Non-Convex Bilevel Games with Critical Point Selection Maps

Anonymous Author(s)
Affiliation
Address
email

Abstract

Bilevel optimization problems involve two nested objectives, where an upper-level objective depends on a solution to a lower-level problem. When the latter is non-convex, multiple critical points may be present, leading to an ambiguous definition of the problem. In this paper, we introduce a key ingredient for resolving this ambiguity through the concept of a *selection* map which allows one to choose a particular solution to the lower-level problem. Using such maps, we define a class of hierarchical games between two agents that resolve the ambiguity in bilevel problems. This new class of games requires introducing new analytical tools in Morse theory to characterize their evolution. In particular, we study the differentiability of the selection, an essential property when analyzing gradient-based algorithms for solving these games. We show that many existing algorithms for bilevel optimization, such as unrolled optimization, solve these games up to approximation errors due to finite computational power. Our analysis allows introducing a simple correction to these algorithms for removing the errors.

1 Introduction

Bilevel optimization has proven to be a major tool for solving machine learning problems that possess a nested structure such as hyper-parameter optimization [12], meta-learning [6], reinforcement learning [17, 25] or dictionary learning [30]. Introduced in the field of economic game theory in [38], a bilevel optimization problem can be understood as a game between a *leader* and a *follower* each of which optimizes their own objective function but where the leader can anticipate follower's actions. In the context of machine learning, the leader typically optimizes a hyper-parameter over a validation loss while the follower optimizes the model parameter on a training loss [29].

Bilevel optimization introduces many challenges. In particular, when multiple optimal solutions are available to the follower, the leader would need to optimize a different objective depending on the follower's strategy to select an optimal solution. As a result, the bilevel problem becomes ambiguously defined without knowing the follower's strategy [27]. A large body of work on bilevel programs for machine learning gets around these considerations by assuming the follower to have a unique optimal choice, a situation that typically occurs when the follower's objective is strongly convex, leading to efficient and scalable algorithms [1, 2, 7, 9, 15, 24, 25, 37].

However, in many machine learning applications, the strong convexity of the follower's objective is an unrealistic assumption. This is particularly the case in the context of deep learning, where the follower's objective, the training loss, can be highly non-convex in the parameters of the model and can have regions of flat optima due to symmetries and other degeneracies [10, 22].

In the literature on mathematical optimization, the ambiguity is often resolved by making an additional assumption on the follower's strategy for choosing their optimal solution. In particular, two

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problems are often considered: *optimistic and pessimistic bilevel programs*, see [8]. Both problems rely on two assumptions: (i) the follower is using a strategy for selecting a solution to their problem that is either improving or degrading the leader's objective and (ii) the leader knows exactly what strategy the follower is using. These assumptions are strong from a game-theoretical perspective and often unrealistic for machine learning problems such as hyper-parameter optimization. Still, optimistic/pessimistic bilevel games are well defined and early works have proposed several algorithms to solve them with strong convergence guarantees [42, 43, 44]. Yet, these algorithms are often ill-suited to large-scale and high-dimensional problems arising in machine learning applications as they rely on second-order optimization methods such as Newton's method [16]. For this reason, scalable first-order algorithms for such games have been proposed recently [26, 27].

However, many of the best-performing approaches for hyper-parameter optimization rely neither on an optimistic nor a pessimistic formulation of the bilevel problem. Instead, they often rely on algorithms initially designed for bilevel problems with strongly convex lower objectives even though the convexity assumption does not hold [29]. While these algorithms are seemingly solving an ill-defined bilevel program, due to the ambiguity in the way the follower selects their solution, their ability to provide models with good empirical performance raises the following question: Are these algorithms solving another class of well-defined hierarchical problems that go beyond optimistic and pessimistic bilevel programs but are still relevant for machine learning?

In this work, we answer this question and introduce *Bilevel Games with Selection* (BGS), a class of well-defined games between two agents: a leader and a follower, where the leader anticipates a solution from the follower but does not need to know the exact follower's strategy. We construct the anticipatory strategy using the notion of a *selection*, which is simply a map for selecting a particular solution to the follower's objective given the current state of the game. In particular, BGS recovers the usual bilevel program when the follower's objective admits a unique solution. By playing a BGS, the agents seek an equilibrium point for which each of their objectives ceases to vary. Provided the selection is differentiable, the equilibrium point can be characterized by a first-order optimality condition. We leverage this characterization to show that popular algorithms for bilevel optimization such as Iterative Differentiation (ITD) [5] admit fixed points that are approximately equal to the BGS's equilibrium points up to an error due to finite computational power.

We consider a general construction of the selection as the limit of a gradient flow of the follower's objective. We then show this selection to be differentiable near local minimizers provided the follower's objective satisfies a relatively mild condition that we call "*parameteric Morse-Bott property*". This generalizes the more classical *Morse-Bott property* used in differential geometry [4, 11] to the case where the function depends on additional parameters and which allows us to consider a general setting where the follower's objective is non-convex and has possibly degenerate critical points. We then characterize the differential of the selection as a solution to a linear system, which we use to introduce a simple correctional term to algorithms such as (ITD) to ensure that the fixed points obtained by these algorithms correspond exactly to the equilibrium points of a BGS problem.

