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卷积神经网络(CNN)的简单实现(MNIST)

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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*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*5*6+6=150+6，神经元数量28*28*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*6+6=6+6，神经元数量14*14*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*16=96，输出特征图大小10*10，可训练参数5*5*(6*16)+16=2400+16，神经元数量10*10*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*16+16=16+16，神经元数量5*5*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*120=1920，输出特征图大小1*1，可训练参数5*5*(16*120)+120=48000+120，神经元数量1*1*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*10=1200，输出特征图大小1*1，可训练参数1*(120*10)+10=1200+10，神经元数量1*1*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的下采用图，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]

```cpp
#ifndef _CNN_HPP_
#define _CNN_HPP_

#include <vector>
#include <unordered_map>

namespace ANN {

```

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```
#define width_image_input_CNN       32 //归一化图像宽
#define height_image_input_CNN      32 //归一化图像高
#define width_image_C1_CNN      28
#define height_image_C1_CNN     28
#define width_image_S2_CNN      14
#define height_image_S2_CNN     14
#define width_image_C3_CNN      10
#define height_image_C3_CNN     10
#define width_image_S4_CNN      5
#define height_image_S4_CNN     5
#define width_image_C5_CNN      1
#define height_image_C5_CNN     1
#define width_image_output_CNN      1
#define height_image_output_CNN     1

#define width_kernel_conv_CNN       5 //卷积核大小
#define height_kernel_conv_CNN      5
#define width_kernel_pooling_CNN    2
#define height_kernel_pooling_CNN   2
#define size_pooling_CNN        2

#define num_map_input_CNN       1 //输入层map个数
#define num_map_C1_CNN          6 //C1层map个数
#define num_map_S2_CNN          6 //S2层map个数
#define num_map_C3_CNN          16 //C3层map个数
#define num_map_S4_CNN          16 //S4层map个数
#define num_map_C5_CNN          120 //C5层map个数
#define num_map_output_CNN      10 //输出层map个数

#define num_patterns_train_CNN      60000 //训练模式对数(总数)
#define num_patterns_test_CNN       10000 //测试模式对数(总数)
#define num_epochs_CNN          100 //最大迭代次数
#define accuracy_rate_CNN       0.985 //要求达到的准确率
#define learning_rate_CNN       0.01 //学习率
#define eps_CNN             1e-8

#define len_weight_C1_CNN       150 //C1层权值数，5*5*6*1=150
#define len_bias_C1_CNN         6 //C1层阈值数，6
#define len_weight_S2_CNN       6 //S2层权值数,1*6=6
#define len_bias_S2_CNN         6 //S2层阈值数,6
#define len_weight_C3_CNN       2400 //C3层权值数，5*5*16*6=2400
#define len_bias_C3_CNN         16 //C3层阈值数,16
#define len_weight_S4_CNN       16 //S4层权值数，1*16=16
#define len_bias_S4_CNN         16 //S4层阈值数，16
#define len_weight_C5_CNN       48000 //C5层权值数，5*5*16*120=48000
#define len_bias_C5_CNN         120 //C5层阈值数，120
#define len_weight_output_CNN       1200 //输出层权值数，120*10=1200
#define len_bias_output_CNN     10 //输出层阈值数，10

#define num_neuron_input_CNN        1024 //输入层神经元数，32*32=1024
#define num_neuron_C1_CNN       4704 //C1层神经元数，28*28*6=4704
#define num_neuron_S2_CNN       1176 //S2层神经元数，14*14*6=1176
#define num_neuron_C3_CNN       1600 //C3层神经元数，10*10*16=1600
#define num_neuron_S4_CNN       400 //S4层神经元数，5*5*16=400
#define num_neuron_C5_CNN       120 //C5层神经元数，1*120=120
#define num_neuron_output_CNN       10 //输出层神经元数，1*10=10

class CNN {
public:
    CNN();
    ~CNN();

    void init(); //初始化，分配空间
    bool train(); //训练
    int predict(const unsigned char* data, int width, int height); //预测
    bool readModelFile(const char* name); //读取已训练

protected:
    typedef std::vector<std::pair<int, int> > wi_connections;
    typedef std::vector<std::pair<int, int> > wo_connections;
    typedef std::vector<std::pair<int, int> > io_connections;

    void release(); //释放申请的空间
    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
    bool initWeightThreshold(); //初始化，产生[-1, 1]之间的随机小数
    bool getSrcData(); //读取MNIST数据
    double test(); //训练完一次计算一次准确率
    double activation_function_tanh(double x); //激活函数:tanh
```

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```
    double activation_function_tanh_derivative(double x); //激活函数tanh的导数
    double activation_function_identity(double x);
    double activation_function_identity_derivative(double x);
    double loss_function_mse(double y, double t); //损失函数:mean squared error
    double loss_function_mse_derivative(double y, double t);
    void loss_function_gradient(const double* y, const double* t, double* dst, int len);
    double dot_product(const double* s1, const double* s2, int len); //点乘
    bool muladd(const double* src, double c, int len, double* dst); //dst[i] += c * src[i
    void init_variable(double* val, double c, int len);
    bool uniform_rand(double* src, int len, double min, double max);
    double uniform_rand(double min, double max);
    int get_index(int x, int y, int channel, int width, int height, int depth);
    void calc_out2wi(int width_in, int height_in, int width_out, int height_out, int deptl
    void calc_out2bias(int width, int height, int depth, std::vector<int>& out2bias);
    void calc_in2wo(int width_in, int height_in, int width_out, int height_out, int depth_
    void calc_weight2io(int width_in, int height_in, int width_out, int height_out, int de
    void calc_bias2out(int width_in, int height_in, int width_out, int height_out, int de

    bool Forward_C1(); //前向传播
    bool Forward_S2();
    bool Forward_C3();
    bool Forward_S4();
    bool Forward_C5();
    bool Forward_output();
    bool Backward_output();
    bool Backward_C5(); //反向传播
    bool Backward_S4();
    bool Backward_C3();
    bool Backward_S2();
    bool Backward_C1();
    bool Backward_input();
    bool UpdateWeights(); //更新权值、阈值
    void update_weights_bias(const double* delta, double* e_weight, double* weight, int le

private:
    double* data_input_train; //原始标准输入数据，训练,范围：[-1, 1]
    double* data_output_train; //原始标准期望结果，训练,取值：-0.8/0.8
    double* data_input_test; //原始标准输入数据，测试,范围：[-1, 1]
    double* data_output_test; //原始标准期望结果，测试,取值：-0.8/0.8
    double* data_single_image;
    double* data_single_label;

    double weight_C1[len_weight_C1_CNN];
    double bias_C1[len_bias_C1_CNN];
    double weight_S2[len_weight_S2_CNN];
    double bias_S2[len_bias_S2_CNN];
    double weight_C3[len_weight_C3_CNN];
    double bias_C3[len_bias_C3_CNN];
    double weight_S4[len_weight_S4_CNN];
    double bias_S4[len_bias_S4_CNN];
    double weight_C5[len_weight_C5_CNN];
    double bias_C5[len_bias_C5_CNN];
    double weight_output[len_weight_output_CNN];
    double bias_output[len_bias_output_CNN];

    double E_weight_C1[len_weight_C1_CNN];
    double E_bias_C1[len_bias_C1_CNN];
    double E_weight_S2[len_weight_S2_CNN];
    double E_bias_S2[len_bias_S2_CNN];
    double E_weight_C3[len_weight_C3_CNN];
    double E_bias_C3[len_bias_C3_CNN];
    double E_weight_S4[len_weight_S4_CNN];
    double E_bias_S4[len_bias_S4_CNN];
    double* E_weight_C5;
    double* E_bias_C5;
    double* E_weight_output;
    double* E_bias_output;

    double neuron_input[num_neuron_input_CNN]; //data_single_image
    double neuron_C1[num_neuron_C1_CNN];
    double neuron_S2[num_neuron_S2_CNN];
    double neuron_C3[num_neuron_C3_CNN];
    double neuron_S4[num_neuron_S4_CNN];
    double neuron_C5[num_neuron_C5_CNN];
    double neuron_output[num_neuron_output_CNN];

    double delta_neuron_output[num_neuron_output_CNN]; //神经元误差
    double delta_neuron_C5[num_neuron_C5_CNN];
    double delta_neuron_S4[num_neuron_S4_CNN];
```

