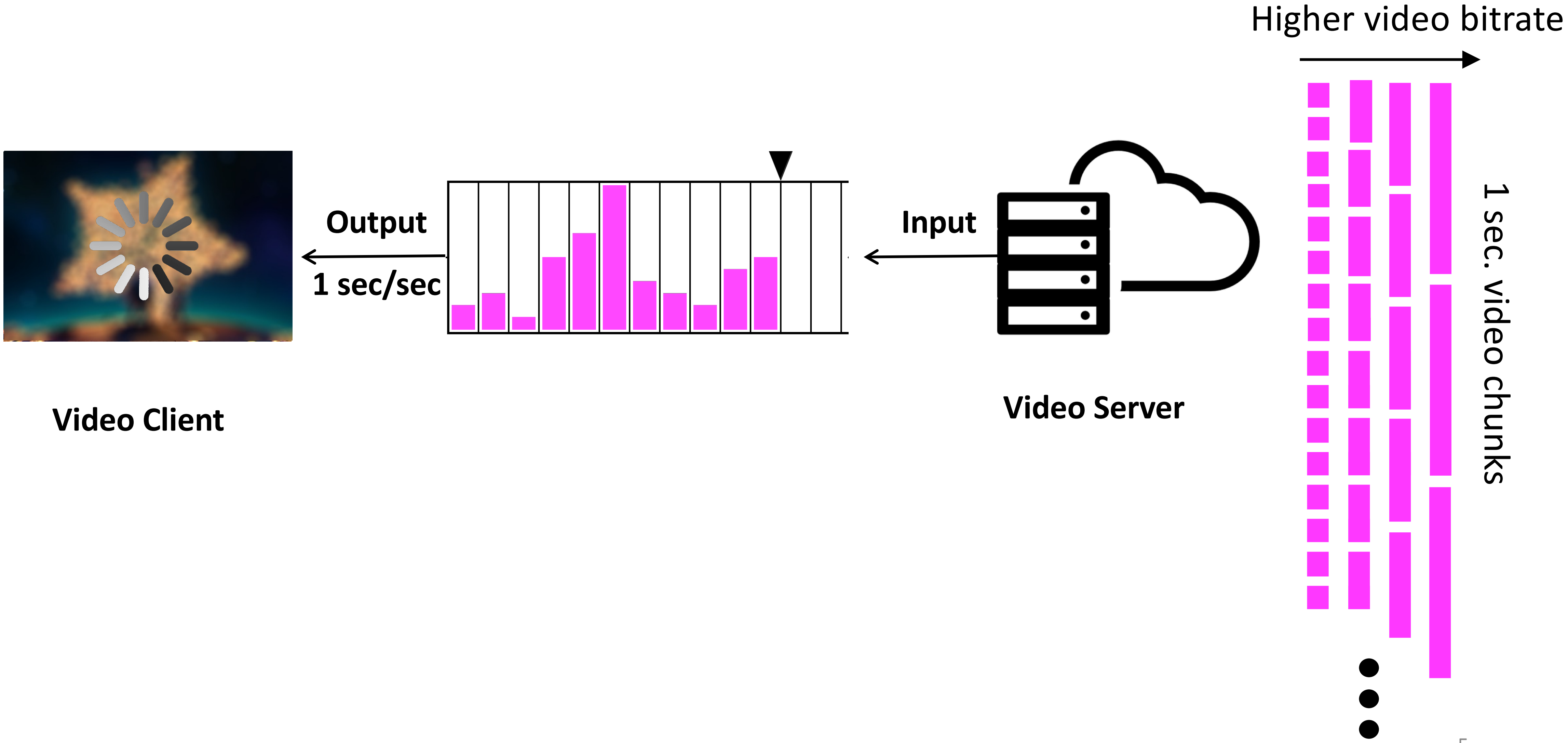
Input

1 sec. video chunks

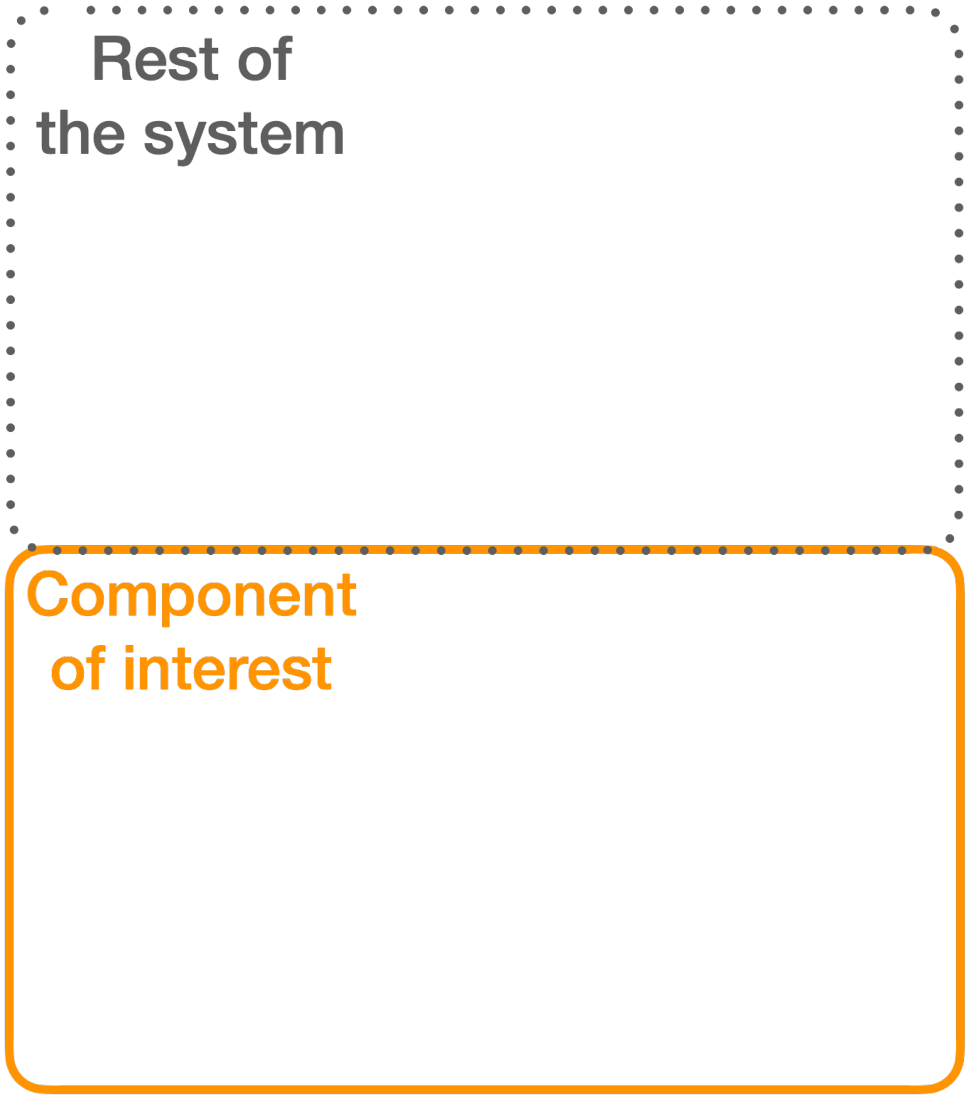
Video Client

Video Server

Example: Adaptive Bitrate Video Streaming (ABR)



Trace-driven simulation for ABR



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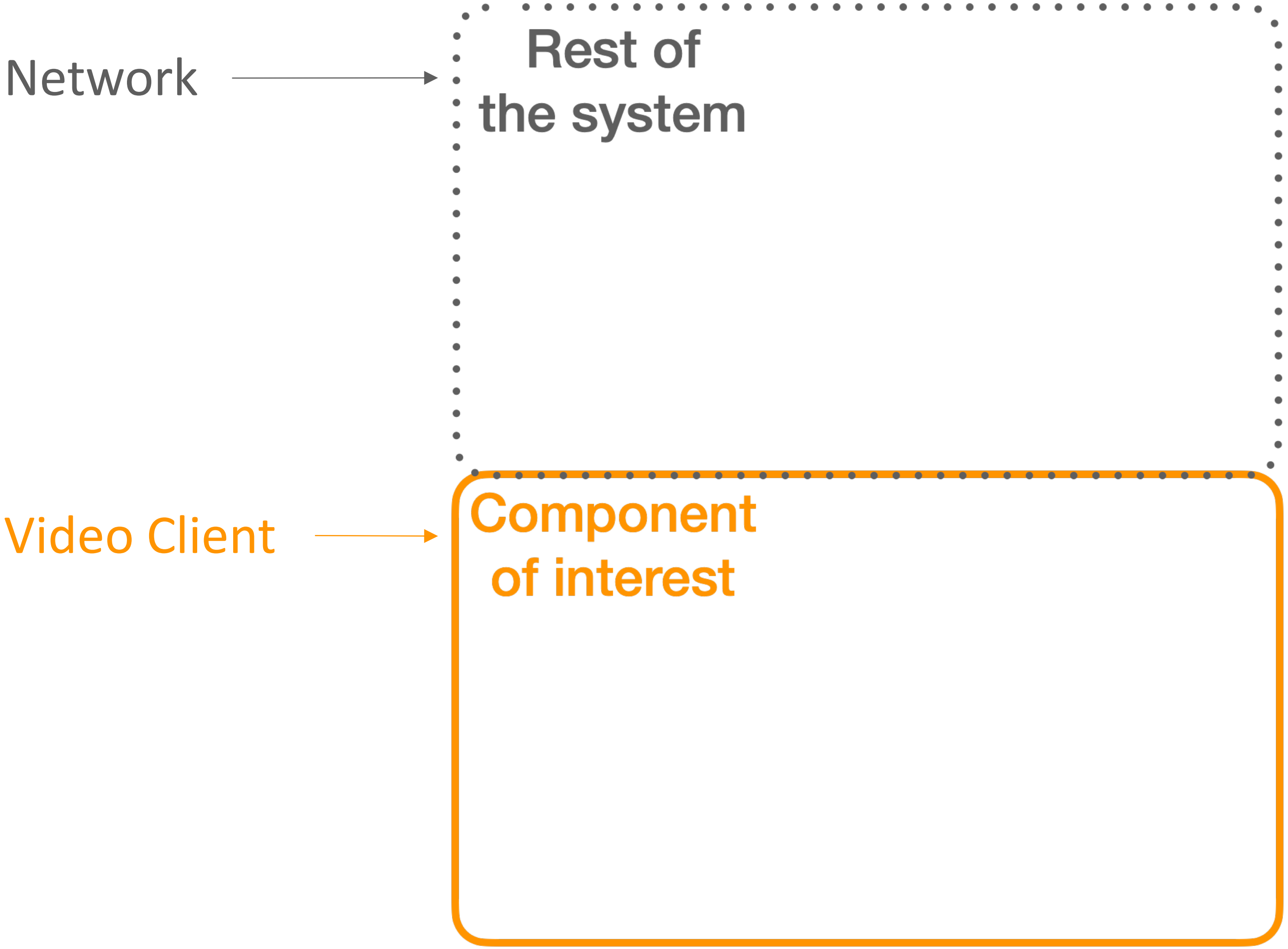

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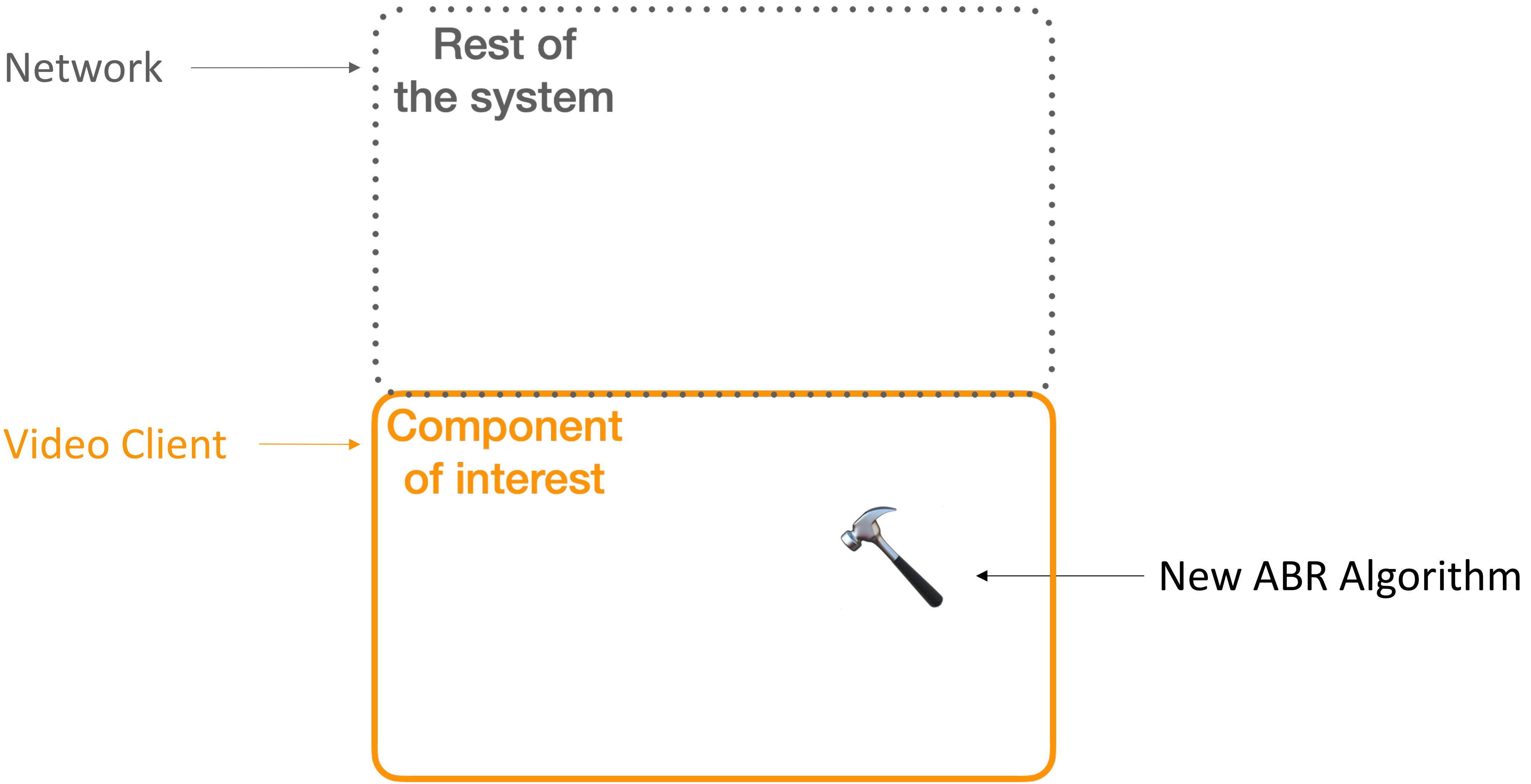

