CSC 411: Introduction to Machine Learning
CSC 411 Lecture 23: Algorithmic Fairness

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Final Exam

- Thursday, Apr. 25, from 9am–12pm BN3.
- Covers all lectures except the final week (Lectures 23 and 24).
- Similar difficulty to midterm.
- Practice exams will be posted.
As ML starts to be applied to critical applications involving humans, the field is wrestling with the societal impacts:

- **Security:** what if an attacker tries to poison the training data, fool the system with malicious inputs, “steal” the model, etc.?
- **Privacy:** avoid leaking (much) information about the data the system was trained on (e.g. medical diagnosis)
- **Fairness:** ensure that the system doesn’t somehow disadvantage particular individuals or groups
- **Transparency:** be able to understand why one decision was made rather than another
- **Accountability:** an outside auditor should be able to verify that the system is functioning as intended

If some of these definitions sound vague, that’s because formalizing them is half the challenge!
Overview: Fairness

FAIRNESS IN AUTOMATED DECISIONS

Credit: Richard Zemel
Overview: Fairness

SUBTLER BIAS
Overview: Fairness

- This lecture: algorithmic fairness

- Goal: identify and mitigate bias in ML-based decision making, in all aspects of the pipeline

Sources of bias/discrimination

- Data
  - Imbalanced/impoverished data
  - Labeled data imbalance
  - Labeled data incorrect / noisy

- Model
  - ML prediction error imbalanced
  - Compound injustices (Hellman)

Credit: Richard Zemel
Overview: Fairness

- **Notation**
  - $X$: input to classifier
  - $S$: sensitive feature (age, gender, race, etc.)
  - $Z$: latent representation
  - $Y$: prediction
  - $T$: true label

- We use capital letters to emphasize that these are random variables.
Fairness Criteria

- Most common way to define fair classification is to require some invariance with respect to the sensitive attribute
  - Demographic parity: $Y \perp \perp S$
  - Equalized odds: $Y \perp \perp S \mid T$
  - Equal opportunity: $Y \perp \perp S \mid T = t$, for some $t$
  - Equal (weak) calibration: $T \perp \perp S \mid Y$
  - Equal (strong) calibration: $T \perp \perp S \mid Y$ and $Y = \Pr(T = 1)$
  - Fair subgroup accuracy: $\mathbb{I}[T = Y] \perp \perp S$

- $\perp \perp$ denotes stochastic independence

- Many of these definitions are incompatible!
Learning Fair Representations

- Idea: separate the responsibilities of the (trusted) society and (untrusted) vendor

- Goal: find a representation $Z$ that removes any information about the sensitive attribute

- Then the vendor can do whatever they want!

Image Credit: Richard Zemel
A naïve attempt: simply don’t use the sensitive feature.
- Problem: the algorithm implicitly learn to predict the sensitive feature from other features (e.g. race from zip code)

Another idea: limit the algorithm to a small set of features you’re pretty sure are safe and task-relevant
- This is the conservative approach, and commonly used for both human and machine decision making
- But removing features hurts the classification accuracy. Maybe we can make more accurate decisions if we include more features and somehow enforce fairness algorithmically?

Can we learn fair representations, which can make accurate classifications without implicitly using the sensitive attribute?
Desiderata for the representation:

- Retain information about $X \Rightarrow$ high mutual information between $X$ and $Z$
- Obfuscate $S \Rightarrow$ low mutual information between $S$ and $Z$
- Allow high classification accuracy $\Rightarrow$ high mutual information between $T$ and $Z$
Learning Fair Representations

First approach: Zemel et al., 2013, “Learning fair representations”

- Let $Z$ be a discrete representation (like K-means)
- Determine $Z$ stochastically based on distance to a prototype for the cluster (like the cluster center in K-means)

$$
Pr(Z = k \mid x) \propto \exp(-d(x, v_k)),
$$

where $d$ is some distance function (e.g. Euclidean distance)

- Use the Bayes classifier $y = Pr(T = 1 \mid Z)$
- Need to fit the prototypes $v_k$
Learning Fair Representations

- Retain information about $X$: penalize reconstruction error
  \[
  
  \mathcal{L}_{\text{reconst}} = \frac{1}{N} \sum_{i=1}^{N} \| x^{(i)} - \tilde{x}^{(i)} \|^2
  
  \]

- Predict accurately: cross-entropy loss
  \[
  \mathcal{L}_{\text{pred}} = \frac{1}{N} \sum_{i=1}^{N} -t^{(i)} \log y^{(i)} - (1 - t^{(i)}) \log(1 - y^{(i)})
  
  \]

- Obfuscate $S$:
  \[
  \mathcal{L}_{\text{discrim}} = \frac{1}{K} \sum_{k=1}^{K} \left| \frac{1}{N_0} \sum_{i:s^{(i)} = 0} \Pr(Z = k | x^{(i)}) - \frac{1}{N_1} \sum_{i:s^{(i)} = 1} \Pr(Z = k | x^{(i)}) \right|
  
  \]

  where we assume for simplicity $S \in \{0, 1\}$ and $N_0$ is the count for $s = 0$. 
Learning Fair Representations