关闭

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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=...
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展开


```
    double delta_neuron_C3[num_neuron_C3_CNN];
    double delta_neuron_S2[num_neuron_S2_CNN];
    double delta_neuron_C1[num_neuron_C1_CNN];
    double delta_neuron_input[num_neuron_input_CNN];

    double delta_weight_C1[len_weight_C1_CNN]; //权值、阈值误差
    double delta_bias_C1[len_bias_C1_CNN];
    double delta_weight_S2[len_weight_S2_CNN];
    double delta_bias_S2[len_bias_S2_CNN];
    double delta_weight_C3[len_weight_C3_CNN];
    double delta_bias_C3[len_bias_C3_CNN];
    double delta_weight_S4[len_weight_S4_CNN];
    double delta_bias_S4[len_bias_S4_CNN];
    double delta_weight_C5[len_weight_C5_CNN];
    double delta_bias_C5[len_bias_C5_CNN];
    double delta_weight_output[len_weight_output_CNN];
    double delta_bias_output[len_bias_output_CNN];

    std::vector<wi_connections> out2wi_S2; // out_id -> [(weight_id, in_id)]
    std::vector<int> out2bias_S2;
    std::vector<wi_connections> out2wi_S4;
    std::vector<int> out2bias_S4;
    std::vector<wo_connections> in2wo_C3; // in_id -> [(weight_id, out_id)]
    std::vector<io_connections> weight2io_C3; // weight_id -> [(in_id, out_id
    std::vector<std::vector<int> > bias2out_C3;
    std::vector<wo_connections> in2wo_C1;
    std::vector<io_connections> weight2io_C1;
    std::vector<std::vector<int> > bias2out_C1;
};

}

#endif //_CNN_HPP_
```

CNN.cpp：

[cpp]

```
#include <CNN.hpp>
#include <assert.h>
#include <time.h>
#include <iostream>
#include <fstream>
#include <numeric>
#include <windows.h>
#include <random>
#include <algorithm>
#include <string>

namespace ANN {

CNN::CNN()
{
    data_input_train = NULL;
    data_output_train = NULL;
    data_input_test = NULL;
    data_output_test = NULL;
    data_single_image = NULL;
    data_single_label = NULL;
    E_weight_C5 = NULL;
    E_bias_C5 = NULL;
    E_weight_output = NULL;
    E_bias_output = NULL;
}

CNN::~CNN()
{
    release();
}

void CNN::release()
{
    if (data_input_train) {
        delete[] data_input_train;
        data_input_train = NULL;
    }
    if (data_output_train) {
        delete[] data_output_train;
        data_output_train = NULL;
```

关闭

```
    }
    if (data_input_test) {
        delete[] data_input_test;
        data_input_test = NULL;
    }
    if (data_output_test) {
        delete[] data_output_test;
        data_output_test = NULL;
    }

    if (E_weight_C5) {
        delete[] E_weight_C5;
        E_weight_C5 = NULL;
    }
    if (E_bias_C5) {
        delete[] E_bias_C5;
        E_bias_C5 = NULL;
    }
    if (E_weight_output) {
        delete[] E_weight_output;
        E_weight_output = NULL;
    }
    if (E_bias_output) {
        delete[] E_bias_output;
        E_bias_output = NULL;
    }
}

// connection table [Y.Lecun, 1998 Table.1]
#define O true
#define X false
static const bool tbl[6][16] = {
    O, X, X, X, O, O, O, X, X, O, O, O, O, X, O, O,
    O, O, X, X, X, O, O, O, X, X, O, O, O, O, X, O,
    O, O, O, X, X, X, O, O, O, X, X, O, X, O, O, O,
    X, O, O, O, X, X, O, O, O, O, X, X, O, X, O, O,
    X, X, O, O, O, X, X, O, O, O, O, X, O, O, X, O,
    X, X, X, O, O, O, X, X, O, O, O, O, X, O, O, O
};
#undef O
#undef X

void CNN::init_variable(double* val, double c, int len)
{
    for (int i = 0; i < len; i++) {
        val[i] = c;
    }
}

void CNN::init()
{
    int len1 = width_image_input_CNN * height_image_input_CNN * num_patterns_train_CNN;
    data_input_train = new double[len1];
    init_variable(data_input_train, -1.0, len1);

    int len2 = num_map_output_CNN * num_patterns_train_CNN;
    data_output_train = new double[len2];
    init_variable(data_output_train, -0.8, len2);

    int len3 = width_image_input_CNN * height_image_input_CNN * num_patterns_test_CNN;
    data_input_test = new double[len3];
    init_variable(data_input_test, -1.0, len3);

    int len4 = num_map_output_CNN * num_patterns_test_CNN;
    data_output_test = new double[len4];
    init_variable(data_output_test, -0.8, len4);

    std::fill(E_weight_C1, E_weight_C1 + len_weight_C1_CNN, 0.0);
    std::fill(E_bias_C1, E_bias_C1 + len_bias_C1_CNN, 0.0);
    std::fill(E_weight_S2, E_weight_S2 + len_weight_S2_CNN, 0.0);
    std::fill(E_bias_S2, E_bias_S2 + len_bias_S2_CNN, 0.0);
    std::fill(E_weight_C3, E_weight_C3 + len_weight_C3_CNN, 0.0);
    std::fill(E_bias_C3, E_bias_C3 + len_bias_C3_CNN, 0.0);
    std::fill(E_weight_S4, E_weight_S4 + len_weight_S4_CNN, 0.0);
    std::fill(E_bias_S4, E_bias_S4 + len_bias_S4_CNN, 0.0);
    E_weight_C5 = new double[len_weight_C5_CNN];
    std::fill(E_weight_C5, E_weight_C5 + len_weight_C5_CNN, 0.0);
    E_bias_C5 = new double[len_bias_C5_CNN];
    std::fill(E_bias_C5, E_bias_C5 + len_bias_C5_CNN, 0.0);
```

