

# **Artistic Style Transfer Implementation with Tensorflow**

GR5242 Advanced Machine Learning Final Project

**Tian Gao**

*tg2585*

[tian.gao@columbia.edu](mailto:tian.gao@columbia.edu)

GR5242 Advanced Machine Learning Final Project

October 28, 2017

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Project background . . . . .	1
1.2	Related works . . . . .	1
1.3	Development environment and hardware specifications . . . . .	1
<b>2</b>	<b>Mathematical Foundation</b>	<b>2</b>
2.1	Covolutional neural network . . . . .	2
2.2	VGG-network . . . . .	2
2.3	Loss function . . . . .	2
<b>3</b>	<b>Tensorflow Implementation</b>	<b>3</b>
3.1	System overview . . . . .	3
3.2	Pre-defined parameters . . . . .	3
<b>4</b>	<b>Sample Results</b>	<b>5</b>
4.1	When New York meets Van Gogh . . . . .	5
4.1.1	Checkpoint output . . . . .	5
4.1.2	Loss convergence . . . . .	6
4.2	More examples . . . . .	7
<b>5</b>	<b>Discussion</b>	<b>8</b>
5.1	Tuning parameters optimization . . . . .	8
5.1.1	Loss weighting . . . . .	8
5.1.2	Convolutional layer selection . . . . .	8
5.1.3	Gradient descent parameters . . . . .	8
5.2	Run time optimization . . . . .	8
<b>A</b>	<b>Code Manuscript</b>	<b>9</b>
<b>B</b>	<b>Python Code</b>	<b>10</b>
B.1	style_transfer.py . . . . .	10
B.2	neural_network.py . . . . .	12
B.3	visual_geometry_group.py . . . . .	15

## List of Figures

3-1 Tensorflow implementation system overview . . . . .	3
4-1 Raw input of New York photo and Van Gogh painting . . . . .	5
4-2 Overlay Starry Night on New York . . . . .	5
4-3 Raw input of New York photo and Van Gogh painting . . . . .	6
4-4 Overlay Picasso on New York . . . . .	7
4-5 Overlay Pollock on New York . . . . .	7

## List of Tables

3-1 Pre-defined model parameters . . . . .	4
3-2 Pre-defined feature extraction layers . . . . .	4
A-1 Project directory . . . . .	9

## 1 Introduction

### 1.1 Project background

### 1.2 Related works

### 1.3 Development environment and hardware specifications

## 2 Mathematical Foundation

### 2.1 Covolutional neural network

### 2.2 VGG-network

### 2.3 Loss function

## 3 Tensorflow Implementation

### 3.1 System overview

The style transfer system is implemented mainly with Python Tensorflow, with auxiliary packages including NumPy, SciPy, and Pillows. A flowchart of the system overview is provided in Fig. 3–1.

