
Gradient-Driven Rewards to Guarantee Fairness in Collaborative Machine Learning

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Abstract

Collaborative machine learning provides a promising framework for different agents to pool their resources (e.g., data) for a common learning task. In realistic settings where agents are self-interested and not altruistic, they may be unwilling to share data or model without adequate rewards. Furthermore, as the data/model shared by the agents may differ in quality, designing rewards which are fair to them is important so that they do not feel exploited and discouraged from sharing. In this paper, we adopt *federated learning* as a gradient-based formalization of collaborative machine learning, propose a novel cosine gradient Shapley value to evaluate the agents' uploaded model parameter updates/gradients, and design theoretically guaranteed fair rewards in the form of better model performance. Compared to existing baselines, our approach is more efficient and does not require a validation dataset. We perform extensive experiments to demonstrate that our proposed approach achieves better fairness and predictive performance.

1 Introduction

In *collaborative machine learning* (CML), multiple agents (e.g., researchers, organizations, companies) pool their resources (e.g., data) together for a common learning task. It spans a wide variety of real-world applications such as digital healthcare [48], clinical trial research [13, 23], wake word detection for smart voice assistants [27], and next word prediction on mobile devices [15].

Federated learning (FL) provides one natural formalization of CML [18, 40, 42, 55, 59]. In FL, the agents perform local model training (e.g., via stochastic gradient descent) and share their resulting model parameter updates/gradients [39, 54, 57]. An important distinction of our work here from the common FL literature is that we allow the agents to be self-interested and so, they are not necessarily cooperative like the worker nodes in distributed learning. The implication is that in order to achieve competitive predictive performance for the learning task, it is imperative to incentivize/reward the agents for contributing/sharing information in the form of gradients [46, 47, 51].

Our work here adopts FL as the particular formalization of gradient-based CML to investigate and design a fair reward mechanism. So, the (self-interested) agents who contribute more would not feel exploited, i.e., if these agents are rewarded equally with others who contributed much less. This is often termed as fairness in cooperative game theory [41], mechanism design [4], and computational social choice [11]. To design such a fair reward mechanism, we need to address three main questions.

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For the first question, what is a suitable notion of fairness? The Shapley value (SV) [49] from cooperative game theory is an appealing choice and has been used in FL [53, 54]. However, the effectiveness of existing SV-based methods is limited by the validation process which requires an auxiliary dataset and more time overhead [53, 54]. To address these challenges, we propose to consider the vector alignment between the shared/uploaded gradients by the agents as it circumvents the need for validation and implicitly captures model performance. We therefore propose our SV-based definition using the cosine similarity between gradients called the cosine gradient Shapley value (CGSV) which can be efficiently and accurately approximated.

For the subsequent question, what shall we use as reward? Various choices such as monetary rewards from a pre-allocated budget [62] or the total revenue generated from collaboration [10] have been proposed. Unfortunately, though it is natural to consider monetary incentives, these methods may not be readily practical due to the open problem of the denomination between data/gradient and dollar value [45]. Instead, we propose to consider the downloaded gradients from the server as the reward to agents. In this manner, we can avoid the need of external resources and the ensuing practical challenges.

For the last question, how should rewards be allocated to guarantee fairness? Using the downloaded gradients as rewards, we propose a mechanism which controls the quality of the gradients that the agents download according to their uploaded model parameter update/gradients, thereby avoiding gradient-trick [2, 7]. This mechanism allows us to provide fairness guarantees in the form of model performance such that the agent who contributes/uploads the best model parameter updates/gradients receives a model with the best performance (i.e., lowest training loss) [51].

In comparison with the related works, our proposed fair gradient reward mechanism has the following practical advantages: (a) Evaluation without an auxiliary dataset: Our fair gradient reward mechanism does not require any auxiliary dataset to evaluate the quality of the agents' gradients, as opposed to existing methods [6, 53, 54], hence saving the additional costs from procuring and processing this dataset [51]. (b) Inherent rewards: Our fair gradient reward mechanism does not need external resources and circumvents the challenge of determining the form and denomination between an external resource such as money and gradients/data point [45]. (c) Training-time rewards: Our fair gradient reward mechanism dynamically determines the appropriate rewards (i.e., fair) to agents and realizes them during training instead of post-hoc [47, 51, 62], hence saving post-processing costs.

In summary, the contributions of our work here to FL include the following:

We propose a novel cosine gradient Shapley value (CGSV) to fairly evaluate the quality of uploaded gradients without any auxiliary dataset and present an efficient approximation with bounded error. Based on CGSV, we design a novel training-time fair gradient reward mechanism to determine and realize the rewards (i.e., the downloaded gradients by the agents) with theoretical fairness guarantees (i.e., allocate models of lower training losses to agents who upload better gradients). We empirically demonstrate the effectiveness of our fair gradient reward mechanism on multiple benchmark datasets in terms of fairness, predictive performance, and time overhead.

2 Related Work

Reward design and choice in CML. In related fields such as FL [9, 35, 37, 46, 57, 60, 63], Bayesian CML [51], and data sharing [3, 23, 47], designing appropriate rewards to encourage collaboration (e.g. sharing data, gradient, or other information) is a non-trivial practical problem. A useful solution concept should provide a formalization of fairness, a suitable form and denomination of reward, and a principled way to guarantee fairness via a carefully constructed reward design mechanism. Previous approaches have considered monetary rewards from a pre-allocated budget [63] or the total revenue generated from collaboration [10], or simply an abstract and quantifiable form of reward [46, 47]. These methods usually face the practical challenge of determining a suitable denomination between money and data/gradient [45]. The work of [63] has explored a different avenue of using a reverse auction to guarantee truthfulness in its mechanism instead of fairness.