关闭

```
    E_weight_output = new double[len_weight_output_CNN];
    std::fill(E_weight_output, E_weight_output + len_weight_output_CNN, 0.0);
    E_bias_output = new double[len_bias_output_CNN];
    std::fill(E_bias_output, E_bias_output + len_bias_output_CNN, 0.0);

    initWeightThreshold();
    getSrcData();
}

double CNN::uniform_rand(double min, double max)
{
    static std::mt19937 gen(1);
    std::uniform_real_distribution<double> dst(min, max);
    return dst(gen);
}

bool CNN::uniform_rand(double* src, int len, double min, double max)
{
    for (int i = 0; i < len; i++) {
        src[i] = uniform_rand(min, max);
    }

    return true;
}

bool CNN::initWeightThreshold()
{
    srand(time(0) + rand());
    const double scale = 6.0;

    double min_ = -std::sqrt(scale / (25.0 + 150.0));
    double max_ = std::sqrt(scale / (25.0 + 150.0));
    uniform_rand(weight_C1, len_weight_C1_CNN, min_, max_);
    for (int i = 0; i < len_bias_C1_CNN; i++) {
        bias_C1[i] = 0.0;
    }

    min_ = -std::sqrt(scale / (4.0 + 1.0));
    max_ = std::sqrt(scale / (4.0 + 1.0));
    uniform_rand(weight_S2, len_weight_S2_CNN, min_, max_);
    for (int i = 0; i < len_bias_S2_CNN; i++) {
        bias_S2[i] = 0.0;
    }

    min_ = -std::sqrt(scale / (150.0 + 400.0));
    max_ = std::sqrt(scale / (150.0 + 400.0));
    uniform_rand(weight_C3, len_weight_C3_CNN, min_, max_);
    for (int i = 0; i < len_bias_C3_CNN; i++) {
        bias_C3[i] = 0.0;
    }

    min_ = -std::sqrt(scale / (4.0 + 1.0));
    max_ = std::sqrt(scale / (4.0 + 1.0));
    uniform_rand(weight_S4, len_weight_S4_CNN, min_, max_);
    for (int i = 0; i < len_bias_S4_CNN; i++) {
        bias_S4[i] = 0.0;
    }

    min_ = -std::sqrt(scale / (400.0 + 3000.0));
    max_ = std::sqrt(scale / (400.0 + 3000.0));
    uniform_rand(weight_C5, len_weight_C5_CNN, min_, max_);
    for (int i = 0; i < len_bias_C5_CNN; i++) {
        bias_C5[i] = 0.0;
    }

    min_ = -std::sqrt(scale / (120.0 + 10.0));
    max_ = std::sqrt(scale / (120.0 + 10.0));
    uniform_rand(weight_output, len_weight_output_CNN, min_, max_);
    for (int i = 0; i < len_bias_output_CNN; i++) {
        bias_output[i] = 0.0;
    }

    return true;
}

static int reverseInt(int i)
{
    unsigned char ch1, ch2, ch3, ch4;
    ch1 = i & 255;
```

关闭

```
    ch2 = (i >> 8) & 255;
    ch3 = (i >> 16) & 255;
    ch4 = (i >> 24) & 255;
    return((int)ch1 << 24) + ((int)ch2 << 16) + ((int)ch3 << 8) + ch4;
}

static void readMnistImages(std::string filename, double* data_dst, int num_image)
{
    const int width_src_image = 28;
    const int height_src_image = 28;
    const int x_padding = 2;
    const int y_padding = 2;
    const double scale_min = -1;
    const double scale_max = 1;

    std::ifstream file(filename, std::ios::binary);
    assert(file.is_open());

    int magic_number = 0;
    int number_of_images = 0;
    int n_rows = 0;
    int n_cols = 0;
    file.read((char*)&magic_number, sizeof(magic_number));
    magic_number = reverseInt(magic_number);
    file.read((char*)&number_of_images, sizeof(number_of_images));
    number_of_images = reverseInt(number_of_images);
    assert(number_of_images == num_image);
    file.read((char*)&n_rows, sizeof(n_rows));
    n_rows = reverseInt(n_rows);
    file.read((char*)&n_cols, sizeof(n_cols));
    n_cols = reverseInt(n_cols);
    assert(n_rows == height_src_image && n_cols == width_src_image);

    int size_single_image = width_image_input_CNN * height_image_input_CNN;

    for (int i = 0; i < number_of_images; ++i) {
        int addr = size_single_image * i;

        for (int r = 0; r < n_rows; ++r) {
            for (int c = 0; c < n_cols; ++c) {
                unsigned char temp = 0;
                file.read((char*)&temp, sizeof(temp));
                data_dst[addr + width_image_input_CNN * (r + y_padding) + c + x_padding] =
            }
        }
    }
}

static void readMnistLabels(std::string filename, double* data_dst, int num_image)
{
    const double scale_max = 0.8;

    std::ifstream file(filename, std::ios::binary);
    assert(file.is_open());

    int magic_number = 0;
    int number_of_images = 0;
    file.read((char*)&magic_number, sizeof(magic_number));
    magic_number = reverseInt(magic_number);
    file.read((char*)&number_of_images, sizeof(number_of_images));
    number_of_images = reverseInt(number_of_images);
    assert(number_of_images == num_image);

    for (int i = 0; i < number_of_images; ++i) {
        unsigned char temp = 0;
        file.read((char*)&temp, sizeof(temp));
        data_dst[i * num_map_output_CNN + temp] = scale_max;
    }
}

bool CNN::getSrcData()
{
    assert(data_input_train && data_output_train && data_input_test && data_output_test);

    std::string filename_train_images = "E:/GitCode/NN_Test/data/train-images.idx3-
ubyte";
    std::string filename_train_labels = "E:/GitCode/NN_Test/data/train-labels.idx1-
ubyte";
    readMnistImages(filename_train_images, data_input_train, num_patterns_train_CNN);
```

关闭

```
    readMnistLabels(filename_train_labels, data_output_train, num_patterns_train_CNN);

    std::string filename_test_images = "E:/GitCode/NN_Test/data/t10k-images.idx3-
ubyte";
    std::string filename_test_labels = "E:/GitCode/NN_Test/data/t10k-labels.idx1-
ubyte";
    readMnistImages(filename_test_images, data_input_test, num_patterns_test_CNN);
    readMnistLabels(filename_test_labels, data_output_test, num_patterns_test_CNN);

    return true;
}

bool CNN::train()
{
    out2wi_S2.clear();
    out2bias_S2.clear();
    out2wi_S4.clear();
    out2bias_S4.clear();
    in2wo_C3.clear();
    weight2io_C3.clear();
    bias2out_C3.clear();
    in2wo_C1.clear();
    weight2io_C1.clear();
    bias2out_C1.clear();

    calc_out2wi(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
    calc_out2bias(width_image_S2_CNN, height_image_S2_CNN, num_map_S2_CNN, out2bias_S2);
    calc_out2wi(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_image_
    calc_out2bias(width_image_S4_CNN, height_image_S4_CNN, num_map_S4_CNN, out2bias_S4);
    calc_in2wo(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_image_S
    calc_weight2io(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_ima
    calc_bias2out(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN, height_imag
    calc_in2wo(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_S
    calc_weight2io(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_ima
    calc_bias2out(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_imag

    int iter = 0;
    for (iter = 0; iter < num_epochs_CNN; iter++) {
        std::cout << "epoch: " << iter + 1;

        for (int i = 0; i < num_patterns_train_CNN; i++) {
            data_single_image = data_input_train + i * num_neuron_input_CNN;
            data_single_label = data_output_train + i * num_neuron_output_CNN;

            Forward_C1();
            Forward_S2();
            Forward_C3();
            Forward_S4();
            Forward_C5();
            Forward_output();

            Backward_output();
            Backward_C5();
            Backward_S4();
            Backward_C3();
            Backward_S2();
            Backward_C1();
            Backward_input();

            UpdateWeights();
        }

        double accuracyRate = test();
        std::cout << ",    accuray rate: " << accuracyRate << std::endl;
        if (accuracyRate > accuracy_rate_CNN) {
            saveModelFile("E:/GitCode/NN_Test/data/cn
            std::cout << "generate cnn model" << std::endl;
            break;
        }
    }

    if (iter == num_epochs_CNN) {
        saveModelFile("E:/GitCode/NN_Test/data/cnn.model");
        std::cout << "generate cnn model" << std::endl;
    }

    return true;
}