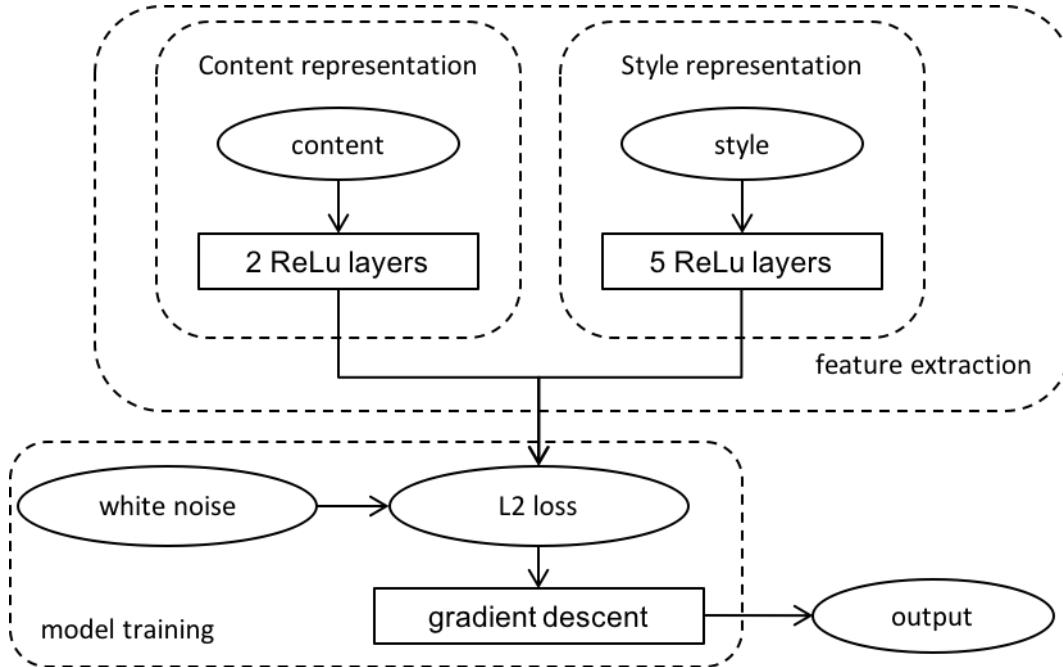


Figure 3–1: Tensorflow implementation system overview

In feature extraction part, the pre-trained VGG network is used for both content representation and style representation. One ReLu layers (relu4\_2) is for content feature extraction and five ReLu layers (relu1\_1, relu2\_1, relu3\_1, relu4\_1, relu5\_1) are for style representation, which are different from the original work [1].

In model training part, the final output is initialized with a white noise picture, and a gradient-based optimization methodology known as Adam is used. As is described in [2], Adam optimizer is based on first-order gradient. Other optimizers including traditional gradient descent method can also be implemented.

### 3.2 Pre-defined parameters

Some tuning parameters are hard-wired in the system. Most of the choices follow the original work [1], or the reference [3] and some are modified.

There is plenty of room with cross-validation optimization for performance improvement (see Sec 5.1 for more details). For simplicity, they are fixed in this system for now and the user can easily modify part of them in `constants.py` following instruction in A.

Some pre-defined parameters are listed below in Table 3–1. The ratio of content loss and style loss is arbitrarily set while [1] explores different loss ratios and corresponding output results. Parameters can always be modified and optimized with techniques like cross-validation.

parameter type	parameter value
content weight	5
style weight	500
total variation weight	100
Adam learning rate	10
Adam $\beta_1$	0.9
Adam $\beta_2$	0.999
Adam $\epsilon$	$10^{-8}$
maximum iteration	1000
pooling layer method	max

Table 3–1: Pre-defined model parameters

Apart from model parameters, neural network choice in this work is also different.

		layers used
content representation	this work	relu4_2
	original work	conv1_1, conv4_2
	Anish work	relu4_2, relu5_2 (weight adjustable)
style representation	this work	relu1_1, relu2_1, relu3_1, relu4_1, relu5_1
	original work	conv1_1, conv2_1, conv3_1, conv4_1, conv5_1
	Anish work	relu1_1, relu2_1, relu3_1, relu4_1, relu5_1

Table 3–2: Pre-defined feature extraction layers

Specifically, all layers in style representation are equally weighted. The random initialization, i.e. process to generate the white noise graph is arbitrary as well but has little impact on the output results, and thus is omitted here.

## 4 Sample Results

### 4.1 When New York meets Van Gogh

The first sample output here is overlay Van Gogh's starry night<sup>1</sup> on a picture of New York<sup>2</sup>.

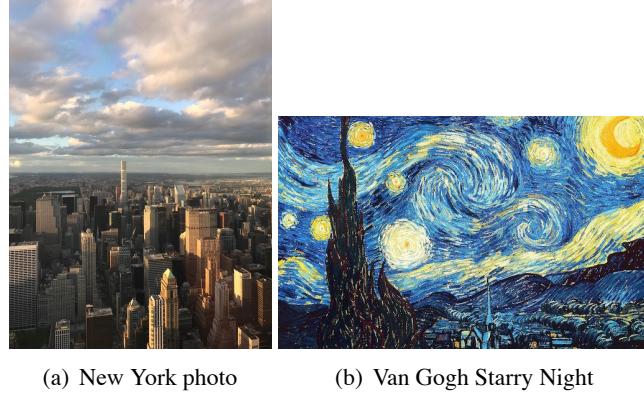


Figure 4–1: Raw input of New York photo and Van Gogh painting

With default parameters specified in Sec. 3.2, we have the output graph below as Fig. 4–2



Figure 4–2: Overlay Starry Night on New York

#### 4.1.1 Checkpoint output

By default, we set number of iteration to 1000, and save intermediate results every 100 steps. In Fig. 4–3, we list the output image at each checkpoint  $N$ , including the initial white noise graph.

