
Sharp Bounds for Federated Averaging (Local SGD) and Continuous Perspective*

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Abstract

Federated Averaging (FEDAVG), also known as Local SGD, is one of the most popular algorithms in Federated Learning (FL). Despite its simplicity and popularity, the convergence rate of FEDAVG has thus far been undetermined. Even under the simplest assumptions (convex, smooth, homogeneous, and bounded covariance), the best known upper and lower bounds do not match, and it is not clear whether the existing analysis captures the capacity of the algorithm. In this work, we first resolve this question by providing a lower bound for FEDAVG that matches the existing upper bound, which shows the existing FEDAVG upper bound analysis is not improvable. Additionally, we establish a lower bound in a heterogeneous setting that nearly matches the existing upper bound. While our lower bounds show the limitations of FEDAVG, under an additional assumption of third-order smoothness, we prove more optimistic state-of-the-art convergence results in both convex and non-convex settings. Our analysis stems from a notion we call *iterate bias*, which is defined by the deviation of the expectation of the SGD trajectory from the noiseless gradient descent trajectory with the same initialization. We prove novel sharp bounds on this quantity, and show intuitively how to analyze this quantity from a Stochastic Differential Equation (SDE) perspective.

1 Introduction

Federated Learning (FL) is an emerging distributed learning paradigm in which a massive number of clients collaboratively participate in the training process without disclosing their private local data to the public [Konecny et al., 2015]. Typically, federated learning is orchestrated by a central server who oversees the clients, e.g. mobile devices or a group of organizations. The training process combines local training of a model at the clients with infrequent aggregation of the locally trained models at the central server.

Reflecting the goal of minimizing a loss function aggregated across clients, we consider the distributed optimization problem $\min F(\mathbf{x}) := \frac{1}{M} \sum_{m=1}^M F_m(\mathbf{x})$, where each client $m \in [M]$ holds a local objective F_m realized by its local data distribution \mathcal{D}_m , namely $F_m(\mathbf{x}) := \mathbb{E}_{\xi \sim \mathcal{D}_m} f(\mathbf{x}; \xi)$. Federated Learning is *heterogeneous* by design as \mathcal{D}_m can vary across clients. In the special case when $\mathcal{D}_m \equiv \mathcal{D}$ for all clients m , the problem is called *homogeneous*.

Federated Averaging (FEDAVG, McMahan et al. 2017), also known as Local SGD (Stich 2019), is one of the most popular algorithms applied in Federated Learning. In its simplest form, FEDAVG proceeds in R communication rounds, where at the beginning of each round, a central server sends the current iterate to each of the M clients. Each client then locally takes K steps of SGD, and then returns its final iterate to the central server. The central server averages these iterates to obtain the first iterate of the next round. We state the FEDAVG algorithm formally in Algorithm 1.

*Please visit <https://arxiv.org/abs/2111.03741> for the complete and latest version of this paper.

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Table 1: **Convergence Rates of FEDAVG**. Some lower order terms as $R \rightarrow \infty$ omitted. H : smoothness, R : number of rounds, K : local iterations per round, M : number of clients, σ : noise, $D : \|\mathbf{x}^{(0,0)} - \mathbf{x}^*\|$. The lower and upper bound use a slightly different metric of heterogeneity (ζ and ζ_*), see Remark 3.2 for details. We bold the terms where our analysis improves upon previous work.

	Homogeneous (Assumption 1)	Heterogeneous (Assumption 1 and 3)
Previous Upper Bound	$\frac{HD^2}{KR} + \frac{D}{\sqrt{MKR}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}}$ [Khaled et al., 2020]	$\frac{HD^2}{KR} + \frac{D}{\sqrt{MKR}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{R^{\frac{2}{3}}}$ [Khaled et al., 2020, Woodworth et al., 2020a]
Our Lower Bound	$\frac{HD^2}{KR} + \frac{D}{\sqrt{MKR}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}}$ Theorem 3.1	$\frac{HD^2}{KR} + \frac{D}{\sqrt{MKR}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{R^{\frac{2}{3}}}$ Theorem 3.3
Previous Lower Bound	$\frac{D}{\sqrt{MKR}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}}$ [Woodworth et al., 2020b]	$\frac{D}{\sqrt{MKR}} + \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}} + \min \frac{HD^2}{R}, \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{R^{\frac{2}{3}}}$ [Woodworth et al., 2020a]

Algorithm 1 Federated Averaging (FEDAVG)

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1: procedure FEDAVG ( $\mathbf{x}^{(0,0)}, \eta$ )
2: for  $r = 0, \dots, R - 1$  do
3:   on client for  $m \in [M]$  in parallel do
4:      $\mathbf{x}_m^{(r,0)} \leftarrow \mathbf{x}^{(r,0)}$  ▷ broadcast current iterate
5:     for  $k = 0, \dots, K - 1$  do
6:        $\xi_m^{(r,k)} \sim \mathcal{D}_m$ 
7:        $\mathbf{g}_m^{(r,k)} \leftarrow \nabla f(\mathbf{x}_m^{(r,k)}; \xi_m^{(r,k)})$ 
8:        $\mathbf{x}_m^{(r,k+1)} \leftarrow \mathbf{x}_m^{(r,k)} - \eta \cdot \mathbf{g}_m^{(r,k)}$  ▷ client update
    $\mathbf{x}^{(r+1,0)} \leftarrow \frac{1}{M} \sum_{m=1}^M \mathbf{x}_m^{(r,K)}$  ▷ server averaging

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While the FEDAVG algorithm is popular in practice, a thorough theoretical understanding of FEDAVG has not been established. Even under the simplest setting (convex, smooth, homogeneous and bounded covariance, see Assumption 1), the state-of-the-art upper bounds for FEDAVG due to Khaled et al. [2020] and Woodworth et al. [2020b] do not match the state-of-the-art lower bound due to Woodworth et al. [2020b], see Table 1. This suggests that at least one side of the analysis is not sharp. Therefore a fundamental question remains:

Does the current convergence analysis of FEDAVG fully capture the capacity of the algorithm?

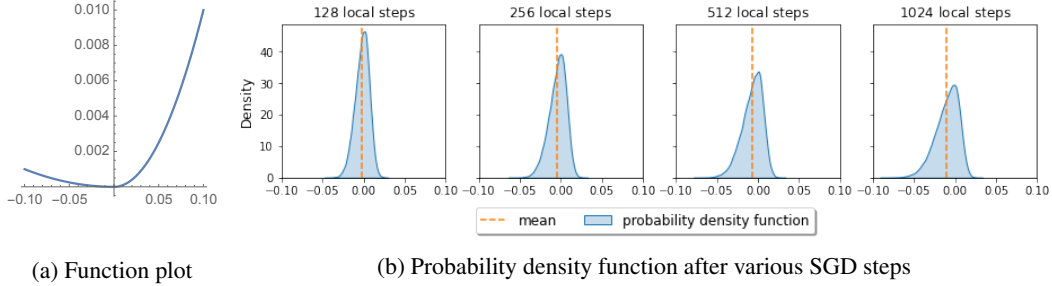
Our first contribution is to answer this question definitively under the standard smoothness and convexity assumptions. We establish a sharp lower bound for FEDAVG that matches the existing upper bound (Theorem 3.1), showing that the existing FEDAVG analysis is *not* improvable. Moreover, we establish a stronger lower bound in the *heterogeneous* setting, Theorem 3.3, which suggests the best known *heterogeneous* upper bound analysis [Khaled et al., 2020, Woodworth et al., 2020a] is also (almost)³ not improvable.

Our proofs highlight exactly what can go wrong in FEDAVG, yielding these slow convergence rates. Specifically, our lower bound analysis stems from a notion we call *iterate bias*, which is defined by the deviation of the expectation of the SGD trajectory from the (noiseless) gradient descent trajectory with the same initialization (see Definition 2.1 for details). We show that even for convex and smooth objectives, the mean of SGD initialized at the optimum can drift away from the optimum at the rate of $\Theta(\eta^2 k^{\frac{3}{2}})$ after k steps,⁴ for sufficiently small learning rate η . We depict this phenomenon in Fig. 1.⁵The iterate bias thus quantifies the fundamental difficulty encountered by FEDAVG:

³Up to a minor variation of the definition of heterogeneity measure, see Table 1.

⁴This rate is also sharp according to our matching upper and lower bounds, see Theorems 2.2 and 2.3 for details.

⁵Code see <https://github.com/hongliny/Sharp-Bounds-for-FedAvg-and-Continuous-Perspective>.



(a) Function plot (b) Probability density function after various SGD steps

Figure 1: **Illustration of the iterate bias of SGD.** Consider the objective $F(x) = \begin{cases} x^2 & x \geq 0 \\ \frac{1}{10}x^2 & x < 0 \end{cases}$ as shown in (a), and $f(x; \xi) := \xi x + F(x)$ where $\xi \sim \mathcal{N}(0, 0.01)$. We initialize the SGD at optimum $x^* = 0$, and run 1024 steps of SGD with step size 10^{-2} . We repeat this random process for 65536 times, and estimate the density function after 128, 256, 512 and 1024 steps. Observe that the density function and the average gradually move to the left (away from the optimum, where the curvature is smaller). This figure explains the intrinsic difficulty for FEDAVG to handle objective with drastic Hessian change.

Even with infinite number of homogeneous clients, FEDAVG can drift away from the optimum even if initialized at the optimum.

Indeed, we show in Section B.2 that the sharp lower bound of SGD iterate bias leads directly to our sharp lower bound of FEDAVG convergence rate.

The discouraging lower bound of FEDAVG under a standard smoothness assumption does not conform well with its empirical efficiency observed in practice [Lin et al., 2020c]. This motivates us to consider whether additional modeling assumptions could better explain the empirical performance of FEDAVG. The aforementioned lower bound is attained by a special piece-wise quadratic function with a sudden curvature change, which is smooth (has bounded second-order derivatives) but has unbounded third-order derivatives. A natural assumption to exclude this corner case is third-order smoothness, which has been considered before in the context of federated learning [Yuan and Ma, 2020], and may be representative of objectives in practice. For instance, loss functions used to learn many generalized linear models, such as logistic regression, often exhibit third-order smoothness [Hastie et al., 2009].

With this third-order smoothness assumption, we show that the iterate bias reduces to $\Theta(\eta^3 k^2)$, one order higher in η than the rate under only second-order smoothness.⁶ While the proofs for bounding the iterate bias are quite technical, we show that it is easy to analyze the bias via a continuous approach. More specifically, by studying the stochastic differential equation (SDE) corresponding to the continuous limit of SGD, one can derive the limit of the iterate bias of generic objectives by using the Kolmogorov backward equation of the SDE, see Section 2.3.

Leveraging this intuition from the bias, we prove state-of-the-art rates for FEDAVG under third-order smoothness in *both* convex and non-convex settings (Theorems 4.1 and 4.2). In non-convex settings, our convergence rate scales with $1/R^{\frac{4}{5}}$, which improves upon the best known rate of $1/R^{\frac{2}{3}}$ [Yu et al., 2019b] if we do not assume third-order smoothness.

1.1 Organization and Notation

In Section 2, we formally define the iterate bias of SGD, and state sharp bounds on its rate. In Section 3, we state our lower bounds for FEDAVG, and show how the iterate bias can be used to achieve our sharp bounds. In Section 4, we state our convergence results for FEDAVG under third-order smoothness. All proofs are deferred to the appendix.

We use bold lower case character to denote vectors (e.g., \mathbf{x}). We use $\|\cdot\|$ to denote the ℓ_2 -norm of a vector, $[n]$ to denote the set $\{1, \dots, n\}$. Throughout the paper, we use O, Ω, Θ notation to hide absolute constants only.

We defer the literature review to Section A due to space constraints.

⁶This rate is sharp according to our matching upper and lower bounds, see Theorems 2.4 and 2.5.

2 Setup and Technical Overview: Intuition From Iterate Bias of SGD

The intuition from our lower bound comes from studying the behaviour of FEDAVG when the number of clients, M , tends to infinity. In this case, the averaged iterate $\mathbf{x}^{(r+1,0)}$ is precisely the *expected* iterate after K iterations of SGD starting from the last averaged iterate, $\mathbf{x}^{(r,0)}$. This motivates the following definition.

Definition 2.1 (Iterate Bias of SGD). *Let $\{\mathbf{x}_{\text{SGD}}^{(k)}\}_{k=0}^{\infty}$ and $\{\mathbf{z}_{\text{GD}}^{(k)}\}_{k=0}^{\infty}$ be the trajectories of SGD and GD initialized at the same point \mathbf{x} , formally*

$$\begin{aligned} \mathbf{x}_{\text{SGD}}^{(k+1)} &= \mathbf{x}_{\text{SGD}}^{(k)} - \eta \nabla F(\mathbf{x}_{\text{SGD}}^{(k)}; \xi^{(k)}); & \mathbf{x}_{\text{SGD}}^{(0)} &= \mathbf{x}; \\ \mathbf{z}_{\text{GD}}^{(k+1)} &= \mathbf{z}_{\text{GD}}^{(k)} - \eta \nabla F(\mathbf{z}_{\text{GD}}^{(k)}); & \mathbf{z}_{\text{GD}}^{(0)} &= \mathbf{x}; \end{aligned}$$

*The **iterate bias** (or in short “bias”) from \mathbf{x} at the k -th step is defined as $\mathbb{E} \mathbf{x}_{\text{SGD}}^{(k)} - \mathbf{z}_{\text{GD}}^{(k)}$, the difference between the mean of SGD trajectory and the (deterministic) GD trajectory.*

One important special case of Definition 2.1 is the iterate bias from a stationary point \mathbf{x}^* . In this case, the gradient descent trajectory $\mathbf{z}_{\text{GD}}^{(k)}$ will stay at the optimum since $\nabla F(\mathbf{z}_{\text{GD}}^{(k)}) \equiv \nabla F(\mathbf{x}^*) = \mathbf{0}$. The iterate bias then reduces to $\mathbb{E}[\mathbf{x}_{\text{SGD}}^{(k)}] - \mathbf{x}^*$. Notably, even for convex smooth objectives f , the expected iterate $\mathbb{E}[\mathbf{x}_{\text{SGD}}^{(k)}]$ may drift away from the optimum \mathbf{x}^* , even if initialized at the \mathbf{x}^* . This occurs because of a difference between the gradient of the expectation of an iterate, $\nabla f(\mathbb{E}[\cdot])$, and the expectation of the gradient of the iterate, $\mathbb{E}[\nabla f(\cdot)]$.

In Fig. 1, we illustrate this phenomenon via a one-dimensional objective. This figure, and our formal results below, illustrate that for sufficiently small step sizes, the bias increases in k . For this reason, doing more than one local step can sometimes be counterproductive (when $k = 1$, the bias is always zero). This phenomenon is key to the poor dependence on K in the convergence rate we prove for FEDAVG.

2.1 The Bias Under Second-Order Smoothness

In this subsection, we provide sharp bounds on the iterate bias under standard assumptions, formally given below.

Assumption 1. *Assume $f(\mathbf{x}; \xi)$ is second-order differentiable w.r.t. \mathbf{x} , and*

- (a) *Convexity: $f(\mathbf{x}; \xi)$ is convex with respect to \mathbf{x} for any ξ .*
- (b) *Smoothness: $f(\mathbf{x}; \xi)$ is H -smooth with respect to \mathbf{x} . That is, for any ξ , for any \mathbf{x}, \mathbf{y} , we have $\|\nabla f(\mathbf{x}; \xi) - \nabla f(\mathbf{y}; \xi)\|_2 \leq H\|\mathbf{x} - \mathbf{y}\|_2$.*
- (c) *Bounded covariance: for any \mathbf{x} , $\mathbb{E}_{\xi \sim \mathcal{D}} \|\nabla f(\mathbf{x}, \xi) - \nabla F(\mathbf{x})\|_2^2 \leq \sigma^2$.*

We establish the following upper bound on the bias.⁷

Theorem 2.2 (Simplified from Theorem C.1). *Under Assumption 1, there exists an absolute constant \bar{c} such that for any initialization \mathbf{x} , for any $\eta \leq \frac{1}{H}$, the iterate bias satisfies $\left\| \mathbb{E} \mathbf{x}_{\text{SGD}}^{(k)} - \mathbf{z}_{\text{GD}}^{(k)} \right\|_2 \leq \bar{c} \cdot \eta^2 k^{\frac{3}{2}} H \sigma$.*

In fact, we show in the following theorem that this upper bound of iterate bias is sharp.