2 Related Work

Unrolled optimization (ITD). is a class of methods that approximates the solution map of lower-level objective by a differentiable function obtained through successive gradient updates [5]. When the lower-level objective is strongly convex, [19] has shown these algorithms to solve a well-defined bilevel problem up to an error that can be controlled by increasing the computational budget for the approximate solution map. Our analysis suggests a simple algorithmic correction to these approaches that is applicable even when the lower-level objective is not strongly convex and which can result in solutions to a bilevel game with a constant budget for the approximate solution map.

Approximate Implicit Differentiation (AID). When the lower-level objective is strongly convex, the works of [13, 14, 33, 34] consider AID, a class of methods based on the Implicit Function theorem for approximating the solution map of the lower-level objective. These algorithms admit fixed points that match to solutions to the bilevel problem [14, 17, 18, 19]. As such, they typically require a smaller computational budget [2, 19]. The algorithmic correction that we propose for unrolled optimization can be viewed as a generalization of the AID to functions that have degenerate critical points. Our analysis obtains such a correction without using the implicit function theorem which is not applicable in the non-convex possibly degenerate setting.

Optimistic and pessimistic bilevel optimization. As discussed previously, when the lower-level objective is non-convex, the ambiguity of the problem can be resolved by optimizing the upper-level over all possible lower-level solutions [40, 45]. The *optimistic* and *pessimistic* problems arise when either minimizing or maximizing the upper-level over the lower-level solutions. In terms of algorithms, early works in [42, 43, 44] proposed to solve these problems using second-order optimization methods such as Newton's method or a smoothing method [41]. These approaches are hard to scale to the high dimensional problems arising in machine learning. Recent works considered first-order methods based on unrolled optimization [27] and interior-point methods [26] for solving optimistic bilevel problems and provided approximation guarantees. However, recent work in [39] points out that most practical applications to bilevel optimization rely on a formulation that goes beyond optimistic or pessimistic formulations. The present work departs from these approaches and instead introduces a bilevel game that is more tractable to solve. We show that popular bilevel algorithms, such as unrolled optimization, yield approximations of these games.

3 Non-Convex Bilevel Optimization with Selection

Notations. Define $\mathcal{X} = \mathbb{R}^p$ and $\mathcal{Y} = \mathbb{R}^d$ for some positive integers p and d. We consider two real valued functions f and g defined on $\mathcal{X} \times \mathcal{Y}$ and assume that g is twice-continuously differentiable.

3.1 Background on Bilevel Optimization

A bilevel program is an optimization problem where an upper-level objective f defined over a set $\mathcal{X} \times \mathcal{Y}$ of variables (x, y) is optimized in the first variable x under the constraint that the second variable y is optimal for a lower-level objective $y \mapsto g(x, y)$ depending on the upper-variable x. When $g(x, .)$ admits a unique minimizer denoted by $y^\star(x)$, which is the case if $y \mapsto g(x, y)$ is strongly convex, the bilevel problem is well-defined and can be expressed as:

$$\min_{x \in \mathcal{X}} f(x, y^\star(x)), \qquad y^\star(x) := \arg\min_{y \in \mathcal{Y}} g(x, y). \tag{BP}$$

When g is non-convex, the set of minimizers $T(x) := \arg\min_y g(x, y)$ may contain more than one element making (BP) ambiguous. A possible approach for resolving the ambiguity is to adopt a game-theoretical point of view, where a lower-level agent uses a particular strategy for selecting a solution in $T(x)$. For instance, *pessimistic* bilevel games seek a solution of

$$\textbf{(UL)}: \quad \min_{x \in \mathcal{X}} f(x, y), \qquad \text{and} \quad \textbf{(LL)}: \quad \max_{y \in \mathcal{Y}} f(x, y) \quad \text{s.t.} \quad y \in T(x), \tag{pessimistic-BG}$$

where the upper agent minimizes the upper objective f with respect to x, while the lower agent chooses a minimizer of $g(., y)$ that is adversarial with respect to f. Similarly, an *optimistic* bilevel game can be obtained by replacing maximization with minimization such that both agents cooperate. Unfortunately, while the game-theoretical point of view is highly relevant, many machine learning applications do not rely on a pessimistic/optimistic bilevel formulation. For instance, for hyper-parameter optimization, the lower agent may have access to training data, but it should not have access to the validation data processed (used in f) by the upper agent. Instead, a popular approach consists of applying algorithms designed for bilevel programs that admit unique solutions for the lower problems, even though this assumption may not hold in practice [29]. In the next section, we introduce a class of games that do not suffer from this issue and provide the first characterization of equilibrium points obtained by these previous popular approaches for non-convex problems.

3.2 Bilevel Games with Selection (BGS)

We introduce a new class of nested games for bilevel optimization with two agents, a *leader* optimizing a variable x in $\mathcal{X}$ for minimizing f, and a follower optimizing y in $\mathcal{Y}$ for minimizing g. The ambiguity problem of (BP) is solved via a *selection map*: $\phi : \mathcal{X} \times \mathcal{Y} \to \mathcal{Y}$ such that for all pair (x, y) in $\mathcal{X} \times \mathcal{Y}$, the map selects a critical point $\phi(x, y)$ of $g(x, .)$. The Bilevel Game with Selection (BGS) is then defined as the following game between the leader and follower:

$$\textbf{(UL)}: \quad \min_{x \in \mathcal{X}} \mathcal{L}_\phi(x, y) := f(x, \phi(x, y)), \qquad \textbf{(LL)}: \quad \min_{y \in \mathcal{Y}} g(x, y). \tag{BGS}$$

Before we give a more formal definition and concrete examples for ϕ, we note that (BGS) solves the ambiguity problem. Typically, $\phi(x, y)$ represents the critical point that is *selected* by an optimization strategy used by the follower (*e.g.*, the limit of a gradient flow for a gradient descent algorithm).

