

AnonymousNet: Natural Face De-Identification with Measurable Privacy

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Abstract

With billions of personal images being generated from social media and cameras of all sorts on a daily basis, security and privacy are unprecedently challenged. Although extensive attempts have been made, existing face image de-identification techniques are either insufficient in photo-reality or incapable of balancing privacy and usability qualitatively and quantitatively, i.e., they fail to answer counterfactual questions such as “is it private now?”, “how private is it?”, and “can it be more private?” In this paper, we propose a novel framework called AnonymousNet, with an effort to address these issues systematically, balance usability, and enhance privacy in a natural and measurable manner. The framework encompasses four stages: facial attribute estimation, privacy-metric-oriented face obfuscation, directed natural image synthesis, and adversarial perturbation. Not only do we achieve the state-of-the-arts in terms of image quality and attribute prediction accuracy, we are also the first to show that facial privacy is measurable, can be factorized, and accordingly be manipulated in a photo-realistic fashion to fulfill different requirements and application scenarios. Experiments further demonstrate the effectiveness of the proposed framework.

1. Introduction

The deployment of internet of things devices, such as surveillance cameras and sensors, are rising dramatically in recent years. Particularly, the popularity of smartphones allows billions of photos being uploaded to social networks and shared among people on a daily basis. Although the blooming development has advanced machine learning applications to bring convenience and enhance user experience, it may capture confidential information incidentally and increases the risks of privacy leakage. To protect privacy, the most straightforward approach is access control [51], such as the “Restrict Others” setting in Facebook [31]. Cryptography techniques such as encryption and secure multi-party computation [28] can also be applied to mitigate

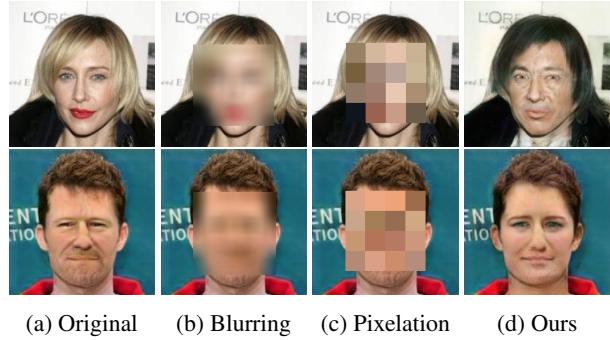


Figure 1: A brief comparison of obfuscation methods. Our approach not only de-identifies an image by synthesizing a photo-realistic alternative, but also provides a controllable and measurable way for privacy preservation. Moreover, an adversarial perturbation is introduced to further enhance security and privacy against malicious detectors.

privacy threats. In computer vision community, privacy-enhancing technologies are mainly obfuscation-based; for example, obfuscating sensitive information like faces and numbers in an image by using traditional approaches including blurring, pixelation, and masking (see Figure 2). However, there are at least two drawbacks with these traditional approaches. First, researchers have shown these techniques are vulnerable. The faceless person recognition system proposed in [43] can be trained with limited training samples and then identify the target in an obfuscated image by using body features. Another study also shows that deep learning models can successfully identify faces in images encrypted with these techniques with high accuracies [38]. Second, images processed with these techniques result in unsatisfying perception in general. A study shows that both blurring and blocking will impact image perception scores, and even lower scores are observed for images obfuscated by blocking [31].

On the other hand, new techniques and mechanisms are being applied to enhance image obfuscation. A game-the-

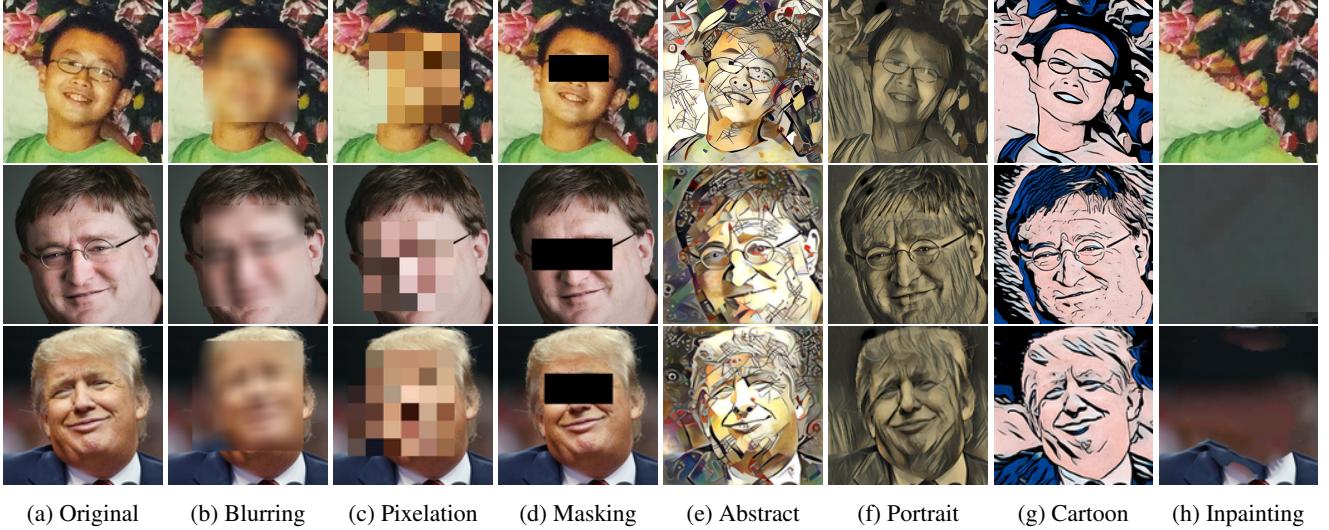


Figure 2: Comparison of canonical image processing methods for face obfuscation. From left to right are blurring, pixelation, masking, deep Convolutional Neural Network-based style transfer [19] (abstract painting style, portrait painting style, and cartoon style [15]), and Generative Adversarial Network-based image inpainting [61].

ory framework called Adversarial Image Perturbation has been proposed to determine effective image obfuscation approach when the choice of countermeasures is unknown [44]. Recently, the generative adversarial networks (GAN) can generate realistic natural images following original input data distribution via adversarial training [11], therefore it has become more and more popular for novel image obfuscation techniques. Wu *et al.* [60] developed a GAN with two newly designed modules verifier and regulator for face de-identification. Considering subjects in social media photos appear in diverse activities and head orientations, Sun *et al.* [52] proposed a two-stage model to inpaint the head region conditioned on facial landmarks.

