CausalSim: A Causal Inference Framework for Unbiased Trace-Driven Simulation

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Abstract

We present CausalSim, a causal inference framework for unbiased trace-driven simulation. Current trace-driven simulators assume that the interventions being simulated (e.g., a new algorithm) would not affect the validity of the traces. However, real-world traces are often biased by the choices of algorithms made during trace collection, and hence replaying traces under an intervention may lead to incorrect results. CausalSim addresses this challenge by learning a causal model of the system dynamics and latent factors capturing the underlying system conditions during trace collection. It learns these models using an initial randomized control trial (RCT) under a fixed set of algorithms, and then applies them to remove biases from trace data when simulating new algorithms.

Key to CausalSim is mapping unbiased trace-driven simulation to a tensor completion problem with extremely sparse observations. By exploiting a basic distributional invariance property present in RCT data, CausalSim enables a novel tensor completion method despite the sparsity of observations. Our extensive evaluation of CausalSim on both real and synthetic datasets, including more than ten months of real data from the Puffer video streaming system show it improves simulation accuracy, reducing errors by 53% and 61% on average compared to expert-designed and supervised learning baselines. Moreover, CausalSim provides markedly different insights about ABR algorithms compared to the biased baseline simulator, which we validate with a real deployment.

1 Introduction

Causa Latet Vis Est Notissima – The cause is hidden, but the result is known. (Ovid: Metamorphoses IV, 287)

Trace-driven simulation is a widely used method for evaluating new ideas in systems. In contrast to full-system simulation (e.g., NS3 [30]), which requires detailed knowledge of system characteristics (e.g., topology, traffic patterns, hardware details, etc.), trace-driven simulation does not model all components of a system. Instead, it focuses on simulating one (or a few) components of interest, where we wish to experiment with an intervention, e.g., a new design, algorithm, or architectural choice. To account for the effect of the remaining components that are not simulated, we collect a trace capturing their behavior and replay it while simulating the component of interest with the proposed intervention.

The key assumption here is that the interventions would not affect the trace being replayed, which we refer to as the exogenous trace assumption. If this assumption does not hold, replaying the trace is invalid and could lead to incorrect simulation results. This problem has been referred to as bias in trace-driven (or data-driven) simulation [15, 36].

It is difficult to guarantee the exogenous trace assumption in traces collected from real-world systems. Consider, for example, trace-driven simulation of adaptive bitrate (ABR) algorithms [34, 49, 61, 72]. It is common to use network throughput traces from real video streaming sessions on Internet paths [37, 72]. However, the throughput achieved when the player downloads a video chunk is caused by certain latent properties of the network path (e.g., the underlying bottleneck capacity, the number and type of competing flows, etc.), as well as the particular choices made by the ABR algorithm (the bitrate chosen for each chunk). In other words, the trace data reflects the combined effect of these two causes and is biased by the ABR algorithms used during trace collection. To simulate a new algorithm, we need to tease apart the effect of the two causes, and predict how the trace would have changed under the decisions of the new algorithm.

We present CausalSim, a causal inference framework for unbiased trace-driven simulation. CausalSim relaxes the exogenous trace assumption by explicitly modeling the fact that interventions can affect trace data. Using traces collected from a randomized control trial (RCT) under a fixed set of algorithms, it infers both the latent factors capturing the underlying conditions of the system and a causal model of its dynamics, including the unknown relationship between latents, algorithm decisions, and observed trace data. To simulate a new algorithm, CausalSim first estimates the latent factors at every time step of each trace. Then, it uses the estimated latent factors to predict the alternate evolution of trace, actions, and observed variables of the component of interest, under the same latent conditions that were present when the trace was collected. This two-step process allows CausalSim to remove the bias in the trace data when simulating new algorithms.

CausalSim provides two benefits: (i) it improves the accuracy of trace-driven simulation when the intervention could affect (in possibly subtle ways) the trace data; (ii) it enables trace-driven simulation of systems where defining an exogenous

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trace is not possible and therefore standard trace-driven simulation is not applicable. We evaluate both settings in this paper, using simulation of ABR and heterogeneous server load balancing algorithms as examples for cases (i) and (ii) respectively.

CausalSim requires training data from an RCT. Large network operators have increasingly invested in RCT infrastructure to evaluate new ideas, but due to their low throughput and risk of disruptions or SLA violations [41], they can afford to evaluate only a fraction of proposed ideas in RCTs. CausalSim greatly extends the utility of RCT data by learning a model that can simulate a wide range of algorithms using traces from a fixed set of algorithms. Periodically or whenever an operator believes the underlying system characteristics have changed significantly, they can collect fresh data using an RCT (again, with the same fixed set of algorithms) to retrain CausalSim.

CausalSim’s design begins with the observation that unbiased trace-driven simulation can be viewed as a matrix (or tensor) completion problem [9, 14]. Consider a matrix $M$ of traces (it is a tensor if traces are higher dimensional), with rows corresponding to possible actions and columns corresponding to different time steps in the trace data. For each column, the entry for one action is “revealed”; all other entries are missing. Our task can be viewed as recovering the missing entries.

A significant body of work has shown that it is possible to recover a matrix from sparse observations under certain assumptions about the matrix and the pattern of missing data. Roughly speaking, the typical assumptions that make recovery feasible are that the matrix has low rank, the entries revealed are chosen at random, and that enough entries are revealed. Low-rank structure is prevalent in many real-world problems [67] and has also been observed in network measurement data [16, 42, 43, 58]. But unfortunately the other two assumptions do not hold in our problem. As we detail in §4.3, one observed entry per column is below the information-theoretic bound for low-rank matrix completion (even for rank $r = 1$). Moreover, not only are the entries revealed in our problem not random, they depend on other entries of the matrix, since the actions are being taken by algorithms based on observed variables.

CausalSim exploits a novel form of additional problem structure to overcome these challenges. First, it assumes a causal model (§3) where the latent factors are exogenous and are not affected by the interventions we want to simulate in the component of interest. This exogenous latent assumption relaxes (and is therefore implied by) the exogenous trace assumption in standard trace-driven simulation. For example, in ABR, it says that underlying factors like the bottleneck link speed on a network path are not affected by a user’s ABR algorithm, whereas ABR decisions can impact the trace that user observes (i.e., the achieved throughput).

Second, CausalSim uses a basic property of trace data collected via an RCT. Since the assignment of an algorithm to a trace is completely random in an RCT, the distribution of latent factors should be the same for the traces obtained using different algorithms, i.e., the latent distribution is invariant to the algorithm. We provide conditions on the RCT data (e.g., in terms of the number and diversity of algorithms) that guarantee recoverability of the low-rank matrix using this invariance property (§4.2), and we operationalize this idea in a practical learning method that exploits the invariance using an adversarial neural network training technique (§5).

We evaluate CausalSim on two use cases, ABR and server load balancing, with both real-world and synthetic datasets, and further verify CausalSim’s predictions with a test in the wild on the Puffer [69] video streaming testbed. Our main findings are:

1. We use CausalSim to debug and improve an ABR algorithm, BOLA1 [51, 61]. In a ten month experiment on Puffer [69], BOLA1 exhibited high stalling compared to BBA [34], with slightly better quality. Using CausalSim, we tune BOLA1’s parameters via Bayesian Optimization and deploy our improved version on Puffer. We show that it improves the stall rate of this well-known algorithm by $3.5 \times$, achieving $2.7 \times$ lower stall rate than BBA with similar perceptual quality. The expert-designed baseline simulator that ignores bias predicts the exact opposite: that the new variant should stall $4.9 \times$ more than BBA. This case study shows that removing bias is crucial to draw accurate conclusions from trace-driven simulation.

2. Evaluation of CausalSim on more than ten months of real data from Puffer shows that CausalSim’s error in stall rate prediction is bounded to 28%, while expert-designed and standard supervised learning baselines have errors in the range of 49–68% and 26–204% respectively. Similar observations are also made for perceptual quality metrics and buffer occupancy levels.

3. CausalSim opens up new avenues to apply trace-driven simulation to systems where the exogenous trace assumption is invalid. Using a synthetic environment modeling a heterogeneous server load balancing problem, we show how CausalSim reduces average simulation error by $3.8 \times$, a stark improvement compared to a baseline simulator with 102.4% error rate.

Our code is available at https://github.com/CausalSim/Unbiased-Trace-Driven-Simulation.

2 Motivation

2.1 Bias in Trace-Driven Simulation

Trace-driven simulation is a widely used technique to design and evaluate systems. Unlike full-system simulation, trace-driven simulation does not model all components of a system. Instead, it focuses on simulating one (or a few) components of interest, where we wish to experiment with an intervention, e.g., a new design, algorithm, or architectural choice. To account for the effect of the remaining components that are not simulated, we collect a trace that captures their behavior and replay it while simulating the component of interest with the proposed intervention. For example, to simulate new ABR algorithms, it
is common to replay network throughput traces from real Internet paths in a simulator modeling only the video player/server.

The key assumption here is that the interventions being simulated would not affect the trace being replayed; otherwise, replaying the trace would be invalid. We refer to this as the exogenous trace assumption, and it is central to standard trace-driven simulation. Figure 1a is a visual depiction of the exogenous trace assumption. In the figure, a represents the intervention we want to simulate; for example, the actions taken by a new algorithm. o is the observed state of the component being simulated. u represents the latent state of the rest of the system, which we do not observe or simulate. Finally, m is the trace, which captures the behavior of the other components. The existence of each edge represents a causal effect. For example, the trace m and intervention a both affect o. Note the absence of the edge from a to m, which implies that the intervention cannot affect the trace (the exogenous trace assumption).

The simulator designer must define the trace carefully to meet this assumption. But what happens if it does not hold, i.e., there exists an edge from a to m (as in Figure 1b)? Ignoring the violation of exogenous trace assumption leads to biased simulation outcomes, as we will see next.

2.2 An Example Using Real-world Traces

In this section, we use more than ten months of real-world data from Puffer [69], a recently deployed system for experimenting with video streaming protocols, to illustrate the issue of bias in trace-driven simulation.

Puffer collects data from a continual Randomized Control Trial (RCT) that tests several Adaptive Bit Rate (ABR) algorithms. In the period of interest (July 27, 2020 – June 2, 2021), the tested algorithms include Buffer-Based Algorithm (BBA) [34], two versions of BOLA-BASIC (henceforth called BOLA) [61], and two versions of an algorithm called Fugu developed by the Puffer authors. The dataset includes more than 56 million chunk downloads from more than 230 thousand streaming sessions, totaling 3.5 years of streamed videos. For each streaming session, it provides logs of the chosen chunk sizes, available chunk sizes, achieved chunk download throughputs, and playback buffer levels. \(^3\)

Consider a typical trace-driven simulation scenario, where we wish to simulate a new ABR algorithm using traces from previous video streaming sessions. We define such a task on the Puffer data as follows. We let one of the algorithms, say BBA, be the algorithm that we wish to simulate. We leave out the data for this algorithm and ask whether it is possible to predict its performance using the other algorithms’ traces. In evaluating a new ABR algorithm, we may be interested in various performance measurements, e.g. buffer occupancy, rebuffering rate, chosen bitrates, etc. Here, we focus on predicting the behavior of playback buffer occupancy, which is one of the key indicators of an ABR algorithm’s behavior [34].

The goal of trace-driven simulation is to predict the trajectory of the system (e.g., buffer, bitrates, etc.) for one algorithm in the same underlying conditions that were present when a trace was collected using a different algorithm. When simulating algorithm B based on a trace collected using algorithm A, we will refer to A as the “source” algorithm and to B as the “target” algorithm.

It is generally not possible to evaluate the accuracy of individual simulated trajectories using real-world data, because we do not have ground truth trajectories for the target algorithm under the same exact network conditions that were present when running the source algorithm. However, since the Puffer data was obtained using an RCT, we can evaluate predictions about distributional properties of the target algorithm, such as the distribution of the buffer occupancy achieved by the algorithm over the population of network paths present in the RCT.

To summarize, our task is: predict the distribution of the buffer occupancy for the users assigned to BBA (the target algorithm) in the Puffer dataset, using only the data from the other (source) algorithms.

2.2.1 Simulation via Expert Modeling (ExpertSim)

As our first strawman, we build a simple trace-driven simulator (ExpertSim) using our knowledge of how an ABR system works. ExpertSim models the playback buffer dynamics for each step, where a step corresponds to one ABR decision and the download of a single video chunk. Let \( \hat{c}_t \) be the throughput achieved in step \( t \) (for the \( t^{th} \) chunk) of a particular video streaming session using, say, the BOLA2 algorithm. To simulate BBA for the same user, ExpertSim assumes that the user would achieve the same throughput \( \hat{c}_t \) in each step under the

\(^3\)Variables in Fig. 1a can be multidimensional and vary with time.

