



Universidade Federal da Bahia
Instituto de Matemática e Estatística

Programa de Graduação em Ciência da Computação

**A DEEP LEARNING APPROACH TO
RECOGNIZE SOURCE CODE AUTHORSHIP**

Roberto Sales Caldeira

TRABALHO DE CONCLUSÃO DE CURSO

Salvador
?? de dezembro de 2018

Universidade Federal da Bahia
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Roberto Sales Caldeira

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A DEEP LEARNING APPROACH TO RECOGNIZE SOURCE CODE AUTHORSHIP

Este Trabalho de Conclusão de Curso foi julgado adequado à obtenção do título de Bacharel em Ciência da Computação e aprovado em sua forma final pelo Programa de Graduação em Ciência da Computação da Universidade Federal da Bahia.

Salvador, ?? de dezembro de 2018

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DIGITE OS AGRADECIMENTOS AQUI

DIGITE AQUI A CITACAO
—AUTOR (NOTA)

RESUMO

COLOQUE O RESUMO. Se preferir, crie um arquivo separado e o inclua via comando `include`.

Para evitar problemas de formato neste template (de uso geral), usamos acentuação mostrada abaixo.

`\c{c} \~{a} \'{a} \^{e} \'\{i}`

Não precisa fazer dessa forma, caso use pacotes adequados (latin1, etc.).

Palavras-chave: PALAVRAS-CHAVE.

ABSTRACT

Source code authorship identification is the task of deciding who is the author of a program given its source code. This is usually based on the analysis of previously collected samples from a set of candidate authors. There are several use cases for such a method, including attribution and detection of malicious codes, copyright infringement incident resolution, plagiarism detection, etc. As with texts in natural language, there are many distinguishing features in a piece code, like variable names, indentation style, etc. Some of these features are part of the coding style of a programmer. In this work, we investigate authorship attribution of C++ source codes based on the coding style of the authors. We also propose an end-to-end deep learning method for deciding if two source codes are from the same author, even if the involved authors are unknown to the system.

Keywords: software forensics, authorship identification, plagiarism detection

CONTENTS

Chapter 1—Introduction	1
1.1 Biometrics and Coding Style	1
1.2 Motivation	1
1.3 Applications	2
1.3.1 Plagiarism Detection	2
1.3.2 Copyright Infringement	2
1.3.3 Cyber Attack Identification	3
1.3.4 Exposing Anonymous Programmers	3
1.4 Challenges	3
1.5 Related Work	4
1.6 Contribution	4
Chapter 2—Methodology	7
2.1 Problem Formulation	7
2.2 Datasets	7
2.2.1 Google Code Jam	7
2.2.2 Codeforces	8
2.3 Source Code Embedding Model	8
2.3.1 Coding Style Descriptor	8
2.3.2 Models	9
2.3.2.1 Based on Convolutional Layers	9
2.3.2.2 Based on Long Short-Term Memory Cells	9
2.3.3 Optimization	10
2.3.3.1 Softmax Cross-Entropy Loss	10
2.3.3.2 Triplet Loss	11
Chapter 3—Evaluation	15
Chapter 4—Conclusion	17

LIST OF FIGURES

2.1	Overview of style descriptor generation pipeline.	8
2.2	The architecture of the LSTM-based model.	9
2.3	The region in red represents the margin area beyond p with diameter α . Before loss optimization (a), the negative pair is closer than the positive. During loss optimization (b), the negative pair is pushed further than the positive, but n is still in the margin area. After loss optimization (c), the positive pair is finally closer and n is beyond the margin.	12
2.4	Overview of style descriptor generation pipeline.	13

INTRODUCTION

Programmers often have to choose between tabs and spaces, between `while` loops and `for` loops, between positioning the open bracket in the next line or in the current line, etc. These are choices that can be regarded as their coding styles. Are these choices distinguishing features? In this chapter we will discuss what is style-based source code authorship identification, what challenges it poses, what has been done and what it is useful for. We will also introduce our contributions on the subject.

