Learning to Optimize: A Primer and A Benchmark

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Abstract

Learning to optimize (**L2O**) is an emerging approach that leverages machine learning to develop optimization methods, aiming at reducing the laborious iterations of hand engineering. It automates the design of an optimization method based on its performance on a set of training problems. This data-driven procedure generates methods that can efficiently solve problems similar to those in training. In sharp contrast, the typical and traditional designs of optimization methods are theory-driven, so they obtain performance guarantees over the classes of problems specified by the theory. The difference makes L2O suitable for repeatedly solving a particular optimization problem over a specific distribution of data, while it typically fails on out-of-distribution problems. The practicality of L2O depends on the type of target optimization, the chosen architecture of the method to learn, and the training procedure. This new paradigm has motivated a community of researchers to explore L2O and report their findings.

This article is poised to be the first comprehensive survey and benchmark of L2O for continuous optimization. We set up taxonomies, categorize existing works and research directions, present insights, and identify open challenges. We benchmarked many existing L2O approaches on a few representative optimization problems. For reproducible research and fair benchmarking purposes, we released our software implementation and data in the package **Open-L2O** at `https://github.com/VITA-Group/Open-L2O`.

Keywords: learning to optimize, meta learning, optimization, algorithm unrolling

1. Introduction

1.1 Background and Motivation

Classic optimization methods are typically hand-built by optimization experts based on theories and experience. As a paradigm shift from this conventional design, *learning to optimize* (**L2O**[1]) uses machine learning to improve an optimization method or even generate

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1. We provide a complete list of abbreviations used in this work in Appendix A.

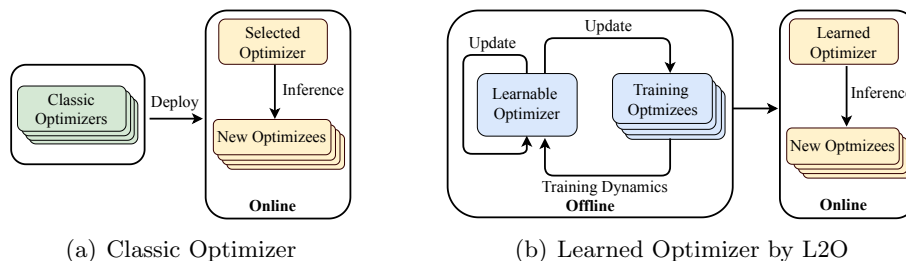(a) Classic Optimizer   (b) Learned Optimizer by L2O

Figure 1: Deployment procedures of classic or learned optimizers, both consisting of an offline design phase and an online deployment phase. (a) Classic optimizers are manually designed; they usually have few or no tuning parameters; (b) Learned optimizers are trained in an L2O framework over a set of similar optimizees (called a task distribution) and designed to solve unseen optimizees from the same distribution.

a completely new method. This paper provides a timely and up-to-date review of the rapidly growing body of L2O results, with a focus on continuous optimization.

Classic optimization methods are built upon components that are basic methods—such as gradient descent, conjugate gradient, Newton steps, Simplex basis update, and stochastic sampling—in a theoretically justified manner. Most conventional optimization methods can be written in a few lines, and their theories guarantee their performance. To solve an optimization problem in practice, we can select a method that supports the problem type at hand and expect the method to return a solution no worse than its guarantee.

L2O is an alternative paradigm that develops an optimization method by training, i.e., learning from its performance on sample problems. The method may lack a solid theoretical basis but improves its performance during the training process. The training process often occurs offline and is time-consuming. However, the online application of the method is (aimed to be) time-saving. When it comes to problems where the target solutions are difficult to obtain, such as nonconvex optimization and inverse-problem applications, the solution of a well-trained L2O method can have better qualities than those of classic methods. Let us call the optimization method (either hand-engineered or trained by L2O) the *optimizer* and call the optimization problem solvable by the method the *optimizee*.[2] Figure 1 compares classic optimizers and L2O optimizers and illustrates how they are applied to optimizees (yellow boxes).

In many optimization applications, the task is to repeatedly perform a certain type of optimization over a specific distribution of data. Each time, the input data that define the optimization are new but similar to the past. We say such an application has a narrow *task distribution*. Conventional optimizers may be tuned for task distribution, but the underlying methods are designed for a theory-specified class of optimization problems. We often describe a conventional optimizer by the formulation (and its math properties), not

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2. *Optimization problem* and *optimizee* are equivalent terms in this paper. We will use *optimizee* by default in the remaining of this paper but sometimes use them interchangeably depending on the context when necessary. Please also refer to Section 1.2 for more details of notations and terminology.
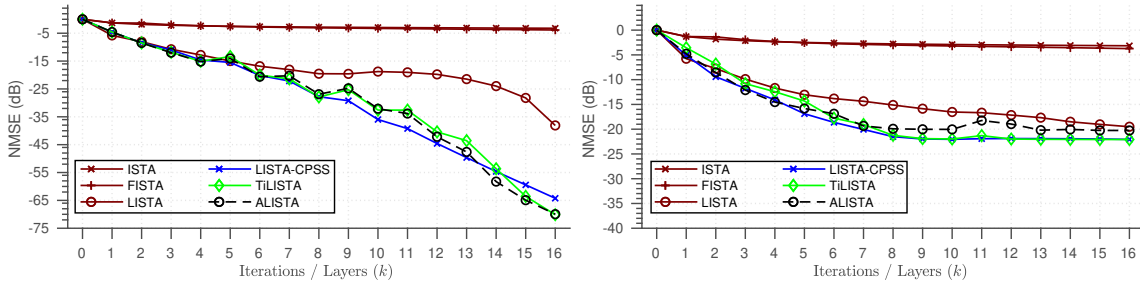
Figure 2: L2O for compressive sensing. In our prior work [43; 126], we successfully demonstrated that L2O optimizers (LISTA, LISTA-CPSS, TiLISTA and ALISTA) converge much faster than the two popular iterative solvers (ISTA, FISTA). Left: noiseless case. Right: noisy case (SNR = 20). X-axis is the number of iterations; Y-axis is normalized mean squared error (lower is better). *See more details from the image source: Figure 1 of [126].*

the task distribution. For example, we say an optimizer can minimize a *smooth-and-convex* objective function subject to *linear* constraints. In L2O, the process that trains the learned optimizers shapes the optimizer according to both the formulation *and* the task distribution. When the distribution is concentrated, the learned optimizer can "overfit" the tasks and may discover "short cuts" that classic optimizers do not take.

L2O aims to generate optimizers with the following strengths:

1. An optimizer learned by L2O is expected to complete a set of optimizees from the same task distribution much faster than classic methods. In particular, such an L2O method can run even faster than so-called optimal methods such as Nesterov's faster gradient descent (FGD) [163] on a set of problems well suited for these optimal methods.

2. The learned optimizer may also return a higher-quality solution to a difficult task than classic methods, given a similar amount of computing budget. For instance, an L2O method can recover a sparse signal that is much more faithful (meanwhile much faster) than LASSO.[3]

Therefore, L2O presents a potential approach to breaking the limits of analytic methods for a small set of optimization tasks.

L2O has started to demonstrate great potential in some areas of optimization and applications. Examples include convex ℓ_1-minimization [75], neural network training [13], black-box optimization [53] and combinatorial optimization [104]. For example, a class of L2O methods, in the form of algorithm unrolling (which we review below), has state-of-the-art results in compressed sensing and inverse problems. The L2O methods in [43; 126] converge much faster than the classic ISTA/FISTA optimizers (see Figure 2), using an order-of-magnitude fewer iterations on unseen optimizees from the same distribution to reach the same accuracy. The symbolic L2O in [261] further scales better than other neural network based L2Os via symbolic distillation. [102] provides a Transformer-based end-to-end solution for symbolic L2O that directly predicts the full mathematical expression,

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3. In this example, the task is to recover a sparse signal, not necessarily solving the LASSO minimization.

constants included, in one shot. Application areas benefiting from L2O methods include computer vision [223; 255; 58], medical imaging [124; 249], signal processing and communication [31; 15], policy learning [143], game theory [209; 210; 85], computational biology [37; 46], and even software engineering [8]. For example, the applications of algorithm unrolling, a popular form of model-based L2O, has been specifically reviewed in Section 3.3. As another example, in the practical application of domain adaptation, model-free L2O has demonstrated the ability to adapt a pre-trained classifier to a new domain at less computational resource costs, achieving the same accuracy or generalization performance [116; 42]. Instead of learning brand-new optimizers, the authors of [92] drew inspiration from L2O to learn how to combine a pool of *teacher* optimizers into a single *student* optimizer which can have stronger problem-specific performance. [83] also adopts L2O to derive explainable AI applications.

1.2 Preliminaries

L2O starts with an architecture of the optimizer with free parameters to learn, so one must prepare a set of training samples that represent the task distribution, as well as choose a training approach. The training process (Figure 1 (b) left) executes the approach, which iteratively applies the current optimizer to the sample optimizees and uses the observed performance to update the parameters. Over time, the optimizer adapts to the training samples. This process trains an optimizer to take a series of actions on the optimizees, analogous to classic learning, where we train ML models to make predictions or decisions.

We now formalize our notation. Consider an optimizee, i.e., an optimization problem or task, $\min_{\mathbf{x}} f(\mathbf{x})$ where $\mathbf{x} \in \mathbb{R}^d$. As of now, we only consider optimizees without constraints, i.e., unconstrained optimization problems. In these cases, the *objective function* $f(\mathbf{x})$ is all it takes to characterize an optimizee. A classic optimizer often iteratively updates $\mathbf{x}$ based on a handcrafted rule. For example, the first-order gradient descent algorithm takes an update at each iteration t based on the local landscape information at the instantaneous point $\mathbf{x}_t : \mathbf{x}_{t+1} = \mathbf{x}_t - \alpha \nabla f(\mathbf{x}_t)$, where α is the step size.

An L2O optimizer updates $\mathbf{x}$ following a similar rule to the first-order gradient descent: $\mathbf{x}_{t+1} = \mathbf{x}_t - m(\mathbf{z}_t; \phi)$. Here, $m(\mathbf{z}_t; \phi) : \mathcal{Z} \to \mathbb{R}^d$ is a mapping function that generates an update to $\mathbf{x}$ given the *input feature* $\mathbf{z}_t \in \mathcal{Z}$, where $\mathcal{Z}$ denotes the input feature space. The L2O optimizer is usually modeled as a neural network (e.g., an LSTM network) parameterized by the learnable weights ϕ. L2O has lots of freedom to use the available information as the input feature to generate the update. The input feature $\mathbf{z}_t$ at time t can include the existing iterates $\mathbf{x}_0, \ldots, \mathbf{x}_t$ as well as their gradients $\nabla f(x_0), \ldots, \nabla f(\mathbf{x}_t)$, etc. Note that the L2O optimizer reduces to the first-order gradient descent if we manually select $m(\mathbf{z}_t; \phi) = \alpha \nabla f(\mathbf{x}_t)$ with step size α. Finding an optimal update rule can then be formulated mathematically as searching for a good ϕ over the parameter space of m that minimizes a *training loss* function defined on an ensemble $\mathcal{T}$ of optimizees, which represent the target task distribution. For example, [13] proposed to formulate the training loss as the weighted sum of the objective function $f(\mathbf{x}_t)$ over a time span (which is called the unrolling length) T given by:

$$\min_{\phi} \mathbb{E}_{f \in \mathcal{T}} \left[\sum_{t=1}^{T} w_t f(\mathbf{x}_t) \right], \quad \text{with} \quad \mathbf{x}_{t+1} = \mathbf{x}_t - m(\mathbf{z}_t, \phi), \ t = 1, \ldots, T-1, \qquad (1)$$

where $w_1, \ldots, w_T$ are the re-weighting coefficients and f denotes the objective function of an optimizee sampled from the target distribution $\mathcal{T}$ and the input feature $z_t = \nabla f(x_t)$. Note that the parameter ϕ determines the objective value through determining the iterates $\mathbf{x}_t$. L2O solves the training problem (1) for a desirable ϕ and the update rule $m(\mathbf{z}_t; \phi)$. To avoid potential confusion, we specifically distinguish the usage of *training loss* and *objective function* in the remaining of this work. We only refer to *training loss* as the function being minimized to train an L2O optimizer, e.g., in (1). In contrast, an *objective function* is what characterizes an optimizee and is not related to optimizers at all.

In practice, the choices of w_t vary by case and depend on empirical settings. For example, many L2O optimizers for sparse coding unroll to a fixed length T for all optimizees, and then only minimize the step-T functional value [262; 84], i.e., $w_T = 1$ and $w_1 = \cdots = w_{T-1} = 0$. The work in [13], on the other hand, assigns nonzero w_t values and report more efficient Backpropagation Through Time (BPTT).

In L2O, one specifies the architecture of an optimizer, which consists of both learnable components ϕ and fixed components. We address both of them in this paper. The update rule m is often parameterized by multi-layer neural networks or recurrent neural networks. In theory, neural networks are universal approximators, so L2O may discover entirely new, optimal update rules without referring to any existing update rule adopted by classic optimizers. We hence refer to it as *model-free* L2O. Here, the term "model" represents the prior knowledge in an optimization problem, which the experts usually exploit to design classic optimizers.[4]

The shortcomings of model-free L2O include: lacking convergence guarantees and requiring a high number of training samples. On tasks where classic operations are critical to good performance, such as projection, normalization, and decaying step sizes, model-free L2O either cannot achieve good performance or require enormous training problems to discover classic operations from scratch. To avoid these shortcomings, we consider incorporating the existing methods as base or starting points for learning, which reduces the search to fewer parameters and a smaller space of algorithms. We call this alternative approach *model-based* L2O.