Note that there exists a tradeoff between privacy protection and dataset usability [63, 14]. High obfuscation levels fail to preserve utility for various tasks while low obfuscation levels lead to recognition of private information. Unfortunately, current methods are unable to find a way to quantify this matter; neither can they be adapted with correspondence to various privacy metrics nor real-world scenarios under different requirement settings. To tackle these, we propose the AnonymousNet, a four-stage frameworks consisted of facial semantic extraction powered by a deep Convolutional Neural Network [23]; a attribute selection method with regards to privacy metrics such as k -anonymity [54], l -diverse [37], and t -closeness [24]; a Generative Neural Network [11] for photo-realistic image generator; and a universal adversarial perturbation [40] to mitigate potential security and privacy threats.

The rest of the paper is organized as follows: Section 2

provides necessary background in privacy-preserving data mining and reviews recent advances in facial image editing; Section 3 formalizes the face de-identification problem and introduce privacy metrics; Section 4 outlines the four-stage AnonymousNet framework, including facial feature extraction, semantic-based attribute obfuscation, de-identified face generation, and adversarial perturbation; Section 5 details experiment settings and evaluate the results; we conclude this paper in Section 6 by discussions of future research directions.

2. Related Work

Facial Landmark Detection Photo privacy protection includes two important aspects: sensitive content detection and obfuscation method [30]. Facial information is one of the highest sensitive contents. Various head poses, orientations, lighting conditions and so on make photo privacy protection more challenging. Facial landmark detection has been an active research field because it is the first important step for other facial-related applications. In the past few decades, numerous algorithms like support vector machine [46] and random forecast [2] have been proposed. Despite these models have made significant progress, they rely on handcrafted local features and may not operate under a wide range of conditions like illumination, occultation, poses.

Recently deep learning models have made huge advances to deal with issues like occultation and variability in facial landmark detection. [53] proposed a cascaded convolutional network for facial keypoint detection which can utilize the texture context information over the entire face

and encode geometric constraints implicitly. Further, a deep multi-task learning framework is presented that combine facial landmark detection with correlated tasks like head pose estimation [64]. Dong *et al.* (2018) adopted a generative adversarial network to transform facial images into style-aggregated ones, which are then deployed together to train a facial landmark detector [8].

Image Inpainting Previous study shows that comparing with image blurring and blocking, image inpainting provides a more effective and better user experience [30]. Face replacement has become a popular image inpainting technology for privacy protection. [4] created a large face library from public internet. Given an input face, the most similar one in the library will be chosen for face replacement. [39] applied a 2D morphable model to adjust the shape of a source face to match the target face. [33] proposed a framework to generate a personalized 3D head model from one frontal face. The 3D head model can then be rendered at any pose to swap with the face in the target image. Figure 2 compares several classic image processing methods for face identity obfuscation.

GAN-based Face Generation Generative Adversarial Network (GAN) is a system of two neural networks who contests with each other under a zero-sum game setting. GAN was first introduced by Goodfellow *et al.* [11] in 2014. Since then, great progresses have been made, as shown in Figure 3: in 2015, Radford *et al.* [45] designed deep convolutional generative adversarial networks (DCGANs) which demonstrated the adversarial pair (both the generator and discriminator) can learn a hierarchy of representations from object parts to scenes; Liu *et al.* [34] proposed coupled generative adversarial network (CoGAN) in 2016, which is capable of learning a joint distribution with only samples from marginal distributions and without tuple of corresponding images from different domains; Karras *et al.* [20] described a new training method for GAN in 2017, whose main idea is to train generator and discriminator progressively by starting from a low resolution and adding new layers of the model with fine details incrementally; and more recently, Karras *et al.* [21] proposed a style-based generator architecture (StyleGAN) that is able to learn high-level facial attributes in a automated and unsupervised manner, generates images with stochastic variations, and achieves the state-of-the-art.

Privacy-Preserving Data Mining Theories and practices of privacy-preserving techniques have been studied extensively in the database and data mining communities; to name a few: [1, 6, 56]. To measure the disclosure risk of an anonymized table of a database, Samarati & Sweeney (1998) [50] introduced the k -anonymity property such that



Figure 3: Progresses of GAN-based face generation since 2014 [10] (from left to right: GAN (2014) [11], DCGAN (2015) [45], CoGAN (2016) [34], Karras *et al.* (2017) [20], and StyleGAN (2018) [21]).

each record in the database is indistinguishable with at least $k - 1$ records. Although being sufficient to protect against identity disclosure, k -anonymity is limited to prevent attribute disclosure. In regards to that, Machanavajjhala *et al.* (2006) [37] introduced a new privacy property called l -diversity, which requires protected attributes to have at least l well-represented values in each equivalence class. Newton *et al.* (2005) [42] introduced the first privacy-enabling algorithm, k -Same, to the context of image databases. Gross *et al.* (2005) [13] demonstrated a tradeoff between disclosure risk (i.e., image obfuscation level) and classification accuracy. To tackle this, they introduced k -Same-Select to balance privacy and usability. Zhang (2018) [63] further designed a OBFUSCATE function that adds random noises to existing samples or creates new samples, in an effort to hide sensitive information in the dataset while preserving model accuracy.

3. Preliminary

3.1. Formulation of Face De-Identification

We first formally define the problem of face de-identification, extending notations and definitions from Newton *et al.* [42]. This process is important as it helps us to precisely define the methods and to build a solid foundation for following discussions of theoretical properties.

Definition 3.1. (Face Image). A face image (or simple ‘face’ or ‘image’) is a 3D matrix I of m columns, n rows, and c channels. c is usually 3 in common color spaces (e.g., RGB and YUV). Each cell in I stores a color coding for a pixel, ranging from 0 to 255 inclusively. A face image contains a normalized image of only one person’s face.