1.1 BIOMETRICS AND CODING STYLE

Biometrics is the field of computer vision that studies how certain human characteristics can be used to distinguish individuals. Even though physiological characteristics such as fingerprint, iris and face are probably the first ones that come to mind, the study of behavioral characteristics such as typing rhythm, voice, signature and writing style have brought new less intrusive means of distinguishing people. Even though using behavioral characteristics effectively has been made possible throughout the years, the fact that behavior is way more susceptible to change than physiological characteristics poses a big challenge.

Identifying authors of texts based on their writing styles is not a new topic (MENDENHALL, 1887). Throughout the years, computing has evolved and machine learning has reached its peek, making its way through writing style recognition. Narayanan et al. (2012) made it possible to identify the author of a text among tens of thousands of writers. It wasn't long until we were able to distinguish programmers by their coding styles (CALISKAN-ISLAM et al., 2015).

1.2 MOTIVATION

Throughout this work, we mainly consider the task of an investigator interested in deciding whether two anonymous pieces of code were authored by the same programmer or not. The actual authors of these pieces of code may be unknown to the investigator.

Also, these codes may aim to solve different problems, therefore the investigator intends to distinguish them solely based on stylistic features of such pieces.

We also consider easier scenarios where the set of possible authors are known to the investigator and labeled samples from this set are available.

We approach these problems from a deep learning perspective, training a deep neural model that can be subsequently used to resolve authorship of source codes and applying it to the different scenarios an investigator can face.

1.3 APPLICATIONS

Resolving source code authorship has a few real-world applications both in industry and academy. Although we haven't directly studied those, in this section we briefly describe a few of them. In Section (...) we also describe how the experimental formulations we propose in Section (...) are related to each of them.

1.3.1 Plagiarism Detection

Plagiarism can be generally defined as the unauthorized re-use of the work of another individual. Source code plagiarism is a widespread problem in academic institutions. Checking for plagiarism manually is time-consuming and not extremely effective, becoming impractical as the size of the code base increases.

Although automatic source code plagiarism detection is a recurring and well-studied problem (MARTINS et al., 2014), the approaches consolidated by widely used tools such as MOSS (SCHLEIMER et al., 2003), Sherlock (??, tem uma TODO) and JPlag (PRECHELT et al., 2000) are mainly based on code similarity metrics which are greatly correlated to the task the code was written to solve.

For example, let's consider the specific case of *ghostwriting*, where the code the individual claims to be of his authorship was neither written by him nor copied from a colleague, but was actually written by another person (a former student, for example). It may not be possible to compare the suspicious code with another code by the same author, since the ghostwriter may actually be unknown. On the other hand, if pieces of code of the accused party are available, it's possible to determine if his coding style matches the coding style present in the suspicious code.

Also, an analyst may strongly suspect that a piece of code a programmer claims to be of his authorship is actually not, but have no clue of who the actual author might be. This can be modeled as a binary classification problem where positive samples are other pieces of code of the same author and negative samples are pieces from unrelated programmers. We propose another approach to this problem in Section (...).

1.3.2 Copyright Infringement

Software forensics is the science of examining source code and binary code in order to identify, preserve, analyze and present facts and opinions about pieces of software. Although it can also be used in civil proceedings, it's most often associated with the investigation of a wide variety of computer crimes, one of which is copyright infringement.

Code correlation analysis plays an important role at copyright disputes. In this case, an analyst has labeled codes from the involved parties and the task of determining if there was infringement or not.

1.3.3 Cyber Attack Identification

Cyber attack identification is a powerful application of software forensics in cyber security. Files left behind by an intruder during a cyber attack may have just enough information for an analyst to identify who the intruder is or to relate such an attack to a previous incident. Therefore, comparing the coding style of the attacker to those of authors of previous attacks and authors of public code repositories is of great interest to the analyst.

1.3.4 Exposing Anonymous Programmers

Although there are many helpful applications of source code authorship identification, systems capable of de-anonymizing programmers pose a threat to those who want to remain anonymous, in special for anonymous open source contributors (DAUBER et al., 2017). There may be good reasons for a programmer to be anonymous, like working in a software a hostile government doesn't like.

