

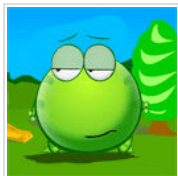
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卷积神经网络(CNN)的基础介绍见<http://blog.csdn.net/fengbingchun/article/details/50529500>，这里主要以代码实现为主。

CNN是一个多层的神经网络，每层由多个二维平面组成，而每个平面由多个独立神经元组成。

以MNIST作为数据库，仿照LeNet-5和tiny-cnn(<http://blog.csdn.net/fengbingchun/article/details/50573841>)设计一个简单的7层CNN结构如下：

输入层Input：神经元数量 $32 \times 32 = 1024$ ；

C1层：卷积窗大小 5×5 ，输出特征图数量6，卷积窗种类6，输出特征图大小 28×28 ，可训练参数(权值+阈值(偏置)) $5 \times 5 \times 6 + 6 = 150 + 6$ ，神经元数量 $28 \times 28 \times 6 = 4704$ ；

S2层：卷积窗大小 2×2 ，输出下采样图数量6，卷积窗种类6，输出下采样图大小 14×14 ，可训练参数 $1 \times 6 + 6 = 6 + 6$ ，神经元数量 $14 \times 14 \times 6 = 1176$ ；

C3层：卷积窗大小 5×5 ，输出特征图数量16，卷积窗种类 $6 \times 16 = 96$ ，输出特征图大小 10×10 ，可训练参数 $5 \times (6 \times 16) + 16 = 2400 + 16$ ，神经元数量 $10 \times 10 \times 16 = 1600$ ；

S4层：卷积窗大小 2×2 ，输出下采样图数量16，卷积窗种类16，输出下采样图大小 5×5 ，可训练参数 $1 \times 16 + 16 = 16 + 16$ ，神经元数量 $5 \times 5 \times 16 = 400$ ；

C5层：卷积窗大小 5×5 ，输出特征图数量120，卷积窗种类 $16 \times 120 = 1920$ ，输出特征图大小 1×1 ，可训练参数 $5 \times 5 \times (16 \times 120) + 120 = 48000 + 120$ ，神经元数量 $1 \times 1 \times 120 = 120$ ；

输出层Output：卷积窗大小 1×1 ，输出特征图数量10，卷积窗种类 $120 \times 10 = 1200$ ，输出特征图大小 1×1 ，可训练参数 $1 \times (120 \times 10) + 10 = 1200 + 10$ ，神经元数量 $1 \times 1 \times 10 = 10$ 。

下面对实现执行过程进行描述说明：

1. 从MNIST数据库中分别获取训练样本和测试样本数据：

(1)、原有MNIST库中图像大小为 28×28 ，这里缩放为 32×32 ，数据值范围为 $[-1, 1]$ ，扩充值均取-1；总共60000个 32×32 训练样本，10000个 32×32 测试样本；

(2)、输出层有10个输出节点，在训练阶段，对应位置的节点值设为0.8，其它节点设为-0.8。

2. 初始化权值和阈值(偏置)：权值就是卷积图像，每一个特征图上的神经元共享相同的权值和阈值，特征图的数量等于阈值的个数

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(1)、权值采用uniform rand的方法初始化；

(2)、阈值均初始化为0.

3. 前向传播：根据权值和阈值，主要计算每层神经元的值

(1)、输入层：每次输入一个32*32数据。

(2)、C1层：分别用每一个5*5的卷积图像去乘以32*32的图像，获得一个28*28的图像，即对应位置相加再求和，stride长度为1；一共6个5*5的卷积图像，然后对每一个神经元加上一个阈值，最后再通过tanh激活函数对每一个神经元进行运算得到最终每一个神经元的结果。

(3)、S2层：对C1中6个28*28的特征图生成6个14*14的下采样图，相邻四个神经元分别进行相加求和，然后乘以一个权值，再求均值即除以4，然后再加上一个阈值，最后再通过tanh激活函数对每一个神经元进行运算得到最终每一个神经元的结果。

(4)、C3层：由S2中的6个14*14下采样图生成16个10*10特征图，对于生成的每一个10*10的特征图，是由6个5*5的卷积图像去乘以6个14*14的下采样图，然后对应位置相加求和，然后对每一个神经元加上一个阈值，最后再通过tanh激活函数对每一个神经元进行运算得到最终每一个神经元的结果。

(5)、S4层：由C3中16个10*10的特征图生成16个5*5下采样图，相邻四个神经元分别进行相加求和，然后乘以一个权值，再求均值即除以4，然后再加上一个阈值，最后再通过tanh激活函数对每一个神经元进行运算得到最终每一个神经元的结果。

(6)、C5层：由S4中16个5*5下采样图生成120个1*1特征图，对于生成的每一个1*1的特征图，是由16个5*5的卷积图像去乘以16个5*5的下采样图，然后相加求和，然后对每一个神经元加上一个阈值，最后再通过tanh激活函数对每一个神经元进行运算得到最终每一个神经元的结果。

(7)、输出层：即全连接层，输出层中的每一个神经元均是由C5层中的120个神经元乘以相对应的权值，然后相加求和；然后对每一个神经元加上一个阈值，最后再通过tanh激活函数对每一个神经元进行运算得到最终每一个神经元的结果。

4. 反向传播：主要计算每层神经元、权值和阈值的误差，以用来更新权值和阈值

(1)、输出层：计算输出层神经元误差；通过mse损失函数的导数函数和tanh激活函数的导数函数来计算输出层神经元误差。

(2)、C5层：计算C5层神经元误差、输出层权值误差、输出层阈值误差；通过输出层神经元误差乘以输出层权值，求和，结果再乘以C5层神经元的tanh激活函数的导数，获得C5层每一个神经元误差；通过输出层神经元误差乘以C5层神经元获得输出层权值误差；输出层误差即为输出层阈值误差。

(3)、S4层：计算S4层神经元误差、C5层权值误差、C5层阈值误差；通过C5层权值乘以C5层神经元误差，求和，结果再乘以S4层神经元的tanh激活函数的导数，获得S4层每一个神经元误差；通过S4层神经元乘以C5层神经元误差，求和，获得C5层权值误差；C5层神经元误差即为C5层阈值误差。

(4)、C3层：计算C3层神经元误差、S4层权值误差、S4层阈值误差；

(5)、S2层：计算S2层神经元误差、C3层权值误差、C3层阈值误差；

(6)、C1层：计算C1层神经元误差、S2层权值误差、S2层阈值误差；

(7)、输入层：计算C1层权值误差、C1层阈值误差。

代码文件：

CNN.hpp：

```
[cpp]
01. #ifndef _CNN_HPP_
02. #define _CNN_HPP_
03.
04. #include <vector>
05. #include <unordered_map>
06.
07. namespace ANN {
08.
```

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```
09. #define width_image_input_CNN      32 //归一化图像宽
10. #define height_image_input_CNN     32 //归一化图像高
11. #define width_image_C1_CNN         28
12. #define height_image_C1_CNN        28
13. #define width_image_S2_CNN         14
14. #define height_image_S2_CNN        14
15. #define width_image_C3_CNN         10
16. #define height_image_C3_CNN        10
17. #define width_image_S4_CNN         5
18. #define height_image_S4_CNN        5
19. #define width_image_C5_CNN         1
20. #define height_image_C5_CNN        1
21. #define width_image_output_CNN     1
22. #define height_image_output_CNN    1
23.
24. #define width_kernel_conv_CNN       5 //卷积核大小
25. #define height_kernel_conv_CNN      5
26. #define width_kernel_pooling_CNN    2
27. #define height_kernel_pooling_CNN   2
28. #define size_pooling_CNN            2
29.
30. #define num_map_input_CNN            1 //输入层map个数
31. #define num_map_C1_CNN              6 //C1层map个数
32. #define num_map_S2_CNN              6 //S2层map个数
33. #define num_map_C3_CNN              16 //C3层map个数
34. #define num_map_S4_CNN              16 //S4层map个数
35. #define num_map_C5_CNN              120 //C5层map个数
36. #define num_map_output_CNN          10 //输出层map个数
37.
38. #define num_patterns_train_CNN       60000 //训练模式对数(总数)
39. #define num_patterns_test_CNN       10000 //测试模式对数(总数)
40. #define num_epochs_CNN               100 //最大迭代次数
41. #define accuracy_rate_CNN           0.985 //要求达到的准确率
42. #define learning_rate_CNN           0.01 //学习率
43. #define eps_CNN                     1e-8
44.
45. #define len_weight_C1_CNN            150 //C1层权值数, 5*5*6*1=150
46. #define len_bias_C1_CNN              6 //C1层阈值数, 6
47. #define len_weight_S2_CNN            6 //S2层权值数, 1*6=6
48. #define len_bias_S2_CNN              6 //S2层阈值数, 6
49. #define len_weight_C3_CNN            2400 //C3层权值数, 5*5*16*6=2400
50. #define len_bias_C3_CNN              16 //C3层阈值数, 16
51. #define len_weight_S4_CNN            16 //S4层权值数, 1*16=16
52. #define len_bias_S4_CNN              16 //S4层阈值数, 16
53. #define len_weight_C5_CNN            48000 //C5层权值数, 5*5*16*120=48000
54. #define len_bias_C5_CNN              120 //C5层阈值数, 120
55. #define len_weight_output_CNN        1200 //输出层权值数, 120*10=1200
56. #define len_bias_output_CNN          10 //输出层阈值数, 10
57.
58. #define num_neuron_input_CNN          1024 //输入层神经元数, 32*32=1024
59. #define num_neuron_C1_CNN             4704 //C1层神经元数, 28*28*6=4704
60. #define num_neuron_S2_CNN             1176 //S2层神经元数, 14*14*6=1176
61. #define num_neuron_C3_CNN             1600 //C3层神经元数, 10*10*16=1600
62. #define num_neuron_S4_CNN             400 //S4层神经元数, 5*5*16=400
63. #define num_neuron_C5_CNN             120 //C5层神经元数, 1*120=120
64. #define num_neuron_output_CNN         10 //输出层神经元数, 1*10=10
65.
66. class CNN {
67. public:
68.     CNN();
69.     ~CNN();
70.
71.     void init(); //初始化, 分配空间
72.     bool train(); //训练
73.     int predict(const unsigned char* data, int width, int height); //预测
74.     bool readModelFile(const char* name); //读取已训练好的模型
75.
76. protected:
77.     typedef std::vector<std::pair<int, int> > wi_connections;
78.     typedef std::vector<std::pair<int, int> > wo_connections;
79.     typedef std::vector<std::pair<int, int> > io_connections;
80.
81.     void release(); //释放申请的空间
82.     bool saveModelFile(const char* name); //将训练好的model保存起来, 包括各层的节点数, 权值和阈值
83.
84.     bool initWeightThreshold(); //初始化, 产生[-1, 1]之间的随机小数
85.     bool getSrcData(); //读取MNIST数据
86.     double test(); //训练完一次计算一次准确率
87.     double activation_function_tanh(double x); //激活函数:tanh
```

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```
87. double activation_function_tanh_derivative(double x); //激活函数tanh的导数
88. double activation_function_identity(double x);
89. double activation_function_identity_derivative(double x);
90. double loss_function_mse(double y, double t); //损失函数:mean squared error
91. double loss_function_mse_derivative(double y, double t);
92. void loss_function_gradient(const double* y, const double* t, double* dst, int len);
93. double dot_product(const double* s1, const double* s2, int len); //点乘
94. bool muladd(const double* src, double c, int len, double* dst); //dst[i] += c * src[i]
95. void init_variable(double* val, double c, int len);
96. bool uniform_rand(double* src, int len, double min, double max);
97. double uniform_rand(double min, double max);
98. int get_index(int x, int y, int channel, int width, int height, int depth);
99. void calc_out2wi(int width_in, int height_in, int width_out, int height_out, int depth_in,
100. void calc_out2bias(int width, int height, int depth, std::vector<int>& out2bias);
101. void calc_in2wo(int width_in, int height_in, int width_out, int height_out, int depth_in,
102. void calc_weight2io(int width_in, int height_in, int width_out, int height_out, int depth_in,
103. void calc_bias2out(int width_in, int height_in, int width_out, int height_out, int depth_in,
104.
105. bool Forward_C1(); //前向传播
106. bool Forward_S2();
107. bool Forward_C3();
108. bool Forward_S4();
109. bool Forward_C5();
110. bool Forward_output();
111. bool Backward_output();
112. bool Backward_C5(); //反向传播
113. bool Backward_S4();
114. bool Backward_C3();
115. bool Backward_S2();
116. bool Backward_C1();
117. bool Backward_input();
118. bool UpdateWeights(); //更新权值、阈值
119. void update_weights_bias(const double* delta, double* e_weight, double* weight, int len);
120.
121. private:
122. double* data_input_train; //原始标准输入数据, 训练, 范围: [-1, 1]
123. double* data_output_train; //原始标准期望结果, 训练, 取值: -0.8/0.8
124. double* data_input_test; //原始标准输入数据, 测试, 范围: [-1, 1]
125. double* data_output_test; //原始标准期望结果, 测试, 取值: -0.8/0.8
126. double* data_single_image;
127. double* data_single_label;
128.
129. double weight_C1[len_weight_C1_CNN];
130. double bias_C1[len_bias_C1_CNN];
131. double weight_S2[len_weight_S2_CNN];
132. double bias_S2[len_bias_S2_CNN];
133. double weight_C3[len_weight_C3_CNN];
134. double bias_C3[len_bias_C3_CNN];
135. double weight_S4[len_weight_S4_CNN];
136. double bias_S4[len_bias_S4_CNN];
137. double weight_C5[len_weight_C5_CNN];
138. double bias_C5[len_bias_C5_CNN];
139. double weight_output[len_weight_output_CNN];
140. double bias_output[len_bias_output_CNN];
141.
142. double E_weight_C1[len_weight_C1_CNN];
143. double E_bias_C1[len_bias_C1_CNN];
144. double E_weight_S2[len_weight_S2_CNN];
145. double E_bias_S2[len_bias_S2_CNN];
146. double E_weight_C3[len_weight_C3_CNN];
147. double E_bias_C3[len_bias_C3_CNN];
148. double E_weight_S4[len_weight_S4_CNN];
149. double E_bias_S4[len_bias_S4_CNN];
150. double* E_weight_C5;
151. double* E_bias_C5;
152. double* E_weight_output;
153. double* E_bias_output;
154.
155. double neuron_input[num_neuron_input_CNN]; //data_single_image
156. double neuron_C1[num_neuron_C1_CNN];
157. double neuron_S2[num_neuron_S2_CNN];
158. double neuron_C3[num_neuron_C3_CNN];
159. double neuron_S4[num_neuron_S4_CNN];
160. double neuron_C5[num_neuron_C5_CNN];
161. double neuron_output[num_neuron_output_CNN];
162.
163. double delta_neuron_output[num_neuron_output_CNN]; //神经元误差
164. double delta_neuron_C5[num_neuron_C5_CNN];
165. double delta_neuron_S4[num_neuron_S4_CNN];
```