1.3 Broader Contexts

When the tasks are general machine learning tasks, e.g., determining the parameters of a prediction model by minimizing its training loss, L2O overlaps with meta-learning [214; 90; 44]. It is worth noting that "meta-learning" in different communities has different meanings. Here, meta-learning refers to using a method to improve learning algorithm(s), also called "learning to learn" [13; 53]. Recent results in this line of research contribute a significant portion of L2O development [119]. The goal of L2O captures two main aspects of meta learning: rapid learning within tasks and transferable learning across many tasks from the same distribution. However, L2O is not entirely meta-learning because it considers domain knowledge of optimization and applies to many non-learning optimization tasks such as solving inverse problems.

L2O shares many similarities with AutoML [247]. The term "AutoML" broadly refers to automating any step(s) in the ML lifecycle. Traditionally, AutoML research focuses

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4. For clarity, we avoid using the term "model" in other scenarios for the remaining of this work.

on model selection, algorithm selection, and hyperparameter optimization. These methods accelerate the design iterations of many types of ML algorithms, such as random forests, gradient boosting, and neural networks. AutoML recently drew (back) the mainstream attention because of its significant success in enhancing the performance of deep learning [67]. Among the topics under AutoML, those most relevant to L2O are algorithm configuration [94] and hyperparameter optimization (HPO) [68]. Algorithm configuration determines a high-performing configuration of some algorithm across a given set of problem instances. HPO tunes a set of hyperparameters specifically for an ML algorithm, via Bayesian optimization [109] or classification-based optimization [251]. [206] has combined algorithm selection and hyperparameter optimization, also known as CASH. The main difference between these works and L2O lies in that L2O can discover *new optimization methods* from a parameterized algorithmic space of optimizers, rather than only *selecting* from or *tuning* a few existing optimizers. Yet, the boundary between HPO and L2O is often blurry since certain L2O methods [126; 240; 219] configure or predict hyperparameters for existing optimizers only.

L2O is closely related to the new frontier of *learning-augmented algorithms* [1]. Classic algorithms are designed with worst-case performance guarantees and do not adapt to actual inputs. On the other hand, ML algorithms often achieve competitive performance by adapting to inputs, but their worst-case performance on (unseen) inputs degrades significantly. Learning-augmented algorithms combine the best of both worlds, using ML to improve the performance of classic algorithms by adapting their behaviors to the input distribution. Examples include learning-augmented data structures [113; 155], streaming and sketching algorithms [100; 91], online algorithms [69], error-correcting codes [106; 107], scheduling algorithms [156], approximation algorithms [96], and safeguarded learned algorithms [84]. L2O can be counted as a subset of those learning-augmented algorithms. A comprehensive list of relevant materials can be found in [1].

Previous review articles and differences There have been a number of review articles on meta learning [214; 90] and AutoML [247; 95; 82].

The work in [159] surveys algorithm unrolling. The work in [181] reviews model-based deep learning. These articles have overlapping scopes with ours, as algorithm unrolling is one of the main (but not the only) techniques of model-based L2O. This article features comprehensive coverage, including both model-based and model-free L2O approaches. The work in [12] provides an excellent tutorial on L2O methods but with a different focus on categorization of modeling and learning methods.

Lastly, let us mention recent works that leverage ML for combinatorial and discrete optimization [123; 61; 24; 25; 38]. [21] provides a comprehensive review on ML for combinatorial optimization.

1.4 Paper Scope and Organization

We draw distinctions between model-free and model-based L2O approaches and review many L2O techniques. Emphases are given to recurrent network-based L2O methods, algorithm unrolling, and plug-and-play. We discuss how to train them effectively and how their designs can benefit from the structures of the optimizees and classic optimization methods.

Paper	Optimizer Architecture	Input Feature $\mathbf{z}_t$	L2O Training Loss	Additional Technique	Evaluation Metric
[13]	LSTM	Gradient	Training Loss	Transform input gradient ∇ into $\log(\nabla)$ and $\text{sign}(\nabla)$	Objective Value
[53]	LSTM	Objective Value	Objective Value	N/A	Objective Value
[135]	LSTM	Gradient	Training Loss	Random Scaling Combination with Convex Functions	Objective Value
[227]	Hierarchical RNNs	Scaled averaged gradients, relative log gradient magnitudes, relative log learning rate	Log Training Loss	Gradient History Attention Nesterov Momentum	Objective Value
[149]	MLP	Gradient	Training Loss	Unbiased Gradient Estimators	Objective Value Testing Loss
[118]	RNN Controller	Loss, Gradient	Training Loss	Coordinate Groups	Objective Value
[20]	Searched Mathematical Rule by Primitive Functions	Scaled averaged gradients	Training Loss	N/A	Testing Accuracy
[37]	Multiple LSTMs	Gradient, momentum, particle's velocity and attraction	Training Loss and Entropy Regularizer	Sample- and Feature- Attention	Objective Value
[99]	RNN	Input Images, Input Gradient	Training Loss	N/A	Standard and Robust Test Accuracies
[237]	LSTM	Input Gradient	Training Loss	N/A	Objective Value and Robust Test Accuracy

Table 1: Summary and comparison of representative model-free L2O methods.

We benchmark existing model-based and model-based L2O approaches on a few representative optimization problems. We have released our software implementation and test cases as the **Open-L2O** package at (`https://github.com/VITA-Group/Open-L2O`), in the spirit of reproducible research and fair benchmarking.

The rest of the article is organized as follows. Section 2 and Section 3 review and categorize the existing works in model-free and model-based L2O, respectively. Section 4 describes the Open-L2O testbeds, our comparison experiments, and our result analyses. The article is concluded by Section 5 with a discussion on research gaps and future work.

2. Model-Free L2O Approaches

A model-free L2O approach, in general, aims to learn a parameterized update rule of optimization without taking the form of any analytic update (except the updates being iterative). The recent mainstream works in this vein [13; 53; 135; 227; 37] leverage recurrent neural networks (RNNs), most of which use the long short-term memory (LSTM) architecture. An LSTM is unrolled to perform iterative updates and trained to find short optimization trajectories. One set of parameters is shared across all the unrolled steps. At each step, the LSTM inputs the optimizee's local states (such as zero-order and first-order information) and returns the next iterate.

Model-free L2O shares the same high-level workflow depicted in Figure 1 (b). It is divided into two stages: an offline *L2O training* stage that learns the optimizer with a set of optimizees sampled from the task distribution $\mathcal{T}$; then an online *L2O testing* stage that applies the learned optimizer to new optimizees, assuming they are samples from the same task distribution. Table 1 compares a few recent, representative works in this area from multiple lenses, including what optimizer architecture to select, what objectives and metrics that meta training and meta testing each uses, and what input features and other techniques are adopted. There is a great variety.

2.1 LSTM Optimizer for Continuous Minimization: Basic Idea and Variants

As the optimization process can be regarded as a trajectory of iterative updates, RNNs are one natural option with a good inductive bias to learn the update rule. The first pioneering model-free L2O method [13] proposed to model the update rule implicitly by gradient descent. This first LSTM method for L2O has often been referred to as L2O-DM in literature.[5] In the remainder of this paper, we will refer to a learned optimizer parameterized as an LSTM network as an *LSTM optimizer*.

At high-level, the learned optimizer (parameterized as an LSTM network) is updated by the gradients from minimizing the objective function values induced by the optimizee, and optimizees are updated by the update rule predicted by the optimizer:

$$\mathcal{L}(\phi) = \mathbb{E}_{(\theta_0, f) \in \mathcal{T}} \left[\sum_{t=1}^{\mathtt{T}} w_t f(\theta_t) \right] \quad \text{where} \quad \begin{array}{c} \theta_{t+1} = \theta_t + g_t \\ \left[\begin{array}{c} g_t \\ h_{t+1} \end{array} \right] = m(\nabla_t, h_t, \phi) \end{array} . \quad (2)$$

In Eq. 2, f represents an optimizee (e.g. a neural network with its objective function), with θ_0 denoting the initialization of f. A set of optimizees and their initializations are sampled from the task distribution $\mathcal{T}$. ϕ is the parameters of the L2O optimizer. $\nabla_t = \nabla_\theta f(\theta_t)$ is the gradient of the objective function with respect to the optimizee's parameters. m is the LSTM optimizer, and g and h are update and hidden state produced by m, respectively. $\mathtt{T}$ is the maximal unrolling length for LTSM, often set due to the memory limitation; and w_t = 1 was used here for every t.

Some ad-hoc training techniques were exploited here. Firstly, each optimization variable (sometimes called coordinate) of the optimizee's parameter θ_t shared the same LSTM weights, but with different hidden states, in order to reduce the memory overhead faced when scaling up the number of optimization coordinates; many LSTM-type L2O works have inherited this trick. Secondly, to stabilize the optimizer's training, the authors proposed to reduce the dynamic range of the optimizee's gradient magnitudes, by preprocessing ∇_t into $(\log(\nabla_t), \text{sgn}(\nabla_t))$ as the input into the optimizer. Another critical heuristic introduced in [13] was the assumption that the gradients of the optimizee do not depend on the optimizer parameters, which avoids computing second derivatives of the optimizee's objective function. This heuristic has been widely adopted in the work that followed [13].

The authors of [13] conducted a few proof-of-concept studies on small-scale tasks such as MNIST classification, where they showed the learned optimizer m could converge faster than some stochastic gradient descent based optimizers such as SGD, RMSprop, and Adam. Despite this initial success, the scalability and generalizability of [13] remain underwhelming. Two specific questionable shortcomings are:

- **Generalizability of learned optimizer to unseen and potentially more complicated optimizees.** The L2O training set contains sampled optimizees from the target distribution. Like typical machine learning models, we might expect a learned optimizer to interpolate and extrapolate from the seen (L2O) training set, the latter being more challenging. Taking training deep networks as an example, during L2O testing, we might expect the learned optimizer to generalize (extrapolate) to

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5. Methods that are underscored in this section are also later evaluated and benchmarked in Section. 4.

the training of deeper or wider networks beyond instances seen in the meta training set. This generalizability is also demanded due to the memory bottleneck during meta training. To update the L2O optimizer $m(\phi)$ using back-propagation, we need to keep the gradients and the computation graph of the optimizee in memory. Therefore, the memory bottleneck arises when the unrolling length of the $m(\phi)$ becomes large, or the dimension of optimizee's parameter θ is high. Other types of generalization, such as training a network with unseen different activation functions or objective functions, are also found to be desirable, yet challenging [13].

Moreover, applying the L2O optimizers to train more complex neural networks may meet more sophisticated loss landscapes, which cannot be well learned from observing simple training dynamics from small networks. For example, it is well known that training over-parameterized networks will exhibit sharply distinct behaviors at small and large learning rates, and the two regimes usually co-exist in practical training and are separated by a phase transition [114; 115; 230].

- **Generalizability of learned optimizer to longer training iterations.** Training larger networks naturally takes more iterations, which calls for longer-term L2O modeling. An LSTM optimizer can in principle characterize longer-term dependency by unfolding more time steps (i.e., longer unrolling length T). However, that often results in L2O training instability due to the optimization artifacts of LSTM, such as gradient explosion or vanishing, in addition to the practical memory bottleneck. Therefore, most LSTM-based L2O methods [13; 53; 135; 227; 149; 37; 46; 47] are forced to limit their maximal unroll lengths and to truncate the unrolled optimization (e.g., up to 20 steps). As a result, the entire optimization trajectory is divided into consecutive shorter pieces, where each piece is optimized by applying a truncated LSTM.

  However, choosing the unrolling (or division) length faces a well-known dilemma [135]. On one hand, a short-truncated LSTM can result in premature termination of the iterative solution. Naively unfolding an LSTM-based L2O optimizer (trained with a small T) to more time steps during L2O testing usually yields unsatisfactory results. The resulting "truncation bias" causes learned optimizers to exhibit instability and yield poor-quality solutions when applied to training optimizees. On the other hand, although a longer truncation is favored for optimizer modeling, one may quickly run into LSTM training pitfalls such as gradient explosion [167] if unrolling too long. This dilemma is empirically demonstrated in Figure 3.

The above research gaps motivate several lines of follow-up works, as summarized below:

Debiasing LSTM truncation. As explained above, selecting the unrolling length T reflects a fundamental dilemma in LSTM-type L2O models: a longer T causes optimization difficulty at L2O training. In contrast, a smaller T incurs a larger "truncation bias" and hampers the generalization during L2O testing.