An example of a famous open source anonymous programmer is Bitcoin's creator, Satoshi Nakamoto. For example, if we had a set of labeled codes from programmers that are likely to be Nakamoto, we could try to match their coding style to the early versions of Bitcoin, of course, assuming that Nakamoto didn't try to obfuscate his own coding style.

1.4 CHALLENGES

Although comparison metrics have proved to work well for source codes, extracting features that encode the author's style and, therefore, are independent of the task being solved have proved to be challenging. For example, features such as methods and variables names can often be misleading. This task gets even more challenging as we need to select features that are steady across different programs and capable of distinguishing between programmers. In this work, we propose an end-to-end model that solves this problem.

Also, the environment the programmer is inserted can heavily affect the difficulty of the task. For example, in projects that have a rigid style guide to be followed, much less of the programmer's own coding style might prevail. We don't study the impact of such environments in this work. Moreover, in multi-contributor projects, usually powered by VCS (version control systems), certain pieces of code can contain contributions of many authors, turning the task of relating a single author to the style present on such piece very hard. Although we believe our contributions can be applied to multi-contributor environments, we leave this for future work.

In each of the mentioned applications, the claimed author may act adversarially and try to actively modify the coding style of the program. In the ghostwriting scenario, the involved parties may act together to make the style of the code written by one to match

the other’s. During a cyber attack development, an attacker may explicitly try to hide his own coding style. In a copyright infringement, the suspect may modify the code to match his own style. In this work, adversary interference is not considered.

1.5 RELATED WORK

Spafford and Weeber (1993) were among the first that suggested attributing source code based on style. Even though they suggested a lot of features, they did not propose an automated method nor a thorough analysis on how those features were useful. Hayes and Offutt (2010) examined the conjecture that programmers are unique and that this uniqueness can be observed in the code they write. They conducted an experiment with programmers and graduate students, and found that programmers do have distinguishable style features which they use consistently.

Ranking approaches to source code authorship attribution were proposed by Burrows and Tahaghoghi (2007), Burrows et al. (2007, 2009) and Frantzeskou et al. (2007). Burrows and Tahaghoghi used an information retrieval technique to solve the task, obtaining token-level n-gram representations of the source codes, building an index from these representations and querying that index for programs with unknown authors. The authors of the top-ranked programs were considered the authors of the queried program. Frantzeskou et al. used byte-level n-gram features to tackle the problem. An author profile is composed of the most frequent n-grams in training data of that author. Then, the author of an unclaimed program is considered the one with the most common n-grams to this code. Both works achieved high accuracy on very small suspect sets but didn’t scale well.

Use of ASTs (abstract syntax trees) for authorship attribution was first introduced by Pellin (2000). Caliskan-Islam et al. (2015) have proposed using fuzzy ASTs and random forests to classify authorship of source code. Moreover, they proposed a coding style feature set for C/C++ source codes and a dataset for authorship attribution, based on Google Code Jam, which is a programming competition that resembles laboratory conditions. Dauber et al. (2017) showed that Caliskan-Islam et al. results could be extended to previously unexplored conditions, by adapting their techniques to work for small blocks of code of GitHub repositories.

Macdonell et al. (1999) introduced neural networks to the subject by using feed-forward neural networks and multiple discriminant analysis to attribute source codes. Bandara and Wijayarathna (2013) studied how deep neural networks could be competitive to previous methods given enough training data.

1.6 CONTRIBUTION

In this work, we introduce the concept of *coding style descriptors*, which are compact representations that capture distinguishing stylistic features of a source code. We propose an end-to-end deep model that produces coding style descriptors from source code. Then, we study how the generated descriptors encode meaningful properties to the source code attribution problem by solving many of its variations.

We also introduce the Codeforces dataset for source code attribution, a C++ dataset with more than 30,000 samples extracted from Codeforces, a website specialized in holding online programming competitions. We briefly describe how the dataset was constructed and how it differs from previously published datasets.

METHODOLOGY

In this chapter, we present formulations to the many variants of the source code attribution problem in Section 2.1, we describe how the Codeforces dataset was assembled in Section 2.2 and present a top-down approach to how the end-to-end model was developed in section 2.3.

