Optimization-Based Approaches for Enforcing Fairness in Machine Learning

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Abstract

1. Introduction

Over the past few years, machine learning (ML) and artificial intelligence (AI) have become increasingly more common for high-stakes decision making. Researchers have proposed machine learning algorithms for applications such as credit scoring (Huang et al., 2007), personalized medicine (Poplin et al., 2018), and redicivism prediction (Tollenaar & Van der Heijden, 2013).

In light of our increased adoption of ML/AI methods, it is important that we do not allow these technologies to foster unfairness within our society. Machine learning algorithms fundamentally rely on past data in order to function. They attempt to generalize patterns found in the data and apply these patterns to make predictions in future scenarios. However, in certain situations, historical injustices against presently protected subgroups of a population may have led to the recording of biased data. Natively training a model on this biased data may lead to a biased algorithm that discriminates against these protected subgroups. Subsequently using this algorithm for high-stakes decision making may lead to further injustices and bias the collection of future data, thereby leading to a dangerous positive feedback loop.

Thus, finding ways to enforce fair predictions for machine learning algorithms is a problem of utmost importance. In this paper, we propose some methods that strive to achieve this goal. These methods are primarily optimization-based, meaning that they each involve augmenting the objective function of machine learning methods in some manner and can be seen as a form of regularization. We employ our methods in neural networks, models that have garnered a great deal of popularity in recent years due to empirical success across many domains. Our empirical results are presented on the *adult income dataset*[1], which was collected from 1994 census data (Kohavi, 1996). We show that our proposed approaches can significantly reduce model bias defined in the form of *disparate impact* and uphold desired levels of *demographic parity* without sacrificing a prohibitive amount of accuracy.

1.1. Related Work

Talk about COMPAS, other work in fairness, etc.

2. Background

2.1. Adult Income Dataset

The adult income dataset (Kohavi, 1996) contains data from $N = 48,842$ respondents to the 1994 United States Census. Each person n is characterized by $J = 14$ attributes, denoted $\boldsymbol{x}^{(n)} = \{x_1^{(n)}, \ldots, x_J^{(n)}\}$, including education level, occupation type, capital gains, capital losses, and number of hours worked per week. The goal is to predict a binary variable $y^{(n)} \in \{0, 1\}$, which indicates whether or not person n makes over \$50,000 a year.

In this case, the protected attributes $\boldsymbol{z}^{(n)}$ for person n are their *sex* and their *race*. Historical inequities have led to groups such as women and African Americans having significantly lower fractions of individuals making over \$50,000 a year. Using a model naively trained on the adult income dataset for high stakes decision making in the present day – such as estimating a person's income for loan approval or determining how much to pay a new hire – may lead to heavily biased results. Thus, there is motivation to incorporate predictive fairness into the model training process.

2.2. Disparate Impact and Demographic Parity

Disparate impact is the notion in which a model's biased classification process leads to outcomes that disproportionately hurt (or benefit) people with sensitive attributes. It was first introduced by Zafar et al. (2015). Simply removing the sensitive attributes $\boldsymbol{z}$ from the dataset and training a model on the remaining attributes $\boldsymbol{x} \setminus \boldsymbol{z}$ may still yield biased predictions, because $\boldsymbol{z}$ may be correlated with the remaining

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[1]This dataset is publicly available at `https://archive.ics.uci.edu/ml/datasets/adult`.

subset (Agarwal et al., 2018).

To counter disparate impact, we wish to enforce *demographic parity*, which demands that the distribution of scores for any protected classes is the same. Let $\hat{y}$ be a model's prediction. Formally, demographic parity is defined as:

$$p(\hat{y} = 1 \mid \boldsymbol{z} = k_1) = p(\hat{y} = 1 \mid \boldsymbol{z} = k_2), \tag{1}$$

where k_1 and k_2 are different realizations of the random variable $\boldsymbol{z}$. For example, if $\boldsymbol{z}$ is sex, k_1 could be `Male` and k_2 could be `Female`. Intuitively, this means that only changing the protected attribute $\boldsymbol{z}$ should not influence the predictions in any way.