Theorem 2.3 (Simplified from Theorem C.2). *There exists an absolute constant \underline{c} such that for any H, σ , there exists an objective $f(\mathbf{x}; \xi)$ and distribution $\xi \sim \mathcal{D}$ satisfying Assumption 1 such that for any integer K , for any $\eta \leq \frac{1}{2KH}$, and integer $k \in [2, K]$, the iterate bias from the optimum \mathbf{x}^* of F is lower bounded as $\left\| \mathbb{E} \mathbf{x}_{\text{SGD}}^{(k)} - \mathbf{z}_{\text{GD}}^{(k)} \right\|_2 \geq \underline{c} \cdot \eta^2 k^{\frac{3}{2}} H \sigma$.*

Theorem 2.3 shows that the SGD trajectory can indeed drift away (in expectation) from the optimum \mathbf{x}^* despite being initialized at \mathbf{x}^* . Our lower bound improves over the best known lower bound

⁷Throughout this section, we mainly focus on the iterate bias bound in the regime of sufficiently small η for simplicity and easy comparison. Our complete theorem in appendix covers the case of general η choice.

$\Omega(\eta^2 k H \sigma)$ due to Woodworth et al. [2020b]. The lower bound is attained by running SGD with Gaussian noise on the piecewise quadratic function $f(x) := \begin{cases} \frac{1}{2} H x^2 & x \geq 0, \\ \frac{1}{4} H x^2 & x < 0. \end{cases}$, first analyzed in Woodworth et al. [2020b].

Recall that the bias originates from the difference between $\nabla f(\mathbb{E}[\mathbf{x}_{\text{SGD}}^{(k)}])$ and $\mathbb{E}[\nabla f(\mathbf{x}_{\text{SGD}}^{(k)})]$. This piecewise quadratic function has an unbounded third order derivative at 0, which causes this difference to be large whenever the distribution of $\mathbf{x}_{\text{SGD}}^{(k)}$ spans both sides of 0. This worst case construction motivates our further study of the bias under a third-order derivative bound.

2.2 The Bias Under Third-Order Smoothness

We formally state our third-order smoothness condition in the following assumption.

Assumption 2. Assume $f(\mathbf{x}; \xi)$ is third-order differentiable w.r.t. \mathbf{x} for any ξ , and

- (a) $f(\mathbf{x}; \xi)$ is Q -3rd-order-smooth, i.e. for any ξ , for any \mathbf{x}, \mathbf{y} , $\|\nabla^2 f(\mathbf{x}; \xi) - \nabla^2 f(\mathbf{y}; \xi)\|_2 \leq Q \|\mathbf{x} - \mathbf{y}\|_2$.
- (b) $\nabla f(\mathbf{x}, \xi)$ has σ^4 -bounded 4th order central moment, i.e. for all \mathbf{x} , $\mathbb{E}_\xi \left[\|\nabla f(\mathbf{x}, \xi) - \nabla F(\mathbf{x})\|^4 \right] \leq \sigma^4$.

We show that under this additional assumption, the iterate bias reduces to $O(\eta^3 k^2 Q \sigma^2)$, which scales on the order of η^3 (rather than η^2) as η goes to 0.

Theorem 2.4 (Simplified from Theorem C.3). Under Assumptions 1 and 2, there exists an absolute constant \bar{c} such that for any initialization \mathbf{x} , for any $\eta \leq \frac{1}{2H}$, the iterate bias satisfies $\left\| \mathbb{E} \mathbf{x}_{\text{SGD}}^{(k)} - \mathbf{z}_{\text{GD}}^{(k)} \right\|_2 \leq \bar{c} \cdot \eta^3 k^2 Q \sigma^2$.

Theorem 2.4 also reveals the dependency on the third-order smoothness Q . In the extreme case where $Q = 0$ (f is quadratic), the iterate bias will disappear. It is worth noting that since Assumption 1 is still required in Theorem 2.4, the original upper bound $O(\eta^2 k^{\frac{3}{2}} H \sigma)$ from Theorem 2.2 still applies, and one can formulate the upper bound as the minimum of the two.

The following lower bound shows that the upper bound in Theorem 2.4 is sharp.

Theorem 2.5 (Simplified from Theorem C.4). There exists an absolute constant \underline{c} such that for any H, σ, K , for any sufficiently small Q (polynomially dependent on H, σ, K), there exists an objective $f(\mathbf{x}; \xi)$ and distribution $\xi \sim \mathcal{D}$ satisfying Assumptions 1 and 2 such that for any $\eta \leq \frac{1}{2HK}$ and integer $k \in [2, K]$, the iterate bias from the optimum \mathbf{x}^* is lower bounded as $\left\| \mathbb{E} \mathbf{x}_{\text{SGD}}^{(k)} - \mathbf{z}_{\text{GD}}^{(k)} \right\|_2 \geq \underline{c} \cdot \eta^3 k^2 Q \sigma^2$.

2.3 Revealing Iterate Bias Via Continuous Perspective

While the proofs of the results above are quite technical, the intuition for these bounds is much easier to see in a continuous view of SGD. As an example, we demonstrate how the $\Theta(\eta^3 k^2 Q \sigma^2)$ term shows up in Theorems 2.4 and 2.5.

Consider a one-dimensional instance of SGD with Gaussian noise, where $f(x; \xi) = F(x) - \xi x$, and $\xi \sim \mathcal{N}(0, \sigma^2)$. The SGD then follows

$$\mathbf{x}_{\text{SGD}}^{(k+1)} = \mathbf{x}_{\text{SGD}}^{(k)} - \eta F(\mathbf{x}_{\text{SGD}}^{(k)}) + \eta \xi^{(k)}; \text{ where } \xi^{(k)} \sim \mathcal{N}(0, \sigma^2); \quad (2.1)$$

The continuous limit of (2.1) corresponds to the following SDE, with the scaling $t = \eta k$:

$$dX(t) = -F'(X(t))dt + \sigma dB_t; \quad (2.2)$$

where B_t denotes the Brownian motion (also known as the Wiener process).⁸

⁸To justify the relation of Eq. (2.1) and Eq. (2.2), note that Eq. (2.1) can be viewed as a numerical discretization (Euler-Maruyama discretization [Kloeden and Platen, 1992]) of the SDE (2.2) with time step-size η .

To get a handle of the iterate bias, our goal is to study $E[X(t) | X(0) = x]$, the expectation of the SDE solution $X(t)$ initialized at x . We view this quantity as a multivariate function $u(t; x)$ of t and x , with the objective to Taylor expand $u(t; x)$ around $(0; x)$ in t :

$$u(t; x) = u(0; x) + u_t(0; x)t + \frac{1}{2}u_{tt}(0; x)t^2 + o(t^2):$$

For brevity, we use subscript notation to denote partial derivatives u_{t_i} etc. The relationship of $u(t; x)$ and the SDE (2.2) is established by the Kolmogorov backward equation as follows.

Claim 2.6 (Kolmogorov backward equation [Øksendal, 2003]) Let $u(t; x) = E[X(t) | X(0) = x]$, then $u(t; x)$ satisfies the following partial differential equation:

$$u_t = F_x u_x + \frac{1}{2} u_{xx} \sigma^2; \quad \text{with } u(0; x) = x. \quad (2.3)$$

Using this claim, we can compute the first two derivatives of $u(t; x)$ in t , as follows:

Lemma 2.7. Suppose $u(t; x)$ satisfies the PDE (2.3), then $u_t(0; x) = F_x$; $u_{tt}(0; x) = F_x F_{xx} + \frac{1}{2} F_{xxx} \sigma^2$.

With Lemma 2.7 we can expand $u(t; x)$ around $(0; x)$:

$$u(t; x) = x + F_x t + \frac{1}{2} F_x F_{xx} t^2 + \frac{1}{2} F_{xxx} \sigma^2 t^2 + o(t^2):$$

Ignoring higher order terms in the term $\frac{1}{2} F_{xxx} \sigma^2 t^2$ reflects the difference between the noiseless GD trajectory from x and $E[X(t) | X(0) = x]$, that is, the iterate bias. Converting back to the discrete trajectory (Eq. (2.1)) via the scaling $t = k$, we obtain

$$E[X_{SGD}^{(k)}] - z_{GD}^{(k)} = \frac{1}{2} \sigma^2 k^2 F_{xxx}(x):$$

When the third derivative of F is bounded by Q , this recovers the upper bound $O(\sigma^2 k^2 Q)$ in Theorem 2.4. The lower bound of Theorem 2.5 follows by choosing a function with third derivative Q at x^* .

3 Lower Bound Results

In this section, we present our lower bounds for FEDAVG in both convex homogeneous and heterogeneous settings, and discuss its implications. We then show how we use the lower bound on the bias of SGD from Section 2 to establish a lower bound on the convergence of FEDAVG.

Our main result for the homogeneous setting is the following theorem.

Theorem 3.1 (Lower bound for homogeneous FEDAVG (see Theorem D.1)) For any $K \geq 2, R, M, \rho$, and D , there exists $\delta(x^*; \rho)$ and distribution D satisfying Assumption 1 with optimum x^* , such that for some initialization $x^{(0;0)}$ with $\|x^{(0;0)} - x^*\|_2 < D$, the final iterate of FEDAVG with any step size satisfies:

$$E \|F(x^{(R;0)}) - F(x^*)\| \geq \frac{HD^2}{KR} + \rho \frac{D}{MKR} + \min \left(\rho \frac{D}{KR}; \frac{H \frac{1}{3} \frac{\sigma^2}{3} D \frac{4}{3}}{K \frac{1}{3} R \frac{2}{3}} \right):$$

This lower bound matches the best upper bound given by the theorem 2 of [Woodworth et al., 2020b].

We extend our results to FEDAVG in the heterogeneous setting. Recall that in this setting, we allow each client m to draw from its own distribution D_m . We prove our results under the following assumption on heterogeneity of the gradient at the optimum.

Assumption 3 (Bounded gradient heterogeneity at optimum) $\sum_{m=1}^M \kappa_r F_m(x^*) \kappa_2^2 \leq \rho$:

Remark 3.2. While the right measure of heterogeneity is a subject of significant debate in the FL community, the most popular are either a bound on gradient heterogeneity (as Assumption 3), or a stronger assumption of uniform gradient heterogeneity: for any x , $\sum_{m=1}^M \kappa_r F_m(x) \kappa_2^2 \leq \rho$. The best-known lower bound, due to Woodworth et al. [2020a], considers the weaker Assumption 3. We remark however that most upper bounds use the stronger uniform assumption (e.g., [Khaled et al., 2020]).

Theorem 3.3 (Lower bound for heterogeneous FEDAVG (see Theorem D.1)) For any $K \geq 2$; R, M, H, D, σ , and ϵ , there exist $(x; \gamma)$ and distributions $\mathcal{D}_m, \mathcal{G}$, each satisfying Assumption 1, and together satisfying Assumption 3, such that for some initialization $(x^{(0:0)}, \gamma^{(0)})$ with $\|x^{(0:0)} - x^*\|_2 < D$, the final iterate of FEDAVG with any step size satisfies:

$$\mathbb{E} \|F(x^{(R;0)}) - F(x^*)\| \leq \frac{HD^2}{KR} + \frac{D}{M} + \min \left(\frac{D}{KR}; \frac{H^{\frac{1}{3}} D^{\frac{2}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}} \right) + \min \left(\frac{\sigma^2}{H}; \frac{H^{\frac{1}{3}} D^{\frac{2}{3}}}{R^{\frac{2}{3}}} \right)$$

Theorem 3.3 is nearly tight, up to a difference in the definitions of heterogeneity (See Remark 3.2). We compare our result to existing lower bounds and upper bounds in Table 1.

4 Upper Bounds for FEDAVG Under Third-Order Smoothness

In light of the limitations of FEDAVG discussed in Section 3, it is natural to ask if there are additional assumptions under which FEDAVG may perform better. Several classes of additional assumptions have been suggested for studying the performance of FEDAVG. Perhaps the most common, and the one supported from our intuition on the bias, is an assumption of third-order smoothness, stated formally in Assumption 2. Previously it has been shown that under such an assumption, FEDAVG may converge faster. We present several state-of-the-art bounds for FEDAVG under Assumption 2, including for the non-convex case.

Theorem 4.1 (Upper bound for FEDAVG under 3rd order smoothness (see Theorem E.5)) Suppose $f(x; \gamma)$ satisfies Assumptions 1 and Assumptions 2. Then for some step size, FEDAVG satisfies

$$\mathbb{E} \|k^r f(x^*)\|_2^2 \leq O \left(\frac{HB}{KR} + \frac{D}{M} + \frac{B^{\frac{4}{5}} G^{\frac{4}{5}} Q^{\frac{2}{5}}}{K^{\frac{2}{5}} R^{\frac{4}{5}}} \right)$$

where $x^* := \frac{1}{M} \sum_m x_m^{(r,k)}$ for a random choice of $k \in [K]$, and $r \in [R]$, and $B := F(x^{(0:0)}) - \inf_x F(x)$.

In the non-convex setting, as is standard in the FL literature [Stich, 2019, Yu et al., 2019b, Reddi et al., 2021], we require an assumption bounding moments of the stochastic gradients. Note that this is stronger than Assumption 1 which bounds variance of the stochastic gradients.

Assumption 4 (Bounded gradients) For any x , we have $\mathbb{E} \|k^r f(x; \gamma)\|_2^4 \leq G^4$.

Theorem 4.2 (Upper bound for FEDAVG with non-Convex objectives under third-order smoothness, see Theorem E.2) Suppose $F(x)$ is H -smooth and $(x; \gamma)$ satisfies Assumptions 2 and 4. Then for some step size, we have

$$\mathbb{E} \|k^r f(x^*)\|_2^2 \leq O \left(\frac{HB}{KR} + \frac{D}{M} + \frac{B^{\frac{4}{5}} G^{\frac{4}{5}} Q^{\frac{2}{5}}}{R^{\frac{4}{5}}} \right);$$

where $x^* := \frac{1}{M} \sum_m x_m^{(r,k)}$ for a random choice of $k \in [K]$, and $r \in [R]$, and $B := F(x^{(0:0)}) - \inf_x F(x)$.

This theorem shows that the convergence rate of FEDAVG improves substantially under third order smoothness. In comparison, the best known rate for FEDAVG with non-convex objectives (under second-order smoothness alone) is $\frac{HB}{KR} + \frac{D}{M} + \frac{B^{\frac{2}{3}} G^{\frac{2}{3}} H^{\frac{2}{3}}}{R^{\frac{2}{3}}}$, due to Yu et al. [2019b]. Observe that we improve the dependence from $R^{\frac{2}{3}}$ in the third term to $R^{\frac{4}{5}}$.

5 Conclusion

In this work we provided sharp lower bounds for homogeneous and heterogeneous FEDAVG that matches the existing upper bound. By solving this open problem, we highlight the obstacles to FEDAVG, and show how a third-order smoothness assumption can lead to faster convergence. We expect the proposed techniques can shed light on the analysis of other federated algorithms and aid design of more efficient federated algorithms.

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A Related Work

FEDAVG Analysis. The understanding of local update algorithms such as FEDAVG is one of the most important topics in distributed optimization. The first upper bound of FEDAVG (with multiple averaging rounds) was established by Stich [2019] in the convex homogeneous setting, and was later improved by Khaled et al. [2020], Woodworth et al. [2020b]. In the convex heterogeneous setting, the first upper bound of FEDAVG is due to Li et al. [2020c], and was later improved by Khaled et al. [2020], Woodworth et al. [2020a]. For non-convex objectives, a series of recent works (e.g. Yu and Jin 2019, Yu et al. 2019a) has established upper bounds of FEDAVG in various settings.

Under only convexity and second-order smoothness, FEDAVG is known to be outperformed by the naive single-machine SGD or minibatch SGD algorithm [Woodworth et al., 2021], whose accelerated variant achieves the minimax rate for distributed optimization in this setting. To reveal the advantages of FEDAVG, a series of work has studied its convergence under stronger assumptions, yielding improved rates. Woodworth et al. [2020b] considered FEDAVG in the special case of quadratic objectives, while Yuan and Ma [2020] and Dieuleveut and Patel [2019] considered third-order smoothness assumptions. Other assumptions have been suggested for settings, see the discussion in Woodworth [2021].

The existence and effect of iterate bias has been observed in various forms in the current literature [Dieuleveut et al., 2020, Charles and Kong, 2020, Woodworth et al., 2020b], yet our paper is the

rst to sharply characterize the rate of the bias, both in the second-order smooth case and third-order smooth case.