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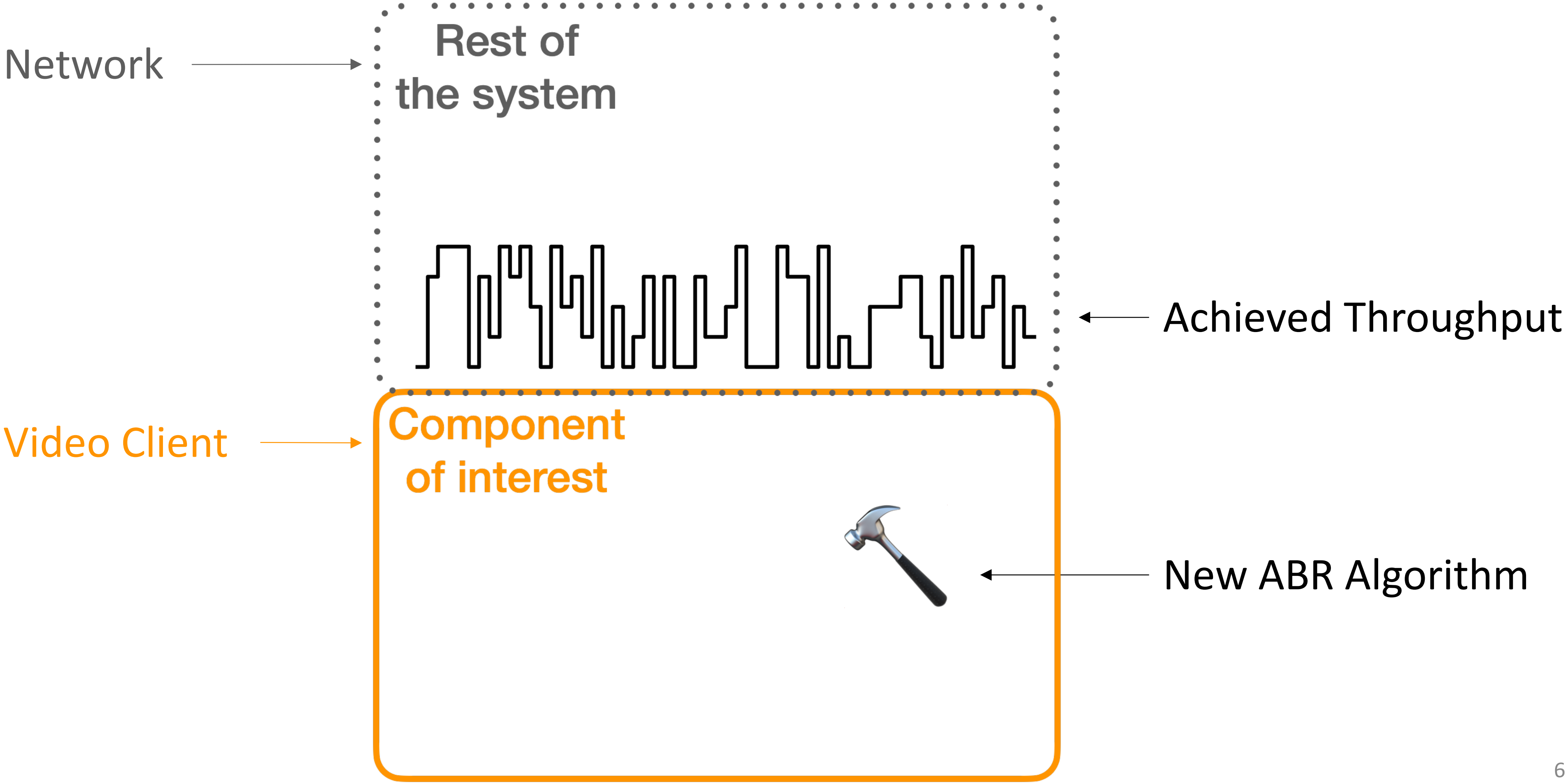

Trace-driven simulation for ABR

- ExpertSim

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download time

playback buffer
(in sec)

$$b_{t+1} = \max\left(b_t - \ d_t \ , 0\right) + T$$

Trace-driven simulation for ABR

- ExpertSim

chunk size (The new algorithm’s choice)

playback buffer (in sec)

$$b_{t+1} = \max\left(b_t - \frac{a_t}{m_t}, 0\right) + T$$

achieved throughput (from the replayed trace)

Trace-driven simulation for ABR

- ExpertSim
  - [Yin et al. SIGCOMM’15][Mao et al. SIGCOMM’17]

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The Puffer dataset

- The Puffer Randomized Control Trial [Yan et al. NSDI 2020]
  - July 2020 – June 2021
  - 5 ABR algorithms
  - 56M downloaded chunks over 230K streaming sessions
  - 3.5 years worth of streamed video

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Task: Given the traces for all except one ABR algorithm, simulate the held out algorithm on the same paths

A typical trace

Chunk #	1	2	3	
Bitrate	360p	480p	480p	
Achieved Throughput	1Mbps	0.8Mbps	1.2Mbps	• • •
Playback Buffer	5s	3s	7s	

<u>Algorithm</u>

BBA

(“**source**”)

A typical trace

Chunk #	1	2	3	
Bitrate	360p	480p	480p	
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Algorithm
BBA
("**source**")

Algorithm
BOLA1
("**target**")

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<u>Algorithm</u>
BBA
("**source**")

A simulated trajectory

Chunk #	1
Bitrate	**720p**
Achieved Throughput	**?**
Playback Buffer	**?**

<u>Algorithm</u>
BOLA1
("**target**")

A typical trace

Chunk #	1	2	3	
Bitrate	360p	480p	480p	
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Algorithm
BBA
(“**source**”)

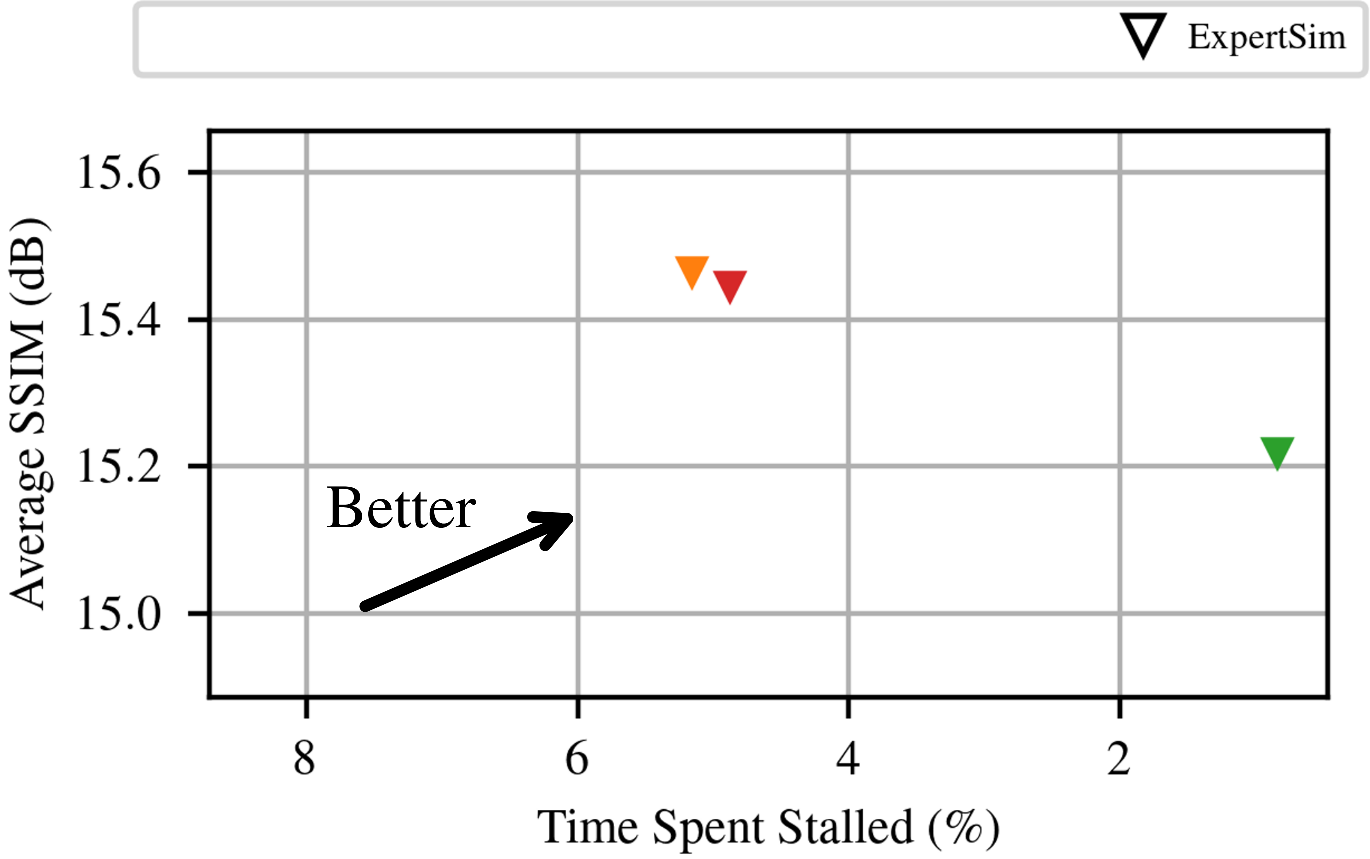
A simulated trajectory

Chunk #	1	2	3	
Bitrate	**720p**	**?**	**?**	
Achieved Throughput	**?**	**?**	**?**	…
Playback Buffer	**?**	**?**	**?**	

Algorithm
BOLA1
(“**target**”)

How accurate is trace-driven simulation?

- Source data: The Puffer Dataset with 5 algorithms
- Target algorithm (unseen): BBA, BOLA1, BOLA2



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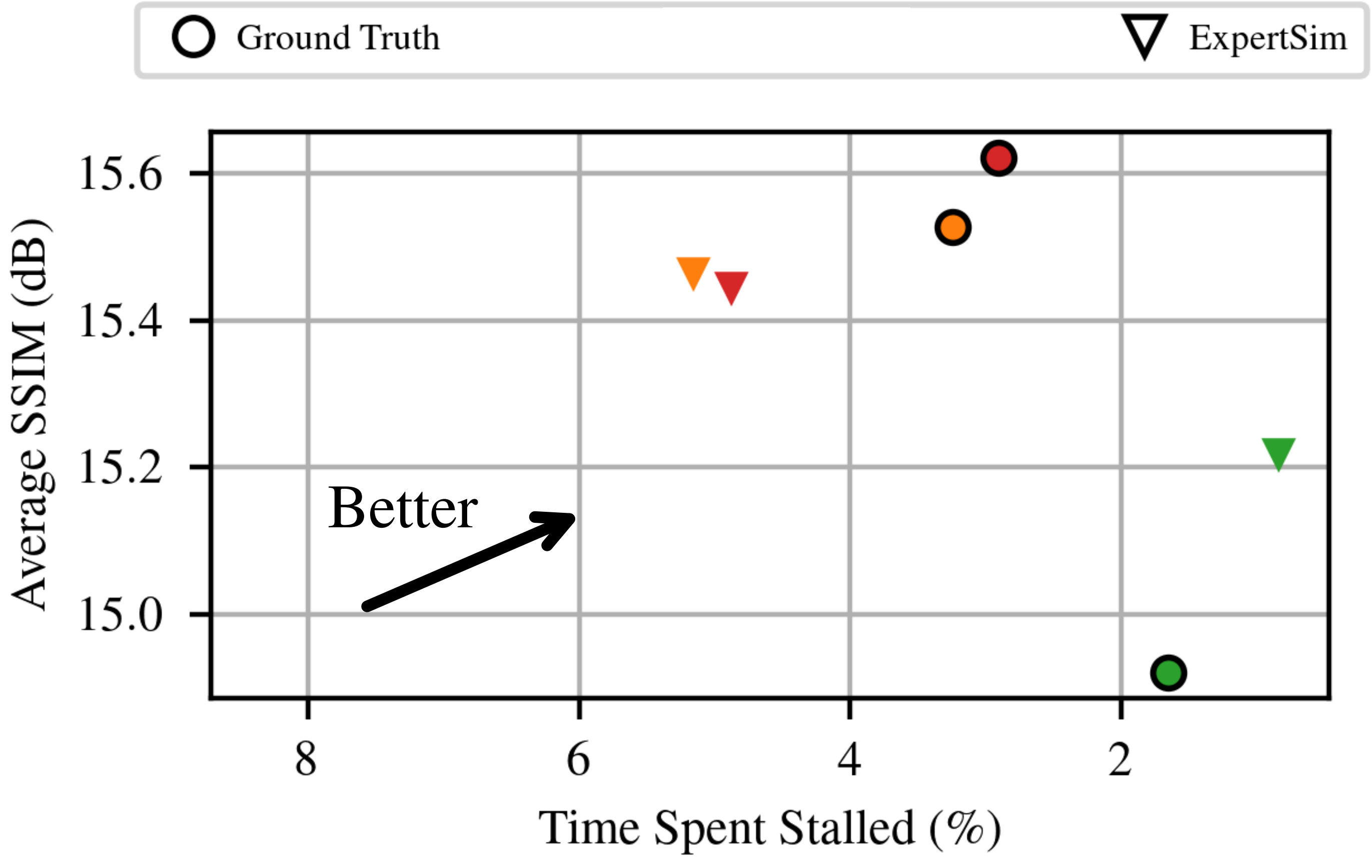