关闭

卷积神经网络(CNN)的简单实现([hugl950123: @fengbingchun](#):下的是新的,我在CNN.cpp文件中每个函数都设置了断点,还是没有变化=...

卷积神经网络(CNN)的简单实现([fengbingchun: @hugl950123](#):你用的是GitHub上最新的吗?既然能编译过,在Debug下设断点,应该很快...

卷积神经网络(CNN)的简单实现([hugl950123](#): 博主, 请问我按照您的代码成功编译后执行结果窗口一闪而过,并且里面什么内容也没有,应该如何解决,能不能...

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展开



液态硬盘



```
166.     double delta_neuron_C3[num_neuron_C3_CNN];
167.     double delta_neuron_S2[num_neuron_S2_CNN];
168.     double delta_neuron_C1[num_neuron_C1_CNN];
169.     double delta_neuron_input[num_neuron_input_CNN];
170.
171.     double delta_weight_C1[len_weight_C1_CNN]; //权值、阈值误差
172.     double delta_bias_C1[len_bias_C1_CNN];
173.     double delta_weight_S2[len_weight_S2_CNN];
174.     double delta_bias_S2[len_bias_S2_CNN];
175.     double delta_weight_C3[len_weight_C3_CNN];
176.     double delta_bias_C3[len_bias_C3_CNN];
177.     double delta_weight_S4[len_weight_S4_CNN];
178.     double delta_bias_S4[len_bias_S4_CNN];
179.     double delta_weight_C5[len_weight_C5_CNN];
180.     double delta_bias_C5[len_bias_C5_CNN];
181.     double delta_weight_output[len_weight_output_CNN];
182.     double delta_bias_output[len_bias_output_CNN];
183.
184.     std::vector<wi_connections> out2wi_S2; // out_id -> [(weight_id, in_id)]
185.     std::vector<int> out2bias_S2;
186.     std::vector<wi_connections> out2wi_S4;
187.     std::vector<int> out2bias_S4;
188.     std::vector<wo_connections> in2wo_C3; // in_id -> [(weight_id, out_id)]
189.     std::vector<io_connections> weight2io_C3; // weight_id -> [(in_id, out_id)]
190.     std::vector<std::vector<int> > bias2out_C3;
191.     std::vector<wo_connections> in2wo_C1;
192.     std::vector<io_connections> weight2io_C1;
193.     std::vector<std::vector<int> > bias2out_C1;
194. };
195.
196. }
197.
198. #endif // _CNN_HPP_
```

CNN.cpp :

```
[cpp] C ⓘ
01. #include <CNN.hpp>
02. #include <assert.h>
03. #include <time.h>
04. #include <iostream>
05. #include <fstream>
06. #include <numeric>
07. #include <windows.h>
08. #include <random>
09. #include <algorithm>
10. #include <string>
11.
12. namespace ANN {
13.
14. CNN::CNN()
15. {
16.     data_input_train = NULL;
17.     data_output_train = NULL;
18.     data_input_test = NULL;
19.     data_output_test = NULL;
20.     data_single_image = NULL;
21.     data_single_label = NULL;
22.     E_weight_C5 = NULL;
23.     E_bias_C5 = NULL;
24.     E_weight_output = NULL;
25.     E_bias_output = NULL;
26. }
27.
28. CNN::~CNN()
29. {
30.     release();
31. }
32.
33. void CNN::release()
34. {
35.     if (data_input_train) {
36.         delete[] data_input_train;
37.         data_input_train = NULL;
38.     }
39.     if (data_output_train) {
40.         delete[] data_output_train;
41.         data_output_train = NULL;
```

关闭

```

42.     }
43.     if (data_input_test) {
44.         delete[] data_input_test;
45.         data_input_test = NULL;
46.     }
47.     if (data_output_test) {
48.         delete[] data_output_test;
49.         data_output_test = NULL;
50.     }
51.
52.     if (E_weight_C5) {
53.         delete[] E_weight_C5;
54.         E_weight_C5 = NULL;
55.     }
56.     if (E_bias_C5) {
57.         delete[] E_bias_C5;
58.         E_bias_C5 = NULL;
59.     }
60.     if (E_weight_output) {
61.         delete[] E_weight_output;
62.         E_weight_output = NULL;
63.     }
64.     if (E_bias_output) {
65.         delete[] E_bias_output;
66.         E_bias_output = NULL;
67.     }
68. }
69.
70. // connection table [Y.Lecun, 1998 Table.1]
71. #define O true
72. #define X false
73. static const bool tbl[6][16] = {
74.     0, X, X, X, 0, 0, 0, X, X, 0, 0, 0, 0, X, 0, 0,
75.     0, 0, X, X, X, 0, 0, 0, X, X, 0, 0, 0, 0, X, 0,
76.     0, 0, 0, X, X, X, 0, 0, 0, X, X, 0, X, 0, 0, 0,
77.     X, 0, 0, 0, X, X, 0, 0, 0, 0, X, X, 0, X, 0, 0,
78.     X, X, 0, 0, 0, X, X, 0, 0, 0, 0, X, 0, 0, X, 0,
79.     X, X, X, 0, 0, 0, X, X, 0, 0, 0, 0, 0, X, 0, 0,
80. };
81. #undef O
82. #undef X
83.
84. void CNN::init_variable(double* val, double c, int len)
85. {
86.     for (int i = 0; i < len; i++) {
87.         val[i] = c;
88.     }
89. }
90.
91. void CNN::init()
92. {
93.     int len1 = width_image_input_CNN * height_image_input_CNN * num_patterns_train_CNN;
94.     data_input_train = new double[len1];
95.     init_variable(data_input_train, -1.0, len1);
96.
97.     int len2 = num_map_output_CNN * num_patterns_train_CNN;
98.     data_output_train = new double[len2];
99.     init_variable(data_output_train, -0.8, len2);
100.
101.     int len3 = width_image_input_CNN * height_image_input_CNN * num_patterns_test_CNN;
102.     data_input_test = new double[len3];
103.     init_variable(data_input_test, -1.0, len3);
104.
105.     int len4 = num_map_output_CNN * num_patterns_test_CNN;
106.     data_output_test = new double[len4];
107.     init_variable(data_output_test, -0.8, len4);
108.
109.     std::fill(E_weight_C1, E_weight_C1 + len_weight_C1_CNN, 0.0);
110.     std::fill(E_bias_C1, E_bias_C1 + len_bias_C1_CNN, 0.0);
111.     std::fill(E_weight_S2, E_weight_S2 + len_weight_S2_CNN, 0.0);
112.     std::fill(E_bias_S2, E_bias_S2 + len_bias_S2_CNN, 0.0);
113.     std::fill(E_weight_C3, E_weight_C3 + len_weight_C3_CNN, 0.0);
114.     std::fill(E_bias_C3, E_bias_C3 + len_bias_C3_CNN, 0.0);
115.     std::fill(E_weight_S4, E_weight_S4 + len_weight_S4_CNN, 0.0);
116.     std::fill(E_bias_S4, E_bias_S4 + len_bias_S4_CNN, 0.0);
117.     E_weight_C5 = new double[len_weight_C5_CNN];
118.     std::fill(E_weight_C5, E_weight_C5 + len_weight_C5_CNN, 0.0);
119.     E_bias_C5 = new double[len_bias_C5_CNN];
120.     std::fill(E_bias_C5, E_bias_C5 + len_bias_C5_CNN, 0.0);