\(^3\)BOLA1 and BOLA2 are variations on BOLA adjusted to target the SSIM quality metric instead of bitrate [51]. They pursue different objective functions and use different principles for hyperparameter adjustment.

\(^3\)We use ‘slow stream’ logs (by Puffer’s definition, streams with TCP delivery rates below 6Mbps) available on the Puffer website [1].
next attempt, we turn to machine learning and try to learn the system dynamics from data. Specifically, we use supervised learning to train a neural network that models the step-wise dynamics of the system. This fully connected neural network includes 2 hidden layers, each with 128 ReLU activated neurons. For each timestep $t$, the neural network takes as input the buffer level before download of the $t^{th}$ chunk $b_t$, the achieved throughput $c_t$ for chunk $t$, and the chunk size $s_t$ (which depends on the bitrate chosen by ABR). The neural network outputs the buffer level after the download of the $t^{th}$ chunk, $b_{t+1}$. We train the neural network to minimize the mean squared error of the predictions (L2 loss) on our dataset. To avoid information leaking, we exclude the logs for BBA from the training data.

Figure 2a shows the predicted buffer level distribution via this approach (SLSim) for BBA. As with ExpertSim, we use the traces collected from BOLA2 users as the source algorithm. The results are similar to ExpertSim; once again, the predicted buffer distribution is closer to that of BOLA2 than BBA.

2.2.3 What Went Wrong?

To understand the limitations of ExpertSim and SLSim, we plot the distribution of achieved per-chunk throughput for users assigned to BOLA2 and BBA in Figure 2b. Since algorithm selection is completely random, we would expect inherent network path properties such as bottleneck link capacity to have the same distribution for users assigned to different ABR algorithms. However, such an invariance should not be expected for achieved throughput, because even on the same path different ABR algorithms could achieve different throughput. For example, since congestion control protocols take time to discover available bandwidth (e.g., in slow start) or converge to their fair share rate when competing against other flows, an ABR algorithm that tends to choose lower bitrates (and hence download less data per chunk) may achieve less throughput than an ABR algorithm that picks higher bitrates [33, 62]. We can see this behavior in the Puffer dataset. The achieved throughput for BOLA2 and BBA is clearly different in Figure 2b.

This confirms that ABR algorithms cause a bias in the measured throughput traces, and the exogenous trace property does not hold. To perform accurate trace-driven simulation, we need to account for this bias when simulating new ABR algorithms.

2.3 Causal Inference to the Rescue!

If the traces were the underlying network capacity when each chunk was downloaded (rather than the achieved throughput), the exogenous trace assumption would hold and our problem would be simple. First, we would learn the relationship between network capacity and achieved throughput for different ABR actions using our data. Then, to simulate BBA for a given trace, we would start with the network capacity at each step of the trace and predict the achieved throughput taking into account the bitrate chosen by BBA in that step.

BOLA2 algorithm as well. In other words, it assumes that ABR decisions do not affect the observed network throughput (the exogenous trace assumption). Under this assumption, ExpertSim models the evolution of the video playback buffer as follows. Let $b_t$ be the buffer level at the beginning of step $t$ (before the download of chunk $t$), $r_t$ be the bitrate chosen in step $t$, and $s_t$ be the size of the $t^{th}$ chunk implied by the chosen bitrate. Then the buffer at the end of step $t$ is derived as: $b_{t+1} = \max(0, b_t - s_t/c_t) + T$, where $T$ is the chunk duration. Although simple, the assumption that throughput is an exogenous property of a network path is common in modelling ABR protocols. For example, both FastMPC [72] and FESTIVE [37] assume that the observed throughput does not depend on the chosen bitrate.

Figure 2a shows the true distribution of buffer level for BOLA2 and BBA users in the Puffer dataset (the two dashed lines), as well as the distribution predicted by running BBA on the traces collected from BOLA2 users using ExpertSim (solid blue line). The predictions are inaccurate: the buffer distribution generated by ExpertSim are more similar to the buffer distribution of BOLA2 users (the target algorithm) than the buffer distribution of BBA users (the target algorithm).

2.2.2 Simulation via Supervised Learning (SLSim)

Perhaps the simple model of buffer dynamics in ExpertSim does not accurately reflect the actual system behavior. As a
This would then allow us to predict how the buffer evolves. This works because unlike achieved throughput, underlying capacity is an exogenous property of a network path and is not affected by the ABR actions.

However, underlying network capacity is a latent quantity — we do not observe it in our traces. The key challenge is therefore to infer such latent quantities from observational data. Concretely, in our running example, we wish to estimate the latent factors like network capacity in each step of a trace, using observations such as the bitrate, the chunk size, the achieved throughput, etc.\(^5\)

Inferring such latent confounders and using them for counterfactual prediction is the core issue in the field of causal inference [55, 56]. In this paper, we develop CausalSim, a causal inference framework for unbiased trace-driven simulation. CausalSim relaxes the exogenous trace assumption in trace-driven simulation. It explicitly models the fact that interventions can affect trace data (the edge from \(a\) to \(m\) in Figure 1b), and infers both the latent factors and a causal model of the system dynamics. This allows CausalSim to correct for the bias in trace data when simulating an intervention. As an illustration, Figure 2a shows the predicted buffer occupancy distribution when simulating BBA on the traces of users assigned to BOLA2, using CausalSim. CausalSim matches the ground-truth distribution for BBA much more accurately than the alternatives.

3 Model and Problem Statement

3.1 Causal Model

Consider the following discrete-time dynamical model corresponding to Figure 1b:

\[
\begin{align*}
  m_t &= \mathcal{F}_{\text{trace}}(a_t, u_t), \\
  o_{t+1} &= \mathcal{F}_{\text{system}}(o_t, m_t, a_t).
\end{align*}
\]

Here, \(t\) denotes the time index, \(m_t\) is the trace, \(a_t\) is the intervention, \(u_t\) is the latent factor, and \(o_t\) is the observed state of the component of interest. The function \(\mathcal{F}_{\text{trace}}\) models the effect of interventions on the trace (which traditional methods ignore), and \(\mathcal{F}_{\text{system}}\) models the dynamics of the component of interest. When the intervention changes some algorithm in the component of interest, \(a_t\) can be viewed as the action taken by that algorithm at time \(t\).

We assume that interventions do not affect the internal state of the rest of the system, i.e., that the latent factors are exogenous. This assumption is implicit in the dynamical system equations, and also visualized in Figure 1b by absence of the edge from \(a\) to \(u\). Note that this is a strict relaxation of the exogenous trace assumption in standard trace-driven simulation. There, the trace itself is assumed to be unaffected by intervention, which also implies exogenous latent factors.

In our running ABR example, we want to simulate the video player and server (components of interest) without precisely modeling the entire network path (the rest of the system). Each time step \(t\) corresponds to the download of a new chunk, and \(u_t\) represents latent network conditions during that transmission, e.g., bottleneck link speed, number of competing flows sharing the same path, type of congestion control used by competing flows, etc. At each time step, the ABR algorithm chooses a bitrate \(a_t\), which together with \(u_t\) generate \(m_t\), the achieved throughput when downloading a chunk. Typically, latent network conditions are exogenous factors, beyond the impact of a particular user’s actions. For instance, the bottleneck link speed, number of competing flows and type of congestion control that they use, are not affected by the actions of the ABR algorithm.

Note that the achieved throughput depends on the ABR action as well as the latent network conditions. Equation (1) captures this relationship and is the source of the bias induced by the ABR algorithm, which we demonstrated in §2.2.3.

When is the model applicable? The causal model applies in any trace-driven simulation setting where the trace may be impacted by interventions. Examples include:

- Job scheduling, where we wish simulate a workload’s performance under different types of machines. The trace is the job performance (e.g., runtime), interventions are the scheduling decisions, and latent factors are intrinsic properties of each job (e.g., compute intensity) or latent aspects of the machines such as collocated interfering workloads.

- Network simulation, where we wish simulate how some aspect of network’s design (e.g., congestion control, packet scheduling, traffic engineering, etc.) impacts application performance. The trace is an application’s traffic pattern, the intervention is the network design, and latent factors are the internals of the application that dictate its traffic demand.

In some cases, like our running ABR example, the exogenous trace assumption may not hold exactly but still be roughly valid. Here, CausalSim removes bias and improves simulation accuracy.\(^6\) But in certain problems, ignoring the effect of interventions is meaningless. For example, consider scheduling or load balancing on heterogeneous machines (e.g., with different hardware capabilities). Given a trace of job performance on specific machines, it isn’t possible to merely replay the trace for new machine assignments. In such problems, CausalSim enables trace-driven simulation by explicitly modeling the effect of interventions on the trace.

When is the model invalid? Our causal model relaxes the exogenous trace assumption but still requires exogenous latents, i.e. that the latents are unaffected by the intervention.

\(^5\)For simplicity, we only mention network capacity here, but other latent path conditions like the number of competing flows could also affect achieved throughput and the same reasoning applies to them.

\(^6\)Even in these cases, biased simulation can produce entirely incorrect conclusions (§6.2).
3.2 Problem Formulation

We are given \( N \) trajectories, collected using \( K \) specific policies. Let \( H_i \) be the length of trajectory \( i \in \{1, \ldots, N\} \). For trajectory \( i \), we observe \( \{(a_t, m_t, \alpha_t)_{t=1}^{H_i}\} \). We assume that trajectories are generated using an RCT, i.e., that each trajectory is assigned one of the \( K \) policies at random.

Our goal is to estimate the observations under an arbitrary given intervention (e.g., a new algorithm) for each of the \( N \) trajectories.

Let \( \{(a_t')_{t=1}^{H_i}\} \). We assume that trajectories are generated using an RCT, i.e., that each trajectory is assigned one of the \( K \) policies at random.

For trajectory \( i \), we observe \( \{(a_t, m_t, \alpha_t)_{t=1}^{H_i}\} \). We assume that trajectories are generated using an RCT, i.e., that each trajectory is assigned one of the \( K \) policies at random.

Consider a simple example where \( A = 2 \) and \( U = 2n \), and the rank of potential outcome matrix \( M \) is equal to 1. Rank 1 implies that \( M = a u^T \) for some \( u \in \mathbb{R}^2 \) and \( a \in \mathbb{R}^{2n} \) with \( M_{a,b} = a_b \cdot u_a \). Suppose we have \( K = 2 \) policies, where each policy always chooses only one of the two actions. Furthermore, we consider an RCT setting. That is, the distribution of latent factors across trajectories assigned to both policies should be the same.

Without loss of generality, we can re-order the columns of \( M \) so that the first \( n \) columns correspond to the latent factors of \( \alpha \) and \( u \).

4 CausalSim: Theoretical Insights

In this section, we cast counterfactual estimation as a challenging variant of the matrix completion problem [14]. We then formalize conditions that allow us to complete the matrix using a certain distributional invariance property that is present in data collected in an RCT.

4.1 Counterfactual Estimation as Matrix Completion

Recall from §3.2 the task of estimating the counterfactual trace \( \{\hat{m}_i\}_{t=1}^{H_i} \) consistent with Equation (1). In this section, we pose this task as a variant of the classical matrix completion problem. For simplicity, let action \( a_t' \) be one of the finitely many options \( \{1, \ldots, A\} \) for some \( A \geq 2 \). Imagine an \( A \) by \( U \) matrix \( M \), where rows correspond to \( A \) potential actions, and columns corresponds to \( U = \sum_{i=1}^{N} H_i \) latent factors (\( u_t' \) for different choices of \( i \) and \( t \)) in the dataset. To order the columns, we may index \( u_t' \) as a tuple \((i, t)\) and order these tuples in lexicographic order. The matrix \( M \) is called the potential outcome matrix in the causal inference literature [59].

At the \( i^{th} \) step of the \( j^{th} \) trajectory, we observe \( m_t' = f_{\text{trace}}(a_t', u_t') \), which is the entry in \( M \) in the row corresponding to \( a_t' \) and the column corresponding to \( u_t' \). The counterfactual quantities of interest, \( \hat{m}_i' = f_{\text{trace}}(\hat{a}_i, u_t') \) for \( \hat{a}_i' \neq a_t' \), are the missing entries in \( M \) in the same column. In summary, we observe one entry per column of the matrix \( M \) and we wish to estimate the missing values in the matrix.

The task of filling missing values in a matrix based on its partially observed entries is known as Matrix Completion [19], a topic that has seen tremendous progress in the past two decades [18, 20, 46]. However, standard matrix completion methods do not apply to our problem (see §4.3 for details).

We use a distributional invariance property of data collected using an RCT to complete the potential outcome matrix \( M \). The key observation is that, in an RCT, the latent factors for trajectories collected under each of the policies will have the same distribution. For example, in Puffer’s RCT, incoming users are assigned to an ABR algorithm at random. Therefore each ABR algorithm will “experience” the same distribution of underlying latent network conditions, which is precisely why we can compare their performance in the RCT. The same property helps us recover the matrix \( M \), as we show next.