<sup>1</sup>Vincent Van Gogh, Starry Night (1889)

<sup>2</sup>The author took this photo in May 2017

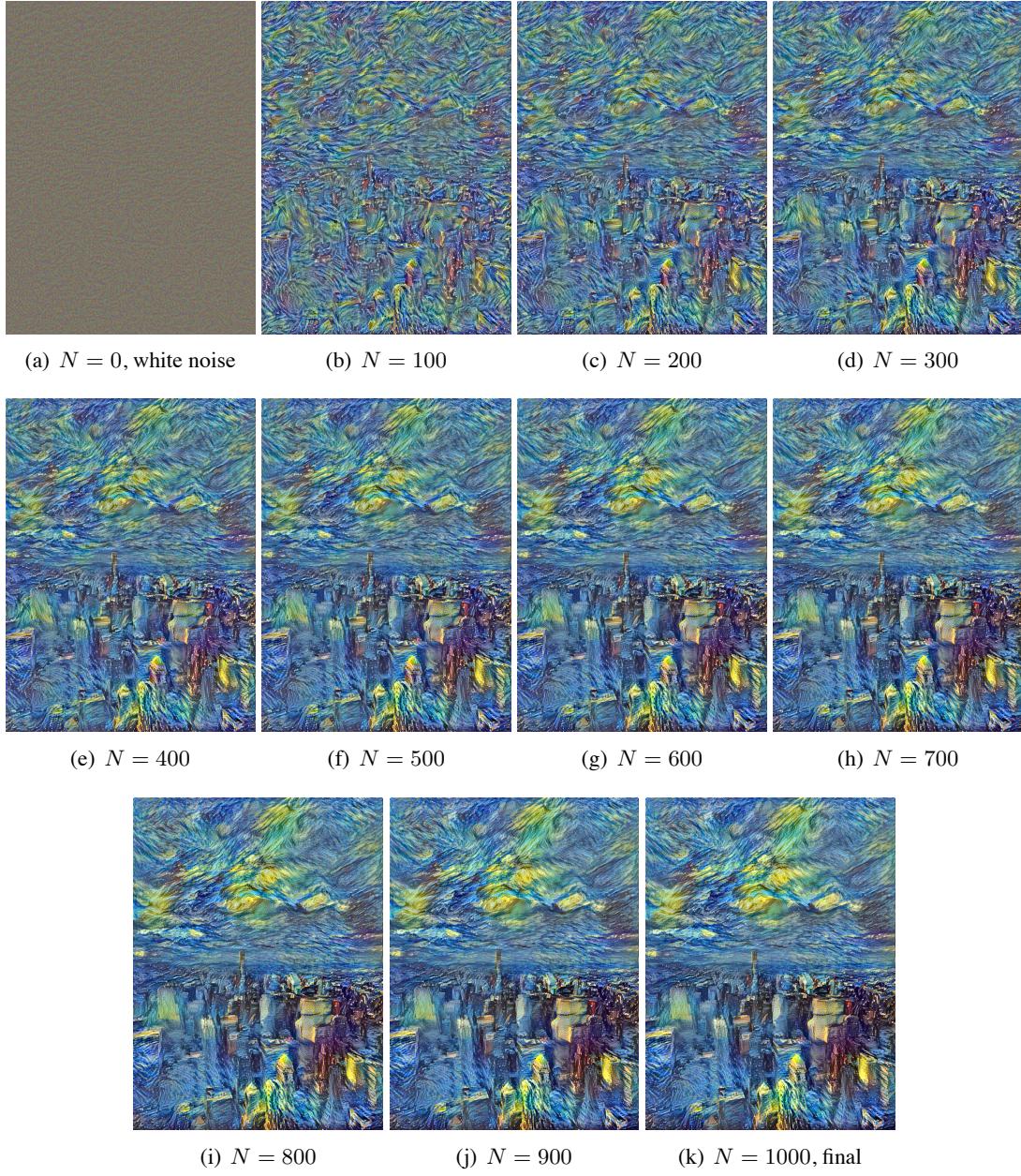


Figure 4–3: Raw input of New York photo and Van Gogh painting

As is shown from the illustration above, the initial learning rate of the algorithm is fast and then the speed slows down; the output result has almost converged after  $N = 500$ . This pattern fits the common process of other deep learning algorithms.

#### 4.1.2 Loss convergence

As is pointed out in Sec. 4.1.1, total loss declines rapidly at initial stage and then converges around  $N = 600$ . Fig. ?? shows the loss function values at each iteration. The concave shape of total loss can be viewed as a proof of the finding.

## 4.2 More examples

We also performed a few more experiments with other artistic styles. Among many artists who have a very strong characteristic and aesthetic style, we chose Pablo Picasso and Jackson Pollock as two examples. Furthermore, the works we chose (Guernica by Picasso<sup>3</sup> and Number 30 by Pollock<sup>4</sup>) both have a very strong and identifiable style.

In Fig. 4–4 and Fig. 4–5 we present the original photo, artistic work, and style transferred output picture.

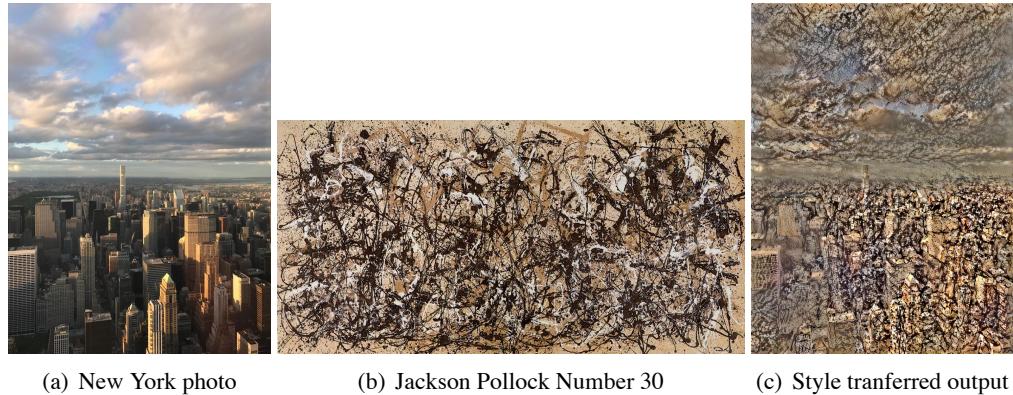


(a) New York photo

(b) Pablo Picasso Guernica

(c) Style tranferred output

Figure 4–4: Overlay Picasso on New York



(a) New York photo

(b) Jackson Pollock Number 30

(c) Style tranferred output

Figure 4–5: Overlay Pollock on New York

The procedure of these two examples are the same as of the Van Gogh example. Therefore, checkpoint output images and loss function plot are not provided here.

The reader can easily replicate the examples with the Python code appended (see Appendix A and Appendix B).

<sup>3</sup>Pablo Picasso, Guernica (1937)

<sup>4</sup>Jackson Pollock, Autumn Rhythm (Number 30, 1950)

## 5 Discussion

### 5.1 Tuning parameters optimization

In Sec. 3.2 we presented a pre-defined parameter list. For simplicity they are fixed in this work, but there is room for improvement in performance with parameter optimization.

#### 5.1.1 Loss weighting

In the original work [1] the authors discussed the trade-off between content representation loss and style representation loss. Different ratios will lead to various focus on content versus style, and the user should be able to adjust the parameter to achieve a more suitable output result based on different needs.

In this work the ratio of content loss and style loss is set to  $10^{-2}$  arbitrarily, and according to [1] this ratio exerts relatively higher emphasis on content feature extraction, therefore the output would resemble the raw input more.