Fairness notions. Due to several desirable properties including symmetry and null player, the Shapley value (SV) [49] from cooperative game theory is commonly considered as a theoretically principled fairness formalization [11, 41]. Existing SV-based methods consider fairness in the sense of rewarding agents according to their contributions [3, 53, 54]. However, they typically encounter two practical challenges: significant time incurred from computing the SV using validation (i.e.,

further exacerbated by the long training time [19, 54]) and additional cost to procure the auxiliary validation dataset [6, 51]. In contrast, the work of [30] has adopted an egalitarian notion of fairness by aiming to equalize the local individual performance among agents, which is fundamentally different from SV.

Different from the fairness definition in [30], we adopt the fairness notion formalized by SM [19, 51, 53, 54]. A novelty of our approach is in our application of SV: While previous works use the validation accuracy [4, 19, 53, 54], we leverage the cosine similarity between gradient vectors in gradient-based ML models [2]. We thus propose cosine gradient Shapley value (CGSV) to fairly measure the quality of the uploaded gradients of the agents. Based on CGSV, we design a gradient reward mechanism with fairness guarantees (Sec. 3.5) and empirically show that it outperforms the adapted variants of some existing approaches in important aspects, including predictive model performance and time overhead (Sec. 4.2).

3 Fair Gradient Reward Mechanism

3.1 Vanilla Federated Learning (FL) Problem Setting and Notations

The vanilla FL problem [4, 57] involves a set $\mathcal{N} := \{i=1, \dots, N\}$ of N honest agents learning a D -dimensional vector $w \in \mathbb{R}^D$ of model parameters to minimize a loss function $F(w)$ that can be additively decomposed into local differentiable loss functions $F_i(w)$ defined using the local dataset \mathcal{D}_i of agent $i \in \mathcal{N}$ and weighted by its importance $\rho_i > 0$ (e.g., proportional to $|\mathcal{D}_i|$). That is, $F(w) := \sum_{i \in \mathcal{N}} \rho_i F_i(w)$ where $\sum_{i \in \mathcal{N}} \rho_i = 1$. We call \mathcal{N} the grand coalition; a coalition $S \subseteq \mathcal{N}$ is then a subset of the grand coalition of N agents. In iteration $t = 0$, every agent $i \in \mathcal{N}$ starts with the same initialized parameter vector $w_{i,t=0} := w_0$ as the server. In iteration $t > 0$, every agent $i \in \mathcal{N}$ calculates a parameter update $u_{i,t} := -\eta \nabla F_i(w_{i,t-1})$ with step size η and gradient $\nabla F_i(w_{i,t-1})$ w.r.t. parameter vector $w_{i,t-1}$ and uploads it to a trusted server who normalizes and aggregates all agents' parameter updates as follows:

$$u_{i,t} := \frac{\rho_i}{\sum_{j \in \mathcal{N}} \rho_j} \nabla F_j(w_{j,t-1}); \quad u_{N,t} := \sum_{i \in \mathcal{N}} \rho_i u_{i,t} \quad (1)$$

where ρ_i is a normalization coefficient used to prevent gradient explosion [32, 44] and the importance coefficient ρ_i will be described later in Sec 3.4. So, we call the gradient aggregation step (1) the gradient download step. Then follows where every agent $i \in \mathcal{N}$ downloads the aggregated parameter update/gradient $u_{N,t}$ (1) from the server (as reward) for updating its model parameters $w_{i,t} := w_{i,t-1} + u_{N,t}$ to the same $w_{i,t} := w_{N,t} + u_{N,t}$ as the server. That is, $w_{i,t} = w_{N,t}$ for all $i \in \mathcal{N}$ and $t \in \mathbb{Z}^+$ [40]. We define $u_{S,t}$ for any coalition $S \subseteq \mathcal{N}$ in a similar way as $u_{N,t}$ (1). For brevity, we omit from our notations in Secs. 3.2 and 3.3 since we only refer to iteration

3.2 Cosine Gradient Shapley Value (CGSV) for Fairness

In the gradient aggregation step (1), the quality/value of coalition S 's (normalized) aggregated parameter update/gradient can be measured by its cosine similarity $\cos(u_S; u_N) := \frac{\langle u_S, u_N \rangle}{\|u_S\| \|u_N\|}$ to the grand coalition \mathcal{N} 's aggregated parameter update/gradient [12, 28, 34]. We use this cosine similarity measure as our gradient valuation function (S) := $\cos(u_S; u_N)$. Intuitively, if the direction of u_S aligns more closely with that of u_N , then its quality/value (S) is higher. Using \cos , the contribution ϕ_i of agent $i \in \mathcal{N}$ is defined based on the notion of Shapley value (SV) [49] which measures its expected marginal contribution when joining the other agents preceding it in any permutation and satisfies certain desirable fairness properties [5], such as null player (i.e., an agent with no marginal contribution has zero SV), symmetry (i.e., agents with identical marginal contributions have equal SVs), among others, as formally discussed in Appendix A.1:

Definition 1 (Cosine gradient Shapley value (CGSV)) Let \mathcal{P}_N be a set of all possible permutations of \mathcal{N} and $S_{i,j}$ be the coalition of agents preceding agent i in permutation $\pi \in \mathcal{P}_N$. The CGSV of agent $i \in \mathcal{N}$ is defined as

$$\phi_i := \frac{1}{(N-1)!} \sum_{\pi \in \mathcal{P}_N} (\cos(u_{S_{i,j}}; u_{\pi}) - \cos(u_{S_{i,j}}; u_{\pi'})) \quad (2)$$

If ϕ_i is negative, then it follows from the weighted sum of parameter updates/gradients that u_i points in an opposite direction to some other parameter updates/gradients and hence has negative cosine similarities to them. In practice, due to the noisy training arising from the stochastic

gradient descent (SGD) and/or a highly non-convex loss function, may at times be negative even for an honest agent. When the number of such cases is limited, training via SGD can still converge to yield a competitive predictive performance, as empirically validated in [12].