2.1 PROBLEM FORMULATION

2.2 DATASETS

The first step to develop an effective deep learning model is to gather enough training data. In this work, we decided to work with C++ source codes written in a laboratory environment – we assume the whole code is written by the author under no external style enforcement such as a style guide.

2.2.1 Google Code Jam

Although there are many public C++ laboratory datasets, the Google Code Jam¹ dataset (CALISKAN-ISLAM et al., 2015) is probably the biggest of them all. Samples from this dataset are collected from previous editions of Google Code Jam, an annual programming competition held by Google. In this competition, participants are given algorithmic tasks to be solved in a limited amount of time. As such, it’s very likely that code written by a participant manifests his own coding style.

Google Code Jam holds nearly 10 rounds every year. Most of these rounds are eliminatory. Thus, the availability of samples from less experienced participants is expected to be low. If we want to build a balanced training set not biased by the way experienced participants code, we are limited by the small amount of code less experienced participants wrote.

Although this dataset was not extensively used throughout the development phase, it was a reference for the Codeforces dataset introduced in Section 2.2.2.

¹<https://codingcompetitions.withgoogle.com/codejam>

2.2.2 Codeforces

Codeforces² is a website specialized in holding online programming contests. Contest format is similar to Google Code Jam’s, but they are not eliminatory. Thus, we are able to find a lot of samples from both non-experienced and experienced users.

We wrote a Python script that receives target constraints for the dataset and scrapes Codeforces for samples. Using this script, we assembled a balanced dataset with more than 30,000 samples from nearly 2,000 authors, meaning that we have around 15 samples per author. This dataset was packaged and made public³.

2.3 SOURCE CODE EMBEDDING MODEL

In this section, we propose a deep learning model that embeds source codes, from their string representations, into a denser latent space. In Section 2.3.1, we describe what is a style descriptor. In Section 2.3.2, we describe network architectures used in our work. In Section 2.3.3, we describe how our embedding network was trained to generate meaningful descriptors.

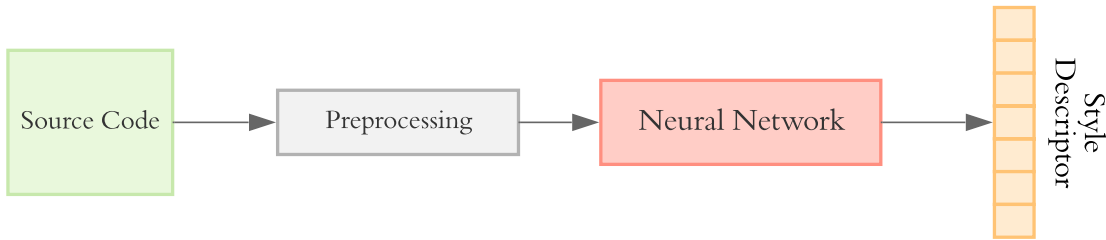


Figure 2.1: Overview of style descriptor generation pipeline.

2.3.1 Coding Style Descriptor

The performance of machine learning methods is heavily affected by the choice of data representation. Thus, much of the effort of the machine learning community has been put into developing algorithms that transform otherwise unmanageable data into representations that can be effectively used by learning methods (BENGIO et al., 2013).

A Coding Style Descriptor (hereon referred simply as *style descriptor*) is a d -dimensional representation of a source code in a latent space. A latent space is a space where representations of similar objects lie close to each other. Therefore, the latent space of style descriptors captures stylistic similarities of source codes. Ideally, style descriptors should encode everything a machine learning model needs to solve the problems posed in Section 2.1. Thus, we can build simpler classifiers for these problems if we can provide a good $f(x) \in \mathbb{R}^d$ which maps source codes to d -dimensional descriptors.

²<http://codeforces.com>

³[link-pro-dataset](#)

Deep feed-forward networks are a natural approach to representation learning. In the remainder of this chapter, we will mainly study deep learning embedding techniques and apply them to our problem.