The ratio choice would also be reflected on the difference convergence rate of loss function, as is shown in Fig. ??.

#### 5.1.2 Convolutional layer selection

Different layers can be used for feature extraction. Usually convolutional layers and rectified linear units layers are used.

Apart from the choice of layer, number of layers can also be adjusted, for purpose of faster iteration or more elaborate representation.

#### 5.1.3 Gradient descent parameters

The Adam optimizer takes four parameters, which are arbitrarily set in this project. The topic on the optimizer is beyond the scope of this work, and the reader can refer to [2] for more detailed specifications.

### 5.2 Run time optimization

All output results in this work are generated with a laptop with hardware specifications listed in Sec. 1.3. Average run time of a single batch of generation is roughly 36000 seconds, or 10 hours.

From the perspective of computing power escalation, common methods include using more CPUs, running with GPUs, implementing cloud computing services, or set up parallel computation mechanisms.

As to algorithm optimization, necessary parameter fixation and functionality elimination is required. In exchange for higher speed, the user would need to face with higher information loss (in both style representation and content representation) and more coarse output results.

There have been some works on fast style transfer, among which [4] is an excellent implementation. Perceptual loss and quality improvement in fast stylization are also discussed in [5, 6].

## A Code Manuscript

Please refer to <https://github.com/tian-gao/AdvML-fall17-project> for detailed instructions. All source code are provided.

The following table shows the required directories and files to use the system.

	folder or file name	usage
folders	input output logs	put content picture and style picture inside store output pictures for Tensorboard logs
neural network	visual_geometry_group.py	pre-process the trained VGG network data
Tensorflow model	neural_network.py	feature extraction and model training with Tensorflow
system	style_transfer.py	main function to accept arguments
utility	utils.py constants.py settings.py logger.py	utility functions VGG network layers and pre-defined parameters file paths definition formatted standard screen output
data	imagenet-vgg-verydeep-19.mat	VGG network data

Table A-1: Project directory

In order to carry out style transfer, do

```
python style_transfer.py --content content.jpg --style style.jpg --output output.jpg
```

to transfer “style” to “content” and get the “output”.

Instructions to run the Python code and download the data are all explained in details on the GitHub repository.

## B Python Code

### B.1 style\_transfer.py

```
1 import os
2 import sys
3 import time
4 import scipy.misc
5 from argparse import ArgumentParser
6 from utils import read_image, save_image
7
8 from logger import logger
9 from settings import PATH_INPUT_STYLE, PATH_INPUT_CONTENT, PATH_OUTPUT, TRAINED_NETWORK_DATA
10 from constants import (
11     CONTENT_WEIGHT, STYLE_WEIGHT, TV_WEIGHT, POOLING,
12     LEARNING_RATE, BETA1, BETA2, EPSILON, MAX_ITERATION
13 )
14 from visual_geometry_group import VGG
15 from neural_network import NeuralNetwork
16
17
18 def style_transfer(
19     content_name, style_name, output_name, content_weight, style_weight, tv_weight,
20     pooling, learning_rate, beta1, beta2, epsilon, max_iteration, check_point):
21     time_start = time.time()
22
23     # read images
24     content = read_image(PATH_INPUT_CONTENT + content_name)
25     style = read_image(PATH_INPUT_STYLE + style_name)
26     style = scipy.misc.imresize(style, content.shape[1] / style.shape[1])
27
28     # initialize objects
29     vgg = VGG(TRAINED_NETWORK_DATA, pooling)
30     nn = NeuralNetwork(content, style, vgg, content_weight, style_weight, tv_weight)
31
32     # train model
33     for k, output_image in nn.train_model(learning_rate, beta1, beta2, epsilon,
34                                           max_iteration, check_point):
35         name_list = output_name.split('.')
36         image_name = PATH_OUTPUT + '.'.join(name_list[:-1]) + '_{{}.{}'.format(str(k)) if not
37             k % check_point else 'final', name_list[-1])
38         save_image(output_image, image_name)
39
40     time_end = time.time()
41     logger.info('Time elapsed: {} seconds'.format(round(time_end - time_start)))
42
43 def build_parser():
44     parser = ArgumentParser()
45     parser.add_argument('--content', dest='content', required=True,
46                         help='Content image, e.g. "input.jpg"')
47     parser.add_argument('--style', dest='style', required=True,
48                         help='Style image, e.g. "style.jpg"')
49     parser.add_argument('--output', dest='output', required=True,
50                         help='Output image, e.g. "output.jpg"')
51
52     return parser
```

```
51
52
53 if __name__ == '__main__':
54     parser = build_parser()
55     args = parser.parse_args()
56
57     # check if network data file exists
58     if not os.path.isfile(TRAINED_NETWORK_DATA):
59         logger.error('Cannot find pre-trained network data file!')
60         sys.exit()
61
62     style_transfer(
63         content_name=args.content,
64         style_name=args.style,
65         output_name=args.output,
66
67         content_weight=CONTENT_WEIGHT,
68         style_weight=STYLE_WEIGHT,
69         tv_weight=TV_WEIGHT,
70         pooling=POOLING,
71
72         learning_rate=LEARNING_RATE,
73         beta1=BETA1,
74         beta2=BETA2,
75         epsilon=EPSILON,
76         max_iteration=MAX_ITERATION,
77         check_point=MAX_ITERATION / 10
78     )
```