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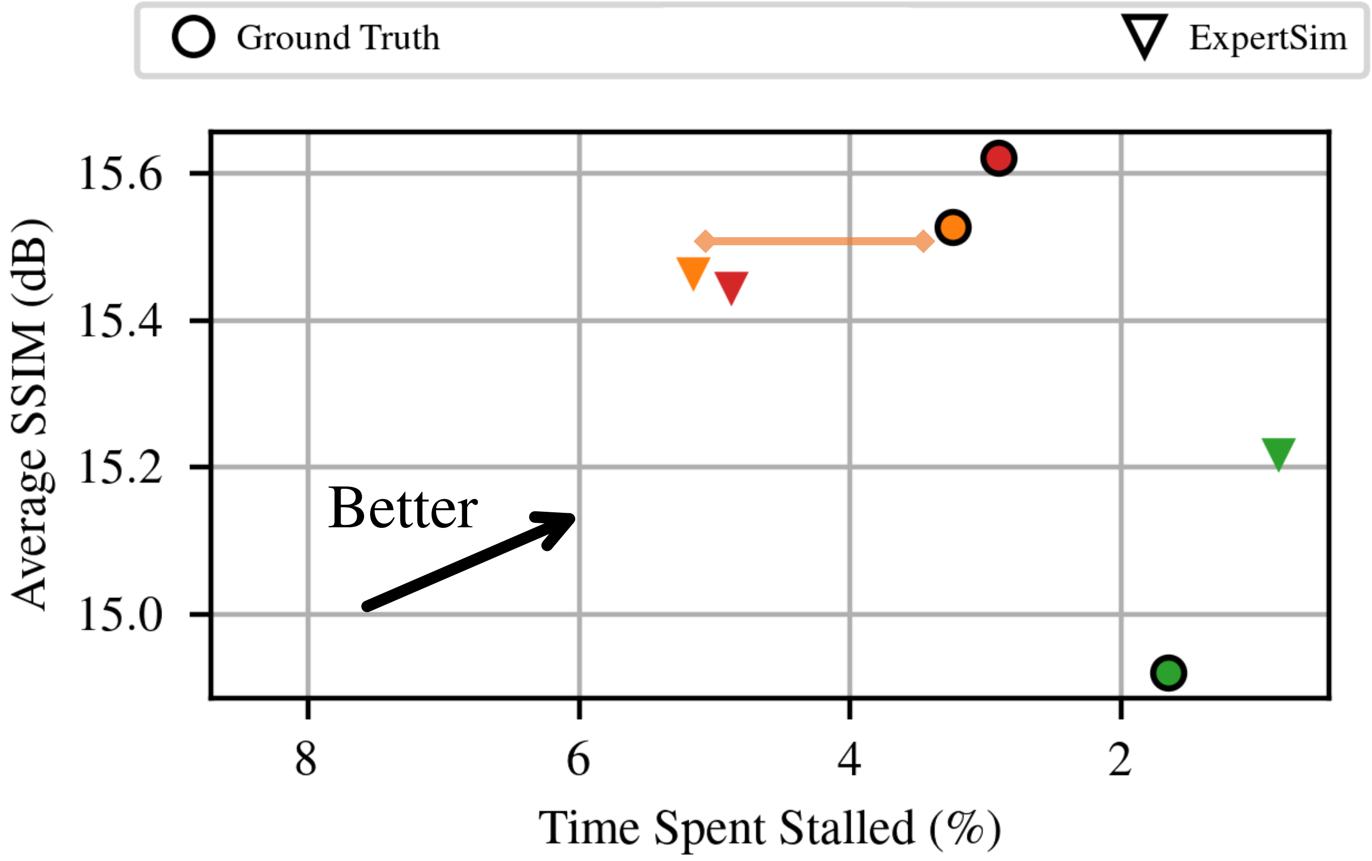

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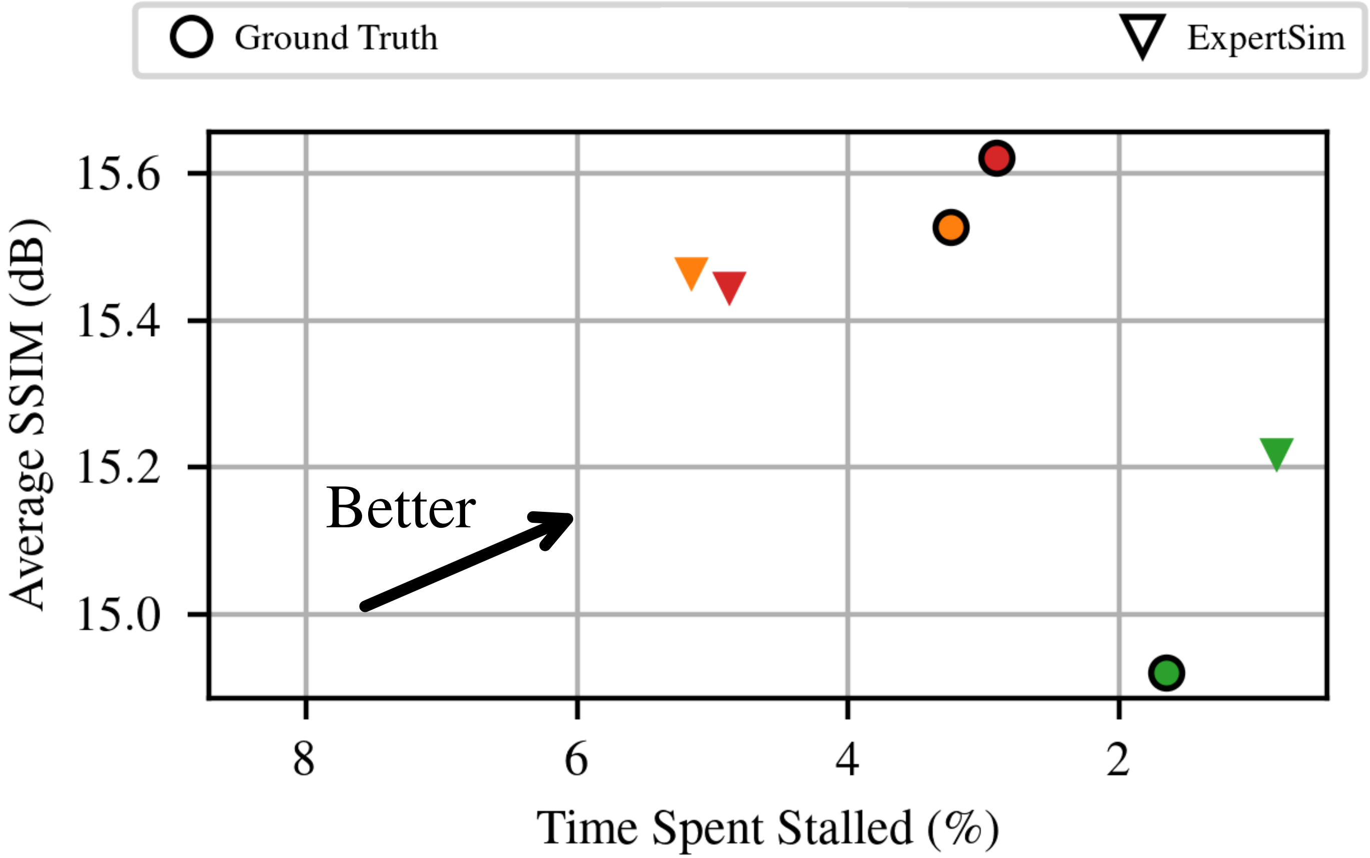
Exogenous trace assumption



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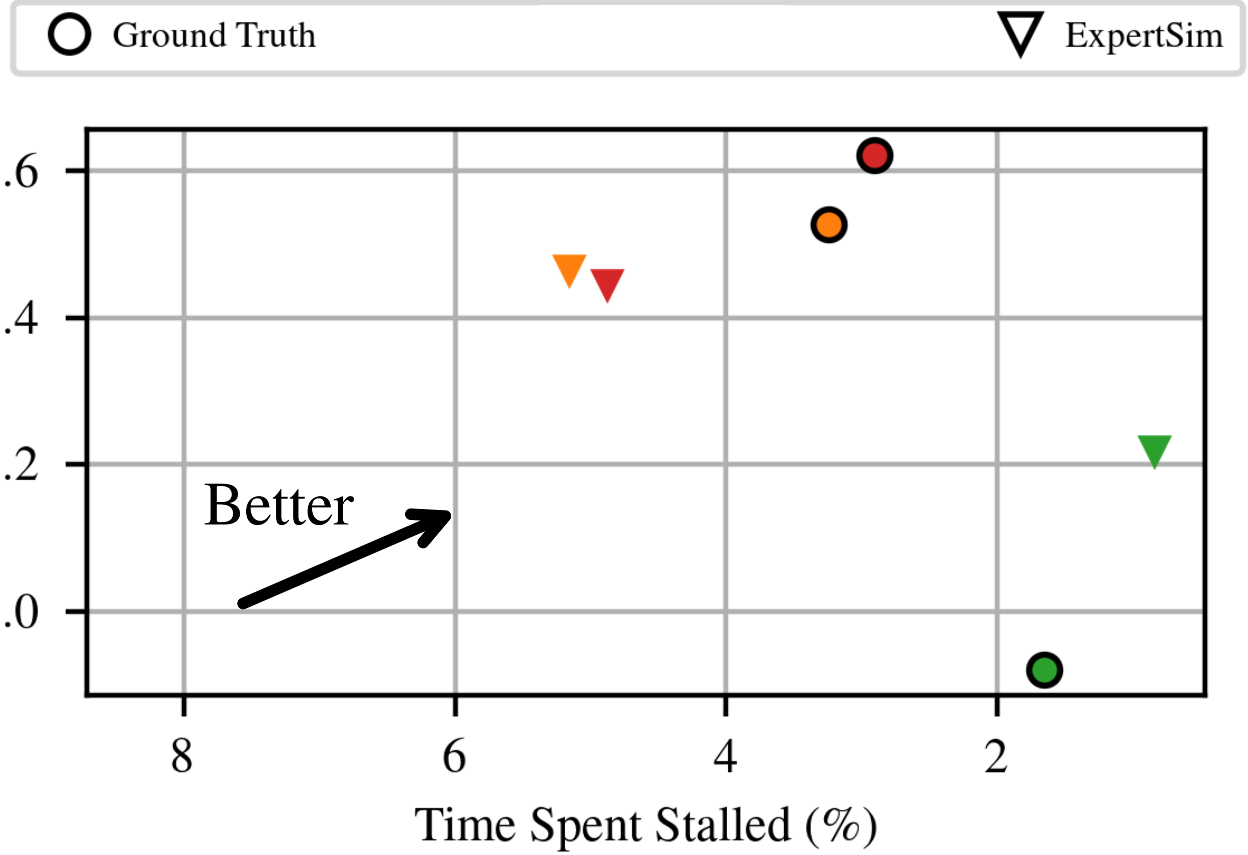
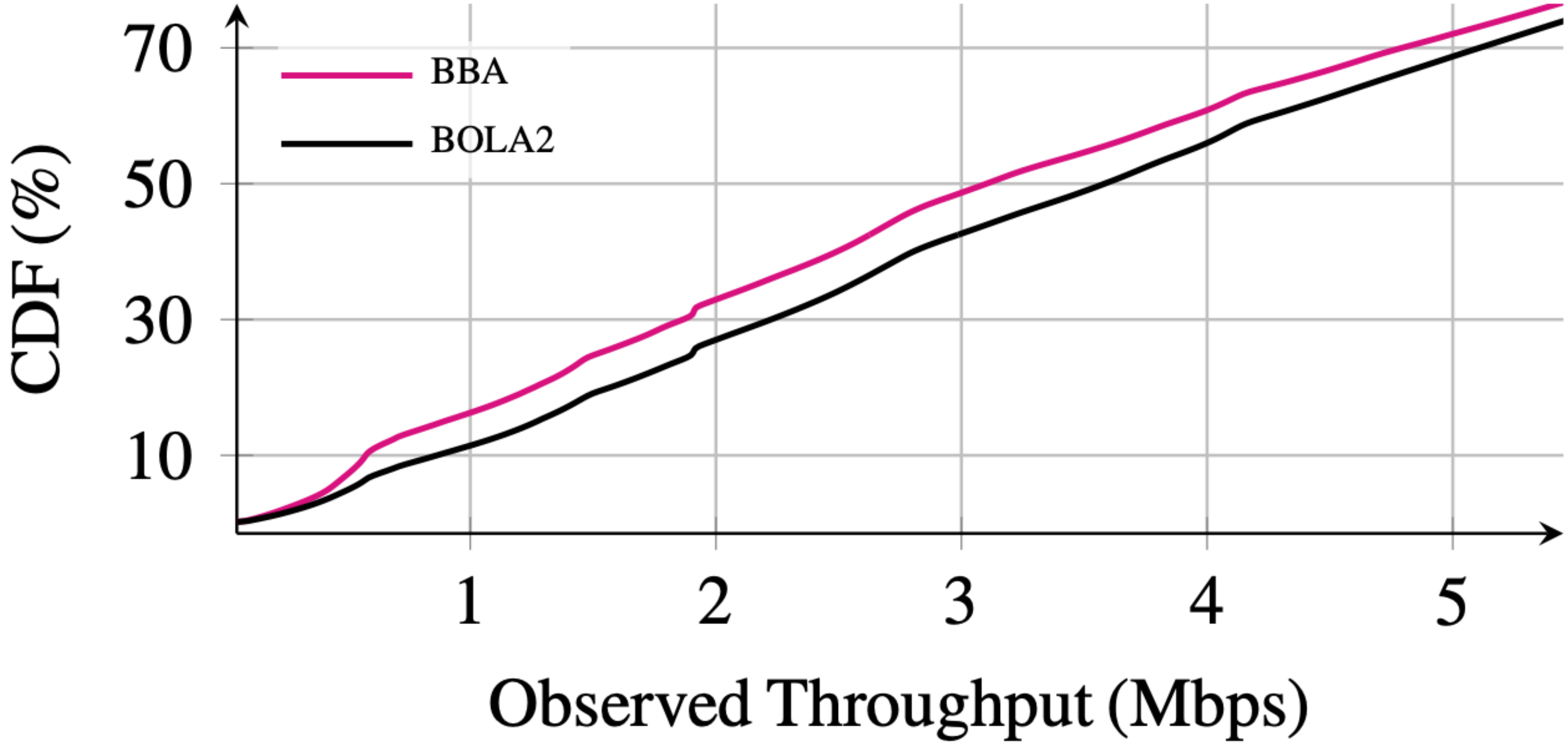