4.2 Exploiting RCT for Matrix Completion

We use a minimal non-trivial example to give intuition about how we can exploit an RCT for matrix completion, before stating our main theoretical result.

Consider a simple example where \( A = 2 \) and \( U = 2n \), and the rank of potential outcome matrix \( M \) is equal to 1. Rank 1 implies that \( M = au^T \) for some \( u \in \mathbb{R}^2 \) and \( a \in \mathbb{R}^{2n} \) with \( M_{a,b} = a_b \cdot u_a \). Suppose we have \( K = 2 \) policies, where each policy always chooses only one of the two actions. Furthermore, we consider an RCT setting. That is, the distribution of latent factors across trajectories assigned to both policies should be the same.

Without loss of generality, we can re-order the columns of \( M \) so that the first \( n \) columns correspond to the latent factors of \( \alpha \) and \( u \).
the trajectories assigned to policy 1, and the second $n$ columns are those assigned to policy 2. Then the observed entries of matrix $M$ appear as

$$
[M_{1,1} \quad M_{1,2} \quad \ldots \quad M_{1,n} \quad * \quad \ldots \quad * \quad * \quad *]
$$

where $*$ represents the missing values.

Let us consider recovering the missing observation $M_{2,1}$. For column 1, we know the observation under the first action, i.e. $M_{1,1}$. Due to rank 1 structure, we have

$$
\frac{M_{2,1}}{M_{1,1}} = \frac{a_2 u_1}{a_1 u_1} = \frac{a_2}{a_1}, \quad (3)
$$

Therefore, to find $M_{2,1}$ (and by a similar argument, to find all missing entries of $M$), we need to estimate the ratio $\frac{a_2}{a_1}$.

Due to the distributional invariance induced by RCT, the samples $u_1, \ldots, u_n$ (which correspond to the latent factors encountered by policy 1) come from the same distribution as the samples $u_{n+1}, \ldots, u_{2n}$ (which correspond to the latent factors encountered by policy 2), for large enough $n$. Thus, their expected value should be equal:

$$
1 - \frac{n}{n+1} u_\beta \approx 1 - \frac{2n}{n+1} u_\beta, \quad (4)
$$

Equation (4) implies

$$
\frac{\sum_{\beta=1}^{n} a_1 u_\beta}{\sum_{\beta=1}^{2n} a_2 u_\beta} = \frac{\sum_{\beta=1}^{n} a_1 u_\beta}{\sum_{\beta=n+1}^{2n} a_2 u_\beta} \approx \frac{a_1}{a_2}. \quad (5)
$$

This provides precisely the quantity of interest in Equation (3) based on the observed entries, enabling us to complete the matrix.

**Formal Result.** This simple illustrative example relied on a convenient observational pattern (based on policies that always choose one action) and rank 1 structure. But the idea can be generalized. If the trace includes D measurements, $M_{\alpha,\beta,\gamma} \in \mathbb{R}^{A \times U \times D}$ becomes a tensor rather than a matrix, where $\alpha, \beta, \gamma$ index the actions, latent factors, and measurements, respectively. The following theorem provides conditions where completion is possible for a rank $r$ tensor. For more details and the proof, refer to Appendix A.

**Theorem 4.1.** We can recover all entries of $M$ by only observing one $D$-dimensional element in each column (corresponding to one latent and action) if the following is satisfied:

1. **(Low-Rank Factorization)** $M$ is a low-rank tensor (rank = $r$), i.e. it admits the following factorization: $M_{\alpha,\beta,\gamma} = \sum_{\alpha=1}^{A} a_{\alpha} u_{\beta} z_{\alpha,\gamma}$.
2. **(Invertibility)** The factorization implies existence of a linear mapping from latent encoding to trace for each action. This linear mapping is invertible.
3. **(Sufficient measurements)** $D \geq r$.

### 4.3 Discussion

**Why not standard tensor completion?** Tensor completion methods [26, 40, 47, 75] make several assumptions. First, the tensor $M$ must be (approximately) low rank, which CausalSim also requires. Low-rank structure holds in many real-world problems [67] and has been observed in network measurements, e.g., in traffic matrices [16, 42, 43, 58] and network distance (i.e., RTT) [45, 50, 64]. As an example of how it emerges in the problems we study in this paper, we use a simple model of congestion control in Appendix D.2 to provide intuition about low-rank structure in ABR data.

Second, the pattern of missing entries should be random. If the missing patterns is not random and depends on latent factors or the entries themselves [8], standard approaches have difficulty recovering the tensor. This assumption does not hold in trace-driven simulation. Revealed entries are determined by the actions taken by the policies, which often use recent observations to make their decisions (e.g., an ABR policy may use recent throughput measurements). Hence the revealed/missing entries in a column are not random and depend on the entries in previous columns.

Third, a sufficient number of entries need to be revealed. For example, when $D = 1$ (i.e., when $M$ is a matrix), the information theoretic lower bound to on the number of revealed entries needed to recover $M$ is $4r^2 - r^2$ [38, 68]. Thus even for rank $r = 1$, it requires 4 entries per column, whereas only one entry per column is revealed in trace-driven simulation.

Since the second and third assumptions do not necessarily hold in our setup, we cannot use existing tensor completion methods. However, as we argued in §4.2, exploiting the additional problem structure imposed by RCT data can make tensor completion feasible in certain conditions.

**Limitations of Theorem 4.1.** The proof of Theorem 4.1 (Appendix A) provides an analytical method for recovering the tensor $M$ that generalizes the procedure described for the simple example in §4.2. While this provides a theoretical basis for why tensor recovery is possible, the analytical approach is not practical. First, it relies on $M$ being exactly rank $r$; if it is approximately rank $r$, we have found the calculation to be brittle. Second, it applies only to discrete action spaces. Third, it gives sufficient conditions for recovery, but they’re not all necessary. One reason is that the analytical method uses only mean invariance, i.e. the fact that the mean of the latent factors is the same across all policies (as in Eq. (4)), even though RCT data has the stronger property that the entire distribution of latents does not depend on the policy. In the next section, we
describe our practical implementation of CausalSim that uses learning techniques and neural networks to overcome these limitations (at the expense of theoretical guarantees).

5 CausalSim: Implementation

CausalSim builds upon the insights presented earlier but replaces the factorized model with a learning algorithm based on Neural Networks (NNs). For ease of notation, for any variable in the dataset such as the latent factor \( u_t : t \leq H, i \leq N \), we will drop the trajectory index, i.e. we will refer to \( u_t \) as \( u_t \).

**CausalSim architecture.** As discussed, CausalSim aims to extract \( u_t \) and learn \( f_\text{Trace} \) and \( f_\text{System} \) from observed trajectories \((a_{t+1}, o_t, m_t, a_t) : t < H \). Figure 3 summarizes CausalSim’s algorithmic structure.

To extract latent factors, we use a NN that takes in \( a_t \) and \( m_t \), and computes \( \hat{u}_t \) (an estimate of \( u_t \)). To apply invariance on the extracted latents, i.e. distribution of \( u_t \) being the same regardless of the policy applied to it, we use a NN called the Policy Discriminator. This NN aims to predict the policy pertaining to that sample given \( \hat{u}_t \), and if invariance is upheld, it will fail to do so. Unlike the analytical approach, the policy discriminator can enforce policy invariance on the entire latent distribution, potentially improving the accuracy of the estimate.

To calculate the counterfactual traces and observations, we need to learn \( f_\text{Trace} \) and \( f_\text{System} \). However, we can simplify the learning problem by merging these two into one single combined function. Thus, we use a NN that takes in counterfactual actions \( \tilde{a}_t \), observation \( o_t \) and estimated latent \( \hat{u}_t \), and computes counterfactual observation \( \tilde{o}_{t+1} \). Of course, we can explicitly use separate NNs for \( f_\text{Trace} \) and \( f_\text{System} \) if we require access to the simulated trace \( (\tilde{m}_t) \) values.

Overall, CausalSim uses three NNs for counterfactual simulation; \( E_\theta \) as the latent factor extractor, \( W_\gamma \) as the policy discriminator and \( P_\phi \) as the combination of \( f_\text{Trace} \) and \( f_\text{System} \). Figure 3 depicts the structure. Training these NNs is quick; on an A100 Nvidia GPU, CausalSim’s time to convergence on 56M data points (230K streams) was less than 10 minutes, and each simulation step in inference (on CPU) takes less than 150\( \mu \)s. A full inference run on the same volume of data takes less than 6 hours on a single CPU core and less than 20 minutes on 32 cores.

**Training procedure.** CausalSim’s training procedure alternates between: (i) training the policy discriminator using a discrimination loss \( L_{\text{disc}} \); and (ii) training other modules using an aggregated loss \( L_{\text{total}} \). Algorithm 1 in the appendix provides a detailed pseudo code of this training procedure.

**Training the policy discriminator** (Lines 5–10 in Algorithm 1). Distributional invariance means restricting the distribution of latent factors \( u_t \) to be identical across policies. To that end, we first use \( E_\theta \) to extract latents \( \hat{u}_t \), and then search for invariance violations via a discriminator neural network, a standard approach in the paradigm of adversarial learning [28, 66]. Specifically, the policy discriminator aims to predict the policy \( \pi_t \) that took action \( a_t \) from the estimated latent factor \( \hat{u}_t \) (see Figure 3). Towards that, we use a cross-entropy loss to train the policy discriminator:

\[
L_{\text{disc}} = \mathbb{E}_B[-\log(W_\gamma(\pi_i | \hat{u}))],
\]

where the expectation is over the sampled minibatch \( B \) from dataset \( D \). We train the policy discriminator to minimize this loss, by repeating gradient decent \( \text{num\_disc\_it} \) times, as the policy discriminator needs multiple iterations to catch up to changes in the latent factors.

**Training simulation modules** (Lines 11–17 in Algorithm 1). In this step, we need to impose consistency with observations, all while preserving the distributional invariance. Thus, we compute latent factors \( \hat{u}_t \) with \( E_\theta \) and simulate the next step of the trajectory \( \hat{o}_{t+1} \) with \( P_\phi \). We use an aggregated loss to enforce consistency and invariance. This loss combines the negated discriminator loss with a quadratic consistency loss using a mixing hyper-parameter \( \kappa \):

\[
L_{\text{total}} = \mathbb{E}_B \left[ (a_{t+1} - \hat{o}_{t+1})^2 \right] - \kappa L_{\text{disc}},
\]

where the expectation is over the a sampled minibatch \( B \) from dataset \( D \). Here, we used a quadratic loss function, but one could use any consistency loss fit to the specific type of variable (e.g. Huber loss, Cross entropy, ...).

Note the negative sign of discriminator loss, which means we train these NNs to maximize discriminator loss i.e., fool the discriminator to ensure policy invariance. If the extracted latent factors are policy invariant, the policy discriminator should do no better at its task than guessing at random.

**Counterfactual estimation.** To produce counterfactual estimates, as described above, the estimated latents \( \hat{u}_t \) are extracted from observed data. Using the extracted latents factors, along with the learned combined function \( P_\phi \), we start with \( o_1 \) and predict counterfactual observations \( \hat{o}_{t+1} \), one step at a time.
6 Evaluation

We evaluate CausalSim’s ability to do accurate counterfactual simulation (§6.1 and §6.3) using offline trace data from one real-world and one synthetic dataset. As a rigorous proof of concept, we debug and improve an ill-performing ABR policy with CausalSim (§6.2), and verify it through deployment on a public ABR testing infrastructure. Our baselines are as follows:

1. ExpertSim: Uses the analytical model described in §2.2.1.
2. SLSim: Uses a standard supervised-learning technique to learn system dynamics from data, as described in §2.2.2.

Finally, we show how CausalSim enables trace-driven simulation in problems where defining an exogenous trace is not straightforward and traditional trace-driven simulation is not applicable (§6.4). We have further supporting experiments in the appendix that provide more details about how CausalSim operates (§C.1, §C.2, §C.3, §C.4, §D.2, §D.3, §D.4 and §E.1).

6.1 Simulation Accuracy

We use CausalSim to predict the end performance of ABR policies, and compare them with ground truth data. We explore the same two metrics reported by Puffer to evaluate algorithms: 1) stall rate, which is the fraction of time a user spent rebuffering, i.e. paused and waiting for a new chunk to download; 2) average Structural Similarity Index Measure (SSIM) in decibels, which is a perceptual quality metric. Our ground truth data comes from public logs of ‘slow streams’ on Puffer. Whenever a client initiates a video streaming session in Puffer’s website, a random ABR algorithm is chosen and assigned to that session. Sessions are logged (buffer levels, chunk sizes, timestamps, download times, etc) anonymously and the data is available for public use. Our dataset contains more than 230K trajectories from an RCT during July 2020 to June 2021, where five ABR algorithms (BBA, BOLA1, BOLA2, Fugu-CL, Fugu-2019) were evaluated. Exhaustive details of the setup and data can be found in §C.5.