Definition 3.2. (Face Set). A face set is a set of M face images: $\{\Gamma_i : i = 1, \dots, M\}$.

Definition 3.3. (Person-Specific Face Set). Let \mathbf{H} be a face set of M face images, $\{\Gamma_i, \dots, \Gamma_M\}$. \mathbf{H} is said to be

person-specific if and only if each $\Gamma_i \in \mathbf{H}$ only relates to one person and $\Gamma_i \neq \Gamma_j$ for any $i \neq j$.

Definition 3.4. (Face De-Identification Function). Let \mathbf{H} and \mathbf{H}_d be person-specific face set.

$$f : \mathbf{H} \rightarrow \mathbf{H}_d \quad (1)$$

is called face de-identification function if it attempts to obfuscate the identity of the original face image.

Definition 3.5. (De-Identified Face). Given $\Gamma \in \mathbf{H}$ and de-identification function f , $\Gamma_d \in \mathbf{H}_d$ is a f de-identified face of Γ if

$$\Gamma_d = f(\Gamma) \quad (2)$$

Figure 2 illustrates several canonical image processing methods for face de-identification, including blurring, pixelation, masking, deep Convolutional Neural Network-based style transfer [19] (abstract painting style, portrait painting style, and cartoon style [15]), and Generative Adversarial Network-based image inpainting [61].

3.2. Privacy Metrics

The motivation of privacy metrics is to provide qualitative and quantitative measurement of the degree of privacy enjoyed by specific users (personal images in our case) and the proper amount of privacy protection offered with correspondence to trade-offs in usability. This section, we only discuss metrics that are used in our framework. [57] provides a more comprehensive list for interested readers.

k -Anonymity k -anonymity is a widely applied metric to evaluate a dataset's level of anonymity [50]. It requires that each record in the dataset is indistinguishable with at least $k - 1$ other records with respect to quasi-identifiers, which refer to attributes that can potentially be taken together to identify an individual like zip code or birth date [24]. In the case of a face dataset, these quasi-identifiers may include semantic attributes like eyeglasses, pointy nose, and oval face, and so on. If a dataset satisfies the condition of k -Anonymity, with only quasi-identifiers of one individual known, the true record can only be chosen with a probability of $1/k$.

However, there are some scenarios that k -anonymity cannot provide enough protection. For example, for k subjects that have the same values for the quasi-identifiers, if they all have the same sensitive attribute like heart disease, an adversary can be certain that the target identify in the k subjects must have heart disease. The k -Anonymity thus fails to protect sensitive information from the homogeneity attack [24].

l -Diversity l -diversity is proposed to address the limitations of k -anonymity [37]. The basic concept is that for the equivalence class representing a set of records with the same values for the quasi-identifiers, it should have at least l “well-represented” values for the sensitive attribute.

The most straightforward definition of “well-represented” values is to ensure the equivalence class has l distinct values for the sensitive attribute. In this definition, the frequencies of l distinct values are not considered. An adversary may conclude that the sensitive attribute of a targeted identity has the value with the highest frequency. Therefore there is a stronger definition of l -diversity named Entropy l -diversity, which is defined as follows:

$$\text{Entropy}(E) \geq \log l \quad (3)$$

$$\text{Entropy}(E) = - \sum_{s \in S} p(E, s) \log p(E, s) \quad (4)$$

where E is the equivalence class, S is the value set of the sensitive attribute, and $p(E, s)$ is the fraction of records in E that have sensitive value s .

t -Closeness Adversaries sometimes have knowledge of the global distribution of sensitive attributes, for example, the distributions of facial attributes are easy to obtain (see Figure 6). To prevent privacy disclosure by an adversary with such knowledge, [24] introduced t -closeness, which updates k -anonymity with correspondence to the distribution of sensitive values, requiring that the distribution S_E of sensitive values in any equivalence class E must be close to their distribution S in the entire database, i.e.,

$$\forall E : d(S, S_E) \leq t \quad (5)$$

where $d(S, S_E)$ is the distance between distribution S and S_E measured by the Earth Mover Distance [47] and t is the privacy threshold at which $d(S, S_E)$ should not exceed.

Randomness Randomization is another approach to protect data privacy. It is realized by adding random noise to existing samples [63]. Given an individual sample, we can randomly select part of its features with a ratio of γ , and add Gaussian noise $N(0, \sigma)$. Instead of random feature selection, we can also identify sensitive features first, and add Gaussian noise $N(0, \sigma)$. Another randomization approach is to introduce new samples into the dataset [63]. To generate a new sample, we can randomly pick an original sample from the dataset, revise its feature value and add small amount of noise at the same time. For example, the value x_i of pixel i in an original image can be replaced with $255 - x_i$ with Gaussian noise $N(0, \sigma)$ added in the new sample. From a broader perspective, adversarial perturbation can also be consider as a randomization method.

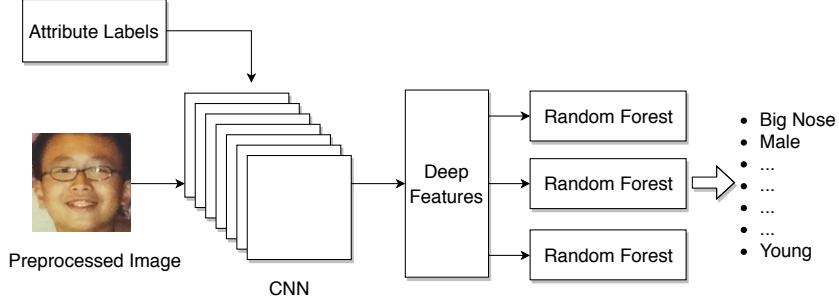


Figure 4: Overview of the facial attribute prediction pipeline. We train a deep Convolutional Neural Network (CNN) fed by preprocessed and labelled images, and then extract deep features from the fully connected (FC) layer of the CNN and accordingly train random forest classifiers to predict facial attributes (the full attribute list can be found in Figure 6).