3.3 Efficient Approximation of CGSV

Since evaluating agent's CGSV \hat{u}_i (2) exactly incurs $\mathcal{O}(2^N D)$ time and is thus costly, we propose an efficient approximation by directly measuring the cosine similarity of its (normalized) parameter update/gradient u_i to the grand coalition's aggregated parameter update/gradient, which reduces the incurred time by a factor of 2^N and has a bounded error from (Theorem 1):

$$\hat{u}_i \approx u_i := \cos(u_i; u_N) : \quad (3)$$

Theorem 1 (Approximation Error). Let $\alpha \in \mathbb{R}^+$. Suppose that $\|u_i\| = \alpha$ and $\|u_N\| = 1$ for all $i \in \{1, \dots, N\}$. Then, $\|u_i - \hat{u}_i\| \leq \alpha \sqrt{1 - \alpha^2}$ where the multiplicative factor α can be normalized away.

Its proof is in Appendix A.2. From Theorem 1, the approximation error is bounded and decreases quadratically with normalization coefficient. However, α cannot be reduced to be arbitrarily small, which may cause $\|u_i; u_N\| = 1$ not to hold. It also does not hold when u_i is orthogonal to u_N or is close to the zero vector, hence implying the quality of that agent's parameter update/gradient is not high enough. So, every agent is encouraged to contribute a parameter update/gradient of sufficiently high quality in order to ensure the quality of the approximation (Theorem 1).

We have performed a simple experiment to compare the quality of our approximation with that of a sampling-based (ϵ)-approximation \hat{u}_i [38], the latter of which is widely used by existing works in data valuation and CML/FL [4, 19, 51, 54]. In this experiment, we have drawn random D -dimensional vectors from a standard multivariate normal distribution to simulate $u_i; u_N$ and calculated the resulting exact CGSVs $\hat{u}_i = (u_i)_{i=1, \dots, N}$, our approximation $\hat{u}_i := (u_i)_{i=1, \dots, N}$, and the sampling-based ($\epsilon; 0.1$)-approximation $\hat{u}_i := (u_i)_{i=1, \dots, N}$. Fig. 1 shows the results for error, ℓ_2 error, and the incurred time averaged over 10 runs: Our approximation performs better in all three metrics with varying D (right figure) and the performance gap widens with an increasing number N of agents (left figure).

Figure 1: Comparison of ℓ_1 error (blue), ℓ_2 error (orange), and incurred time (green) (i.e., averaged over 10 runs) between our approximation (solid lines) vs. a sampling-based approximation (dashed lines) [38] of the exact CGSVs with (left) varying number N of agents and (right) varying vector dimension $D = 1024$, and $N = 10$. For all metrics, lower is better.

Figure 2: (Left) ℓ_2 distance between model parameters of agent $i = 1; \dots; 5$ (abbreviated to A_i) vs. that of the server, and (right) corresponding training loss for an FL problem with $N = 5$ agents using local MNIST datasets of 10 images each to collaboratively learn a 2-layer CNN with (left) varying number N of agents and parameters where the datasets of A_1 (blue), A_2 (orange), and A_3 (green) have 20%, 40% and 60% randomly corrupted labels, respectively. The brown line denotes ℓ_2 distance between w_0 (initialization) vs. server's model parameters.

3.4 Server-Side Training-Time Gradient Reward Mechanism

We will now describe the exact details of the gradient aggregation and download steps performed by the server to implement our proposed fair gradient reward mechanism:

Gradient Aggregation Step. With a specified normalization coefficient and an initialized coefficient $r_{i,0}$, the server performs normalization and aggregation of all agents' parameter updates into

$u_{N;t}$ using (1), as previously discussed in the FL problem setting (Sec. 3.1). Then, the server computes our approximation $\hat{r}_{i;t}$ (3) of the CGSV $r_{i;t}$ (2) and updates (and normalizes) the importance coefficient $r_{i;t}$ in iteration t via a moving average of $\hat{r}_{i;t}$ given the relative weight α on $r_{i;t-1}$ from previous iteration $t-1$:

$$r_{i;t} := \alpha r_{i;t-1} + (1-\alpha) \hat{r}_{i;t}; \quad r_{i;t} = \frac{1}{\sum_{i \in \mathcal{N}} r_{i;t}} \sum_{i \in \mathcal{N}} r_{i;t} \quad (4)$$

where $r_{i;0} := 0$. Note that $r_{i;t}$ (4) is used for deriving the sparsified gradient (5) in the gradient download step as well as the aggregation of all agents' parameter updates $\theta_{i;t}$ into (1) in iteration $t+1$. The use of a moving average of $\hat{r}_{i;t}$ to compute $r_{i;t}$ (4) provides a smoothed estimate without abrupt fluctuations and reduces the effect of noisy training due to the use of SGD in practice. It also allows a flexible weighting over the iterations of the entire training process: In particular, setting $\alpha < 1$ can effectively mitigate the noise from random initialization of model parameters because the weight α^t in earlier iteration $0 < t$ decays exponentially with [53].

Gradient Download Step. Recall from the vanilla FL problem setting (Sec. 3.1) that in each iteration t , this step involves all agents downloading an identical aggregated parameter update/gradient from the server (as reward) for updating their model parameters to the server, which is expected to converge to yield a competitive predictive performance [3, 31]. However, such equal rewards to all agents is unfair and will discourage any agent from uploading/contributing a parameter update/gradient of higher quality [6, 60] when it can afford to. To ensure fairness, each agent should download some form of aggregated parameter update/gradient as reward that is commensurate to the quality/value of its uploaded/contributed parameter update/gradient. Consequently, an agent who uploads/contributes higher-quality parameter updates/gradients over the entire training process should eventually be rewarded with converged model parameters whose resulting training loss (and hence predictive performance) is closer to that of the server (Theorem 2).