## B.2 neural\_network.py

```
1 import numpy as np
2 import tensorflow as tf
3 from functools import reduce
4 from operator import mul
5
6 from logger import logger
7 from constants import CONTENT_LAYERS, STYLE_LAYERS
8 from utils import process_image, unprocess_image
9
10
11 class NeuralNetwork(object):
12     """NeuralNetwork provides an interface to formulate the Tensorflow neural network model
13     and perform style transfer algorithm"""
14     def __init__(self, content, style, vgg, content_weight, style_weight, tv_weight):
15         logger.info('Initializing neural network.....')
16         self.content = content
17         self.style = style
18         self.vgg = vgg
19
20         self.content_weight = content_weight
21         self.style_weight = style_weight
22         self.tv_weight = tv_weight
23
24         self.content_shape, self.style_shape, self.content_layer_weights, self.
25             style_layer_weights = self.get_parameters()
26         self.content_features, self.style_features = self.get_features()
27
28     def get_parameters(self):
29         logger.info('Fetching images parameters.....')
30         content_shape = (1, ) + self.content.shape
31         style_shape = (1, ) + self.style.shape
32
33         # get content layer weights
34         content_layer_weights = {}
35         content_layer_weights['relu4_2'] = 1.0
36         content_layer_weights['relu5_2'] = 0.0
37
38         # get style layer weights
39         style_layer_weights = {}
40         for style_layer in STYLE_LAYERS:
41             style_layer_weights[style_layer] = 1.0 / len(STYLE_LAYERS)
42
43         return content_shape, style_shape, content_layer_weights, style_layer_weights
44
45     def get_features(self):
46         content_features = self._get_content_feature()
47         style_features = self._get_style_feature()
48         return content_features, style_features
49
50     def _get_content_feature(self):
51         logger.info('Fetching content features.....')
52         content_features = {}
53         graph = tf.Graph()
54         with graph.as_default(), graph.device('/cpu:0'), tf.Session() as session:
55             content_image = tf.placeholder('float', shape=self.content_shape)
56             content_net = self.vgg.load_net(content_image)
57             content_pre = np.array([
```

```

57     process_image(self.content, self.vgg.mean_pixel)])
58     for content_layer in CONTENT_LAYERS:
59         content_features[content_layer] = content_net[content_layer].eval(feed_dict
60             ={content_image: content_pre})
61
62     return content_features
63
64 def _get_style_feature(self):
65     logger.info('Fetching style features.....')
66     style_features = {}
67     graph = tf.Graph()
68     with graph.as_default(), graph.device('/cpu:0'), tf.Session() as session:
69         style_image = tf.placeholder('float', shape=self.style_shape)
70         style_net = self.vgg.load_net(style_image)
71         style_pre = np.array([
72             process_image(self.style, self.vgg.mean_pixel)])
73         for style_layer in STYLE_LAYERS:
74             feature = style_net[style_layer].eval(feed_dict={style_image: style_pre})
75             feature = np.reshape(feature, (-1, feature.shape[3]))
76             gram = feature.T.dot(feature) / feature.size
77             style_features[style_layer] = gram
78
79     return style_features
80
81 def train_model(self, learning_rate, beta1, beta2, epsilon, max_iteration, check_point):
82     with tf.Graph().as_default():
83         # initialize with random guess
84         logger.info('Initializing tensorflow graph with random guess.....')
85         noise = np.random.normal(size=self.content_shape, scale=np.std(self.content) *
86             0.1)
87         initial_guess = tf.random_normal(self.content_shape) * 0.256
88         input_image = tf.Variable(initial_guess)
89         parsed_net = self.vgg.load_net(input_image)
90
91         # calculate loss
92         content_loss = self._calculate_content_loss(parsed_net)
93         style_loss = self._calculate_style_loss(parsed_net)
94         tv_loss = self._calculate_tv_loss(input_image)
95         loss = content_loss + style_loss + tv_loss
96
97         # summary statistics
98         tf.summary.scalar('content_loss', content_loss)
99         tf.summary.scalar('style_loss', style_loss)
100        tf.summary.scalar('tv_loss', tv_loss)
101        tf.summary.scalar('total_loss', loss)
102        summary_loss = tf.summary.merge_all()
103
104        # initialize optimization
105        train_step = tf.train.AdamOptimizer(learning_rate, beta1, beta2, epsilon).
106            minimize(loss)
107
108        with tf.Session() as session:
109            summary_writer = tf.summary.FileWriter('logs/neural_network', session.graph)
110            logger.info('Saving graph.....')
111
112            session.run(tf.global_variables_initializer())
113            logger.info('Initializing optimization.....')
114            logger.info('Current total loss: {}'.format(loss.eval()))