```

关闭


```
121.     E_weight_output = new double[len_weight_output_CNN];
122.     std::fill(E_weight_output, E_weight_output + len_weight_output_CNN, 0.0);
123.     E_bias_output = new double[len_bias_output_CNN];
124.     std::fill(E_bias_output, E_bias_output + len_bias_output_CNN, 0.0);
125.
126.     initWeightThreshold();
127.     getSrcData();
128. }
129.
130. double CNN::uniform_rand(double min, double max)
131. {
132.     static std::mt19937 gen(1);
133.     std::uniform_real_distribution<double> dst(min, max);
134.     return dst(gen);
135. }
136.
137. bool CNN::uniform_rand(double* src, int len, double min, double max)
138. {
139.     for (int i = 0; i < len; i++) {
140.         src[i] = uniform_rand(min, max);
141.     }
142.
143.     return true;
144. }
145.
146. bool CNN::initWeightThreshold()
147. {
148.     srand(time(0) + rand());
149.     const double scale = 6.0;
150.
151.     double min_ = -std::sqrt(scale / (25.0 + 150.0));
152.     double max_ = std::sqrt(scale / (25.0 + 150.0));
153.     uniform_rand(weight_C1, len_weight_C1_CNN, min_, max_);
154.     for (int i = 0; i < len_bias_C1_CNN; i++) {
155.         bias_C1[i] = 0.0;
156.     }
157.
158.     min_ = -std::sqrt(scale / (4.0 + 1.0));
159.     max_ = std::sqrt(scale / (4.0 + 1.0));
160.     uniform_rand(weight_S2, len_weight_S2_CNN, min_, max_);
161.     for (int i = 0; i < len_bias_S2_CNN; i++) {
162.         bias_S2[i] = 0.0;
163.     }
164.
165.     min_ = -std::sqrt(scale / (150.0 + 400.0));
166.     max_ = std::sqrt(scale / (150.0 + 400.0));
167.     uniform_rand(weight_C3, len_weight_C3_CNN, min_, max_);
168.     for (int i = 0; i < len_bias_C3_CNN; i++) {
169.         bias_C3[i] = 0.0;
170.     }
171.
172.     min_ = -std::sqrt(scale / (4.0 + 1.0));
173.     max_ = std::sqrt(scale / (4.0 + 1.0));
174.     uniform_rand(weight_S4, len_weight_S4_CNN, min_, max_);
175.     for (int i = 0; i < len_bias_S4_CNN; i++) {
176.         bias_S4[i] = 0.0;
177.     }
178.
179.     min_ = -std::sqrt(scale / (400.0 + 3000.0));
180.     max_ = std::sqrt(scale / (400.0 + 3000.0));
181.     uniform_rand(weight_C5, len_weight_C5_CNN, min_, max_);
182.     for (int i = 0; i < len_bias_C5_CNN; i++) {
183.         bias_C5[i] = 0.0;
184.     }
185.
186.     min_ = -std::sqrt(scale / (120.0 + 10.0));
187.     max_ = std::sqrt(scale / (120.0 + 10.0));
188.     uniform_rand(weight_output, len_weight_output_CNN, min_, max_);
189.     for (int i = 0; i < len_bias_output_CNN; i++) {
190.         bias_output[i] = 0.0;
191.     }
192.
193.     return true;
194. }
195.
196. static int reverseInt(int i)
197. {
198.     unsigned char ch1, ch2, ch3, ch4;
199.     ch1 = i & 255;
```

关闭

```
200.     ch2 = (i >> 8) & 255;
201.     ch3 = (i >> 16) & 255;
202.     ch4 = (i >> 24) & 255;
203.     return((int)ch1 << 24) + ((int)ch2 << 16) + ((int)ch3 << 8) + ch4;
204. }
205.
206. static void readMnistImages(std::string filename, double* data_dst, int num_image)
207. {
208.     const int width_src_image = 28;
209.     const int height_src_image = 28;
210.     const int x_padding = 2;
211.     const int y_padding = 2;
212.     const double scale_min = -1;
213.     const double scale_max = 1;
214.
215.     std::ifstream file(filename, std::ios::binary);
216.     assert(file.is_open());
217.
218.     int magic_number = 0;
219.     int number_of_images = 0;
220.     int n_rows = 0;
221.     int n_cols = 0;
222.     file.read((char*)&magic_number, sizeof(magic_number));
223.     magic_number = reverseInt(magic_number);
224.     file.read((char*)&number_of_images, sizeof(number_of_images));
225.     number_of_images = reverseInt(number_of_images);
226.     assert(number_of_images == num_image);
227.     file.read((char*)&n_rows, sizeof(n_rows));
228.     n_rows = reverseInt(n_rows);
229.     file.read((char*)&n_cols, sizeof(n_cols));
230.     n_cols = reverseInt(n_cols);
231.     assert(n_rows == height_src_image && n_cols == width_src_image);
232.
233.     int size_single_image = width_image_input_CNN * height_image_input_CNN;
234.
235.     for (int i = 0; i < number_of_images; ++i) {
236.         int addr = size_single_image * i;
237.
238.         for (int r = 0; r < n_rows; ++r) {
239.             for (int c = 0; c < n_cols; ++c) {
240.                 unsigned char temp = 0;
241.                 file.read((char*)&temp, sizeof(temp));
242.                 data_dst[addr + width_image_input_CNN * (r + y_padding) + c + x_padding] :
243.             }
244.         }
245.     }
246. }
247.
248. static void readMnistLabels(std::string filename, double* data_dst, int num_image)
249. {
250.     const double scale_max = 0.8;
251.
252.     std::ifstream file(filename, std::ios::binary);
253.     assert(file.is_open());
254.
255.     int magic_number = 0;
256.     int number_of_images = 0;
257.     file.read((char*)&magic_number, sizeof(magic_number));
258.     magic_number = reverseInt(magic_number);
259.     file.read((char*)&number_of_images, sizeof(number_of_images));
260.     number_of_images = reverseInt(number_of_images);
261.     assert(number_of_images == num_image);
262.
263.     for (int i = 0; i < number_of_images; ++i) {
264.         unsigned char temp = 0;
265.         file.read((char*)&temp, sizeof(temp));
266.         data_dst[i * num_map_output_CNN + temp] = scale_max;
267.     }
268. }
269.
270. bool CNN::getSrcData()
271. {
272.     assert(data_input_train && data_output_train && data_input_test && data_output_test);
273.
274.     std::string filename_train_images = "E:/GitCode/NN_Test/data/train-images.idx3-
ubyte";
275.     std::string filename_train_labels = "E:/GitCode/NN_Test/data/train-labels.idx1-
ubyte";
276.     readMnistImages(filename_train_images, data_input_train, num_patterns_train_CNN);
```

关闭


```

277.         readMnistLabels(filename_train_labels, data_output_train, num_patterns_train_CNN);
278.
279.         std::string filename_test_images = "E:/GitCode/NN_Test/data/t10k-images.idx3-
ubyte";
280.         std::string filename_test_labels = "E:/GitCode/NN_Test/data/t10k-labels.idx1-
ubyte";
281.         readMnistImages(filename_test_images, data_input_test, num_patterns_test_CNN);
282.         readMnistLabels(filename_test_labels, data_output_test, num_patterns_test_CNN);
283.
284.         return true;
285.     }
286.
287.     bool CNN::train()
288.     {
289.         out2wi_S2.clear();
290.         out2bias_S2.clear();
291.         out2wi_S4.clear();
292.         out2bias_S4.clear();
293.         in2wo_C3.clear();
294.         weight2io_C3.clear();
295.         bias2out_C3.clear();
296.         in2wo_C1.clear();
297.         weight2io_C1.clear();
298.         bias2out_C1.clear();
299.
300.         calc_out2wi(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
301.         calc_out2bias(width_image_S2_CNN, height_image_S2_CNN, num_map_S2_CNN, out2bias_S2);
302.         calc_out2wi(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_image_
303.         calc_out2bias(width_image_S4_CNN, height_image_S4_CNN, num_map_S4_CNN, out2bias_S4);
304.         calc_in2wo(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_image_
305.         calc_weight2io(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_image_
306.         calc_bias2out(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_image_
307.         calc_in2wo(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
308.         calc_weight2io(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
309.         calc_bias2out(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
310.
311.         int iter = 0;
312.         for (iter = 0; iter < num_epochs_CNN; iter++) {
313.             std::cout << "epoch: " << iter + 1;
314.
315.             for (int i = 0; i < num_patterns_train_CNN; i++) {
316.                 data_single_image = data_input_train + i * num_neuron_input_CNN;
317.                 data_single_label = data_output_train + i * num_neuron_output_CNN;
318.
319.                 Forward_C1();
320.                 Forward_S2();
321.                 Forward_C3();
322.                 Forward_S4();
323.                 Forward_C5();
324.                 Forward_output();
325.
326.                 Backward_output();
327.                 Backward_C5();
328.                 Backward_S4();
329.                 Backward_C3();
330.                 Backward_S2();
331.                 Backward_C1();
332.                 Backward_input();
333.
334.                 UpdateWeights();
335.             }
336.
337.             double accuracyRate = test();
338.             std::cout << ",    accuray rate: " << accuracyRate << std::endl;
339.             if (accuracyRate > accuracy_rate_CNN) {
340.                 saveModelFile("E:/GitCode/NN_Test/data/cnn
341.                 std::cout << "generate cnn model" << std::endl;
342.                 break;
343.             }
344.         }
345.
346.         if (iter == num_epochs_CNN) {
347.             saveModelFile("E:/GitCode/NN_Test/data/cnn.model");
348.             std::cout << "generate cnn model" << std::endl;
349.         }
350.
351.         return true;
352.     }
353.

```

关闭

```

354. double CNN::activation_function_tanh(double x)
355. {
356.     double ep = std::exp(x);
357.     double em = std::exp(-x);
358.
359.     return (ep - em) / (ep + em);
360. }
361.
362. double CNN::activation_function_tanh_derivative(double x)
363. {
364.     return (1.0 - x * x);
365. }
366.
367. double CNN::activation_function_identity(double x)
368. {
369.     return x;
370. }
371.
372. double CNN::activation_function_identity_derivative(double x)
373. {
374.     return 1;
375. }
376.
377. double CNN::loss_function_mse(double y, double t)
378. {
379.     return (y - t) * (y - t) / 2;
380. }
381.
382. double CNN::loss_function_mse_derivative(double y, double t)
383. {
384.     return (y - t);
385. }
386.
387. void CNN::loss_function_gradient(const double* y, const double* t, double* dst, int len)
388. {
389.     for (int i = 0; i < len; i++) {
390.         dst[i] = loss_function_mse_derivative(y[i], t[i]);
391.     }
392. }
393.
394. double CNN::dot_product(const double* s1, const double* s2, int len)
395. {
396.     double result = 0.0;
397.
398.     for (int i = 0; i < len; i++) {
399.         result += s1[i] * s2[i];
400.     }
401.
402.     return result;
403. }
404.
405. bool CNN::muladd(const double* src, double c, int len, double* dst)
406. {
407.     for (int i = 0; i < len; i++) {
408.         dst[i] += (src[i] * c);
409.     }
410.
411.     return true;
412. }
413.
414. int CNN::get_index(int x, int y, int channel, int width, int height, int depth)
415. {
416.     assert(x >= 0 && x < width);
417.     assert(y >= 0 && y < height);
418.     assert(channel >= 0 && channel < depth);
419.     return (height * channel + y) * width + x;
420. }
421.
422. void CNN::calc_out2wi(int width_in, int height_in, int width_out, int height_out, int depth_out)
423. {
424.     for (int i = 0; i < depth_out; i++) {
425.         int block = width_in * height_in * i;
426.
427.         for (int y = 0; y < height_out; y++) {
428.             for (int x = 0; x < width_out; x++) {
429.                 int rows = y * width_kernel_pooling_CNN;
430.                 int cols = x * height_kernel_pooling_CNN;
431.
432.                 wi_connections wi_connections_;