Exogenous trace assumption

Bitrates chosen by the ABR algorithm affect the achieved throughput.

ABR algorithms affect throughput



Can we relax the exogenous trace assumption?

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$$\overset{\substack{\text{Achieved Throughput}\\ \nwarrow}}{m_t}$$

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Achieved Throughput

$$m_t = f(\qquad\qquad)$$

Can we relax the exogenous trace assumption?

$$\overset{\text{Achieved Throughput}}{\uparrow}\; m_t = f(\overset{\text{Bitrate}}{\uparrow}\; a_t \qquad)$$

Can we relax the exogenous trace assumption?

$$\overset{\text{Achieved Throughput}}{\overset{\nwarrow}{m_t}} = f\left(\overset{\text{Bitrate}}{\overset{\uparrow}{a_t}}, \overset{\text{Latent Network Conditions}}{\overset{\nearrow}{u_t}}\right)$$

Can we relax the exogenous trace assumption?

Achieved Throughput Bitrate Latent Network Conditions

$$m_t = f(a_t, u_t)$$

Both u_t and $f(\cdot)$ are unknown

Towards a solution

$$m_t = f(a_t, u_t)$$

Towards a solution

- If u and $f(\cdot)$ were known…

$$m_t = f(a_t, u_t)$$

Towards a solution

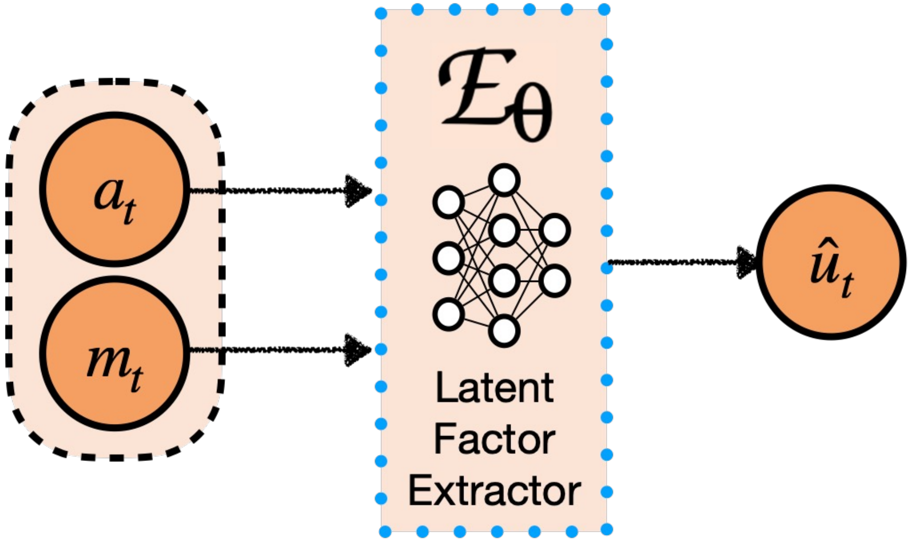
- If u and $f(\cdot)$ were known…

$$\widetilde{m}_t = f(\tilde{a}_t, u_t)$$

simulated bitrate
(counterfactual)

A learning approach

$m_t = f(a_t, u_t)$



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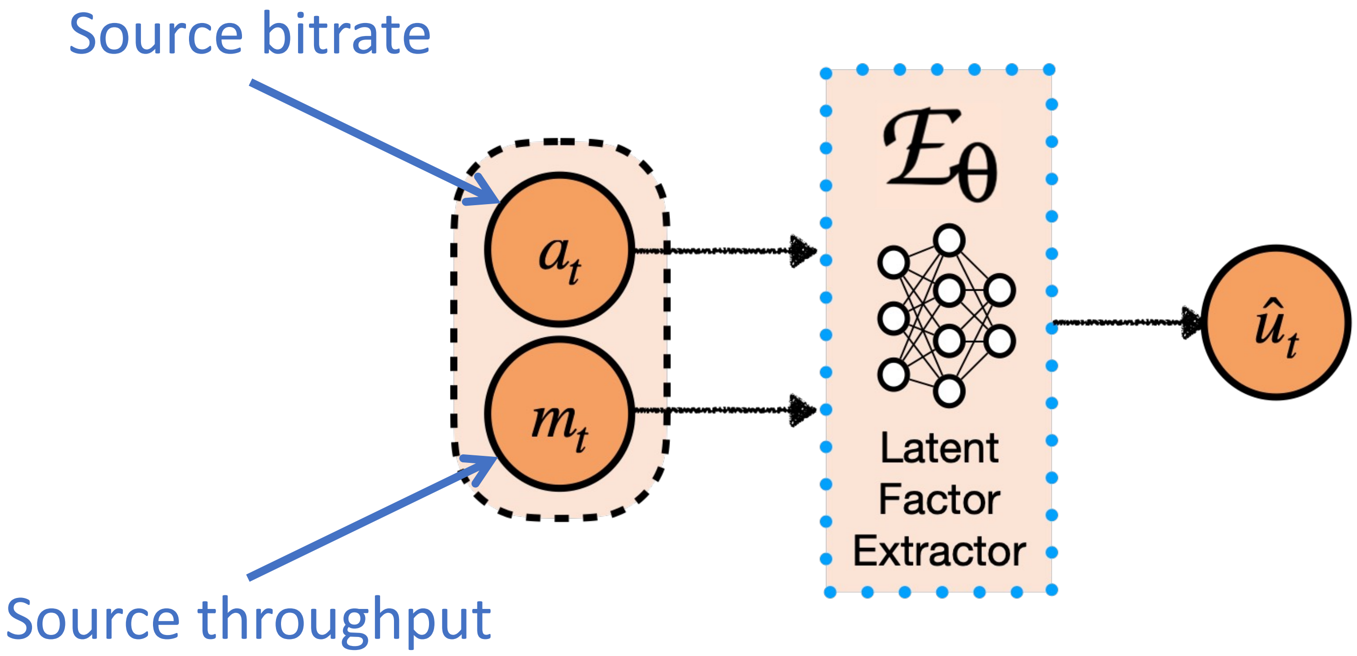

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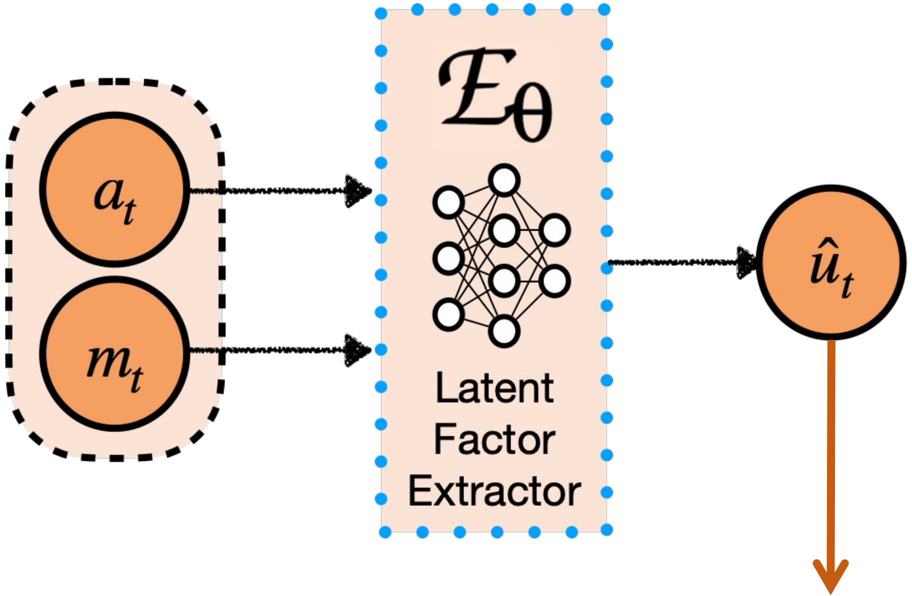
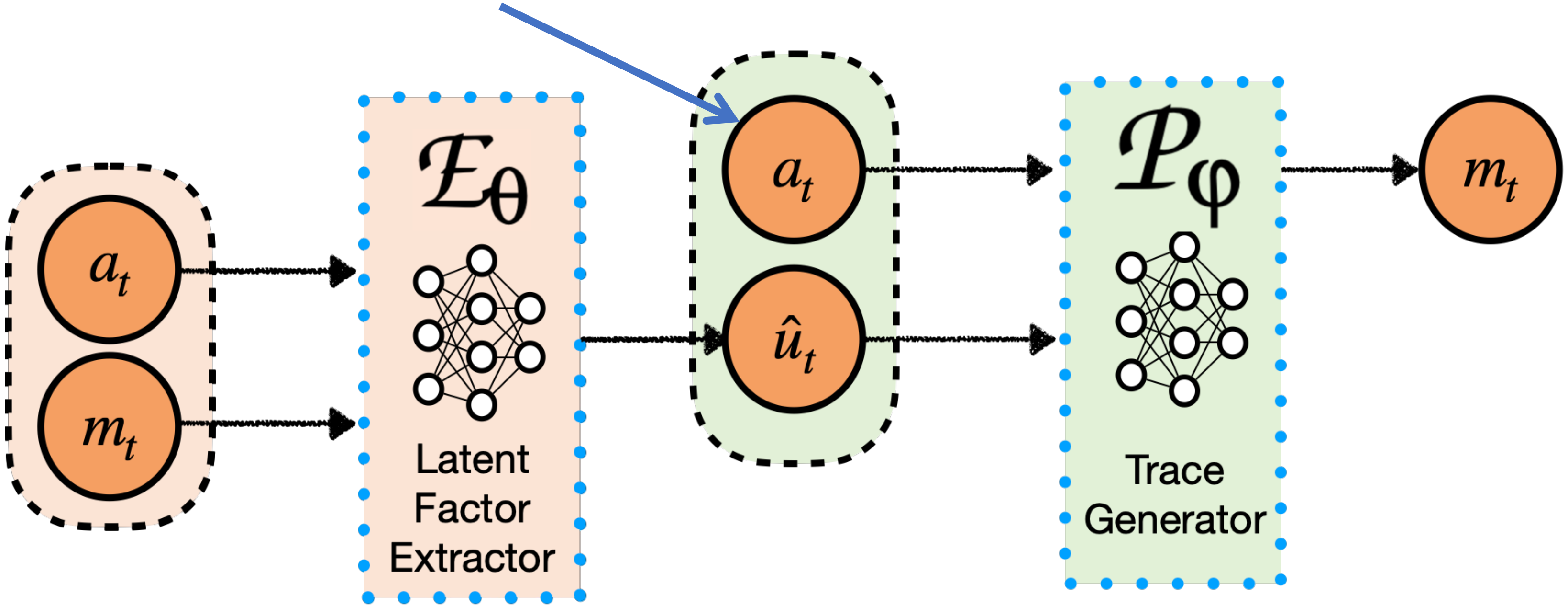