6.1.1 Can CausalSim simulate a policy it has not seen?

We choose one of BBA, BOLA1, and BOLA2\(^9\) as the new policy that we want to simulate, and call it the target policy. The remaining four policies are called source policies. Traces assigned to the four source policies comprise our training dataset, which we use for training CausalSim and the two baselines. The goal is to simulate the outcome of applying the target policy on trajectories assigned to any of the source policies.

Figure 4 plots the stall rate and SSIM in the simulated trajectories and ground truth, denoting each target policy with a different color. For either metric, CausalSim is the most faithful to ground truth among all simulators. For example, in stall rate, CausalSim’s relative error spans 2\(−\)28%, while ExpertSim spans 49\(−\)68% and SLSim spans 26\(−\)204%.

6.2 Case Study: CausalSim in the Wild

An accurate simulator allows researchers to debug and improve protocols without repeated and invasive deployments. We shall demonstrate this with CausalSim, by improving a well-known ABR policy, and verifying our findings with a real-world deployment on Puffer.

Recall that in the particular RCT we evaluated on in §6.1, five ABR algorithms (BBA, BOLA1, BOLA2, Fugu-CL, Fugu-2019) were evaluated. Figure 5 shows the result of this evaluation for BBA, BOLA1 and BOLA2, across ‘slow streams’.\(^{10}\) Similar to Figure 4, the X-axis shows the stall rate, and the Y-axis is the average SSIM. BOLA1 exhibited 82% more rebuffering compared to BBA. A revised version of BOLA1, called BOLA2, was deployed alongside it, since the Puffer team and the authors of BOLA believed the SSIM metric (in decibels) is incompatible with the protocol [51]. This new version had 12.8% less rebuffering and slightly higher quality, but still far too much stalling compared to BBA.

BOLA1 is a heuristic ABR policy with two hyperparameters, similar to BBA, and our hypothesis was that BOLA1 uses sub-optimal hyperparameters. To investigate this, we used the logged data pertaining to that plot, along with CausalSim to exhaustively analyze the performance of BOLA1 and BBA, for a range of hyperparameters. Using Bayesian Optimization\(^{11}\), we explored the parameter space and created a Pareto frontier curve for each policy. During this process, we evaluated over 150 different algorithms in two days, which is achievable only in a simulator. Each curve demonstrates the trade-off between quality and stall rate in that policy. Figure 6 presents

\(^9\)We exclude Fugu as a test policy since it requires access to some TCP information which is not fully logged in the dataset (see §C.5).

\(^{10}\)The data for this plot comes directly from Puffer [2, 3].

\(^{11}\)We use a Gaussian Process prior with a Matern Kernel [52].
Figure 5: In an experiment preceding this work, BOLA1 exhibits high stalling. By deploying a BOLA1 variant in a later experiment CausalSim improved the stall rate by 3.5 ×, with comparable quality to BBA. User population is ‘slow streams’ and error bars denote 2.5%–97.5% confidence intervals.

Figure 6: Pareto frontier curves for BOLA1 and BBA variants. CausalSim correctly predicts BOLA1’s potential, while ExpertSim fails to do so.

the curves, where the left and right plots show CausalSim and ExpertSim predictions. For ease of comparison, we highlight where the original BOLA1 and BBA lie. CausalSim confirms our suspicion; the curve for BOLA1 is strictly better than that of BBA. We can revise the hyperparameters in BOLA1 for an improved BOLA1 variant, henceforth called ‘BOLA1-CausalSim’. We chose BOLA1-CausalSim, such that it would have better quality and stall rate compared to BBA.

Interestingly, ExpertSim predicts the complete opposite. It predicts that not only will BBA always improve on any BOLA1 variant in at least one metric, but also that any BOLA1 variant will stall more. This serves as a great opportunity to test CausalSim’s edge compared to traditional (biased) trace-driven simulation, which is used in prior work [37,49,72]. The results of BOLA1-CausalSim’s deployment can be seen in Figure 5. Considering confidence intervals, it is clear that it stalls less than BBA; in fact, BBA stalls 168% more than BOLA1-CausalSim on average. The confidence intervals for quality are wide and will need more data to be separable12, but based on the ongoing trend, BOLA1-CausalSim will have similar, if not better, quality compared to BBA.

Our goal was to show CausalSim’s potential, and for that we targeted one of several plots on Puffer (‘slow streams’). We could have chosen a different plot to optimize on, but it would not affect the takeaway. Note that our opportunities for deployment on Puffer are limited, as other researchers use Puffer as well; hence we only deployed one BOLA1 variant. Furthermore, we hoped to also compare CausalSim’s prediction of stall rate and quality with the deployment results, but the client population has clearly changed; as shown in Figure 5, BBA achieves different statistics for the two periods of time. Since CausalSim’s predictions are based on data from the previous RCT, comparing the predicted values to results from the new RCT isn’t meaningful. However, as our results show, the old RCT data allows us to compare different schemes.

6.3 A Closer Look at Simulated Trajectories

For a deep dive in simulator accuracy, we focus on buffer occupancy level, a key indicator of ABR algorithm behavior. Ideally, we would like to compare simulated trajectories to ground truth. But this isn’t possible using real trace data, since it requires us to have multiple traces of different policies running under the exact same underlying path conditions. To overcome this issue, we resort to distributional evaluation. Puffer data is collected in an RCT setting; hence the characteristics of network paths assigned to each policy is the same. If we accurately simulate the target policy on traces assigned to one of the source policies, the distribution of each variable (e.g. buffer level) must be similar in the simulated trajectory and ground truth trace assigned to the target policy. This motivates using distributional similarity as our performance metric.

To quantify the similarity of two distributions, we use the Earth Mover Distance (EMD) [60]. We can calculate EMD for one-dimensional distributions as $\text{EMD}(P, Q) = \int_{-\infty}^{\infty} |P(x) - Q(x)| dx$, where $P(x)$ and $Q(x)$ are the Cumulative Distribution Function (CDF)s of $p$ and $q$, respectively. A small EMD between two distributions implies that they are similar.

Figure 7a shows the CDF of the EMD (between actual and simulated buffer level distributions) for CausalSim and baselines, over all possible source/target policy pairs. EMD of CausalSim is smaller than EMD of baselines across almost all experiments. In terms of the median EMD across all experiments, CausalSim bests ExpertSim and SLSim by 53% and 61% respectively. Figure 2a shows the source, target, and simulated buffer level distribution in a typical scenario, where BBA and BOLA1 are source and target policies respectively.

In about 30% of cases, SLSim is slightly better than CausalSim. These cases are “easy” simulation scenarios

12Updated plots can be found on the ‘Experimental Results’ page of the Puffer website [1], under “Current experiment, full contiguous duration, slow streams only”.


CausalSim’s simulations for each time step in real data, but we can do this in a reproducible synthetic environment. In §D.3, we evaluate CausalSim using ground truth counterfactual labels and show that it still outperforms baselines. Specifically, CausalSim achieves a MAPE of (~5%), which is significantly lower than both ExpertSim’s and SLSim’s (~10%).

6.4 A Second Example: Server Load Balancing

We now focus on simulating load balancing policies with heterogeneous servers, where defining an exogenous trace is not possible and therefore standard trace-driven simulation is not applicable. This example shows how CausalSim opens up new avenues in trace-driven simulation.

We use a synthetic environment which consists of $N = 8$ servers and a load balancer, and a series of jobs that need to be processed on these servers. Each job has a specific size which is unknown to the load balancer. Each server can process jobs at a specific rate $\{r_i\}_{i=1}^N$, which is also unknown to the load balancer. The load balancer receives jobs and must assign them to one of $N$ servers. Assuming the $k^{th}$ arriving job has size $S_k$ and gets assigned to server $a_k$, the job processing time will be $S_k/r_{a_k}$. If this job is not blocked by some other job being processed, its latency will equal its processing time. If it is blocked, and the jobs ahead of it in the queue take $T_k$ to be processed, the incurred latency is $S_k/r_{a_k} + T_k$.

We generate a collection of 5000 trajectories each with 1000 steps and use 16 policies in the load balancer. For a detailed explanation of the policies, job size generation process, and server processing rates, refer to §E.2.

6.4.1 Experiment setup

The aim of this experiment is to evaluate whether we can simulate new unseen server assignment policies in this environment, using traces collected with other policies. Recall that while we observe the processing time of each job, the actual size of the job is not observed, i.e., it acts as the latent factor in this problem. For all simulators, we assume access to $f_{\text{system}}$ (the queue model) and focus on the more challenging task of learning $f_{\text{trace}}$ and estimating the counterfactual traces $\tilde{n}^i_t$, for $i \leq 5000$, and $t \leq 1000$. This translates to enforcing consistency for the observed traces, rather than observations in the algorithm (see §5). The trace we collect is the processing time when using a source server assignment policy. To simulate a target server assignment policy, we need to estimate the processing time of a job on servers other than the one where its processing time was measured (without knowing either the job size or the server processing rates).

Standard trace-driven simulation assumes an exogenous trace (job processing time), but this is the same as assuming
As is done in the ABR case studies, we train CausalSim and \( \hat{p} \) and \( p \), the two competing models. Let \( \hat{p} = \{ \hat{p}_i \}_{i=1}^N \) and \( p = \{ p_i \}_{i=1}^N \) denote the vectors of predicted and ground truth quantity of interest, respectively. Then, \( \text{MAPE}(\hat{p}, p) = \frac{1}{N} \sum_{i=1}^N \frac{|\hat{p}_i - p_i|}{p_i} \). 

6.4.2 Can CausalSim Faithfully Simulate New Policies?

As is done in the ABR case studies, we train CausalSim and SLSim models based on a dataset generated using all policies except one, which will be the target policy. We use the same hyperparameter tuning approach explained in §C.4. We carry out this evaluation on eight target policies. We evaluate the performance for each pair of source-target policies, as was done in §6.1. In total, we have 120 different source/target policy pairs.

In Figure 8a and Figure 8b, we show the CDF of the MAPE of estimating the processing time and the latency, respectively, using both CausalSim and SLSim. As evident in these two figures, CausalSim’s error is significantly lower than that of SLSim for both the processing time and latency. In particular, the average MAPE when estimating processing time/latency is 27.1%/29.1% for CausalSim and 102.4%/240.8% for SLSim. For a complementary view, we compare the latent factors CausalSim extracts to the real latent job sizes and observe how closely they match, in §E.1 in the appendix.

7 Related-Work

Data-driven simulation. Packet level simulators [21, 30, 44] tend to sacrifice either scalability or accuracy when simulating large networks. Recent research combines machine learning with packet-level modeling [70] to improve speed and accuracy of datacenter [74] and wide-area network [13] simulators. The aforementioned approaches are full-system simulators, whereas CausalSim focuses on trace-driven simulation of a specific component and must therefore deal with latent factors and biases present in trace data.

A very recent work, Veritas [17] (published on arXiv in Aug. 2022), models trace-driven simulation for ABR as a Hidden Markov Model (HMM) with a known emission process. This is equivalent to assuming that \( f_{\text{trace}} \) is known in our model (see Eq. (1)). Veritas uses the Viterbi algorithm to decode the latent factors, which are then used for counterfactual simulation. CausalSim solves a more general problem where \( f_{\text{trace}} \) is not known and must be learned. It therefore requires less knowledge of the system’s latents and underlying dynamics to apply. On the other hand, CausalSim requires RCT data whereas Veritas does not. Comparing the fidelity of these approaches using real-world ABR data would be interesting future work (Veritas evaluates its method in a network emulator).

Policy evaluation. Policy evaluation techniques such as Inverse Propensity Scoring [32] and Doubly Robust [15] aim to predict population-level performance statistics for a given intervention. WISE [65] builds a Causal Bayesian Network from the data that is able to answer interventional (what-if) queries about the future, but the method requires absence of latent confounding variables. Sage [25] uses a Causal Bayesian Network model with latent factors to diagnose performance issues in microservice applications. It answers what-if questions about how interventions like changing the resources allocated to a microservice impacts the end-to-end application latency. Trace-driven simulation is distinct from all these methods, in that it requires counterfactual predictions of how an intervention would have changed specific previously-measured trajectories rather than how it changes population-level statistics.

Appendix F provides a broader overview of the causal inference literature.

8 Concluding Remarks

The exogenous trace assumption is central to traditional trace-driven simulation. CausalSim relaxes this key assumption, by modeling the intervention effect on the trace and learning to replay the trace in an unbiased manner. We showed how this improves the accuracy of trace-driven simulation using real-world ABR data, and how CausalSim provides insights for algorithm improvement that are in contrast with standard trace-driven simulators’ predictions, which we validated in a real-world deployment. Furthermore, we showed how this expands the applicability of trace-driven simulation to problems
where defining an exogenous trace is not possible by applying it to heterogeneous server load balancing. We believe CausalSim could be applied to many other system simulation tasks.