```

关闭

```
433.         std::pair<int, int> pair_;
434.
435.         for (int m = 0; m < width_kernel_pooling_CNN; m++) {
436.             for (int n = 0; n < height_kernel_pooling_CNN; n++) {
437.                 pair_.first = i;
438.                 pair_.second = (rows + m) * width_in + cols + n + block;
439.                 wi_connections_.push_back(pair_);
440.             }
441.         }
442.         out2wi.push_back(wi_connections_);
443.     }
444. }
445. }
446. }
447.
448. void CNN::calc_out2bias(int width, int height, int depth, std::vector<int>& out2bias)
449. {
450.     for (int i = 0; i < depth; i++) {
451.         for (int y = 0; y < height; y++) {
452.             for (int x = 0; x < width; x++) {
453.                 out2bias.push_back(i);
454.             }
455.         }
456.     }
457. }
458.
459. void CNN::calc_in2wo(int width_in, int height_in, int width_out, int height_out, int depth_in)
460. {
461.     int len = width_in * height_in * depth_in;
462.     in2wo.resize(len);
463.
464.     for (int c = 0; c < depth_in; c++) {
465.         for (int y = 0; y < height_in; y += height_kernel_pooling_CNN) {
466.             for (int x = 0; x < width_in; x += width_kernel_pooling_CNN) {
467.                 int dymax = min(size_pooling_CNN, height_in - y);
468.                 int dxmax = min(size_pooling_CNN, width_in - x);
469.                 int dstx = x / width_kernel_pooling_CNN;
470.                 int dsty = y / height_kernel_pooling_CNN;
471.
472.                 for (int dy = 0; dy < dymax; dy++) {
473.                     for (int dx = 0; dx < dxmax; dx++) {
474.                         int index_in = get_index(x + dx, y + dy, c, width_in, height_in, c);
475.                         int index_out = get_index(dstx, dsty, c, width_out, height_out, c);
476.
477.                         wo_connections_ wo_connections_;
478.                         std::pair<int, int> pair_;
479.                         pair_.first = c;
480.                         pair_.second = index_out;
481.                         wo_connections_.push_back(pair_);
482.
483.                         in2wo[index_in] = wo_connections_;
484.                     }
485.                 }
486.             }
487.         }
488.     }
489. }
490.
491. void CNN::calc_weight2io(int width_in, int height_in, int width_out, int height_out, int depth_in)
492. {
493.     int len = depth_in;
494.     weight2io.resize(len);
495.
496.     for (int c = 0; c < depth_in; c++) {
497.         for (int y = 0; y < height_in; y += height_kernel_pooling_CNN) {
498.             for (int x = 0; x < width_in; x += width_kernel_pooling_CNN) {
499.                 int dymax = min(size_pooling_CNN, height_in - y);
500.                 int dxmax = min(size_pooling_CNN, width_in - x);
501.                 int dstx = x / width_kernel_pooling_CNN;
502.                 int dsty = y / height_kernel_pooling_CNN;
503.
504.                 for (int dy = 0; dy < dymax; dy++) {
505.                     for (int dx = 0; dx < dxmax; dx++) {
506.                         int index_in = get_index(x + dx, y + dy, c, width_in, height_in, c);
507.                         int index_out = get_index(dstx, dsty, c, width_out, height_out, c);
508.
509.                         std::pair<int, int> pair_;
510.                         pair_.first = index_in;
511.                         pair_.second = index_out;
```

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512.         weight2io[c].push_back(pair_);
513.     }
514. }
515. }
516. }
517. }
518. }
519. }
520.
521. void CNN::calc_bias2out(int width_in, int height_in, int width_out, int height_out, int depth_in)
522. {
523.     int len = depth_in;
524.     bias2out.resize(len);
525.
526.     for (int c = 0; c < depth_in; c++) {
527.         for (int y = 0; y < height_out; y++) {
528.             for (int x = 0; x < width_out; x++) {
529.                 int index_out = get_index(x, y, c, width_out, height_out, depth_out);
530.                 bias2out[c].push_back(index_out);
531.             }
532.         }
533.     }
534. }
535.
536. bool CNN::Forward_C1()
537. {
538.     init_variable(neuron_C1, 0.0, num_neuron_C1_CNN);
539.
540.     for (int o = 0; o < num_map_C1_CNN; o++) {
541.         for (int inc = 0; inc < num_map_input_CNN; inc++) {
542.             int addr1 = get_index(0, 0, num_map_input_CNN * o + inc, width_kernel_conv_CNN, height_kernel_conv_CNN, num_map_input_CNN);
543.             int addr2 = get_index(0, 0, inc, width_image_input_CNN, height_image_input_CNN, num_map_input_CNN);
544.             int addr3 = get_index(0, 0, o, width_image_C1_CNN, height_image_C1_CNN, num_map_C1_CNN);
545.
546.             const double* pw = &weight_C1[0] + addr1;
547.             const double* pi = data_single_image + addr2;
548.             double* pa = &neuron_C1[0] + addr3;
549.
550.             for (int y = 0; y < height_image_C1_CNN; y++) {
551.                 for (int x = 0; x < width_image_C1_CNN; x++) {
552.                     const double* ppw = pw;
553.                     const double* ppi = pi + y * width_image_input_CNN + x;
554.                     double sum = 0.0;
555.
556.                     for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
557.                         for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
558.                             sum += *ppw++ * ppi[wy * width_image_input_CNN + wx];
559.                         }
560.                     }
561.
562.                     pa[y * width_image_C1_CNN + x] += sum;
563.                 }
564.             }
565.         }
566.
567.         int addr3 = get_index(0, 0, o, width_image_C1_CNN, height_image_C1_CNN, num_map_C1_CNN);
568.         double* pa = &neuron_C1[0] + addr3;
569.         double b = bias_C1[o];
570.         for (int y = 0; y < height_image_C1_CNN; y++) {
571.             for (int x = 0; x < width_image_C1_CNN; x++) {
572.                 pa[y * width_image_C1_CNN + x] += b;
573.             }
574.         }
575.     }
576.
577.     for (int i = 0; i < num_neuron_C1_CNN; i++) {
578.         neuron_C1[i] = activation_function_tanh(neuron_C1[i]);
579.     }
580.
581.     return true;
582. }
583.
584. bool CNN::Forward_S2()
585. {
586.     init_variable(neuron_S2, 0.0, num_neuron_S2_CNN);
587.     double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);
588.
589.     assert(out2wi_S2.size() == num_neuron_S2_CNN);
590.     assert(out2bias_S2.size() == num_neuron_S2_CNN);