4. The AnonymousNet

In an effort to obfuscate facial identities and generate photo-realistic alternatives, balance privacy and usability qualitatively and quantitatively, answer counterfactual questions such as “is it private now?”, “how private is it?”, and “can it be more/less private?”, and finally achieve controllable and measurable privacy, we propose the AnonymousNet framework, which encompasses four stages: facial feature extraction, semantic-based attribute obfuscation, de-identified face generation, and adversarial perturbation, as detailed below.

Stage-I: Facial Attribute Prediction

We adopt GoogLeNet [55] for facial attribute extraction, which consists of 22 layers with 9 Inception blocks and excelled in ImageNet Large-Scale Visual Recognition Challenge 2014 [49]. Unlike most other classifiers in ImageNet [7], GoogLeNet is not trained for one label, but rather is fed with 40 facial attributes at the same time and outputs multiple classification results accordingly. GoogLeNet further leverages a trick of using 1×1 kernels to increase depth while reducing dimension and reserving computational resources. Figure 4 outlines the facial attribute prediction pipeline, where labelled images are first fed into the model, features are extracted from the fully connected (FC) layer, and then 40 random forest classifiers [32] are trained and facial attributes are subsequently obtained.

Stage-II: Privacy-Aware Face Obfuscation

Provided with semantic information of each facial image as well as attribute distribution over the entire database (see Figure 6), we are one step closer towards our goal: face de-identification with privacy guarantees. We first consider a toy example: database consist of 2 identities, both of which share a common attribute `<Male>`. In this case, modifying the gender attribute will not change the level of privacy, since altering this attribute will not change the

Algorithm 1: The PPAS algorithm.

```

Result: Attribute set  $\mathbb{A}''$ .
1 Attribute set  $\mathbb{A} \leftarrow \{E_1, \dots, E_n\}$ ;
2 Attribute set  $\mathbb{A}' \leftarrow \emptyset$ ;
3 Size  $N \leftarrow |\mathbb{A}|$  ;
4 for  $i = 1, \dots, N$  do
5   if  $d(S, S_{E_i}) \leq t$  then
6     | Add attribute  $E_i$  to  $\mathbb{A}'$  ;
7   else
8     | Add attribute  $\neg E_i$  to  $\mathbb{A}'$  ;
9   end
10 end
11 return  $\mathbb{A}'' \leftarrow \text{Perturbation}(\mathbb{A}', \epsilon)$  ;

```

possibility of guessing the identity given gender. Consider another example that for the same database and each entity has three boolean attributes: `<Male, Big_Nose, Black_Hair>` and one identity has black hair and the other does not. For this case, both of them should be updated to either black hair or non-black hair since the identity will be revealed if the hair color is known. These two example provide us insights of how to select facial attributes such that k -anonymity and l -diversity are satisfied.

However, as discussed in Section 3.2, this may not be enough to protect privacy, since sensitive information that reveals identities can still be revealed by exploiting global distributions of the attributes [24]. Here, we propose the Privacy-Preserving Attribute Selection (PPAS) Algorithm, a method to select and update facial attributes such that the distribution S_E of any attribute E is close to its real world distribution S subject to constraint defined in Equation 5. Unlike normal t -closeness, we further introduce a stochastic perturbation in the attribute selection process working toward ϵ -differential privacy [9]. Our approach is formalized in Algorithm 1 (for binary attributes).

Stage-III: Natural and Directed De-Identification

To obfuscate facial images while preserve visual reality, we adopt a generative adversarial network (GAN) [11], which is designed as two players, D and G , playing a min-max game with adversarial loss:

$$L_{adv} = \mathbb{E}[\log(D(\mathbf{x}))] + \mathbb{E}[\log(1 - D(G(\mathbf{x})))] \quad (6)$$

where generator G is trained to fool discriminator D , who tries to distinguish real images from adversarial ones. GAN has been successful in many applications [21, 29] yet is notoriously difficult to train [27]. As the face de-identification task can be categorized as a image-to-image translation problem, we customize the GAN model based on StarGAN [5], which has been widely demonstrated to have high usability along with realistic results, and the keys of which are attribute classification loss L_{cls} and image reconstruction loss L_{rec} . L_{adv} , L_{cls} and L_{rec} forms the final objective function:

$$L = \lambda_1 L_{adv} + \lambda_2 L_{cls} + \lambda_3 L_{rec} \quad (7)$$

Stage-IV: Adversarial Perturbation

Adding a Gaussian noise to an image is generally considered as a simple and effective way to trick deep neural network-based detectors which have been showcased to be vulnerable against this attack. There are also approaches that carefully craft perturbations for each data point. For example, [12] propose a fast gradient sign method to perturb an input through one step of gradient ascent. Furthermore, [40] shows there exists a universal adversarial perturbation that can cause images misclassified with high probability by state-of-the-art deep neural networks. The basic idea is formulated as follows: Suppose μ is the a distribution of images in \mathbb{R}^d , \hat{k} is a classifier that the output given an image x is $\hat{k}(x)$. The universal perturbation vector $v \in \mathbb{R}^d$ that can fool the classifier \hat{k} should satisfy:

$$\|v\|_p \leq \xi \quad (8)$$

$$\mathbb{P}_{x \sim \mu}(\hat{k}(x + v) \neq \hat{k}(x)) \geq 1 - \delta \quad (9)$$

where ξ limits the size of the universal perturbation vector, δ quantifies the failure rate of all the adversarial samples.

In this work, we introduce a universal perturbation vector as identified through an iterative approach. For each iteration i , we apply DeepFool [41] to identify the minimal perturbation to let \hat{k} misclassify each input, and update the universal perturbation corresponding to hyperparameter ϵ_i to the total perturbation v . It is shown that the algorithm works on a small portion of images sampled from the training dataset, and the universal perturbation generalizes well with respect to the data and the network architectures. Figure 5 outlines the proposed perturbation pipeline.