Informative for throughput reconstruction

A learning approach

$m_t = f(a_t, u_t)$

Source bitrate



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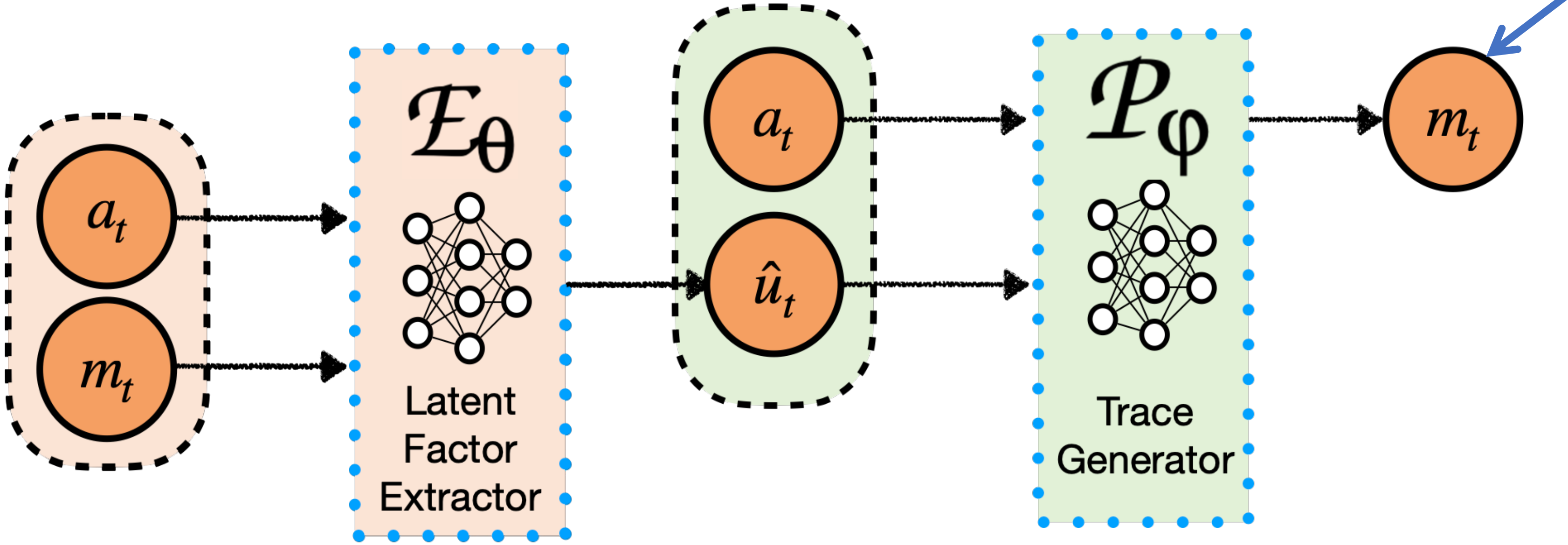

Source throughput

Learning goal

- Fit observed data

A learning approach

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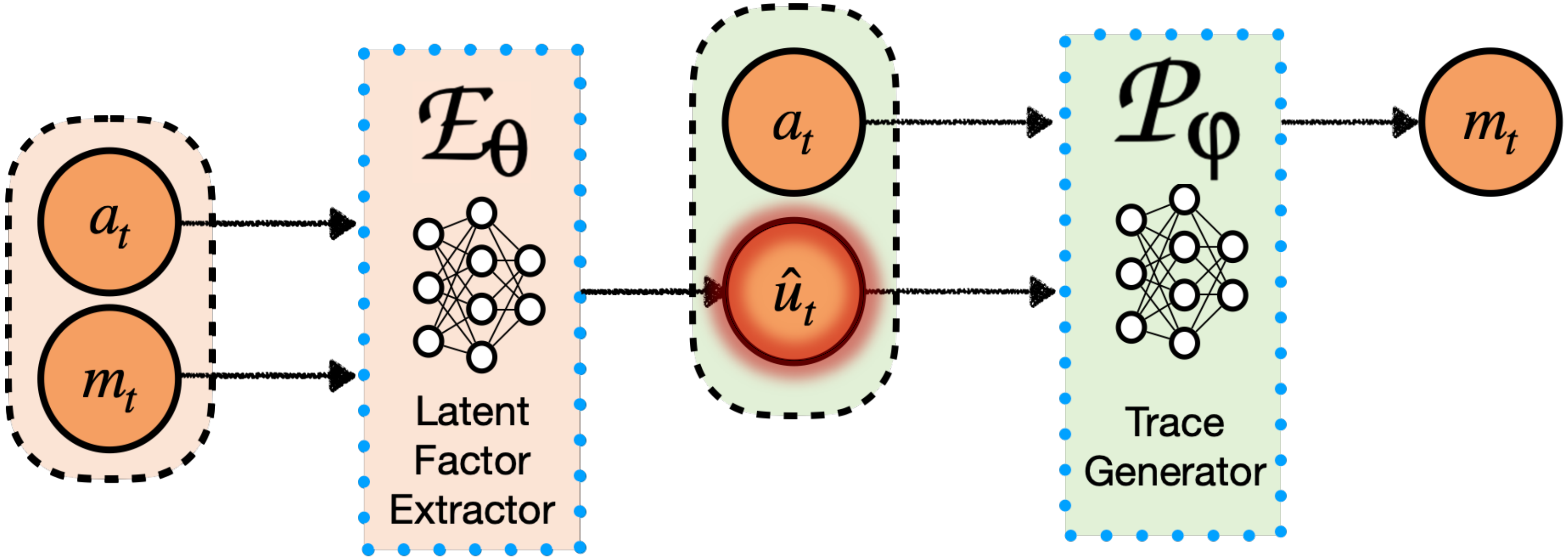

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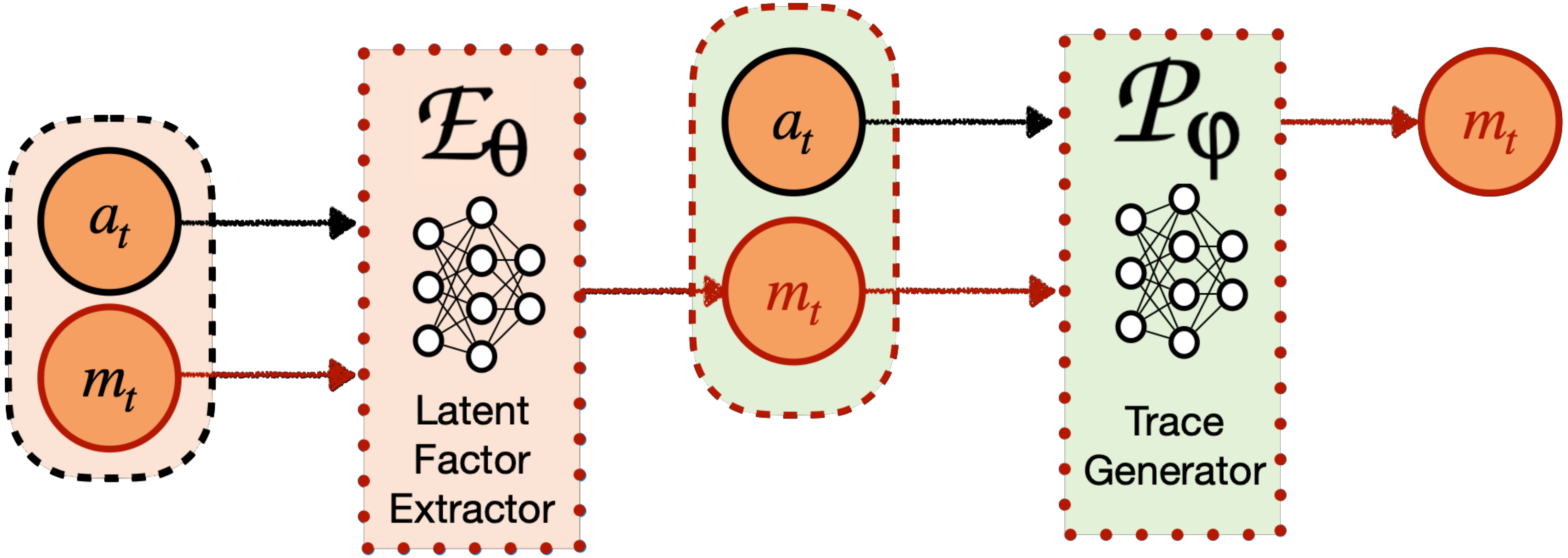

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A degenerate solution

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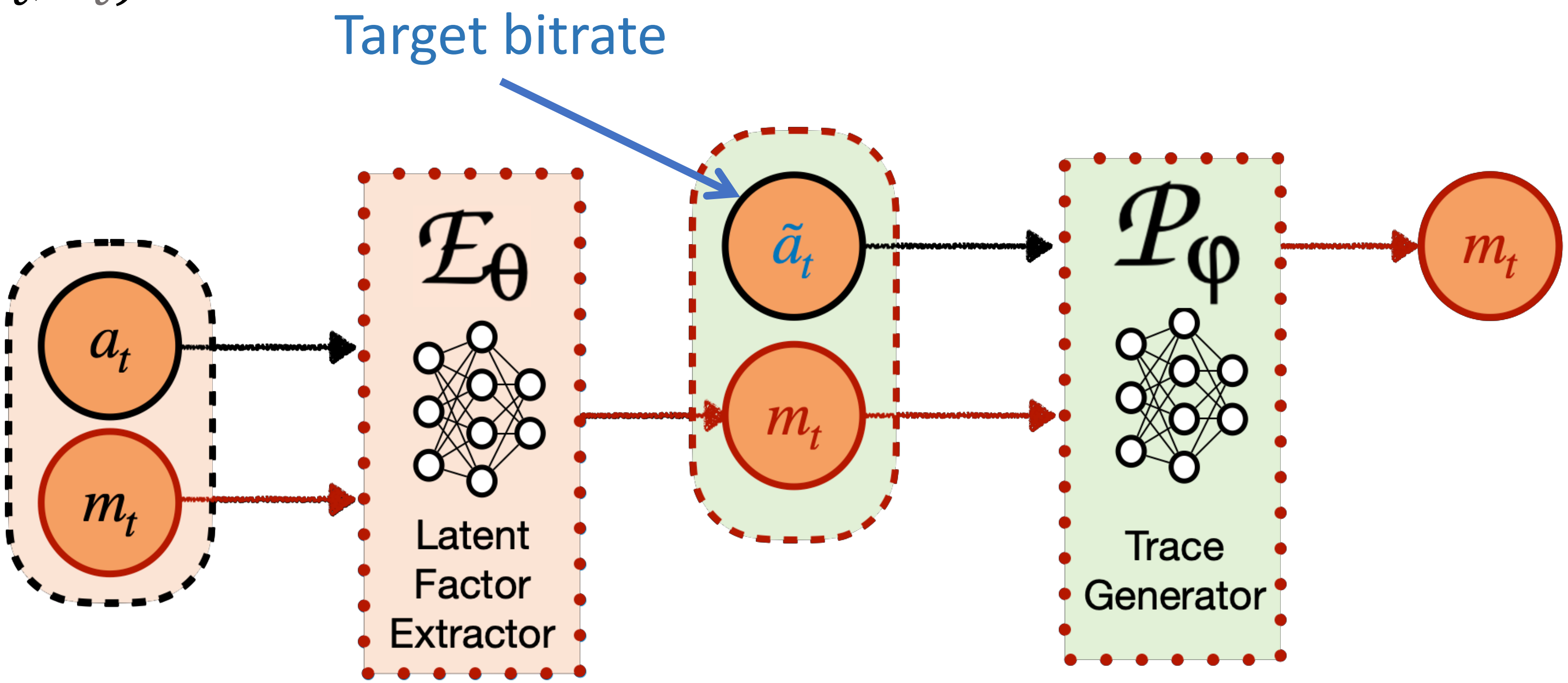

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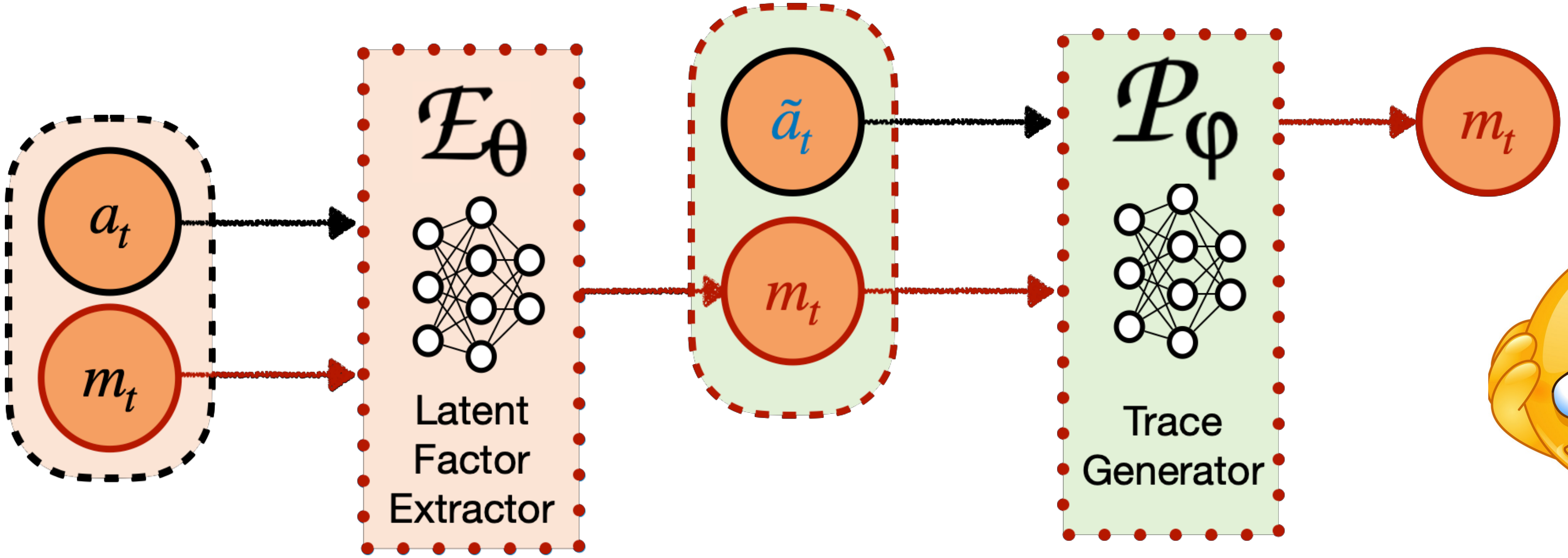

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A degenerate solution

RCT to the rescue!