Definition 1 (**Selection map**). *Given a continuously differentiable function $g : \mathcal{X} \times \mathcal{Y} \to \mathbb{R}$, the map $\phi : \mathcal{X} \times \mathcal{Y} \to \mathcal{Y}$ is a selection if it satisfies the following properties for any pair $(x, y) \in \mathcal{X} \times \mathcal{Y}$:*

1. **Criticality:** *The element $\phi(x, y)$ is a critical point of $g(x, .)$, i.e. $\partial_y g(x, \phi(x, y))$.*
2. **Self-consistency:** *If y is a critical point of $g(x, .)$ i.e. $\partial_y g(x, y)$=0, then $\phi(x, y) = y$.*

We will see in Section 4, under mild assumptions on g that do not require uniqueness of the minimizers, that it is always possible to define a selection ϕ, for instance, as the limit of a continuous-time gradient flow of $y \mapsto g(x, y)$ initialized at y. The selection $\phi(x, y)$ can be viewed as a rational guess from the leader about how the follower obtains their optimal actions knowing the current state of the game (x, y). *Criticality* ensures the leader possesses a hierarchical advantage in that they know what are the optimal choices accessible to the follower. *Self-consistency* implies that the leader makes a guess that is not contradicting the current choice y of the follower. Both properties ensure that a leader using such a selection can rationally anticipate the follower's actions.

Connection to (BP). When the lower-level objective $y \mapsto g(x, y)$ admits a unique minimizer $y^\star(x)$, it is easy to check that there exists a unique selection map ϕ satisfies $\phi(x, y)$=$y^\star(x)$. Hence, (BGS) recovers the bilevel problem in (BP) as a particular case.

Connection to (pessimistic-BG) or the optimistic variant. Key differences between (BGS) and pessimistic or optimistic games is that (i) the follower has never access to the upper function f with (BGS), which matches practical hyper-parameter optimization applications where f relies on a validation dataset, whereas g relies on a distinct training set; (ii) the leader in (pessimistic-BG) does not take into account the strategy used by the follower, whereas the leader in (BGS) makes more rational choices by guessing the strategy of the follower through the selection map ϕ.

First-order equilibrium conditions. The agents can play the game (BGS) by successively taking actions (x_k, y_k) to improve their own objectives $x \mapsto \mathcal{L}_\phi(x, y_{k-1})$ and $y \mapsto g(x_k, y)$, by hoping the strategy will reach an equilibrium pair (x^*, y^*). In the case where f, g and ϕ are differentiable at (x^*, y^*), the equilibrium pair is characterized by a first-order stationary condition:

$$\partial_x \mathcal{L}_\phi(x^\star, y^\star) = \partial_x f(x^\star, y^\star) + \partial_x \phi(x^\star, y^\star) \partial_y f(x^\star, y^\star) = 0, \qquad \partial_y g(x^\star, y^\star) = 0. \tag{SC}$$

When g is smooth and strongly convex in y, the implicit function theorem [20, Theorem 5.9] ensures that ϕ is differentiable and provides an expression of $\partial_x \phi(x^\star, y^\star)$ as a solution to a linear system depending only on second-order derivatives of g at the equilibrium $(x^\star, y^\star)$. This allows to devise efficient algorithms using estimates of the gradient $\partial_x \mathcal{L}_\phi$, see, *e.g.*, [2]. However, such a theorem is not available when g is non-convex with possibly degenerate critical points without making very strong assumptions on the objective [21], which are unrealistic in machine learning. In the next section, we introduce instead a large class of functions g that admit particular selection maps arising from a gradient flow. We provide new analytical tools for studying the differentiability of such a selection w.r.t. x at equilibrium points allowing us to obtain an expression for $\partial_x \phi(x^\star, y^\star)$ that will be key for devising first-order methods for solving (BGS), as discussed in Section 5.

4 Selection Based on Gradient Flows for Parameteric Morse-Bott Functions

We will consider a particular construction for a selection $\phi(x, y)$ as the limit of a gradient flow of $g(x, .)$ when initialized at y. A fundamental question for (BGS) is the *differentiability* of $\phi(x, y)$ with respect to x, which requires to analyze the dynamics of the gradient flow. For general non-convex functions with degenerate critical points, the selection might indeed not be differentiable since a slight perturbation to the parameter x can drastically change the geometry of the set of critical points of g, causing the perturbed flow to move away from the non-perturbed one. We are therefore interested in functions g that preserve the local geometry near critical points as x varies. In Section 4.1, we introduce such a class of functions called parametric Morse-Bott functions, which covers many practical machine learning models. We then show, in Section 4.2, that the selection ϕ constructed as a limit of a gradient flow of such functions is differentiable near local minima.

4.1 Parameteric Morse-Bott Functions

We introduce parametric Morse-Bott functions, a class of parametric functions $g : \mathcal{X} \times \mathcal{Y} \to \mathbb{R}$ with parameter x in $\mathcal{X}$ extending the more familiar notion of Morse-Bott functions (Appendix A.1, [11]) to account for the effect of the parameter x on the geometry of critical points.