CausalSim opens up several interesting paths for future work. First, evaluating CausalSim in problems with higher-dimensional latent factors would be interesting. Second, it is a natural next step to use CausalSim for more complex policy optimization methods, e.g., using reinforcement learning. Last, as discussed in §4.3, our theoretical analysis of CausalSim’s approach, i.e. exploiting the policy invariance of latent factors distributions, is not tight, and improving it could potentially relax the assumptions of our analytical method.

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Appendix A  Tensor Completion with policy invariance

Here, we discuss a more generic version of the problem considered in §4.2 from the lens of tensor completion. Specifically, in §4 we considered the simplified setting where the trace was considered to be one-dimensional. Here, we shall consider higher dimensional traces. This, naturally suggests using the lens of Tensor instead of Matrix completion. We will also discuss how higher dimensional trace can enable recovery of more complex system dynamics or models compared to the simple solution we discussed in §4 for rank 1 setup.

Potential Outcomes Tensor. As considered in §4 let all possible actions be denoted as \([A] = \{1, \ldots, A\}\) for some \(A \geq 2\). Let the trace be of \(D\) dimension. As before, we have \(N\) trajectories of interest with trajectory \(i \in [N]\) being of length \(H_i \geq 1\) time steps. As before, let \(U = \sum_{i \in H_i}\).

Consider an order-3 tensor \(M\) of dimension \(A \times U \times D\), where \(M = \{m_{a\beta\gamma} : \alpha \in [A], \beta \in [U], \gamma \in [D]\}\) with \(m_{a\beta\gamma}\) corresponds to the \(\gamma\)th co-ordinate of the \(D\)-dimensional trace corresponding to action \(a_t = \alpha \in [A]\) when latent factor is \(H_t\), with \(\beta\) corresponding to enumeration of \((i,t)\) for some \(i \in [N]\) and \(t \leq H_i\). Recall that, as explained in Section 4, all possible \((i,t) : 1 \leq t \leq H_i, i \in [N]\) are mapped to an integer in \([U]\). We call this tensor \(M\) as the Potential Outcomes Tensor.

Indeed, if we know \(M\) completely, then we can answer the task of simulation or counterfactual estimation well since we will be able to estimate the mediator for each trajectory under a given possible sequence of counterfactual actions, and subsequently estimate the counterfactual observation (assuming we could learn the \(J_{\text{systems}}\).

We shall assume that there are \(P \geq 1\) policies under which these traces were observed. In particular, each trajectory was observed under one of these \(P\) policies and the assignment of policy to the trajectory was done uniformly at random. Define \(\Pi_p \subset [U]\) as collection of indices corresponding to trajectories \(i \in [N]\) and their times \(t \leq H_i\) where trajectory \(i\) was assigned policy \(p\) for \(p \in [P]\). Let \(U_p = |\Pi_p|\).

Tensor factorization, low CP-rank. The tensor \(M\) admits (not necessarily unique) factorization of the form: for any \(\alpha \in [A], \beta \in [U], \gamma \in [D]\)

\[
m_{a\beta\gamma} = \sum_{\ell=1}^{r} x_{\alpha \beta \gamma} y_{\alpha \ell} z_{\ell \beta \gamma},
\]

for some \(r \geq 1\). For any tensor, such a factorization exists with \(r\) at most \(\text{poly}(A,U,D)\).

Assumption 1 (low-rank factorization). We shall make an assumption that \(r\) is small, i.e. does not scale with \(A,U,D\) and specifically a small constant.

Assumption 2 (sufficient measurements). We shall assume that number of measurements per instance, \(D\), is at least as large as the underlying rank \(r\) of the tensor \(M\), i.e. \(D \geq r\).

Distributional invariance and RCT. As before, we shall assume that the distribution of latent factors is the same across different policies due to random assignment of policies to trajectories in the setup of RCT. In the context of the tensor \(M\), this corresponds to the distribution invariance of factors \(y_{p\alpha} \in \mathbb{R}^r\) over \(\beta \in \Pi_p\), for any \(p \in [P]\). Concretely, for any \(p \neq p' \in [P]\) and \(\ell \in [r]\), we have

\[
\frac{1}{U_p} \sum_{\beta \in \Pi_p} y_{p\beta \ell} \approx \frac{1}{U_{p'} \sum_{\beta' \in \Pi_{p'}} y_{p'\beta' \ell}}.
\]

More generally, any finite moment (not just first moment or average) of latent factors should be empirically invariant across policies. As in §4, we would like to utilize property (9) to estimate the tensor \(M\).

A Simple Estimation Method and When It Works. We describe a simple method that can recover entire tensor as long as rank \(r \leq D\). For simplicity, we shall assume \(r = D\) (the largest possible rank for which method will work). By (8), for a given fixed \(\alpha \in [A]\) and across \(\beta \in [U], \gamma \in [D]\),

\[
m_{a\beta\gamma} = \sum_{\ell=1}^{r} y_{\alpha \ell} z_{\ell \beta \gamma},
\]

where \(\alpha \beta \gamma = x_{\alpha \beta \gamma}y_{\alpha \ell}z_{\ell \beta \gamma}\). Since \(D = r\), the matrix \(\tilde{Z}^\alpha = [\alpha \beta \gamma : \gamma \in [D], \ell \in [r]]\) is a square matrix. With this notation, we have that for any fixed \(\alpha \in [A]\), the matrix \(M^\alpha = [m_{a\beta\gamma} : \beta \in [U], \gamma \in [D]] \in \mathbb{R}^{U \times D}\) (or \(\mathbb{R}^{U \times r}\) since \(r = D\)) can be represented as

\[
M^\alpha = Y \tilde{Z}^\alpha T,
\]

where \(Y = [y_{p\beta} : \beta \in [U], \ell \in [r]] \in \mathbb{R}^{U \times r}\).

Assumption 3 (invertibility). We shall assume that the \(D \times D\) (i.e. \(r \times r\)) square matrices \(\tilde{Z}^\alpha\) for each \(\alpha \in [A]\) are full rank and hence invertible.

The Assumption 3 implies that \(Y = M^\alpha (\tilde{Z}^\alpha)^{-1}\) for all \(\alpha \in [A]\).

For policy \(p \in [P]\), indices \(\beta \in \Pi_p\) are relevant. For a given \(\beta \in \Pi_p\), if the policy \(p\) utilized action \(\alpha \in [A]\), \(m_{a\beta\gamma} \in \mathbb{R}^D\) is observed. To that end, let \(\Pi_{p,\alpha} = \{\beta \in \Pi_p : \text{policy utilized action } \alpha\}\). Let \(U_{p,\alpha} = |\Pi_{p,\alpha}|\) for any \(\alpha \in [A]\). Then, define \(y^{p,\alpha} = [y_{p\beta} : \beta \in \Pi_{p,\alpha}, \ell \in [r]] \in \mathbb{R}^{U_{p,\alpha} \times r}\), \(M^{p,\alpha} = [m_{a\beta\gamma} : \beta \in \Pi_{p,\alpha}, \gamma \in [D]]\). Then we have \(Y^{p,\alpha} = M^{p,\alpha} (\tilde{Z}^{p,\alpha})^{-1}\).

Therefore, for any \(\ell \in [r = D]\),

\[
\sum_{\beta \in \Pi_{p,\alpha}} y_{p\beta \ell} = \sum_{\beta \in \Pi_{p,\alpha}} 1^{p,\alpha,\ell} y^{p,\alpha,\ell},
\]

\[
= e_{\ell}^T Y^{p,\alpha} 1^{p,\alpha},
\]

\[
= e_{\ell}^T (\tilde{Z}^{p,\alpha})^{-1} M^{p,\alpha} 1^{p,\alpha},
\]

where \(1^{p,\alpha} \in \mathbb{R}^{U_{p,\alpha}}\) is vector of all 1s, and \(e_{\ell} \in \mathbb{R}^{r}\) be vector with all entries 0 but the \(\ell\)th co-ordinate 1.
Then, for any $\ell \in [r]$ and $p \in [P]$,

$$
\frac{1}{U_p} \sum_{b \in B_p} y_{b \ell} = \frac{1}{U_p} \sum_{a \in [A]} \sum_{b \in B_p} y_{b \ell} = \frac{1}{U_p} \sum_{a \in [A]} e_{i}^T \tilde{Z}^{-1} \alpha \tilde{1} \alpha^{p, \alpha} = \sum_{a \in [A]} e_{i}^T \tilde{Z}^{-1} \alpha \tilde{1} \alpha^{p, \alpha} = \sum_{a \in [A]} e_{i}^T \tilde{Z}^{-1} \alpha \tilde{1} \alpha^{p, \alpha},
$$

(13)

where $\alpha^{p, \alpha} = \frac{1}{U_p} \alpha \tilde{1} p, \alpha \in \mathbb{R}^{1,r}$ is an observed quantity, while $\tilde{Z}^{-1}$ is unknown. Using (13) and (9), we obtain that for any $\ell \in [r]$ and $p \neq p' \in [P]$,  

$$
\sum_{a \in [A]} e_{i}^T \tilde{Z}^{-1} \alpha \tilde{1} \alpha^{p, \alpha} \approx \sum_{a \in [A]} e_{i}^T \tilde{Z}^{-1} \alpha \tilde{1} \alpha^{p, p'}. 
$$

(14)

Let $z_{a, \ell} = e_i^T (\tilde{Z}^{-1})_a \in \mathbb{R}^{1,r}$ be the $\ell$th row of the $r \times r$ matrix $(\tilde{Z}^{-1})_a$. Then (14) implies that for any $\ell \in [r]$ and $p \neq p' \in [P]$,  

$$
\sum_{a \in [A]} z_{a, \ell} (\alpha^{p, p'} - \alpha^{p, p'}) = 0. 
$$

(15)

Which can be written in matrix form as

$$
\begin{bmatrix}
z_{1, \ell} & z_{2, \ell} & \ldots & z_{A, \ell}
\end{bmatrix}
\begin{bmatrix}
\alpha^{p, p'} - \alpha^{p, p'} \\
\alpha^{p, p'} - \alpha^{p, p'} \\
\vdots \\
\alpha^{p, p'} - \alpha^{p, p'} 
\end{bmatrix} = 0.
$$

(16)

By noting that that this hold for all $\ell \in [r]$, and recalling that $z_{a, \ell}$ is the $\ell$-th row of the $r \times r$ matrix $(\tilde{Z}^{-1})_a$, we get

$$
\begin{bmatrix}
\tilde{Z}_1^{-1} & \tilde{Z}_2^{-1} & \ldots & \tilde{Z}_A^{-1}
\end{bmatrix}
\begin{bmatrix}
\alpha^{p, p'} - \alpha^{p, p'} \\
\alpha^{p, p'} - \alpha^{p, p'} \\
\vdots \\
\alpha^{p, p'} - \alpha^{p, p'} 
\end{bmatrix} = 0,
$$

(16)

where 0 is a vector of zeros of size $r$. Note that the above is a system of $r$ linear equations, with $Ar^2$ unknowns (recall that the $r \times r$ matrices $(\tilde{Z}^{-1})_a$ are unknown for $a \in [A]$). Let $Z \in \mathbb{R}^{r \times Ar}$ and $v^{p, p'} \in \mathbb{R}^{Ar}$ denote the first and second matrix in the left hand side, respectively, then (16) can be re-written as,

$$
Zv^{p, p'} \approx 0. 
$$

(17)

By definition, $v^{p, p'}$ is observed quantity for each $p \neq p' \in [P]$. Now if we consider $P-1$ equations produced by considering pair of policies $(1,2), (1,3), \ldots, (1,P)$ in (17), by design they are non-redundant linear equations. Let matrix $V \in \mathbb{R}^{Ar \times P-1}$ be formed by stacking $v^{1,2}, \ldots, v^{1,P}$ column-wise.

Furthermore, let us define $s^p \in \mathbb{R}^{Ar}$ as $[M^{1,p}, \ldots, M^{A,p}]^T$. Define $S \in \mathbb{R}^{Ar \times P}$ by stacking $s^1, \ldots, s^P$ column-wise.

**Assumption 4 (Sufficient, Diverse Policies).** Let $P \geq Ar$ and the rank of $S=Ar$.

Under Assumption 4, it follows that rank of $V$ is $Ar-1$ because we can derive $V$ from $S$ by subtracting the first column from all other columns, and removing the first column. As rank of $V$ is $Ar-1$, we can uniquely (upto scaling) recover $Z$ by solving for system of linear equation $ZV = 0$ as the null space of $V$ of dimension 1.