💡 ***RCT property:*** Distribution of latent network conditions is the same in trajectories assigned to different algorithms.

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↳ Latent network condition is independent of the source algorithm (used for trace collection).

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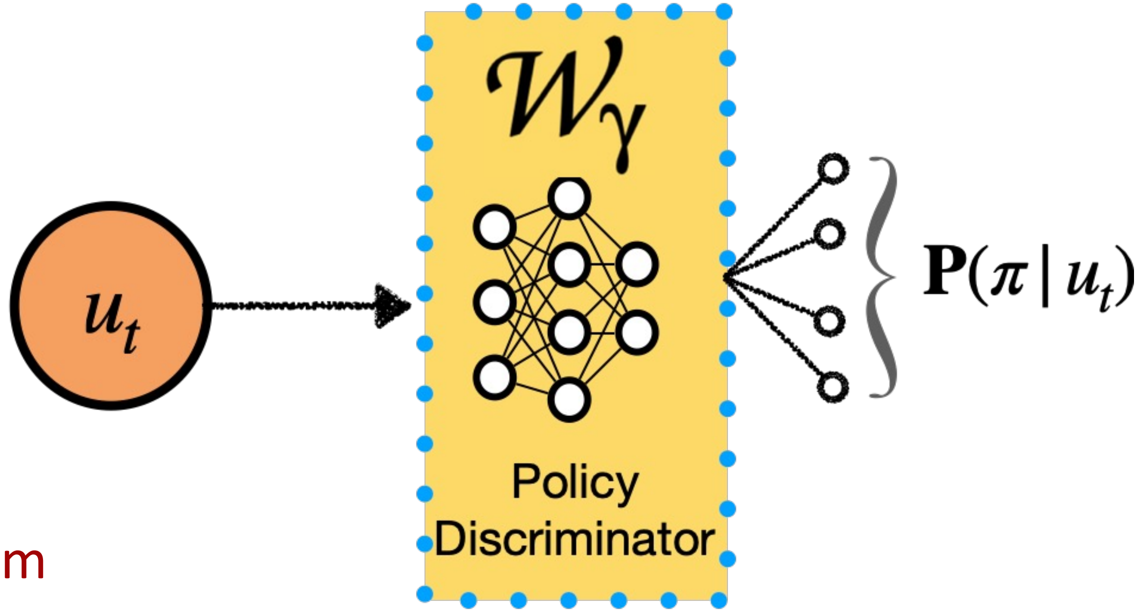
💡 ***RCT property:*** Distribution of latent network conditions is the same in trajectories assigned to different algorithms.

↳ Latent network condition is independent of the source algorithm (used for trace collection).

↳ Latent network condition does not give any information about the source algorithm.

RCT to the rescue!

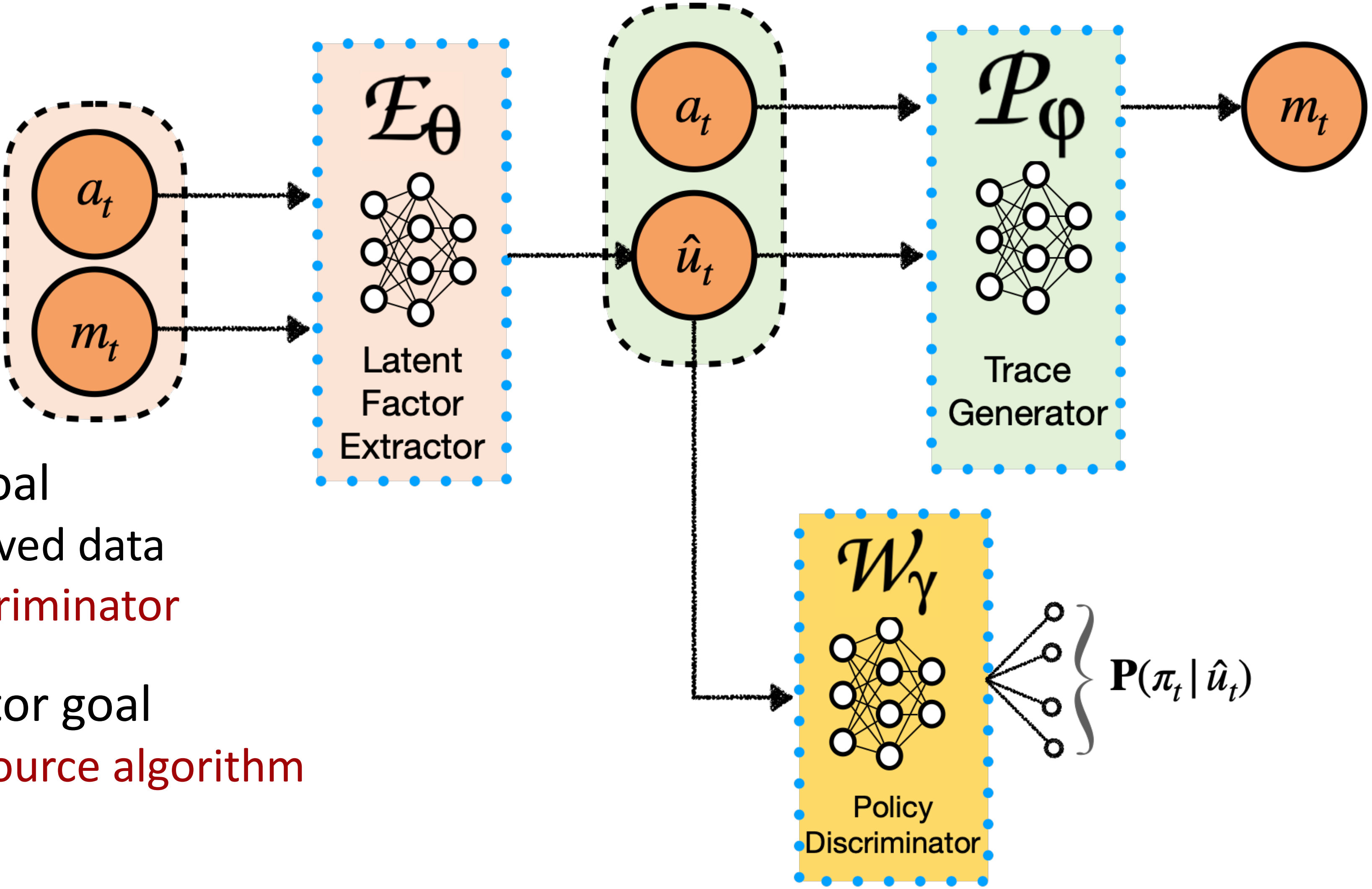
RCT property: Distribution of latent network conditions is the same in trajectories assigned to different algorithms.



Discriminator goal

- Predict source algorithm

Exploiting the RCT property



Learning goal

- Fit observed data
- Fool discriminator

Discriminator goal

- Predict source algorithm

RCT property is sufficient for unbiased simulation

Theorem: The RCT property (independence of u and the algorithm) is sufficient for estimating the counterfactual trace if

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RCT property is sufficient for unbiased simulation

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1. (**Invertibility**) $\forall \mathrm{a}$: $\mathrm{m} = \mathrm{f}(\mathrm{a}, \mathrm{u})$ is invertible.
2. (**Low-rank factorization**) Matrix representation of f has rank r, and $\mathrm{r} \leq \dim(\mathrm{trace})$.

RCT property is sufficient for unbiased simulation

Theorem: The RCT property (independence of u and the algorithm) is sufficient for estimating the counterfactual trace if

1. (**Invertibility**) $\forall \mathrm{a}:\ \mathrm{m} = \mathrm{f}(\mathrm{a}, \mathrm{u})$ is invertible.
2. (**Low-rank factorization**) Matrix representation of f has rank r, and $\mathrm{r} \leq \dim(\mathrm{trace})$.
3. Traces are collected using sufficient number of **diverse** algorithms (See the paper for the precise statement).

Fulfilling the initial promise

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- Key source of bias
  - Exogenous Trace Assumption

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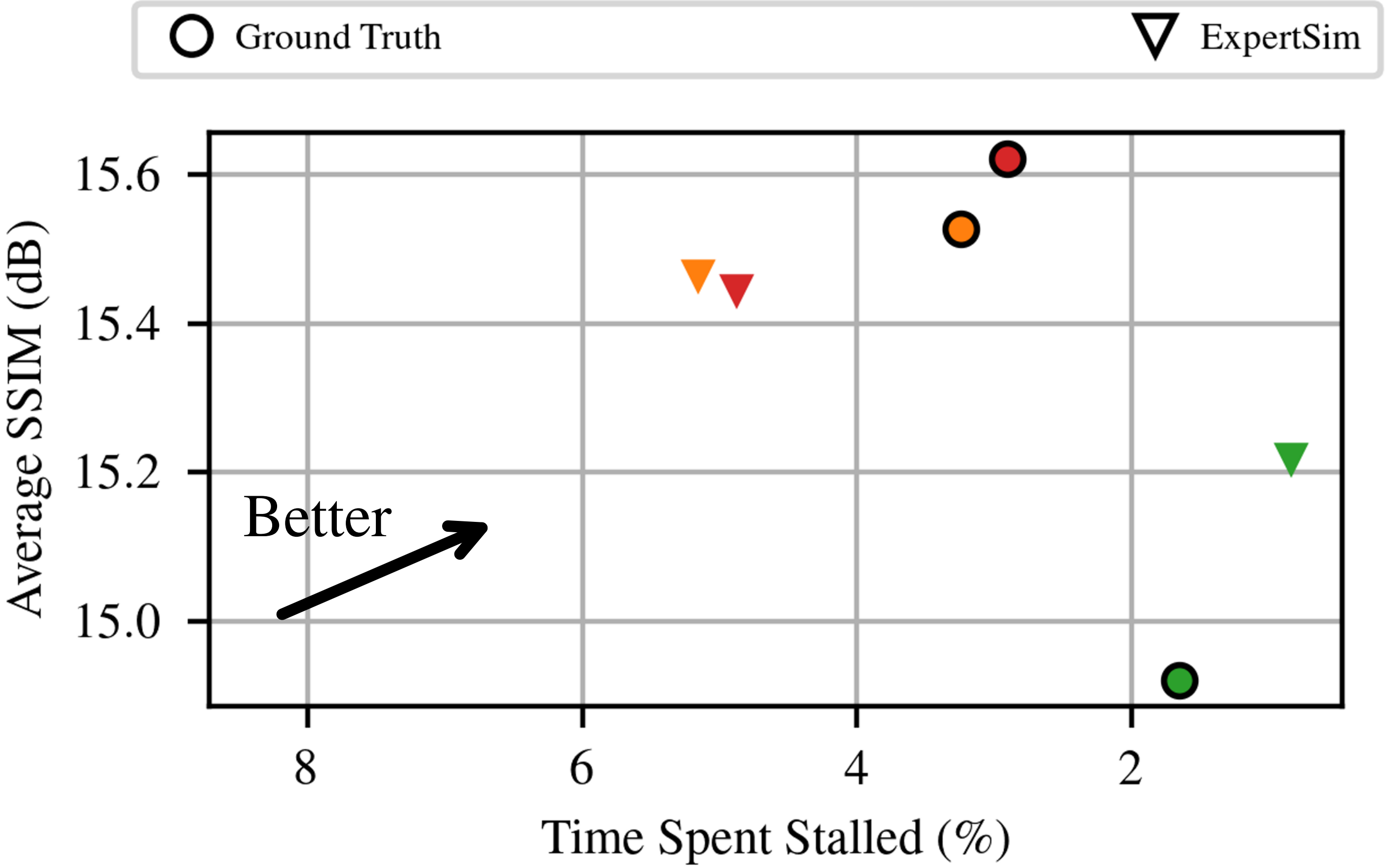
- How to do unbiased trace-driven simulation?
  - CausalSim

Simulation accuracy

- Source data: The Puffer Dataset with 5 algorithms
- Target algorithm (unseen in training): BBA, BOLA1, BOLA2