```

```

113     for k in range(max_iteration):
114         logger.info('Iteration {} total loss {}'.format(str(k+1), loss.eval()))
115         train_step.run()
116         summary = session.run(summary_loss)
117         summary_writer.add_summary(summary, k)
118
119         # save intermediate images at checkpoints
120         if (check_point and (not k % check_point)) or k == max_iteration - 1:
121             output_temp = input_image.eval()
122             output_image = unprocess_image(output_temp.reshape(self.
123                 content_shape[1:])), self.vgg.mean_pixel)
124             yield k, output_image
125
126     def _calculate_content_loss(self, parsed_net):
127         logger.info('Calculating content loss.....')
128         losses = []
129         for content_layer in CONTENT_LAYERS:
130             losses += [
131                 self.content_layer_weights[content_layer] * self.content_weight * (
132                     2 * tf.nn.l2_loss(
133                         parsed_net[content_layer] - self.content_features[content_layer]
134                         ) / self.content_features[content_layer].size)]
135         return reduce(tf.add, losses)
136
137     def _calculate_style_loss(self, parsed_net):
138         logger.info('Calculating style loss.....')
139         losses = []
140         for style_layer in STYLE_LAYERS:
141             layer = parsed_net[style_layer]
142             _, height, width, number = map(lambda x: x.value, layer.get_shape())
143             size = height * width * number
144             feats = tf.reshape(layer, (-1, number))
145             gram = tf.matmul(tf.transpose(feats), feats) / size
146             style_gram = self.style_features[style_layer]
147             losses += [
148                 self.style_layer_weights[style_layer] * 2 * tf.nn.l2_loss(gram - style_gram)
149                         / style_gram.size]
150         return self.style_weight * reduce(tf.add, losses)
151
152     def _calculate_tv_loss(self, image):
153         # total variation denoising
154         logger.info('Calculating total variation loss.....')
155         tv_y_size = self._get_tensor_size(image[:, 1:, :, :])
156         tv_x_size = self._get_tensor_size(image[:, :, 1:, :])
157         tv_loss = self.tv_weight * 2 * (
158             tf.nn.l2_loss(image[:, 1:, :, :] - image[:, :self.content_shape[1]-1, :, :]) /
159                 tv_y_size) +
160             tf.nn.l2_loss(image[:, :, 1:, :] - image[:, :, :self.content_shape[2]-1, :]) /
161                 tv_x_size)
162         return tv_loss
163
164     def _get_tensor_size(self, tensor):
165         return reduce(mul, (d.value for d in tensor.get_shape()), 1)