Other Extensions of FEDAVG. Throughout this work, we study the simplest form of FEDAVG (Algorithm 1) to keep our efforts focused. There are many other extensions of FEDAVG applied in practice. For example, instead of letting all the clients to participate in computation, one may randomly draw a subset of clients to participate every round. Most of our results (e.g., all of the homogeneous results) can be directly extended to this sub-sampling variant. Other variants of FEDAVG include letting clients run different number of steps per round, or average the client states nonuniformly. We refer readers to Wang et al. [2021] for a more comprehensive survey of these extensions.

One special extension of FEDAVG introduces a “server learning rate”, which we name FEDAVG-SLR to distinguish it. Instead of taking the client averaging as the initialization of the next round, FEDAVG-SLR extrapolates (or interpolates) between the round initialization and the clients averaging [Charles and Koenig, 2020, Reddi et al., 2021], or formally $x^{(r+1;0)} = x^{(r;0)} + \eta_s \frac{1}{M} \sum_{m=1}^M x_m^{(r;K)}$. By definition, FEDAVG-SLR reduces to the classic FEDAVG when $\eta_s = 1$. Notably, FEDAVG-SLR also reduces to mini-batch SGD when the client learning rate goes to 0, and the server learning rate goes to infinity. Therefore, FEDAVG-SLR can at least attain the best convergence rate of the classic FEDAVG and the mini-batch SGD. However, to the best of our knowledge, it is not known whether FEDAVG-SLR can outperform the best of the two, and there are no results that characterize FEDAVG-SLR beyond the two special regimes. While our lower bounds do not apply to the generic form of FEDAVG-SLR, we anticipate that our techniques (e.g., iterate bias) can be applicable to the study of FEDAVG-SLR in the future work.

Other Federated Learning Algorithms. Besides the FEDAVG framework, there are many other federated optimization algorithms that aims to improve communication efficiency [Yuan and Ma, 2020, Reddi et al., 2021] or tackle the heterogeneity in FL [Li et al., 2020b, Karimireddy et al., 2020]. We expect the techniques developed in this work can shed light on the analysis of broader existing federated algorithms and promote the design of more efficient federated algorithms. We refer readers to Kairouz et al. [2019], Wang et al. [2021] for a comprehensive survey of the recent progress in Federated Learning.

Connection to Implicit Bias. It is possible to view the iterate bias as an implicit bias of the FEDAVG algorithm, which pushes the iterate towards flatter regions of the objective. This effect is similar to other instances of implicit bias observed for stochastic gradient descent, which has drawn connections between noise in the gradients and flat minima [Hochreiter and Schmidhuber, 1997, Jastrzebski et al., 2017, Blanc et al., 2020, Damian et al., 2021]. While in many instances, implicit bias has been linked to choosing favorable optima that generalize well [Neyshabur, 2017], in our setting, the bias affects the convergence rate.

Federated Learning. The past half decade has witnessed a booming interest in various aspects of Federated Learning. Data heterogeneity is one of the most important patterns in Federated Learning, and is known to cause performance degradation in practice [Hsu et al., 2019]. Numerous existing works have aimed to understand and mitigate the negative effect of heterogeneity in various ways [Mohri et al., 2019, Liang et al., 2019, Chen et al., 2020, Deng et al., 2020, Li et al., 2020a, Reisizadeh et al., 2020, Wang et al., 2019, Pathak and Wainwright, 2020, Zhang et al., 2020, Yuan et al., 2021b, Acar et al., 2021, Al-Shedivat et al., 2021, Yuan et al., 2021a]. In practice, the system heterogeneity will also affect the performance of Federated Learning [Smith et al., 2017, Diao et al., 2021]. In deep learning context, a recent array of works has studied the alternative approaches of model ensembling beyond averaging in parameter space [Bistriz et al., 2020, He et al., 2020, Lin et al., 2020b, Chen and Chao, 2021, Yoon et al., 2021].

This paper mainly considers the classic FL settings in which the same model is learned from and deployed to all the clients. There is an alternative setup in FL, known as personalized setting, which aims to learn a different (personalized) model for different clients. Numerous recent papers have proposed Federated Learning models and algorithms to accommodate personalization [Smith et al., 2017, Jiang et al., 2019, Chen et al., 2019, Fallah et al., 2020, Hanzely et al., 2020, London, 2020, T. Dinh et al., 2020, Hanzely and Richtárik, 2020, Agarwal et al., 2020, Lin et al., 2020a, Deng et al., 2020]. We anticipate the techniques developed in this work can be applied to personalized FL algorithms, especially the ones that applied local updates approach.

We refer readers to [Kairouz et al., 2019, Wang et al., 2021] for a more comprehensive survey on the recent progress of Federated Learning.

History of FEDAVG analysis. The understanding of local updates algorithm such as FEDAVG is one of the most important topics in distributed optimization. The early analysis of FEDAVG preceded the proposal of Federated Learning, typically under the name of Local SGD or parallel SGD [McDonald et al., 2009, Zinkevich et al., 2010, Shamir and Srebro, 2014, Rosenblatt and Nadler, 2016, Jain et al., 2018, Zhou and Cong, 2018]. The primary focus of this literature is the special case of one-shot averaging, in which only one round of averaging (communication) is conducted at the end of the algorithm. The first upper bound of FEDAVG (with multiple averaging rounds) was established by Stich [2019] in the convex homogeneous setting, which imposes uniform gradient bound assumption. The result was further improved by Khaled et al. [2020], Woodworth et al. [2020b] with improved rates and relaxed assumptions. In the convex heterogeneous setting, the first upper bound of FEDAVG is due to Li et al. [2020c]. This result was improved by Khaled et al. [2020], Woodworth et al. [2020a]. For non-convex objectives, a series of recent works [Zhou and Cong, 2018, Haddadpour et al., 2019, Wang and Joshi, 2018, Yu and Jin, 2019, Yu et al., 2019a] has established various upper bounds of FEDAVG in homogeneous and heterogeneous settings. On the lower bound side, the best known result for convex FEDAVG is established by Woodworth et al. [2020b] (for homogeneous) and Woodworth et al. [2020a] (for heterogeneous). To the best of our knowledge, we are unaware of any lower bound for FEDAVG in non-convex settings.

B More on Lower Bound Results

B.1 Interpretation of Theorem 3.3

To better understand the convergence rates in the Theorems above, first observe that the first two terms in both rates $\frac{HD^2}{KR} + \rho \frac{D}{MKR}$ is familiar from the standard SGD convergence rate. The term $\frac{HD^2}{KR}$ corresponds to the deterministic convergence, which appears even when there is no noise. The term $\rho \frac{D}{MKR}$ is a standard statistical noise term that applies to any algorithm which accesses total stochastic gradients.

The third term in both theorems $\frac{H^{\frac{1}{3}} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}}$ depends on the variance of the noise, and arises due to the iterate bias of SGD. This term appears even in the homogeneous setting where all clients access the same distribution. Our main contribution is proving the appearance of this term in the lower bound. The previous best lower bound, due to Woodworth et al. [2020b], achieved in comparison the term $\frac{H^{\frac{1}{3}} D^{\frac{4}{3}}}{K^{\frac{2}{3}} R^{\frac{2}{3}}}$, which is a factor of $K^{\frac{1}{3}}$ weaker. We expand on how we achieve this term in subsection B.2.

The last term of Theorem 3.3, $\frac{H^{\frac{1}{3}} D^{\frac{4}{3}}}{R^{\frac{2}{3}}}$ is due to another bias that scales with the heterogeneity of the data among the clients. In comparison, the best known lower bound on the dependence on the heterogeneity is $\min \left\{ \frac{HD^2}{R}, \frac{H^{\frac{1}{3}} D^{\frac{4}{3}}}{R^{\frac{2}{3}}} \right\}$. Note that as R becomes large, the minimum is achieved by $\frac{HD^2}{R}$, yielding a significantly weaker lower bound which doesn't depend at all on the heterogeneity.

Our lower bound shows that under only and assumption of second order smoothness and convexity (Assumptions 1) FEDAVG may achieve a rate as slow as $\frac{1}{3} R^{-\frac{2}{3}}$. Prior work has pointed out that this rate can be beat by alternative algorithms that use the same (or less) communication and gradient computation. One such algorithm is minibatch SGD, which replaces the K iterations of local SGD at each client with a single iteration. This results in the same outcome as K iterations of SGD with minibatch size M . A second such algorithm is single-machine SGD, which ignores all but one client, and results in the same outcome as K iterations of SGD. Under Assumption 1, the best of these two algorithms (minibatch SGD and single-machine SGD) achieves a rate of

$$\frac{HD^2}{KR} + \rho \frac{D}{MKR} + \min \left\{ \frac{HD^2}{R}; \rho \frac{D}{KR} \right\} :$$

It turns out that this rate always dominates the the sharp rate we have shown for FEDAVG. Further, when ρ and K are large, this rate is dominated by $\frac{HD^2}{R}$, while the rate of FEDAVG is dominated by

$\frac{H^{\frac{1}{3}} D^{\frac{2}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}}$. In this regime, the rate of this “naive” algorithm may improve on the rate of FedAVG by a factor of $\frac{R^2 H^2}{K}$.

B.2 Constructing Lower Bound from Iterate Bias

In this subsection, we theoretically establish the relationship between the iterate bias (Definition 2.1) and the lower bound on the function error of FedAVG.

Recall that in Theorem 2.3, we proved a lower bound on bias from the optimum which came from analyzing SGD with Gaussian noise on the piecewise quadratic function, which we abbreviate “ $f(x)$ ”:

$$f(x) = \begin{cases} \frac{1}{2} H x^2 & x \geq 0; \\ \frac{1}{4} H x^2 & x < 0; \end{cases}$$

where $N(0, 1)$.

To construct our lower bound, we show that this same bias, persists more generally from any x which is not too far from the optimum $x^* = 0$. Loosely speaking, we can achieve this same bias whenever a constant fraction of the mass of the iterate $x_{\text{SGD}}^{(k)}$ lies on each side of x^* . Since the variance of $x_{\text{SGD}}^{(k)}$ is on the order of $\frac{1}{2k}$, we can prove that the bias from x will continue at the rate given Theorem 2.3 from any x with $|x| \geq \frac{1}{\sqrt{2k}}$. In fact, we can extend this observation to the case when the initial iterate $x_{\text{SGD}}^{(0)}$ is a random variable, and its expectation is bounded, yielding the following lemma:

Lemma B.1 (Simplified from Lemma D.3) If $\frac{1}{2k} \geq \frac{1}{2kH}$, then there exist constants c_1 and c_2 such that for any random variable x with $E[x]^2 \leq c_1 k^{-2}$ and $E[x] \geq 0$, we have

$$E_{x_{\text{SGD}}^{(k)}} [x_{\text{SGD}}^{(k)}] \geq E_{x_{\text{SGD}}^{(0)}} [x_{\text{SGD}}^{(0)}] - c_2 \frac{1}{2kH}$$

Directly applying Lemma B.1, we can show that the expectation of the FedAVG iterate $x^{(r,0)}$ moves in the negative direction each round:

$$E[x^{(r+1,0)}] \leq (1 - \frac{1}{2kH})^r E[x^{(r,0)}] - c_2 \frac{1}{2kH}; \quad (\text{B.1})$$

so long as $\frac{1}{2kH} \geq \frac{1}{c_1 k}$ and $E[x^{(r,0)}] \geq 0$.

Of course, when $E[x^{(r,0)}]$ becomes too negative, the force of the gradient in the positive direction exceeds the negative bias. Once this occurs, we are in the “mixing” regime. One can check from Eq. (B.1) that this occurs roughly when $E[x^{(r,0)}] \leq -\frac{1}{2kH}$. Combining these observations, we obtain the following lemma, stated to include the more general case when $\frac{1}{2kH} < \frac{1}{c_1 k}$.

Lemma B.2. There exists a universal constant c such that for $\frac{1}{2kH} \geq \frac{1}{c_1 k}$, if $x^{(0,0)} = 0$, then $E[f(x^{(R,0)})] \leq \frac{c^2}{4} \min(R, \frac{1}{2kH})^3$.

With this bound on the function error of the step function, proving our lower bound for the homogeneous case follows by considering the function f used in the lower bound construction of Woodworth et al. [2020b]. We state this function fully in the appendix.

Our lower bound for the heterogeneous setting is similar, but involves the following additional ingredient:

Lemma B.3. Consider FedAVG with M clients with

$$f^{(3)}(x; (\gamma_1; \gamma_2)) = \begin{cases} Hx^2 & x \geq \gamma_1 = 1; \\ \frac{H}{2} x^2 & x \geq \gamma_1 = 2; \end{cases}$$

and for all the odd $m \in [M]$, we have $(\gamma_1; \gamma_2) = (1; \gamma_2)$ always, while for all the even $m \in [M]$ we have $(\gamma_1; \gamma_2) = (2; \gamma_2)$. There exists a universal constant c such that for $\frac{1}{2kH} \geq \frac{1}{c_1 k}$, if $x^{(0,0)} = 0$, then FedAVG with R rounds and K steps per round results in

$$x^{(R,0)} \leq \frac{c}{H} \min(1; HK; (HK)^2 R)$$

⁹For simplicity, in this section we focus on the regime where $\frac{1}{2kH} \geq \frac{1}{c_1 k}$, though our proofs in the Appendix we consider any $O(\frac{1}{H})$.

The functions studied in this lemma appear in the heterogeneous lower bound construction in [Woodworth et al. \[2020a\]](#), but the analysis we give in this lemma is much tighter than theirs.

C Formal Theorems and Proofs on the Bounds of Iterate Bias

In this section, we list and prove the complete theorems on the lower and upper bounds of iterate bias discussed in Section 2.

C.1 Formal Theorems Statement

Theorem C.1 (Upper bound of iterate bias under second-order smoothness, complete version of Theorem 2.2) Assume $F(x) := \mathbb{E} f(x; \cdot)$ satisfies Assumption 1. Let $\{x_{\text{SGD}}^{(k)}\}_{k=0}^n$ be the trajectory of SGD initialized at $x_{\text{SGD}}^{(0)} = x$, and $\{z_{\text{GD}}^{(k)}\}_{k=0}^n$ be the trajectory of GD initialized at $z_{\text{GD}}^{(0)} = x$, namely

$$x_{\text{SGD}}^{(k+1)} := x_{\text{SGD}}^{(k)} - \eta \nabla f(x_{\text{SGD}}^{(k)}; \cdot^{(k)}); \quad z_{\text{GD}}^{(k+1)} := z_{\text{GD}}^{(k)} - \eta \nabla F(z_{\text{GD}}^{(k)}); \quad \text{for } k = 0; 1; \dots;$$

Then for any $\frac{1}{H}$, the following inequality holds

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 \leq \min\{4^{-2} k^{\frac{3}{2}} H; k^{\frac{1}{2}} \eta\} \quad (\text{C.1})$$

The proof of Theorem C.1 is provided in Section C.2.

Theorem C.2 (Lower bound of iterate bias under second-order smoothness, complete version of Theorem 2.3) For any $H; \eta; K$, there exists a function $f(x; \cdot)$ and a distribution D satisfying Assumption 1 such that for any $\frac{1}{2H}$, for any $k < K$ the following iterate bias inequality holds for SGD and GD initialized at the optimum

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 \geq 0.002 \min\{k^{\frac{3}{2}} H; \frac{1}{2} H \eta^{\frac{1}{2}}\}.$$

Theorem C.2 is proved in Section D.2 as a special case of Lemma D.8, by taking θ to be the optimum.

Theorem C.3 (Upper bound of iterate bias under third-order smoothness, complete version of Theorem 2.4) Assume $F(x) := \mathbb{E} f(x; \cdot)$ satisfies Assumptions 1 and 2. Let $\{x_{\text{SGD}}^{(k)}\}_{k=0}^n$ be the trajectory of SGD initialized at $x_{\text{SGD}}^{(0)} = x$, and $\{z_{\text{GD}}^{(k)}\}_{k=0}^n$ be the trajectory of GD initialized at $z_{\text{GD}}^{(0)} = x$, namely

$$x_{\text{SGD}}^{(k+1)} := x_{\text{SGD}}^{(k)} - \eta \nabla f(x_{\text{SGD}}^{(k)}; \cdot^{(k)}); \quad z_{\text{GD}}^{(k+1)} := z_{\text{GD}}^{(k)} - \eta \nabla F(z_{\text{GD}}^{(k)}); \quad \text{for } k = 0; 1; \dots;$$

Then for any $\frac{1}{H}$, the following inequality holds

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 \leq \min\left\{\frac{1}{4} k^3 Q^2; 4^{-2} k^{\frac{3}{2}} H; k^{\frac{1}{2}} \eta\right\}.$$

The proof of Theorem C.3 is provided in Section C.3.