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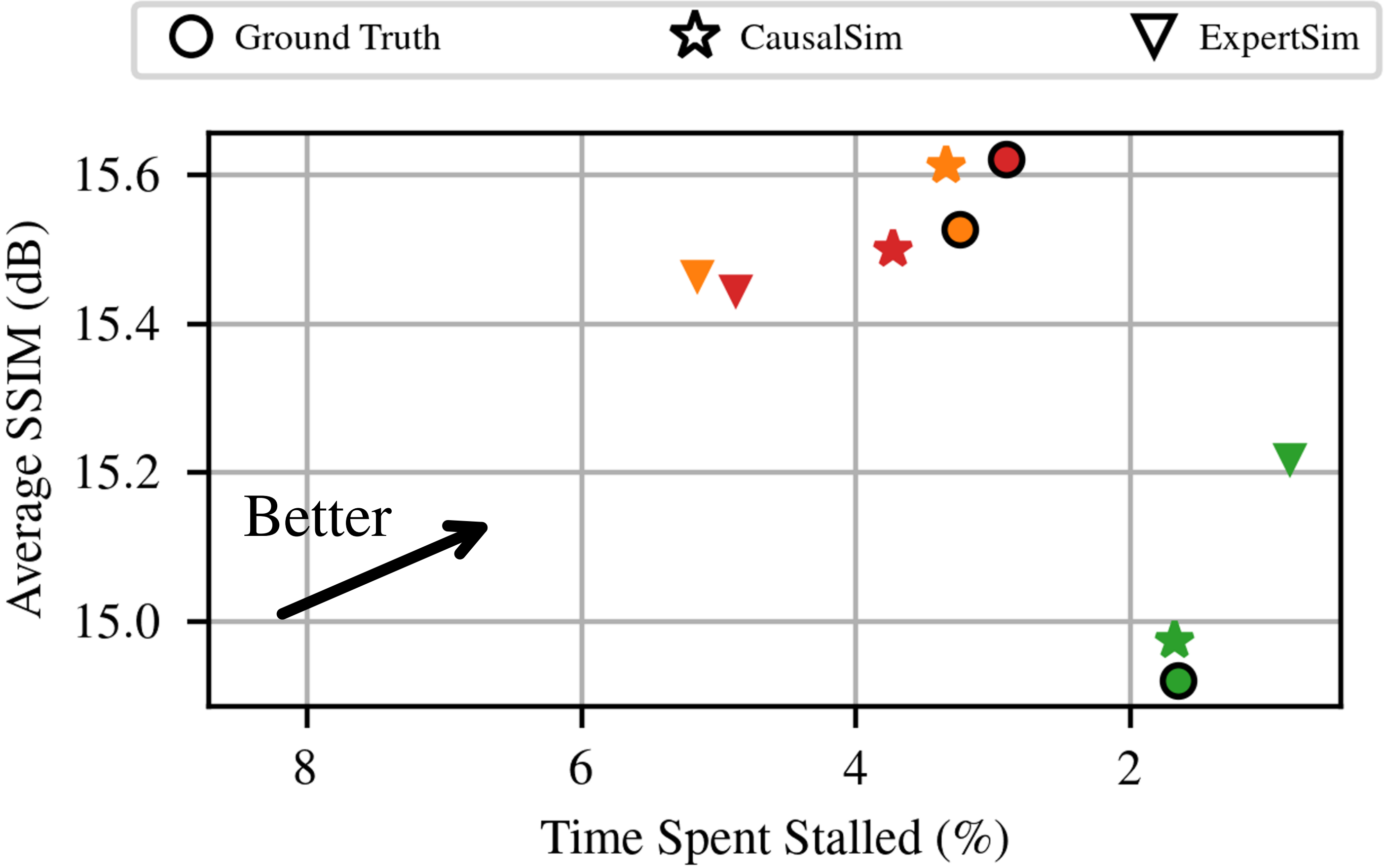

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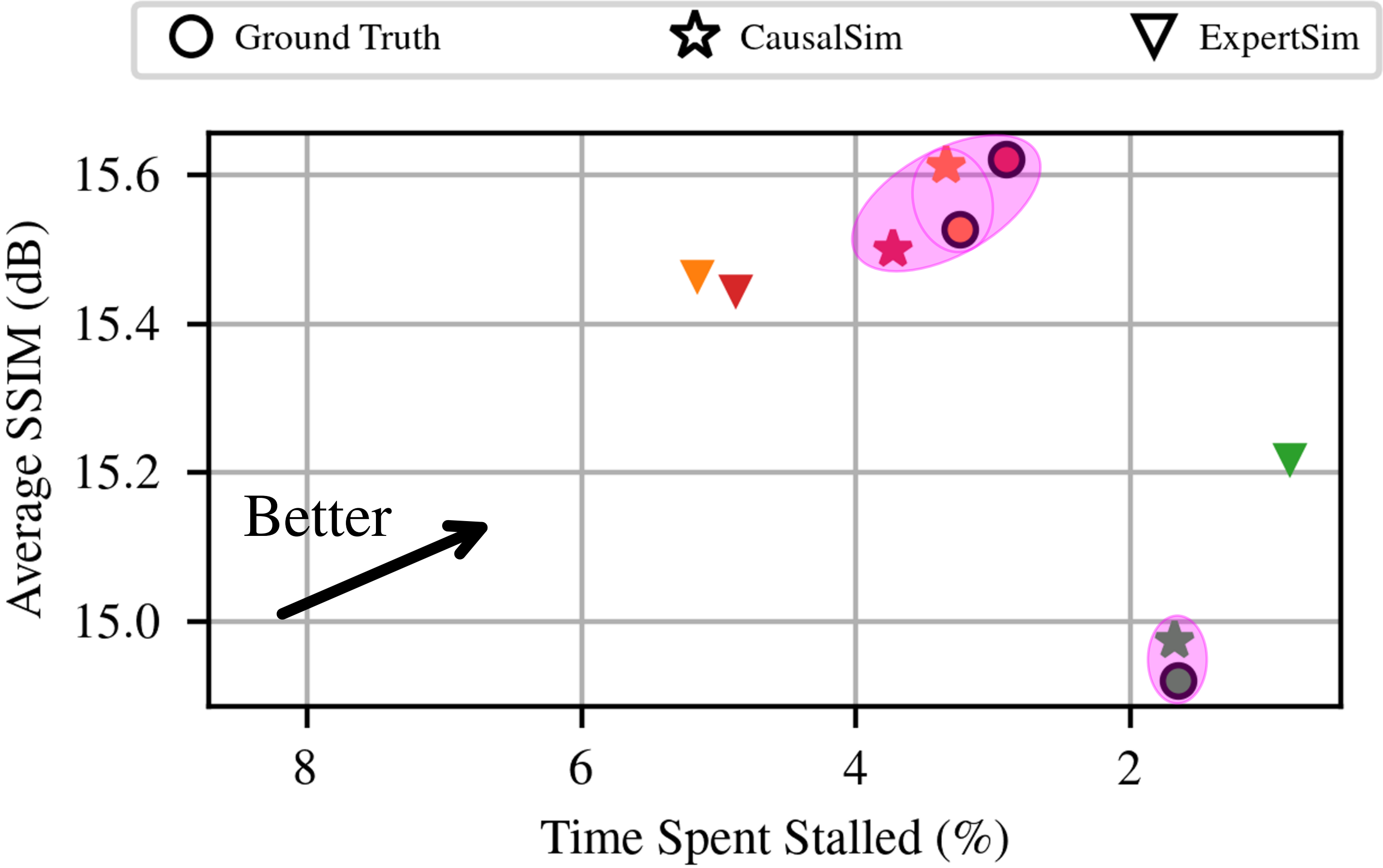

Case study: CausalSim in the wild

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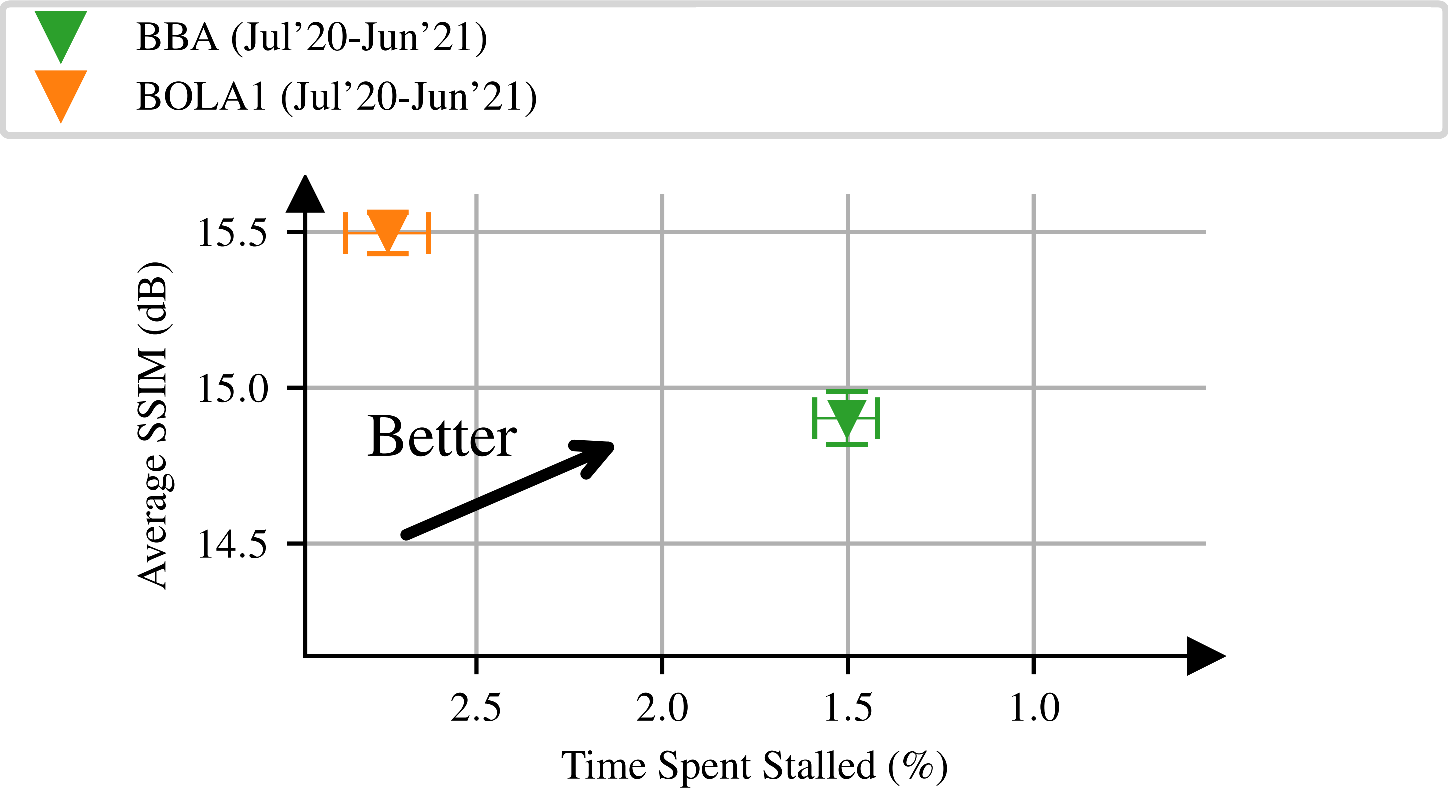
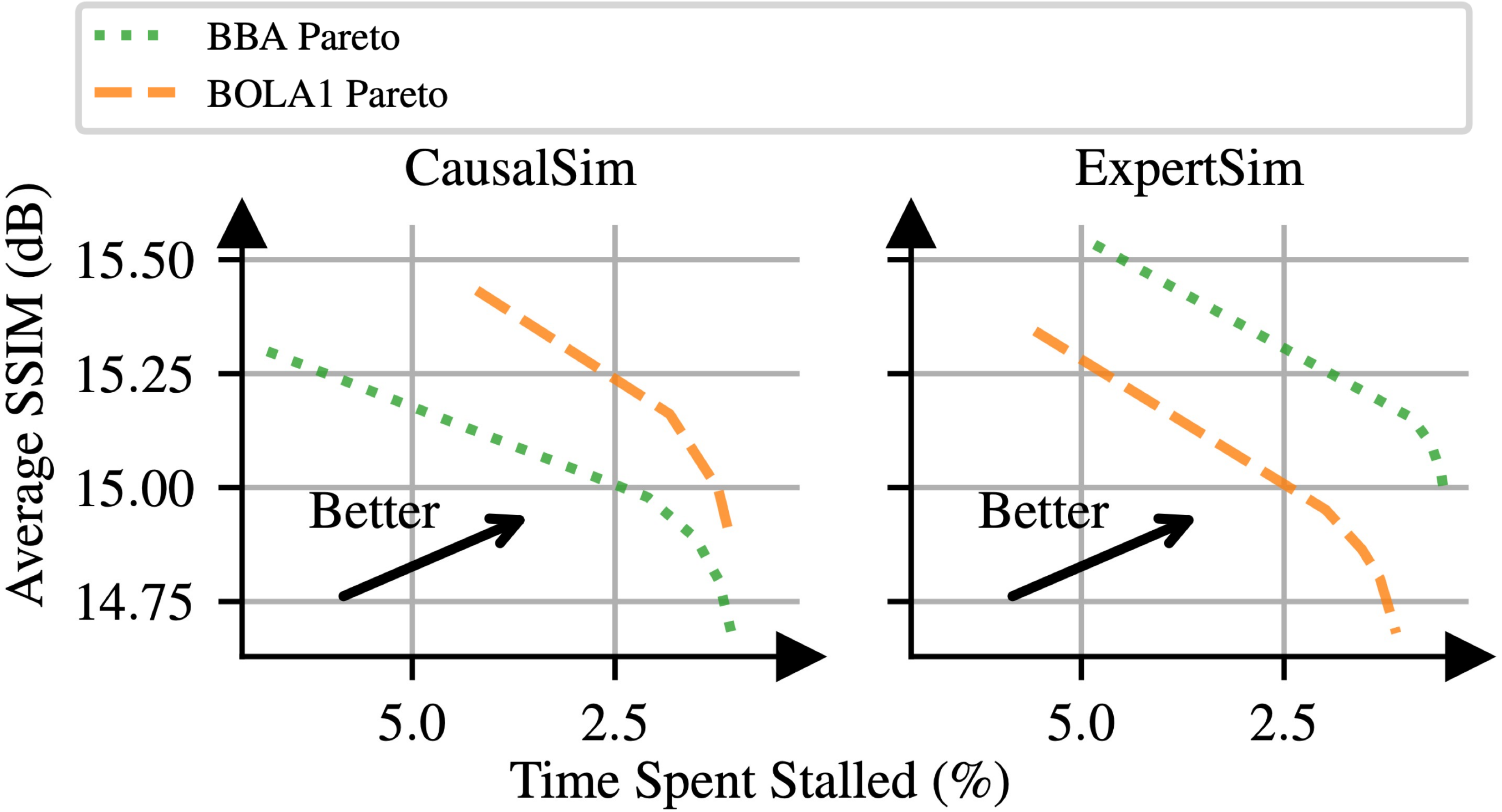


- Can we use CausalSim to improve algorithms?