Many LSTM-type works focus on addressing this truncation bias. [227] drew the unrolling length of their truncated optimization from a heavy-tailed distribution. [149] proposed to replace LSTM with just MLP for the optimizer. The authors of [149] proposed to smooth the loss landscape by using two unbiased gradient estimators with dynamic re-
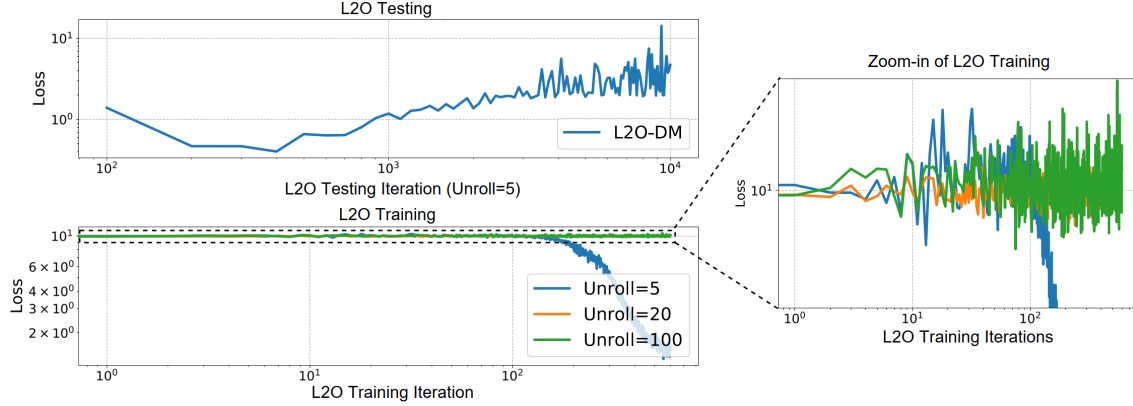
Figure 3: The dilemma of choosing unrolling length in L2O testing and L2O training: (1) *generalization failure* at L2O testing: the upper figure shows the objective value of the vanilla L2O method [13] to quickly diverge, as we increase the number of steps during L2O testing. This failure case was also observed in Figure 2 of [227] and in Figure 2 of [135]. (2) *optimization failure* at L2O training: the bottom figure shows the L2O training loss to also not decrease when it adopts longer unrolling lengths, due to the optimization artifacts of LSTM such as gradient explosion or vanishing.

weighting:

$$g_{\mathrm{rp}} = \frac{1}{S} \sum_{s=1}^{S} \nabla_\theta f(\theta + n_s), \quad n_1, \cdots, n_S \sim N(0, \sigma^2 I) \quad \text{i.i.d.,} \tag{3}$$

$$g_{\mathrm{es}} = \frac{1}{S} \sum_{s=1}^{S} f(\tilde{\theta}_s) \nabla_\theta [\log(\mathbb{P}(\tilde{\theta}_s))], \quad \tilde{\theta}_1, \cdots, \tilde{\theta}_S \sim N(\theta, \sigma^2 I) \quad \text{i.i.d.,} \tag{4}$$

$$g_{\mathrm{merged}} = \frac{g_{\mathrm{rp}} \sigma_{\mathrm{rp}}^{-2} + g_{\mathrm{es}} \sigma_{\mathrm{es}}^{-2}}{\sigma_{\mathrm{rp}}^{-2} + \sigma_{\mathrm{es}}^{-2}}, \tag{5}$$

g_{rp} and g_{es} are gradient estimated by "reparameterization trick" [108] and "evolutionary strategies" [228], and σ_{rp} and σ_{es} are empirical estimates of the variances of g_{rp} and g_{es}, respectively. In this way, they demonstrated L2O could train convolutional network networks faster in wall-clock time compared to tuned first-order methods, with reduced test losses. Their later work [150] also found that the learned optimizer can train image classification models such that they are robust to unseen image corruptions.

Stronger LSTM architectures. Another direction explored is to introduce stronger RNN/LSTM architecture to L2O. Instead of using a single RNN layer, Wichrowska et al. [227] leveraged three RNN layers to learn the optimization on different scales. They organized three RNN layers in a hierarchical fashion, which we simply denote as "bottom RNN", "middle RNN", "upper RNN". The "bottom RNN" directly takes the scaled gradients from the optimizee as input. Given a specific training step, the "middle RNN" receives the average of all hidden states from "bottom RNN" across the optimizee's parameter coordinates and outputs a bias term to the "bottom RNN". Further, the "upper RNN" takes

the averaged hidden states from "middle RNN" across a certain window of optimizee's training steps. Using smaller hidden states in "bottom RNN", this hierarchical design of the L2O optimizer achieved lower memory and computing overhead while achieving better generalization. We refer [227] as L2O-Scale in this article.

Improved L2O training techniques. In order to improve the generalization of the learned optimizer to both longer unrolling (i.e., longer optimization iterations) and unseen functions, [135] proposed two training tricks. The first one, called *random scaling*, could be viewed as a special "data augmentation" for L2O: a coordinate-wise scaling factor **c** was randomly generated at each iteration to scale the parameters of the optimizee during L2O training: $f_{\mathbf{c}}(\theta) = f(\mathbf{c} \odot \theta)$, where $\odot$ is the Hadamard product, i.e., the coordinate-wise multiplication. It was motivated by the observation that in many optimization problems, such as the quadratic function $f(\theta) = \lambda\|\theta\|_2^2$, the ideal update rule should achieve the same minima under varying λ. The second trick was to add a convex term during L2O training, as inspired by the proximal algorithms [166], and avoid large random updates when the L2O optimizer is under-trained. We refer [135] as L2O-RNNprop in this article.

Lately, the authors of [41] took a deeper dive into improved training techniques for L2O models. The authors first presented a progressive training scheme, which gradually increased the optimizer unroll length to mitigate the L2O dilemma of truncation bias (shorter unrolling) versus gradient explosion (longer unrolling). Furthermore, they presented an off-policy imitation learning approach to guide the L2O training by forcing the L2O optimizer to mimic the update rules generated by analytic optimizers. The authors of [41] evaluated their improved training techniques with a variety of state-of-the-art L2O models [13; 135; 227], and achieved boosted performance (lower training losses of unseen optimizees) without changing the original L2O RNN architecture in each method. We refer [41] as L2O-enhanced in this article.

More recently, the authors of [148] include Behler-Parrinello radial symmetry features [18] to model the interactions between parameters to be optimized so that the improved optimizers can learn to "hop" local minima points on rough landscapes. [139] performs reverse engineering on learned optimizers and identifies behaviors such as momentum, gradient clipping and learning rate adaptation etc. The work [152] identifies and quantifies the key designing challenges with respect to the memory, computing, and performance trade-offs for learned and classic optimizers, and further leverages their analysis to construct a learned optimizer that is both faster and more memory efficient.

2.2 Other Common Implementations for Model-Free L2O

While LSTM is so far the mainstream model, other optimizer models have also been explored. We describe two alternatives: *reinforcement learning* (RL), and *neural symbolics*.

[118] proposed to learn an RL policy π to predict the update rule as the learned optimizer. The policy π samples the update steps from a Gaussian distribution. The mean and variance of the Gaussian distribution are learnable parameters of the L2O policy, updated by reinforcement learning. The observation of the policy is composed of the current value of the objective function (i.e., loss), the recent gradients, and changes of the objective values up to H steps ($H = 25$ in their experiments). The policy receives the decrease in training loss as a reward. Logistic regression functions and two-layer neural nets were leveraged as

the testbeds. Further on, [119] proposed to group coordinates under permutation invariance (e.g., weight matrix or a bias vector) into a coordinate group. This formulation reduced the computation cost of expensive optimization problems, making the proposed method extensible to wider neural networks. The generalizability of the learned policy was also studied by training the policy on shallow and narrow networks and testing on wider layers. [11] learned to update optimizer hyperparameters instead of model parameters, directly using novel features, actions, and a reward function to feed RL. They demonstrated promising scalability to real large-scale problems.

It is worthy to mention a special L2O work [20], that explored L2O from the neural symbolic perspective. The authors also leveraged an RL controller but avoided directly modeling the update rules. Instead, they designed a search space of operands (gradient g, gradient's running exponential moving average $\hat{m}$, etc.), unary functions of input x (e^x, $\log(x)$, $\sqrt{|x|}$, etc.), and binary functions (mapping (x, y) to $x + y$, $x - y$, $x * y$, etc.). The RL controller was learned to select a sequence of elements from the search space, formulate a function to process the input, and output the update rule. Their searched best L2O optimizer (the RL controller) shows strong transferability and improves training performance (lower training losses) on different tasks and architectures, including ImageNet classification and Google's neural machine translation system. Their idea was further developed in [174] to automatically discover complete machine learning algorithms from basic mathematical operations as building blocks, which concerns a more general problem than L2O.

2.3 More Optimization Tasks for Model-Free L2O

Black-box optimization. [53] pioneered the extension of the LSTM L2O framework [13] to derivative-free or black-box function optimization. Due to the absence of the optimizee's gradients as input, the authors of [53] instead treated the query-response pairs as the observations of the optimizer, and formulated the optimization as an exploration-exploitation trade-off problem. To be specific, at time t, the current iterate $\mathbf{x}_t$ is used as a *query* for a *response* $y_t \in \mathbb{R}$. y_t conceptually corresponds to the objective value $f(\mathbf{x}_t)$ of the optimizee at the point $\mathbf{x}_t$ like in (1). But we use the *query-response* terminology because the objective function f is a black box without a closed-form formulation in this setting. The authors proposed to use an RNN to update the optimizer's hidden state $\mathbf{h}_{t+1}$ with the current observation $(\mathbf{x}_t, y_t)$ and to generate a new query point $\mathbf{x}_{t+1}$ to explore

$$\mathbf{h}_{t+1}, \mathbf{x}_{t+1} = \text{RNN}_\theta\left(\mathbf{h}_t, \mathbf{x}_t, y_t\right) \tag{6}$$

$$y_{t+1} \sim p\left(y \mid \mathbf{x}_{t+1}\right). \tag{7}$$

Here, the response value y_{t+1} is incrementally sampled from a Gaussian Process (p) at the new query point $\mathbf{x}_{t+1}$ in the experiments. During L2O training, it is assumed that the derivatives of function value y_t can be computed with respect to the input $\mathbf{x}_t$, which means the errors will be backpropagated for L2O training, but not needed at L2O testing time. [53] demonstrated that their learned RNN optimizers are competitive with state-of-the-art Bayesian optimization packages (Spearmint [184], SMAC [94], and TPE [22]).

Particle swarm optimization. Current L2O methods mostly learn in the space of continuous optimization algorithms that are point-based and uncertainty unaware. Inspired by population-based algorithms (e.g., swarm optimization), [37] estimated the posterior di-

rectly over the global optimum and used an uncertainty measure to help guide the learning process. The authors designed a novel architecture where a population of LSTMs jointly learned iterative update formula for a population of samples (or a swarm of particles). The model can take as input both point-based input features, such as gradient momentum, and population-based features, such as particle's velocity and attraction from swarm algorithms. To balance exploration and exploitation in search, the authors directly estimated the posterior over the optimum and included the differential entropy of the posterior in the training loss function. Furthermore, they learn feature- and sample-level importance reweighting (often called "attention" in deep learning) in the L2O model for more interpretable learned optimization rules. Their empirical results over non-convex test functions and the protein-docking application demonstrated that this new L2O largely outperforms the off-the-shelf Particle Swarm Optimization (PSO) algorithm [157] and the vanilla LSTM-based L2O methods that are not uncertainty-aware [13]. We refer [37] as L2O-Swarm in this article.

Minimax optimization. One more challenging testbed for model-free L2O is to solve continuous minimax optimization, which is of extensive practical interest [73; 138; 233], yet notoriously unstable and challenging. Three prior works [99; 177; 237] tried to plug in L2O into a specific application of minimax optimization called adversarial training [138]:

$$\min_{\theta} \mathbb{E}_{(\boldsymbol{x},\boldsymbol{y})\sim D} \left\{ \max_{\boldsymbol{x}'\in\mathbb{B}(\boldsymbol{x},\epsilon)} \mathcal{L}\left(f\left(\boldsymbol{x}'\right),\boldsymbol{y}\right) \right\}, \tag{8}$$

where D is the empirical distribution of input data, and the inner maximization is defined as the worst-case loss within a small neighborhood $\mathbb{B}(\boldsymbol{x},\epsilon) = \{\boldsymbol{x}' \mid dist(\boldsymbol{x},\boldsymbol{x}') \leq \epsilon\}$. Here $dist(\cdot,\cdot)$ is a distance measurement function designated by the user. Common examples include ℓ_p norms with $p = 1, 2, \infty$. In both works, the L2O only predicted update directions for the inner maximization problem, while the outer minimization was still solved by classic optimizer. They empirically showed that L2O can improve the solution quality to the inner maximization optimization, hence also leading to a better minimax solution and a more robustly trained model.

The latest work [180] extended L2O to solve minimax optimization from end to end for the first time. The authors proposed Twin L2O, consisting of two LSTMs for separately updating min and max variables. Ablation experiments showed this decoupled design to facilitate learning, especially when the min and max variables are highly non-symmetric. Several enhanced variants and training techniques were also discussed. The authored benchmarked their L2O algorithm on several relatively fundamental and low-dimensional test problems, and on which L2O compared favorably against state-of-the-art minimax solvers. How to scale up L2O for fully solving minimax problems of practical interest, such as adversarial training or GANs, remained an open challenge.

Game theory. RL-based model-free L2O has very recently found interest in the game theory field. [209] proposed to train multi-agent systems (MAS) to achieve symmetric pure Nash equilibria. Such equilibria need to satisfy certain constraints so that MAS are calibrated for practical use. The authors adopted a novel dual-RL-based algorithm to fit emergent behaviors of agents in a shared equilibrium to external targets. They used parameter sharing with decentralized execution to training multiple agents using a single policy network, while each agent can be conditioned on agent-specific information. The method-

13

ology shared similarities to [37]. Another work [210] extended consensus optimization to the constrained case. They introduced a new framework for online learning in non-zero-sum games, where the update rule's gradient and Hessian coefficients along a trajectory are learned by an RL policy, conditioned on the game signature. The authors mentioned that the same problem might potentially be solved by using the LSTM-based approach too [180].

Few-shot learning. Another application of the LSTM L2O framework [13] explores the application of model-free L2O in the small data regime. [173] first adopted a model-free L2O approach to learn a few-shot classifier, accessing only very few labeled examples per class at training. The authors of [173] proposed to learn an LSTM-based optimizer to optimize each task-specific classifier using the cell states in the LSTM, inspired by their observation that the gradient descent update on the parameters in the classifier resembles the cell state update in an LSTM. [122] simplified [173] by constraining the optimization on the learner classifier to one step of gradient descent but with learnable initialization and step size.