```

关闭

```
double CNN::activation_function_tanh(double x)
{
    double ep = std::exp(x);
    double em = std::exp(-x);

    return (ep - em) / (ep + em);
}

double CNN::activation_function_tanh_derivative(double x)
{
    return (1.0 - x * x);
}

double CNN::activation_function_identity(double x)
{
    return x;
}

double CNN::activation_function_identity_derivative(double x)
{
    return 1;
}

double CNN::loss_function_mse(double y, double t)
{
    return (y - t) * (y - t) / 2;
}

double CNN::loss_function_mse_derivative(double y, double t)
{
    return (y - t);
}

void CNN::loss_function_gradient(const double* y, const double* t, double* dst, int len)
{
    for (int i = 0; i < len; i++) {
        dst[i] = loss_function_mse_derivative(y[i], t[i]);
    }
}

double CNN::dot_product(const double* s1, const double* s2, int len)
{
    double result = 0.0;

    for (int i = 0; i < len; i++) {
        result += s1[i] * s2[i];
    }

    return result;
}

bool CNN::muladd(const double* src, double c, int len, double* dst)
{
    for (int i = 0; i < len; i++) {
        dst[i] += (src[i] * c);
    }

    return true;
}

int CNN::get_index(int x, int y, int channel, int width, int height, int depth)
{
    assert(x >= 0 && x < width);
    assert(y >= 0 && y < height);
    assert(channel >= 0 && channel < depth);
    return (height * channel + y) * width + x;
}

void CNN::calc_out2wi(int width_in, int height_in, int width_out, int height_out, int dept
{
    for (int i = 0; i < depth_out; i++) {
        int block = width_in * height_in * i;

        for (int y = 0; y < height_out; y++) {
            for (int x = 0; x < width_out; x++) {
                int rows = y * width_kernel_pooling_CNN;
                int cols = x * height_kernel_pooling_CNN;

                wi_connections wi_connections_;
```

关闭

```
                std::pair<int, int> pair_;

                for (int m = 0; m < width_kernel_pooling_CNN; m++) {
                    for (int n = 0; n < height_kernel_pooling_CNN; n++) {
                        pair_.first = i;
                        pair_.second = (rows + m) * width_in + cols + n + block;
                        wi_connections_.push_back(pair_);
                    }
                }
                out2wi.push_back(wi_connections_);
            }
        }
    }
}

void CNN::calc_out2bias(int width, int height, int depth, std::vector<int>& out2bias)
{
    for (int i = 0; i < depth; i++) {
        for (int y = 0; y < height; y++) {
            for (int x = 0; x < width; x++) {
                out2bias.push_back(i);
            }
        }
    }
}

void CNN::calc_in2wo(int width_in, int height_in, int width_out, int height_out, int deptl
{
    int len = width_in * height_in * depth_in;
    in2wo.resize(len);

    for (int c = 0; c < depth_in; c++) {
        for (int y = 0; y < height_in; y += height_kernel_pooling_CNN) {
            for (int x = 0; x < width_in; x += width_kernel_pooling_CNN) {
                int dymax = min(size_pooling_CNN, height_in - y);
                int dxmax = min(size_pooling_CNN, width_in - x);
                int dstx = x / width_kernel_pooling_CNN;
                int dsty = y / height_kernel_pooling_CNN;

                for (int dy = 0; dy < dymax; dy++) {
                    for (int dx = 0; dx < dxmax; dx++) {
                        int index_in = get_index(x + dx, y + dy, c, width_in, height_in, (
                        int index_out = get_index(dstx, dsty, c, width_out, height_out, de

                        wo_connections wo_connections_;
                        std::pair<int, int> pair_;
                        pair_.first = c;
                        pair_.second = index_out;
                        wo_connections_.push_back(pair_);

                        in2wo[index_in] = wo_connections_;
                    }
                }
            }
        }
    }
}

void CNN::calc_weight2io(int width_in, int height_in, int width_out, int height_out, int (
{
    int len = depth_in;
    weight2io.resize(len);

    for (int c = 0; c < depth_in; c++) {
        for (int y = 0; y < height_in; y += height_kernel_pooling_CNN) {
            for (int x = 0; x < width_in; x += width_l
                int dymax = min(size_pooling_CNN, height_in - y);
                int dxmax = min(size_pooling_CNN, width_in - x);
                int dstx = x / width_kernel_pooling_CNN;
                int dsty = y / height_kernel_pooling_CNN;

                for (int dy = 0; dy < dymax; dy++) {
                    for (int dx = 0; dx < dxmax; dx++) {
                        int index_in = get_index(x + dx, y + dy, c, width_in, height_in, (
                        int index_out = get_index(dstx, dsty, c, width_out, height_out, de

                        std::pair<int, int> pair_;
                        pair_.first = index_in;
                        pair_.second = index_out;
```

关闭

```
                        weight2io[c].push_back(pair_);
                    }
                }
            }
        }
    }
}

void CNN::calc_bias2out(int width_in, int height_in, int width_out, int height_out, int de
{
    int len = depth_in;
    bias2out.resize(len);

    for (int c = 0; c < depth_in; c++) {
        for (int y = 0; y < height_out; y++) {
            for (int x = 0; x < width_out; x++) {
                int index_out = get_index(x, y, c, width_out, height_out, depth_out);
                bias2out[c].push_back(index_out);
            }
        }
    }
}

bool CNN::Forward_C1()
{
    init_variable(neuron_C1, 0.0, num_neuron_C1_CNN);

    for (int o = 0; o < num_map_C1_CNN; o++) {
        for (int inc = 0; inc < num_map_input_CNN; inc++) {
            int addr1 = get_index(0, 0, num_map_input_CNN * o + inc, width_kernel_conv_CNN
            int addr2 = get_index(0, 0, inc, width_image_input_CNN, height_image_input_CNN
            int addr3 = get_index(0, 0, o, width_image_C1_CNN, height_image_C1_CNN, num_ma

            const double* pw = &weight_C1[0] + addr1;
            const double* pi = data_single_image + addr2;
            double* pa = &neuron_C1[0] + addr3;

            for (int y = 0; y < height_image_C1_CNN; y++) {
                for (int x = 0; x < width_image_C1_CNN; x++) {
                    const double* ppw = pw;
                    const double* ppi = pi + y * width_image_input_CNN + x;
                    double sum = 0.0;

                    for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                        for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                            sum += *ppw++ * ppi[wy * width_image_input_CNN + wx];
                        }
                    }

                    pa[y * width_image_C1_CNN + x] += sum;
                }
            }
        }

        int addr3 = get_index(0, 0, o, width_image_C1_CNN, height_image_C1_CNN, num_map_C1
        double* pa = &neuron_C1[0] + addr3;
        double b = bias_C1[o];
        for (int y = 0; y < height_image_C1_CNN; y++) {
            for (int x = 0; x < width_image_C1_CNN; x++) {
                pa[y * width_image_C1_CNN + x] += b;
            }
        }
    }

    for (int i = 0; i < num_neuron_C1_CNN; i++) {
        neuron_C1[i] = activation_function_tanh(neuron_C1[i]);
    }

    return true;
}

bool CNN::Forward_S2()
{
    init_variable(neuron_S2, 0.0, num_neuron_S2_CNN);
    double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);

    assert(out2wi_S2.size() == num_neuron_S2_CNN);
    assert(out2bias_S2.size() == num_neuron_S2_CNN);
```