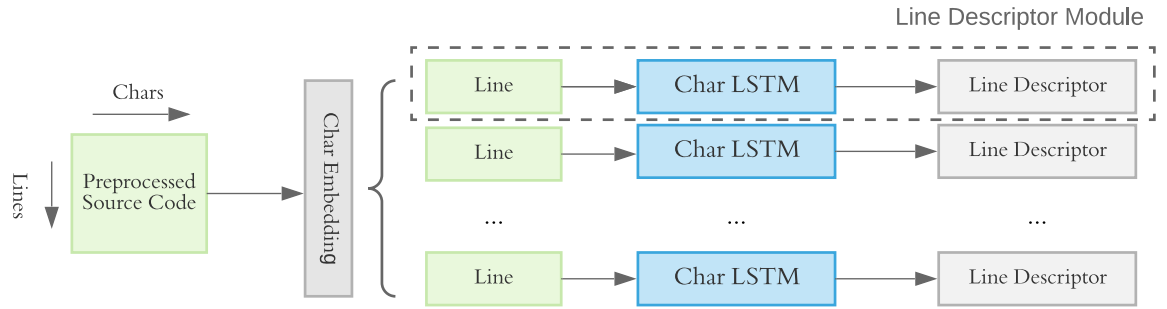
2.3.2 Models

2.3.2.1 Based on Convolutional Layers

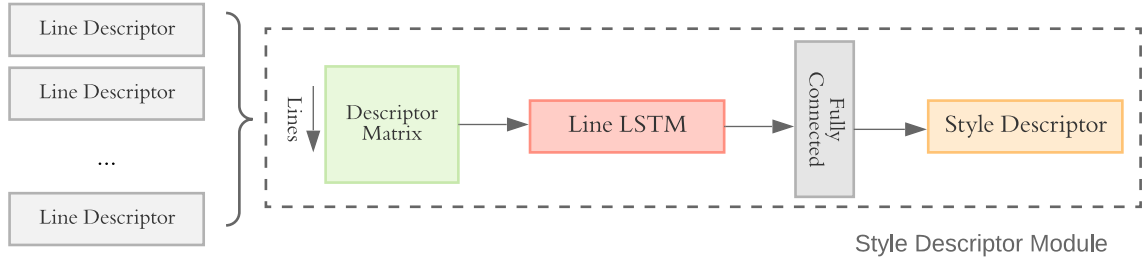
Network Architecture

2.3.2.2 Based on Long Short-Term Memory Cells

Preprocessing



(a) Char embedding layer and line descriptor module



(b) Style descriptor module

Figure 2.2: The architecture of the LSTM-based model.

Network Architecture Our proposed architecture can be split in three parts: the char embedding layer, the line descriptor module (Fig. 2.2a) and the style descriptor module (Fig. 2.2b).

Char Embedding Layer Neural networks can't handle discrete types – like chars – naturally. As such, we need to map the alphabet Σ of source codes to real-valued vectors.

We could simply convert each char to a $|\Sigma|$ -dimensional one-hot vector. As opposed to arbitrarily defining a mapping, we could also let the network learn it.

The char embedding layer is responsible for learning an embedding $f_c(x) \in \mathbb{R}^{d_c}$ that maps chars to d_c -dimensional vectors. Thus, each char in the source code is converted to a real-valued vector. Hereon, we will simply refer to the char embeddings as chars.

Line Descriptor Module This module is responsible for learning an embedding $f_l(x) \in \mathbb{R}^{d_l}$ that maps lines of code to d_l -dimensional descriptors. Each line of the source code is fed – char by char – to the same char-level bidirectional LSTM with (...) hidden units.

Style Descriptor Module The line descriptors generated by the line descriptor module are stacked back into a descriptor matrix. This module is responsible for learning an embedding $f_s(x) \in \mathbb{R}^d$ that maps descriptor matrices to d -dimensional style descriptors. Thus, the whole descriptor matrix is fed – line by line – to a line-level bidirectional LSTM, passed through a fully-connected layer and normalized to lie on the d -sphere. The resulting descriptor is the desired style descriptor.

We believe this architecture encourages the network to learn in a divide-and-conquer manner, by learning the individual features of each line and how to combine them into a single descriptor. The hyperparameter values chosen through the validation phase are given in Table 2.1.