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```
591.
592.     for (int i = 0; i < num_neuron_S2_CNN; i++) {
593.         const wi_connections& connections = out2wi_S2[i];
594.         neuron_S2[i] = 0;
595.
596.         for (int index = 0; index < connections.size(); index++) {
597.             neuron_S2[i] += weight_S2[connections[index].first] * neuron_C1[connections[index].second];
598.         }
599.
600.         neuron_S2[i] *= scale_factor;
601.         neuron_S2[i] += bias_S2[out2bias_S2[i]];
602.     }
603.
604.     for (int i = 0; i < num_neuron_S2_CNN; i++) {
605.         neuron_S2[i] = activation_function_tanh(neuron_S2[i]);
606.     }
607.
608.     return true;
609. }
610.
611. bool CNN::Forward_C3()
612. {
613.     init_variable(neuron_C3, 0.0, num_neuron_C3_CNN);
614.
615.     for (int o = 0; o < num_map_C3_CNN; o++) {
616.         for (int inc = 0; inc < num_map_S2_CNN; inc++) {
617.             if (!tbl[inc][o]) continue;
618.
619.             int addr1 = get_index(0, 0, num_map_S2_CNN * o + inc, width_kernel_conv_CNN, height_kernel_conv_CNN);
620.             int addr2 = get_index(0, 0, inc, width_image_S2_CNN, height_image_S2_CNN, num_map_S2_CNN);
621.             int addr3 = get_index(0, 0, o, width_image_C3_CNN, height_image_C3_CNN, num_map_C3_CNN);
622.
623.             const double* pw = &weight_C3[0] + addr1;
624.             const double* pi = &neuron_S2[0] + addr2;
625.             double* pa = &neuron_C3[0] + addr3;
626.
627.             for (int y = 0; y < height_image_C3_CNN; y++) {
628.                 for (int x = 0; x < width_image_C3_CNN; x++) {
629.                     const double* ppw = pw;
630.                     const double* ppi = pi + y * width_image_S2_CNN + x;
631.                     double sum = 0.0;
632.
633.                     for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
634.                         for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
635.                             sum += *ppw++ * ppi[wy * width_image_S2_CNN + wx];
636.                         }
637.                     }
638.
639.                     pa[y * width_image_C3_CNN + x] += sum;
640.                 }
641.             }
642.         }
643.
644.         int addr3 = get_index(0, 0, o, width_image_C3_CNN, height_image_C3_CNN, num_map_C3_CNN);
645.         double* pa = &neuron_C3[0] + addr3;
646.         double b = bias_C3[o];
647.         for (int y = 0; y < height_image_C3_CNN; y++) {
648.             for (int x = 0; x < width_image_C3_CNN; x++) {
649.                 pa[y * width_image_C3_CNN + x] += b;
650.             }
651.         }
652.     }
653.
654.     for (int i = 0; i < num_neuron_C3_CNN; i++) {
655.         neuron_C3[i] = activation_function_tanh(neuron_C3[i]);
656.     }
657.
658.     return true;
659. }
660.
661. bool CNN::Forward_S4()
662. {
663.     double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);
664.     init_variable(neuron_S4, 0.0, num_neuron_S4_CNN);
665.
666.     assert(out2wi_S4.size() == num_neuron_S4_CNN);
667.     assert(out2bias_S4.size() == num_neuron_S4_CNN);
668.
669.     for (int i = 0; i < num_neuron_S4_CNN; i++) {
```

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670.         const wi_connections& connections = out2wi_S4[i];
671.         neuron_S4[i] = 0.0;
672.
673.         for (int index = 0; index < connections.size(); index++) {
674.             neuron_S4[i] += weight_S4[connections[index].first] * neuron_C3[connections[index].second];
675.         }
676.
677.         neuron_S4[i] *= scale_factor;
678.         neuron_S4[i] += bias_S4[out2bias_S4[i]];
679.     }
680.
681.     for (int i = 0; i < num_neuron_S4_CNN; i++) {
682.         neuron_S4[i] = activation_function_tanh(neuron_S4[i]);
683.     }
684.
685.     return true;
686. }
687.
688. bool CNN::Forward_C5()
689. {
690.     init_variable(neuron_C5, 0.0, num_neuron_C5_CNN);
691.
692.     for (int o = 0; o < num_map_C5_CNN; o++) {
693.         for (int inc = 0; inc < num_map_S4_CNN; inc++) {
694.             int addr1 = get_index(0, 0, num_map_S4_CNN * o + inc, width_kernel_conv_CNN, height_kernel_conv_CNN, num_map_S4_CNN);
695.             int addr2 = get_index(0, 0, inc, width_image_S4_CNN, height_image_S4_CNN, num_map_S4_CNN);
696.             int addr3 = get_index(0, 0, o, width_image_C5_CNN, height_image_C5_CNN, num_map_C5_CNN);
697.
698.             const double *pw = &weight_C5[0] + addr1;
699.             const double *pi = &neuron_S4[0] + addr2;
700.             double *pa = &neuron_C5[0] + addr3;
701.
702.             for (int y = 0; y < height_image_C5_CNN; y++) {
703.                 for (int x = 0; x < width_image_C5_CNN; x++) {
704.                     const double *ppw = pw;
705.                     const double *ppi = pi + y * width_image_S4_CNN + x;
706.                     double sum = 0.0;
707.
708.                     for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
709.                         for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
710.                             sum += *ppw++ * ppi[wy * width_image_S4_CNN + wx];
711.                         }
712.                     }
713.
714.                     pa[y * width_image_C5_CNN + x] += sum;
715.                 }
716.             }
717.
718.             int addr3 = get_index(0, 0, o, width_image_C5_CNN, height_image_C5_CNN, num_map_C5_CNN);
719.             double *pa = &neuron_C5[0] + addr3;
720.             double b = bias_C5[o];
721.             for (int y = 0; y < height_image_C5_CNN; y++) {
722.                 for (int x = 0; x < width_image_C5_CNN; x++) {
723.                     pa[y * width_image_C5_CNN + x] += b;
724.                 }
725.             }
726.         }
727.
728.         for (int i = 0; i < num_neuron_C5_CNN; i++) {
729.             neuron_C5[i] = activation_function_tanh(neuron_C5[i]);
730.         }
731.
732.         return true;
733.     }
734. }
735.
736. bool CNN::Forward_output()
737. {
738.     init_variable(neuron_output, 0.0, num_neuron_output_CNN);
739.
740.     for (int i = 0; i < num_neuron_output_CNN; i++) {
741.         neuron_output[i] = 0.0;
742.
743.         for (int c = 0; c < num_neuron_C5_CNN; c++) {
744.             neuron_output[i] += weight_output[c * num_neuron_output_CNN + i] * neuron_C5[c];
745.         }
746.
747.         neuron_output[i] += bias_output[i];
748.     }

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749.
750.     for (int i = 0; i < num_neuron_output_CNN; i++) {
751.         neuron_output[i] = activation_function_tanh(neuron_output[i]);
752.     }
753.
754.     return true;
755. }
756.
757. bool CNN::Backward_output()
758. {
759.     init_variable(delta_neuron_output, 0.0, num_neuron_output_CNN);
760.
761.     double dE_dy[num_neuron_output_CNN];
762.     init_variable(dE_dy, 0.0, num_neuron_output_CNN);
763.     loss_function_gradient(neuron_output, data_single_label, dE_dy, num_neuron_output_CNN);
764.     失函数: mean squared error(均方差)
765.
766.     // delta = dE/da = (dE/dy) * (dy/da)
767.     for (int i = 0; i < num_neuron_output_CNN; i++) {
768.         double dy_da[num_neuron_output_CNN];
769.         init_variable(dy_da, 0.0, num_neuron_output_CNN);
770.
771.         dy_da[i] = activation_function_tanh_derivative(neuron_output[i]);
772.         delta_neuron_output[i] = dot_product(dE_dy, dy_da, num_neuron_output_
773.     }
774.
775.     return true;
776. }
777.
778. bool CNN::Backward_C5()
779. {
780.     init_variable(delta_neuron_C5, 0.0, num_neuron_C5_CNN);
781.     init_variable(delta_weight_output, 0.0, len_weight_output_CNN);
782.     init_variable(delta_bias_output, 0.0, len_bias_output_CNN);
783.
784.     for (int c = 0; c < num_neuron_C5_CNN; c++) {
785.         // propagate delta to previous layer
786.         // prev_delta[c] += current_delta[r] * W[c * out_size_ + r]
787.         delta_neuron_C5[c] = dot_product(&
788.         delta_neuron_output[0], &weight_output[c * num_neuron_output_CNN], num_neuron_output_CNN);
789.         delta_neuron_C5[c] *= activation_function_tanh_derivative(neuron_C5[c]);
790.
791.         // accumulate weight-step using delta
792.         // dw[c * out_size + i] += current_delta[i] * prev_out[c]
793.         for (int c = 0; c < num_neuron_C5_CNN; c++) {
794.             muladd(&delta_neuron_output[0], neuron_C5[c], num_neuron_output_CNN, &delta_weight
795.         }
796.
797.         for (int i = 0; i < len_bias_output_CNN; i++) {
798.             delta_bias_output[i] += delta_neuron_output[i];
799.         }
800.
801.         return true;
802.     }
803. }
804.
805. bool CNN::Backward_S4()
806. {
807.     init_variable(delta_neuron_S4, 0.0, num_neuron_S4_CNN);
808.     init_variable(delta_weight_C5, 0.0, len_weight_C5_CNN);
809.     init_variable(delta_bias_C5, 0.0, len_bias_C5_CNN);
810.
811.     // propagate delta to previous layer
812.     for (int inc = 0; inc < num_map_S4_CNN; inc++) {
813.         for (int outc = 0; outc < num_map_C5_CNN; outc++) {
814.             int addr1 = get_index(0, 0, num_map_S4_CNN);
815.             int addr2 = get_index(0, 0, outc, width_image_C5_CNN, height_image_C5_CNN, num
816.             int addr3 = get_index(0, 0, inc, width_image_S4_CNN, height_image_S4_CNN, num
817.
818.             const double* pw = &weight_C5[0] + addr1;
819.             const double* pdelta_src = &delta_neuron_C5[0] + addr2;
820.             double* pdelta_dst = &delta_neuron_S4[0] + addr3;
821.
822.             for (int y = 0; y < height_image_C5_CNN; y++) {
823.                 for (int x = 0; x < width_image_C5_CNN; x++) {
824.                     const double* ppw = pw;
825.                     const double pppdelta_src = pdelta_src[y * width_image_C5_CNN + x];
826.                     double* pppdelta_dst = pdelta_dst + y * width_image_S4_CNN + x;

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826.         for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
827.             for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
828.                 ppdelta_dst[wy * width_image_S4_CNN + wx] += *ppw++ * ppdelta;
829.             }
830.         }
831.     }
832. }
833. }
834. }
835.
836. for (int i = 0; i < num_neuron_S4_CNN; i++) {
837.     delta_neuron_S4[i] *= activation_function_tanh_derivative(neuron_S4[i]);
838. }
839.
840. // accumulate dw
841. for (int inc = 0; inc < num_map_S4_CNN; inc++) {
842.     for (int outc = 0; outc < num_map_C5_CNN; outc++) {
843.         for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
844.             for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
845.                 int addr1 = get_index(wx, wy, inc, width_image_S4_CNN, height_image_S4_CNN);
846.                 int addr2 = get_index(0, 0, outc, width_image_C5_CNN, height_image_C5_CNN);
847.                 int addr3 = get_index(wx, wy, num_map_S4_CNN * outc + inc, width_kernel_conv_CNN);
848.
849.                 double dst = 0.0;
850.                 const double* prevo = &neuron_S4[0] + addr1;
851.                 const double* delta = &delta_neuron_C5[0] + addr2;
852.
853.                 for (int y = 0; y < height_image_C5_CNN; y++) {
854.                     dst += dot_product(prevo + y * width_image_S4_CNN, delta + y * width_image_C5_CNN);
855.                 }
856.
857.                 delta_weight_C5[addr3] += dst;
858.             }
859.         }
860.     }
861. }
862.
863. // accumulate db
864. for (int outc = 0; outc < num_map_C5_CNN; outc++) {
865.     int addr2 = get_index(0, 0, outc, width_image_C5_CNN, height_image_C5_CNN, num_map_S4_CNN);
866.     const double* delta = &delta_neuron_C5[0] + addr2;
867.
868.     for (int y = 0; y < height_image_C5_CNN; y++) {
869.         for (int x = 0; x < width_image_C5_CNN; x++) {
870.             delta_bias_C5[outc] += delta[y * width_image_C5_CNN + x];
871.         }
872.     }
873. }
874.
875. return true;
876. }
877.
878. bool CNN::Backward_C3()
879. {
880.     init_variable(delta_neuron_C3, 0.0, num_neuron_C3_CNN);
881.     init_variable(delta_weight_S4, 0.0, len_weight_S4_CNN);
882.     init_variable(delta_bias_S4, 0.0, len_bias_S4_CNN);
883.
884.     double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);
885.
886.     assert(in2wo_C3.size() == num_neuron_C3_CNN);
887.     assert(weight2io_C3.size() == len_weight_S4_CNN);
888.     assert(bias2out_C3.size() == len_bias_S4_CNN);
889.
890.     for (int i = 0; i < num_neuron_C3_CNN; i++) {
891.         const wo_connections& connections = in2wo_C3[i];
892.         double delta = 0.0;
893.
894.         for (int j = 0; j < connections.size(); j++) {
895.             delta += weight_S4[connections[j].first] * delta_neuron_S4[connections[j].second];
896.         }
897.
898.         delta_neuron_C3[i] = delta * scale_factor * activation_function_tanh_derivative(neuron_C3[i]);
899.     }
900.
901.     for (int i = 0; i < len_weight_S4_CNN; i++) {
902.         const io_connections& connections = weight2io_C3[i];
903.         double diff = 0;
904.

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905.         for (int j = 0; j < connections.size(); j++) {
906.             diff += neuron_C3[connections[j].first] * delta_neuron_S4[connections[j].second];
907.         }
908.
909.         delta_weight_S4[i] += diff * scale_factor;
910.     }
911.
912.     for (int i = 0; i < len_bias_S4_CNN; i++) {
913.         const std::vector<int>& outs = bias2out_C3[i];
914.         double diff = 0;
915.
916.         for (int o = 0; o < outs.size(); o++) {
917.             diff += delta_neuron_S4[outs[o]];
918.         }
919.
920.         delta_bias_S4[i] += diff;
921.     }
922.
923.     return true;
924. }
925.
926. bool CNN::Backward_S2()
927. {
928.     init_variable(delta_neuron_S2, 0.0, num_neuron_S2_CNN);
929.     init_variable(delta_weight_C3, 0.0, len_weight_C3_CNN);
930.     init_variable(delta_bias_C3, 0.0, len_bias_C3_CNN);
931.
932.     // propagate delta to previous layer
933.     for (int inc = 0; inc < num_map_S2_CNN; inc++) {
934.         for (int outc = 0; outc < num_map_C3_CNN; outc++) {
935.             if (!tbl[inc][outc]) continue;
936.
937.             int addr1 = get_index(0, 0, num_map_S2_CNN * outc + inc, width_kernel_conv_CNI);
938.             int addr2 = get_index(0, 0, outc, width_image_C3_CNN, height_image_C3_CNN, num);
939.             int addr3 = get_index(0, 0, inc, width_image_S2_CNN, height_image_S2_CNN, num);
940.
941.             const double *pw = &weight_C3[0] + addr1;
942.             const double *pdelta_src = &delta_neuron_C3[0] + addr2;
943.             double* pdelta_dst = &delta_neuron_S2[0] + addr3;
944.
945.             for (int y = 0; y < height_image_C3_CNN; y++) {
946.                 for (int x = 0; x < width_image_C3_CNN; x++) {
947.                     const double* ppw = pw;
948.                     const double ppdelta_src = pdelta_src[y * width_image_C3_CNN + x];
949.                     double* ppdelta_dst = pdelta_dst + y * width_image_S2_CNN + x;
950.
951.                     for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
952.                         for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
953.                             ppdelta_dst[wy * width_image_S2_CNN + wx] += *ppw++ * ppdelta_src;
954.                         }
955.                     }
956.                 }
957.             }
958.         }
959.     }
960.
961.     for (int i = 0; i < num_neuron_S2_CNN; i++) {
962.         delta_neuron_S2[i] *= activation_function_tanh_derivative(neuron_S2[i]);
963.     }
964.
965.     // accumulate dw
966.     for (int inc = 0; inc < num_map_S2_CNN; inc++) {
967.         for (int outc = 0; outc < num_map_C3_CNN; outc++) {
968.             if (!tbl[inc][outc]) continue;
969.
970.             for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
971.                 for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
972.                     int addr1 = get_index(wx, wy, inc, width_image_S2_CNN, height_image_S2_CNN, num);
973.                     int addr2 = get_index(0, 0, outc, width_image_C3_CNN, height_image_C3_CNN, num);
974.                     int addr3 = get_index(wx, wy, num_map_S2_CNN * outc + inc, width_image_S2_CNN, height_image_S2_CNN, num);
975.
976.                     double dst = 0.0;
977.                     const double* prevo = &neuron_S2[0] + addr1;
978.                     const double* delta = &delta_neuron_C3[0] + addr2;
979.
980.                     for (int y = 0; y < height_image_C3_CNN; y++) {
981.                         dst += dot_product(prevo + y * width_image_S2_CNN, delta + y * width_image_C3_CNN);
982.                     }
983.                 }
984.             }
985.         }
986.     }
987. }

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关闭

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984.         delta_weight_C3[addr3] += dst;
985.     }
986. }
987. }
988. }
989.
990. // accumulate db
991. for (int outc = 0; outc < len_bias_C3_CNN; outc++) {
992.     int addr1 = get_index(0, 0, outc, width_image_C3_CNN, height_image_C3_CNN, num_ma
993.     const double* delta = &delta_neuron_C3[0] + addr1;
994.
995.     for (int y = 0; y < height_image_C3_CNN; y++) {
996.         for (int x = 0; x < width_image_C3_CNN; x++) {
997.             delta_bias_C3[outc] += delta[y * width_image_C3_CNN + x];
998.         }
999.     }
1000. }
1001.
1002. return true;
1003. }
1004.
1005. bool CNN::Backward_C1()
1006. {
1007.     init_variable(delta_neuron_C1, 0.0, num_neuron_C1_CNN);
1008.     init_variable(delta_weight_S2, 0.0, len_weight_S2_CNN);
1009.     init_variable(delta_bias_S2, 0.0, len_bias_S2_CNN);
1010.
1011.     double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);
1012.
1013.     assert(in2wo_C1.size() == num_neuron_C1_CNN);
1014.     assert(weight2io_C1.size() == len_weight_S2_CNN);
1015.     assert(bias2out_C1.size() == len_bias_S2_CNN);
1016.
1017.     for (int i = 0; i < num_neuron_C1_CNN; i++) {
1018.         const wo_connections& connections = in2wo_C1[i];
1019.         double delta = 0.0;
1020.
1021.         for (int j = 0; j < connections.size(); j++) {
1022.             delta += weight_S2[connections[j].first] * delta_neuron_S2[connections[j].sec
1023.         }
1024.
1025.         delta_neuron_C1[i] = delta * scale_factor * activation_function_tanh_derivative(n
1026.     }
1027.
1028.     for (int i = 0; i < len_weight_S2_CNN; i++) {