Using demographic parity as a definition of machine learning fairness offers some advantages. First and foremost, there exists legal support for this definition in the United States. In 1978, four government agencies – including the EEOC, Department of Labor, Department of Justice, and the Civil Service Commission – proposed the four-fifths (or 80%) rule as a benchmark with assessing adverse disparate impact for protected classes (Bobko & Roth, 2004). Specifically, these agencies required that

$$\min\left\{\frac{p(\hat{y} = 1 \mid \boldsymbol{z} = k_1)}{p(\hat{y} = 1 \mid \boldsymbol{z} = k_2)}, \frac{p(\hat{y} = 1 \mid \boldsymbol{z} = k_2)}{p(\hat{y} = 1 \mid \boldsymbol{z} = k_1)}\right\} \geq \frac{q}{100} \tag{2}$$

where $q = 80$ in the legal definition. Recently, Hu and Chen (2018) additionally argue that short-term enforcement of demographic parity has long-term benefits for countering discrimination against minorities in the labor market.

3. Methods for Enforcing Demographic Parity

We present two optimization-based methods for enforcing demographic parity in neural networks.

A neural network is a cascade of linear and nonlinear transformations of the input vector $\boldsymbol{x}$ to yield an output vector $\boldsymbol{h}_L$ (Goodfellow et al., 2016). An L-layer neural network can be described by the equations,

$$\begin{aligned} \boldsymbol{h}_1 &= f^{(1)}(W^{(1)}\boldsymbol{x} + b^{(1)}), & \ldots \\ \boldsymbol{h}_\ell &= f^{(\ell)}(W^{(\ell)}\boldsymbol{h}_{\ell-1} + b^{(\ell)}), & \ldots \\ \boldsymbol{h}_L &= f^{(L)}(W^{(L)}\boldsymbol{h}_{L-1} + b^{(L)}), \end{aligned} \tag{3}$$

where each pair $(W^{(\ell)}, b^{(\ell)})$ parameterizes an affine transformation (via matrix multiplication and bias addition), each $f^{(\ell)}$ is a nonlinear function applied element-wise, and each $\boldsymbol{h}_\ell$ denotes an intermediary hidden state representation of the input.

In binary classifiers, it is common to let $W^{(L)}$ be a row vector, $b^{(L)}$ be a single scalar, and $f^{(L)}$ be the sigmoid function $\sigma(a) = 1/(1 + \exp(-a))$. Such constraints force the final output $\hat{p} = \boldsymbol{h}_L$ to be a scalar within the range $[0, 1]$, which allows us to interpret it as the estimated probability of $y = 1$. For selected nonlinearities $\{f^{(\ell)}\}_{\ell=1}^{L}$, the weights $\{W^{(\ell)}\}_{\ell=1}^{L}$ and biases $\{b^{(\ell)}\}_{\ell=1}^{L}$ are trained to minimize the *binary cross-entropy loss* Q over the entire dataset, which is defined as

$$Q = \sum_{n=1}^{N} y^{(n)} \cdot \log \hat{p}^{(n)} + (1 - y^{(n)}) \cdot \log(1 - \hat{p}^{(n)}), \tag{4}$$

where each $\hat{p}^{(n)}$ is generated by passing $\boldsymbol{x}^{(n)}$ through the neural network.

3.1. Regularizing Decision Boundary Covariance

Zafar et al. (2015) propose regularizing the covariance between the distance to the decision boundary of a classifier and the protected classes $\boldsymbol{z}$ to enforce demographic parity. They apply their framework to logistic regression and support vector machines. We generalize this method to working with neural networks.

Using the neural network binary classifier of Equation 3, we define the *decision boundary distance* $d^{(n)}$ of training example n as the value obtained before the final nonlinearity, i.e.

$$d^{(n)} = W^{(L)}\boldsymbol{h}_{L-1}^{(n)} + b^{(L)}. \tag{5}$$

To see why $d^{(n)}$ is related to the decision boundary of the neural network classifier, observe that the estimated probability of $y^{(n)} = 1$ is $\hat{p}^{(n)} = \sigma(d^{(n)})$. Thus, if $d^{(n)} > 0$, then $\hat{p}^{(n)} > 1/2$ (so it makes more sense to classify n as class 1) and if $d^{(n)} < 0$, then $\hat{p}^{(n)} < 1/2$ (so it makes more sense to classify n as class 0). Thus, the variable d encodes a scale centered at zero and characterizes the confidence of the classifier to classify as class 0 or class 1.