Case study: CausalSim in the wild



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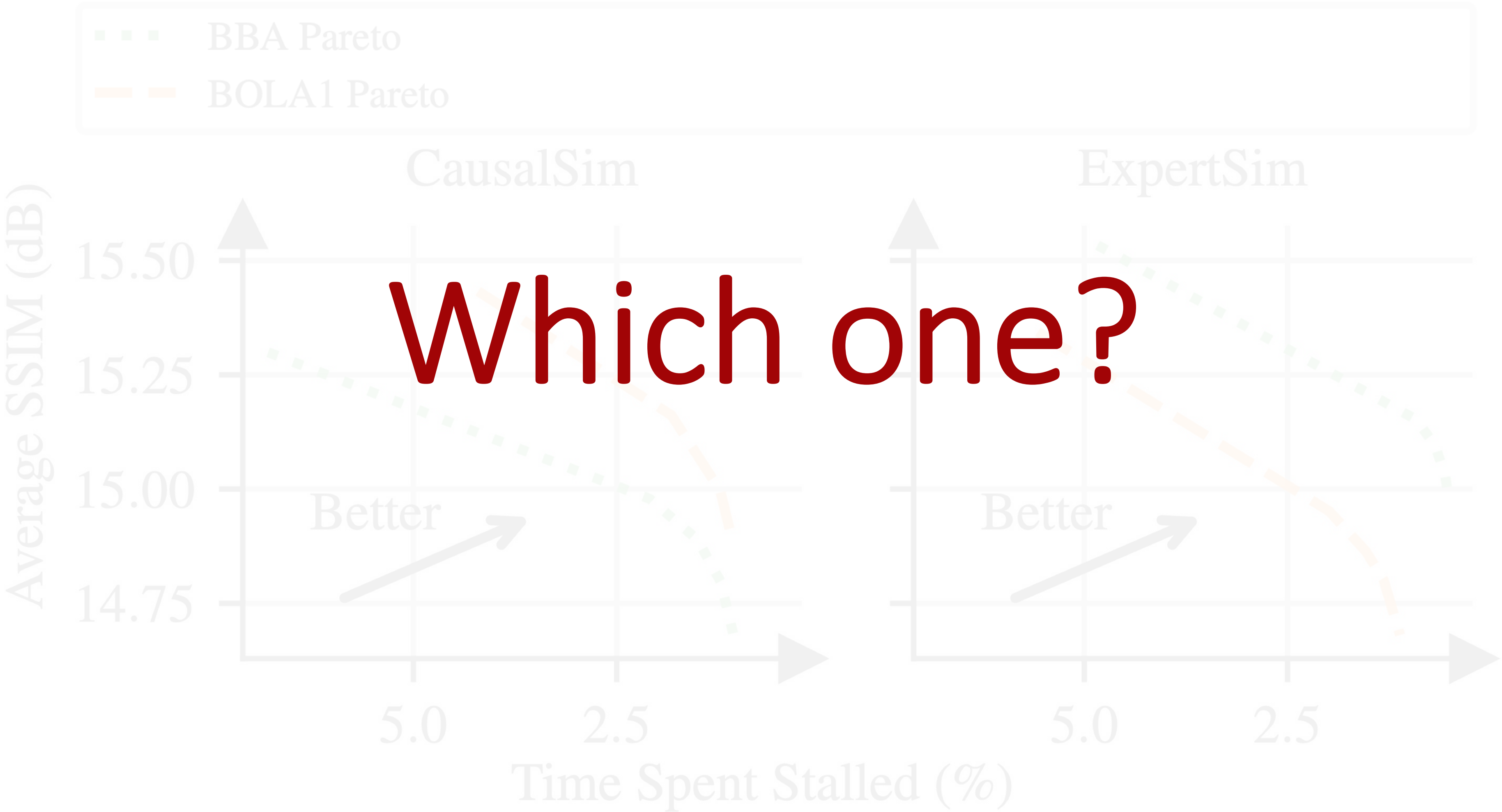
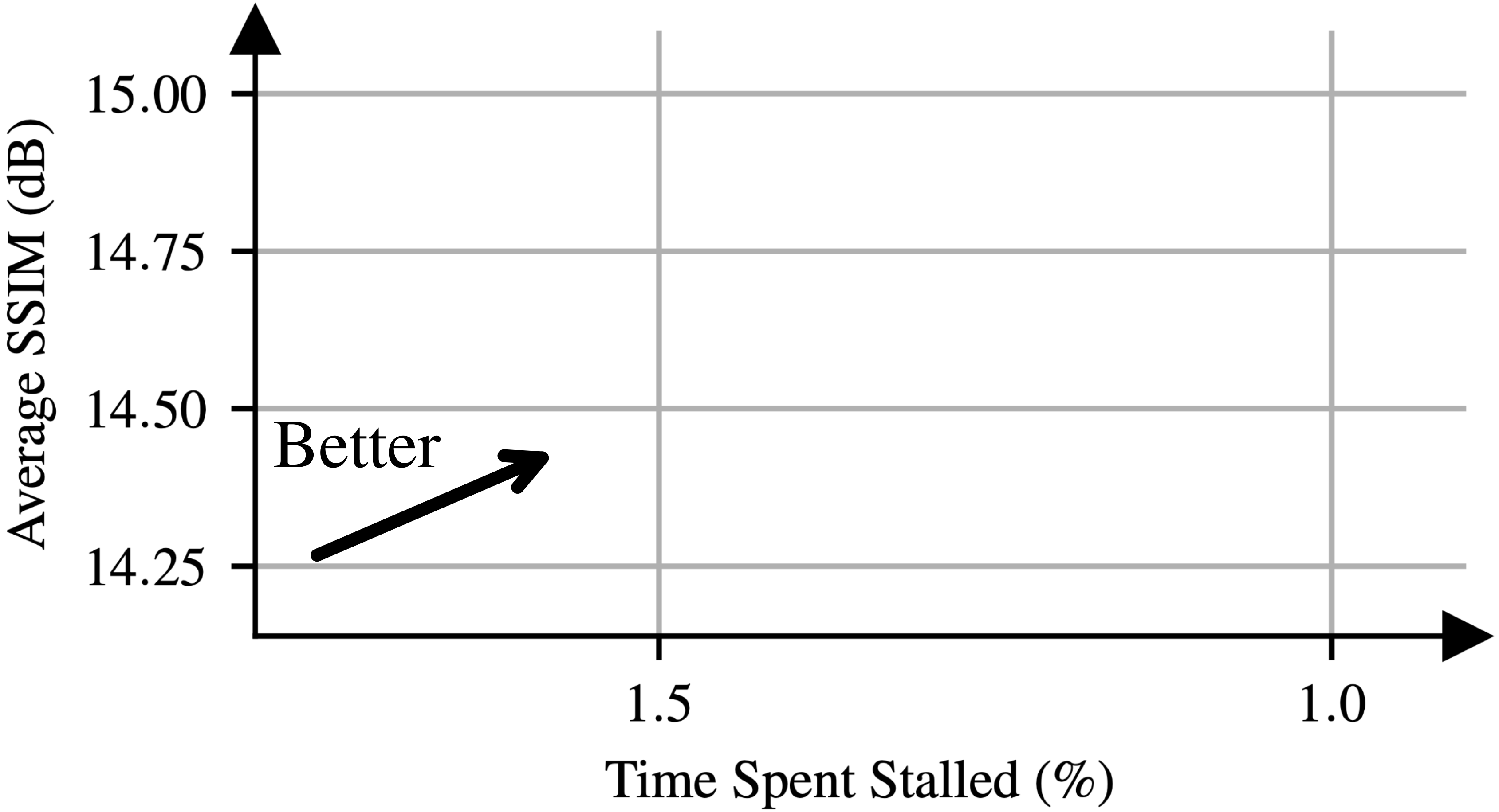


Which one?

Case study: CausalSim in the wild



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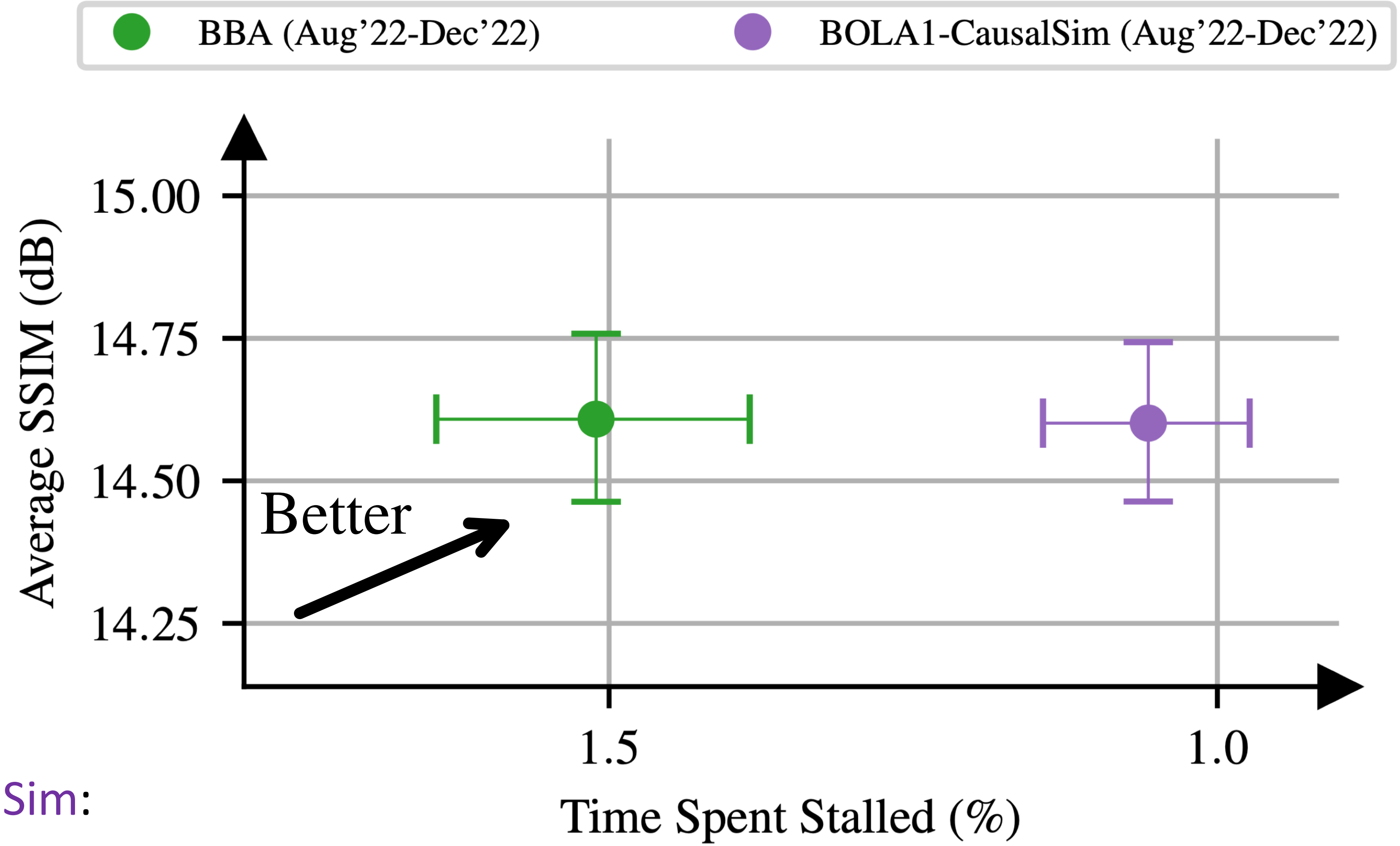

BOLA1-CausalSim:

- Deployment: 1.4x less stalling than BBA

Contributions

❑ Identified *Exogenous Trace Assumption* as a key source of bias in trace-driven simulation.

❑ Proposed ***CausalSim*** for eliminating bias, by modeling the effect of interventions on the trace.

❑ Demonstrated ***CausalSim***'s impact by a real-world ABR algorithm design and deployment.

🔗 **causalsim**.csail.mit.edu