Definition 2 (Parametric Morse-Bott function.). *Let $g : \mathcal{X} \times \mathcal{Y}$ be a real-valued twice continuously differentiable function and define the set of* augmented critical points *$\mathcal{M}$ as follows:*

$$\mathcal{M} := \{(x, y) \in \mathcal{X} \times \mathcal{Y} \mid \partial_y g(x, y) = 0\}$$

Let $(x_0, y_0) \in \mathcal{M}$. We say that g is Morse-Bott at y_0 w.r.t. x_0, if there exists an open neighbordhood $\mathcal{V}$ of (x_0, y_0) s.t. the intersection $\mathcal{M} \cap \mathcal{V}$ is a C^2-connected sub-manifold of $\mathcal{X}\times\mathcal{Y}$ of dimension:

$$dim(\mathcal{M} \cap \mathcal{V}) = dim(\mathcal{X}) + dim\big(Ker(\partial^2_{yy} g(x_0, y_0))\big).$$

g is a parametric Morse-Bott function if for any $(x_0, y_0)\in\mathcal{M}$, g is Morse-Bott at y_0 w.r.t. x_0.

The functions in Definition 2 satisfy a condition that is stronger than simply satisfying the Morse-Bott property at any parameter value x (Definition 3 of Appendix A.1). Indeed, we show in Proposition 7 of Appendix A.2 that, for any $x_0 \in \mathcal{X}$, the function $y \mapsto g(x_0, y)$ is a Morse-Bott function, meaning that the critical set $C(x_0)$ of $y \mapsto g(x_0, .)$ near a critical point y_0 is locally a C^2 connected sub-manifold of $\mathcal{Y}$ of dimension equal to the dimension of the null-space of the Hessian $\partial^2_{yy} g(x_0, y_0)$. For conciseness, we introduce the following assumption which ensures g satisfies the condition of Definition 2 as well as possesses continuous third-order derivatives.

Assumption 1 (Parameteric Morse-Bott property). *The function g is at least three-times continuously differentiable and is a parameteric Morse-Bott function as defined in Definition 2.*

Examples of parametric Morse-Bott function. A notable class of parametric Morse-Bott functions is the one containing all twice-continuously differentiable functions that are strongly convex or, more generally, possess only non-degenerate critical points in the second variable as shown in Proposition 10 of Appendix A.2. Note that parametric Morse-Bott functions need not be convex and can have multiple (possibly degenerate) local minima, saddle-points, and local maxima.

Another class of functions, this time with possibly degenerate critical points, are those that can be expressed as a composition of some Morse-Bott function h and a family $(\tau_x)_{x\in\mathcal{X}}$ of diffeomorphisms on $\mathcal{Y}$ parameterized by x, i.e. $g(x, y)=h(\tau_x(y))$. This particular form is relevant in generative modeling where the diffeomorphisms are defined using normalizing flows of parameter x [35].

The condition in Definition 2 ensures that the degrees of freedom of the augmented critical set $\mathcal{M}$ is exactly determined by the degree of freedom of the parameter x and the degree of degeneracy of the Hessian at a critical point y. This condition is precisely what guarantees the stability of the local shape of critical points when the parameter x varies as we formalize through the next theorem.

Theorem 1 (Morse-Bott lemma with parameters). *Let g be a function satisfying Assumption 1. Let (x_0, y_0) in $\mathcal{M}$ be an augmented critical point of g. Denote by $\mathcal{K}$ the null space of the Hessian $A_0{:=}\partial^2_{yy} g(x_0, y_0)$ and by $\mathcal{K}^\perp$ its orthogonal complement in $\mathcal{Y}$. Let J_0 be a diagonal matrix with diagonal element given by the sign of the non-zero eigenvalues of A_0. Then, there exists open neighborhoods $\mathcal{U}$ and $\mathcal{V}$ of $(x_0, 0, 0)$ and (x_0, y_0) in $\mathcal{X}\times\mathcal{K}\times\mathcal{K}^\perp$ and $\mathcal{X}\times\mathcal{Y}$, and a diffeomorphism $\psi : \mathcal{U} \to \mathcal{V}$ preserving the first variable, i.e. $\psi(x, r, w)=(x, y)$ for any $(x, r, w) \in \mathcal{U}$, with $\psi(x_0, 0, 0)=(x_0, y_0)$ such that g admits the representation:*

$$g(\psi(x, r, w)) = g(\psi(x, 0, 0)) + \frac{1}{2} w^\top J_0 w, \qquad \forall (x, r, w) \in \mathcal{U}.$$

Theorem 1, which is proven in Appendix A.3, shows that, near an augmented critical point (x_0, y_0), g looks like a quadratic function up to an additive term that depends only on the parameter x. Moreover, slightly varying the parameter x, does not change the quadratic function and thus preserves the local shape near critical points. Theorem 1 is an extension of the Morse-Bott lemma [11, Theorem 2.10] to the case when there is a dependence on a parameter x. It can also be seen as an extension of the *Morse lemma with parameters* [11, Theorem 4] which allows dependence to a parameter x but requires the critical points to be non-degenerate (invertible matrix A_0). To our knowledge, Theorem 1 is the first result in the literature providing a decomposition of parametric functions with degenerate critical points into the sum of a quadratic non-degenerate term and a singular term depending only on the parameter x. We present now a corollary of Theorem 1 which is a strengthened version of the standard Łojasiewicz inequality [28] that will be essential for our subsequent analysis.