To achieve this, we adopt the trick of sparsifying² the aggregated parameter update/gradient downloaded by agents as reward in each iteration. Specifically, we zero out fewer of its smallest components (hence higher-quality gradient reward) when the importance coefficient $r_{i;t}$ (i.e., moving average of the approximate CGSV $\hat{r}_{i;t}$) is larger:

$$v_{i;t} := \text{mask}(u_{N;t}; q_{i;t}); \quad q_{i;t} := \text{bD} \tanh(r_{i;t}) = \max_{i \in \mathcal{N}} \tanh(r_{i;t}) c \quad (5)$$

where $\text{mask}(u; q)$ retains the largest $\max(0; q)$ components (in magnitude) of u and zeros out all of its other components [58], and bD specifies the degree of altruism: Greater altruism gives any agent with a smaller $r_{i;t}$ a larger improvement in the quality of its gradient reward, i.e., a larger reduction in the sparsity of its downloaded reward. In the extreme case of $\text{bD} = 1$, we recover the vanilla FL problem setting (Sec. 3.1) where all agents are rewarded equally with $u_{N;t}$ (i.e., best-quality gradient reward $v_{i;t} = u_{N;t}$ for all $i \in \mathcal{N}$ with no sparsification), albeit with importance coefficients $r_{i;t}$ possibly differing across agents $\in \mathcal{N}$ and dynamically updated over iteration $t \in \mathbb{Z}^+$. Hence, increasing from 1 to bD trades off fairness for equality in gradient rewards by being more altruistic to any agent with a smaller $r_{i;t}$; we empirically show the effect of varying on training loss in Fig. 7 of Sec. 4.2. Note the agent $i^* = \arg\max_{i \in \mathcal{N}} \tanh(r_{i;t})$ with the largest possible $r_{i;t}$ does not benefit from such altruism since it already downloads the best-quality gradient reward (i.e., $u_{N;t}$) according to (5).

Suppose that there exists a known threshold $\underline{r} > 0$ s.t. $r_{i;t} \geq \underline{r}$ for all $i \in \mathcal{N}$ and $t \in \mathbb{Z}^+$ and we want to limit the sparsity of any downloaded reward, or, equivalently, ensure the minimum quality of any gradient reward: Specifically, given a predefined threshold $\underline{c} \in (0, 1]$, we want to guarantee $v_{i;t} \geq \text{bD} \underline{c}$ holds for all $i \in \mathcal{N}$ and $t \in \mathbb{Z}^+$. By setting $\underline{c} = \text{bD} \tanh(\underline{r})$, it follows from (5) and $\max_{i \in \mathcal{N}} \tanh(r_{i;t}) \geq 1$ that $\tanh(r_{i;t}) \geq \max_{i \in \mathcal{N}} \tanh(r_{i;t}) \tanh(\underline{r}) = \underline{c}$ and hence $v_{i;t} \geq \text{bD} \underline{c}$ ensues. By using the property that $\tanh(\underline{r}) = (\exp(2\underline{r}) - 1) / (\exp(2\underline{r}) + 1)$, $\ln((1+c)/(1-c)) = (2\underline{r})$ can be derived and used for setting. It further informs us that reducing the sparsity of any downloaded reward, equivalently, improving the minimum quality of any gradient reward (i.e., by increasing \underline{c}), requires greater altruism to be introduced, while improving the minimum quality of uploaded/contributed parameter updates/gradients by any agent over the entire training process (hence **reduces** the need of introducing greater altruism).

To see why the sparsifying gradient trick (5) can ensure fairness, we illustrate its effect in an FL problem with $N = 5$ agents using local MNIST datasets of 10 images each to collaboratively learn

²Sparsifying a parameter update/gradient vector means zeroing out some of its components and leaving the others unchanged [7, 32].

the parameters of a 2-layer convolutional neural network (CNN) where the datasets of agents 1, 2, and 3 have 20%, 40%, and 60% randomly corrupted labels, respectively. The uploaded/contributed parameter updates/gradients thus decrease in quality from agents 1, 2, and 3 (i.e., $r_{1,t} = 0.194$, $r_{2,t} = 0.088$, and $r_{3,t} = 0.043$ on average) due to increasingly noisy labels in their datasets, while agents 4 and 5 upload/contribute parameter updates/gradients of high quality (i.e., $r_{4,t} = 0.331$ and $r_{5,t} = 0.342$ on average) due to uncorrupted labels in their datasets. Consequently, agents 1, 2, and 3 have increasing sparsity (resp. 34.9%, 67.6%, and 83.0% on average) while agents 4 and 5 have little/no sparsity (resp. 3.5% and 1.1% on average) in their downloaded parameters as rewards ($r = 1$). Fig. 2 shows that the converged model parameters of agents 1, 2, and 3 grow in ℓ_2 distance from that of the server (hence increasing training loss) while agents 4 and 5 have the closest converged model parameters (hence lowest training loss).

We provide the pseudocodes performed by the server and agent in each iteration below. We will discuss in Sec 4.2 how to set the hyperparameters, and α , in (1), (4), and (5) respectively in our experiments.