3. Model-Based L2O Approaches

We now overview model-based L2O approaches, which mark the recent movement to fuse traditional model-based optimization algorithms with powerful deep learning architectures [159]. Rather than using general-purpose LSTMs, these methods model their iterative update rules through a learnable architecture that is inspired by analytic optimization algorithms. Often, these learned methods can approximate problem solutions with tens of iterations, whereas their classic counterparts make require hundreds or thousands of iterations [126].

At a high level, model-based L2O can be viewed as a "semi-parameterized" option that takes advantage of both model-based structures/priors and data-driven learning capacity.[6] The growing popularity of this approach lies in its demonstrated effectiveness in developing compact, data-efficient, interpretable, and high-performance architectures when the underlying optimization model is assumed available or can be partially inferred. There is ample design space to balance the two flexibly. Most model-based L2O methods take one of the two following mainstream approaches.

The first approach is known as **plug and play (PnP)**. The key idea here is to *plug* a previously trained neural network (NN) into part of the update for an optimization algorithm (i.e., in place of an analytic expression), and then *play* by immediately applying the modified algorithm to optimizees sampled from the same task distribution (without additional training). We illustrate this with the common alternating direction method of multipliers (ADMM) formulation of PnP (e.g., see [213]). Here the underlying task of the original optimization algorithm is to minimize the sum of two functions f and g, i.e., to find $x^* \in \arg\min_x f(x) + g(x)$, which is equivalent to an constrained form with an auxiliary variable y introduced:

$$\min_{x,y} f(y) + g(x), \quad \text{subject to} \quad x = y. \tag{9}$$

---

6. We slightly abused the term of *semi-parametric model* from statistical learning, to represent different meanings: here it refers to blending pre-defined structures/priors into black-box learning models.

ADMM solves (9) with the following iterative manner:

$$x^{k+1} = \text{prox}_{\beta g}(y^k - u^k) \tag{10a}$$

$$y^{k+1} = \text{prox}_{\alpha f}(x^{k+1} + u^k) \tag{10b}$$

$$u^{k+1} = u^k + x^{k+1} - y^{k+1}. \tag{10c}$$

Briefly speaking, the iterations in (10a) and (10b) are the proximal operations for $f(x)$ and $g(y)$ terms, respectively, where α and β are step sizes. (10c) updates the dual variable u. We refer the readers to [32] for more details of ADMM algorithm.

In one sentence, the PnP formulation replaces (10a), i.e., the proximal for g, with an operator H_θ to obtain the iteration:

$$x^{k+1} = H_\theta(y^k - u^k). \tag{10a$'$}$$

Before inserting H_θ into the iteration above, the parameters θ are learned independently as the solution to a training problem, i.e.,

$$\theta \in \arg\min_{\tilde{\theta}} \mathcal{L}(\tilde{\theta}). \tag{11}$$

The loss function $\mathcal{L}$ is designed with an independent goal (e.g., to learn a natural image denoising operator). For example, one might model an image recovery problem by using total variation (TV) as a regularizer [178]. In the optimization scheme chosen (e.g., ADMM) to recover the image, one step of the process could be to perform a proximal operation with TV, which effectively acts as a denoiser. The PnP framework proposes replacement of the TV proximal with an existing denoiser (e.g., a neural network [179] or BM3D [60]).

The second approach is known as **algorithm unrolling**. Consider a general optimization algorithm that targets regressing an unknown signal $x^\star$ from the observation d with the updating form

$$x^{k+1} = T(x^k; d), \quad k = 0, 1, 2, \cdots, \infty. \tag{12}$$

In this case, we say d is the *input* to the optimization algorithm. Algorithm unrolling *unrolls* and truncates optimization algorithm into the structure of a neural network [159]. The new updates take the form

$$x^{k+1} = T_{\theta^k}(x^k; d), \quad k = 0, 1, 2, \cdots, K-1, \tag{13}$$

where K is the depth of the unrolled network, and θ^k are the learnable weights in the k-th layer. An unrolled network example is illustrated in Figure 4. Upon establishing this form, the parameters are learned by an end-to-end approach:

$$\min_{\{\theta^k\}_{k=0}^{K-1}} \mathcal{L}\big(x^K(\{\theta^k\}_{k=0}^{K-1})\big), \tag{14}$$

where $\mathcal{L}$ is the loss function we use in training. We emphasize the distinction that the parameters in unrolled schemes are trained end-to-end using the iterate x^K as a function of each θ^k whereas training occurs separately for PnP. We will introduce how to design $\mathcal{L}$ later in this section. Below, we discuss these approaches, their typical features, and which approach is suitable for various applications.
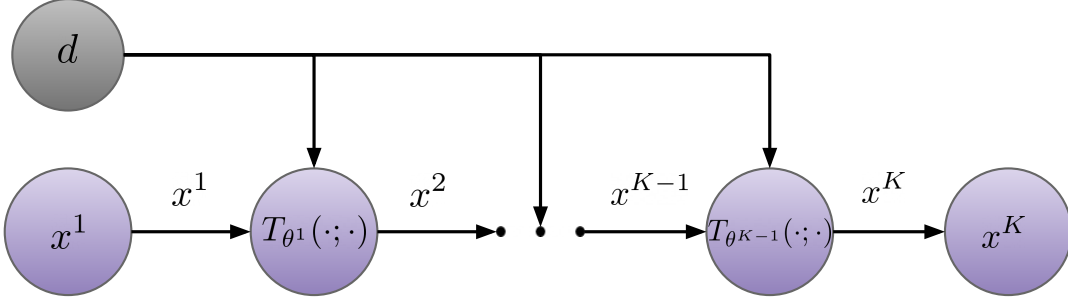
Figure 4: A common approach in various L2O schemes is to form feed forward networks by unrolling an iterative algorithm, truncated to K iterations, and tuning parameters at each layer/iteration k. This generalizes the update formula $x^{k+1} = T(x^k; d)$ to include a dependence on weights θ^k, denoted by a subscript.

3.1 Plug and Play

PnP methods date back to 2013, when they were first proposed for ADMM [213]. The authors replaced one of the proximal operators in ADMM with a denoiser (e.g., K-SVD [9], BM3D [60], and non-local means [34]) and showed empirical performance surpassing the original ADMM algorithm. Several other PnP schemes were also introduced and their empirical success was shown in the literature [88; 154; 176; 33; 220; 164; 103; 81; 76; 243; 248; 136; 257; 252; 10; 145; 186]. The theoretical guarantees of convergence of PnP-ADMM were first provided in [191] under the assumption that the derivative of the denoiser was doubly stochastic. Then [40] proved the convergence of PnP-ADMM with the use of a more realistic "bounded denoisers" assumption. Some other PnP schemes were analyzed under different assumptions [203; 204; 35; 65; 207; 39; 197; 71; 238; 199; 198].

PnP was initially not connected to L2O until some contemporary works [146; 175; 256] introduced the concept of "learning operators" into a PnP framework. Instead of using a manual-designed denoiser, they modeled the proximal operator as a deep neural network

	Opt	IP	PnP
Tunable Optimization Model		✓	✓
Tunable Update Formulas	✓	✓	✓
Training Loss tied to Model	✓		
Training Loss measure $x^\star$ error		✓	
Convergence guarantee to ideal $x^\star$	S	S	
Interpretable Updates	S	S	✓

Table 2: Comparison of properties for three types of model-based L2O methods: unrolled objective-based (Opt), inverse problem (IP), and Plug and Play (PnP) methods. Here ✓ and S mean that the corresponding property *always* and *sometimes* holds, respectively.

and learned it from data. The empirical performance of such an approach vastly exceeded the prior PnP works. From an L2O perspective, the learned methods improved performance by either accelerating execution of a subroutine in the optimization algorithm or providing a "better" solution than previously obtained.

Besides learning the operators in a PnP framework, one can also learn a function as the regularizer. [27; 26] modeled the statistical distribution of natural images as a Denoising Autoencoder (DAE) and constructed the optimization objective by maximizing the likelihood. The DAE is differentiable; thus, gradient-based optimization algorithms can solve the inverse problem. A parameterized discriminator function defined in the Wasserstein distance between two distributions was used by [134] as a learned functional that discriminates between a ground-truth and fake images. The authors treated this learned functional as a regularizer and used it in a gradient descent algorithm for image inverse problems.

Learning is not only able to help find the denoiser/regularizer in PnP but is also able to be used in a more meta manner to help find suitable parameters in PnP. [226] learned a policy network to tune the parameters in Plug-and-Play with reinforcement learning. Using the learned policy, the guided optimization can reach comparable results to those using oracle parameters tuned via the inaccessible ground truth.

The marriage of PnP with L2O also provides theoretical blessings. While a manual-designed regularizer may not guarantee the convergence of PnP to the desired solution, a learning-based method provides the flexibility to meet the condition of convergence. [179] studied the convergence of some PnP frameworks using fixed-point iterations, showing guaranteed convergence under a certain Lipschitz condition on the denoisers. They then proposed a normalization method for training deep learning-based denoisers to satisfy the Lipschitz condition. Similarly, [205] also provided an approach for building convergent PnP algorithms using monotone operator theory and constraining the Lipschitz constant of the denoiser during training. This fixed point framework was extended by [57] to the RED-PRO framework, which also showed convergence to global solutions. Independently of RED-PRO, [87] proposed a method within the RED-PRO framework for learning projection operators onto compact manifolds of true data. Using assumptions about the manifold and sufficient representation by the sampled data, the authors showed that their approach to constructing a PnP operator can provably approximate the projection (in probability) onto a low dimensional manifold of true data.

3.2 Algorithm Unrolling

Herein we overview L2O methods comprised of unrolling iterative optimization algorithms. We start by emphasizing there are two distinct goals of unrolled L2O methods: either to minimize an objective or to recover an unknown signal from its observations. The latter is also referred to as *inverse problems* sometimes. A simple example of inverse problems is image denoising, where the unknown signal we want to recover is the clean image and the observation is the corrupted image. The distinction between the two goals is that the aim for inverse problems is to tune the parameters so that they minimize the reconstruction accuracy of some "true" signal rather than find a minimizer of the model's objective function. The practicality for objective minimization is to speed up convergence or globally solve nonconvex problems that conventional algorithms struggle with. Keeping these cate-

gorizations in mind will help provide the reader with intuitive lenses for looking at different approaches. See Table 2 for a comparison of common qualities in these methods and PnP.

Below we provide a comprehensive and organized review of existing works along multiple dimensions: what problems they solve, what algorithms they unroll, what goals they pursue (objective minimization or signal recovery), and to what extent they freely parameterize their learnable update rule.

3.2.1 Different Target Problems

We broadly categorize the main problems tackled by algorithm unrolling methods into four categories: probabilistic graph models, sparse and low-rank regression, differential equations, and quadratic optimization.

- **Sparse and low rank regression**. The most investigated problems in the unrolling literature include sparse regression. The first seminal work [75] unrolls the Iterative Shrinkage Thresholding Algorithm (ISTA) or its block coordinate variant as a recurrent neural network to solve LASSO for fast sparse coding. The unrolling philosophy is also used in low-rank regression as it shares some common nature with sparse regression.

  - **LASSO.** Most of unrolling works following [75] also solve LASSO-type optimization problems for sparse coding [190; 161; 171; 72; 262; 4; 78; 59; 232]. Beyond naive LASSO, A natural extension is to apply the same *unrolling and truncating* methodology to solve *group LASSO* [189], i.e. finding solutions with structured sparsity constraints. [165; 2] extended solving (convolutional) LASSO in a multi-layer setting, and an adapted version of ISTA was unrolled in [194].

  - **Analysis model.** Different from the sparse prior in LASSO (also known as the *Synthesis* formulation), which assumes the signal is the linear combinations of a small number of atoms in a dictionary, the sparse analysis model assumes the existence of a forward transformation that sparsifies the signal. [55] applied unrolling to regression problems with total variation regularizations, which follows the analysis formulation. Problems with analysis sparse priors were also tackled using unrolling in [140] in a bi-level optimization context.

  - **Other sparse/anti-sparse regression problems.** [222] and [235] unroll the iterative hard thresholding (IHT) algorithm that solves ℓ_0 *minimization* problem instead of LASSO. [79] also solves ℓ_0 *minimization* problem but uses a sparse Bayesian Learning approach. Unrolling for ℓ_∞ minimization was also considered by [224], leading to so-called anti-sparse representation learning [193].

  - **Low rank regression.** [89; 187; 188; 241] all extend the unrolling idea to low-rank matrix factorization. Specifically, [188] proposes tailored pursuit architectures for both robust PCA and non-negative matrix factorization with specialized algorithms inspired by the nonconvex optimization techniques to alleviate the expensive SVD involved in each iteration.

- **Probabilistic graphical model**. The unrolling method can also be adopted to solve probabilistic graphical models. For example, [89] interprets conventional networks

as mean-field inference in Markov random fields and obtains new architectures by modeling the belief propagation algorithm to solve the Markov random field problems. [260] formulate Conditional Random Fields with Gaussian pairwise potentials and mean-field approximate inference as recurrent neural networks.

- **Differential equations**. Another line of works [51; 131; 133; 74] unroll the evolution in *Partial Differential Equation* (PDE) systems. While PDEs are commonly derived based on empirical observations. those recent advances offer new opportunities for data-driven discovery of (time-dependent) PDEs from observed dynamic data. One can train feed-forward or recurrent neural networks to approximate PDEs, with applications such as fluid simulation [229]. Loosely related is also significant work on connecting neural networks with *Ordinary Differential Equation* (ODE) systems.