Theorem C.4 (Lower bound of iterate bias under third-order smoothness, complete version of Theorem 2.5) For any $H; \eta; K$, for any $Q \leq \frac{H^2}{12K}$, there exists a function $f(x; \cdot)$ and a distribution D satisfying Assumptions 1 and 2 such that for any $\frac{1}{2H}$, for any $k < K$, the following iterate bias inequality holds for SGD and GD initialized at the optimum

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 \geq 0.005 k^3 Q^2 \min\left\{\frac{k-1}{H}; k(k-1)\right\}. \quad (\text{C.2})$$

The proof of Theorem C.4 is provided in Section C.4.

C.2 Proof of Theorem C.1: Upper Bound of Iterate Bias Under 2nd-Order Smoothness

The proof of Theorem C.1 is based on the following two lemmas: Lemmas C.5 and C.6.

Lemma C.5. Under the same settings of Theorem C.1, for any $\frac{1}{H}$, the following inequality holds

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 \leq \frac{(1+H)^k}{H} \leq 2^k H k^{\frac{1}{2}} :$$

Proof of Lemma C.5 By definition of $x_{\text{SGD}}^{(k+1)}$ and $z_{\text{GD}}^{(k+1)}$ we obtain

$$\begin{aligned} \mathbb{E} \|x_{\text{SGD}}^{(k+1)} - z_{\text{GD}}^{(k+1)}\|_2^2 &= \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)} - \eta \nabla F(x_{\text{SGD}}^{(k)}) + \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 \\ &= \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + \mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 : \end{aligned}$$

Now we seek an upper bound for $\mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2$. Observe that

$$\begin{aligned} &\mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 \\ &\leq \mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 \quad (\text{Jensen's inequality}) \\ &\leq H \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 \quad (\text{by } H\text{-smoothness of } F) \\ &\leq H \left(\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + \mathbb{E} \|x_{\text{SGD}}^{(k)} - x_{\text{SGD}}^{(k)}\|_2^2 \right) \quad (\text{by triangle inequality}) \\ &\leq H \left(\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + \mathbb{E} \|x_{\text{SGD}}^{(k)} - x_{\text{SGD}}^{(k)}\|_2^2 \right) : \quad (\text{by Holder's inequality}) \end{aligned}$$

By standard convex stochastic analysis (e.g. [Khaled et al., 2020]) one can show that $\mathbb{E} \|x_{\text{SGD}}^{(k)} - x_{\text{SGD}}^{(k)}\|_2^2 \leq 2^k k^2$. Consequently

$$\mathbb{E} \|x_{\text{SGD}}^{(k+1)} - z_{\text{GD}}^{(k+1)}\|_2^2 \leq (1+H) \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + 2^k H k^{\frac{1}{2}} : \quad (\text{C.3})$$

Telescoping Eq. (C.3) completes the proof. \square

Lemma C.6. Under the same settings of Theorem C.1, or any $\frac{1}{H}$, the following inequality holds

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 \leq k^{\frac{1}{2}} :$$

Proof of Lemma C.6 By definition of $x_{\text{SGD}}^{(k+1)}$ and $z_{\text{GD}}^{(k+1)}$ we obtain

$$\begin{aligned} \mathbb{E} \|x_{\text{SGD}}^{(k+1)} - z_{\text{GD}}^{(k+1)}\|_2^2 &= \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)} - \eta \nabla f(x_{\text{SGD}}^{(k)}) + \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 \\ &= \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)} - \eta \nabla F(x_{\text{SGD}}^{(k)}) + \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 + \mathbb{E} \|\eta \nabla f(x_{\text{SGD}}^{(k)}) - \eta \nabla F(x_{\text{SGD}}^{(k)})\|_2^2 : \\ &\quad (\text{by independence and } \sigma^2\text{-bounded covariance}) \end{aligned}$$

Note that

$$\begin{aligned} &\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)} - \eta \nabla F(x_{\text{SGD}}^{(k)}) + \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 \\ &= \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + \mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla F(z_{\text{GD}}^{(k)})\|_2^2 + \mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla f(x_{\text{SGD}}^{(k)})\|_2^2 \\ &\leq \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + \frac{2}{H} \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + \mathbb{E} \|\eta \nabla F(x_{\text{SGD}}^{(k)}) - \eta \nabla f(x_{\text{SGD}}^{(k)})\|_2^2 \quad (\text{by convexity and } H\text{-smoothness}) \\ &\leq \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 : \quad (\text{since } \frac{2}{H}) \end{aligned}$$

Therefore

$$\mathbb{E} \|x_{\text{SGD}}^{(k+1)} - z_{\text{GD}}^{(k+1)}\|_2^2 = \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 + 2\epsilon^2;$$

Telescoping yields

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^2 \leq 2k\epsilon^2;$$

and thus by Jensen's inequality and Holder's inequality

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 = \mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^r \frac{1}{\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2^{2-r}} \leq k^{\frac{1}{2}};$$

□

With Lemmas C.5 and C.6 at hands we are ready to prove Theorem C.1.

Proof of Theorem C.1 We consider the case of $\frac{1}{\text{HK}} \leq \epsilon$ and $\epsilon > \frac{1}{\text{HK}}$ separately. In either case we have $\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 \leq k^{\frac{1}{2}}$ by Lemma C.6.

If $\epsilon \leq \frac{1}{\text{HK}}$, by Lemma C.5, we have

$$\mathbb{E} \|x_{\text{SGD}}^{(k)} - z_{\text{GD}}^{(k)}\|_2 \leq \frac{(1 + H)^k}{H} \frac{1}{2} \epsilon^2 \text{HK}^{\frac{1}{2}} \leq \frac{e^{\text{HK}}}{H} \frac{1}{2} \epsilon^2 \text{HK}^{\frac{1}{2}} \leq 4 \epsilon^2 \text{HK}^{\frac{3}{2}};$$

where the last inequality is due to $e^{\text{HK}} \leq 1 + 2\text{HK}$ since $\text{HK} \leq 1$. Therefore Eq. (C.1) is satisfied.

If $\epsilon > \frac{1}{\text{HK}}$, then $k^{\frac{1}{2}} \leq 2\text{HK}^{\frac{3}{2}}$. Hence Eq. (C.1) is also satisfied. □

C.3 Proof of Theorem C.3: Upper Bound of Iterate Bias Under 3rd-order Smoothness

The proof of Theorem C.3 is based on the following lemma.

Lemma C.7. Consider the same settings of Theorem C.3. For any i , let $u^{(k)}$ be a vector-valued function

$$u^{(k)}(x) = \mathbb{E} \|x_{\text{SGD}}^{(k)} - x^{(0)}\|_2 = x^{(i)};$$

Then the following results hold.

- (a) For any k , $u^{(k+1)}(x) = \mathbb{E} \|u^{(k)}(x) - \text{r f}(x; \cdot)\|_2$.
- (b) For any k , $Du^{(k+1)}(x) = \mathbb{E} \|Du^{(k)}(x) - \text{r f}(x; \cdot)\|_2$. Here D denotes the Jacobian operator.
- (c) For any k , $\sup_x \|Du^{(k)}(x)\|_2 \leq 1$.
- (d) For any k , $\sup_x \|D^2u^{(k)}(x)\|_2 \leq kQ$.
- (e) For any k , $\|u^{(k+1)}(x) - u^{(k)}(x) - \text{r F}(x)\|_2 \leq \frac{1}{2} 3kQ^2$.

Proof of Lemma C.7. (a) Holds by time-homogeneity of the SGD sequence as

$$\begin{aligned} u^{(k+1)}(x) &= \mathbb{E} \|x_{\text{SGD}}^{(k+1)} - x^{(0)}\|_2 = \mathbb{E} \mathbb{E} \|x_{\text{SGD}}^{(k+1)} - x_{\text{SGD}}^{(1)}\|_2 = \mathbb{E} \mathbb{E} \|x_{\text{SGD}}^{(k)} - \text{r f}(x; \cdot)\|_2 \\ &= \mathbb{E} \mathbb{E} \|x_{\text{SGD}}^{(k)} - x_{\text{SGD}}^{(0)}\|_2 = \mathbb{E} \|u^{(k)}(x) - \text{r f}(x; \cdot)\|_2; \end{aligned}$$

(b) Holds by taking derivative on both sides of (a). Indeed, for any $i \in [d]$, one has

$$\text{r } u_i^{(k+1)}(x) = \mathbb{E} \text{r } u_i^{(k)}(x) - \text{r f}_i(x; \cdot);$$

where $u_i^{(k)}$ denotes the i -th coordinate of the vector-valued function $u^{(k)}$.

(c) By (b) one has

$$\|Du^{(k+1)}(x) - Du^{(k)}(x)\| \leq \frac{L}{H} \|r^2 f(x; \cdot) - r^2 f(x; \cdot)\|$$

Since $f(x; \cdot)$ is convex and H -smooth w.r.t. x , and $\frac{1}{H}$, one has $\sup_x \|r^2 f(x; \cdot) - r^2 f(x; \cdot)\| \leq 1$. Therefore

$$\sup_x \|Du^{(k+1)}(x) - Du^{(k)}(x)\| \leq \frac{L}{H}$$

By definition of $u^{(0)}(x) = Du^{(0)}(x) = I$. Telescoping the above inequality yields (c).

(d) Taking twice derivatives w.r.t. on both sides of (a) gives (for any)

$$r^2 u_i^{(k+1)}(x) = E \left(\|r^2 f(x; \cdot)\| r^2 u_i^{(k)}(x) + (r^2 f(x; \cdot))' r^3 f(x; \cdot) [r u_i^{(k)}(x) - r f(x; \cdot)] \right)$$

Therefore

$$\sup_x \|D^2 u^{(k+1)}(x)\| \leq \sup_x \|D^2 u^{(k)}(x)\| + \sup_x \|r^2 f(x; \cdot)\| + \sup_x \|r^3 f(x; \cdot)\| \sup_x \|Du^{(k)}(x)\|$$

Since $f(x; \cdot)$ is convex and H -smooth w.r.t. x and $\frac{1}{H}$, one has $\sup_x \|r^2 f(x; \cdot)\| \leq 1$. Also by (c), we arrive at

$$\sup_x \|D^2 u^{(k+1)}(x)\| \leq \sup_x \|D^2 u^{(k)}(x)\| + Q$$

Telescoping from 0 to k yields (d).

(e) By (a)

$$\begin{aligned} \|u^{(k+1)}(x) - u^{(k)}(x)\| &= E \|u^{(k)}(x) - r F(x)\| \\ &= E \|u^{(k)}(x) - r f(x; \cdot) - (r f(x; \cdot) - r F(x))\| \\ &\leq E \|u^{(k)}(x) - r f(x; \cdot)\| + E \|r f(x; \cdot) - r F(x)\| \\ &\leq \frac{1}{2} \sup_x \|D^2 u^{(k)}(x)\| \|r f(x; \cdot) - r F(x)\| + \frac{1}{2} \|r f(x; \cdot) - r F(x)\|^2 \\ &\leq \frac{1}{2} k Q^2 = \frac{1}{2} 3^k Q^2. \end{aligned}$$

□

We are now ready to finish the proof of Theorem C.3.

Proof of Theorem C.3 By Lemma C.7(e), for any $2 \leq j \leq k$

$$\|u^{(k-j)}(z_{GD}^{(j)}) - u^{(k-j-1)}(z_{GD}^{(j+1)})\| \leq \frac{1}{2} 3^{k-j-1} Q^2$$

Consequently

$$E \|z_{GD}^{(k)} - z_{GD}^{(0)}\| \leq \|u^{(k)}(z_{GD}^{(0)}) - u^{(0)}(z_{GD}^{(k)})\| + \sum_{j=0}^{k-1} \|u^{(k-j)}(z_{GD}^{(j)}) - u^{(k-j-1)}(z_{GD}^{(j+1)})\| \leq \frac{1}{4} 3^k Q^2.$$

□

C.4 Proof of Theorem C.4: Lower Bound of Iterate Bias Under 3rd-order Smoothness

Before we state the proof of Theorem C.4, let us first describe the following helper function used to construct the lower bound instance. Define

$$\psi(x) = \int_0^x \log(\cosh(x)) dx; \quad (\text{C.4})$$

In the following lemma, we show that this $\psi(x)$ satisfies the following properties

Lemma C.8. The following properties hold for the $\psi(x)$ defined in Eq.(C.4).

- (a) $\psi'(x) = \log(\cosh(x))$. Therefore $\psi'(x) \leq x$. In particular $\psi'(0) = 0$.
- (b) $\psi''(x) = \tanh(x)$. In particular $\psi''(0) = 0$, $\lim_{x \rightarrow +\infty} \psi''(x) = 1$, $\lim_{x \rightarrow -\infty} \psi''(x) = -1$, and $\psi''(x) \in [-1, 1]$ for any $x \in \mathbb{R}$.
- (c) $\psi'''(x) = \text{sech}^2(x)$. In particular $\psi'''(0) = 1$, $\lim_{x \rightarrow +\infty} \psi'''(x) = 0$, $\lim_{x \rightarrow -\infty} \psi'''(x) = 0$, and $\psi'''(x) \in [0, 1]$ for any $x \in \mathbb{R}$. Also $\psi'''(x) \geq \frac{1}{2}$ for any $x \in [-\frac{1}{2}, \frac{1}{2}]$.
- (d) $\psi^{(4)}(x) = -2 \text{sech}^2(x) \tanh(x)$. In particular $\psi^{(4)}(x) \in (-1, 1)$ for any $x \in \mathbb{R}$.

Proof of Lemma C.8 All results follow by standard trigonometry analysis. \square

Next we establish the following lemma

Lemma C.9. Consider

$$f(x; \theta) = \frac{3}{8} H x^2 + \frac{H^3}{64 Q^2} \psi\left(\frac{4Q}{H} x + \theta\right); \quad F(x) := \mathbb{E}_{U \in [-\frac{1}{2}, \frac{1}{2}]} f(x; \theta); \quad (\text{C.5})$$

where ψ is defined in Eq.(C.4). Then

- (a) $f^{(0)}(x; \theta) = F^{(0)}(x) = \frac{3}{4} H + \frac{1}{4} H \psi''\left(\frac{4Q}{H} x + \theta\right)$. Therefore $F^{(0)}(x) \in [\frac{1}{2} H, H]$ for any $x \in \mathbb{R}$.
- (b) $f^{(000)}(x; \theta) = F^{(000)}(x) = Q \psi'''(\frac{4Q}{H} x + \theta)$. Therefore $F^{(000)}(x) \in [0, Q]$ for any $x \in \mathbb{R}$. In particular $F^{(000)}(0) = Q$, and $F^{(000)}(x) \geq \frac{1}{2} Q$ for any $x \in [-\frac{H}{8Q}, \frac{H}{8Q}]$.
- (c) $f(x; \theta)$ satisfies Assumptions 1 and 2.

Proof of Lemma C.9(a,b) follow from Lemma C.8. (c) follows by (a, b) and the fact that the variance of $U \in [-\frac{1}{2}, \frac{1}{2}]$ is $\frac{1}{3}$. \square

The following lemma studies the SGD trajectory defined in Eq. (C.5).

Lemma C.10. Let $\{x_{\text{SGD}}^{(k)}\}_{k=0}^{\infty}$ be the SGD trajectory on the function defined in Eq.(C.5), with learning rate η , that is

$$x_{\text{SGD}}^{(k+1)} = x_{\text{SGD}}^{(k)} - \eta \nabla f(x_{\text{SGD}}^{(k)}; \theta^{(k)}); \quad \theta^{(k)} \in U \left[-\frac{1}{2}, \frac{1}{2}\right];$$

Define

$$u_k(x) := \mathbb{E}[x_{\text{SGD}}^{(k)} | x_{\text{SGD}}^{(0)} = x];$$

Then the following results hold

- (a) $u_{k+1}(x) = \mathbb{E}[u_k(x - \eta \nabla f(x; \theta))]$
- (b) $u_{k+1}^0(x) = \mathbb{E}[(1 - \eta F^{(0)}(x)) u_k^0(x - \eta \nabla f(x; \theta))]$.
- (c) $u_{k+1}^{000}(x) = \mathbb{E}[(1 - \eta F^{(0)}(x))^2 u_k^{000}(x - \eta \nabla f(x; \theta)) - \eta F^{(000)}(x) u_k^0(x - \eta \nabla f(x; \theta))]$.
- (d) For any k , $\inf_x f u_k^0(x) \geq (1 - \eta H)^k$ holds.
- (e) For any k , $\sup_x f u_k^{000}(x) \leq 0$.