1029.         const io_connections& connections = weight2io_C1[i];
1030.         double diff = 0.0;
1031.
1032.         for (int j = 0; j < connections.size(); j++) {
1033.             diff += neuron_C1[connections[j].first] * delta_neuron_S2[connections[j].seco
1034.         }
1035.
1036.         delta_weight_S2[i] += diff * scale_factor;
1037.     }
1038.
1039.     for (int i = 0; i < len_bias_S2_CNN; i++) {
1040.         const std::vector<int>& outs = bias2out_C1[i];
1041.         double diff = 0;
1042.
1043.         for (int o = 0; o < outs.size(); o++) {
1044.             diff += delta_neuron_S2[outs[o]];
1045.         }
1046.
1047.         delta_bias_S2[i] += diff;
1048.     }
1049.
1050.     return true;
1051. }
1052.
1053. bool CNN::Backward_input()
1054. {
1055.     init_variable(delta_neuron_input, 0.0, num_neuron_input_CNN);
1056.     init_variable(delta_weight_C1, 0.0, len_weight_C1_CNN);
1057.     init_variable(delta_bias_C1, 0.0, len_bias_C1_CNN);
1058.
1059.     // propagate delta to previous layer
1060.     for (int inc = 0; inc < num_map_input_CNN; inc++) {
1061.         for (int outc = 0; outc < num_map_C1_CNN; outc++) {
1062.             int addr1 = get_index(0, 0, num_map_input_CNN * outc + inc, width_kernel_conv

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1063.         int addr2 = get_index(0, 0, outc, width_image_C1_CNN, height_image_C1_CNN, num_map_input_CNN);
1064.         int addr3 = get_index(0, 0, inc, width_image_input_CNN, height_image_input_CNN, num_map_input_CNN);
1065.
1066.         const double* pw = &weight_C1[0] + addr1;
1067.         const double* pdelta_src = &delta_neuron_C1[0] + addr2;
1068.         double* pdelta_dst = &delta_neuron_input[0] + addr3;
1069.
1070.         for (int y = 0; y < height_image_C1_CNN; y++) {
1071.             for (int x = 0; x < width_image_C1_CNN; x++) {
1072.                 const double* ppw = pw;
1073.                 const double pppdelta_src = pdelta_src[y * width_image_C1_CNN + x];
1074.                 double* pppdelta_dst = pdelta_dst + y * width_image_input_CNN + x;
1075.
1076.                 for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
1077.                     for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
1078.                         pppdelta_dst[wy * width_image_input_CNN + wx] += *ppw++ * pppdelta_src;
1079.                     }
1080.                 }
1081.             }
1082.         }
1083.     }
1084. }
1085.
1086. for (int i = 0; i < num_neuron_input_CNN; i++) {
1087.     delta_neuron_input[i] *= activation_function_identity_derivative(data_single_image[i]);
1088. }
1089.
1090. // accumulate dw
1091. for (int inc = 0; inc < num_map_input_CNN; inc++) {
1092.     for (int outc = 0; outc < num_map_C1_CNN; outc++) {
1093.         for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
1094.             for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
1095.                 int addr1 = get_index(wx, wy, inc, width_image_input_CNN, height_image_input_CNN, num_map_input_CNN);
1096.                 int addr2 = get_index(0, 0, outc, width_image_C1_CNN, height_image_C1_CNN, num_map_C1_CNN);
1097.                 int addr3 = get_index(wx, wy, num_map_input_CNN * outc + inc, width_image_input_CNN, height_image_input_CNN, num_map_input_CNN);
1098.
1099.                 double dst = 0.0;
1100.                 const double* prevo = data_single_image + addr1; // &neuron_input[0]
1101.                 const double* delta = &delta_neuron_C1[0] + addr2;
1102.
1103.                 for (int y = 0; y < height_image_C1_CNN; y++) {
1104.                     dst += dot_product(prevo + y * width_image_input_CNN, delta + y * width_image_input_CNN);
1105.                 }
1106.
1107.                 delta_weight_C1[addr3] += dst;
1108.             }
1109.         }
1110.     }
1111. }
1112.
1113. // accumulate db
1114. for (int outc = 0; outc < len_bias_C1_CNN; outc++) {
1115.     int addr1 = get_index(0, 0, outc, width_image_C1_CNN, height_image_C1_CNN, num_map_C1_CNN);
1116.     const double* delta = &delta_neuron_C1[0] + addr1;
1117.
1118.     for (int y = 0; y < height_image_C1_CNN; y++) {
1119.         for (int x = 0; x < width_image_C1_CNN; x++) {
1120.             delta_bias_C1[outc] += delta[y * width_image_C1_CNN + x];
1121.         }
1122.     }
1123. }
1124.
1125. return true;
1126. }
1127.
1128. void CNN::update_weights_bias(const double* delta, double learning_rate_CNN) {
1129. {
1130.     for (int i = 0; i < len; i++) {
1131.         e_weight[i] += delta[i] * delta[i];
1132.         weight[i] -= learning_rate_CNN * delta[i] / (std::sqrt(e_weight[i]) + eps_CNN);
1133.     }
1134. }
1135.
1136. bool CNN::UpdateWeights() {
1137. {
1138.     update_weights_bias(delta_weight_C1, E_weight_C1, weight_C1, len_weight_C1_CNN);
1139.     update_weights_bias(delta_bias_C1, E_bias_C1, bias_C1, len_bias_C1_CNN);
1140.
1141.     update_weights_bias(delta_weight_S2, E_weight_S2, weight_S2, len_weight_S2_CNN);

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1142.         update_weights_bias(delta_bias_S2, E_bias_S2, bias_S2, len_bias_S2_CNN);
1143.
1144.         update_weights_bias(delta_weight_C3, E_weight_C3, weight_C3, len_weight_C3_CNN);
1145.         update_weights_bias(delta_bias_C3, E_bias_C3, bias_C3, len_bias_C3_CNN);
1146.
1147.         update_weights_bias(delta_weight_S4, E_weight_S4, weight_S4, len_weight_S4_CNN);
1148.         update_weights_bias(delta_bias_S4, E_bias_S4, bias_S4, len_bias_S4_CNN);
1149.
1150.         update_weights_bias(delta_weight_C5, E_weight_C5, weight_C5, len_weight_C5_CNN);
1151.         update_weights_bias(delta_bias_C5, E_bias_C5, bias_C5, len_bias_C5_CNN);
1152.
1153.         update_weights_bias(delta_weight_output, E_weight_output, weight_output, len_weight_output_CNN);
1154.         update_weights_bias(delta_bias_output, E_bias_output, bias_output, len_bias_output_CNN);
1155.
1156.         return true;
1157.     }
1158.
1159. int CNN::predict(const unsigned char* data, int width, int height)
1160. {
1161.     assert(data && width == width_image_input_CNN && height == height_image_input_CNN);
1162.
1163.     const double scale_min = -1;
1164.     const double scale_max = 1;
1165.
1166.     double tmp[width_image_input_CNN * height_image_input_CNN];
1167.     for (int y = 0; y < height; y++) {
1168.         for (int x = 0; x < width; x++) {
1169.             tmp[y * width + x] = (data[y * width + x] / 255.0) * (scale_max - scale_min) +
1170.                 scale_min;
1171.         }
1172.     }
1173.
1174.     data_single_image = &tmp[0];
1175.
1176.     Forward_C1();
1177.     Forward_S2();
1178.     Forward_C3();
1179.     Forward_S4();
1180.     Forward_C5();
1181.     Forward_output();
1182.
1183.     int pos = -1;
1184.     double max_value = -9999.0;
1185.
1186.     for (int i = 0; i < num_neuron_output_CNN; i++) {
1187.         if (neuron_output[i] > max_value) {
1188.             max_value = neuron_output[i];
1189.             pos = i;
1190.         }
1191.     }
1192.
1193.     return pos;
1194. }
1195.
1196. bool CNN::loadModelFile(const char* name)
1197. {
1198.     FILE* fp = fopen(name, "rb");
1199.     if (fp == NULL) {
1200.         return false;
1201.     }
1202.
1203.     int width_image_input = 0;
1204.     int height_image_input = 0;
1205.     int width_image_C1 = 0;
1206.     int height_image_C1 = 0;
1207.     int width_image_S2 = 0;
1208.     int height_image_S2 = 0;
1209.     int width_image_C3 = 0;
1210.     int height_image_C3 = 0;
1211.     int width_image_S4 = 0;
1212.     int height_image_S4 = 0;
1213.     int width_image_C5 = 0;
1214.     int height_image_C5 = 0;
1215.     int width_image_output = 0;
1216.     int height_image_output = 0;
1217.
1218.     int width_kernel_conv = 0;
1219.     int height_kernel_conv = 0;
1220.     int width_kernel_pooling = 0;
1221.     int height_kernel_pooling = 0;

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```
1221.
1222.     int num_map_input = 0;
1223.     int num_map_C1 = 0;
1224.     int num_map_S2 = 0;
1225.     int num_map_C3 = 0;
1226.     int num_map_S4 = 0;
1227.     int num_map_C5 = 0;
1228.     int num_map_output = 0;
1229.
1230.     int len_weight_C1 = 0;
1231.     int len_bias_C1 = 0;
1232.     int len_weight_S2 = 0;
1233.     int len_bias_S2 = 0;
1234.     int len_weight_C3 = 0;
1235.     int len_bias_C3 = 0;
1236.     int len_weight_S4 = 0;
1237.     int len_bias_S4 = 0;
1238.     int len_weight_C5 = 0;
1239.     int len_bias_C5 = 0;
1240.     int len_weight_output = 0;
1241.     int len_bias_output = 0;
1242.
1243.     int num_neuron_input = 0;
1244.     int num_neuron_C1 = 0;
1245.     int num_neuron_S2 = 0;
1246.     int num_neuron_C3 = 0;
1247.     int num_neuron_S4 = 0;
1248.     int num_neuron_C5 = 0;
1249.     int num_neuron_output = 0;
1250.
1251.     fread(&width_image_input, sizeof(int), 1, fp);
1252.     fread(&height_image_input, sizeof(int), 1, fp);
1253.     fread(&width_image_C1, sizeof(int), 1, fp);
1254.     fread(&height_image_C1, sizeof(int), 1, fp);
1255.     fread(&width_image_S2, sizeof(int), 1, fp);
1256.     fread(&height_image_S2, sizeof(int), 1, fp);
1257.     fread(&width_image_C3, sizeof(int), 1, fp);
1258.     fread(&height_image_C3, sizeof(int), 1, fp);
1259.     fread(&width_image_S4, sizeof(int), 1, fp);
1260.     fread(&height_image_S4, sizeof(int), 1, fp);
1261.     fread(&width_image_C5, sizeof(int), 1, fp);
1262.     fread(&height_image_C5, sizeof(int), 1, fp);
1263.     fread(&width_image_output, sizeof(int), 1, fp);
1264.     fread(&height_image_output, sizeof(int), 1, fp);
1265.
1266.     fread(&width_kernel_conv, sizeof(int), 1, fp);
1267.     fread(&height_kernel_conv, sizeof(int), 1, fp);
1268.     fread(&width_kernel_pooling, sizeof(int), 1, fp);
1269.     fread(&height_kernel_pooling, sizeof(int), 1, fp);
1270.
1271.     fread(&num_map_input, sizeof(int), 1, fp);
1272.     fread(&num_map_C1, sizeof(int), 1, fp);
1273.     fread(&num_map_S2, sizeof(int), 1, fp);
1274.     fread(&num_map_C3, sizeof(int), 1, fp);
1275.     fread(&num_map_S4, sizeof(int), 1, fp);
1276.     fread(&num_map_C5, sizeof(int), 1, fp);
1277.     fread(&num_map_output, sizeof(int), 1, fp);
1278.
1279.     fread(&len_weight_C1, sizeof(int), 1, fp);
1280.     fread(&len_bias_C1, sizeof(int), 1, fp);
1281.     fread(&len_weight_S2, sizeof(int), 1, fp);
1282.     fread(&len_bias_S2, sizeof(int), 1, fp);
1283.     fread(&len_weight_C3, sizeof(int), 1, fp);
1284.     fread(&len_bias_C3, sizeof(int), 1, fp);
1285.     fread(&len_weight_S4, sizeof(int), 1, fp);
1286.     fread(&len_bias_S4, sizeof(int), 1, fp);
1287.     fread(&len_weight_C5, sizeof(int), 1, fp);
1288.     fread(&len_bias_C5, sizeof(int), 1, fp);
1289.     fread(&len_weight_output, sizeof(int), 1, fp);
1290.     fread(&len_bias_output, sizeof(int), 1, fp);
1291.
1292.     fread(&num_neuron_input, sizeof(int), 1, fp);
1293.     fread(&num_neuron_C1, sizeof(int), 1, fp);
1294.     fread(&num_neuron_S2, sizeof(int), 1, fp);
1295.     fread(&num_neuron_C3, sizeof(int), 1, fp);
1296.     fread(&num_neuron_S4, sizeof(int), 1, fp);
1297.     fread(&num_neuron_C5, sizeof(int), 1, fp);
1298.     fread(&num_neuron_output, sizeof(int), 1, fp);
1299.
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```
1300.     fread(weight_C1, sizeof(weight_C1), 1, fp);
1301.     fread(bias_C1, sizeof(bias_C1), 1, fp);
1302.     fread(weight_S2, sizeof(weight_S2), 1, fp);
1303.     fread(bias_S2, sizeof(bias_S2), 1, fp);
1304.     fread(weight_C3, sizeof(weight_C3), 1, fp);
1305.     fread(bias_C3, sizeof(bias_C3), 1, fp);
1306.     fread(weight_S4, sizeof(weight_S4), 1, fp);
1307.     fread(bias_S4, sizeof(bias_S4), 1, fp);
1308.     fread(weight_C5, sizeof(weight_C5), 1, fp);
1309.     fread(bias_C5, sizeof(bias_C5), 1, fp);
1310.     fread(weight_output, sizeof(weight_output), 1, fp);
1311.     fread(bias_output, sizeof(bias_output), 1, fp);
1312.
1313.     fflush(fp);
1314.     fclose(fp);
1315.
1316.     out2wi_S2.clear();
1317.     out2bias_S2.clear();
1318.     out2wi_S4.clear();
1319.     out2bias_S4.clear();
1320.
1321.     calc_out2wi(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
1322.     calc_out2bias(width_image_S2_CNN, height_image_S2_CNN, num_map_S2_CNN, out2bias_S2);
1323.     calc_out2wi(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, num_map_S4_CNN,
1324.     calc_out2bias(width_image_S4_CNN, height_image_S4_CNN, num_map_S4_CNN, out2bias_S4);
1325.
1326.     return true;
1327. }
1328.
1329. bool CNN::saveModelFile(const char* name)
1330. {
1331.     FILE* fp = fopen(name, "wb");
1332.     if (fp == NULL) {
1333.         return false;
1334.     }
1335.
1336.     int width_image_input = width_image_input_CNN;
1337.     int height_image_input = height_image_input_CNN;
1338.     int width_image_C1 = width_image_C1_CNN;
1339.     int height_image_C1 = height_image_C1_CNN;
1340.     int width_image_S2 = width_image_S2_CNN;
1341.     int height_image_S2 = height_image_S2_CNN;
1342.     int width_image_C3 = width_image_C3_CNN;
1343.     int height_image_C3 = height_image_C3_CNN;
1344.     int width_image_S4 = width_image_S4_CNN;
1345.     int height_image_S4 = height_image_S4_CNN;
1346.     int width_image_C5 = width_image_C5_CNN;
1347.     int height_image_C5 = height_image_C5_CNN;
1348.     int width_image_output = width_image_output_CNN;
1349.     int height_image_output = height_image_output_CNN;
1350.
1351.     int width_kernel_conv = width_kernel_conv_CNN;
1352.     int height_kernel_conv = height_kernel_conv_CNN;
1353.     int width_kernel_pooling = width_kernel_pooling_CNN;
1354.     int height_kernel_pooling = height_kernel_pooling_CNN;
1355.
1356.     int num_map_input = num_map_input_CNN;
1357.     int num_map_C1 = num_map_C1_CNN;
1358.     int num_map_S2 = num_map_S2_CNN;
1359.     int num_map_C3 = num_map_C3_CNN;
1360.     int num_map_S4 = num_map_S4_CNN;
1361.     int num_map_C5 = num_map_C5_CNN;
1362.     int num_map_output = num_map_output_CNN;
1363.
1364.     int len_weight_C1 = len_weight_C1_CNN;
1365.     int len_bias_C1 = len_bias_C1_CNN;
1366.     int len_weight_S2 = len_weight_S2_CNN;
1367.     int len_bias_S2 = len_bias_S2_CNN;
1368.     int len_weight_C3 = len_weight_C3_CNN;
1369.     int len_bias_C3 = len_bias_C3_CNN;
1370.     int len_weight_S4 = len_weight_S4_CNN;
1371.     int len_bias_S4 = len_bias_S4_CNN;
1372.     int len_weight_C5 = len_weight_C5_CNN;
1373.     int len_bias_C5 = len_bias_C5_CNN;
1374.     int len_weight_output = len_weight_output_CNN;
1375.     int len_bias_output = len_bias_output_CNN;
1376.
1377.     int num_neuron_input = num_neuron_input_CNN;
1378.     int num_neuron_C1 = num_neuron_C1_CNN;
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1379.     int num_neuron_S2 = num_neuron_S2_CNN;
1380.     int num_neuron_C3 = num_neuron_C3_CNN;
1381.     int num_neuron_S4 = num_neuron_S4_CNN;
1382.     int num_neuron_C5 = num_neuron_C5_CNN;
1383.     int num_neuron_output = num_neuron_output_CNN;
1384.
1385.     fwrite(&width_image_input, sizeof(int), 1, fp);
1386.     fwrite(&height_image_input, sizeof(int), 1, fp);
1387.     fwrite(&width_image_C1, sizeof(int), 1, fp);
1388.     fwrite(&height_image_C1, sizeof(int), 1, fp);
1389.     fwrite(&width_image_S2, sizeof(int), 1, fp);
1390.     fwrite(&height_image_S2, sizeof(int), 1, fp);
1391.     fwrite(&width_image_C3, sizeof(int), 1, fp);
1392.     fwrite(&height_image_C3, sizeof(int), 1, fp);
1393.     fwrite(&width_image_S4, sizeof(int), 1, fp);
1394.     fwrite(&height_image_S4, sizeof(int), 1, fp);
1395.     fwrite(&width_image_C5, sizeof(int), 1, fp);
1396.     fwrite(&height_image_C5, sizeof(int), 1, fp);
1397.     fwrite(&width_image_output, sizeof(int), 1, fp);
1398.     fwrite(&height_image_output, sizeof(int), 1, fp);
1399.
1400.     fwrite(&width_kernel_conv, sizeof(int), 1, fp);
1401.     fwrite(&height_kernel_conv, sizeof(int), 1, fp);
1402.     fwrite(&width_kernel_pooling, sizeof(int), 1, fp);
1403.     fwrite(&height_kernel_pooling, sizeof(int), 1, fp);
1404.
1405.     fwrite(&num_map_input, sizeof(int), 1, fp);
1406.     fwrite(&num_map_C1, sizeof(int), 1, fp);
1407.     fwrite(&num_map_S2, sizeof(int), 1, fp);
1408.     fwrite(&num_map_C3, sizeof(int), 1, fp);
1409.     fwrite(&num_map_S4, sizeof(int), 1, fp);
1410.     fwrite(&num_map_C5, sizeof(int), 1, fp);
1411.     fwrite(&num_map_output, sizeof(int), 1, fp);
1412.
1413.     fwrite(&len_weight_C1, sizeof(int), 1, fp);
1414.     fwrite(&len_bias_C1, sizeof(int), 1, fp);
1415.     fwrite(&len_weight_S2, sizeof(int), 1, fp);
1416.     fwrite(&len_bias_S2, sizeof(int), 1, fp);
1417.     fwrite(&len_weight_C3, sizeof(int), 1, fp);
1418.     fwrite(&len_bias_C3, sizeof(int), 1, fp);
1419.     fwrite(&len_weight_S4, sizeof(int), 1, fp);
1420.     fwrite(&len_bias_S4, sizeof(int), 1, fp);
1421.     fwrite(&len_weight_C5, sizeof(int), 1, fp);
1422.     fwrite(&len_bias_C5, sizeof(int), 1, fp);
1423.     fwrite(&len_weight_output, sizeof(int), 1, fp);
1424.     fwrite(&len_bias_output, sizeof(int), 1, fp);
1425.
1426.     fwrite(&num_neuron_input, sizeof(int), 1, fp);
1427.     fwrite(&num_neuron_C1, sizeof(int), 1, fp);
1428.     fwrite(&num_neuron_S2, sizeof(int), 1, fp);
1429.     fwrite(&num_neuron_C3, sizeof(int), 1, fp);
1430.     fwrite(&num_neuron_S4, sizeof(int), 1, fp);
1431.     fwrite(&num_neuron_C5, sizeof(int), 1, fp);
1432.     fwrite(&num_neuron_output, sizeof(int), 1, fp);
1433.
1434.     fwrite(weight_C1, sizeof(weight_C1), 1, fp);
1435.     fwrite(bias_C1, sizeof(bias_C1), 1, fp);
1436.     fwrite(weight_S2, sizeof(weight_S2), 1, fp);
1437.     fwrite(bias_S2, sizeof(bias_S2), 1, fp);
1438.     fwrite(weight_C3, sizeof(weight_C3), 1, fp);
1439.     fwrite(bias_C3, sizeof(bias_C3), 1, fp);
1440.     fwrite(weight_S4, sizeof(weight_S4), 1, fp);
1441.     fwrite(bias_S4, sizeof(bias_S4), 1, fp);
1442.     fwrite(weight_C5, sizeof(weight_C5), 1, fp);
1443.     fwrite(bias_C5, sizeof(bias_C5), 1, fp);
1444.     fwrite(weight_output, sizeof(weight_output), 1, fp);
1445.     fwrite(bias_output, sizeof(bias_output), 1, fp);
1446.
1447.     fflush(fp);
1448.     fclose(fp);
1449.
1450.     return true;
1451. }
1452.
1453. double CNN::test()
1454. {
1455.     int count_accuracy = 0;
1456.
1457.     for (int num = 0; num < num_patterns_test_CNN; num++) {
```