Once we know $z$, i.e. by undoing flattening, we obtain $(\tilde{Z}^{-1})_a$ for each $a \in [A]$. Since for each policy $p \in [P]$ and $a \in [A], Y^{p, a} = \alpha^{a, p} (\tilde{Z}^{-1})_a$ and we observe $\alpha^{a, p}$, we can recover $Y^{p, a}$ and hence subsequently $Y = \mathbb{2}$. By (11), we can now recover slice of tensor $M$, the $\alpha^a$ for each $a \in [A]$, and hence we can recover entire tensor $M$ as desired.

**Interpretation of Assumption 4.** Consider $\beta$ Column of the matrix $S$, i.e., $[E[m^{1,i} | i = 1, \pi_0] | E[m^{2,i} | i = 1, \pi_0], \ldots, E[m^{r,i} | i = 1, \pi_0]]$ where $i$ denotes the action index and $\beta$ the policy index. This column is a vector of statistics associated with traces collected using policy $\beta$. Each element in this vector consists of two components: the first component is the conditional mean of the trace given a specific action, and the second element is the probability of taking this action. We interpret linear independence of each of these components for different policy vectors as policy diversity. For instance, think of the second component which captures probability vectors of different actions for each policy. Its linear independence across different policies roughly means that each policy should assign new probability vectors to different actions, and not a probability vector similar (linearly dependent) to that of previous policies. Also note that this assumption is not satisfied if an action is not taken by any of the policies which makes all elements of the corresponding row equal to zero.
Appendix B  CausalSim Algorithm

Algorithm 1 CausalSim Training

1: initialize parameter vectors $\gamma, \theta, \phi$
2: initialize hyper-parameters $num\_disc\_it, \kappa$
3: initialize dataset $D \leftarrow \{(o_i, m_i, a_i, \pi_i)\}_{i=1}^m$ from an RCT
4: for each iteration do
5:     for $num\_disc\_it$ do
6:         sample minibatch $B \leftarrow \{(o_i, m_i, a_i, \pi_i)\}_{i=1}^b$
7:         $u_i \leftarrow \mathcal{E}_\theta(m_i, a_i)$ for $l \in \{1, \ldots, b\}$
8:         $L_{\text{disc}} \leftarrow \frac{1}{b} \sum_{i=1}^b \left[ -\log \mathcal{W}_l(\pi_i | u_i) \right]$
9:         $\gamma = \gamma - \lambda_e \nabla_{\gamma} L_{\text{disc}}$
10:    end for
11:    sample minibatch $B \leftarrow \{(o_{i+1}, a_i, m_i, a_i, \pi_i)\}_{i=1}^b$
12:    $u_i \leftarrow \mathcal{E}_\theta(m_i, a_i)$ for $l \in \{1, \ldots, b\}$
13:    $L_{\text{disc}} \leftarrow \frac{1}{b} \sum_{i=1}^b \left[ -\log \mathcal{W}_l(\pi_i | u_i) \right]$
14:    $L_{\text{pred}} \leftarrow \frac{1}{b} \sum_{i=1}^b \left[ \left( o_{i+1} - \mathcal{P}(o_i, a_i, a_i) \right)^2 \right]$
15:    $L_{\text{total}} \leftarrow L_{\text{pred}} - \kappa \cdot L_{\text{disc}}$
16:    $\theta = \theta - \lambda_\theta \nabla_{\theta} L_{\text{total}}$
17:    $\phi = \phi - \lambda_\phi \nabla_{\phi} L_{\text{pred}}$
18: end for

Appendix C  Real-world ABR

C.1 Comprehensive results

In Figure 7a, we presented a concise view of simulator fidelity, for an internal variable in ABR sessions called buffer occupancy level. Specifically, we considered the simulation of a target policy, given trajectories collected using a different source policy. We measured the error between buffer simulations and ground truth through EMD, a similarity index for distributions. For a complementary view, we provide the full distributions in Figure 9, for all simulators and ground truth for target and source policies. Below each plot, we also report the EMD of CausalSim predictions.

C.2 What makes a simulation scenario easy/hard?

In §6.3, we compared the accuracy of CausalSim, ExpertSim and SLSim, in a simulation task on real ABR data. We observed that in about 30% of scenarios, which we call easy scenarios, all simulators perform well. However, in about 70% of the source/target scenarios, which we call hard simulation scenarios, baseline predictions are highly biased towards the source distributions. In these hard scenarios, CausalSim is able to de-bias the trajectories and its predictions match target distribution pretty well. It is possible to observe this in Figure 9.

So it is natural to wonder what makes a simulation scenario easy/hard? An easy simulation scenario happens when source and target policies take similar actions. Similar action means that the factual achieved throughput (of the source policy) is similar to the counterfactual achieved throughput (of the target policy). This is what both ExpertSim (explicitly) and SLSim (implicitly) assume for doing simulation. Making this assumption is the core reason their simulations are biased in hard cases, where source and target policies take different actions, as we discussed in detail in §2.2.3.

Figure 10 validates our reasoning for difficulty of a simulation scenario. X axis shows the Mean Absolute Difference (MAD) between source and simulation actions (bitrates) when simulating with SLSim in a specific source/target scenario. Y axis shows EMD (Our performance metric for simulation, smaller is better) of both baselines in that specific scenario.

Two main cluster of points are clearly visible in this figure. The pink cluster on the bottom left corresponds to easy simulations. It includes all source/target simulation scenarios where baselines perform well (bottom), and at the same time, source and target actions are quite similar (left). The green cluster no the top right corresponds to the hard simulations. It includes all source/target simulation scenarios where baselines fail to perform an unbiased simulation (top), and at the same time, source and target actions are quite different (right).

C.3 A More Fine-grained Evaluation

Ideally, we would like to evaluate CausalSim’s simulation to ground truth on a step-by-step basis for a given trajectory. But as discussed in §6.3, this is not possible in real-world data, as we only see the outcome of one ABR algorithm’s chosen action for a single step. In other words, there is no way to get ground truth for individual steps in the observational data, which is referred to as the fundamental problem of Causal Inference [31]. This is the reason we evaluated predictions on a distributional level.

However, there is a way to evaluate CausalSim’s predictions at a more fine-grained level. Instead of evaluating the predicted distribution of buffer occupancy across the whole population, we can evaluate on certain sub-populations of users. The only requirement is that the way we select these sub-populations should be statistically independent of the ABR algorithm. For example, we can partition users by a metric such as Min RTT, which is independent of the policy chosen for each user in the RCT. Min RTT is an inherent property of a network path which is similar to the counterfactual achieved throughput (of the source policy) that the factual achieved throughput (of the source policy) and Min RTT is an inherent property of a network path [31], and we would expect Min RTT distribution to be the same for users assigned to different ABR policies.

13This is true to a first order approximation, if we ignore the possibility that a video streaming session drives up queueing delays throughout the course of a video, thereby inflating the observed Min RTT.
Figure 9: Buffer level distribution of source, target, CausalSim predictions, and baseline predictions across all source/target scenarios.
Figure 10: Simulation difficulty is related to how different counterfactual actions are from factual ones. This figure shows scatterplot of EMD versus mean absolute bitrate difference, for ExpertSim and SLSim, over all possible source left-out pairs. The pink cluster signifies the ‘easy’ scenarios and the green cluster signifies ‘hard’ ones.

We use the MinRTT to create the following four sub-populations:

1. Sub1: users with Min RTT < 35ms
2. Sub2: users with 35ms ≤ Min RTT < 70ms
3. Sub3: users with 70ms ≤ Min RTT < 100ms
4. Sub4: users with 100ms ≤ Min RTT

Now, we can ask question of the following type: had the users in sub-population two, who were assigned the source ABR algorithm, instead used the left-out ABR algorithm, what would the distribution of their buffer level look like? As the ground truth answer to this question, we can use the buffer level distribution of users in sub-population two assigned to the left-out policy.

Figure 11b shows the CDF of EMD when simulating the left-out ABR algorithm over each sub-population. CausalSim maintains the highest accuracy in each sub-population. This further suggests that even at surgically small sub-populations, CausalSim remains faithful, and does not overfit to the whole distribution.

C.4 How to Tune CausalSim’s Hyper-parameters?

Counterfactual prediction is not a standard supervised learning task that optimizes in-distribution generalization. Rather, it is always an OOD generalization problem, i.e., we collect data from a training policy (distribution 1), and want to accurately simulate data under a different policy (distribution 2) Since we do not use data from the test policy when we train CausalSim, we use the following natural proxy for tuning hyper-parameters: Simulating ABR algorithms in the training data using trajectories of other ABR algorithms in the training data. This of course can be viewed as an OOD problem as well. We claim that if a choice of hyper-parameters results in a robust model that performs well OOD across all validation ABR algorithms in the training data, it should work well for the actual left-out test policy as well.

We verify this hyper-parameter tuning procedure empirically. For each choice of the three left-out ABR algorithms (hence training dataset), we train twelve different CausalSim models with different choices of \( \kappa \) (defined in (7)). We consider two metrics: (i) Test EMD, defined as the average EMD when simulating the left-out ABR algorithm from the ABR algorithms in the training dataset. This is our main performance objective. (ii) Validation EMD, defined as the average EMD when simulating ABR algorithms in the training dataset from other ABR algorithms in the training dataset. This is our proxy objective for hyper-parameter tuning.

For each model (36 in all: 3 datasets, 12 example hyper-
parameters), we calculate both Test EMD and Validation EMD, which results in one (Validation EMD, Test EMD) point in Figure 11a. The Pearson Correlation Coefficient (PCC) between Valid EMD and Test EMD is 0.92, which shows high linear correlation. Hence, though CausalSim might not always perform well (i.e., Test EMD is not low for some combinations of training dataset and hyper-parameters), we can have a very good idea of how well it works by measuring Validation EMD.

C.5 Dataset & Algorithms

Our trajectories in the real-world (Puffer) data come from ‘slow streams’ in the time span of July 27, 2020 until June 2, 2021. In this period of time, 5 ABR algorithms appear consistently and are listed in Table 1. Each trajectory is an active client session streaming a live TV channel. We follow Puffer’s definition of ‘slow streams’; streams with TCP delivery rates below 6 Mbps. We use ‘slow streams’ data, since the highest quality chunks will always stream the highest quality chunks under all policies. Puffer used the same reasoning and evaluates algorithms at two population levels; ‘slow streams’ and ‘all streams’.

In aggregating ‘slow stream’ logs, we met several difficulties that we outline here for reproducibility. Data without these difficulties would potentially improve CausalSim’s accuracy. Note that this does not affect Figure 5, as the data for plot is reported directly on Puffer [2, 3]. Puffer logs are reported as three separate event groups; 1) ‘video_sent’: the first packet of a chunk is sent, 2) ‘video_acked’: The last packet of a chunk is received, 3) ‘client’: The client sent a message. Stall rate is computed using the ‘client’ logs and quality is computed using the ‘video_sent’ logs.

1. To compute download time, we have to merge ‘video_sent’ and ‘video_acked’, and ensure of merged logs are consecutive in timestamps, i.e. no chunk is missing in between two other chunks. However, in the current data this removes all chunks that have been sent but not acknowledged, usually the last chunk. Puffer uses these chunks in measuring quality level, but we can’t. This did not have any measurable impact, however.

2. To compute stall rate, both total stall time and total watch time are computed with ‘client’ logs. The very last entry in the log that obeys a set of rules is used for this. We have to compute stall time and watch time using our merged logs (merged logs are also what we get out of simulation). This would be easy on the original data, if ‘client’ logs and ‘video_sent’ were in sync, but they are not; whenever a rebuffering is reported by the client, ‘client’ log is updated but ‘video_sent’ is updated in the next few chunks. To circumvent this, we compute rebuffering as \( r = \max(0, t_d - b) \), where \( t_d \) is rebuffering, \( b \) is buffer occupancy and \( t_d \) is download time. This formula is off by half of an RTT, and leads to stall rate growing by \( 1.26 - 1.31x \), for all policies.

In the absence of synchronized data, this is the best we can recover, but it does not affect the comparison among policies. Hence, we believe simulating with this data should lead to similar trends as with clean unperturbed data.

3. We cannot calculate watch time as Puffer does, since we have to use the merged log. We tried several simple formulas that should calculate watch time, but oddly most turn out to be inaccurate. One reason is that in some streams, buffer playback rate is not 1, i.e. one second of buffer is not depleted per second. These streams are likely due to browser tabs put in background, and throttled by the browser threading system. As a workaround, we use the original watch time minus the original stall time that Puffer computed for a stream, and offset it by the total stall time in the simulation.

4. At each step, the buffer should not increase by more than a single chunk, 2.002 seconds, but it does (sometimes by as much as 14 seconds). We filter such data out.

5. When we are about to send a chunk, our last reported buffer value must never dip below 2.002 (except in the beginning). When buffer is below 15 seconds, the next chunk must be sent immediately after the last one. If rebuffering occurs, the next buffer value will be exactly 2.002 and if it doesn’t, it will be larger than 2.002. We frequently (more than one million instances) observe buffer values below 2.002. We do not filter them out, as this would invalidate most logs.