(f) For any $x \in \mathbb{R}$ and k , it is the case that $u_{k+1}^{00}(x) = (1 - H)^2 E [u_k^{00}(x - F^0(x; \cdot))] - (1 - H) F^{00}(x)$.

Proof of Lemma C.10. (a) Proved in Lemma C.7(a).

(b) Proved in Lemma C.7(b).

(c) Holds by taking derivative with respect to x on both sides of (b).

(d) Since $F^0(x) \in [\frac{1}{2}H; H]$, by (b), we have

$$\inf_x u_{k+1}^0(x) - (1 - H) \inf_x u_k^0(x) \geq 0$$

By definition of u_0 we have $u_0(x) = x$ and thus $u_0^0(x) = 1$. Telescoping the above inequality gives (d).

(e) We prove by induction. For $k = 0$ we have $u_0^0(x) = 0$ which clearly satisfies (e). Now assume (e) holds for the case k and we study the case $k+1$.

Since $F^0(x) \in [\frac{1}{2}H; H]$ and $F^{00}(x) = 0$, by (c) and (d), we have

$$\sup_x u_{k+1}^{00}(x) - (1 - H)^2 \sup_x u_k^{00}(x) - \inf_x F^{00}(x) (1 - H)^k = 0,$$

completing the induction.

(f) Holds by (c-e).

□

We further have the following lemma.

Lemma C.11. Under the same setting of Lemma C.10, the following results hold.

(a) For any $x \in [\frac{H}{8Q}; \frac{H}{8Q}]$ and k ,

$$u_{k+1}^{00}(x) - (1 - H)^2 \sup_{z \in [x - \frac{H}{8Q}; x + \frac{H}{8Q}]} f u_k^{00}(z) \geq (1 - H) \frac{Q}{2}$$

(b) Assuming $Q \geq \frac{H}{24K}$, then for any $k < K$, the following inequality holds

$$\sup_{x \in [\frac{H}{12Q}; \frac{H}{12Q}]} u_k^{00}(x) \leq \sum_{j=0}^{k-1} (1 - H)^{2j+1} \frac{Q}{2}$$

(c) Assuming $\frac{1}{2H} \leq Q \leq \frac{H}{24K}$, then for any $k < K$, for any $x \in [\frac{H}{24Q}; \frac{H}{24Q}]$, one has

$$u_{k+1}(x) - u_k(x - F^0(x)) \geq \frac{1}{12} \sum_{j=0}^{k-1} (1 - H)^{2j+1} \frac{Q}{2}$$

Proof of Lemma C.11. (a) Holds by (f) and the fact that $f^0(x; \cdot) = F^0(x)$ and $\inf_{x \in [\frac{H}{8Q}; \frac{H}{8Q}]} F^{00}(x) = \frac{Q}{2}$.

(b) Since $\frac{H}{12Q} + K \leq \frac{H}{8Q}$ (due to the assumption that $Q \geq \frac{H}{24K}$), we can repeatedly apply (a) for K times. Therefore

$$\begin{aligned} & \sup_{x \in [\frac{H}{12Q}; \frac{H}{12Q}]} f u_k^{00}(x) \\ & \leq (1 - H)^2 \sup_{x \in [\frac{H}{12Q}; \frac{H}{12Q}]} f u_{k-1}^{00}(x) \geq (1 - H) \frac{Q}{2} \\ & \leq (1 - H)^{2k} \sup_{x \in [\frac{H}{12Q}; \frac{H}{12Q}]} f u_0^{00}(x) \leq \sum_{j=0}^{k-1} (1 - H)^{2j+1} (1 - H) \frac{Q}{2} \end{aligned}$$

Plugging in $u_0^0(x) = 0$ gives (b).

(c) By Lemma C.10(a),

$$\begin{aligned}
 u_{k+1}(x) - u_k(x; F^0(x)) &= E[u_k(x; f^0(x; \cdot)) - u_k(x; F^0(x))] \\
 &= E[u_k^0(x; F^0(x)) - (f^0(x; \cdot) - F^0(x)) + \frac{1}{2} \sup_{z \in [x - F^0(x), x + F^0(x)]} u^{00}(z) - \frac{1}{2} (f^0(x; \cdot) - F^0(x))^2] \\
 &\leq \frac{1}{6} \sup_{z \in [x - F^0(x), x + F^0(x)]} u^{00}(z)
 \end{aligned}$$

Since $x \in [\frac{H}{24Q}, \frac{H}{24Q}]$, we know that $F^0(x) \in [\frac{H}{24Q}, \frac{H}{24Q}]$ by construction of F . Since $Q \geq \frac{H}{24K}$ we know that $[x - F^0(x), x + F^0(x)] \subset [\frac{H}{12Q}, \frac{H}{12Q}]$. Therefore (b) is applicable, which suggests

$$u_{k+1}(x) - u_k(x; F^0(x)) \leq \frac{1}{12} \sum_{j=0}^{k-1} (1 - H)^{2j+1};$$

□

We are ready to finish the proof of Theorem C.4 now.

Proof of Theorem C.4 For $k = 1$ the bound trivially holds. From now on assume $k \geq 2$.

Consider the one-dimensional instance defined in Eq. (C.5). The optimum of $f = E[f(x; \cdot)]$ is clearly 0. We will actually show a stronger result that Eq. (C.2) holds for $x \in [\frac{H}{24Q}, \frac{H}{24Q}]$, in addition to 0.

Since $\frac{1}{2H} \leq \frac{1}{24Q}$, for any $x \in [\frac{H}{24Q}, \frac{H}{24Q}]$, one has $F^0(x) \in [\frac{H}{24Q}, \frac{H}{24Q}]$. Therefore one can repeatedly apply Lemma C.11(c), which yields

$$E[x_{SGD}^{(k)}] - z_{GD}^{(k)} \leq \frac{1}{12} \sum_{j=0}^{k-1} \sum_{i=0}^{j-1} (1 - H)^{2i+1};$$

If $k \leq \frac{1}{H}$ then

$$\sum_{j=1}^k \sum_{i=0}^{j-1} (1 - H)^{2i+1} \leq k(k-1)(1 - H)^{2k-3} \leq k(k-1) \leq \frac{1}{k} \leq \frac{1}{e^2} k(k-1) \leq \frac{k(k-1)}{16};$$

If $k > \frac{1}{H}$ then

$$\sum_{j=1}^k \sum_{i=0}^{j-1} (1 - H)^{2i+1} = \frac{(1 - H)((1 - H)^{2k} + H(2 - H)k - 1)}{2H^2(2 - H)^2} \leq \frac{\frac{3}{2} Hk - 1}{8 - 2H^2} \leq \frac{Hk}{16 - 2H^2} \leq \frac{k - 1}{16H};$$

where in the second from the last inequality we used the assumption that $\frac{1}{2}$. In either case we have

$$\sum_{j=1}^k \sum_{i=0}^{j-1} (1 - H)^{2i+1} \leq \min\left\{\frac{k-1}{16H}, \frac{1}{16}k(k-1)\right\};$$

and hence

$$E[x_{SGD}^{(k)}] - z_{GD}^{(k)} \leq 0.005 \sum_{j=0}^{k-1} (k-1) \min\left\{\frac{1}{H}, k\right\};$$

□

D Proof of Theorems 3.1 and 3.3: Lower Bounds of FEDAVG Under 2nd-Order Smoothness

The main objective of this section is to prove the following Theorem, which implies both Theorems 3.1 and 3.3.

Theorem D.1. For any $K \geq 2; R; M, H, D, \epsilon$, and α , there exist $(x; \sigma)$ and distributions \mathcal{D}_m , each satisfying Assumption 1, and together satisfying Assumption 3, such that for some initialization $x^{(0;0)}$ with $\|x^{(0;0)} - x^*\|_2 < D$, the n -th iterate of FEDAVG with any step size satisfies:

$$\mathbb{E} [F(x^{(R;0)})] - F(x^*) \leq \frac{HD^2}{KR} + \frac{D}{MKR} + \min \left(\frac{D}{KR}; \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{K^{\frac{1}{3}} R^{\frac{2}{3}}} \right) + \min \left(\frac{2}{H}; \frac{H^{\frac{1}{3}} \frac{2}{3} D^{\frac{4}{3}}}{R^{\frac{2}{3}}} \right) \cdot \epsilon$$

In particular, if $\epsilon = 0$, then it is possible to choose all distributions \mathcal{D}_m to be the same distribution \mathcal{D} .

Remark D.2. Note that $\epsilon = 0$ does not necessarily imply that the distributions are homogeneous. Hence for this theorem to imply Theorem 3.1, we ensure that in the case where $\epsilon = 0$, all of the distributions \mathcal{D}_m are equal.

In Section D.1, we provide a high level overview of the proof techniques of this theorem in the homogeneous case. The main technical lemmas from this overview are proved in Sections D.2 and D.3. In Section D.4, we provide the additional technical lemmas for the heterogeneous case. Finally, we finish the proof of Theorem D.1 in Section D.5.

D.1 Proof Overview of Theorem D.1 in Homogeneous Case

To prove the lower bound in Theorem D.1 for the homogeneous case, we construct the following function.

$$f(x; \sigma) = f_1(x_1; \sigma) + f_2(x_2) + f_3(x_3); \tag{D.1}$$

where

$$f_1(x; \sigma) = \frac{L}{2} (x) + x; \quad f_2(x) = x^2; \quad f_3(x) = Hx^2;$$

and where

$$(x) := \begin{cases} \frac{1}{2}x^2 & x < 0 \\ x^2 & x \geq 0 \end{cases}$$

$N \in (0; \frac{1}{2}]; L = H=6$, and σ is some function of $K; R; D; H$, and ϵ .

We will analyze the convergence of FEDAVG starting at $x^{(0;0)} = (0; D=2; D=2)$ such that the initial distance to optimum $\|x^{(0;0)} - x^*\|_2 < D$. Observe that the only noise is Gaussian noise in the gradient of the first coordinate.

The sole objective of including f_3 is to ensure that we can limit our analysis to cases with small step size, α . Indeed, by standard arguments, if $\alpha > \frac{1}{H}$, then the third coordinate of x would diverge.

The role of the function f_2 is to provide a direction (the x_2 -axis) in which f is only slightly convex. Indeed, this term requires that σ is sufficiently large for convergence, which we formalize in Lemma D.16.

The novelty in our analysis stems from our sharp analysis of the $\mathbb{E} [F(x^{(R;0)})]$ from running SGD on the piecewise quadratic function, pictured in Figure 2.

Our main technique is comparing the iterates $x^{(0)}; x^{(1)}; \dots$ from running SGD on the piecewise quadratic function $f_1(x; \sigma)$ to the iterates $y^{(k)}$ and $z^{(k)}$ obtained from running SGD on the quadratic functions

$$f_l(x; \sigma) := \frac{L}{4}x^2 + x; \quad \text{and} \quad f_u(x; \sigma) := \frac{L}{2}x^2 + x;$$

respectively. We will show in Lemma D.7 that $x^{(0)} = y^{(0)} = z^{(0)}$, then the iterate $x^{(k)}$ is first-order stochastically dominated by both $y^{(k)}$ and $z^{(k)}$ (see Definition D.6 for the formal definition).

(a) (b) (c)

Figure 2: The piecewise quadratic function and its first two derivatives.

of first-order stochastic dominance). Fortunately, the iterates $y^{(k)}$ and $z^{(k)}$ are easy to analyze. A straightforward calculation in Lemma D.5 yields the closed form solutions

$$y^{(k)} = y^{(0)} + N(0; \frac{2}{y}); \quad \text{and} \quad z^{(k)} = z^{(0)} + N(0; \frac{2}{z});$$

where

$$\frac{2}{y} := 1 - L; \quad \frac{2}{z} := 1 - L; \quad \frac{2}{y} := \frac{2 - 2(1 - \frac{k}{y})}{1 - \frac{k}{y}}; \quad \frac{2}{z} := \frac{2 - 2(1 - \frac{k}{z})}{1 - \frac{k}{z}}; \quad (\text{D.2})$$

We can then bound the expectation of $x^{(k)}$ in the following way:

$$E[x^{(k)}] = \int_{c=1}^{Z_0} \Pr[x^{(k)} \leq c] + \int_{c=0}^{Z_1} \Pr[x^{(k)} \leq c] = \int_{c=1}^{Z_0} \Pr[y^{(k)} \leq c] + \int_{c=0}^{Z_1} \Pr[z^{(k)} \leq c];$$

This decomposition means that the higher variance of $y^{(k)}$ contributes to the negative term, while the relatively lower variance of $z^{(k)}$ contributes to the positive term.

To give some intuition, consider the case where $x^{(0)} = y^{(0)} = z^{(0)} = 0$, and $Lk \ll 1$. Here we have $y^{(k)} \sim N(0; \frac{2}{y})$ and $z^{(k)} \sim N(0; \frac{2}{z})$. Plugging in the cdf of a Gaussian, we obtain

$$\int_{c=1}^{Z_0} \Pr[y^{(k)} \leq c] + \int_{c=0}^{Z_1} \Pr[z^{(k)} \leq c] = \Phi\left(\frac{y}{2}\right) + \Phi\left(\frac{z}{2}\right);$$

Using the fact that $Lk \ll 1$, we can approximate

$$\frac{2}{y} \frac{2 - 2(Lk = 2 + (Lk)^2 = 8)}{L = 2} = 2 - 2k(1 - Lk = 4);$$

and

$$\frac{2}{z} \frac{2 - 2(Lk = 2 + (Lk)^2 = 2)}{L} = 2 - 2k(1 - Lk = 2);$$

such that

$$E[x^{(k)}] = \Phi\left(\frac{y}{2}\right) + \Phi\left(\frac{z}{2}\right) - \frac{p}{2} \frac{Lk}{8};$$

When $x^{(0)}$ is non-zero but sufficiently small, we can prove that this same negative iterate bias occurs in the expectation $E[x^{(k)}] - x^{(0)}$. With slightly more effort, we can show that so long as the expectation $E[x^{(0)}]$ is sufficiently small, there is a negative drift $E[x^{(k)}] - E[x^{(0)}]$.

We formalize these observations in the following lemma. Note that this lemma also captures the case when $Lk \ll 1$, where $\frac{2}{y} = \frac{2}{z} = \frac{1}{1 - 2Lk}$.

Lemma D.3. There exist universal constants c_1 and c_2 such that the following holds. Suppose we run SGD with step size $\frac{1}{6L}$ on the function $f(x) = \frac{L}{2}x^2 + x$ for $N \in \mathbb{N}$ with step size $\frac{1}{6L}$, starting at a possibly random iterate $x^{(0)}$. If

$$\mathbb{P}\left[\frac{y}{k} \leq \mathbb{E}[x^{(0)}] \leq 0\right]$$

then for any k ,

$$\mathbb{E}[x^{(k)}] \leq (1 - L/2)^k \mathbb{E}[x^{(0)}] + \frac{1}{2} c_2 \min(1; Lk)^{3/2};$$

where c_1 and c_2 are defined in Eq.(D.2). In particular, we can choose $c_1 = 0.0005$ and $c_2 = 0.002$.

The proof of Lemma D.3 is relegated to Section D.2.

Using Lemma D.3 inductively, we can show that the bias accumulates over many rounds of FedAvg. Loosely speaking, the bias grows linearly with the number of rounds until the force of the gradient exceeds the drift from the difference $\frac{1}{6L}$.

Lemma D.4. Suppose we run FedAvg for R rounds with K local steps and step size $\frac{1}{6L}$ on the 1-dimensional function $f(x) = \frac{L}{2}x^2 + x$ for $N \in \mathbb{N}$. There exists a universal constant c such that for $\frac{1}{6L}$, if $x^{(0;0)} = 0$, then

$$\mathbb{E}[x^{(R;0)}] \leq c \frac{1}{L} \min\left(R, \frac{1}{L}\right)^{3/2}; \frac{1}{L} \min\left(R, \frac{1}{L}\right)^{1/2}$$

In particular, we can choose $c = 0.0005$.

The proof of Lemma D.4 is relegated to Section D.3.

Now consider the FedAvg procedure on the 3-dimensional objective defined in Eq. (D.1). Since the trajectories of coordinates $\mathbf{x} = (x_1; x_2; x_3)$ are completely decoupled, we prove Theorem D.1 by combining Lemma D.4 with bounds that relate the choice of the suboptimality in the coordinates x_2 and x_3 . This yields the first term $\frac{D}{KR} \min\left(\frac{2=3}{K}, \frac{H=3}{R}, \frac{D=3}{R}\right)$, in Theorem D.1. To obtain the final term, we recall that any first order method which uses at most MKR stochastic gradients has a lower bound $\frac{D}{\sqrt{MKR}}$ in expected function error. It follows immediately that the function error of FedAvg is at least the maximum these two terms, which is on the same order as their sum. The details of the proof of Theorem D.1 are provided in Section D.5.