- **Quadratic optimization**. Some recent works investigate the unrolling method in quadratic optimization problems [219; 48], which are easier to solve compared to the problems studied above. The focus here is more on the theoretical analysis of the convergence and/or the interplay between the unrolled algorithm and the resultant deep model's property (e.g., generalization and stability).

In some scenarios, we are not directly interested in the output of the unrolled model but use it for downstream tasks, e.g. clustering [221] and classification [222; 262; 59]. That will often lead to task-driven joint optimization, and the end task output becomes the focus of evaluation in place of the original unrolling algorithm's output fidelity. We think that these works have their unique position in L2O literature—they adopt the L2O methodology, but their aim has changed from learning accurate or fast *optimizers* to learning informative encoding of features for the end tasks, which is a good complement to the two primary aims of L2O described in Section 1.1.

Inverse problems. In many cases, however, optimization problems with manually designed objective functions only provide approximations to the original signals we are interested in. This is often due to inexact prior knowledge about the original signals. For example, sparsity and total variation regularizations only partially reflect the complexity of natural images (approximated sparsity and smoothness), which are hardly true in real-world applications and do not depict the exact characteristics of natural images. Therefore, many works solve the *inverse problem* directly, striving to recover the original signals we are really interested in. We return to this task in a later subsection.

Constrained optimization problems. Most target problems mentioned above in this subsection are unconstrained optimization problems. Some exceptions, such as the sparsity-constrained and low-rank regression problems, e.g., LASSO, have equivalent unconstrained formulation under proper regularizations. Some others have easy-to-implement forms of projection onto the constraint sets, including the $\ell_{0/\infty}$-constrained regression [222; 235; 224], and non-negative matrix factorization with non-negative constraints [188].

A few efforts have directly tackled more general constrained optimization problems using unrolling. [125] unrolled Frank-Wolfe algorithm to solve the structured regression with general ℓ_p-norm constraint ($p \geq 1$) and proposed a novel closed-form nonlinear pooling unit parameterized by p for the projection. [168] unrolled Frank-Wolfe algorithm for least-squares problems with affine, non-negative, and ℓ_p-norm constraints. It was also the first

to apply the unrolled network to financial data processing. [58; 23] investigated image restoration with various hard constraints and unrolled proximal interior point algorithms while incorporating the constraints using a logarithmic barrier.

3.2.2 DIFFERENT ALGORITHMS UNROLLED

For the bulk of iterative optimization algorithms that have been unrolled, we classify them into three categories: forward-backward splitting (FBS), primal-dual methods, and *others*. The first two categories consist entirely of first-order algorithms. They have low computational complexities, and their resultant L2O methods are often more reliable to train. Although various works discussed below may use the same underlying algorithm as the base, they can vary significantly in their performance depending on which parameters are learned and which safeguard precautions are used to ensure convergence (discussed further in subsequent sections). We also emphasize that most of these algorithms revolve around obtaining some form of sparsity/low-rank solution.

We begin with FBS. The simplest learned scheme is *Gradient Descent*, which is where the the gradient descent operation is applied (i.e., the forward operator) and the backward operator is simply the identity. This class of methods is studied in many works (e.g., see [72; 76; 63; 200; 48; 5; 6; 64; 172; 51; 134; 162; 232; 215; 112]). However, the most popular focus in the literature is on problems with sparsity constraints, which are usually modeled by ℓ_1/ℓ_0-minimization. The former, also known as LASSO, can be solved by the *iterative shrinkage-thresholding algorithm* (ISTA) [28] and its variants. This has yielded great interest in L2O schemes, as evidenced by the fact the works [75; 221; 189; 223; 255; 43; 126; 201; 4; 98; 246; 78; 3; 19], among others, provide various ways to unroll the original ISTA algorithm. Additionally, [161; 171; 208; 3] unroll a Nesterov accelerated ISTA known as *FISTA* (Fast ISTA) [16]. Continuing in the vein of sparsity, [30; 31; 153] unroll another algorithm, called *approximate message passing* (AMP), which introduces Onsager correction terms that whitens the noise in intermediate signals while [80; 98; 201] unroll *Orthogonal AMP* [137], an extension to the original AMP. For the ℓ_0-minimization problems, the *iterative hard-thresholding* (IHT) algorithm, which replaces the soft-thresholding function in ISTA with hard-thresholding, is unrolled in [222; 235]. Switching gears, for optimization problems that involve minimizing an objective that is the sum of several terms, the incremental proximal gradient method has also been unrolled [110]. Further generalization of FBS is given by an abstract collection of flexible, iterative modularization algorithms (FIMAs) [129], which perform updates using the composition of two learned operators (provided that the composition monotonically decreases an energy). A caveat of this particular approach is that the learned operator is also composed of a classic proximal-gradient operation.

The next category of unrolled L2O algorithms consists of primal-dual schemes. These typically include variations of *primal-dual hybrid gradient* (PDHG) and the *alternating direction method of multipliers* (ADMM) (e.g., see [190; 196; 175; 6; 234; 59; 54]). Another variation used is the *Condat-Vu primal-dual hybrid gradient* [101]. As above, many of these methods also focus on leveraging the sparse structure of data.

The remaining group of miscellaneous methods takes various forms. These include another first-order algorithm, *Half Quadratic Splitting* (HQS), for image restoration [256; 243]. Using a substitution and soft constraint, the HQS approach solves a problem using a model that approximates variational problems (VPs). Beyond first-order algorithms, unrolling is also applied to *second-order (Newton or Quasi-Newton) methods* [236; 120], *Differential Equations* [131; 132; 259] and *Interior Point* method [58; 23], and *Frank-Wolfe* algorithm [125; 168]. *Conjugate Gradient* was proposed [7] to help yield more accurate enforcement of the data-consistency constraint at each iteration than comparable proximal-gradient methods. The authors of [79] investigated sparse Bayesian Learning algorithms to solve ℓ_0 minimization problems and found that LSTM-like networks can be derived using algorithm unrolling. Lastly, the authors of [105] proposed an unfolded version of a greedy pursuit algorithm, i.e., *orthogonal matching pursuit* (OMP), that directly targets the original combinatorial sparse selection problem. Their methods, called Learned Greedy Method (LGM), can accommodate a dynamic number of unfolded layers and a stopping mechanism based on representation error, both adapted to the input. Besides, there are also L2O schemes that appear to be based entirely on heuristic combinations of classic optimization methods (e.g., see [93]).

3.2.3 OBJECTIVE-BASED V.S. INVERSE PROBLEMS

Objective based. The most straightforward L2O unrolling scheme is objective-based. Training is applied here to yield rapid convergence for a particular data distribution. The training loss can take various forms, including minimizing the expectation of an objective function [4], the objective's gradient norm, the distance to the optimal solution or the fixed point residual of the algorithm [84] (e.g., if T is the update operator, then $\|x - T(x)\|$ is the fixed point residual). Examples of objectives that have been extensively studied in the literature are presented in Section. 3.2.1.

In addition, *safeguarding* can be used in this situation, for guiding learned updates to ensure convergence [158; 84]. This can be accomplished in multiple ways. A typical approach is to generate a tentative update using an L2O scheme and then check whether the tentative update satisfies some form of descent inequality (e.g., yields a lesser energy value or fixed point residual). If descent is obtained, then the tentative update is used; otherwise, a classic optimization update is used. These safeguarded schemes reduce computational costs while maintaining theoretical convergence guarantees.

Inverse problems. Several L2O methods attempt to solve inverse problems (IPs) (e.g., see [77; 93; 101; 111; 112; 117; 129; 162]). Here the task is to reconstruct a signal $x^\star$ from noisy indirect measurements. The measurements are typically expressed by $d \in \mathbb{R}^m$ and are related to a forward operator $A : \mathbb{R}^n \to \mathbb{R}^m$ by

$$d = A(x^\star) + \varepsilon, \tag{15}$$

where ε is noise. A few repeated themes arise in the L2O IP literature. The typical process is to i) set up a variational problem (VP) as a surrogate model, ii) choose a parameterized optimization algorithm that can solve[7] (VP), and iii) perform supervised learning to identify the optimal parameter settings. We expound upon these themes and their nuances below.

---

7. We mean to say that, for some choice of parameters, the algorithm solves (VP).

First, by creating a variational problem, one assumes $x^\star$ approximately solves

$$\min_{x\in\mathbb{R}^n} \ell\left(d, A(x)\right) + J(x), \tag{VP}$$

where $\ell : \mathbb{R}^m \times \mathbb{R}^m \to \mathbb{R}$ is a fidelity term that encourages the estimate x to be consistent with the measurements d and $J : \mathbb{R}^n \to \mathbb{R}$ is a regularizer. Learning comes into play since $x^\star$ is usually *not* the solution to (VP), but instead some "close" variant. Thus, upon choosing the form of ℓ and J, one includes tunable parameters in the model and unrolls a parameterized optimization scheme for (typically) a fixed number K of iterations. Algorithm updates can be parameterized beyond their classic form (e.g., replace a fixed matrix with a matrix that has tunable entries as done in [75]). In most cases, the training loss takes the form of minimizing the expected value of the square of the Euclidean distance between the output estimate x^K and the true signal $x^\star$, i.e., the parameters Θ are trained to solve

$$\min_{\Theta} \mathbb{E}_{d\sim\mathcal{D}}\left[\|x^K(\Theta, d) - x_d^\star\|^2\right]. \tag{16}$$

The primary alternative training loss for L2O is to use estimates of the Wasserstein-1 distance between the distribution of reconstructed signals and the distribution of true signals (e.g., see [134]), which yields unsupervised training.

3.2.4 LEARNED PARAMETER ROLES

A key aspect of unrolled L2O methods is determining how to parameterize each update. This subsection discusses some of the common considerations and roles for these parameters.

Learning parameters in the iterations. First, the direct method of parameterization is to convert scalars/vectors/matrix/filters used in iterative algorithms into learnable parameters and learn them through data-driven training process. With this type of parameterization, learning can overcome the need of manually choosing hyperparameters. For example, LISTA [75] unrolls ISTA, which usually has update formulation

$$x^{k+1} = \eta_{\lambda/L}\left(x^k - \frac{1}{L}A^T(Ax^k - d)\right), \tag{17}$$

where λ is the coefficient before the ℓ_1 regularization in LASSO, L is the largest eigenvalue of $A^T A$, and $\eta_\theta(\cdot)$ is the coordinate-wise soft-thresholding function parameterized with threshold θ.[8] Then LISTA parameterizes ISTA as a recurrent formulation

$$x^{k+1} = \eta_\theta\left(W_e d + S x^k\right), \tag{18}$$

where taking $W_e \equiv A^T/L$, $S \equiv I - A^T A/L$ and $\theta \equiv \lambda/L$ reduces (18) to ISTA. A large amount of unrolling works follow the same methodology, but differ in the parameterization process, e.g., drop the recurrent structure in [75] and use feed-forward modeling by untying the learnable parameters in different layers and update them independently [89; 30]. This untying formulation can enlarge the capacity of the unrolled model [89]. However, it can also cause training instability due to the overwhelming parameter space and the difficulty of theoretical analysis of the convergence and other properties of the unrolled model.

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8. The soft-thresholding function takes the formula as $\eta_\theta(z) = \text{sign}(z) \cdot \max(0, |z| - \theta)$

To this end, there has been a line of efforts that strive to reduce the number of trainable parameters by relating and coupling different parts of parameterization [235; 43] and analytically generating parameters that satisfy certain constraints [126]. ALISTA [126] learns thresholds and stepsize parameters, reducing the number of parameters significantly to two scalars per layer, thus stabilizing the data-driven process and achieving state-of-the-art recovery performance at the time with theoretical convergence guarantee.

Besides, recent trends also started to apply model-free L2O methods to predict hyperparameters in classic iterative optimization algorithms. This is seen as the fusion among model-free L2O (since the algorithmic techniques are LSTM- or RL-based), model-specific L2O (as the update rule is eventually based on the classic iterates), and more traditional hyperparameter optimization. Examples include learning an adaptive learning rate schedule for training deep networks with stochastic graduate descent [240; 66; 183]; coordinating specifically for layer-wise training [250] or domain adaptation speeds [42]; predicting the update combination weights and decay rates in Adam [217]; or estimating training sample importance [183; 49], among others.

Deep priors learned from data. Another popular parameterization in unrolling is to use a deep model to learn a data-dependent prior on the interesting signals to replace hand-designed priors such as sparsity and total variation, which are not accurate in real-world applications and thus introduce bias. However, previous works have various ways to use the "learned prior". Th works [175; 153; 76; 256]use data-driven training to learn a proximal or a projection operator and apply it in the unrolled algorithm. The learned operator takes recovered signals that are contaminated by noises and artifacts as inputs and outputs a refined estimation. Sometimes the learned operator is found to fit a denoiser. The main difference between these learned-prior methods from Plug-and-Play methods is that the operator is usually learned end-to-end, making it overfitting to the current task or data distribution and not being able to be plugged into other algorithms. [29; 212] supposed that the relevant vectors lie near the range of a generative model, and hence used generative adversarial networks (GANs) as a learning-based prior for image compressive sensing. [134; 162] perceive the prior as a loss function that can distinguish between coarsely recovered signals without considering any priors and on-domain real signals with good quality. The prior as a loss function is adversarially trained to output high losses for coarse recoveries and low losses for real signals. Then we use the (sub-)gradient generated by the learned network via back-propagation in the unrolled algorithms e.g., gradient descent.

Others. Besides the above two significant ways of parameterization, some works learn black-box agents that directly generate next-step estimations given the current iterate and historical information [5; 236; 172]. For instance, [19] learns an LSTM network that generates the step sizes and threshold parameters within each layer in ALISTA instead of training them using back-propagation.