关闭

```

    for (int i = 0; i < num_neuron_S2_CNN; i++) {
        const wi_connections& connections = out2wi_S2[i];
        neuron_S2[i] = 0;

        for (int index = 0; index < connections.size(); index++) {
            neuron_S2[i] += weight_S2[connections[index].first] * neuron_C1[connections[in
        }

        neuron_S2[i] *= scale_factor;
        neuron_S2[i] += bias_S2[out2bias_S2[i]];
    }

    for (int i = 0; i < num_neuron_S2_CNN; i++) {
        neuron_S2[i] = activation_function_tanh(neuron_S2[i]);
    }

    return true;
}

bool CNN::Forward_C3()
{
    init_variable(neuron_C3, 0.0, num_neuron_C3_CNN);

    for (int o = 0; o < num_map_C3_CNN; o++) {
        for (int inc = 0; inc < num_map_S2_CNN; inc++) {
            if (!tbl[inc][o]) continue;

            int addr1 = get_index(0, 0, num_map_S2_CNN * o + inc, width_kernel_conv_CNN, h
            int addr2 = get_index(0, 0, inc, width_image_S2_CNN, height_image_S2_CNN, num_
            int addr3 = get_index(0, 0, o, width_image_C3_CNN, height_image_C3_CNN, num_ma

            const double* pw = &weight_C3[0] + addr1;
            const double* pi = &neuron_S2[0] + addr2;
            double* pa = &neuron_C3[0] + addr3;

            for (int y = 0; y < height_image_C3_CNN; y++) {
                for (int x = 0; x < width_image_C3_CNN; x++) {
                    const double* ppw = pw;
                    const double* ppi = pi + y * width_image_S2_CNN + x;
                    double sum = 0.0;

                    for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                        for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                            sum += *ppw++ * ppi[wy * width_image_S2_CNN + wx];
                        }
                    }

                    pa[y * width_image_C3_CNN + x] += sum;
                }
            }
        }

        int addr3 = get_index(0, 0, o, width_image_C3_CNN, height_image_C3_CNN, num_map_C3
        double* pa = &neuron_C3[0] + addr3;
        double b = bias_C3[o];
        for (int y = 0; y < height_image_C3_CNN; y++) {
            for (int x = 0; x < width_image_C3_CNN; x++) {
                pa[y * width_image_C3_CNN + x] += b;
            }
        }
    }

    for (int i = 0; i < num_neuron_C3_CNN; i++) {
        neuron_C3[i] = activation_function_tanh(neuron_C3[i]);
    }

    return true;
}

bool CNN::Forward_S4()
{
    double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);
    init_variable(neuron_S4, 0.0, num_neuron_S4_CNN);

    assert(out2wi_S4.size() == num_neuron_S4_CNN);
    assert(out2bias_S4.size() == num_neuron_S4_CNN);

    for (int i = 0; i < num_neuron_S4_CNN; i++) {
```

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```
        const wi_connections& connections = out2wi_S4[i];
        neuron_S4[i] = 0.0;

        for (int index = 0; index < connections.size(); index++) {
            neuron_S4[i] += weight_S4[connections[index].first] * neuron_C3[connections[ir
        }

        neuron_S4[i] *= scale_factor;
        neuron_S4[i] += bias_S4[out2bias_S4[i]];
    }

    for (int i = 0; i < num_neuron_S4_CNN; i++) {
        neuron_S4[i] = activation_function_tanh(neuron_S4[i]);
    }

    return true;
}

bool CNN::Forward_C5()
{
    init_variable(neuron_C5, 0.0, num_neuron_C5_CNN);

    for (int o = 0; o < num_map_C5_CNN; o++) {
        for (int inc = 0; inc < num_map_S4_CNN; inc++) {
            int addr1 = get_index(0, 0, num_map_S4_CNN * o + inc, width_kernel_conv_CNN, h
            int addr2 = get_index(0, 0, inc, width_image_S4_CNN, height_image_S4_CNN, num_
            int addr3 = get_index(0, 0, o, width_image_C5_CNN, height_image_C5_CNN, num_ma

            const double *pw = &weight_C5[0] + addr1;
            const double *pi = &neuron_S4[0] + addr2;
            double *pa = &neuron_C5[0] + addr3;

            for (int y = 0; y < height_image_C5_CNN; y++) {
                for (int x = 0; x < width_image_C5_CNN; x++) {
                    const double *ppw = pw;
                    const double *ppi = pi + y * width_image_S4_CNN + x;
                    double sum = 0.0;

                    for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                        for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                            sum += *ppw++ * ppi[wy * width_image_S4_CNN + wx];
                        }
                    }

                    pa[y * width_image_C5_CNN + x] += sum;
                }
            }
        }

        int addr3 = get_index(0, 0, o, width_image_C5_CNN, height_image_C5_CNN, num_map_C5
        double *pa = &neuron_C5[0] + addr3;
        double b = bias_C5[o];
        for (int y = 0; y < height_image_C5_CNN; y++) {
            for (int x = 0; x < width_image_C5_CNN; x++) {
                pa[y * width_image_C5_CNN + x] += b;
            }
        }
    }

    for (int i = 0; i < num_neuron_C5_CNN; i++) {
        neuron_C5[i] = activation_function_tanh(neuron_C5[i]);
    }

    return true;
}

bool CNN::Forward_output()
{
    init_variable(neuron_output, 0.0, num_neuron_output_CNN);

    for (int i = 0; i < num_neuron_output_CNN; i++) {
        neuron_output[i] = 0.0;

        for (int c = 0; c < num_neuron_C5_CNN; c++) {
            neuron_output[i] += weight_output[c * num_neuron_output_CNN + i] * neuron_C5[c
        }