D.2 Proof of Lemma D.3

As outlined in the proof overview, we will compare the iterates of SGD on the piecewise quadratic function to the iterates of SGD on quadratic functions. The following lemma gives a closed form for the SGD iterates of a quadratic function.

Lemma D.5 (Distribution of SGD on Quadratic objectives). Let $x^{(0)} \sim \mathcal{N}(0; \sigma^2)$ be the iterates of SGD on the stochastic function $f(x) = \frac{L}{2}x^2 + x$ with step size $\frac{1}{6L}$ and $N \in \mathbb{N}$. Then $x^{(t)} \sim \mathcal{N}\left((1 - L/6)^t x^{(0)} + \frac{1}{6L} \frac{(1 - (L/6)^t)^2}{2}\right)$.

Proof of Lemma D.5 Let $x^{(i)} \sim \mathcal{N}(0; \sigma^2)$, such that

$$x^{(i+1)} = x^{(i)} - \frac{1}{6L} (Lx^{(i)} + 1) = (1 - L/6)x^{(i)} - \frac{1}{6L}$$

Recurring, we have

$$x^{(t)} = (1 - L/6)^t x^{(0)} + \sum_{i=1}^t \frac{1}{6L} (1 - L/6)^{t-i} \frac{1}{6L}$$

$$(1 - L/6)^t x^{(0)} + \frac{1}{6L} \sum_{i=1}^t (1 - L/6)^{t-i} \frac{1}{6L}$$

$$(1 - L/6)^t x^{(0)} + \frac{1}{6L} \frac{(1 - (L/6)^t)^2}{2}$$

□

We introduce the following definition to facilitate the proof.

Definition D.6. A random variable Y first-order stochastically dominates a random variable X if for all values $c \in \mathbb{R}$,

$$\Pr[Y \leq c] \leq \Pr[X \leq c].$$

We will use the following lemma.

Lemma D.7 (Markov Chain Stochastic Dominance). Let X_t and Y_t be time-homogeneous discrete-time Markov chains on \mathbb{R} such that for any z , the random variable $Y_1 | Y_0 = z$ first-order stochastically dominates $X_1 | X_0 = z$. Then for any c and any $t > 0$, $Y_t | Y_0 = c$ first-order stochastically dominates $X_t | X_0 = c$.

Proof of Lemma D.7. We prove this by induction on t . Note that it holds trivially for $t = 0$.

Let p_x be the distribution of $X_{t-1} | X_0 = c$ and p_y be the distribution of $Y_{t-1} | Y_0 = c$, such that by our inductive hypothesis, p_y stochastically dominates p_x .

Then for any c , we have

$$\begin{aligned} \Pr[Y_t \leq c | Y_{t-1} \sim p_y] &= \Pr[Y_1 \leq c | Y_0 \sim p_y] \\ &\leq \Pr[X_1 \leq c | X_0 \sim p_y] \\ &\leq \Pr[X_1 \leq c | X_0 \sim p_x] \\ &= \Pr[X_t \leq c | X_{t-1} \sim p_x]. \end{aligned}$$

Here the equalities follow from the fact that X_t and Y_t are Markov chains. The first inequality follows from our assumption that for any z , $Y_1 | Y_0 = z$ first-order stochastically dominates $X_1 | X_0 = z$. The second inequality follows from the fact that the function $f(z) := \Pr[X_1 \leq c | X_0 = z]$ is increasing in z , so its expectation is at least as large under p_y as under p_x . \square

Lemma D.3, the more general form of Lemma B.1, gives the bias of SGD on the piecewise quadratic function if the expectation of the starting iterate is bounded. The most important part of its proof is the following weaker lemma, which gives the bias of SGD if the first iterate is deterministic and bounded.

Recall the variables introduced in the proof overview Eq. (D.2), which we restate here for ease of reference:

$$y := 1 - L = 2; \quad z := 1 - L; \quad \frac{z}{y} := \frac{2 - 2(1 - \frac{k}{y})}{1 - y}; \quad \frac{z}{z} := \frac{2 - 2(1 - \frac{k}{z})}{1 - z}.$$

Lemma D.8. If $L = 1/6$ and

$$p_{\frac{c_1 - y}{k}} x^{(0)} \leq p_{\frac{c_1 - y}{k}};$$

then

$$E[x^{(k)} | x^{(0)}] \leq \max \left\{ (1 - L)^k x^{(0)}; (1 - L = 2)^k x^{(0)} \right\} + \frac{p - c_2}{L} \min(Lk; 1)^{3=2};$$

where $c_1 = 0.0005$ and $c_2 = 0.002$.

The proof of Lemma D.8 is deferred to Section D.2.1.

The following lemma covers the edge cases when $|x^{(0)}|$ is large.

Lemma D.9. For all $x^{(0)} \in \mathbb{R}$,

$$E[x^{(k)} | x^{(0)}] \leq (1 - L)^k x^{(0)};$$

and

$$E[x^{(k)} | x^{(0)}] \geq 1 - \frac{L}{2} x^{(0)}.$$

We begin by proving Lemma D.9.

Proof of Lemma D.9. This follows immediately from Lemma D.7, since $x^{(k)}$ is stochastically dominated by k steps of the SGD processes $x^{(k)}$ and $z^{(k)}$ on the functions $f_v(x; \gamma) := \frac{L}{4}x^2 + x$ and $f_u(x; \gamma) := \frac{L}{2}x^2 + x$ respectively, with $x^{(0)} = z^{(0)} = x^{(0)}$. Indeed by Lemma D.5,

$$E[x^{(k)}] - E[z^{(k)}] = (1 - L)^k x^{(0)};$$

and

$$E[x^{(k)}] - E[y^{(k)}] = 1 - \frac{L}{2}^k x^{(0)};$$

□

We now prove Lemma D.3 from Lemmas D.8 and D.9.

Proof of Lemma D.3. We divide the proof into two cases. Let $\alpha := \frac{p}{C_1 - \frac{\gamma}{k}}$ and let $\beta := c_2^{-1} L^{-1} \min(1; Lk)^{3-2}$.

Case 1: $\Pr[B \leq x^{(0)} \leq B] \leq \frac{1}{2}$. In this case, using the second statement of Lemma D.9 in the first inequality and Lemma D.8 in the second inequality, we achieve

$$\begin{aligned} E[x^{(k)}] &= \Pr[jx^{(0)} \leq B] E[x^{(k)} | jx^{(0)} \leq B] + \Pr[jx^{(0)} > B] E[x^{(k)} | jx^{(0)} > B] \\ &= \Pr[jx^{(0)} \leq B] E[(1 - L/2)^k x^{(0)} | jx^{(0)} \leq B] + \Pr[jx^{(0)} > B] E[x^{(k)} | jx^{(0)} > B] \\ &= (1 - L/2)^k E[x^{(0)} | jx^{(0)} \leq B] + \Pr[jx^{(0)} > B] E[x^{(k)} | jx^{(0)} > B] \\ &= (1 - L/2)^k E[x^{(0)}] + \frac{\beta}{2}. \end{aligned}$$

This gives the desired result.

Case 2: $\Pr[B \leq x^{(0)} \leq B] > \frac{1}{2}$. In this case, using the first statement of Lemmas D.9 in the first inequality, and the second statement of Lemma D.9 in the second inequality, we have

$$\begin{aligned} E[x^{(k)}] &= \Pr[x^{(0)} \leq B] E[x^{(k)} | x^{(0)} \leq B] + \Pr[x^{(0)} > B] E[x^{(k)} | x^{(0)} > B] \\ &= \Pr[x^{(0)} \leq B] E[1 - \frac{L}{2}^k x^{(0)} | x^{(0)} \leq B] + \Pr[x^{(0)} > B] E[x^{(k)} | x^{(0)} > B] \\ &= \Pr[x^{(0)} \leq B] E[1 - \frac{L}{2}^k x^{(0)} | x^{(0)} \leq B] + \Pr[x^{(0)} > B] E[(1 - L)^k x^{(0)} | x^{(0)} > B] \\ &= 1 - \frac{L}{2}^k E[x^{(0)}] + \Pr[x^{(0)} > B] E[(1 - L)^k x^{(0)} | x^{(0)} > B]. \end{aligned}$$

Now

$$\begin{aligned} (1 - L/2)^k &= (1 - L)^k \frac{1 - Lk/2}{1 - L/2} \\ &= (1 - L)^k \frac{1 - Lk/2}{1 - L/2} \\ &= (1 - L)^k \frac{1 - Lk/2}{1 - L/2} \\ &= (1 - L)^k \frac{1 - Lk/2}{1 - L/2} \end{aligned}$$

Plugging this in to the previous equation, it follows that

$$E[x^{(k)}] = 1 - \frac{L}{2}^k E[x^{(0)}] + \Pr[x^{(0)} > B] E[x^{(0)} | x^{(0)} > B] \frac{Lk}{4} \frac{Lk}{4} \frac{1-2}{Lk} \frac{1-2}{Lk} \quad (D.3)$$

This concludes the proof of the lemma aside from the proof of the three claims. To prove these, observe that $z \leq y$, and $z \leq y$. □

Deferred Proof of Claim D.10.

$$\begin{aligned}
 z \frac{e^{-\frac{(\frac{k}{z}x^{(0)})^2}{2}}}{p^{\frac{y}{2}}} &= y \frac{e^{-\frac{(\frac{k}{y}x^{(0)})^2}{2}}}{p^{\frac{y}{2}}} = \frac{z}{p^{\frac{y}{2}}} e^{-\frac{(\frac{k}{z}x^{(0)})^2}{2}} + p^{\frac{y}{2}} e^{-\frac{(\frac{k}{z}x^{(0)})^2}{2}} e^{-\frac{(\frac{k}{y}x^{(0)})^2}{2}} \\
 &= \frac{z}{p^{\frac{y}{2}}} e^{-c_1=2} + p^{\frac{y}{2}} e^{-\frac{(\frac{k}{z}x^{(0)})^2}{2}} e^{-\frac{(\frac{k}{y}x^{(0)})^2}{2}} \\
 &= \frac{z}{p^{\frac{y}{2}}} e^{-c_1=2} + p^{\frac{y}{2}} \frac{(\frac{k}{z}x^{(0)})^2}{2} \frac{(\frac{k}{y}x^{(0)})^2}{2} \max \left\{ e^{-\frac{(\frac{k}{z}x^{(0)})^2}{2}}; e^{-\frac{(\frac{k}{y}x^{(0)})^2}{2}} \right\} \\
 &= \frac{z}{p^{\frac{y}{2}}} e^{-c_1=2} + p^{\frac{y}{2}} \frac{(\frac{k}{z}x^{(0)})^2}{2} \frac{(\frac{k}{y}x^{(0)})^2}{2} \\
 &= \frac{z}{p^{\frac{y}{2}}} e^{-c_1=2} + \frac{y(x^{(0)})^2}{2} \frac{2k}{z} \frac{2k}{y} \\
 &= \frac{z}{p^{\frac{y}{2}}} e^{-c_1=2} + \frac{y(x^{(0)})^2}{2} \frac{2k}{z} \frac{2k}{y} :
 \end{aligned}$$

By the assumption of $(x^{(0)})^2$ in the lemma, we have

$$\frac{y(x^{(0)})^2}{2} \frac{2k}{z} \frac{2k}{y} \leq \frac{y(x^{(0)})^2}{2} \frac{2k}{y} \leq \frac{p^{c_1}}{2} \frac{p^{-c_1}}{2} : \tag{D.6}$$

Now if $Lk = 1=2$,

$$\begin{aligned}
 \frac{y(x^{(0)})^2}{2} \frac{2k}{z} \frac{2k}{y} &= \frac{(x^{(0)})^2}{2} \frac{2k}{y} \frac{(1-L)}{(1-L=2)}^{2k} \\
 &= \frac{(x^{(0)})^2}{2} \frac{2k}{y} (1-L)^{2k} \\
 &= \frac{(x^{(0)})^2}{2} \frac{2k}{y} (2Lk) \\
 &= \frac{y^{c_1} Lk}{(1-(1-L=2)^k)^2} c_1 Lk \\
 &= \frac{1-(1-Lk=2)}{L=2} c_1 Lk \\
 &= c_1^2 Lk^{3=2}.
 \end{aligned} \tag{D.7}$$

Here in the second inequality we used the condition $(x^{(0)})^2$. This proves the claim. □

Deferred Proof of Claim D.11. Observe that

$$x^{(0)} \Pr \left\{ N(0; \frac{z}{2}) \leq \frac{k}{z} x^{(0)} \right\} = x^{(0)} \Pr \left\{ N(0; \frac{z}{2}) \leq \frac{k}{y} x^{(0)} \right\}$$

Figure 3: Comparison of CDFs. Top: the regions in the first line of Equation D.4. Bottom: The inequality used in Equation D.8 for both positive and negative z .

and

$$\begin{aligned}
 \frac{k}{y} x^{(0)} \Pr \left[N \left(0; \frac{z}{y} \right) \right] &= \frac{k}{y} x^{(0)} \Pr \left[N \left(0; \frac{z}{z} \right) \right] + \frac{k}{y} x^{(0)} \int_{\frac{z}{y} x^{(0)}}^0 \frac{z(c)}{y(c)} dc \\
 &= \frac{k}{y} x^{(0)} \Pr \left[N \left(0; \frac{z}{z} \right) \right] + \frac{2k}{y} (x^{(0)})^2 \max_{c=1} \frac{z(c)}{y(c)} ;
 \end{aligned}
 \tag{D.8}$$

as shown in Figure 3.

Now

$$\begin{aligned}
 \max_{c_1} & p \frac{1}{2} e^{-c^2} - q \frac{1}{2} e^{-c^2} = p \frac{1}{2} - q \frac{1}{2} \\
 & = p \frac{1}{2} - q \frac{1}{2} \\
 & = p \frac{1}{2} - q \frac{1}{2} \\
 & = \frac{(p - q)}{2}
 \end{aligned} \tag{D.9}$$

To bound this term, observe that

$$\frac{2}{z} = \frac{(1 - \frac{k}{y})(1 - \frac{z}{y})}{(1 - \frac{k}{z})(1 - \frac{y}{y})} = 2 \frac{(1 - \frac{k}{y})}{(1 - \frac{k}{z})} > 2;$$

so

$$\begin{aligned}
 & \frac{2^k (x^{(0)})^2}{2} \frac{y}{z} p \frac{1}{2} - \frac{y}{z} q \frac{1}{2} && \left(\frac{2}{y} - \frac{2}{z} \right) \\
 & c_1 \frac{y}{z} p \frac{1}{2} - \frac{y}{z} q \frac{1}{2} && ((x^{(0)})^2 - \frac{2}{y^k}) \\
 & c_1 \left(\frac{y}{z} - \frac{y}{z} \right) && \left(\frac{2}{y} - \frac{2}{z} \right)
 \end{aligned}$$

Plugging Equation D.9 into Equation D.8, and then plugging in this last equation, we obtain

$$\frac{k}{y} x^{(0)} \Pr N(0; \frac{2}{y}) - \frac{k}{z} x^{(0)} \Pr N(0; \frac{2}{z}) + c_1 \left(\frac{y}{z} - \frac{y}{z} \right) \tag{D.10}$$

We combine Equations D.5 with D.10 to yield

$$\begin{aligned}
 & x^{(0)} \frac{k}{z} \Pr N(0; \frac{2}{z}) - \frac{k}{z} x^{(0)} + \frac{k}{y} \Pr N(0; \frac{2}{y}) - \frac{k}{y} x^{(0)} \\
 & \max(x^{(0)} \frac{k}{y}; x^{(0)} \frac{k}{z}) + c_1 \left(\frac{y}{z} - \frac{y}{z} \right)
 \end{aligned}$$

Now by similar calculations as in Equation D.6 and D.7, we have

$$\begin{aligned}
 & \max(x^{(0)} \frac{k}{y}; x^{(0)} \frac{k}{z}) = x^{(0)} \frac{k}{y} + \left(\frac{k}{z} - \frac{k}{y} \right) x^{(0)} \\
 & x^{(0)} \frac{k}{y} + \frac{p}{c_1} \frac{Lk}{y} \frac{Lk}{2} \quad Lk \quad 1=2; \\
 & x^{(0)} \frac{k}{y} + \frac{p}{c_1} \frac{2}{2} \frac{Lk}{2} \quad Lk \quad 1=2; \\
 & x^{(0)} \frac{k}{y} + \frac{p}{c_1} \frac{2}{2} \frac{Lk}{2} \quad Lk \quad 1=2;
 \end{aligned}$$

Plugging this in to the previous equation concludes the proof of the claim. □

Deferred Proof of Claim D.12 If $Lk \geq 1=2$, we have the following:

$$\begin{aligned}
 y & z = \frac{0 s \frac{1}{1} \frac{k}{y} \frac{1}{1} \frac{k}{z} A}{1} \\
 & = \frac{0 s \frac{1}{L=2} \frac{(1-L=2)^k}{L} \frac{1}{L} \frac{(1-L)^k}{L} A}{1} \\
 & @ \frac{0 s \frac{1}{Lk=2} \frac{(L)^2 k(k-1)=8}{L=2} \frac{1}{L} \frac{(L)^2 k(k-1)=2+(L)^3 \frac{k}{3} A}{L}}{1}
 \end{aligned}$$

because for any integer 2 and $0 < x < 1$,

$$1 - rx + \frac{r}{2} x^2 - \frac{r}{3} x^3 \leq (1-x)^r \leq 1 - rx + \frac{r}{2} x^2:$$

Continuing, we have

$$\begin{aligned}
 & = \frac{0 s \frac{1}{Lk=2} \frac{(L)^2 k(k-1)=8}{L=2} \frac{1}{L} \frac{(L)^2 k(k-1)=2+(L)^3 \frac{k}{3} A}{L}}{1} \\
 & = \frac{p}{k} \frac{p}{1-L(k-1)=4} \frac{p}{1-L(k-1)=2+(L)^2(k-1)(k-2)=6} \\
 & \frac{p}{2} \frac{p}{k} \frac{p}{L(k-1)=4} \frac{p}{(L)^2(k-1)(k-2)=6} \\
 & \frac{p}{2} \frac{p}{k} (L(k-1)(1=4-1=12)) \quad (Lk \geq 1=2) \\
 & \frac{2Lk^3=2}{24}: \quad (k \geq 2)
 \end{aligned}$$

Here the first inequality follows from the fact that the derivative of $(1-x)^r$ is at least $-\frac{r}{2}$ for $0 < x < 1$.