If the covariance between the decision boundary distance d and the protected attribute $\boldsymbol{z}$ is zero, then knowing $\boldsymbol{z}$ should have no impact on knowing $p(y \mid \boldsymbol{x})$, which is the definition of satisfying demographic parity. We can empirically estimate this covariance by observing the following:

$$\begin{aligned} \mathbb{C}\text{ov}(\boldsymbol{z}, d) &= \mathbb{E}[(\boldsymbol{z} - \bar{\boldsymbol{z}}) \cdot (d - \bar{d})] \\ &= \mathbb{E}[(\boldsymbol{z} - \bar{\boldsymbol{z}}) \cdot d] - \mathbb{E}[(\boldsymbol{z} - \bar{\boldsymbol{z}})] \cdot \bar{d} \\ &= \mathbb{E}[(\boldsymbol{z} - \bar{\boldsymbol{z}}) \cdot d] - 0 \\ &\approx \frac{1}{N}\sum_{n=1}^{N}(\boldsymbol{z}^{(n)} - \hat{\boldsymbol{z}}) \cdot d^{(n)}, \end{aligned} \tag{6}$$

where $\hat{\boldsymbol{z}} = 1/N \cdot \sum_{n=1}^{N} \boldsymbol{z}^{(n)}$. Since Zafar et al. (2015) work with only convex classifiers, they simply add the following convex constraint to their logistic regression and support vector machine settings:

$$\left| \frac{1}{N} \sum_{n=1}^{N} (\boldsymbol{z}^{(n)} - \hat{\boldsymbol{z}}) \cdot d^{(n)} \right| \leq \boldsymbol{c}, \tag{7}$$

for some constant $\boldsymbol{c}$ corresponding to the level of desired demographic parity. In our neural network setting, we directly add the empirical covariance as a penalized regularization term to the binary cross entropy objective function of Equation 4. Thus, the full objective function is

$$\begin{aligned} Q_1 = \sum_{n=1}^{N} y^{(n)} \log \hat{p}^{(n)} + (1 - y^{(n)}) \log(1 - \hat{p}^{(n)}) \quad (8) \\ + \lambda \cdot \left| \frac{1}{N} \sum_{n=1}^{N} (\boldsymbol{z}^{(n)} - \hat{\boldsymbol{z}}) \cdot d^{(n)} \right|, \end{aligned}$$

where λ controls the degree of regularization.

3.2. Regularizing Representation Space Bias

4. Results

Our empirical results are evaluated on the adult income dataset. We first naively train a vanilla neural network and show how it suffers from disparate impact. Then, we apply our methods for enforcing demographic parity to exhibit how this disparate impact can be mitigated.

4.1. Vanilla Neural Network

5. Discussion and Conclusion

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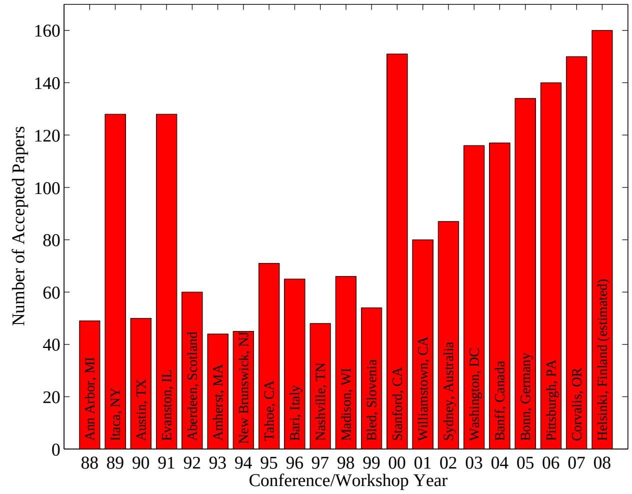

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Algorithm 1 Bubble Sort

```
Input: data x_i, size m
repeat
   Initialize noChange = true.
   for i = 1 to m - 1 do
      if x_i > x_{i+1} then
         Swap x_i and x_{i+1}
         noChange = false
      end if
   end for
until noChange is true
```

Table 1. Classification accuracies for naive Bayes and flexible Bayes on various data sets.

DATA SET	NAIVE	FLEXIBLE	BETTER?
BREAST	95.9± 0.2	96.7± 0.2	$\surd$
CLEVELAND	83.3± 0.6	80.0± 0.6	$\times$
GLASS2	61.9± 1.4	83.8± 0.7	$\surd$
CREDIT	74.8± 0.5	78.3± 0.6	
HORSE	73.3± 0.9	69.7± 1.0	$\times$
META	67.1± 0.6	76.5± 0.5	$\surd$
PIMA	75.1± 0.6	73.9± 0.5	
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