To test out CausalSim, we need to simulate the streaming session using a different algorithm than the one that was actually used in that session. This requires implementation of the ABR algorithms. However, Fugu’s implementation needs access to the history of the streaming session’s Transmission Control Protocol (TCP) info, which is not fully logged in the data-set. More specifically, our attempts for reconstructing Fugu’s chosen chunk sizes fail to match the logged ones in the data-set. Therefore, we do not consider Fugu-2019 or Fugu-CL as candidates for left-out algorithms.

C.6 Training setup

We use Multi Layer Perceptron (MLP)s as the neural network structures for CausalSim models and the SLSim model. All implementations use the Pytorch [54] library. Table 2 is a comprehensive list of all hyperparameters used in training.

Appendix D Synthetic ABR

As explained in §6.3.1, we also evaluate CausalSim in a synthetic ABR environment, in which we can obtain ground truth for individual counterfactual predictions on a step-by-step basis for a trajectory. In these experiments, we also use a larger set of policies than available in the real data.
| Policies            | Hyperparameter | Value                                      | Used as source | Used as left out |
|---------------------|----------------|--------------------------------------------|----------------|------------------|
| BBA                 | Cushion        | 3 (as used in puffer)                      | ✓              | ✓                |
|                     | Reservoir      | 10.5 (as used in puffer)                   |                |                  |
| BOLA-BASIC v1       | V              | 0.67 (As computed in puffer)               | ✓              | ✓                |
|                     | γ              | -0.43 (As computed in puffer)              |                |                  |
|                     | Utility function| \(\log_{10}(1 - ssim)\) (As used in puffer)|                |                  |
|                     | Minimum utility| 0 (As used in puffer)                      |                |                  |
|                     | Maximum utility| 60 (As used in puffer)                     |                |                  |
| BOLA-BASIC v2       | V              | 51.4 (As computed in puffer)               |                |                  |
|                     | γ              | -0.43 (As computed in puffer)              | ✓              | ✓                |
|                     | Utility function| ssim (As used in puffer)                   |                |                  |
|                     | Minimum utility| 0 (As used in puffer)                      |                |                  |
|                     | Maximum utility| 1 (As used in puffer)                      |                |                  |
| Fugu-CL             | -              | -                                         | ✓              | ×                |
| Fugu-2019           | -              | -                                         | ✓              | ×                |

Table 1: ABR algorithms used in the real-world dataset and experiments

| Model                  | Hyperparameter        | Value                                      |
|------------------------|-----------------------|--------------------------------------------|
| **SLSim (1 network)**  | Hidden layers         | (128, 128)                                 |
|                        | Hidden layer Activation function | Rectified Linear Unit (ReLU) |
|                        | Output layer Activation function | Identity mapping |
|                        | Optimizer             | Adam [39]                                   |
|                        | Learning rate         | 0.001                                       |
|                        | \(\beta_1\)           | 0.9                                         |
|                        | \(\beta_2\)           | 0.999                                       |
|                        | \(\epsilon\)          | \(10^{-8}\)                                 |
|                        | Batch size            | \(2^{17}\)                                  |
| **CausalSim**          | \(\kappa\)           | \(\{0.01, 0.05, 0.1, 0.5, 1.0, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 40.0\}\) |
|                        | \(\delta\)           | \(\{0\}\)                                   |
|                        | Training iterations (num_train_it) | 5000                               |
|                        | num_disc_it           | 10                                          |
| **SLSim**              | Training iterations   | 10000                                       |

Table 2: Training setup and hyperparameters for the real-world ABR experiment
D.1 Simulation Dynamics

In each simulated training session, we start with an empty playback buffer and a latent network path characterized by an RTT and a capacity trace. In each step, an ABR algorithm chooses a chunk size, which is transported over this network path to the client as the buffer is depleting. Once the user receives the chunk, the buffer level increases by the chunk duration. This simple system can be modeled as follows:

\[ b_{t+1} = \min(b_t - d_t, 0) + c \]  

(18)

where \( b_t, d_t \) and \( c \) refer to the buffer level at time step \( t \), the download time of the chunk at time step \( t \), and the chunk video length in seconds, respectively. Streaming the next chunk is started immediately following receiving the previous one, except when the buffer level surpasses a certain value (in our case, 10 seconds to mimic a live-stream ABR setting).

To compute \( d_t \), we model the transport as a TCP session with an Additive Increase - Multiplicative Decrease (AIMD) congestion control mechanism with slow start. For every chunk, the TCP connection starts from the minimum window size of 2 packets and increases the window according to slow start. Therefore, it takes the transport some time to begin fully utilizing the available network capacity. The overhead incurred by slow start depends on the RTT and bandwidth-delay product of the path. When downloading chunks with large sizes, the probing overhead is minimal but it can be significant for small chunks. Therefore, as we observed in the Puffer data, the throughput achieved for a given chunk in this synthetic simulation depends on the size of the chunk.

Our simulation consists of 5000 to 16000 trajectories, for each of whom a policy is randomly chosen from the list of available policies. For a full explanation of the simulation setup, network capacity generation procedure, and the simulated policies, refer to §D.5.

Performance Metric: We compare CausalSim predictions with ground truth counterfactual trajectories, via the Mean Squared Error (MSE) distance between the two time series:

\[ \text{MSE}(\mathbf{p}, \mathbf{q}) = ||\mathbf{p} - \mathbf{q}||_2^2 \]  

(19)

Here, \( \mathbf{p} = \{p_t\}_{t=1}^N \) and \( \mathbf{q} = \{q_t\}_{t=1}^N \) are time series vectors. Better predictions yield smaller MSE values, where an ideal MSE is 0.

D.2 Low-rank structure

As discussed in §4.1, we can formulate the counterfactual estimation problem in the context of matrix completion. For each time step, we know the chosen bitrate (action) and the achieved throughput (mediator). We also know the mediator is computed using a latent factor and the action. Suppose the latent factor is the network bottleneck capacity \( c_t \), \( c_t \) describes how the achieved throughput (the mediator) relates to this latent factor. Intuitively, this should be a close-to-linear function, \( m_t \approx c_t \). But it’s not exactly linear; for example, congestion control may under-utilize the network capacity for small transfers on high-RTT paths.

We form a matrix \( M \), where the rows denote actions \( a_t \in [A] \) and the columns denote the latent factors \( u_j \) for each trajectory. The ‘factual’ data we have are single observed mediator values in each column, i.e for each step and each latent, we have observed the mediator from a single action. To estimate counterfactuals, we must complete the matrix. This modeling inherently assumes low-rank structure \( M \), which results from \( \mathcal{F}_\text{mediation} \). However, we have no way of knowing the true \( \mathcal{F}_\text{mediation} \) in the Puffer dataset. But to get a sense for what it might look like and whether it’s plausible that \( M \) is low rank, we can investigate this in a simple controlled ABR environment which confirms the low-rank assumption.

Let us consider a simple model of congestion control that allows us to compute the observed throughput. We describe this model in detail in §D.1, but the basic idea is to assume that for each chunk, the congestion control begins in slow start and ramps up its window size over several RTTs until it fills up the available capacity or the transfer completes. For this model, \( \mathcal{F}_\text{mediation} \) takes the following form:

\[ \text{Let } RTT^* := \frac{RTT}{\ln(2)} \]

\[ m_t = \begin{cases} 
\frac{c_t}{1 + \frac{RTT \cdot (\ln(c_t/c) - c + \hat{c})}{s_t}} & \text{if } s_t \geq RTT^* \cdot (c_t - \hat{c}) \\
\frac{s_t}{RTT \cdot \ln\left(\frac{s_t}{c_t} \cdot \frac{RTT}{\hat{c}} + 1\right)} & \text{otherwise}
\end{cases} \]

(20)

where \( s_t \) is the chunk size (which itself is determined by the bitrate chosen by ABR) and \( \hat{c} \) is the starting download rate in the slow start algorithm (in our case, equal to 2 MTUs). We use this model to generate a version of \( M \) with \( A = 6 \) actions and \( U = 49000 \) latent network conditions. We compute the singular value decomposition with the 6 singular values represented in non-increasing order (\( \sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_6 \)). The total “energy” of matrix is given by sum of squares of these singular values. It turns out that \( \frac{\sigma_1^2 + \sigma_2^2}{\text{total energy}} \) is more than 0.999. This suggests that most of the matrix is captured by its rank-2 approximation, as depicted in Figure 12. In other words, \( M \) is approximately low (= 2) rank.

D.3 Can CausalSim Faithfully Simulate New Policies?

Similar to our real-data evaluations, we train models based on training data generated using all policies except a left-out policy, for which the model does not observe any data. Although traces come from the same generative process, no two trajectories in the dataset collected with different policies share the
We observed how CausalSim can be used to design an im-
proved policy in §6.2, and verified this through deployment in
the wild. We would like to take these experiments one step fur-
ther and ask can CausalSim be used to design learning-based
policies, such as with Reinforcement Learning (RL)?

Recent work has shown that RL algorithms can learn
strong ABR policies by learning through interactions with the
environment [49]. Could we use a CausalSim model to train
high-performance ABR policies without direct environment
interaction? As a first step, we decided to carry out an initial
experiment in the aforementioned synthetic ABR environment.

This allows us to rapidly evaluate policies across a large
number of network traces, and importantly, to compare policies
on the same set of traces eliminating an important source of
variability. Our synthetic environment uses a basic model of
congestion control it to capture the relationship between chunk
size and achieved throughput for paths with different capacity
and RTT; and it uses a statistical model to generate a wide vari-
ety of network capacity behavior (e.g., different average band-
width, variability, etc.). We build a CausalSim model using
traces from a “simulated RCT” on the synthetic environment.
For a full explanation of the simulation setup, network capacity
generation procedure, and the simulated policies, refer to §D.5.

Performance Metric. ABR algorithms are typically evalu-
ated through QoE metrics [72]. Assuming the chosen bitrate
at step $t$ was $q_t$, the download time was $d_t$ and the buffer was
$b_t$, we use the following QoE definition:

$$QoE_t = q_t - |q_t - q_{t-1}| - \mu \cdot \max(0, d_t - b_{t-1})$$

This QoE metric captures three goals (in succession): 1) Stream in high quality, 2) Maintain a stable quality, 3) Avoid
rebuffering. Better policies yield higher QoE values, where
an ideal QoE is equal to the max bitrate.

D.4.1 How to train policies via simulators?

To train the RL agent, we take a set of logged trajectories
where the source policy was MPC and feed them to CausalSim.
In each step, CausalSim will predict the next counterfactual
observation and reward, and the RL agent will choose the
next counterfactual action based on that observation. This
process repeats until this simulated session is over, after which
the counterfactual trajectory is used to train the RL agent.
For the RL algorithm, we utilize the Advantage Actor Critic
(A2C) method, a prominent on-policy algorithm, along with
Generalized Advantage Estimation (GAE). For a detailed
description of the setup and hyperparameters refer to §D.7.

D.4.2 Does CausalSim train better policies?

Figure 15a plots the CDF of average session QoE that each
policy attains. Here, Real Environment refers to training
directly with the synthetic ABR environment, and CausalSim,
ExpertSim and SLSim refer to policies trained by using each
of these simulators. CausalSim trains policies nearly as well
as training directly on the environment, while ExpertSim
and SLSim fail to provide robust policies across all sessions.
Figure 15b plots the CDFs for the high RTT (above 300 ms)
clients, where the gap between CausalSim and the baseline
simulators is even larger.

In this environment, chunk are downloaded according to
a slow start model, where congestion control must ramp up
its window size over several RTTs before the download rate
can reach the available bandwidth. As a result, downloads of

![Figure 12: Singular values of potential outcome matrix $M$
associated with synthetic ABR suggest that $M$ is approximately
rank 2.](image)
smaller chunks (with lower bitrates) incur a noticeable overhead, particularly on high-RTT paths. This overhead becomes less apparent as chosen bitrates become larger. Biased simulators such as SLSim and ExpertSim, which assume all actions lead to the same observed bandwidth, overestimate the achieved rate when counterfactual bitrates are smaller than factual ones (chosen by the source policy) and underestimate it when the counterfactual bitrates are larger. Since the source policy is conservative and tends to choose low bitrates, ExpertSim and SLSim find larger bitrates to be undesirable in the QoE trade-off. This can be seen in Figure 15c, which visualizes the 3 aspects of QoE in terms of the rebuffering rate and the smoothed bitrate, i.e. the chosen bitrates with the smoothness penalty. Notice how policies trained on the real environment and CausalSim utilize the network by 200 kbps more than other policies. The extra rebuffering that CausalSim incurs is negligible compared to the extra bitrate: 5.9 seconds every hour.