If $Lk \geq 1=2$, we have

$$\begin{aligned}
 y & z = \frac{0 s \frac{1}{1} \frac{k}{y} \frac{1}{1} \frac{k}{z} A}{1} \\
 & = \frac{0 s \frac{1}{L=2} \frac{(1-L=2)^k}{L} \frac{1}{L} \frac{(1-L)^k}{L} A}{1} \\
 & @ \frac{0 s \frac{1}{L=2} \frac{e^{-Lk=2}}{L} \frac{1}{L} \frac{e^{-1:1 Lk=2}}{L} A}{1} \quad (Lk \geq 1=6)
 \end{aligned}$$

For $q \geq 1=2$,

$$1 - e^{-q} \geq 0:52(1 - e^{-1:1q});$$

so letting $q = Lk$, we have

$$y & z @ \frac{0}{2(0:52)} \frac{s \frac{1}{L} \frac{e^{-Lk}}{L} A}{1} \frac{0:12}{p} \frac{1}{L}:$$

□

D.3 Proof of Lemma D.4

We now use Lemma D.3 to prove Lemma D.4, which we restate for the reader's convenience. Recall that we use the notation $x_m^{(r;k)}$ to denote the k -th iterate of FEDAVG at the client m in the r -th round. Recall that we use the notation $x^{(r;0)}$ to denote the starting iterate at all clients in round r .

Lemma D.13 (Same as Lemma D.4) Suppose we run FEDAVG for R rounds with K local steps per round and step size $\eta = \frac{1}{L}$ on the function $f(x; y) = \frac{1}{2} \|x - y\|^2$ for $N \in (0; 2)$. There exists a universal constant c such that for $\frac{1}{\delta L}$, if $x^{(0;0)} = 0$, then

$$\mathbb{E}[x^{(R;0)}] \leq c \frac{\eta}{L} \min\left(R(LK)^{3/2}; 1; (LK)^{1/2}\right);$$

In particular, we can choose $c = 0.0005$.

Proof of Lemma D.13 Let c_1 and c_2 be the constants in Lemma D.3. For simplicity, let $\eta = \min(1; LK)$. By Lemma D.3, for all R , if

$$\frac{\eta}{c_1} \frac{y}{K} \leq \mathbb{E}[x_m^{(r;0)}] \leq \eta;$$

then for any client $m \in [M]$,

$$\mathbb{E}[x^{(r+1;0)}] = \mathbb{E}[x_m^{(r;K)}] \leq (1 - \frac{\eta}{L})^K \mathbb{E}[x_m^{(r;0)}] + \frac{c_2 \eta^{3/2}}{2L} = (1 - \frac{\eta}{L})^K \mathbb{E}[x^{(r;0)}] + \frac{c_2 \eta^{3/2}}{2L};$$

If $\mathbb{E}[x^{(r;0)}] \leq \frac{\eta}{c_1} \frac{y}{K}$, then by Lemma D.7 and comparison to SGD on the quadratic, we have

$$\mathbb{E}[x^{(r+1;0)}] \leq (1 - \frac{\eta}{L})^K \mathbb{E}[x^{(r;0)}] + \frac{\eta}{c_1} \frac{y}{K} + \frac{c_2 \eta^{3/2}}{2L};$$

We will prove the lemma by induction on r . Notice that it holds for $r = 0$. Then for all $r \geq 1$, assuming it holds for r , we have

$$\mathbb{E}[x^{(r+1;0)}] \leq \frac{\eta}{c_1} \frac{y}{K} + (1 - \frac{\eta}{L})^K \left(c \min\left(r^2 K^{3/2}; \frac{\eta}{L}\right) + \frac{c_2 \eta^{3/2}}{2L} \right) + \frac{\eta}{c_1} \frac{y}{K} \leq \frac{\eta}{c_1} \frac{y}{K} + (1 - \frac{\eta}{L})^K \mathbb{E}[x^{(r;0)}] + \frac{c_2 \eta^{3/2}}{2L}; \quad (D.11)$$

Now for $c = \frac{c_2}{4} = 0.0005$ we have

$$\begin{aligned} & (1 - \frac{\eta}{L})^K \left(c \min\left(r^2 K^{3/2}; \frac{\eta}{L}\right) + \frac{c_2 \eta^{3/2}}{2L} \right) \\ & \leq (1 - \eta) \left(c \min\left(r^2 K^{3/2}; \frac{\eta}{L}\right) + \frac{c_2 \eta^{3/2}}{2L} \right) \\ & \leq c \min\left((1 - \eta)r + 2\right) \frac{\eta}{L} + \frac{c_2 \eta^{3/2}}{2L} + \frac{c_2 \eta^{3/2}}{2L} \\ & = c \min\left((1 - \eta)r + 2\right) \frac{\eta}{L} + \frac{c_2 \eta^{3/2}}{L} \\ & \leq c \min\left((r + 1) \frac{\eta}{L}; \frac{\eta}{L}\right); \end{aligned}$$

The last inequality follows from the fact that $(1 - \eta)r + 2 \leq \min((r + 1)\eta; 1)$, for any $0 \leq \eta \leq 1$.

where we have used the fact that $0 < x < 1$ from the Claim.

Now if $HK = 1/2$, we have

$$1 - (1 - H)^K = 1 - (1 - HK)^K = HK:$$

Trivially,

$$1 - (1 - H)^K \leq 1 - (1 - HK)^K = HK:$$

Finally

$$a = (1 - H)^K \leq e^{-KH};$$

so

$$1 - a^R = 1 - e^{-KR} \geq \min(1/2, KR/2):$$

Putting together these approximations, we have

$$x^{(R;0)} = \frac{1 - a^R}{1 - (1 - H)^K} b \geq \frac{c}{H} \min(1/2, HK; (HK)^2 R);$$

for $c = 0.07$. □

D.4.1 Deferred Proof of Claim D.15

Proof of Claim D.15. We follow the same steps as the proof of Claim D.12.

If $HK = 1/2$, we have the following:

$$\begin{aligned} b = 1 - H &= (1 - H)^K = 1 - (1 - H)^K \\ &= \frac{HK + (H)^2 K(K-1)/2 + (H)^3 K^2/3}{H} = \frac{K + (H)^2 K(K-1)/2}{H} \\ &= \frac{K + HK(K-1)/2 + (H)^2 K(K-1)(K-2)/6}{H} \\ &= \frac{2(H)^2 K(K-1)/2 + (H)^2 K(K-1)(K-2)/6}{H} \\ &= \frac{2K(K-1)H + H^2(K-2)/6}{H}; \end{aligned}$$

where we used the fact that for any integer $2 \leq x \leq 1$,

$$1 - rx + \frac{r}{2} x^2 - \frac{r}{3} x^3 \leq (1 - x)^r \leq 1 - rx + \frac{r}{2} x^2:$$

Continuing, we have

$$b \geq \frac{2K(K-1)(H + H/12) + 2K^2(H + H/12)}{H};$$

if $HK = 1/2$ and $H(1/12) \leq 1/2$.

If $HK = 1/2$, then

$$b = 1 - H = (1 - H)^K = 1 - (1 - H)^K \geq \frac{1 - e^{-1/2 HK}}{H} = \frac{1 - e^{-1/4}}{H/2};$$

For $q = 1/2$,

$$1 - e^{-q} \geq 0.52(1 - e^{-1/4q});$$

so letting $q = HK$, we have

$$b \geq (1 - 2(0.52)) \frac{1 - e^{-HK}}{H} \geq \frac{0.04(1 - e^{-1/2})}{H} \geq 0.015 = H:$$

□

D.5 Proof of Theorem D.1: Lower bound of FEDAVG convergence

In this section, we prove our main Theorem D.1. We use the following lemma.

Lemma D.16. Let $f(x) = \frac{1}{2}x^2$, where

$$= \frac{1}{D^2} \max \min \left\{ \frac{D}{K}, \frac{D}{R}, \frac{2^{2-3} H^{1-3} D^{4-3}}{K^{1-3} R^{2-3}}; \frac{2^{2-3} H^{1-3} D^{4-3}}{R^{2-3}}; \frac{H D^2}{K R} \right\};$$

Suppose we run gradient descent starting at $x^0 = D/2$ with step size $\frac{1}{KR}$. After KR iterations, we have

$$f(x^{(KR)}) > \frac{1}{30} \max \min \left\{ \frac{D}{K}, \frac{D}{R}, \frac{2^{2-3} H^{1-3} D^{4-3}}{K^{1-3} R^{2-3}}; \frac{2^{2-3} H^{1-3} D^{4-3}}{R^{2-3}}; \frac{H D^2}{K R} \right\};$$

Proof of Lemma D.16 For any iteration t , we have

$$x^{(t)} = (1 - \frac{1}{KR})^t x^{(0)};$$

such that

$$\begin{aligned} f(x^{(KR)}) &= (1 - \frac{1}{KR})^{2KR} f(x^0) \\ &= (1 - \frac{1}{KR})^{2KR} \frac{D^2}{4} \\ &= e^{-2KR} \frac{D^2}{4} \\ &> \frac{D^2}{30} \frac{1}{D^2} \max \min \left\{ \frac{D}{K}, \frac{D}{R}, \frac{2^{2-3} H^{1-3} D^{4-3}}{K^{1-3} R^{2-3}}; \frac{2^{2-3} H^{1-3} D^{4-3}}{R^{2-3}}; \frac{H D^2}{K R} \right\} \\ &= \frac{1}{30} \max \min \left\{ \frac{D}{K}, \frac{D}{R}, \frac{2^{2-3} H^{1-3} D^{4-3}}{K^{1-3} R^{2-3}}; \frac{2^{2-3} H^{1-3} D^{4-3}}{R^{2-3}}; \frac{H D^2}{K R} \right\}; \end{aligned}$$

□

Proof of Theorem D.1 We will use the following stochastic functions for our lower bound. Note that in the homogeneous case this reduces to the functions introduced in equation D.1.

$$f(x; (\alpha_1; \alpha_2; \alpha_3)) = f^{(1)}(x_1; \alpha_1) + f^{(2)}(x_2) + f^{(3)}(x_3; (\alpha_2; \alpha_3));$$

where

$$f^{(1)}(x; \alpha) = \frac{L}{2} (x - \alpha)^2; \quad f^{(2)}(x) = \frac{H}{2} x^2; \quad f^{(3)}(x; (\alpha_2; \alpha_3)) = \begin{cases} H x^2 & \alpha_2 = 1 \\ \frac{H}{2} x^2 & \alpha_2 = 2 \end{cases};$$

and

$$\alpha_1 = \begin{cases} (1; 0) & \text{homogeneous case,} \\ N(0; \alpha_2); \quad (\alpha_2; \alpha_3) = \begin{cases} (1; \alpha_3) & \text{for odd } m, \\ (2; \alpha_3) & \text{for even } m. \end{cases} \end{cases}$$

with $L := \frac{H}{12}$, and

$$:= \frac{1}{D^2} \max \min \left\{ \frac{D}{K}, \frac{D}{R}, \frac{2^{2-3} H^{1-3} D^{4-3}}{K^{1-3} R^{2-3}}; \frac{2^{2-3} H^{1-3} D^{4-3}}{R^{2-3}}; \frac{H D^2}{K R} \right\};$$

Suppose we run FEDAVG starting at $(0; D/2; D/2; 0)$. Suppose the number of machines M is even. We make the following three observations.

1. If $\frac{1}{KR} > \frac{1}{H}$, then x_3 diverges, and hence it suffices to consider the case when $\frac{1}{KR} \leq \frac{1}{H}$.

2. By Lemma D.16, if $\frac{1}{KR} < \frac{1}{H}$, we have

$$f^{(2)}(x) > \frac{1}{30} \max \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}}; \frac{2=3H^{1=3}D^{4=3}}{R^{2=3}}; \frac{HD^2}{KR} \right\};$$

Furthermore, if $\frac{HD^2}{KR} < \frac{1}{H}$, and so $\frac{1}{H}$ implies that

$$f^{(2)}(x) > \frac{1}{30} \max \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}}; \frac{2=3H^{1=3}D^{4=3}}{R^{2=3}}; \frac{HD^2}{KR} \right\};$$

3. By Lemma D.4, for some constant c , for $\frac{1}{6L} = \frac{2}{H}$, we have

$$\begin{aligned} E[f^{(1)}(x_1^{(R;0)}; 1)] &\leq \frac{L}{4} E[(x_1^{(R;0)})^2] \\ &\leq \frac{L}{4} E[x_1^{(R;0)}]^2 \\ &\leq \frac{L}{4} c^2 \min \left\{ R^2 (LK)^3; 1; (LK)^{1=2} \right\} \\ &= \frac{c^2}{4} \min \left\{ R^2 (LK)^3; 1; LK \right\}; \end{aligned}$$

4. By Lemma D.14, if $\frac{1}{H} < \frac{1}{L}$, for some constant c , we have

$$E_m E_{2,D} [f^{(3)}(x_3^{(R;0)}; 2)] \leq \frac{3H}{4} E[(x_3^{(R;0)})^2] \leq \frac{3H}{4} E[x_3^{(R;0)}]^2 \leq \frac{3c}{4H} \min \left\{ 1; (HK)^2; (HK)^4 R^2 \right\};$$

By items (1) and (2), it suffices to consider the case when $\frac{1}{KR} < \frac{1}{H}$ and when

$$\frac{HD^2}{KR} < \max \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}}; \frac{2=3H^{1=3}D^{4=3}}{R^{2=3}} \right\};$$

Otherwise, we immediately recover the theorem.

We consider two cases depending of the relative order of $\frac{D}{KR}$ and $\frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}}$ and $\frac{2=3H^{1=3}D^{4=3}}{R^{2=3}}$.

Case 1: $\min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}} \right\} < \frac{2=3H^{1=3}D^{4=3}}{R^{2=3}}$.