- **Obfuscate $S$:**

\[
\mathcal{L}_{\text{discrim}} = \frac{1}{K} \sum_{k=1}^{K} \left| \frac{1}{N_0} \sum_{i:s^{(i)}=0} \Pr(Z = k \mid x^{(i)}) - \frac{1}{N_1} \sum_{i:s^{(i)}=1} \Pr(Z = k \mid x^{(i)}) \right|,
\]

- Is this about individual-level or group-level fairness?
- If discrimination loss is 0, we satisfy demographic parity

\[
\Pr(Y = 1 \mid s^{(i)} = 1) = \frac{1}{N_1} \sum_{i:s^{(i)}=1} \sum_{k=1}^{K} \Pr(Z = k \mid x^{(i)}) \Pr(Y = 1 \mid Z = k)
\]

\[
= \sum_{k=1}^{K} \left[ \frac{1}{N_1} \sum_{i:s^{(i)}=1} \Pr(Z = k \mid x^{(i)}) \right] \Pr(Y = 1 \mid Z = k)
\]

\[
= \sum_{k=1}^{K} \left[ \frac{1}{N_0} \sum_{i:s^{(i)}=0} \Pr(Z = k \mid x^{(i)}) \right] \Pr(Y = 1 \mid Z = k)
\]

\[
= \Pr(Y = 1 \mid s^{(i)} = 0)
\]
Datasets

1. **German Credit**
   - **Task:** classify individual as good or bad credit risk
   - **Sensitive feature:** Age

2. **Adult Income**
   - **Size:** 45,222 instances, 14 attributes
   - **Task:** predict whether or not annual income > 50K
   - **Sensitive feature:** Gender

3. **Heritage Health**
   - **Size:** 147,473 instances, 139 attributes
   - **Task:** predict whether patient spends any nights in hospital
   - **Sensitive feature:** Age
Learning Fair Representations

Metrics

- Classification accuracy
- Discrimination

\[
\left| \frac{\sum_{i:s(i)=1}^N y(i)}{N_1} - \frac{\sum_{i:s(i)=0}^N y(i)}{N_0} \right|
\]

Yellow = unrestricted; Blue = theirs
Discrete $Z$ based on prototypes is very limiting. Can we learn a more flexible representation?

Louizos et al., 2015, “The variational fair autoencoder”

The variational autoencoder (VAE) is a kind of autoencoder that represents a probabilistic model, and can be trained with a variational objective similar to the one we used for E-M.

- For this lecture, just think of it as an autoencoder.
- How can we learn an autoencoder such that the code vector $z$ loses information about $s$?
Fair VAE: Maximum Mean Discrepancy

- Our previous non-discrimination criterion only makes sense for discrete $Z$.
- New criterion: ensure that $p(Z \mid s)$ is indistinguishable for different values of $s$.
- **Maximum mean discrepancy (MMD)** is a quantitative measure of distance between two distributions. Pick a feature map $\psi$.

$$\text{MMD}(p; q) = \| \mathbb{E}_{z \sim p}[\psi(z)] - \mathbb{E}_{z \sim q}[\psi(z)] \|^2$$
MMD can be kernelized by expressing it in terms of

\[ k(z, z') = \psi(z)^\top \psi(z'). \]

Let \( \{z_i\}_{i=1}^{N_0} \) and \( \{z'_i\}_{i=1}^{N_1} \) be sets of samples from \( p \) and \( q \). The empirical MMD is given by:

\[
\left\| \frac{1}{N_0} \sum_{i=1}^{N_0} \psi(z_i) - \frac{1}{N_1} \sum_{i=1}^{N_1} \psi(z'_i) \right\|^2
\]

\[
= \frac{1}{N_0^2} \sum_{i=1}^{N_0} \sum_{j=1}^{N_0} k(z_i, z_j) + \frac{1}{N_1^2} \sum_{i=1}^{N_1} \sum_{j=1}^{N_1} k(z'_i, z'_j) - 2 \frac{1}{N_0 N_1} \sum_{i=1}^{N_0} \sum_{j=1}^{N_1} k(z_i, z'_j)
\]

You can show that for certain kernels (e.g. RBF), the MMD is 0 iff \( p = q \). So MMD is a very powerful distance metric.
Train a VAE, with the constraint that the MMD between $p(z \mid s = 0)$ and $p(z \mid s = 1)$ is small.
Fair VAE: tSNE embeddings

- tSNE is an unsupervised learning algorithm for visualizing high-dimensional datasets. It tries to embed points in low dimensions in a way that preserves distances as accurately as possible.
- Here are tSNE embeddings of different distributions, color-coded by the sensitive feature:

![Original inputs](image1)
![VAE latent space](image2)
![Fair VAE latent space](image3)

Figure Credit: Louizos et al., 2015
Individual Fairness

- The work on fair representations was geared towards group fairness.
- Another notion of fairness is individual level: ensuring that similar individuals are treated similarly by the algorithm.
  - This depends heavily on the notion of “similar”.
- One way to define similarity is in terms of the “true label” $T$ (e.g. whether this individual is in fact likely to repay their loan).
  - Can you think of a problem with this definition?
  - The label may itself be biased
    - If based on human judgments
    - If, e.g., societal biases make it harder for one group to pay off their loans
  - We’ll ignore this issue in our analysis. But keep in mind that you’d need to carefully consider the assumptions when applying one of these methods!
Now we’ll turn to Hardt et al., 2016, “Equality of opportunity in supervised learning”.