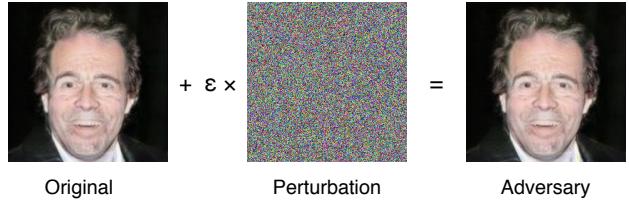


Figure 5: An example of adversarial perturbation. In stage-IV, we introduce a small universal perturbation adjusted by parameter ϵ to synthesized images, tricking malicious detectors while preserving perceptual integrity.

5. Experiment

5.1. Dataset

We use Large-scale CelebFaces Attributes (CelebA) Dataset [36] for facial attribute estimation, which contains 202,599 images and 10,177 identities. Each image has 40 attributes labels of boolean values, and their distributions have been shown in Figure 6. Following the same protocol as described in [36], we split the dataset into three folders: 160,000 images (8,000 identities) for training; 20,000 images (1,000 identities) for validation; and the rest 20,000 images (1,000 identities) for testing.

5.2. Image Preprocessing

Before feeding the data into our deep models, we perform data preprocessing for each images in the datasets, including steps in order: face detection, landmark detection, alignment, and image cropping. To obtain face landmarks, we deploy a Deep Alignment Network (DAN) [22], which is a deep neural network of multiple stages and has demonstrated convincing performance even in extreme pose or lighting conditions in the wild. Based on the 68 landmarks provided by DAN for each image, we align and center the face in the image by calibrating positions of both left and right eyes. Subsequently, we crop the images to a size of 256×256 . Figure 7 illustrates the preprocessing pipeline.

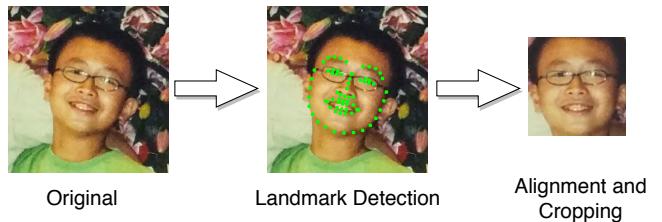


Figure 7: Image preprocessing pipeline. We deploy a Deep Alignment Network (DAN) [22] to obtain facial landmarks, based on which we accordingly align faces and crop images.

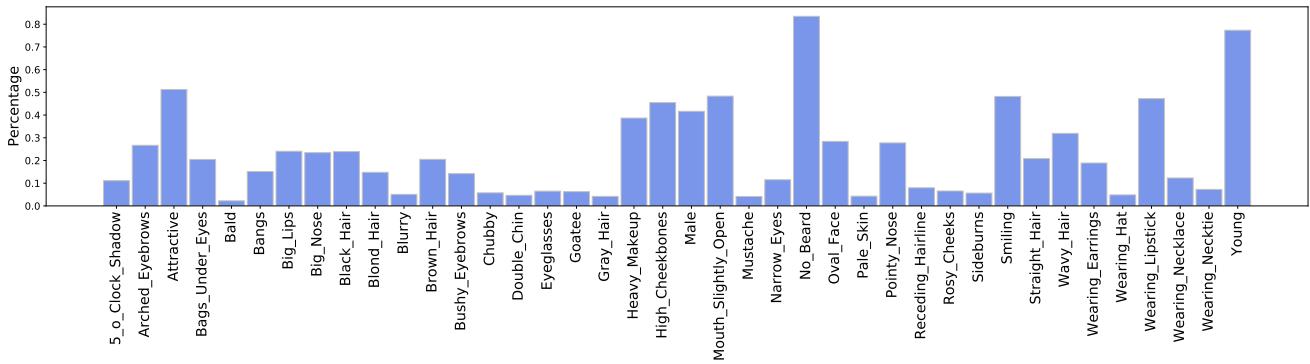


Figure 6: Facial attributes and their distributions in the CeleA dataset [36].

5.3. Training

Attribute Estimation. As discussed in Section 4 earlier, a GoogLeNet [55] is deployed for attribute estimation, using the same training settings as [26]. We adopt sigmoid cross-entropy as the loss function:

$$L = -\frac{1}{n} \sum [y \ln a + (1 - y) \ln(1 - a)] \quad (10)$$

where y is label and a is output. When training, we use a base learning rate of 10^{-5} , which is reduced by a polynomial decay with a gamma of 0.5. Momentum is set to be 0.9 and the weight decay is 2×10^{-4} . 6×10^5 iterations with a batch size of 64 are conducted for the training. After extracting deep features from the FC layer, we train 40 random forest classifiers for attribute estimation and achieve an accuracy that is comparable to current state-of-the-art [48].

Attribute Translation. After obtaining facial attributes that satisfies privacy constraints computed from previous steps, we employ StarGAN [5] for face attributes translation and use CeleA [36] as the training set. We follow the settings in [5], where Wasserstein loss [3] is adopted to expedite the training process and the definition is as below:

$$\mathcal{L}_{adv} = \mathbb{E}_x[D_{src}(X)] - \mathbb{E}_{x,c}[D_{src}(G(x, c))] \quad (11)$$

$$= -\lambda_{gp} \mathbb{E}_{\hat{x}}[(\|\nabla_{\hat{x}} D(\hat{x})\|_2 - 1)^2] \quad (12)$$

where \hat{x} is uniformly sampled between a pair of original and synthesized images and we use $\lambda = 10$ here. In terms of network architecture, we adopt a generator network of two convolutional layers for downsampling, six residual blocks [16], and two transposed convolutional layers for upsampling; and we use PatchGANs [18] as the discriminator network for binary classification (i.e., whether certain image patches are fake or real).

5.4. Evaluation

Figure 1 compares our approach with canonical face obfuscation methods, showcasing a significant improvement in photo-realism and a success in face de-identification. Figure 8 illustrates experimental results in pairs, where left is the original image and right is the result generated by our framework. It demonstrates that face identities are preserved in a perceptually natural manner, and in the meantime, each pair of images still shares certain common attributes in correspondence with various privacy policies and application scenarios (for example, pair (1, 4) differs in hair color, lip color, gender, and age, but shares the same eye sizes; pair (1, 1) only differs in gender and leaves other semantic attributes identical). Also, artifacts introduced by the proposed adversarial perturbation are shown to be visually negligible, even though they have been upscaled for illustrative purposes. Table 1 compare image quality under widely used perceptual metrics. Being aware that these model-based metrics fail to capture many nuances of human perception [62] and a smaller or larger value does not necessarily imply higher or lower image quality [25], we list the results here only for reference purpose.