For

$$\frac{1}{KR} = \frac{D^2}{KR \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}} \right\}};$$

by the third item above, we have for some universal constant

$$\begin{aligned} E[f^{(1)}(x_1^{(R;0)}; 1)] &\leq \frac{c^2 D^2}{4KR \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}} \right\}} \min \left\{ R^2 (LK)^3; 1; LK \right\} \\ &\leq \frac{c^2 D^2}{4KR \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}} \right\}} \min \left\{ 1; \frac{D^2 L}{R \min \left\{ \frac{D}{KR}, \frac{2=3H^{1=3}D^{4=3}}{K^{1=3}R^{2=3}} \right\}} \right\} \\ &= \min \left\{ \frac{c^2 D}{4KR}, \frac{c^2 D^{2=3} 4=3H^{1=3}}{4K^{2=3}R^{1=3}} \right\}; \max \left\{ \frac{c^2 D^2 L}{4R}, \frac{c^2 D^{4=3} 2=3L}{4K^{1=3}R^{2=3}H^{2=3}} \right\} \\ &\leq \min \left\{ \frac{D}{KR}, \frac{D^{4=3} 4=3H^{1=3}}{K^{2=3}R^{1=3}} \right\}; \max \left\{ \frac{D^2 L}{R}, \frac{D^{4=3} 2=3H^{1=3}}{K^{1=3}R^{2=3}} \right\} \\ &\leq \min \left\{ \frac{D}{KR}, \frac{D^{4=3} 2=3H^{1=3}}{K^{1=3}R^{2=3}} \right\}; \end{aligned}$$

where we have used the fact that

$$R L K \quad R K \quad 1$$

to get rid of the first of the three terms in the minimum.

$$\text{Case 2: } \min \left\{ \frac{D}{K^2 R}; \frac{2=3 H^1=3 D^4=3}{K^1=3 R^2=3} < \frac{2=3 H^1=3 D^4=3}{R^2=3} \right\}.$$

For

$$\frac{1}{KR} = \frac{D^2}{KR \frac{H^1=3 \quad 2=3 \quad D^4=3}{R^2=3}};$$

by the fourth item above, we have

$$\begin{aligned} E_m E_{2D} E_m [f(x_3^{(R;0)}; 2)] & \frac{3c_n}{4H} \min(1; (HK)^2; (HK)^4 R^2)^2 \\ & = \frac{3c_n}{4H} \min(1; (HK)^2) \\ & \frac{3c_n}{4H} \min(1; \frac{D^2 HK}{KR \frac{2=3 H^1=3 D^4=3}{R^2=3}}) \\ & = \frac{3c_n}{4H} \min(1; \frac{D^4=3 H^4=3}{R^2=3 \quad 4=3}) \\ & = \frac{3c_n}{4} \min(\frac{2}{H}; \frac{2=3 H^1=3 D^4=3}{R^2=3}) \end{aligned}$$

where we have used in the first equality the fact that

$$R HK \quad R K \quad 1$$

to get rid of the last of the three terms in the minimum.

Combining these two cases proves Theorem D.1. □

E Proof of Theorems 4.1 and 4.2: Upper Bounds of FEDAVG Under 3rd-order Smoothness

In this section, we state and prove the formal theorems on the upper bounds of FEDAVG under third-order smoothness, including both convex and non-convex cases.

Theorem E.1 (Upper bound for FEDAVG under third-order smoothness, complete version of Theorem 4.1.) Suppose $(x; \sigma)$ satisfies Assumptions 1 and 2. Then for step size

$$\min \left\{ \frac{1}{H}; \frac{B}{HRK}; \frac{B^1=5}{K^3=5 R^1=5 Q^2=5 \quad 4=5} \right\}, \text{ FEDAVG satisfies}$$

$$E \| \text{kr} F(x) \|^2 \leq O \left(\frac{HB}{KR} + \frac{B}{MKR} + \frac{B^{\frac{4}{5}} Q^{\frac{4}{5}}}{K^{\frac{2}{5}} R^{\frac{4}{5}}} \right);$$

where $\star := \frac{1}{M} \sum_m x^{(r;k)}$ for a uniformly random choice of $k \in [K]$, and $r \in [R]$, and $B = F(x^{(0;0)}) - \min_x F(x)$.

In the non-convex case, we prove our results under the following assumption, which is slightly weaker than Assumption 4 in the main body.

Assumption 5 (Universal gradient bound of expected objective) For any x ,

$$\| \text{kr} F(x) \| \leq G;$$

where $\|\mathbf{e}_m\|_2 \leq \frac{Q}{2} \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2$. It follows that

$$\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) - \frac{1}{M} \sum_m \nabla F(\mathbf{x}_m^{(r,k)}) \right\|^2 = \left\| \frac{1}{M} \sum_m \mathbf{e}_m \right\|^2 \leq \left(\frac{1}{M} \sum_m \|\mathbf{e}_m\|_2 \right)^2 \leq \frac{Q^2}{4} \left(\frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2 \right)^2.$$

Plugging this into equation E.1, we obtain the claim:

$$\mathbb{E} \left[F(\bar{\mathbf{x}}^{(r,k+1)}) \right] \leq \mathbb{E} \left[F(\bar{\mathbf{x}}^{(r,k)}) \right] - \frac{\eta}{2} \mathbb{E} \left[\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) \right\|^2 \right] + \frac{\eta Q^2}{4} \mathbb{E} \left[\left(\frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2 \right)^2 \right] + \frac{H\eta^2 \sigma^2}{M}.$$

□

The following lemma bounds the term $\mathbb{E} \left[\left(\frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2 \right)^2 \right]$ when f is convex.

Lemma E.5. *With $\mathbf{y} := \mathbb{E}[\mathbf{x}_m^{(r,k)}]$, we have*

$$\mathbb{E} \left[\left(\frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2 \right)^2 \right] \leq \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{y}\|^4].$$

Proof of Lemma E.5. By definition of the mean, we have

$$\frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2 \leq \frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \mathbf{y} \right\|^2$$

By the independence of the $\bar{\mathbf{x}}_m^{(r,k)}$, we have

$$\mathbb{E} \left[\left(\frac{1}{M} \sum_m \left\| \mathbf{x}_m^{(r,k)} - \bar{\mathbf{x}}_m^{(r,k)} \right\|^2 \right)^2 \right] = \frac{1}{M} \mathbb{E} \left[\|\mathbf{x}_m^{(r,k)} - \mathbf{y}\|^4 \right] + \frac{M(M-1)}{M^2} \left(\mathbb{E} \left[\|\mathbf{x}_m^{(r,k)} - \mathbf{y}\|^2 \right] \right)^2.$$

By Jensen's inequality, we can move the square in the second term inside the expectation, so this is less than $\mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{y}\|^4]$. □

In the convex case, we bound this term using a result from Yuan and Ma [2020].

Lemma E.6 (Proposition D.6 in Yuan and Ma [2020]). *Under Assumptions 1 and 2,*

$$\mathbb{E} \left[\left\| \mathbf{x}_m^{(r,k)} - \mathbf{y} \right\|^4 \right] \leq 200k^2 \eta^4 \sigma^4,$$

In the non-convex, we bound the term in Lemma E.5 in the following lemma.

Lemma E.7. *Under Assumptions 2 and 5, with $\mathbf{y} := \mathbb{E}[\mathbf{x}_m^{(r,k)}]$, we have*

$$\mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{y}\|^4] \leq 8\eta^4 (G + \sigma)^4 k^4.$$

Proof of Lemma E.7. First note that $\mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{z}\|^4]$ is minimized over all \mathbf{z} by the expectation \mathbf{y} , hence we have

$$\mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{y}\|^4] \leq \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4]$$

We prove this by induction on k with the following inductive hypothesis:

$$\mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] \leq 8\eta^4 (G + \sigma)^4 k^4.$$

Clearly this holds in the base case for $k = 0$. Suppose it holds for k and we want to prove it for $k = 1$. Then we can expand

$$\begin{aligned}
\mathbb{E}[\|\mathbf{x}_m^{(r,k+1)} - \mathbf{x}_m^{(r,0)}\|^4] &= \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \eta \mathbf{g}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] \\
&\leq \left(\frac{k+1}{k}\right)^3 \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] + (k+1)^3 \mathbb{E}[\|\eta \mathbf{g}_m^{(r,k)}\|^4] \\
&= \left(\frac{k+1}{k}\right)^3 \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] + (k+1)^3 \mathbb{E}[\|\eta \nabla F(\mathbf{x}^{(r,k)}) + \eta(\mathbf{g}_m^{(r,k)} - \nabla F(\mathbf{x}^{(r,k)}))\|^4] \\
&\leq \left(\frac{k+1}{k}\right)^3 \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] + 8(k+1)^3 \left(\eta^4 \|\nabla F(\mathbf{x}^{(r,k)})\|^4 + \eta^4 \mathbb{E}[\|\mathbf{g}_m^{(r,k)} - \nabla F(\mathbf{x}^{(r,k)})\|^4]\right) \\
&\leq \left(\frac{k+1}{k}\right)^3 \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] + 8(k+1)^3 (\eta^4 G^4 + \eta^4 \sigma^4) \\
&\leq \left(\frac{k+1}{k}\right)^3 \mathbb{E}[\|\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}\|^4] + 8(k+1)^3 \eta^4 (G + \sigma)^4 \\
&\leq 8 \left(\frac{k+1}{k}\right)^3 \eta^4 (G + \sigma)^4 k^4 + 8(k+1)^3 \eta^4 (G + \sigma)^4 \\
&= 8\eta^4 (G + \sigma)^4 (k+1)^4.
\end{aligned}$$

where the first inequality following from Jensen's inequality applied to the random variable X , where

$$X = \begin{cases} \frac{k+1}{k}(\mathbf{x}_m^{(r,k)} - \mathbf{x}_m^{(r,0)}) & \text{with probability } \frac{k}{k+1} \\ (k+1)\eta \mathbf{g}_m^{(r,k)} & \text{with probability } \frac{1}{k+1}. \end{cases}$$

□

Finishing the Proof of Theorem E.1. For the convex case, we now put Lemma E.4 together with the moment bounds in Lemmas E.5 and E.6. Telescoping, we achieve the following for the convex case:

Lemma E.8. *Under Assumptions 1 and 2, for $\eta \leq \frac{1}{H}$, we have*

$$\frac{1}{KR} \sum_{r=1}^R \sum_{k=1}^K \mathbb{E} \left[\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) \right\|^2 \right] \leq \frac{2(F(\mathbf{x}^{(0,0)}) - F(\mathbf{x}^*))}{\eta KR} + 50Q^2 \eta^4 \sigma^4 K^2 + \frac{H\eta\sigma^2}{M}.$$

Choosing

$$\eta = \min \left\{ \frac{1}{H}, \frac{\sqrt{BM}}{\sigma\sqrt{HKR}}, \frac{B^{1/5}}{K^{3/5}R^{1/5}Q^{2/5}\sigma^{4/5}} \right\},$$

we achieve from this lemma the convergence bound in Theorem E.1.

Finishing the Proof of Theorem E.2. For the non-convex case, we now put Lemma E.4 together with the moment bounds in Lemmas E.5 and E.7. Telescoping, we achieve the following for the non-convex case:

Lemma E.9. *Under Assumptions 2 and 5, for $\eta \leq \frac{1}{H}$, we have*

$$\frac{1}{KR} \sum_{r=1}^R \sum_{k=1}^K \mathbb{E} \left[\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) \right\|^2 \right] \leq \frac{2(F(\mathbf{x}^{(0,0)}) - F(\mathbf{x}^*))}{\eta KR} + 8Q^2 \eta^4 (G + \sigma)^4 K^4 + \frac{H\eta\sigma^2}{M}.$$

Choosing

$$\eta = \min \left\{ \frac{1}{H}, \frac{\sqrt{BM}}{\sigma\sqrt{HKR}}, \frac{B^{1/5}}{KR^{1/5}Q^{2/5}(\sigma + G)^{4/5}} \right\},$$

we achieve from this lemma the convergence bound in Theorem E.2.

E.1 Upper Bounds of FEDAVG Under Second-Order Smoothness

For completeness, we also prove the following theorem, which can be obtained from Yu et al. [2019b].

Theorem E.10 (Upper bound for FEDAVG for non-convex objectives under second-order smoothness). *Suppose $F(\mathbf{x})$ is H -smooth and $f(\mathbf{x}; \xi)$ satisfies Assumption 5, and the variance of the gradients is bounded σ^2 . Then for step size $\eta = \min \left\{ \frac{1}{H}, \frac{\sqrt{BM}}{\sigma\sqrt{HKR}}, \frac{B^{\frac{1}{3}}}{KR^{\frac{1}{3}}H^{\frac{2}{3}}(G+\sigma)^{\frac{2}{3}}} \right\}$, we have*

$$\mathbb{E} \left[\|\nabla F(\hat{\mathbf{x}})\|^2 \right] \leq \mathcal{O} \left(\frac{HB}{KR} + \frac{\sigma\sqrt{BH}}{\sqrt{MKR}} + \frac{B^{\frac{2}{3}}(G+\sigma)^{\frac{2}{3}}H^{\frac{2}{3}}}{R^{\frac{2}{3}}} \right),$$

where $\hat{\mathbf{x}} := \frac{1}{M} \sum_m \mathbf{x}_m^{(r,k)}$ for a random choice of $k \in [K]$, and $r \in [R]$, and $B := F(\mathbf{x}^{(0,0)}) - \inf_{\mathbf{x}} F(\mathbf{x})$.

Proof of Section E.1. The proof is similar to the Q -third order smooth case. Following the proof of Lemma E.4 up to Eq. (E.1), we obtain from H -smoothness:

$$\mathbb{E} \left[F(\bar{\mathbf{x}}^{(r,k+1)}) \right] \leq \mathbb{E} \left[F(\bar{\mathbf{x}}^{(r,k)}) \right] - \frac{\eta}{2} \mathbb{E} \left[\|\nabla F(\bar{\mathbf{x}}^{(r,k)})\|^2 \right] + \eta \mathbb{E} \left[\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) - \frac{1}{M} \sum_m \nabla F(\mathbf{x}_m^{(r,k)}) \right\|^2 \right] + \frac{H\eta^2\sigma^2}{M},$$

Now by Jensen's inequality and H -smoothness, we have

$$\begin{aligned} \mathbb{E} \left[\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) - \frac{1}{M} \sum_m \nabla F(\mathbf{x}_m^{(r,k)}) \right\|^2 \right] &\leq \frac{1}{M} \sum_m \mathbb{E} \left[\left\| \nabla F(\bar{\mathbf{x}}^{(r,k)}) - \nabla F(\mathbf{x}_m^{(r,k)}) \right\|^2 \right] \\ &\leq \frac{H^2}{M} \sum_m \mathbb{E} \left[\left\| \bar{\mathbf{x}}^{(r,k)} - \mathbf{x}_m^{(r,k)} \right\|^2 \right] \\ &\leq H^2 \mathbb{E} \left[\left\| \mathbf{x}^{(r,0)} - \mathbf{x}_1^{(r,k)} \right\|^2 \right]. \end{aligned}$$

The following claim shows bounds this expectation.

Claim E.11. *For any k ,*

$$\mathbb{E} \left[\left\| \mathbf{x}_1^{(r,k)} - \mathbf{x}^{(r,0)} \right\|^2 \right] \leq 2\eta^2(G+\sigma)^2k^2.$$

The proof of this claim is by induction, and it is nearly identical to the proof of Lemma E.7.

Plugging in this claim, we have

$$\mathbb{E} \left[F(\bar{\mathbf{x}}^{(r,k+1)}) \right] \leq \mathbb{E} \left[F(\bar{\mathbf{x}}^{(r,k)}) \right] - \frac{\eta}{2} \mathbb{E} \left[\|\nabla F(\bar{\mathbf{x}}^{(r,k)})\|^2 \right] + 2\eta^3(G+\sigma)^2k^2 + \frac{H\eta^2\sigma^2}{M},$$

Telescoping, we obtain

$$\frac{1}{KR} \sum_{r=1}^R \sum_{k=1}^K \mathbb{E} \left[\|\nabla F(\bar{\mathbf{x}}^{(r,k)})\|^2 \right] \leq \frac{2(F(\mathbf{x}^{(0,0)}) - F(\mathbf{x}^*))}{\eta KR} + 2H^2\eta^2(G+\sigma)^2K^2 + \frac{H\eta\sigma^2}{M}.$$

Choosing $\eta = \min \left\{ \frac{1}{H}, \frac{\sqrt{BM}}{\sigma\sqrt{HKR}}, \frac{B^{\frac{1}{3}}}{KR^{\frac{1}{3}}H^{\frac{2}{3}}(G+\sigma)^{\frac{2}{3}}} \right\}$, we obtain

$$\frac{1}{KR} \sum_{r=1}^R \sum_{k=1}^K \mathbb{E} \left[\|\nabla F(\bar{\mathbf{x}}^{(r,k)})\|^2 \right] \leq \mathcal{O} \left(\frac{HB}{KR} + \frac{\sigma\sqrt{BH}}{\sqrt{MKR}} + \frac{B^{\frac{2}{3}}(G+\sigma)^{\frac{2}{3}}H^{\frac{2}{3}}}{R^{\frac{2}{3}}} \right).$$

This proves the theorem. \square