        neuron_output[i] += bias_output[i];
    }
```

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```

    for (int i = 0; i < num_neuron_output_CNN; i++) {
        neuron_output[i] = activation_function_tanh(neuron_output[i]);
    }

    return true;
}

bool CNN::Backward_output()
{
    init_variable(delta_neuron_output, 0.0, num_neuron_output_CNN);

    double dE_dy[num_neuron_output_CNN];
    init_variable(dE_dy, 0.0, num_neuron_output_CNN);
    loss_function_gradient(neuron_output, data_single_label, dE_dy, num_neuron_output_CNN
失函数: mean squared error(均方差)

    // delta = dE/da = (dE/dy) * (dy/da)
    for (int i = 0; i < num_neuron_output_CNN; i++) {
        double dy_da[num_neuron_output_CNN];
        init_variable(dy_da, 0.0, num_neuron_output_CNN);

        dy_da[i] = activation_function_tanh_derivative(neuron_output[i]);
        delta_neuron_output[i] = dot_product(dE_dy, dy_da, num_neuron_output_
    }

    return true;
}

bool CNN::Backward_C5()
{
    init_variable(delta_neuron_C5, 0.0, num_neuron_C5_CNN);
    init_variable(delta_weight_output, 0.0, len_weight_output_CNN);
    init_variable(delta_bias_output, 0.0, len_bias_output_CNN);

    for (int c = 0; c < num_neuron_C5_CNN; c++) {
        // propagate delta to previous layer
        // prev_delta[c] += current_delta[r] * W_[c * out_size_ + r]
        delta_neuron_C5[c] = dot_product(&
delta_neuron_output[0], &weight_output[c * num_neuron_output_CNN], num_neuron_output_CNN)
        delta_neuron_C5[c] *= activation_function_tanh_derivative(neuron_C5[c]);
    }

    // accumulate weight-step using delta
    // dW[c * out_size + i] += current_delta[i] * prev_out[c]
    for (int c = 0; c < num_neuron_C5_CNN; c++) {
        muladd(&delta_neuron_output[0], neuron_C5[c], num_neuron_output_CNN, &delta_weigh
    }

    for (int i = 0; i < len_bias_output_CNN; i++) {
        delta_bias_output[i] += delta_neuron_output[i];
    }

    return true;
}

bool CNN::Backward_S4()
{
    init_variable(delta_neuron_S4, 0.0, num_neuron_S4_CNN);
    init_variable(delta_weight_C5, 0.0, len_weight_C5_CNN);
    init_variable(delta_bias_C5, 0.0, len_bias_C5_CNN);

    // propagate delta to previous layer
    for (int inc = 0; inc < num_map_S4_CNN; inc++) {
        for (int outc = 0; outc < num_map_C5_CNN; outc++) {
            int addr1 = get_index(0, 0, num_map_S4_CN
            int addr2 = get_index(0, 0, outc, width_image_C5_CNN, height_image_C5_CNN, nu
            int addr3 = get_index(0, 0, inc, width_image_S4_CNN, height_image_S4_CNN, num_

            const double* pw = &weight_C5[0] + addr1;
            const double* pdelta_src = &delta_neuron_C5[0] + addr2;
            double* pdelta_dst = &delta_neuron_S4[0] + addr3;

            for (int y = 0; y < height_image_C5_CNN; y++) {
                for (int x = 0; x < width_image_C5_CNN; x++) {
                    const double* ppw = pw;
                    const double ppdelta_src = pdelta_src[y * width_image_C5_CNN + x];
                    double* ppdelta_dst = pdelta_dst + y * width_image_S4_CNN + x;

```

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```
                        for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                            for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                                ppdelta_dst[wy * width_image_S4_CNN + wx] += *ppw++ * ppdelta_
                            }
                        }
                    }
                }
            }
        }

        for (int i = 0; i < num_neuron_S4_CNN; i++) {
            delta_neuron_S4[i] *= activation_function_tanh_derivative(neuron_S4[i]);
        }

        // accumulate dw
        for (int inc = 0; inc < num_map_S4_CNN; inc++) {
            for (int outc = 0; outc < num_map_C5_CNN; outc++) {
                for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                    for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                        int addr1 = get_index(wx, wy, inc, width_image_S4_CNN, height_image_S4
                        int addr2 = get_index(0, 0, outc, width_image_C5_CNN, height_image_C5_
                        int addr3 = get_index(wx, wy, num_map_S4_CNN * outc + inc, width_kerne

                        double dst = 0.0;
                        const double* prevo = &neuron_S4[0] + addr1;
                        const double* delta = &delta_neuron_C5[0] + addr2;

                        for (int y = 0; y < height_image_C5_CNN; y++) {
                            dst += dot_product(prevo + y * width_image_S4_CNN, delta + y * wic
                        }

                        delta_weight_C5[addr3] += dst;
                    }
                }
            }
        }

        // accumulate db
        for (int outc = 0; outc < num_map_C5_CNN; outc++) {
            int addr2 = get_index(0, 0, outc, width_image_C5_CNN, height_image_C5_CNN, num_maj
            const double* delta = &delta_neuron_C5[0] + addr2;

            for (int y = 0; y < height_image_C5_CNN; y++) {
                for (int x = 0; x < width_image_C5_CNN; x++) {
                    delta_bias_C5[outc] += delta[y * width_image_C5_CNN + x];
                }
            }
        }

        return true;
    }

    bool CNN::Backward_C3()
    {
        init_variable(delta_neuron_C3, 0.0, num_neuron_C3_CNN);
        init_variable(delta_weight_S4, 0.0, len_weight_S4_CNN);
        init_variable(delta_bias_S4, 0.0, len_bias_S4_CNN);

        double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);

        assert(in2wo_C3.size() == num_neuron_C3_CNN);
        assert(weight2io_C3.size() == len_weight_S4_CNN);
        assert(bias2out_C3.size() == len_bias_S4_CNN);

        for (int i = 0; i < num_neuron_C3_CNN; i++) {
            const wo_connections& connections = in2wo_C3[:
            double delta = 0.0;

            for (int j = 0; j < connections.size(); j++) {
                delta += weight_S4[connections[j].first] * delta_neuron_S4[connections[j].secc
            }

            delta_neuron_C3[i] = delta * scale_factor * activation_function_tanh_derivative(ne
        }

        for (int i = 0; i < len_weight_S4_CNN; i++) {
            const io_connections& connections = weight2io_C3[i];
            double diff = 0;

```

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```
        for (int j = 0; j < connections.size(); j++) {
            diff += neuron_C3[connections[j].first] * delta_neuron_S4[connections[j].secon
        }

        delta_weight_S4[i] += diff * scale_factor;
    }

    for (int i = 0; i < len_bias_S4_CNN; i++) {
        const std::vector<int>& outs = bias2out_C3[i];
        double diff = 0;

        for (int o = 0; o < outs.size(); o++) {
            diff += delta_neuron_S4[outs[o]];
        }

        delta_bias_S4[i] += diff;
    }

    return true;
}

bool CNN::Backward_S2()
{
    init_variable(delta_neuron_S2, 0.0, num_neuron_S2_CNN);
    init_variable(delta_weight_C3, 0.0, len_weight_C3_CNN);
    init_variable(delta_bias_C3, 0.0, len_bias_C3_CNN);

    // propagate delta to previous layer
    for (int inc = 0; inc < num_map_S2_CNN; inc++) {
        for (int outc = 0; outc < num_map_C3_CNN; outc++) {
            if (!tbl[inc][outc]) continue;

            int addr1 = get_index(0, 0, num_map_S2_CNN * outc + inc, width_kernel_conv_CNN
            int addr2 = get_index(0, 0, outc, width_image_C3_CNN, height_image_C3_CNN, nur
            int addr3 = get_index(0, 0, inc, width_image_S2_CNN, height_image_S2_CNN, num_

            const double *pw = &weight_C3[0] + addr1;
            const double *pdelta_src = &delta_neuron_C3[0] + addr2;;
            double* pdelta_dst = &delta_neuron_S2[0] + addr3;

            for (int y = 0; y < height_image_C3_CNN; y++) {
                for (int x = 0; x < width_image_C3_CNN; x++) {
                    const double* ppw = pw;
                    const double ppdelta_src = pdelta_src[y * width_image_C3_CNN + x];
                    double* ppdelta_dst = pdelta_dst + y * width_image_S2_CNN + x;

                    for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                        for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                            ppdelta_dst[wy * width_image_S2_CNN + wx] += *ppw++ * ppdelta_
                        }
                    }
                }
            }
        }
    }

    for (int i = 0; i < num_neuron_S2_CNN; i++) {
        delta_neuron_S2[i] *= activation_function_tanh_derivative(neuron_S2[i]);
    }

    // accumulate dw
    for (int inc = 0; inc < num_map_S2_CNN; inc++) {
        for (int outc = 0; outc < num_map_C3_CNN; outc++) {
            if (!tbl[inc][outc]) continue;

            for (int wy = 0; wy < height_kernel_conv_(
                for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                    int addr1 = get_index(wx, wy, inc, width_image_S2_CNN, height_image_S2
                    int addr2 = get_index(0, 0, outc, width_image_C3_CNN, height_image_C3_
                    int addr3 = get_index(wx, wy, num_map_S2_CNN * outc + inc, width_kerne

                    double dst = 0.0;
                    const double* prevo = &neuron_S2[0] + addr1;
                    const double* delta = &delta_neuron_C3[0] + addr2;

                    for (int y = 0; y < height_image_C3_CNN; y++) {
                        dst += dot_product(prevo + y * width_image_S2_CNN, delta + y * wid
                    }