```

### B.3 visual\_geometry\_group.py

```
1 import numpy as np
2 import scipy.io
3 import tensorflow as tf
4
5 from logger import logger
6 from constants import VGG19_LAYERS
7
8
9 class VGG(object):
10     """VGG provides an interface to extract parameter from pre-trained neural network
11     and formulate Tensorflow layers"""
12     def __init__(self, trained, pooling):
13         logger.info('Loading pre-trained network data.....')
14         self.network = scipy.io.loadmat(trained)
15         self.layers, self.mean_pixel = self.init_net()
16         self.pooling = pooling
17
18     def init_net(self):
19         mean_mat = self.network['normalization'][0][0][0] # shape: (224, 224, 3)
20         mean_pixel = np.mean(mean_mat, axis=(0, 1)) # length: 3
21         layers = self.network['layers'].reshape(-1) # length: 43
22         return layers, mean_pixel
23
24     def load_net(self, input_image):
25         # construct layers using parameters
26         logger.info('Parsing layers.....')
27         parsed_net = {}
28         current_image = input_image
29
30         for layer_name, input_layer in zip(VGG19_LAYERS, self.layers):
31             layer_kind = layer_name[:4]
32
33             if layer_kind == 'conv':
34                 current_image = self._get_conv_layer(current_image, input_layer)
35             elif layer_kind == 'relu':
36                 current_image = self._get_relu_layer(current_image)
37             elif layer_kind == 'pool':
38                 current_image = self._get_pool_layer(current_image)
39             parsed_net[layer_name] = current_image
40
41         assert len(parsed_net) == len(VGG19_LAYERS)
42         return parsed_net
43
44     def _get_conv_layer(self, input_image, input_layer):
45         # get kernel and bias
46         # matconvnet: weights are [width, height, in_channels, out_channels]
47         # tensorflow: weights are [height, width, in_channels, out_channels]
48         kernels, bias = input_layer[0][0][0][0]
49         kernels = np.transpose(kernels, (1, 0, 2, 3))
50         bias = bias.reshape(-1)
51
52         # formulate conv layer
53         conv = tf.nn.conv2d(input_image, tf.constant(kernels), strides=(1, 1, 1, 1), padding
54             ='SAME')
55         layer = tf.nn.bias_add(conv, bias)
56         return layer
```

```
57     def _get_relu_layer(self, input_image):
58         return tf.nn.relu(input_image)
59
60     def _get_pool_layer(self, input_image):
61         if self.pooling == 'avg':
62             layer = tf.nn.avg_pool(input_image, ksize=(1, 2, 2, 1), strides=(1, 2, 2, 1),
63                                   padding='SAME')
64         elif self.pooling == 'max':
65             layer = tf.nn.max_pool(input_image, ksize=(1, 2, 2, 1), strides=(1, 2, 2, 1),
66                                   padding='SAME')
67         return layer
```

## References

- [1] Leon A Gatys, Alexander S Ecker, and Matthias Bethge. Image Style Transfer Using Convolutional Neural Networks. In *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pages 2414–2423. IEEE, 2016.
- [2] Diederik Kingma and Jimmy Ba. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*, 2014.
- [3] Anish Athalye. Neural style. <https://github.com/anishathalye/neural-style>, 2015.
- [4] Logan Engstrom. Fast style transfer. <https://github.com/lengstrom/fast-style-transfer/>, 2016.
- [5] Justin Johnson, Alexandre Alahi, and Li Fei-Fei. Perceptual Losses for Real-Time Style Transfer and Super-Resolution. In *Computer Vision – ECCV 2016*, pages 694–711. Springer International Publishing, Cham, September 2016.
- [6] Dmitry Ulyanov, Andrea Vedaldi, and Victor Lempitsky. Instance Normalization: The Missing Ingredient for Fast Stylization. *arXiv.org*, July 2016.