关闭

```
1458.         data_single_image = data_input_test + num * num_neuron_input_CNN;
1459.         data_single_label = data_output_test + num * num_neuron_output_CNN;
1460.
1461.         Forward_C1();
1462.         Forward_S2();
1463.         Forward_C3();
1464.         Forward_S4();
1465.         Forward_C5();
1466.         Forward_output();
1467.
1468.         int pos_t = -1;
1469.         int pos_y = -2;
1470.         double max_value_t = -9999.0;
1471.         double max_value_y = -9999.0;
1472.
1473.         for (int i = 0; i < num_neuron_output_CNN; i++) {
1474.             if (neuron_output[i] > max_value_y) {
1475.                 max_value_y = neuron_output[i];
1476.                 pos_y = i;
1477.             }
1478.
1479.             if (data_single_label[i] > max_value_t) {
1480.                 max_value_t = data_single_label[i];
1481.                 pos_t = i;
1482.             }
1483.         }
1484.
1485.         if (pos_y == pos_t) {
1486.             ++count_accuracy;
1487.         }
1488.
1489.         Sleep(1);
1490.     }
1491.
1492.     return (count_accuracy * 1.0 / num_patterns_test_CNN);
1493. }
1494.
1495. }
```

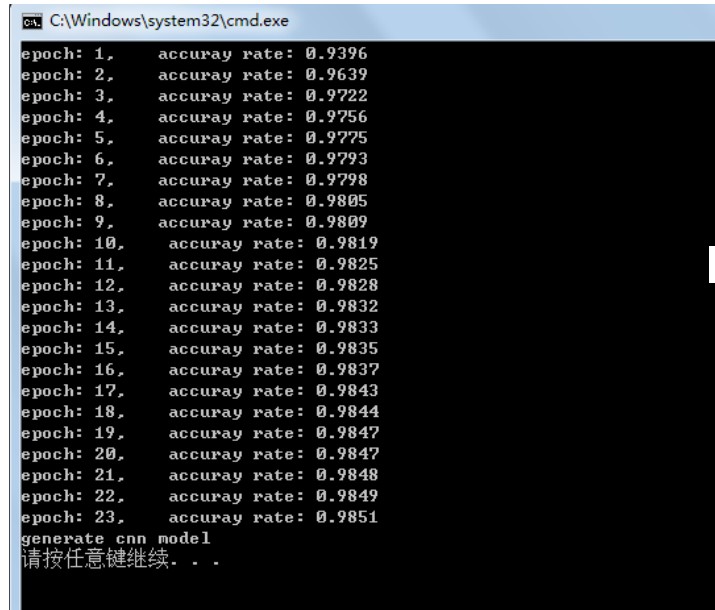
测试代码如下：

```
[cpp] C P
01. int test_CNN_train()
02. {
03.     ANN::CNN cnn1;
04.     cnn1.init();
05.     cnn1.train();
06.
07.     return 0;
08. }
09.
10. int test_CNN_predict()
11. {
12.     ANN::CNN cnn2;
13.     bool flag = cnn2.readModelFile("E:/GitCode/NN_Test/data/cnn.model");
14.     if (!flag) {
15.         std::cout << "read cnn model error" << std::endl;
16.         return -1;
17.     }
18.
19.     int width{ 32 }, height{ 32 };
20.     std::vector<int> target{ 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 };
21.     std::string image_path{ "E:/GitCode/NN_Test/data/images/" };
22.
23.     for (auto i : target) {
24.         std::string str = std::to_string(i);
25.         str += ".png";
26.         str = image_path + str;
27.
28.         cv::Mat src = cv::imread(str, 0);
29.         if (src.data == nullptr) {
30.             fprintf(stderr, "read image error: %s\n", str.c_str());
31.             return -1;
32.         }
33.
34.         cv::Mat tmp(src.rows, src.cols, CV_8UC1, cv::Scalar::all(255));
35.         cv::subtract(tmp, src, tmp);
36.     }
```