Parameter	#
d_c , char embedding size	(...)
d_l , line descriptor size	(...)
d_s , style descriptor size	(...)
char-level LSTM hidden units	(...)
line-level LSTM hidden units	(...)
fully-connected layer units	(...)

Table 2.1: Values for the hyperparameters of the LSTM-based model.

2.3.3 Optimization

2.3.3.1 Softmax Cross-Entropy Loss The softmax function is commonly used in multi-class classification problems. In a d -class scenario, let $f(x) \in \mathbb{R}^d$ be the output of our neural network for a sample x

$$q(i) = \frac{e^{f(x)_i}}{\sum_j e^{f(x)_j}}. \quad (2.1)$$

$q(i)$ assume values ranging from 0 to 1, and $\sum_i q(i) = 1$. Therefore, we can reinterpret $q(i)$ as the estimation of probability the sample x belongs to class i . The softmax cross-entropy loss is given as

$$\mathcal{L} = - \sum_{i=1}^d p(x, i) \log q(i), \quad (2.2)$$

where $p(x, i)$ is the actual probability the sample x is from class i (usually a one-hot vector). Thus, by minimizing \mathcal{L} , we minimize the cross-entropy between the probability distribution p and an estimated distribution q .

Although softmax cross-entropy loss is a very powerful tool, it does not naturally account for the fact that the number of classes may be unknown. Although there are techniques to apply softmax in these scenarios (SUN et al., 2014; TAIGMAN et al., 2014), there are other optimization methods designed for such cases. Therefore, we restrict ourselves to use this method only when the number of classes is known.

2.3.3.2 Triplet Loss Schroff et al. (2015) introduced triplet loss for training embedding networks. In their work, the loss function is used in conjunction with a novel triplet mining algorithm to train an embedding network that maps images to descriptors. These descriptors are then used to solve face recognition. Triplet loss works in scenarios where the number of classes is unknown. As such, it is well-suited for deciding if two pieces of code are of the same person, even if they are unknown to the system.

The embedding is represented by $f(x) \in \mathbb{R}^d$. Additionally, we constrain this embedding to the boundary of a d -sphere, *i.e.* $\|f(x)\|_2 = 1$.

Let a, p, n (stand for anchor, positive and negative, respectively) be a triplet from the training set such that a and p have the same label (positive pair), but a and n have different labels (negative pair). Also, let \mathcal{T} be the set of all possible said triplets.. Then, triplet loss is defined as

$$\mathcal{L} = \sum_{(a,p,n) \in \mathcal{T}} \max\left(\|f(a) - f(p)\|_2 - \|f(a) - f(n)\|_2 + \alpha, 0\right), \quad (2.3)$$

where α is a margin that is enforced between positive and negative pairs. If $\mathcal{L} = 0$, then for every triplet $(a, p, n) \in \mathcal{T}$, it must be true that

$$\|f(a) - f(p)\|_2 + \alpha \leq \|f(a) - f(n)\|_2. \quad (2.4)$$

When Eq. 2.4 is fulfilled, the negative pair of a triplet will be at least as far as the positive pair plus a margin α . Thus, by minimizing \mathcal{L} , we push the distance of positive pairs towards zero as we push the distance of negative pairs to be greater than the correspondent positive's by α . The advantage of this formulation is that, even though all training samples of the same class will form a cluster, they are not required to collapse to a single point. Fig. 2.3 shows an hypothetical scenario of optimization.

Generating all triplets from \mathcal{T} would consider many triplets that easily satisfy Eq. 2.4. This would cause the training to converge slowly, since those triplets would still be fed to the network, but would not contribute to loss minimization. Therefore, it is crucial to select triplets that do not satisfy this condition to keep improving the model. These are called *hard* triplets.