Proposition 1 (Locally Uniform Łojasiewicz gradient inequality). *Let g be a function satisfying Assumption 1 and let (x_0, y_0) be in $\mathcal{M}$ the augmented critical set defined in Definition 2. Then,*

there exists an open neighborhood $\mathcal{U}$ of (x_0, y_0) and a positive number $\mu > 0$ such that $y \mapsto g(x, y)$ is constant on the set $\mathcal{M} \cap \mathcal{U}$ with some common value $G(x) := g(x, y)$ and the following holds:

$$\mu|g(x,y) - G(x)| \leq \frac{1}{2}\|\partial_y g(x,y)\|^2, \qquad \forall (x,y) \in \mathcal{U}.$$

Proposition 1, which is proven in Appendix A.3, ensures that the Łojasiewicz gradient inequality holds uniformly on (x, y) near any augmented critical point (x_0, y_0). This result will be essential in Section 4.2 for defining a selection ϕ obtained as limits of gradient flows and to obtain a locally uniform control of these flows in the parameter x. This in turn will allow us to obtain the differentiability of the selection in the parameter x whenever $\phi(x, y)$ is a local minimum.

4.2 Smoothness of Selections Based on Gradient Flows of a Parametric Morse-Bott Function

We consider a construction for the selection ϕ in Definition 1 as a limit of a continuous-time gradient flow of g. More precisely, we define a continuous-time trajectory $(\phi_t(x, y))_{t\geq 0}$ in $\mathcal{Y}$ initialized at $\phi_0(x, y) = y$ and driven by the differential equation:

$$\frac{d\phi_t(x,y)}{dt} = -\partial_y g(x, \phi_t(x,y)). \tag{GF}$$

Provided $\phi_t(x, y)$ converges towards some element $\phi(x, y)$ as $t \to +\infty$, we can expect such a limit to satisfy both conditions of Definition 1, therefore constituting a valid selection. However, for general non-convex functions, $\phi_t(x, y)$ might not always converge [28]. To guarantee the existence and convergence of the flow, we make the following assumptions on the function g.

Assumption 2 (Smoothness). *There exists $L > 0$ such that $y \mapsto \partial_y g(x, y)$ is L-Lipschitz for any $x \in \mathcal{X}$.*

Assumption 3 (Coercivity). *For any $x \in \mathcal{X}$, if holds that $g(x, y) \to +\infty$ as $\|y\| \to +\infty$.*

The smoothness assumption in Assumption 2 is standard and guarantees the existence of the flow by the Cauchy-Lipschitz theorem. The coercivity condition in Assumption 3 guarantees that $\phi_t(x, y)$ cannot escape to infinity. It can be easily enforced by adding a small ℓ_2-penalty to a non-negative loss (such as cross-entropy or mean-squared loss) which is already a common practice in machine learning. These assumptions, along with Assumption 1 ensure that the limit $\phi(x, y)$ always exists as we summarize in the following proposition, which is proven in Appendix B.

Proposition 2. *Under Assumptions 1 to 3, and for any $(x, y) \in \mathcal{X} \times \mathcal{Y}$, the gradient flow (GF) always converges towards a critical point $\phi(x, y)$ of $y \mapsto g(x, y)$ and the map $(x, y) \mapsto \phi(x, y)$ is a selection map as defined in Definition 1. We call ϕ the* flow selection *relatively to g.*

Proposition 2 is a consequence of a general result that holds for functions satisfying a Łojasiewicz gradient inequality [3, 31] which is the case here by Proposition 1. From now on, we restrict our attention to the selection ϕ defined in Proposition 2. Even though ϕ satisfies the implicit equation $\partial_y g(x, \phi(x, y)) = 0$, we cannot rely anymore on the implicit function theorem for studying the differentiability of $\phi(x, y)$ in x since g can have degenerate critical points. Instead, we propose to characterize the differentiability of ϕ by studying the limit of $U_t(x, y) := \partial_x \phi_t(x, y)$ which is driven by a linear differential equation of the form:

$$-\frac{dU_t(x,y)}{dt} = \partial^2_{xy} g(x, \phi_t(x,y)) + U_t(x,y)\partial^2_{yy} g(x, \phi_t(x,y)). \tag{1}$$

Had we knew in advance that $\phi(x, y)$ is differentiable in x, the limit $U_\infty(x, y)$ of $U_t(x, y)$ as $t \to +\infty$, whenever defined, would be a promising candidate for the differential of $\phi(x, y)$ in x. Such a limit is indeed expected to satisfy the following linear equation:

$$0 = \partial^2_{xy} g(x, \phi(x,y)) + U_\infty(x,y)\partial^2_{yy} g(x, \phi(x,y)). \tag{2}$$

A first challenge is to ensure that U_t does not diverge. For critical points $\phi(x, y)$ that are not local minima, it is easy to see that the Hessian $\partial^2_{yy} g(x, \phi_t(x, y))$ must have a negative eigenvalue for t large enough, therefore causing the system (1) to diverge. Intuitively, unless $\phi(x, y)$ is a local minimum, there is no reason to expect $\phi(x, y)$ to be differentiable or even continuous in x, simply because $\phi(x, y)$ would be an unstable fixed-point of the flow $\phi_t(x, y)$, so that any change in x might cause a large variation in $\phi(x, y)$. The possible non-differentiability of $\phi(x, y)$ for critical points

that are not local minima is not problematic in practice, since for almost all initial conditions y of the flow $\phi_t(x, y)$, the limit $\phi(x, y)$ is guaranteed to be a local minimizer [32]. In addition, we show in Proposition 13 of Appendix B.3 that if $\phi(x_0, y)$ is a local minimum, then $\phi(x, y)$ must also be a local minimum in a neighborhood of x_0.