Assume we make a binary prediction by computing a real-valued score $R = f(X, S)$, and then thresholding this score to obtain the prediction $Y$.

As before, assume $S \in \{0, 1\}$.

Motivating example: predict whether an individual is likely to repay their loan

Two notions of individual fairness:

- **Equalized odds**: equal true positive and false positive rates

  $$\Pr(Y = 1 | S = 0, T = t) = \Pr(Y = 1 | S = 1, T = t) \quad \text{for } t \in \{0, 1\}$$

- **Equal opportunity**: equal true positive rates

  $$\Pr(Y = 1 | S = 0, T = 1) = \Pr(Y = 1 | S = 1, T = 1)$$
Equal Opportunity

- Consider **derived predictors**, which are a function of the real-valued score $R$ and the sensitive feature $S$.
  - I.e., we don’t need to check the original input $X$. This simplifies the analysis.
- Define a loss function $\mathcal{L}(Y, T)$. Since $Y$ and $T$ are binary, there are 4 values to specify.
- They show that:
  - Without a constraint, the optimal predictor is obtained from thresholding $R$.
  - With an equal opportunity constraints, the optimal predictor is obtained by thresholding $R$, but with a different threshold for different values of $S$.
  - Satisfying equalized odds is overconstrained, and may require randomizing $Y$. 
- **Case study: FICO scores**
- **Aim to predict whether an individual has less than an 18% rate of default (which is the threshold for profitability)**

![Non-default rate by FICO score](image1)

![CDF of FICO score by group](image2)

Figure: Hardt et al., 2016
Equal Opportunity

- The “race-blind” solution applies the same threshold for all the groups.
- Problem: non-defaulting black applicants are much less likely to be approved than non-defaulting white applicants.
  - Fraction of non-defaulting applicants in each group = fraction of area under curve which is shaded

![Graph showing non-default rates by FICO score and within-group FICO score percentile for different groups.](image)

Figure: Hardt et al., 2016
Can obtain equal opportunity, equalized odds, demographic parity by setting group-specific thresholds (except equalized odds requires randomizing).

- **Equal Opportunity**
  - Can obtain equal opportunity, equalized odds, demographic parity by setting group-specific thresholds (except equalized odds requires randomizing).

- **Figure 9: FICO thresholds for various definitions of fairness.** The equal odds method does not give a single threshold, but instead $\text{Pr}[bY=1|R,A]$ increases over some not uniquely defined range; we pick the one containing the fewest people. Observe that, within each race, the equal opportunity threshold and average equal odds threshold lie between the max profit threshold and equal demography thresholds.

- The difference between equal odds and equal opportunity is that under equal opportunity, the classifier can make use of its better accuracy among whites. Under equal odds this is viewed as unfair, since it means that white people who wouldn’t pay their loans have a harder time getting them than minorities who wouldn’t pay their loans. An equal odds classifier must classify everyone as poorly as the hardest group, which is why it costs over twice as much in this case. This also leads to more conservative lending, so it is slightly harder for non-defaulters of all groups to get loans.

- The equal opportunity classifier does make it easier for defaulters to get loans if they are minorities, but the incentives are aligned properly. Under max profit, a small group may not be worth figuring out how to classify and so be treated poorly, since the classifier can’t identify the qualified individuals. Under equal opportunity, such poorly-classified groups are instead treated better than well-classified groups. The cost is thus born by the company using the classifier, which can decide to invest in better classification, rather than the classified group, which cannot. Equalized odds gives a similar, but much stronger, incentive since the cost for a small group is not proportional to its size.

- While race blindness achieves high profit, the fairness guarantee is quite weak. As with max profit, small groups may be classified poorly and so treated poorly, and the company has little incentive to improve the accuracy. Furthermore, when race is redundantly encoded, race blindness degenerates into max profit.

**8 Conclusions**

We proposed a fairness measure that accomplishes two important desiderata. First, it remedies the main conceptual shortcomings of demographic parity as a fairness notion. Second, it is fully...
Equal Opportunity

- Different notions of fairness often come into conflict. E.g., demographic parity conflicts with equal opportunity (left).
- Some notions of fairness are harder to achieve than others, in terms of lost profit (right).
- Choosing the right criterion requires careful consideration of the causal relationships between the variables.

Figure: Hardt et al., 2016
Summary

- Fairness is a challenging issue to address
  - Not something you can just measure on a validation set
  - Philosophers and lawyers have been trying to define it for thousands of years
  - Different notions are incompatible. Need to carefully consider the particular problem.
    - individual vs. group
- Explosion of interest in ML over the last few years
- New conference on Fairness, Accountability, and Transparency (FAT*)
- New textbook: [https://fairmlbook.org/](https://fairmlbook.org/)