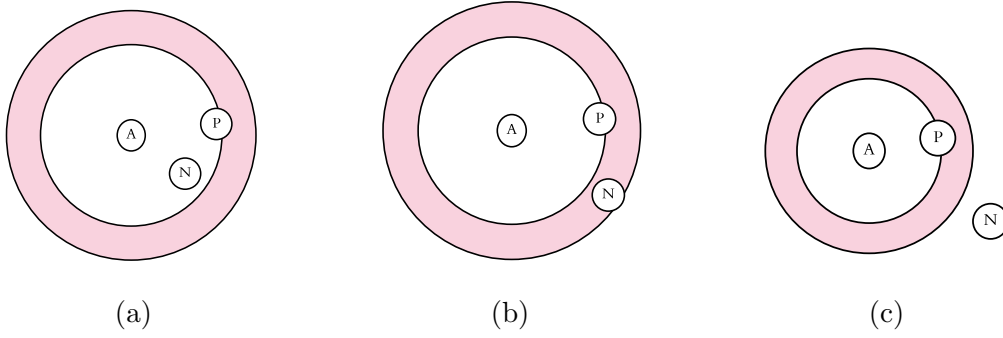


Figure 2.3: The region in red represents the margin area beyond p with diameter α . Before loss optimization (a), the negative pair is closer than the positive. During loss optimization (b), the negative pair is pushed further than the positive, but n is still in the margin area. After loss optimization (c), the positive pair is finally closer and n is beyond the margin.

Online Semi-Hard Triplet Mining One way to select hard triplets from the training set is to consider every sample as the anchor a . Then, select such p that minimizes $\|f(a) - f(p)\|_2$ and such n that maximizes $\|f(a) - f(n)\|_2$. This does not scale with the size of the training set. Moreover, it can cause outliers to dominate the selection process.

Schroff et al. suggested the online semi-hard triplet mining method to tackle both problems. Instead of picking hard triplets from the whole training set, we pick them from the mini-batch. Also, their work suggests that prioritizing triplets such that negatives lie in the margin area (Fig. 2.3b) helps avoiding local minima early in the training. Such triplets are called *semi-hard*.

Although in Chapter (...) we use softmax cross-entropy loss for comparison purposes, we mostly worked with triplet loss. Therefore, our main optimization flow is pictured in Fig. 2.4.

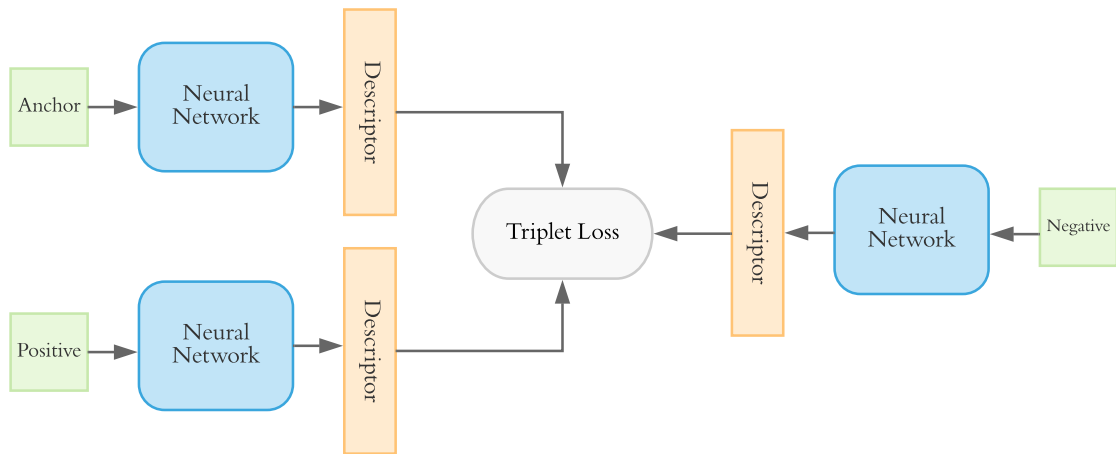
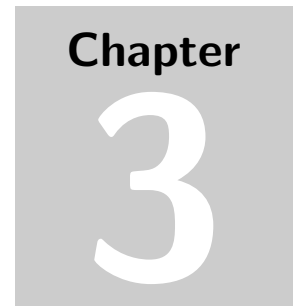


Figure 2.4: Overview of style descriptor generation pipeline.



EVALUATION

Chapter

4

CONCLUSION

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