3.3 Applications

Unrolled L2O schemes have found many applications. Below we identify several of these and note some overlap among the three approaches discussed in this section.

- **Image restoration and reconstruction.** The model-based L2O methods, including both Plug-and-Play and unrolling methods, are widely used for various tasks in

image restoration, enhancement, and reconstruction. Popular application examples include denoising [63; 172; 256; 51; 192; 126; 234; 134; 142], deblurring [63; 256; 146; 127; 58; 142; 162; 257; 121], super-resolution [175; 72; 172; 256; 51; 127; 257], inpainting [175; 172; 192; 3], and compressive sensing [175; 153; 43; 63; 171; 141; 255; 98; 142], JPEG artifacts reduction [223; 51; 70], demosaicking [146], dehazing [243] and deraining [216]. Note that not all those works identically stick to the algorithm's original architecture; instead many only follow loosely the idea, and replace various components with convolutions or other modern deep learning building blocks.

- **Medical and biological imaging.** We specifically separate Medical and Biology Imaging applications from the previous Image Restoration part because the former has its own special scenario and challenges. Techniques in medical imaging such as MRI and CT require accurate reconstructions of images with as few measurements as possible that result in minimal discomfort or side-effect. It is also challenging to extend the model-based methods in natural images to properly deal with the complex-valued inputs [196]. Other work that applies model-based L2O to medical and biology imaging includes [6; 202; 5; 63; 134; 62; 162; 78; 185; 36].

- **Wireless communication.** Tasks in wireless communication systems can also be solved by unrolling methods, e.g. resource management [195; 201; 56], channel estimation [80], signal detection [80] and LDPC coding [215].For example, MIMO detection, which can be formulated as a sparse recovery problem, was shown to benefit from L2O methods based on "deep unfolding" of an iterative algorithm added with trainable parameters [15], such as LISTA. The model-based L2O approaches have already exhibited superior robustness and stability to low signal-to-noise (SNR), channel correlation, modulation symbol, and MIMO configuration mismatches [80]. We refer the readers to a seminal survey about unfolding methods in communication systems [15].

- **Seismic imaging.** Another important application of model-based L2O is seismic imaging [218; 244; 245; 254]. Most of them adopt a more plug-and-play manner to learn CNN-based projectors that are first trained using data and then integrated into classic iterative updates due to the desirable emphasis on physical modeling.

- **Miscellaneous applications.** Examples include clustering [221; 169; 170] and classification [222; 262; 59], phase retrieval [97], RNA second structure prediction [46], speech recognition and source separation [89; 225], remote sensing [130], smart grid [258], graph recovery [182], and photometric stereo estimation [235].

3.4 Theoretical Efforts

Although successful empirical results show the significant potential of L2O, a limited theory exists due to black-box training pertaining to such learned optimizers. That significant gap often makes the broader usability of L2O questionable. We note that the specific optimization problem and algorithm structure in model-based L2O often offer more opportunities for their theoretical analysis. Therefore, model-based L2O in a few specific problems has been the main focus of existing theoretical efforts.

The followings are essential questions regarding why and how model-based L2O methods outperform traditional optimization algorithms:

- (Capacity). Given the model of L2O, do there exist model parameters that provably ensure L2O outperforms traditional optimization algorithms over the task distribution (i.e., "in distribution")? Is there any "safeguard" mechanism to ensure L2O performs no worse than traditional algorithms on out-of-distribution (OoD) tasks?

- (Trainability). Given the existence of such parameters, what training method should we use to obtain those parameters? Do guarantees exist that the training method converges to the ideal parameters?

- (Generalization). Does the trained model generalize, say, to testing instances from the same source of training instances (i.e., "interpolation")? Can the trained models "extrapolate", e.g., on testing instances more complicated than any training one?

- (Interpretability). How can we explain what the L2O models have learned?

We list brief answers to the four questions here. Capacity and interpretability have been partially solved on signal/image-processing related problems by some recent works, as detailed in the subsections below. Generalization has gained increasing attention recently, and some works provide bounds of generalization gap of some specific L2O models. There has been very limited theoretical work on the trainability of L2O, due to the nonconvexity of L2O training objectives (see Section 3.2.3). The main exception here is the recent work [219] discussing the local minima and gradient explosion/vanishing in L2O training for quadratic minimization. This was also partially addressed by [87] where the authors used sorting activation functions [14] and Lipschitz networks to encourage gradient norm preservation.

3.4.1 Capacity

To our best knowledge, [195] is the first effort on theories of L2O. It approximates a traditional method, WMMSE (weighted minimum mean square error), with a fully-connected neural network and proves that the network output can be arbitrarily close to the result of WMMSE when its numbers of layers and units are large enough. In other words, this work estimates the approximation capacity of the neural network.

Approximation capacity is a generic notion in machine learning. Specifically for L2O, **convergence** can be used to describe the model capacity: *Do there exist parameters $\{\theta^k\}_k$ in (13) that make $\{x^k\}$ converge better than classic optimization algorithms as $k \to \infty$?* The work [43] adopts this way to describe the convergence of L2O on the sparse recovery problem and gives a convergence rate of LISTA, which is better than that of classic algorithms ISTA/FISTA. [126; 231; 3; 4; 242; 253; 45] improve the theoretical result of LISTA by designing more delicate networks (i.e., more delicate variants of the operator T in (13)). The authors of [234] analyze the convergence rate of differentiable linearized ADMM.

Instead of studying parameters θ^k, another approach to establish convergence is to propose mathematical conditions on the operators (for example, operator T in (13) and operator H in (10a′)) in the models. These mathematical conditions should not only guarantee the convergence but also can be satisfied practically. [179] proposes a continuity condition

that can be satisfied by a specifically designed training method. [52] assumes smoothness of the operator that is satisfied by choosing smooth activation functions in a neural network (e.g., the sigmoid function). [162] assumes convexity of the regularizer in their math proof and proposes to parameterize the regularizer by a convex neural network. [87] proves the convergence under assumptions about the manifold and sufficient representation by the sampled data, which are usually satisfied in practice. [86] approaches convergence by fusing data-driven regularization and convex feasibility in a theoretically sound manner.

While the above efforts focus on studying the convergence and acceleration effect of L2O over the target task distribution, a parallel and equally important topic is to bound or characterize the convergence of L2O under OoD inputs: how much can the L2O convergence degrade when applied to optimizees deviating from the task distribution? Although the question is seemingly daunting at first glance, the goal may be fulfilled by L2O with a safeguard mechanism, which establishes convergence independent of the parameters and data. In this sense, the capacity of the original L2O models has been enlarged. The most common approach is to i) compute a tentative L2O update using any method under the sun, ii) check if the tentative update yields a reduction in the value of an energy, and iii) accept the L2O update if the energy is less than some relative bound (e.g., the energy at the current iterate). If the tentative L2O update is rejected, then a fallback scheme is to apply the update of a classic optimization algorithm. Because the energy decreases monotonically, we can show that the overall algorithm converges to a minimizer of the energy. The energy is typically defined to be the objective function in the variational problem (VP) or its differential [127; 128; 129; 158]. An alternative approach is to define the energy to measure the residual between updates (e.g., [84]). That is, if T is the update operator for a classic algorithm, then at a tentative update x^k, we check if the residual $\|x^k - T(x^k)\|$ is less than some relevant bound.

3.4.2 Interpretability

Interpretability is significant to a learning model, now even more than ever. Some efforts have been made on the interpretability of L2O, including linking or reducing their behaviors to those of some analytic, better-understood optimization algorithms. [235] studies unrolled iterative hard-thresholding (IHT) and points out that unrolled IHT adopts a better dictionary and has a milder requirement of the RIP condition than IHT. [161] demonstrates that the mechanism of LISTA is related to a specific matrix factorization of the Gram matrix of the dictionary. [72] explains the success of LISTA with a tradeoff between convergence speed and reconstruction accuracy. [126] shows that the weights in LISTA have low coherence with the dictionary and proposes an analytic approach to calculate the weights. [182] analyzes alternating minimization algorithm quantitatively on a graph recovery problem and reveals the analogy between the learned L2O model and solving a sequence of adaptive convex programs iteratively. [200] points out the analogy between deep-unfolded gradient descent and gradient descent with Chebyshev step-size and shows that the learned step size of deep-unfolded gradient descent can be qualitatively reproduced by Chebyshev step-size.

3.4.3 Generalization

Generalization is an important topic for L2O, just like for any other ML domain. Recent work [151; 11] described a "generalization-first" perspective for L2O. The relationship between the generalization gap and the number of training instances gives us an estimate of how many samples we should use. In the recent literature, [48], [17] and [211] studied the Rademacher complexity, an upper bound of generalization gap. [48] estimates the Rademacher complexity of gradient descent and Nesterov's accelerated gradients on a parameterized quadratic optimization problem; [17] estimates the Rademacher complexity of a deep thresholding network on sparse linear representation problem. [211] proposes a reweighted RNN for the signal reconstruction problem and provides its Rademacher complexity. As its definition suggests, generalization measures how the trained L2O models perform on unseen samples from the same distribution seen in training but not on samples deviating from that distribution. Please refer to the previous discussion in Section. 3.4.1 on how methods such as Safeguard can mitigate the challenges of OoD optimizees.

Stability is highly related to generalization [48], some L2O works analyze the stability of their methods. For example, [111] estimates Lipschitz constants of their method to provide stability analysis results both with respect to input signals and network parameters. This yields a growth condition inequality. Another measure of stability is to ensure the stability of the model as the weighting of the regularizer term in (VP) tends to zero [112; 117]. A third approach is to learn a regularizer based on the null space of A and study its stability with the relationship between the learned neural network and the null space. Each of these methods yields different insights into the stability of L2O schemes for inverse problems.

Similar to the bias-variance tradeoff in ML, L2O models are also subject to the tradeoff between the capacity and the generalization. [48] provided insights on such tradeoff in an unrolled model by proving a generalization bound as a function of model depth and related to the properties of the algorithm unrolled.

4. The Open-L2O Benchmark

The community has made various attempts to explore L2O and generated rich literature for solving different optimization tasks on different data or problems, as well as different software implementations on various platforms. Each L2O method has its training recipe and hyperparameters. Because a common benchmark for the field has not yet been established, comparisons among different L2O methods are inconsistent and sometimes unfair. This section presents our efforts toward creating a comprehensive benchmark that enables fair comparisons. To the best of our knowledge, this is the first time such an attempt has been made.

Testbed problems. We choose some popular and representative test problems that have been used in the existing L2O literature: (i) convex sparse optimization, including both sparse inverse problems and LASSO minimization; (ii) minimizing the nonconvex Rastrigin function, and (iii) training neural networks (NNs), which is a more challenging nonconvex minimization problem.

Task distributions. Inspired by both research practice and real-world demands, we define task distributions in the following problem-specific way: (i) for sparse optimization, the optimizees during training and testing are optimization problems with the same objec-

tive function and decision variables but *different data*; (ii) in the Rastrigin-function test, during both training and testing, the optimizees have different decision variables and use random initializations; (iii) in the NN training test, the training optimizees use the same network architecture and data set but random initializations; however, testing samples optimizees from a *different distribution*, that is, the L2O optimizer is applied to train a network of an unseen architecture and on a different data set.

Compared methods and evaluation settings. For each problem, we choose applicable approaches that include both model-free and/or model-based ones, implement them in the TensorFlow framework, ensure identical training/testing data, and evaluate them in the same but problem-specific metrics. After presenting the results, we draw observations from these benchmark experiments.

Our data sets and software are available as the **Open-L2O** package at: `https://github.com/VITA-Group/Open-L2O`. We hope that Open-L2O will foster reproducible research, fair benchmarking, and coordinated development efforts in the L2O field.

4.1 Test 1: Convex Sparse Optimization

In this subsection, we conduct empirical evaluation of L2O methods on two types of sparse optimization: *(i)* sparse recovery problems and *(ii)* LASSO minimization.

4.1.1 LEARNING TO PERFORM SPARSE OPTIMIZATION AND SPARSE-SIGNAL RECOVERY

Problem definition. The sparse recovery problem has been widely studied in the model-based L2O literature [75; 43; 126]. The task is to recover a sparse vector from its noisy linear measurements:

$$b_q = Ax_q^* + \varepsilon_q, \tag{19}$$

where $x_q^* \in \mathbb{R}^n$ is a sparse vector, $\varepsilon_q \in \mathbb{R}^m$ is an additive noise, and q indexes an optimizee instance. While $x_q^*, b_q, \varepsilon_q$ change for each q, the measurement matrix $A \in \mathbb{R}^{m \times n}$ is fixed across all training and testing. In practice, there is a matrix A associated with each sensor or sensing procedure.

Data generation. We generate $51,200$ samples as the training set and $1,024$ pairs as the validation and testing sets, following the i.i.d. sampling procedure in [43]. We sample sparse vectors x_q^* with components drawn i.i.d. drawn from the distribution $\text{Ber}(0.1) \cdot N(0,1)$, yielding an average sparsity of $\sim 10\%$. We run numerical experiments in four settings:

- **Noiseless**. We take $(m, n) = (256, 512)$ and sample A with $A_{ij} \sim N(0, 1/m)$ and then normalize its columns to have the unit ℓ_2 norm. The noise ε is always zero.

- **Noisy**. The same as above except for Gaussian measurement noises ϵ_q with a signal-to-noise ratio (SNR) of 20dB.

- **Coherent**. A Gaussian random matrix is highly incoherent, making sparse recovery relatively easy. To increase the challenge, we compute a dictionary $D \in \mathbb{R}^{256 \times 512}$ from 400 natural images in the BSD500 data set [144] using the block proximal gradient method [239] and, then, use it as the measurement matrix A, which has a high coherence. Other settings remain unchanged from the first setting above.