	Blurring	Pixelation	Masking	Inpainting	Ours
PSNR [17]	24.532	22.802	15.459	18.097	20.079
SSIM [58]	0.8281	0.8226	0.8762	0.8020	0.7894
MS-SSIM [59]	0.8842	0.8784	0.8204	0.7659	0.8650

Table 1: Image quality comparison under different metrics.

6. Conclusion and Future Work

To naturally obfuscate face identities while preserves privacy in a controllable and measurable manner, we proposed the AnonymousNet framework, which consists of four stages: facial feature extraction, semantic-based at-

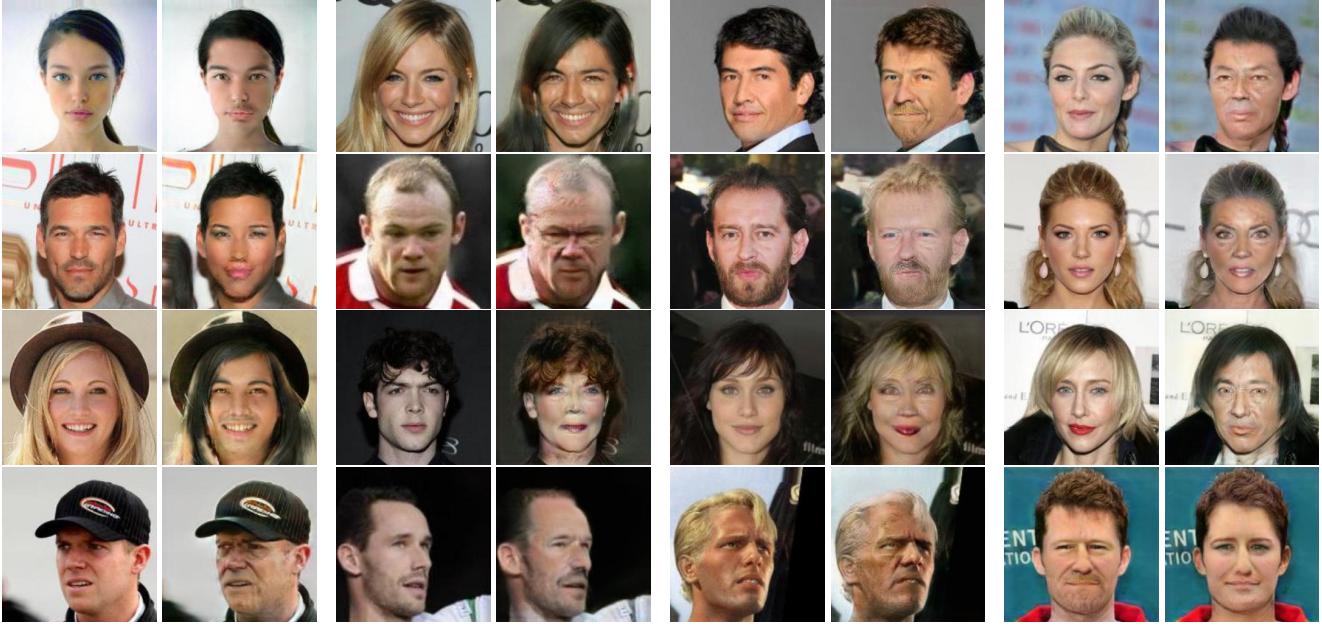


Figure 8: Some experimental results. In each pair, left is the original image and right is the synthesized result with an altered identity. The results show that face identities are preserved in a perceptually natural manner, and in the meantime, each pair of images still shares certain common attributes in correspondence with various privacy policies and application scenarios. Furthermore, artifacts introduced by the proposed the adversarial perturbation are shown to be visually negligible (the perturbation has been intentionally upscaled here for illustrative purposes).

tribute obfuscation, de-identified face generation, and adversarial perturbation. This framework successfully overcomes the shortages of existing methods - being able to generate photo-realistic images with fake identity and capable of balancing privacy and usability both qualitatively and quantitatively. It also answers questions such as “is it private now?”, “how private is it?”, and “can it be more/less private?” counterfactually. Considering the threats from adversaries, especially the malicious detectors that are prevalent in today’s Internet, we further introduced a universal adversarial perturbation so as to trick other deep neural networks as much as possible. Experimental results support the effectiveness of our approach by showing photo-realistic results with negligible artifacts.

In the future, we would like to evaluate perturbation performance among different deep neural network-based detectors qualitatively and quantitatively, which is ignored here due limitations in space and computational resources. We are also interested in robustness, scalability, and extensibility of this framework under various real-world settings. In the experiments, we find that different facial attributes vary in “distinguish power”, i.e., attributes such as Age and Gender are perceptually more powerful in helping distinguish an identity than Cheekbones_Height, which align with our intuitions. This advises a future research direction

that a user study can be made to explore these differences qualitatively and quantitatively, and in the end, figure out “the crux of facial indistinguishability”.