Nevertheless, even for local minima, if the Hessian $\partial^2_{yy} g(x, \phi(x, y))$ is non-invertible, (2) might never hold if $\partial^2_{xy} g(x, \phi(x, y))$ does not belong to the image of the Hessian. However, we show in Proposition 6 of Appendix A.2 that, for any pair (x, y) of critical points, $\partial^2_{xy} g(x, y)$ must always belong to the span of the Hessian $\partial^2_{yy} g(x, y)$ as soon as g satisfies Assumption 1, therefore ensuring that (2) admits a solution. The following theorem, which is proven in Appendix C, establishes the differentiability of ϕ at local minima and shows that $\partial_x \phi$ is exactly given by the limit U_∞.

Theorem 2 (**Differentiability of the flow selection**). *Let g be a function satisfying Assumptions 1 to 3 so that the flow selection ϕ is well-defined. Let (x_0, y_0) be in $\mathcal{X} \times \mathcal{Y}$. If $\phi(x_0, y_0)$ is a local minimizer of $y \mapsto g(x_0, y)$, then there exists a neighborhood $\mathcal{U}$ of x_0 on which $x \mapsto \phi(x, y_0)$ is differentiable with differential $\partial_x \phi(x, y_0) = U_\infty(x, y_0)$. Moreover, if y_0 is a local minimizer of $y \mapsto g(x_0, y)$, then $\partial_x \phi(x_0, y_0)$ is exactly given by:*

$$\partial_x \phi(x_0, y_0) = -\, \partial_{xy} g(x_0, y_0) (\partial_{yy} g(x_0, y_0))^\dagger, \tag{3}$$

where $\dagger$ is the pseudo inverse operator. The expression in (3) is very similar to the one that would arise by application of the implicit function theorem to a strongly convex function g. However, the proof technique does not rely on such a theorem which would not be applicable here. The key technical challenges in proving the above result are: (i) showing that $\phi(x, y)$ must be continuous at x_0 and (ii) controlling the error $\|U_t(x, y) - U_\infty(x, y)\|$ locally uniformly in x. The result follows by the application of classical uniform convergence results [36, Theorem 7.17]. The continuity of ϕ is established in Proposition 12 of Appendix B.3 and relies on a stability analysis of the flow ϕ_t performed in Appendix B.2. The uniform convergence of U_t towards U_∞ is shown in Proposition 17 of Appendix C and relies on a local uniform convergence of the flow ϕ_t towards ϕ which is proven in Proposition 14 of Appendix B.4. It is worth noting that, even though we identified $\partial_x \phi$ to be U_∞, the latter is not fully characterized by (2) as it might contain a non-zero component in the null-space of the Hessian. However, when (x_0, y_0) is an augmented critical pair of g, such a component vanishes, and $\partial_x \phi(x_0, y_0)$ is exactly determined by the minimal norm solution in (3). The latter fact has practical implications when designing algorithms for solving (BGS) as we discuss next.

5 Algorithms

5.1 Unrolled Optimization for BGS

Unrolled optimization constructs a map $\varphi_T(x, y)$ approximating a critical point of the function $y \mapsto g(x, y)$ for any fixed x by applying a finite number $T > 0$ of gradient updates starting from some initial condition y. By convention, we set $\varphi_0(x, y) = y$. Hence, φ_T can be understood as an approximation to the selection map defined in Section 4.2. We emphasize that φ_T is not a selection (Definition 1) since $\varphi_T(x, y)$ is not a critical point of g in general. Nevertheless, it provides a tractable approximation to critical points which is key for constructing practical algorithms for bilevel optimization. The gradient of $\varphi_T(x, y)$ w.r.t. x is then obtained by differentiating through the optimization steps and used to optimize the approximate upper-level objective:

$$\mathcal{L}_T(x, y) := f(x, \varphi_T(x, y)).$$

Given the k-th upper-level iterate x_k and an initial condition $\tilde{y}_k$ for the unrolled optimization, these approaches compute an approximation $y_k = \varphi_T(x_{k-1}, \tilde{y}_k)$ and find an update direction d_k for the upper-level variable x by differentiating $\mathcal{L}_T(x, \tilde{y}_k)$ in x at the current iterate x_{k-1}. The following iterate x_k is obtained by applying an update procedure, such as $x_k = x_{k-1} - \gamma d_k$ for positive small enough step-size γ. In Algorithm 1, we present several variants of these schemes, including a simple correction allowing them to solve (BGS) instead of an approximation.

The initial condition $\tilde{y}_k$ is often computed using a warm-start procedure $\tilde{y}_k{=}\mathcal{I}_M(x_{k-1}, y_{k-1})$. The simplest procedure is to set $\tilde{y}_k{=}y_{k-1}$ in which case $\mathcal{I}_0(x,y){=}y$. However, it is not uncommon to perform $M{>}0$ optimization steps to minimize the objective $y{\mapsto}g(x_{k-1}, y)$ starting from y_{k-1}. By doing so, gradient unrolling stops at $\tilde{y}_k$ and ignores the dependence of $\tilde{y}_k$ on y_{k-1}, resulting in Truncated unrolled optimization [37]. Algorithm 1 summarizes these approaches when the binary variable **AddCorrection** is set to **False**. To characterize the limit points of Algorithm 1, we make the following assumptions on $\mathcal{I}_M$, φ_T.