- **Larger scale**. We scale the noiseless case to $(m, n) = (512, 1024)$; the other settings stay the same.

Model and training settings. All our model-based L2O approaches take measurements b_q as input and return estimates $\hat{x}_q \approx x_q^*$. They are trained to minimize the mean squared error $\mathbb{E}_{q \sim Q} \|\hat{x}_q - x_q^*\|_2^2$. We adopt a progressive training scheme following [31; 43; 231]. We use a batch size of 128 for training and a learning rate of 5×10^{-4}. Other hyperparameters follow the default suggestions in their original papers. After training, the learned models are evaluated on the test set in NMSE (Normalized Mean Squared Error) in the decibel (dB) unit:

$$\text{NMSE}_{\text{dB}}(\hat{x}_q, x_q^*) = 10 \log_{10} \left(\|\hat{x}_q - x_q^*\|^2 / \|x_q^*\|^2 \right).$$

We compare the following model-based L2O approaches, all of which are unrolled to 16 iterations: (1) a feed-forward version **LISTA** as proposed in [75], with untied weights across layers; (2) **LISTA-CP**, a variant of LISTA with weight coupling [235; 43]; (3) **LISTA-CPSS**, a variant of LISTA with weight coupling and support selection techniques [43; 126]; (4) **ALISTA** [126], the variant of LISTA-CPSS with minimal learnable parameters; (5) **LAMP** [31], an L2O network unrolled from the AMP algorithm; (6) **LFISTA** [160], an L2O network unrolled from the FISTA algorithm; (7) **GLISTA** [231], an improved LISTA model by adding gating mechanisms.

Results. Figure 5 summarizes the comparisons; its four subfigures present the NMSEs of sparse recovery under noiseless, noisy, coherent dictionary, and large scale settings, respectively. We make the following observations :

- In the noiseless setting, ALISTA yields the best final NMSE, and the support selection technique in LISTA-CPSS contributes to good performance. LAMP and GLISTA achieve slightly worse NMSEs than LISTA-CPSS but are much better than LISTA. Surprisingly, LFISTA fails to outperform LISTA, which we attribute to its heavier parameterization in [160] than other models and consequently harder training.

- In the noisy setting of 20dB SNR, the performance of LAMP degrades severely while LISTA-CPSS and ALISTA still perform robustly. GLISTA outperforms all the others in the setting.

- In the setting of a coherent dictionary, ALISTA suffers significantly from the coherence. At the same time, the other methods that learn the weight matrices from data can cope with this issue better. In particular, GLISTA has the best performance thanks to the gate mechanisms.

- When it comes to a larger scale setting $(m, n) = (512, 1024)$, LISTA, LISTA-CP, LFISTA, and GLISTA have performance degradation due to the higher parameterization burden. In comparison, ALISTA becomes the best since it has the fewest parameters to learn: only the layer-wise thresholds and stepsizes. Therefore, ALISTA is least impacted by the problem scale and produces nearly the same performance as it does in the smaller setting of $(m, n) = (256, 512)$.
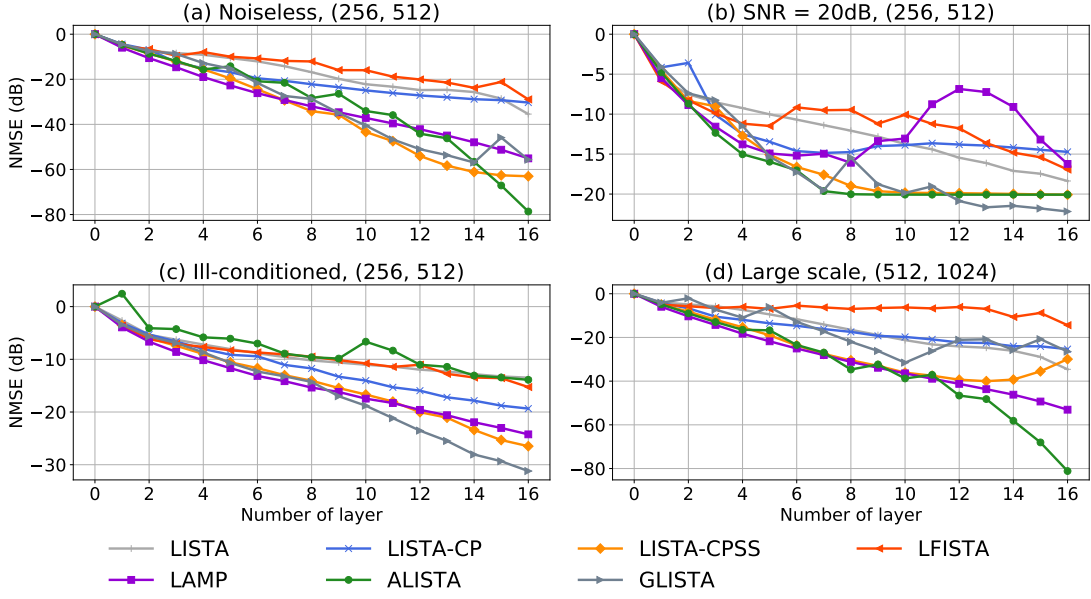
Figure 5: Results of sparse recovery in four different settings: (a) noiseless with $(m, n) = (256, 512)$; (b) additive Gaussian measurement noises of SNR=20dB and $(m, n) = (256, 512)$; (c) coherent dictionary with $(m, n) = (256, 512)$; (d) larger scale with $(m, n) = (512, 1024)$. The x-axis counts the layers and the y-axis is the NMSE of the recovery.

4.1.2 Learning to Minimize the Lasso Model

Problem definition. Instead of sparse recovery, which aims to recover the original sparse vectors, our goal here is to minimize the LASSO objective even though its solution is often different from the true sparse vector:

$$x_q^{\text{Lasso}} = \arg\min_x f_q(x), \quad \text{where } f_q(x) = \frac{1}{2}\|Ax - b_q\|_2^2 + \lambda\|x\|_1, \tag{20}$$

where $A \in \mathbb{R}^{m \times n}$ is a known, fixed, and normalized dictionary matrix, whose elements are sampled i.i.d. from a Gaussian distribution. An optimizee instance with index q is characterized by a sparse vector x_q^* and $b_q \in \mathbb{R}^{m \times 1}$ is the observed measurement under A from x_q^* following the same linear generation model in the previous subsection. λ is a hyperparameter usually selected manually or by cross-validation and is chosen to be 0.005 by default in all our experiments.

Uniquely, we compare **both model-based and model-free** L2O methods in this section. For the former, we can adopt a similar algorithm for unrolling recipes as in the previous subsection. For the latter, we treat the problem as generic minimization and apply LSTM-based L2O methods. To our best knowledge, this is the first comparison between the two distinct L2O mainstreams. We hope the results provide a quantitative understanding of how much we can gain from incorporating problem-specific structures (when available) into L2O.

Data generation. We run the experiments with $(m, n) = (5, 10)$, as well as $(m, n) = (25, 50)$. We did not go larger due to the high memory cost of LSTM-based model-free L2O methods. We sample $12, 800$ pairs of x_q^* and b_q for training and $1, 280$ pairs for validation and testing. The samples are noiseless. We set $1, 000$ iterations for both model-free L2O methods and classic optimizers. We run model-based L2O ones with a smaller fixed number of iterations (layers), which are standard.

For each sample b_q, we let f_q^* denote the optimal Lasso objective value, $f_q(x^{\text{Lasso}})$. The optimization performance is measured with a modified relative loss:

$$R_{f,\mathcal{Q}}(x) = \frac{\mathbb{E}_{q \sim \mathcal{Q}}[f_q(x) - f_q^*]}{\mathbb{E}_{q \sim \mathcal{Q}}[f_q^*]}, \tag{21}$$

where the optimal solution is generated by $2, 000$ iterations of FISTA and the expectations are taken over the entire testing set.

We run four categories of methods to solve the LASSO optimization problem:

- Three sub-gradient descent algorithms: GD, ADAM, and RMSProp, which serve as "natural baselines" with neither learning nor problem-specific structure. All these algorithms use a step size of 10^{-3}. We verified that changing step sizes did not notably alter their performance. (Even though GD and its generalizations do not handle nonsmooth objectives without smoothing or using proximal operators, they are popular optimizers that people try on almost everything, so we choose to test them anyway.)

- Two problem-specific analytic optimizers: ISTA [28], a forward-backward splitting algorithm using a soft-thresholding backward operator and its Nesterov-accelerated version, FISTA [16]. For both methods, we use a step size of $1/L$, where L is the largest eigenvalue of $A^T A$, and a threshold of λ/L for the soft-thresholding function.

- Two model-based L2O models: vanilla LISTA [75] and ALISTA [126], both unrolled to 16 layers. We adopt the same training setting in the last subsection, except that we replace the training loss from the mean squared error (w.r.t. the true solution) with the LASSO loss. Since other compared methods take far more iterations, we also tried to expand LISTA/ALISTA to more iterations during testing by appending FISTA iterations.

- Three model-free L2O methods: L2O-DM [13], L2O-RNNprop [135] and L2O-enhanced optimizers [41] (Section 2.1). All L2O optimizers are trained with the Lasso objective function as the reward for 100 epochs and $1, 000$ iterations per epoch. The reported evaluation is the average performance over 10 random starting points.

Results. From Figure 6, we make the following observations:

- At the small problem size $(5, 10)$, both ISTA and FISTA converge fast in tens of iterations, with FISTA slightly ahead. Both model-based L2O models, ISTA and ALISTA of 16 iterations (layers), converge to solutions of precisions compared to what FISTA can achieve after hundreds of iterations and better than what ISTA can do at 1,000 iterations. The advantages of LISTA and ALISTA can sustain beyond 16 iterations when they are succeeded with FISTA updates.

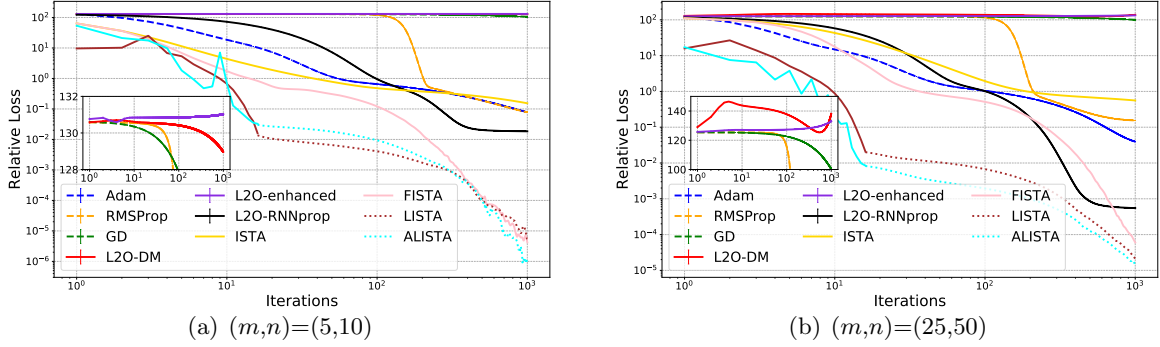(a) $(m,n)=(5,10)$ (b) $(m,n)=(25,50)$

Figure 6: Evaluation comparisons among analytic, model-based L2O, and model-free L2O optimizers on Lasso. y-axis represents the modified relative loss (21), and x-axis denotes the number of iterations, both in the logarithmic scale.

- In comparison, at the small problem size $(5, 10)$, model-free L2O methods exhibit far worse performance. L2O-RNNprop has slower convergence than ISTA/FISTA and only produces reasonably good solutions after 1,000 iterations—though still much better than analytic optimizers Adam and RMSProp. L2O-DM, L2O-enhanced, and vanilla GD fail entirely to decrease the objective value.

- At the larger problem size $(25, 50)$, LISTA and ALISTA still converge to high-precision solutions with only 16 iterations with sustained advantages from the FISTA extension. Interestingly, ISTA has now become much slower than FISTA. All the sub-gradient descent and model-free L2O methods perform poorly; only L2O-RNNprop can converge faster than ISTA and comparable to FISTA, though reaching lower precision.

- Our experiments demonstrate the dominant advantage of incorporating problem-specific structures to the optimizers when it comes to both analytic and learned optimizers.

4.2 Test 2: Minimization of Non-Convex function Rastrigin

We now turn to non-convex minimization. One popular non-convex test function is called the Rastrigin function:

$$f(\boldsymbol{x}) = \frac{1}{2} \sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} \alpha \cos\left(2\pi x_i\right) + \alpha n, \tag{22}$$

where $\alpha = 10$. We consider a broad family of similar functions $f_q(\boldsymbol{x})$ that generalizes Rastrigin function:

$$f_q(\boldsymbol{x}) = \frac{1}{2} \|\boldsymbol{A}_q \boldsymbol{x} - \boldsymbol{b}_q\|_2^2 - \alpha \boldsymbol{c}_q \cos(2\pi \boldsymbol{x}) + \alpha n, \tag{23}$$

where $\boldsymbol{A}_q \in \mathbb{R}^{n \times n}$, $\boldsymbol{b}_q \in \mathbb{R}^{n \times 1}$ and $\boldsymbol{c}_q \in \mathbb{R}^{n \times 1}$ are parameters whose elements are sampled i.i.d. from $\mathcal{N}(0, 1)$. Obviously, the function (22) is a special case in this family with
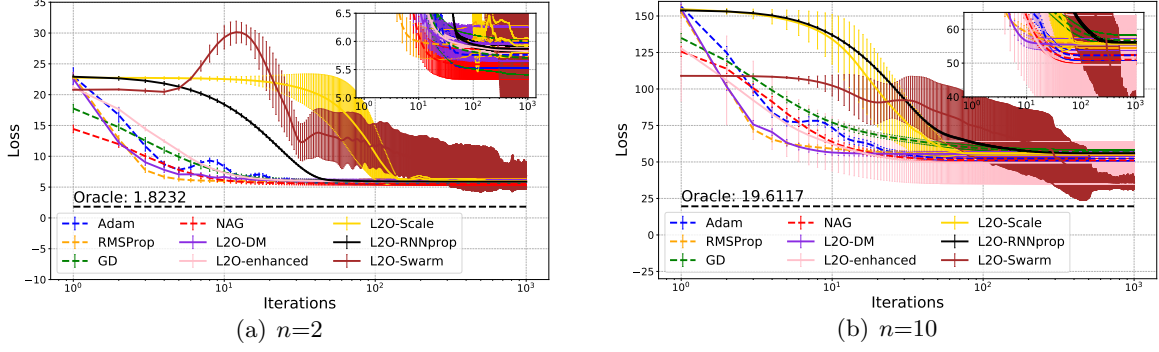
32

Figure 7: Evaluation and comparison across model-free L2O and analytic optimizers on the generalized family of Rastrigin functions. y-axis represents the average loss of function values, and x-axis denotes the number of iterations in the logarithm scale.