Server(t)

```

1: for all  $i \in \{1, 2, \dots, N\}$  do
2:   Download  $w_{i,t}$  from agent  $i$ 
3:   Gradient Aggregation Step
4:   Compute  $u_{i,t}$  and  $u_{N,t}$  (1)
5: for all  $i \in \{1, 2, \dots, N\}$  do
6:   Compute  $r_{i,t}$  (3) and  $r_{i,t}$  (4)
7:   Gradient Download Step
8: for all  $i \in \{1, 2, \dots, N\}$  do
9:   Compute  $v_{i,t}$  (5) for download by agent  $i$ 

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Agent($i; t$)

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1: Upload  $w_{i,t} = r_{i,t} F_i(w_{i,t-1})$  to server
2: Download  $v_{i,t}$  from server
3: Update  $w_{i,t} = w_{i,t-1} + v_{i,t}$ 

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3.5 Fairness Guarantee

We have previously discussed the intuition underlying our notion of fairness in Sec. 3.4 that an agent who uploads/contributes higher-quality parameter updates/gradients over the entire training process should eventually be rewarded with converged model parameters whose resulting training loss (and hence predictive performance) is closer to that of the server. Note that the importance coefficient $r_{i,t}$ (4) measures the overall quality of the parameter updates/gradients uploaded/contributed by agent i over the entire training process till iteration t . Our main result below guarantees a notion of fairness that under some conditions on loss function F and the server's model parameters, if an agent i has a larger importance coefficient $r_{i,t}$ and model parameters $w_{i,t-1}$ closer to that of the server (i.e., $w_{i,t-1}$) than another agent j by at least $2\alpha \|w_{i,t-1} - w_{j,t-1}\|_k$ in previous iteration $t-1$, then it is rewarded with model parameters $w_{i,t}$ incurring smaller training loss $\mathcal{L}(w_{i,t})$ in iteration t :

Theorem 2 (Fairness in Training Loss). Let $\|w\|_k := \|kw\|_k$. Suppose that w_t is near to a stationary point of F for $t \in \mathbb{Z}^+$ and some regularity conditions \mathcal{C} hold. For all $i, j \in \{1, \dots, N\}$ and $t \in \mathbb{Z}^+$, if $r_{i,t} \geq r_{j,t}$ and $\|w_{i,t-1} - w_{j,t-1}\|_k \geq 2\alpha \|w_{i,t-1} - w_{j,t-1}\|_k$, then $\mathcal{L}(w_{i,t}) \leq \mathcal{L}(w_{j,t})$.

Its proof is in Appendix A.3. Our experiments in Appendix B.3 will empirically verify the fairness guarantee in Theorem 2 (and fairness in test accuracy) without needing to impose its conditions.

4 Experiments and Discussion

4.1 Experimental Settings

Datasets. We perform extensive experiments on image classification datasets like MNIST [25] and CIFAR-10 [21] and text classification datasets like movie review (MR) [43] and Stanford sentiment treebank (SST) [20]. We use a 2-layer convolutional neural network (CNN) for MNIST [25], a 3-layer CNN for CIFAR-10 [22], and a text embedding CNN for MR and SST [20].

Baselines. We consider several existing FL baselines such as FedAvg [30], FFL [30], CFFL [36], and an extended contribution index (ECI) method from [53] utilizing validation accuracy-based SV and setting $g_{i,t}$ for $i \in \{1, \dots, N\}$ in (5) to be proportional to the agents' CIs. CFFL also utilizes the validation accuracy but is more efficient by using a leave-one-out approach instead of SV, and FFL aims at

Table 1: Average test accuracy (%) achieved by the agents collaborating via our fair gradient reward mechanism with varying degrees of altruism vs. tested baselines on all datasets. Each value in brackets denotes the highest test accuracy achieved by any agent.

No. Agents	MNIST						CIFAR-10			MR	SST
	10			20			10			5	5
	UNI	POW	CLA	UNI	POW	CLA	UNI	POW	CLA	POW	POW
Standalone	91 (91)	88 (92)	53 (92)	91 (91)	89 (92)	48 (90)	46 (47)	43 (49)	31 (44)	47(56)	31(34)
FedAvg	93 (94)	92 (94)	53 (93)	93 (93)	92 (94)	49 (92)	48 (48)	47 (50)	32 (47)	51(63)	33(35)
q-FFL	85 (91)	27 (45)	44 (64)	88 (91)	48 (53)	40 (59)	41 (46)	36 (36)	22 (28)	12(18)	23(25)
CFFL	90 (92)	85 (90)	34 (44)	91 (93)	88 (91)	39 (46)	39 (41)	35 (45)	22 (40)	44(53)	31(32)
ECI	94 (94)	92 (94)	53 (94)	94 (94)	92 (94)	49 (92)	49 (49)	47 (51)	31 (46)	56(61)	33(34)
DW	93 (94)	92 (94)	53 (93)	93 (93)	92 (94)	49 (92)	48 (48)	47 (50)	32 (47)	51(62)	33(35)
RR	94 (95)	95 (95)	64 (72)	94 (95)	94 (95)	50 (56)	47 (59)	49 (51)	26 (29)	63(65)	36(36)
Ours (EU)	94 (94)	94 (94)	54 (94)	94 (94)	94 (94)	49 (92)	49 (49)	49 (51)	32 (46)	54(59)	34(36)
Ours (= 1)	96 (97)	94 (95)	74(95)	95 (96)	96 (97)	65 (93)	61 (62)	60 (62)	35 (54)	62(76)	35(36)
Ours (= 1 :2)	94 (95)	95 (95)	75(95)	96 (96)	96 (97)	65 (93)	61 (62)	60 (62)	35 (54)	62(75)	34(37)
Ours (= 1 :5)	97 (97)	95 (95)	75(95)	96 (97)	94 (95)	65 (93)	61 (62)	59 (62)	35 (54)	62(74)	35(37)
Ours (= 2)	96 (96)	95 (96)	73 (94)	97 (97)	95 (96)	66 (95)	62 (62)	61 (62)	36 (54)	62(75)	35(37)

achieving egalitarian fairness by equalizing the local training losses of the agents. Furthermore, we implement simple FL baselines based on random robin (RR), dataset weighted download (DW), and Euclidean distance (EU). RR is commonly adopted in mechanism design to ensure fairness [6, 33] and also used in FL to schedule gradient download [50, 64]. For DW (EU), q_i for $i \in \{1, \dots, N\}$ are set to be proportional to the agents' local dataset sizes (negative Euclidean distance of their unnormalized parameter updates from that of the server). We also implement standalone agents as a baseline, i.e., each agent trains its CNN using only its local dataset without involving FL.