D.5 Data & Algorithms

Simulating a trajectory in our synthetic ABR environment needs three components:

- A video, with several bit-rates available. We use “Envivio-Dash3” from the DASH-246 JavaScript reference client [22].
- An ABR algorithm. We have a set of 9 policies to choose from, presented in Table 3.
- A network path, which is characterized by the latent network capacity and the path RTT.

We use random generative processes to generate network traces and RTTs. The RTT for a streaming session is sampled randomly, according to a uniform distribution:

\[
\text{rtt} \sim \text{Unif}(10 \text{ ms}, 500 \text{ ms})
\]

Our trace generator is a bounded Gaussian distribution, whose mean comes from a Markov chain. Prior work shows Markov chains are appropriate models for TCP throughput [63], and Gaussian distributions can model throughputs in stationary segments of TCP flows [48].

Concretely, at the start of the trace, the following parameters are randomly sampled:

\[
\begin{align*}
\nu & \sim \text{Unif}(30, 100) \\
\rho & = \frac{1}{\nu} \\
l, h & \sim \text{Unif}(0.5, 4.5) \\
\text{s.t.} \quad & \frac{h-l}{h+l} > 0.3 \\
s_0 & \sim \text{Unif}(l, h) \\
e_\sigma & \sim \text{Unif}(0.05, 0.3)
\end{align*}
\]
Figure 15: CausalSim trained policies perform well, only marginally behind training on the real environment. Distribution of Quality of Experience (QoE) in policies trained with the real environment, CausalSim, ExpertSim, and the MPC policy. CausalSim does not underestimate bandwidth in high RTT clients and trains policies that strike the best balance in QoE goals.

| Policies                | Hyperparameter   | Value                        | Used as source | Used as left out |
|-------------------------|------------------|------------------------------|----------------|-----------------|
| BBA                     | Cushion          | 5                            | ✓              | ✓               |
|                         | Reservoir        | 10                           |                |                 |
| BOLA-BASIC              | $V$              | 0.71 (Computed using puffer formula) | ✓              | ✓               |
|                         | $\gamma$         | 0.22 (Computed using puffer formula) |                |                 |
|                         | Utility function | $\ln(\text{chunk sizes})$ (As used in BOLA paper [61]) |                |                 |
| Random                  |                  | -                            | ✓              | ✓               |
| BBA-Random mixture 1    | Cushion          | 5                            | ✓              | ✓               |
|                         | Reservoir        | 10                           |                |                 |
|                         | Random choices   | 50%                          |                |                 |
| BBA-Random mixture 2    | Cushion          | 10                           | ✓              | ✓               |
|                         | Reservoir        | 20                           |                |                 |
|                         | Random choices   | 50%                          |                |                 |
| MPC                     | Lookback length  | 5                            | ✓              | ✓               |
|                         | Lookahead length | 5                            |                |                 |
|                         | Rebuffer penalty | 4.3                          |                |                 |
|                         | Throughput estimate | Harmonic mean               |                |                 |
| Rate-based              | Lookback length  | 5                            | ✓              | ✓               |
|                         | Throughput estimate | Harmonic mean               |                |                 |
| Optimistic Rate-based   | Lookback length  | 5                            | ✓              | ✓               |
|                         | Throughput estimate | Max                      |                |                 |
| Pessimistic Rate-based  | Lookback length  | 5                            | ✓              | ✓               |
|                         | Throughput estimate | Min                      |                |                 |

Table 3: ABR algorithms used in the synthetic ABR experiments.
At each time step, the state remains unchanged with probability \( 1 - p \) and changes otherwise. When changing, the next state is sampled from a double exponential distribution centered around the previous state:

\[
\lambda = \text{solve}(1 - e^{h - s_{i-1}} - e^{s_{i-1}-l} = 0)
\]

\[
s_t = \text{DoubleExp}(s_{t-1}, \lambda)
\]

The point for this specific transition kernel is that small changes in network capacity should be more likely than drastic changes. Finally, the network capacity \( c_t \) in each step is sampled from a Gaussian distribution, defined by these parameters:

\[
c_t \sim \text{Normal}(s_t, s_t \cdot \sigma_c)
\]

### D.6 Training setup

Similar to the real-world ABR experiment, we use MLPs as the neural network structures for CausalSim models and the SLSim model. Table 4 comprehensively lists all hyperparameters used in training.

### D.7 RL setup

We use the A2C algorithm for training the policies. Table 5 lists all hyperparameters for the RL training.

### Appendix E Load Balancing

#### E.1 Does CausalSim Faithfully Infer Latent States?

We test the claim that estimating the exogenous latent state and using it to predict the next state was indeed the key to producing accurate counterfactual predictions, as the architecture of CausalSim suggests. To do so, we compare CausalSim’s estimated latent state with the underlying job sizes—the job size is indeed the latent state that dictates the dynamics in the load balancing environment. We find that the estimated latent states and the job sizes are highly correlated, as illustrated in Figure 16, with a PCC of 0.994. This demonstrates that CausalSim can learn faithful representations of true latent states.

#### E.2 Data & Algorithms

To simulate the load balancing problem described in §6.4.1, we need to set the server processing rates \( \{r_i\}_{i=1}^N \), and arriving job sizes \( S_k \). Server rates are generated randomly, as follows:

\[
r_i = e^{u_i}
\]

where \( u_i \sim \text{Unif}(-\ln(5), \ln(5)) \)

We generate job sizes using a time-varying Gaussian distribution. At step \( k \) of the trajectory, job size \( S_k \) is sampled as follows:

\[
S_k \sim \text{Normal}(\mu_k, \sigma_k)
\]

where \( \mu_k \) and \( \sigma_k \) signify the mean and variance of the generative distribution at time step \( k \). At each time step, with a probability of \( p = 1/12000 \), the mean and variance change and with a probability of \( 1 - p \), they remain the same. The mean and variance values are drawn from random distributions, both at the start of a trajectory and when a change occurs, in the following manner:

- If \( k = 0 \) (start of trace) or, mean and variance must change:
  \[
  \begin{align*}
  \mu_k &\sim \text{Pareto}(\alpha = 1, L = 10^1, H = 10^{2.5}) \\
  \sigma_k &\sim \text{Unif}(0, 0.5 \mu_k)
  \end{align*}
  \]

- Else:
  \[
  \begin{align*}
  \mu_k &= \mu_{k-1} \\
  \sigma_k &= \sigma_{k-1}
  \end{align*}
  \]

Jobs generated according to this process are temporally correlated, and therefore not independent and identically distributed. Training data consists of 5000 trajectories of length 1000, each of which was randomly assigned a policy from Table 6.

Finally, Table 6 describes the 16 policies used in these experiments.

#### E.3 Training setup

As before, we use MLP as the neural network structures for CausalSim models and the SLSim model and Table 5 is a comprehensive list of all hyperparameters used in training. Note that, as mentioned in §6.4.1, we assume access to \( J_{\text{system}} \) and focus on the more challenging task of estimating the trace quantities, for both CausalSim and SLSim. Therefore, in training, there are no observations and hence \( \mathcal{L}_{\text{total}} \) consist of two terms: the squared loss of the trace quantities and the discriminator loss.
| Model            | Hyperparameter                          | Value                     |
|------------------|-----------------------------------------|---------------------------|
|                  | Hidden layers (SLSim)                   | (128, 128)                |
|                  | Hidden layers (CausalSim: Extractor, Discriminator and \( f_{\text{system}} \)) | (128, 128) |
|                  | Hidden layers (CausalSim: Action encoder) | (64, 64) |
|                  | Rank \( r \)                            | 2                         |
| \( \text{CausalSim} \) (4 networks) | Hidden layer Activation function         | ReLU                      |
|                  | Output layer Activation function        | Identity mapping          |
|                  | Optimizer                               | Adam [39]                 |
| \( \text{SLSim} \) (1 network)   | Learning rate                           | 0.0001                    |
|                  | \( \beta_1 \)                           | 0.9                       |
|                  | \( \beta_2 \)                           | 0.999                     |
|                  | \( \epsilon \)                          | \( 10^{-8} \)             |
|                  | Batch size                              | \( 2^{13} \)              |
| \( \text{CausalSim} \)            | \( \kappa \)                            | \{0.01, 0.1, 1, 10, 100\} |
|                  | \( \delta \)                            | \{0, 1\}                  |
|                  | Training iterations (num\_train\_it)    | 20000                     |
|                  | num\_disc\_it                          | 10                        |
| \( \text{SLSim} \)                | Training iterations                     | 20000                     |

Table 4: Training setup and hyperparameters for the synthetic ABR experiments.

| Group          | Hyperparameter                           | Value                             |
|----------------|------------------------------------------|-----------------------------------|
| Neural Network | Hidden layers                            | (32, 32)                          |
|                | Hidden layer activation function         | ReLU                              |
|                | Output layer activation function         | A2C actor: Softmax                |
|                |                                          | A2C critic: Identity mapping      |
|                | Optimizer                                | Adam [39]                         |
|                | Learning rate                            | 0.001                             |
|                | \( \beta_1 \)                            | 0.9                               |
|                | \( \beta_2 \)                            | 0.999                             |
|                | \( \epsilon \)                           | \( 10^{-8} \)                     |
|                | Weight decay                             | \( 10^{-4} \)                     |
| A2C training   | Episode lengths                          | 490                               |
|                | Epochs to convergence (\( T_c \))       | 8000 (3920000 samples)            |
|                | Random seeds                             | 4                                 |
|                | \( \gamma \)                             | 0.96                              |
|                | Entropy schedule                         | 0.1 to 0 in 5000 epochs           |
|                | \( \lambda \) (for GAE)                 | 0.95                              |
| Environment    | Chunk length \( c \)                     | 4                                 |
|                | Number of actions (bitrates)             | 6                                 |

Table 5: Training setup and hyperparameters for learning RL policies in the synthetic ABR environment.
### Policies Description

| Policy Description                                      | Used as source | Used as left out |
|--------------------------------------------------------|----------------|-----------------|
| Server limited policy (8 variations)                   |                |                 |
| Randomly assign to only two servers                     | ✓              | ×               |
| Shortest queue                                          | ✓              | ✓               |
| Assign to server with smallest queue                    |                |                 |
| Power of $k$ ($k \in \{2, 3, 4, 5\}$)                  |                |                 |
| Poll queue lengths of $k$ server and assign to shortest queue |                |                 |
| Oracle optimal                                          | ✓              | ✓               |
| Normalize queue sizes with server rates and assign to shortest normalized queue | ✓ | ✓ |
| Tracker optimal                                         |                |                 |
| Similar to oracle, but estimates server rates with historical observations of processing times | ✓ | ✓ |

Table 6: Scheduling policies used in the load balancing experiment.

| Model                  | Hyperparameter                  | Value          |
|------------------------|---------------------------------|----------------|
| Hidden layers (SLSim)  | (128, 128)                      |                |
| Hidden layers (CausalSim: Extractor, Discriminator) | (128, 128) |                |
| Hidden layers (CausalSim: Action encoder)            | No hidden layers                |                |
| Rank $r$              | 1                               |                |
| CausalSim (3 networks) | Hidden layer Activation function | ReLU           |
|                       | Output layer Activation function | Identity mapping |
| Optimizer              | Adam [39]                       |                |
| SLSim (1 network)      | Learning rate                   | 0.0001         |
|                       | $\beta_1$                       | 0.9            |
|                       | $\beta_2$                       | 0.999          |
|                       | $\epsilon$                      | $10^{-8}$      |
|                       | Batch size                      | $2^{13}$       |
| CausalSim              | $\kappa$                        | $[0.01, 0.1, 1, 10, 100]$ |
|                       | $\delta$                        | [1]            |
|                       | Training iterations (num_train_it) | 10000        |
|                       | num_disc_it                     | 10             |
| SLSim                  | Training iterations             | 10000          |

Table 7: Training setup and hyperparameters for the load balancing experiment.

### Appendix F  Causal Inference Related Work

Identifying causal relationships from observational data is a critical problem in many domains [29], including medicine [53], epidemiology [57], economics [35], and education [23]. Indeed, identifying causal structure and answering causal inference queries is an emerging theme in different machine learning tasks recently, including computer vision [71, 73], reinforcement learning [6, 24], fairness [27], and time-series analysis [7] to name a few. One important aspect about causal inference is its ability to answer counterfactual queries. For such queries, many methods were developed; where some approaches are motivated by Pearl’s structural causal model [55], and by Rubin’s potential outcome framework [59]. We refer the interested reader to recent surveys such as [29] and references there in for an overview of recent advances in our ability to infer causal relationships from observational data.

Another related line of work within this literature is synthetic controls and its extension synthetic interventions, which aims to build synthetic trajectories of different units (e.g. individuals, geographic locations) under unseen interventions by appropriately learning across observed trajectories [4, 5, 9–12]. However, these approaches assume a static set of intervention and do not apply to our setting.