```

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```
                    delta_weight_C3[addr3] += dst;
                }
            }
        }
    }

    // accumulate db
    for (int outc = 0; outc < len_bias_C3_CNN; outc++) {
        int addr1 = get_index(0, 0, outc, width_image_C3_CNN, height_image_C3_CNN, num_map
        const double* delta = &delta_neuron_C3[0] + addr1;

        for (int y = 0; y < height_image_C3_CNN; y++) {
            for (int x = 0; x < width_image_C3_CNN; x++) {
                delta_bias_C3[outc] += delta[y * width_image_C3_CNN + x];
            }
        }
    }

    return true;
}

bool CNN::Backward_C1()
{
    init_variable(delta_neuron_C1, 0.0, num_neuron_C1_CNN);
    init_variable(delta_weight_S2, 0.0, len_weight_S2_CNN);
    init_variable(delta_bias_S2, 0.0, len_bias_S2_CNN);

    double scale_factor = 1.0 / (width_kernel_pooling_CNN * height_kernel_pooling_CNN);

    assert(in2wo_C1.size() == num_neuron_C1_CNN);
    assert(weight2io_C1.size() == len_weight_S2_CNN);
    assert(bias2out_C1.size() == len_bias_S2_CNN);

    for (int i = 0; i < num_neuron_C1_CNN; i++) {
        const wo_connections& connections = in2wo_C1[i];
        double delta = 0.0;

        for (int j = 0; j < connections.size(); j++) {
            delta += weight_S2[connections[j].first] * delta_neuron_S2[connections[j].seco
        }

        delta_neuron_C1[i] = delta * scale_factor * activation_function_tanh_derivative(ne
    }

    for (int i = 0; i < len_weight_S2_CNN; i++) {
        const io_connections& connections = weight2io_C1[i];
        double diff = 0.0;

        for (int j = 0; j < connections.size(); j++) {
            diff += neuron_C1[connections[j].first] * delta_neuron_S2[connections[j].seco
        }

        delta_weight_S2[i] += diff * scale_factor;
    }

    for (int i = 0; i < len_bias_S2_CNN; i++) {
        const std::vector<int>& outs = bias2out_C1[i];
        double diff = 0;

        for (int o = 0; o < outs.size(); o++) {
            diff += delta_neuron_S2[outs[o]];
        }

        delta_bias_S2[i] += diff;
    }

    return true;
}

bool CNN::Backward_input()
{
    init_variable(delta_neuron_input, 0.0, num_neuron_input_CNN);
    init_variable(delta_weight_C1, 0.0, len_weight_C1_CNN);
    init_variable(delta_bias_C1, 0.0, len_bias_C1_CNN);

    // propagate delta to previous layer
    for (int inc = 0; inc < num_map_input_CNN; inc++) {
        for (int outc = 0; outc < num_map_C1_CNN; outc++) {
            int addr1 = get_index(0, 0, num_map_input_CNN * outc + inc, width_kernel_conv_
```

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```
                int addr2 = get_index(0, 0, outc, width_image_C1_CNN, height_image_C1_CNN, nur
                int addr3 = get_index(0, 0, inc, width_image_input_CNN, height_image_input_CNI

                const double* pw = &weight_C1[0] + addr1;
                const double* pdelta_src = &delta_neuron_C1[0] + addr2;
                double* pdelta_dst = &delta_neuron_input[0] + addr3;

                for (int y = 0; y < height_image_C1_CNN; y++) {
                    for (int x = 0; x < width_image_C1_CNN; x++) {
                        const double* ppw = pw;
                        const double ppdelta_src = pdelta_src[y * width_image_C1_CNN + x];
                        double* ppdelta_dst = pdelta_dst + y * width_image_input_CNN + x;

                        for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                            for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                                ppdelta_dst[wy * width_image_input_CNN + wx] += *ppw++ * ppde]
                            }
                        }
                    }
                }
            }
        }

        for (int i = 0; i < num_neuron_input_CNN; i++) {
            delta_neuron_input[i] *= activation_function_identity_derivative(data_single_image
        }

        // accumulate dw
        for (int inc = 0; inc < num_map_input_CNN; inc++) {
            for (int outc = 0; outc < num_map_C1_CNN; outc++) {
                for (int wy = 0; wy < height_kernel_conv_CNN; wy++) {
                    for (int wx = 0; wx < width_kernel_conv_CNN; wx++) {
                        int addr1 = get_index(wx, wy, inc, width_image_input_CNN, height_image
                        int addr2 = get_index(0, 0, outc, width_image_C1_CNN, height_image_C1_
                        int addr3 = get_index(wx, wy, num_map_input_CNN * outc + inc, width_ke

                        double dst = 0.0;
                        const double* prevo = data_single_image + addr1;//&neuron_input[0]
                        const double* delta = &delta_neuron_C1[0] + addr2;

                        for (int y = 0; y < height_image_C1_CNN; y++) {
                            dst += dot_product(prevo + y * width_image_input_CNN, delta + y *
                        }

                        delta_weight_C1[addr3] += dst;
                    }
                }
            }
        }

        // accumulate db
        for (int outc = 0; outc < len_bias_C1_CNN; outc++) {
            int addr1 = get_index(0, 0, outc, width_image_C1_CNN, height_image_C1_CNN, num_ma
            const double* delta = &delta_neuron_C1[0] + addr1;

            for (int y = 0; y < height_image_C1_CNN; y++) {
                for (int x = 0; x < width_image_C1_CNN; x++) {
                    delta_bias_C1[outc] += delta[y * width_image_C1_CNN + x];
                }
            }
        }

        return true;
    }

    void CNN::update_weights_bias(const double* delta, do
    {
        for (int i = 0; i < len; i++) {
            e_weight[i] += delta[i] * delta[i];
            weight[i] -= learning_rate_CNN * delta[i] / (std::sqrt(e_weight[i]) + eps_CNN);
        }
    }

    bool CNN::UpdateWeights()
    {
        update_weights_bias(delta_weight_C1, E_weight_C1, weight_C1, len_weight_C1_CNN);
        update_weights_bias(delta_bias_C1, E_bias_C1, bias_C1, len_bias_C1_CNN);

        update_weights_bias(delta_weight_S2, E_weight_S2, weight_S2, len_weight_S2_CNN);
```