Performance Metrics. To measure fairness, we consider the scaled Pearson correlation coefficient $r := 100 \cdot \text{pearson}(r; \cdot) \in [0, 100]$ between the test accuracies achieved by the agents when standalone [36] vs. that achieved by them when collaborating via a gradient reward mechanism in FL after the entire training process has ended at iteration T . The corresponding experimental results will be reported in Sec. 4.2. To empirically verify the fairness guarantee in Theorem 2, we have also reported in Appendix B.3 results on the fairness metric between the importance coefficients' $r := (r_{i,T})_{i=1, \dots, N}$ (4) (i.e., measuring overall qualities of the parameter updates/gradients uploaded/contributed by the agents) vs. test accuracies (or negative training losses) achieved by them. We consider other performance metrics like predictive performance (i.e., average and highest test accuracies achieved by the agents) and time overhead of the tested gradient reward mechanisms.

Data Partitions among Agents. We carefully construct two heterogeneous data partitions by varying the agents' local dataset sizes and corresponding numbers of distinct classes. For balanced dataset sizes (POW), we follow a power law to partition the entire dataset among the agents. For MNIST, we partition the entire dataset of size 60000 into 6000, 12000, respectively, among 5, 10, 20 agents s.t. each agent has a randomly sampled local dataset of size $6000/n$ on average [39]. The size of the local dataset increases from the first to the last agent. Since the local dataset sizes vary significantly (i.e., superlinearly) among the agents, the agents with larger local datasets are expected to achieve better predictive performance. For balanced class numbers (CLA), we vary the number of distinct classes in the local datasets of the agents, while keeping their sizes fixed. For this setting, we only consider MNIST and CIFAR-10 datasets and partition classes in a "linespace" manner as both contain 10 classes. To illustrate, for MNIST with agents, agents 2, 3, 4, 5 own local datasets with 1, 3, 5, 7, 10 classes, respectively; so, agent (5) has a local dataset with (10) class(es). Similarly, the agents with local datasets containing more classes are expected to achieve better predictive performance. We also include the simplest setting of the uniform/homogeneous data partition (UNI) where the agents are expected to achieve comparable predictive performance.

Additional details of the experimental settings are described in Appendix B.1.

4.2 Experimental Results

Predictive Performance. Table 1 shows results of the average and highest test accuracies achieved by the agents collaborating via our fair gradient reward mechanism vs. tested baselines on all datasets. Our fair gradient reward mechanism generally outperforms the tested baselines on both metrics, especially for heterogeneous data partitions and on the MR dataset. On MNIST, for the

³The Pearson correlation coefficient has been applied to a similar use case in [19].

Table 2: Fairness metric 2 [100, 100] achieved by our fair gradient reward mechanism with varying degrees of altruism vs. tested baselines on all datasets. Higher value means greater fairness.

No. Agents	MNIST						CIFAR-10			MR	SST
	10			20			10			5	5
Data Partition	UNI	POW	CLA	UNI	POW	CLA	UNI	POW	CLA	POW	POW
FedAvg	-45.60	55.24	24.12	0.85	-32.58	40.83	18.47	97.48	98.75	48.68	57.50
q-FFL	-44.73	39.00	22.38	-22.01	38.71	48.07	-17.64	51.33	94.06	56.43	-75.92
CFFL	83.57	91.80	81.24	82.52	94.70	85.71	78.25	72.55	81.31	96.85	93.34
ECI	85.26	99.83	99.98	80.95	99.41	95.21	75.85	79.50	99.55	97.69	95.00
DW	89.15	98.93	65.34	86.94	99.63	35.21	-23.14	91.97	45.45	99.20	97.12
RR	83.77	71.17	-26.75	-18.64	25.47	95.86	30.67	0.70	90.67	44.16	-25.11
Ours (EU)	84.25	98.25	99.82	80.55	97.77	99.97	78.25	94.24	94.95	97.58	93.21
Ours (= 1)	94.03	95.74	94.54	84.47	96.39	97.23	98.80	98.78	99.89	96.01	98.20
Ours (= 1 :2)	94.75	97.28	96.23	90.52	97.72	95.21	91.07	91.59	99.82	96.12	98.47
Ours (= 1 :5)	96.34	86.99	95.37	82.68	90.94	98.75	93.55	93.78	95.89	95.32	97.88
Ours (= 2)	94.66	91.20	95.38	96.90	91.33	94.32	89.80	88.78	93.39	92.22	95.74

CLA data partition among 10 agents, our fair gradient reward mechanism achieves average (highest) test accuracy of 75% (95%) at $\alpha = 1:5$, while the best-performing ECI baseline achieves only that of 53% (94%). On CIFAR-10, for the CLA data partition among 10 agents, our fair gradient reward mechanism achieves average (highest) test accuracy of 54% (54%) at $\alpha = 2$, while the best-performing DW baseline achieves only that of 32% (47%). On the MR dataset, our fair gradient reward mechanism achieves average (highest) test accuracy of 76% (76%) at $\alpha = 1$, while the best-performing RR baseline achieves that of 63% (65%). Its better performance may be attributed to the adaptive re-weighting in the gradient aggregation (step 4), which can dynamically account for the heterogeneity in the agents' local datasets. While EU performs comparably to both FedAvg and ECI (i.e., difference in average test accuracies between EU vs. FedAvg/ECI is less than 3%), it does not perform better than our fair gradient reward mechanism (e.g., on MNIST, for the CLA data partition among 10 agents, the difference in average test accuracies between EU vs. our fair gradient reward mechanism at $\alpha = 1:5$ is more than 20%) because unlike cosine similarity, Euclidean distance fails to capture the directional difference between gradients, which is important since the negative gradients are pointing in the direction of lower loss. Importantly, q-FFL aims to equalize the local training losses w.r.t. the agent's local datasets, which may be suboptimal for heterogeneous data partitions like POW and CLA. We provide further results in Appendix B.5 empirically comparing the predictive performances of our fair gradient reward mechanism vs. FedAvg.