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References

- [1] R. Agrawal and R. Srikant. Privacy-preserving data mining. In *ACM Sigmod Record*, volume 29, pages 439–450. ACM, 2000. 3
- [2] B. Amberg and T. Vetter. Optimal landmark detection using shape models and branch and bound. In *2011 International Conference on Computer Vision*, pages 455–462. IEEE, 2011. 2
- [3] M. Arjovsky, S. Chintala, and L. Bottou. Wasserstein gan. *arXiv preprint arXiv:1701.07875*, 2017. 7

- [4] D. Bitouk, N. Kumar, S. Dhillon, P. Belhumeur, and S. K. Nayar. Face swapping: automatically replacing faces in photographs. In *ACM Transactions on Graphics (TOG)*, volume 27, page 39. ACM, 2008. 3
- [5] Y. Choi, M. Choi, M. Kim, J.-W. Ha, S. Kim, and J. Choo. Stargan: Unified generative adversarial networks for multi-domain image-to-image translation. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 8789–8797, 2018. 6, 7
- [6] C. Clifton, M. Kantacioglu, J. Vaidya, X. Lin, and M. Y. Zhu. Tools for privacy preserving distributed data mining. *ACM Sigkdd Explorations Newsletter*, 4(2):28–34, 2002. 3
- [7] J. Deng, W. Dong, R. Socher, L.-J. Li, K. Li, and L. Fei-Fei. Imagenet: A large-scale hierarchical image database. 2009. 5
- [8] X. Dong, Y. Yan, W. Ouyang, and Y. Yang. Style aggregated network for facial landmark detection. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 379–388, 2018. 3
- [9] C. Dwork. Differential privacy. *Encyclopedia of Cryptography and Security*, pages 338–340, 2011. 5
- [10] I. Goodfellow. 4.5 years of GAN progress on face generation., 2019. 3
- [11] I. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, S. Ozair, A. Courville, and Y. Bengio. Generative adversarial nets. In *Advances in neural information processing systems*, pages 2672–2680, 2014. 2, 3, 6
- [12] I. J. Goodfellow, J. Shlens, and C. Szegedy. Explaining and harnessing adversarial examples. *arXiv preprint arXiv:1412.6572*, 2014. 6
- [13] R. Gross, E. Airoltdi, B. Malin, and L. Sweeney. Integrating utility into face de-identification. In *International Workshop on Privacy Enhancing Technologies*, pages 227–242. Springer, 2005. 3
- [14] R. Hasan, E. Hassan, Y. Li, K. Caine, D. J. Crandall, R. Hoyle, and A. Kapadia. Viewer experience of obscuring scene elements in photos to enhance privacy. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, page 47. ACM, 2018. 2
- [15] R. Hasan, P. Shaffer, D. Crandall, E. T. Apu Kapadia, et al. Cartooning for enhanced privacy in lifelogging and streaming videos. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops*, pages 29–38, 2017. 2, 4
- [16] K. He, X. Zhang, S. Ren, and J. Sun. Deep residual learning for image recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 770–778, 2016. 7
- [17] Q. Huynh-Thu and M. Ghanbari. Scope of validity of psnr in image/video quality assessment. *Electronics letters*, 44(13):800–801, 2008. 7
- [18] P. Isola, J.-Y. Zhu, T. Zhou, and A. A. Efros. Image-to-image translation with conditional adversarial networks. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 1125–1134, 2017. 7
- [19] J. Johnson, A. Alahi, and L. Fei-Fei. Perceptual losses for real-time style transfer and super-resolution. In *European conference on computer vision*, pages 694–711. Springer, 2016. 2, 4
- [20] T. Karras, T. Aila, S. Laine, and J. Lehtinen. Progressive growing of gans for improved quality, stability, and variation. *arXiv preprint arXiv:1710.10196*, 2017. 3
- [21] T. Karras, S. Laine, and T. Aila. A style-based generator architecture for generative adversarial networks. *arXiv preprint arXiv:1812.04948*, 2018. 3, 6
- [22] M. Kowalski, J. Naruniec, and T. Trzcinski. Deep alignment network: A convolutional neural network for robust face alignment. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops*, pages 88–97, 2017. 6
- [23] A. Krizhevsky, I. Sutskever, and G. E. Hinton. Imagenet classification with deep convolutional neural networks. In *Advances in neural information processing systems*, pages 1097–1105, 2012. 2
- [24] N. Li, T. Li, and S. Venkatasubramanian. t-closeness: Privacy beyond k-anonymity and l-diversity. In *2007 IEEE 23rd International Conference on Data Engineering*, pages 106–115. IEEE, 2007. 2, 4, 5
- [25] T. Li. SoK: Single image super-resolution. *Technical Report*, 2017. 7
- [26] T. Li. Beauty learning and counterfactual inference. In *CVPR-19 Workshop on Explainable AI*, 2019. 7
- [27] T. Li, K. Fu, M. Choi, X. Liu, and Y. Chen. Toward robust and efficient training of generative adversarial networks with bayesian approximation. In *the Approximation Theory and Machine Learning Conference*, 2018. 6
- [28] T. Li, L. Lin, and S. Gong. AutoMPC: Efficient multi-party computation for secure and privacy-preserving cooperative control of connected autonomous vehicles. In *Proceedings of the Artificial Intelligence Safety Workshop (SafeAI) of the Thirty-Third AAAI Conference on Artificial Intelligence*, 2019. 1
- [29] T. Li, X. Liu, and S. Su. Semi-supervised text regression with conditional generative adversarial networks. In *2018 IEEE International Conference on Big Data (Big Data)*, pages 5375–5377. IEEE, 2018. 6
- [30] Y. Li, W. Troutman, B. P. Knijnenburg, and K. Caine. Human perceptions of sensitive content in photos. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops*, pages 1590–1596, 2018. 2, 3
- [31] Y. Li, N. Vishwamitra, B. P. Knijnenburg, H. Hu, and K. Caine. Blur vs. block: Investigating the effectiveness of privacy-enhancing obfuscation for images. In *2017 IEEE Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, pages 1343–1351. IEEE, 2017. 1
- [32] A. Liaw, M. Wiener, et al. Classification and regression by randomforest. *R news*, 2(3):18–22, 2002. 5
- [33] Y. Lin, S. Wang, Q. Lin, and F. Tang. Face swapping under large pose variations: A 3d model based approach. In *2012 IEEE International Conference on Multimedia and Expo*, pages 333–338. IEEE, 2012. 3
- [34] M.-Y. Liu and O. Tuzel. Coupled generative adversarial networks. In *Advances in neural information processing systems*, pages 469–477, 2016. 3