Algorithm 1 BGS-Opt(x_0, y_0)

Inputs: x_0, y_0,
Parameters: K, T, M , γ **AddCorrection**
for $k \in \{1, ..., K-1\}$ **do**
  $\tilde{y}_k \leftarrow \mathcal{I}_M(x_{k-1}, y_{k-1})$. # Warm-start.
  $y_k{\leftarrow}\varphi_T(x_{k-1}, \tilde{y}_k)$ # Unrolled optimization.
  $d_k \leftarrow \partial_x \mathcal{L}_T(x_{k-1}, \tilde{y}_k)$
  if AddCorrection= True then
    $v_k \leftarrow \partial_y \mathcal{L}_T(x_{k-1}, \tilde{y}_k)$
    $\xi_k{\approx} -(\partial_{yy} g(x_{k-1}, y_k))^{\dagger} v_k$ # Approx. solver
    $d_k \leftarrow d_k{+}\partial_{xy} g(x_{k-1}, y_k)\xi_k$ # Grad. correction
  end if
  $x_k \leftarrow x_{k-1} - \gamma d_k$ # Updating x
end for
Return (x_K, y_K).

Assumption 4. *For any non-negative integers $M, T \geq 0$, the maps $\mathcal{I}_M$ and φ_T are continuous on $\mathcal{X} \times \mathcal{Y}$ and take values in $\mathcal{Y}$, with φ_T being continuously differentiable. Moreover, for any $(x, y) \in \mathcal{X} \times \mathcal{Y}$ s.t. $\partial_y g(x, y){=}0$ and $M, T \geq 0$, there exists a matrix D such that:*

$$\mathcal{I}_M(x, y) = \varphi_T(x, y) = y, \quad \partial_x \varphi_T(x, y) = \partial^2_{xy} g(x, y) D, \quad \partial_y \varphi_T(x, y) = I + \partial^2_{yy} g(x, y) D.$$

Finally, for any $(x, y){\in}\mathcal{X}{\times}\mathcal{Y}$, and $M, T \geq 0$ s.t. $T + M > 0$, the equality $y{=}\varphi_T(x, \mathcal{I}_M(x, y))$ implies that y is a critical point of g, i.e. $\partial_y g(x, y) = 0$.

Assumption 5. *φ_T converges to a selection ϕ and $\partial_x \varphi_T$ converges uniformly near local minima.*

Assumption 4 is satisfied by many mappings used in practice such as T-steps of gradient descents or proximal-point algorithm, whenever g is twice-continuously differentiable and L-smooth as shown in Proposition 19 of Appendix D. Assumption 5 is a discrete-time version of the uniform convergence result in Proposition 17 of Appendix C but that we directly assume here for simplicity. Under these assumptions we show that Algorithm 1 can find equilibria of (BGS) up to an approximation error resulting from the fact that φ_T is not an exact selection.

Proposition 3. *Let M, T be non-negative numbers s.t. $M + T > 0$ and let (x_k, y_k) be the iterates of Algorithm 1 using the maps $\mathcal{I}_M$ and φ_T and without any correction, i.e.* **AddCorrection=False**. *If (x_k, y_k) is bounded, then, under Assumption 4 any limit point $(x^\star, y^\star)$ of (x_k, y_k) satisfies*

$$\partial_x \mathcal{L}_T(x^\star, y^\star) = 0, \qquad \partial_y g(x^\star, y^\star) = 0.$$

Let E_T be the set of all limit points of (x_k, y_k) for a given T. If E_T is uniformly bounded over T, then, under Assumptions 4 and 5, the elements of E_T are approximate equilibria for (BGS):

$$\sup_{(x^\star, y^\star) \in E_T} \|\partial_x \mathcal{L}_\phi(x^\star, y^\star)\| \xrightarrow[T \to +\infty]{} 0, \qquad \sup_{(x^\star, y^\star) \in E_T} \|\partial_y g(x^\star, y^\star)\| = 0, \quad (\forall T > 0).$$

Proposition 3 shows that unrolled optimization algorithms approximately solve (BGS) in the limit where the number of unrolling steps T of the φ_T goes to infinity. This result is consistent with the ones obtained in [19] for the case where g is strongly convex and illustrates the high computational cost for solving (BGS) without correcting for the bias introduced by unrolling. Next, we show how to get rid of such a bias in light of Theorem 2.

5.2 Implicit Gradient Correction

We propose to correct the bias of unrolling by exploiting the expression of the gradient $\partial_x \phi$ provided in Theorem 2. The key idea is to obtain an expression for $\partial_x \mathcal{L}_\phi(x, y)$ in terms of $\mathcal{L}_T$ and the second-order derivatives of g which holds for any local minimizer y of $y \mapsto g(x, y)$ as shown by the proposition below.