Fairness. To empirically verify the fairness guarantee in Theorem 2, Table 2 shows results on the fairness metric achieved by our fair gradient reward mechanism vs. tested baselines on all datasets. From Table 2, our fair gradient reward mechanism achieves a high degree of fairness of 45:60 while the commonly used FedAvg performs suboptimally s.t. it produces the lowest degree of fairness of 45:6. On MNIST, for the POW data partition among 10/20 agents and the CLA data partition among 10 agents, ECI outperforms our fair gradient reward mechanism, albeit at a much higher time overhead of over 100 times and with additional information from an auxiliary dataset. CFFL underperforms our fair gradient reward mechanism and ECI as it adopts the leave-one-out approach which seems less accurate than SV in valuing the contributions of the agents. Both q-FFL and RR promote egalitarian fairness instead of our notion of fairness via SV and hence do not perform optimally. DW achieves high degrees of fairness only for the POW data partition because it uses the agents' local dataset sizes to determine their gradient rewards. Fig. 3 illustrates an intuitive trend of the predictive performances achieved by agents collaborating via our fair gradient reward mechanism for homogeneous and heterogeneous data partitions among the agents on MNIST and CIFAR-10. For the UNI data partition, all agents achieve comparable predictive performance. Their predictive performances vary more (most) for the POW (CLA) data partition, hence demonstrating that our fair gradient reward mechanism can distinguish the contributions of the agents and reward them with sparsified gradients fairly.

We have performed an additional experiment to understand our fair gradient reward mechanism for homogeneous and heterogeneous data partitions among agents on MNIST and CIFAR-10 where for POW and CLA, agent (3) uploads/contributes parameter updates/gradients of lowest (highest) quality over the entire training process. Fig. 4 shows how for agent $i = 1; 3$ varies over iterations t : Interestingly, for the CLA data partition, though agent (3) (brown solid line) is initially mistaken to provide a low contribution, the dynamic update of α (4) allows its true contribution to be recognized quickly. Fig. 5 (Fig. 6) shows how the distance between the downloaded sparsified gradients (5)

Figure 3: Test accuracy achieved by agent 1 ; ::; 10 (abbreviated to A_i) collaborating via our fair gradient reward mechanism at 2 for the UNI (left), POW (middle), and CLA (right) data partitions among the 10 agents on MNIST (top) and CIFAR10 (bottom). Their predictive performances vary least, more, and most for the respective UNI, POW, and CLA data partitions.

Figure 4: Graphs of ℓ_2 distance between last layer's model parameters of agent $i = 1; 3$ and aggregated parameter update/gradient (1) vs. iteration for UNI, POW, and CLA data partitions among agents on MNIST and CIFAR10.

Figure 5: Graphs of ℓ_2 distance between downloaded $v_{i;t}$ (5) of agent $i = 1; 3$ and aggregated parameter update/gradient (1) vs. iteration for UNI, POW, and CLA data partitions among agents on MNIST (left) and CIFAR10 (right).

of agent $i = 1; 3$ and aggregated parameter update/gradient (1) (last layer's model parameters of agent $i = 1; 3$ and that of the server) varies over iterations. In particular, for the CLA data partition, agent $i = 1$ ($i = 3$) who uploads/contributes parameter updates/gradients of lowest (highest) quality over the entire training process downloads as reward that is further from (closer to) $v_{i;t}$, hence training last layer's model parameters to be further from (closer to) that of the server. Such results further validate that in Fig. 2 previously.

Lastly, Fig. 7 confirms that for the CLA data partition among agents on MNIST, increasing the degree of altruism leads to all agents downloading higher-quality gradient rewards (5) and thus incurring smaller training loss. In particular, agent $i = 1$ (abbreviated to A and represented by a blue solid line) who uploads/contributes parameter updates/gradients of lowest quality over the entire training process benefits most as increases, as explained previously in Sec. 3.4. Additional results w.r.t. test loss are reported in Appendix B.4.

Time Overhead. Table 3 compares the time overhead (seconds) of our fair gradient reward mechanism vs. tested baselines on all datasets; the ratio between the time overhead vs. training time is given in brackets. Our fair gradient reward mechanism is much more efficient than ECI and CFFL which also consistently achieve fairness. In particular, our fair gradient reward mechanism incurs a small time overhead of at most 0.4 of the training time, while ECI incurs a significant time overhead of up to 140 of the training time due to the calculation of the CI incurred ($O(2^N)$) time, even with the permutation sampling-based approximation [54] for 10/20 agents. CFFL incurs at most 1 of the training time (i.e. 5-6 times longer than ours) from the additional validation in each iteration.

Hyperparameters. We find that $\alpha = 2$ [0.8; 1] (i.e., relative weight on $v_{i;t-1}$ in (4)), $\beta = 2$ [1; 2] (i.e., degree of altruism in (5)) and $\gamma = 2$ [0.1; 1] (i.e., normalization coefficient in (1)) are effective in