- [35] X. Liu, T. Li, H. Peng, I. C. Ouyang, T. Kim, and R. Wang. Understanding beauty via deep facial features. *arXiv preprint arXiv:1902.05380*, 2019. 8
- [36] Z. Liu, P. Luo, X. Wang, and X. Tang. Deep learning face attributes in the wild. In *Proceedings of the IEEE International Conference on Computer Vision*, pages 3730–3738, 2015. 6, 7
- [37] A. Machanavajjhala, J. Gehrke, D. Kifer, and M. Venkitasubramaniam. l-diversity: Privacy beyond k-anonymity. In *22nd International Conference on Data Engineering (ICDE'06)*, pages 24–24. IEEE, 2006. 2, 3, 4
- [38] R. McPherson, R. Shokri, and V. Shmatikov. Defeating image obfuscation with deep learning. *arXiv preprint arXiv:1609.00408*, 2016. 1
- [39] F. Min, N. Sang, and Z. Wang. Automatic face replacement in video based on 2d morphable model. In *2010 20th International Conference on Pattern Recognition*, pages 2250–2253. IEEE, 2010. 3
- [40] S.-M. Moosavi-Dezfooli, A. Fawzi, O. Fawzi, and P. Frossard. Universal adversarial perturbations. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 1765–1773, 2017. 2, 6
- [41] S.-M. Moosavi-Dezfooli, A. Fawzi, and P. Frossard. Deepfool: a simple and accurate method to fool deep neural networks. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 2574–2582, 2016. 6
- [42] E. M. Newton, L. Sweeney, and B. Malin. Preserving privacy by de-identifying face images. *IEEE transactions on Knowledge and Data Engineering*, 17(2):232–243, 2005. 3
- [43] S. J. Oh, R. Benenson, M. Fritz, and B. Schiele. Faceless person recognition: Privacy implications in social media. In *European Conference on Computer Vision*, pages 19–35. Springer, 2016. 1
- [44] S. J. Oh, M. Fritz, and B. Schiele. Adversarial image perturbation for privacy protection a game theory perspective. In *2017 IEEE International Conference on Computer Vision (ICCV)*, pages 1491–1500. IEEE, 2017. 2
- [45] A. Radford, L. Metz, and S. Chintala. Unsupervised representation learning with deep convolutional generative adversarial networks. *arXiv preprint arXiv:1511.06434*, 2015. 3
- [46] V. Rapp, T. Senechal, K. Bailly, and L. Prevost. Multiple kernel learning svm and statistical validation for facial landmark detection. In *Face and Gesture 2011*, pages 265–271. IEEE, 2011. 2
- [47] Y. Rubner, C. Tomasi, and L. J. Guibas. The earth mover’s distance as a metric for image retrieval. *International journal of computer vision*, 40(2):99–121, 2000. 4
- [48] E. M. Rudd, M. Günther, and T. E. Boult. Moon: A mixed objective optimization network for the recognition of facial attributes. In *European Conference on Computer Vision*, pages 19–35. Springer, 2016. 7
- [49] O. Russakovsky, J. Deng, H. Su, J. Krause, S. Satheesh, S. Ma, Z. Huang, A. Karpathy, A. Khosla, M. Bernstein, et al. Imagenet large scale visual recognition challenge. *International journal of computer vision*, 115(3):211–252, 2015. 5
- [50] P. Samarati and L. Sweeney. Protecting privacy when disclosing information: k-anonymity and its enforcement through generalization and suppression. Technical report, technical report, SRI International, 1998. 3, 4
- [51] R. S. Sandhu and P. Samarati. Access control: principle and practice. *IEEE communications magazine*, 32(9):40–48, 1994. 1
- [52] Q. Sun, L. Ma, S. Joon Oh, L. Van Gool, B. Schiele, and M. Fritz. Natural and effective obfuscation by head inpainting. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 5050–5059, 2018. 2
- [53] Y. Sun, X. Wang, and X. Tang. Deep convolutional network cascade for facial point detection. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 3476–3483, 2013. 2
- [54] L. Sweeney. Achieving k-anonymity privacy protection using generalization and suppression. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, 10(05):571–588, 2002. 2
- [55] C. Szegedy, W. Liu, Y. Jia, P. Sermanet, S. Reed, D. Anguelov, D. Erhan, V. Vanhoucke, and A. Rabinovich. Going deeper with convolutions. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 1–9, 2015. 5, 7
- [56] J. Vaidya and C. Clifton. Privacy preserving association rule mining in vertically partitioned data. In *Proceedings of the eighth ACM SIGKDD international conference on Knowledge discovery and data mining*, pages 639–644. ACM, 2002. 3
- [57] I. Wagner and D. Eckhoff. Technical privacy metrics: a systematic survey. *ACM Computing Surveys (CSUR)*, 51(3):57, 2018. 4
- [58] Z. Wang, A. C. Bovik, H. R. Sheikh, E. P. Simoncelli, et al. Image quality assessment: from error visibility to structural similarity. *IEEE transactions on image processing*, 13(4):600–612, 2004. 7
- [59] Z. Wang, E. P. Simoncelli, and A. C. Bovik. Multiscale structural similarity for image quality assessment. In *The Thirty-Seventh Asilomar Conference on Signals, Systems & Computers, 2003*, volume 2, pages 1398–1402. Ieee, 2003. 7
- [60] Y. Wu, F. Yang, and H. Ling. Privacy-protective-gan for face de-identification. *arXiv preprint arXiv:1806.08906*, 2018. 2
- [61] R. A. Yeh, C. Chen, T. Yian Lim, A. G. Schwinger, M. Hasegawa-Johnson, and M. N. Do. Semantic image inpainting with deep generative models. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 5485–5493, 2017. 2, 4
- [62] R. Zhang, P. Isola, A. A. Efros, E. Shechtman, and O. Wang. The unreasonable effectiveness of deep features as a perceptual metric. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 586–595, 2018. 7
- [63] T. Zhang. Privacy-preserving machine learning through data obfuscation. *arXiv preprint arXiv:1807.01860*, 2018. 2, 3, 4
- [64] Z. Zhang, P. Luo, C. C. Loy, and X. Tang. Facial landmark detection by deep multi-task learning. In *European conference on computer vision*, pages 94–108. Springer, 2014. 3