Proposition 4. *Let ϕ be the selection defined in Section 4.2 and $(x, y) \in \mathcal{X} \times \mathcal{Y}$ be s.t. y is a local minimum of $y \mapsto g(x, y)$. Then, under Assumptions 1 to 4, $\partial_x \mathcal{L}_\phi(x, y)$ is given by the equation:*

$$\partial_x \mathcal{L}_\phi(x, y) := \partial_x \mathcal{L}_T(x, y) - \partial^2_{xy} g(x, y) \big(\partial^2_{yy} g(x, y)\big)^{\dagger} \partial_y \mathcal{L}_T(x, y).$$

Proposition 4, which is proven in Appendix D, suggests a simple correction for the gradient estimate d_k in Algorithm 1. By doing so, the corrected algorithm would be performing an approximate gradient descent on each of the upper-level and lower-level objectives, suggesting that the algorithm may recover equilibrium points of (BGS) without having to increase the computation budget for the unrolling as we show later in Proposition 5. A simple way to proceed would to compute c_k satisfying the approximate equation $c_k \approx -B_k(A_k)^\dagger v_k$, where $A_k = \partial^2_{yy} g(x_{k-1}, y_k)$, $B_k := \partial^2_{xy} g(x_{k-1}, y_k)$ and $v_k = \partial_y \mathcal{L}_T(x_{k-1}, \tilde{y}_k)$. More concretely, c_k can be computed by setting $c_k = B_k \xi_k$ where ξ_k approximates the minimum norm solution to the least squares problem:

$$\xi_k \approx \arg\min_{\xi} \|\xi\|^2, \qquad s.t. \quad \xi \in \arg\min_{\xi} \|A_k \xi + v_k\|^2, \tag{4}$$

Approximate solution to (4). It is possible to solve (4) approximately using an iterative procedure by constructing N iterates ξ^t starting from $\xi^0 = 0$ and performing (conjugate) gradient descent on the quadratic objective. This can be implemented efficiently using only Hessian vector products with the Hessian A_k [29]. The constrained problem (4) can also be expressed as an unconstrained one by re-parametrizing $\xi = A_k z$:

$$\xi_k \approx A_k z_k^\star, \qquad s.t. \quad z_k^\star \in \arg\min_{z} \left\|A_k^2 z + v_k\right\|^2. \tag{5}$$

(5) has the advantage that $z_k^\star$ solves an unconstrained problem. As such, it is more amenable to applying a warm-start strategy, which can yield efficient approximation z_k to $z_k^\star$ by exploiting previously computed approximation z_{k-1} to $z_{k-1}^\star$ [2]. This strategy can be achieved using a standard iterative algorithm $\mathcal{P}$ for approximately solving the least-squares problems, such as a fixed number of conjugate gradient iterations, that takes as input the matrix A_k, vector v_k and initialization $z_{k-1} \approx z_{k-1}^\star$ and returns the next iterate $z_k \approx z_k^\star$. More formally we view $\mathcal{P}$ as a map of $(A, v, z) \mapsto \mathcal{P}(A, v, z)$ returning a vector z' and such that the only fixed points are exact solutions to the least square problem $\min_z \left\|A^2 z + v\right\|^2$. We refer to Appendix D.1 for examples of such maps. We can then define the iterates z_k and ξ_k as follows:

$$\xi_k = A_k z_k, \qquad z_k = \mathcal{P}(A_k, v_k, z_{k-1}). \tag{6}$$

The corrected algorithm is obtained by setting the variable **AddCorrection**=**True** in Algorithm 1 and computing the ξ_k using any approximate solver including, in particular, the ones based on a warm-start strategy as in (6). The following proposition, with proof in Appendix D, shows that the proposed correction indeed yields equilibrium points of (BGS).

Proposition 5. *Let (x_k, y_k) be the iterates obtained using Algorithm 1 with* **AddCorrection**=**True** *and $T + M > 0$ and assume that ξ_k are computed using (6). If (x_k, y_k) remain bounded, then, under Assumptions 1 to 4, any limit point $(x^\star, y^\star)$, is a critical point of $y \mapsto g(x^\star, y)$ and if, in addition, $y^\star$ is a local minimizer, and z_k remains bounded, then (x^*, y^*) must be an equilibrium of (BGS) satisfying: (SC):*

$$\partial_x \mathcal{L}_\phi(x^\star, y^\star) = 0, \qquad \partial_y g(x^\star, y^\star) = 0$$

Proposition 5 shows that the proposed correction allows to recover equilibria of (BGS) without having to increase the number of iterations T of the unrolled algorithm. This is by contrast with Proposition 3 where T must increase to infinity, which would be impractical. It is worth noting though that for large T, the importance of the correction diminishes, as suggested by Proposition 3, however, this comes at an increased computational cost. We discuss in Appendix D.2 how different choices for the parameters T and M recover known algorithms. In particular, that Algorithm 1 with correction allows interpolating between two families of algorithms: (ITD) and (AID) while still recovering the correct equilibria.

6 Discussion

We have introduced a bilevel game that resolves the ambiguity in bilevel optimization with non-convex objectives using the notion of selection maps. We have showed that many algorithms for bilevel optimization approximately solve these games up to a bias due to finite computational power. Our study of the differentiability properties of the selection maps has resulted in practical procedures for correcting such a bias and required the development of new analytical tools. This study opens the way for several avenues of research to understand the tradeoff between unrolling and implicit gradient correction for designing efficient algorithms. In future work, studying these algorithms in a non-smooth and stochastic setting would also be of great theoretical and practical interest.

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Checklist

The checklist follows the references. Please read the checklist guidelines carefully for information on how to answer these questions. For each question, change the default **[TODO]** to [Yes] , [No] , or [N/A] . You are strongly encouraged to include a **justification to your answer**, either by referencing the appropriate section of your paper or providing a brief inline description. Please do not modify the questions and only use the provided macros for your answers. Note that the Checklist section does not count towards the page limit. In your paper, please delete this instructions block and only keep the Checklist section heading above along with the questions/answers below.

1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes]
   (b) Did you describe the limitations of your work? [Yes]
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2. If you are including theoretical results...
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   (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [N/A]
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