$\boldsymbol{A} = \boldsymbol{I}, \boldsymbol{b} = \{0, 0, \ldots, 0\}^{\mathrm{T}}, \boldsymbol{c} = \{1, 1, \ldots, 1\}^{\mathrm{T}}$. For training, we sample $1,280$ triplets of $\{A_q, b_q, c_q\}$ om two problem scales: $n = 2$ and $n = 10$. For evaluation, we sample another 128 combinations of A_q, b_q and c_q and report the average performance over 10 random starting points. The number of steps for evaluation is $1,000$.

Two groups of methods are compared: (1) Four traditional gradient descent algorithms, including ADAM with a 10^{-1} step size, RMSProp with a 3×10^{-1} step size, GD with the line-searched step size started from 10^{-1}, and NAG (Nesterov Accelerated Gradient) with the line-searched step size started from 10^{-1}. All other hyperparamters are tuned by careful grid search. (2) Five model-free L2O methods, including L2O-DM [13], L2O-enhanced [41], L2O-Scale [227], L2O-RNNprop [135] (Section 2.1), and L2O-Swarm [37] (Section 2.3). All L2O optimizers are trained for 100 epochs and 1000 iterations per epoch. At the testing stage, we evaluate and report the logarithmic loss of unseen functions from the same family, which are plotted in Figure 7.

Results. From Figure 7 we draw the following observations:

- ADAM and RMSProp converge slightly more quickly than GD and NAG with line search, especially in the early stage, for both $n = 2$ and $n = 10$. All analytic optimizers converge to local minima of similar qualities for $n = 2$, and NAG finds a slightly better solution for $n = 10$.

- L2O-DM, L2O-enhanced, L2O-RNNProp, and L2O-Scale perform similarly to analytic optimizers regarding solution quality and convergence speed, showing no obvious advantage over analytic optimizers. For $n = 10$, L2O-enhanced finds a better quality solution than the other two. However, the three model-free L2Os have larger error bars at $n = 10$, indicating model instability.

- Although not converging faster than others, L2O-Swarm locates higher quality solutions (lower losses) for both n values, especially $n = 10$. Since L2O-Swarm is the only method that leverages a population of LSTM-based L2O "particles", it explores a

larger landscape than the other methods, so it is not surprising that its higher search cost leads to better solutions.

- The oracle objectives (dashed black lines) in Figure 7 are generated by the Run-and-Inspect method [50], which can provably find a global minimum if the objective function can be decomposed into a smooth, strongly convex function (e.g., a quadratic function) plus a restricted function (e.g., sinusoidal oscillations). For $n = 2$, almost all methods reach a similar loss lied in $[5.5, 6.0]$ in the end. For $n = 10$, L2O-Swarm performs significantly better than other methods in the achieved final loss, though it converges more slowly than most other approaches.

4.3 Test 3: Neural Network Training

Our last test is training multi-layer neural networks (NNs), one of the most common tasks of L2O since its beginning. This has been the playground for model-free L2O methods. There are few problem-specific structures to explore. Common optimizers are stochastic gradient descent and their variants. We hope this test to address two questions:

- Can model-free L2O optimizers outperform analytic ones on neural network training? If so, how much is the margin?

- Can model-free L2O optimizers generalize to unseen network architectures and data?

To fairly compare different methods and answer these questions, we train L2O optimizers on the same neural network used in [13]: a simple Multi-layer Perceptron (MLP) with one 20-dimension hidden layer and the sigmoid activation function, trained on the MNIST data set to minimize the cross-entropy loss. Therefore, the task distribution becomes optimizing the same MLP model with different random initializations.

We probe the (out of distribution) generalizability of the learned optimizers by testing them on two unseen optimization tasks, following the practice in [13; 41]:

1. Train another MLP with one 20-dimension hidden layer, but using the ReLU activation function, on the MNIST data set.

2. Train another ConvNet on the MNIST data set, consisting of two convolution layers, two max-pooling layers, and one last fully connected layer. The first convolution layer uses 16 3×3 filters with stride 2. The second convolution layer uses 32 5×5 filters with stride 2. The max-pooling layers have a size 2×2 with stride 2.

We compare four model-free L2O optimizers: L2O-DM [13], L2O-enhanced [41], L2O-Scale [227], and L2O-RNNprop [135] (Section 2.1), all following the hyperparameters suggested in their original papers. SGD, Adam, and RMSProp are analytical optimizers served as the baselines. All L2O optimizers are trained with the single model from 10,000 different random initializations drawn from $\mathcal{N}(0, 01)$. On each optimizee, now corresponding to a random initialization, the optimizers run for 100 iterations. The training uses a batch size of 128. During each testing run, we evaluate learned optimizers on an unseen testing optimizee for $10,000$ steps, which is much more than the training iteration number. We then report the training loss of the optimizee. We perform ten independent runs and report the error bars.
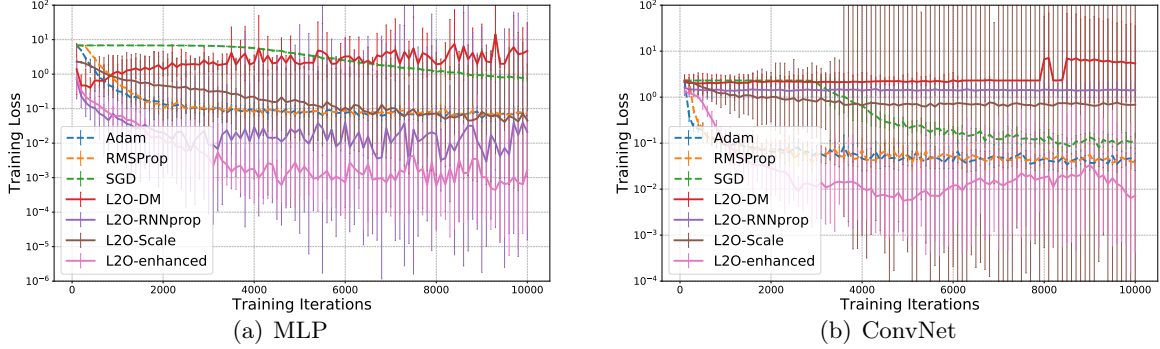
(a) MLP

(b) ConvNet

Figure 8: Evaluation and comparison across model-free L2O and analytic optimizers on neural network training. y-axis represents the average training loss values, and the x-axis denotes the number of iterations. Each curve is the average of ten runs, and error bars are plotted.

It is worth mentioning that current L2O-optimizers can hardly scale to train large neural networks with over 1×10^6 parameters. This is because to update the L2O optimizer using back-propagation, we need to keep the gradients during unrolling and the computation graph of the optimizee in memory, therefore, consuming too much memory. This remains an open challenge.

Results. From Figure 8, we make the following observations:

- The relative performance of analytic optimizers is consistent: both Adam and RM-SProp achieve similar training losses on both ReLU-MLP and ConvNets, and better than SGD. However, the learned optimizers exhibit different levels of transferability. L2O-DM completely diverges on ConvNet, but works on ReLU-MLP when the number of iterations is small, showing poor generalization.

- L2O-Scale and L2O-RNNprop can generalize to ReLU-MLP as they achieve similar or lower training losses than analytic optimizer), but they cannot effectively optimize ConvNet. L2O-RNNprop only works for a small number of iterations, less than 4,000. L2O-Scale generalizes better to larger iteration numbers, thanks to its random scaling during training.

- L2O-enhanced, which adopts increasing unroll length and off-line imitation strategy, achieves the best performance on both unseen networks after extended (optimizee) training iterations.

- The issue of lacking stability during testing exists for all L2O optimizers. On both ReLU-MLP and ConvNet, all L2O optimizers suffer from larger loss variances as the training iteration grows, causing the errors to fluctuate more severely than those of the analytic optimizers.

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4.4 Take-Home Messages

⋆ When an appropriate model or problem structures are available to be leveraged, model-based L2O methods outperform model-free ones and analytic optimizers. On optimizees sampled from the same task distribution, model-based L2O optimizers have solid, consistent, and reliable performance.

⋆ Although we can also observe performance gains of model-free L2O approaches over analytic ones in many cases, the gains are not consistent. The benefits of current model-free L2O approaches come into question when they are applied to larger optimizees or applied with more iterations during testing, let alone to "out-of-distribution" optimizees. We find no clear winner in existing model-free L2O approaches that can consistently outperform others across most tests.

5. Concluding Remarks

This article provided the first "panoramic" review of the state-of-the-art in the emerging L2O field, accompanied by the first-of-its-kind benchmark. The article reveals that, despite its promise, the L2O research is still in its infancy, facing many open challenges and research opportunities from practice to theory.

On the theory side, Section 3.4 has listed many open theoretical questions for us to understand why and how model-based L2O methods outperform traditional optimizers. Besides those, for model-free L2O methods, the theoretical foundation has been scarce, if any at all. For example, although the training of L2O optimizers is often successful empirically, there has been almost no theoretical result established for the convergence performance of such an L2O training process, putting the general feasibility of obtaining L2O models in question. Also, for both model-based and model-free L2O approaches, the generalization or adaption guarantees of trained L2O to optimizees out of the task distribution are under-studied yet highly demanded.

On the practical side, the scalability of model-free L2O methods is perhaps the biggest hurdle to becoming more practical. That includes scaling up to larger and more complicated models and more iterations during L2O testing. For model-specific L2O, the current empirical success is limited to a few special instances in inverse problems and sparse optimization, relying on case-by-case modeling. Exploring broader applications and perhaps building a more general framework is demanded.

Furthermore, there is not an absolute border between mode-based and model-free L2O methods, and the spectrum between the two extremes can hint at many new research opportunities. [159] suggested a good perspective that unrolled networks (as one example of model-based L2O) are an intermediate state between generic networks and analytic algorithms and might be more data-efficient to learn. The view was supported by [147], which further advocated that the unrolled model might be considered as a robust starting point for subsequently data-driven model search. We also believe that current continuous optimization algorithms can improve end-to-end learning approaches to benefit from the theoretical guarantees and state-of-the-art algorithms already available.

So, to conclude this article, let us quote Sir Winston Churchill: *"Now this is not the end. It is not even the beginning of the end. However, it is, perhaps, the end of the beginning."*

Although most approaches we discussed in this paper are still at an exploratory level of deployment and are not yet ready as general-purpose or commercial solvers, we are strongly confident that machine learning has just begun to feed the classic optimization field. The blowout of L2O research progress has yet to start.

Acknowledgments

Appendix A. List of Abbreviations

Abbreviation	Full Name	Description
Adam	Adaptive Moment Estimation	A first-order gradient-based optimization algorithm of stochastic objective functions, based on adaptive estimates of lower-order moments.
ADMM	Alternating Direction Method of Multipliers	An optimization algorithm that solves convex problems by breaking them into smaller pieces, each of which are then easier to handle.
AutoML	Automated Machine Learning	The process of automating the process of applying machine learning to real-world problems.
CASH	Combined Algorithm Selection and Hyperparameter Optimization	A model selection strategy that consider the choosing of data preparation, learning algorithm, and algorithm hyperparameters as one large global optimization problem.
GAN	Generative Adversarial Network	A class of machine learning frameworks [73], where two neural networks contest with each other in a zero-sum game, to learn to generate new data with the same statistics as a given training set.
HPO	Hyperparameter Optimization	The problem of choosing a set of optimal hyperparameters for a machine learning algorithm.
L2O	Learning to Optimize	Learnable optimizers to predict update rules (for optimizees) fit from data.
LASSO	Least Absolute Shrinkage and Selection Operator	A linear regression method that uses shrinkage to encourages simple, sparse models.
LSTM	Long-short Term Memory	A variant of artificial recurrent neural network (RNN) architecture, typically used to process sequence data.
MLP	Multi-layer Perceptron	A class of feedforward artificial neural network (ANN) composed of multiple layers of perceptrons (with threshold activation).
PGD	Projected Gradient Descent	Projected gradient descent minimizes a function subject to a constraint. At each step we move in the direction of the negative gradient, and then "project" onto the feasible set.
ReLU	Rectified Linear Unit	An activation function used in neural networks, defined as $f(x) = \max(x, 0)$.
RL	Reinforcement Learning	RL is an area of machine learning regarding how to make intelligent agents take actions in an environment to maximize the cumulative reward.
RMSProp	Root Mean Square Propagation	RMSprop gradient descent maintains a moving (discounted) average of the square of gradients, and then divide the gradient by the root of this average.

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