关闭

```
37.         cv::resize(tmp, tmp, cv::Size(width, height));
38.
39.         auto ret = cnn2.predict(tmp.data, width, height);
40.
41.         fprintf(stdout, "the actual digit is: %d, correct digit is: %d\n", ret, i);
42.     }
43.
44.     return 0;
45. }
```

通过执行test_CNN_train()函数可生成cnn model文件, 执行结果如下:

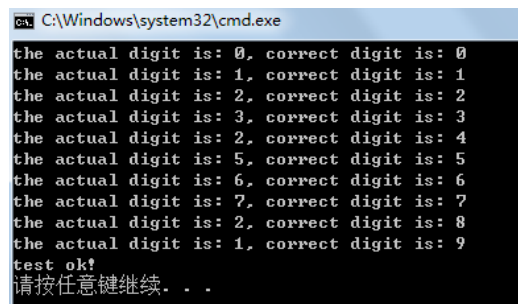


```
C:\Windows\system32\cmd.exe
epoch: 1,    accuray rate: 0.9396
epoch: 2,    accuray rate: 0.9639
epoch: 3,    accuray rate: 0.9722
epoch: 4,    accuray rate: 0.9756
epoch: 5,    accuray rate: 0.9775
epoch: 6,    accuray rate: 0.9793
epoch: 7,    accuray rate: 0.9798
epoch: 8,    accuray rate: 0.9805
epoch: 9,    accuray rate: 0.9809
epoch: 10,   accuray rate: 0.9819
epoch: 11,   accuray rate: 0.9825
epoch: 12,   accuray rate: 0.9828
epoch: 13,   accuray rate: 0.9832
epoch: 14,   accuray rate: 0.9833
epoch: 15,   accuray rate: 0.9835
epoch: 16,   accuray rate: 0.9837
epoch: 17,   accuray rate: 0.9843
epoch: 18,   accuray rate: 0.9844
epoch: 19,   accuray rate: 0.9847
epoch: 20,   accuray rate: 0.9847
epoch: 21,   accuray rate: 0.9848
epoch: 22,   accuray rate: 0.9849
epoch: 23,   accuray rate: 0.9851
generate cnn model
请按任意键继续. . .
```

通过执行test_CNN_predict()函数来测试CNN的准确率, 通过画图工具, 每个数字生成一张图像, 共10幅, 如下图:

0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9

测试结果如下:



```
C:\Windows\system32\cmd.exe
the actual digit is: 0, correct digit is: 0
the actual digit is: 1, correct digit is: 1
the actual digit is: 2, correct digit is: 2
the actual digit is: 3, correct digit is: 3
the actual digit is: 2, correct digit is: 4
the actual digit is: 5, correct digit is: 5
the actual digit is: 6, correct digit is: 6
the actual digit is: 7, correct digit is: 7
the actual digit is: 2, correct digit is: 8
the actual digit is: 1, correct digit is: 9
test ok!
请按任意键继续. . .
```

代码实现解析见: <http://blog.csdn.net/fengbingchun/article/details/53445209>

GitHub: <https://github.com/fengbingchun/NN>

关闭

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3 0

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8楼 [hugl950123](#) 5天前 16:59发表



博主，请问我按照您的代码成功编译后执行结果窗口一闪而过，并且里面什么内容也没有，应该如何解决，能不能帮帮忙==

Re: [fengbingchun](#) 5天前 18:05发表



回复hugl950123：你用的是GitHub上最新的吗？既然能编译过，在Debug下设断点，应该很快能定位到问题原因

Re: [hugl950123](#) 5天前 20:24发表



回复fengbingchun：下的是新的，我在CNN.cpp文件中每个函数都设置了断点，还是没有变化==执行结果的窗口还是一闪而过并且里面什么都没有，是我设置断点的方法不对么。。还有想请教一下现在好多tiny_cnn算法代码的GitHub地址都链接到了tiny_dnn算法，是没法看到原来的tiny_cnn代码了么

Re: [fengbingchun](#) 5天前 21:13发表



回复hugl950123：NN中一共有四个工程，它们之间没有任何关系，都是独立的，如果要运行这篇文章的代码，只需选中NN工程，编译运行它即可。

Re: [hugl950123](#) 前天 23:52发表



回复fengbingchun：博主请问一下，test_CNN_predict()函数是不是需要opencv的支持，为什么我加上了#include <opencv2/opencv.hpp>

Re: [fengbingchun](#) 昨天 08:35发表



回复hugl950123：是需要opencv的支持，你在本地opencv的环境配好了吗，配好了就应该没问题了

Re: [hugl950123](#) 前天 23:51发表



回复fengbingchun：博主请问一下，test_CNN_predict()函数是不是需要opencv的支持，为什么我加上了#include <opencv2/opencv.hpp>后会出现error LNK2019的错误呢==

Re: [hugl950123](#) 前天 09:06发表



回复fengbingchun：谢谢，能够成功运行了现在

7楼 [guanzheng9996](#) 2016-11-26 15:51发表



博主，请问这个在什么环境下运行呢？除了vs2013还需要配置什么，还有就是运行出来的结果是什么样子的呢，我是个新手，麻烦博主指点

Re: [fengbingchun](#) 2016-11-26 17:06发表



回复guanzheng9996：不需要配置什么，结果于<http://blog.csdn.net/fengbingchun/article/details/50573841> 中结果类似，这个还有个bug，后面会把修改后的代码放上去。

Re: [guanzheng9996](#) 2016-11-26 17:14发表



回复fengbingchun：这个和seetaface比，哪个要好，seetaface可以用自己的照片进行训练么？

Re: [fengbingchun](#) 2016-11-26 18:35发表



回复guanzheng9996：好像seetaface还没有提供训练的代码

6楼 [guanzheng9996](#) 2016-11-26 15:51发表



博主，请问这个在什么环境下运行呢？除了vs2013还需要配置什么，还有就是运行出来的结果是什么样子的呢，我是个新手，麻烦博主指点

5楼 [VR_LFB](#) 2016-08-12 17:43发表



万分感谢楼主贴出如此细致的代码！我尝试修改了UpdateWeights()：对其中的梯度向量先做了normalization。而后accuracy就能达到0.97以上了。

Re: [fengbingchun](#) 2016-08-13 18:01发表



回复VR_LFB：赞

4楼 [visionfans](#) 2016-05-22 00:01发表



博主一般是怎么找这样隐藏的很深，很难查出来的bug的？

Re: [fengbingchun](#) 2016-05-22 10:47发表



回复visionfans：感觉没有什么好方法吧，就是多打log，逐函数打印输出结果，看再哪个函数内出的问题

3楼 [fpthink](#) 2016-03-30 22:34发表



博主，我看了你的代码，想请教你一些问题，代码中的和文字描述有不同的地方。关于阈值和权值，的初始值设定。

Re: [fengbingchun](#) 2016-03-31 08:15发表



回复fp1527323876：是有些不同的地方，主要是实现完后，发现识别率一直上不去，就仿照tiny-cnn的改写了下，识别率还是很低，现在还是有些bug。

Re: [fpthink](#) 2016-03-31 09:19发表



回复fengbingchun：s2到c3的convolution，6到16，有一个映射关系，为了好写，直接用16*6，c3层和每一个s2（6*14*14）层的convolution，
//0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
{1, 0, 0, 0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1},
{1, 1, 0, 0, 0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1},
{1, 1, 1, 0, 0, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 1},
{0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 0, 1, 0, 1, 1},
{0, 0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 0, 1},
{0, 0, 0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1}

Re: [fpthink](#) 2016-03-31 09:10发表



回复fengbingchun：比如s4和c5的全连接，用120个卷积核和每一个s4（16*5*5）层的做卷积，最后用激活函数激活c5

2楼 [ccjava5188](#) 2016-03-26 22:48发表



麻烦问一下博主：“C3层：卷积窗大小5*5，输出特征图数量16，卷积窗种类6*16=96”，卷积窗的种类为啥是96个，输出特征图数量为16？

Re: [fengbingchun](#) 2016-03-27 10:35发表

回复ccjava5188：特征图数量可以根据实际需要由自己定。仿照LeNet-5结构，对于C3层，有16个特征map，C3中

关闭



每个特征图由S2中所有6个或者几个特征map组合而成，如果由S2所有6个特征map组合而成，那么卷积窗种类就是16*6了，这里为了实现方便，没有完全按照原有的LeNet-5结构实现。你可以参考下<http://blog.csdn.net/fengbingchun/article/details/50529500>

1楼 吴士龙 2016-03-10 18:48发表



虽然看不太懂，但是呢，楼主很细致呢。

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