Figure 7: Training losses incurred by agent 1 ; : : ; 10 (abbreviated to A) collaborating via our fair gradient reward mechanism with varying degrees of altruism α : 0; 1:2; 1:5; 2 for the CLA data partition on MNIST.

Table 3: Time overhead (seconds) of our fair gradient reward mechanism vs. tested baselines on all datasets. Each value in brackets denotes the ratio between the time overhead vs. training time.

No. Agents	MNIST			CIFAR-10		MR	SST
	5	10	20	5	10	5	5
FedAvg	1.17 (7e-3)	1.05 (1e-2)	4.29 (1e-2)	1.66 (7e-3)	7.41 (1e-2)	1.3 (1e-4)	1.31 (6e-4)
q-FFL	6.14 (4e-2)	4.97 (5e-2)	91.20 (0.3)	97.28 (0.4)	58.94 (7e-2)	90.01 (8e-3)	82.85 (4e-2)
FFFL	32.15 (0.2)	21.79 (0.3)	500.03 (1.6)	570.12 (2.0)	302.44 (0.4)	479.12 (0.2)	487.71 (2e-1)
ECl	2377.33 (16)	11937.80 (141)	23749.06 (74)	3571.75 (15)	58835.83 (84)	422.85 (4e-2)	801.20 (0.4)
DW	0.89 (6e-3)	0.79 (9e-3)	1.60 (5e-3)	1.21 (5e-3)	5.29 (7e-3)	0.99 (1e-5)	0.98 (5e-4)
RR	0.89 (6e-3)	0.82 (9e-3)	1.60 (5e-3)	3.31 (1e-2)	5.41 (7e-3)	1.01 (5e-4)	0.99 (5e-4)
Ours (EU)	0.89 (6e-3)	0.81 (9e-3)	1.61 (5e-3)	1.22 (5e-3)	5.33 (7e-3)	1.01 (5e-4)	0.99 (5e-4)
Ours (Cosine)	6.34 (4e-2)	4.94 (5e-2)	94.30 (0.3)	98.39 (0.4)	54.94 (7e-2)	89.81 (8e-3)	82.87 (4e-2)

achieving competitive predictive performance and fairness. In our experiments, we set $\alpha = [1; 1:2; 1:5; 2]$, and $\alpha = 0.5$ for MNIST, $\alpha = 0.15$ for CIFAR-10, and $\alpha = 1$ for SST and MR.

5 Conclusion and Future Work

We introduce a novel formulation called cosine gradient Shapley value (CGSV) to fairly evaluate the quality/value of the uploaded/contributed model parameter updates/gradients by the agents in federated learning (FL)/gradient-based collaborative machine learning (CML) and use it to design their corresponding rewards in the form of downloaded gradients. Our approach ensures that the agents who upload better gradients can download better gradients, which in turn leads to better local models with lower training losses. We theoretically and empirically demonstrate the effectiveness of our approach on both predictive performance and fairness. Moreover, our approach is much more efficient than existing baselines and non-restrictive, i.e., it requires only slight calculations by the server and does not require an auxiliary dataset.

Our approach provides high flexibility for the trade-off between equitable and strictly fair rewards via a hyperparameter controlling the degree of altruism. Interestingly, a higher altruism degree can sometimes lead to better predictive performance, which naturally raises the following question: Can we achieve both optimally or is there some inescapable trade-off between fairness and performance? For future work, it would be interesting to consider the notion of fairness when there are some adversaries. We would also consider generalizing our work and fairness guarantee to other forms of CML (e.g., model fusion [16, 17, 24]) and collaborative Bayesian optimization [52].

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Checklist

1. For all authors...
 - (a) Do the main claims made in the abstract and introduction accurately reflect the paper’s contributions and scope? **[Yes]** Section 3 formalizes our fairness framework and solution while Section 4 provides the theoretical guarantees.
 - (b) Did you describe the limitations of your work? **[Yes]** See Section 4 where we explicitly point out that the noise in estimation and generalizability are potential limitations.
 - (c) Did you discuss any potential negative societal impacts of your work? **[N/A]**
 - (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? **[Yes]**
2. If you are including theoretical results...
 - (a) Did you state the full set of assumptions of all theoretical results? **[Yes]** The assumptions are stated and interpreted when the results are presented.
 - (b) Did you include complete proofs of all theoretical results? **[Yes]** See Appendix A for complete proof of all theoretical results.
3. If you ran experiments...
 - (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? **[Yes]**
 - (b) Did you specify all the training details (e.g., data splits, hyperparameters, how they were chosen)? **[Yes]** See Section 5 for training details and Appendix B for additional information on hyperparameters.
 - (c) Did you report error bars (e.g., with respect to the random seed after running experiments multiple times)? **[N/A]**
 - (d) Did you include the total amount of compute and the type of resources used (e.g., type of GPUs, internal cluster, or cloud provider)? **[Yes]** See Appendix B for computational resources used.
4. If you are using existing assets (e.g., code, data, models) or curating/releasing new assets...
 - (a) If your work uses existing assets, did you cite the creators? **[Yes]** See Section 5 under the paragraph for Datasets.
 - (b) Did you mention the license of the assets? **[N/A]**
 - (c) Did you include any new assets either in the supplemental material or as a URL? **[No]**
 - (d) Did you discuss whether and how consent was obtained from people whose data you’re using/curating? **[N/A]**
 - (e) Did you discuss whether the data you are using/curating contains personally identifiable information or offensive content? **[N/A]**
5. If you used crowdsourcing or conducted research with human subjects...
 - (a) Did you include the full text of instructions given to participants and screenshots, if applicable? **[N/A]**
 - (b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? **[N/A]**
 - (c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? **[N/A]**