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```
    update_weights_bias(delta_bias_S2, E_bias_S2, bias_S2, len_bias_S2_CNN);

    update_weights_bias(delta_weight_C3, E_weight_C3, weight_C3, len_weight_C3_CNN);
    update_weights_bias(delta_bias_C3, E_bias_C3, bias_C3, len_bias_C3_CNN);

    update_weights_bias(delta_weight_S4, E_weight_S4, weight_S4, len_weight_S4_CNN);
    update_weights_bias(delta_bias_S4, E_bias_S4, bias_S4, len_bias_S4_CNN);

    update_weights_bias(delta_weight_C5, E_weight_C5, weight_C5, len_weight_C5_CNN);
    update_weights_bias(delta_bias_C5, E_bias_C5, bias_C5, len_bias_C5_CNN);

    update_weights_bias(delta_weight_output, E_weight_output, weight_output, len_weight_ou
    update_weights_bias(delta_bias_output, E_bias_output, bias_output, len_bias_output_CNN

    return true;
}

int CNN::predict(const unsigned char* data, int width, int height)
{
    assert(data && width == width_image_input_CNN && height == height_image_input_CNN);

    const double scale_min = -1;
    const double scale_max = 1;

    double tmp[width_image_input_CNN * height_image_input_CNN];
    for (int y = 0; y < height; y++) {
        for (int x = 0; x < width; x++) {
            tmp[y * width + x] = (data[y * width + x] / 255.0) * (scale_max - scale_min) -
        }
    }

    data_single_image = &tmp[0];

    Forward_C1();
    Forward_S2();
    Forward_C3();
    Forward_S4();
    Forward_C5();
    Forward_output();

    int pos = -1;
    double max_value = -9999.0;

    for (int i = 0; i < num_neuron_output_CNN; i++) {
        if (neuron_output[i] > max_value) {
            max_value = neuron_output[i];
            pos = i;
        }
    }

    return pos;
}

bool CNN::readModelFile(const char* name)
{
    FILE* fp = fopen(name, "rb");
    if (fp == NULL) {
        return false;
    }

    int width_image_input =0;
    int height_image_input = 0;
    int width_image_C1 = 0;
    int height_image_C1 = 0;
    int width_image_S2 = 0;
    int height_image_S2 = 0;
    int width_image_C3 = 0;
    int height_image_C3 = 0;
    int width_image_S4 = 0;
    int height_image_S4 = 0;
    int width_image_C5 = 0;
    int height_image_C5 = 0;
    int width_image_output = 0;
    int height_image_output = 0;

    int width_kernel_conv = 0;
    int height_kernel_conv = 0;
    int width_kernel_pooling = 0;
    int height_kernel_pooling = 0;
```

关闭

```

    int num_map_input = 0;
    int num_map_C1 = 0;
    int num_map_S2 = 0;
    int num_map_C3 = 0;
    int num_map_S4 = 0;
    int num_map_C5 = 0;
    int num_map_output = 0;

    int len_weight_C1 = 0;
    int len_bias_C1 = 0;
    int len_weight_S2 = 0;
    int len_bias_S2 = 0;
    int len_weight_C3 = 0;
    int len_bias_C3 = 0;
    int len_weight_S4 = 0;
    int len_bias_S4 = 0;
    int len_weight_C5 = 0;
    int len_bias_C5 = 0;
    int len_weight_output = 0;
    int len_bias_output = 0;

    int num_neuron_input = 0;
    int num_neuron_C1 = 0;
    int num_neuron_S2 = 0;
    int num_neuron_C3 = 0;
    int num_neuron_S4 = 0;
    int num_neuron_C5 = 0;
    int num_neuron_output = 0;

    fread(&width_image_input, sizeof(int), 1, fp);
    fread(&height_image_input, sizeof(int), 1, fp);
    fread(&width_image_C1, sizeof(int), 1, fp);
    fread(&height_image_C1, sizeof(int), 1, fp);
    fread(&width_image_S2, sizeof(int), 1, fp);
    fread(&height_image_S2, sizeof(int), 1, fp);
    fread(&width_image_C3, sizeof(int), 1, fp);
    fread(&height_image_C3, sizeof(int), 1, fp);
    fread(&width_image_S4, sizeof(int), 1, fp);
    fread(&height_image_S4, sizeof(int), 1, fp);
    fread(&width_image_C5, sizeof(int), 1, fp);
    fread(&height_image_C5, sizeof(int), 1, fp);
    fread(&width_image_output, sizeof(int), 1, fp);
    fread(&height_image_output, sizeof(int), 1, fp);

    fread(&width_kernel_conv, sizeof(int), 1, fp);
    fread(&height_kernel_conv, sizeof(int), 1, fp);
    fread(&width_kernel_pooling, sizeof(int), 1, fp);
    fread(&height_kernel_pooling, sizeof(int), 1, fp);

    fread(&num_map_input, sizeof(int), 1, fp);
    fread(&num_map_C1, sizeof(int), 1, fp);
    fread(&num_map_S2, sizeof(int), 1, fp);
    fread(&num_map_C3, sizeof(int), 1, fp);
    fread(&num_map_S4, sizeof(int), 1, fp);
    fread(&num_map_C5, sizeof(int), 1, fp);
    fread(&num_map_output, sizeof(int), 1, fp);

    fread(&len_weight_C1, sizeof(int), 1, fp);
    fread(&len_bias_C1, sizeof(int), 1, fp);
    fread(&len_weight_S2, sizeof(int), 1, fp);
    fread(&len_bias_S2, sizeof(int), 1, fp);
    fread(&len_weight_C3, sizeof(int), 1, fp);
    fread(&len_bias_C3, sizeof(int), 1, fp);
    fread(&len_weight_S4, sizeof(int), 1, fp);
    fread(&len_bias_S4, sizeof(int), 1, fp);
    fread(&len_weight_C5, sizeof(int), 1, fp);
    fread(&len_bias_C5, sizeof(int), 1, fp);
    fread(&len_weight_output, sizeof(int), 1, fp);
    fread(&len_bias_output, sizeof(int), 1, fp);

    fread(&num_neuron_input, sizeof(int), 1, fp);
    fread(&num_neuron_C1, sizeof(int), 1, fp);
    fread(&num_neuron_S2, sizeof(int), 1, fp);
    fread(&num_neuron_C3, sizeof(int), 1, fp);
    fread(&num_neuron_S4, sizeof(int), 1, fp);
    fread(&num_neuron_C5, sizeof(int), 1, fp);
    fread(&num_neuron_output, sizeof(int), 1, fp);

```

关闭

```
    fread(weight_C1, sizeof(weight_C1), 1, fp);
    fread(bias_C1, sizeof(bias_C1), 1, fp);
    fread(weight_S2, sizeof(weight_S2), 1, fp);
    fread(bias_S2, sizeof(bias_S2), 1, fp);
    fread(weight_C3, sizeof(weight_C3), 1, fp);
    fread(bias_C3, sizeof(bias_C3), 1, fp);
    fread(weight_S4, sizeof(weight_S4), 1, fp);
    fread(bias_S4, sizeof(bias_S4), 1, fp);
    fread(weight_C5, sizeof(weight_C5), 1, fp);
    fread(bias_C5, sizeof(bias_C5), 1, fp);
    fread(weight_output, sizeof(weight_output), 1, fp);
    fread(bias_output, sizeof(bias_output), 1, fp);

    fflush(fp);
    fclose(fp);

    out2wi_S2.clear();
    out2bias_S2.clear();
    out2wi_S4.clear();
    out2bias_S4.clear();

    calc_out2wi(width_image_C1_CNN, height_image_C1_CNN, width_image_S2_CNN, height_image_
    calc_out2bias(width_image_S2_CNN, height_image_S2_CNN, num_map_S2_CNN, out2bias_S2);
    calc_out2wi(width_image_C3_CNN, height_image_C3_CNN, width_image_S4_CNN,
    calc_out2bias(width_image_S4_CNN, height_image_S4_CNN, num_map_S4_CNN, out2bias_S4);

    return true;
}

bool CNN::saveModelFile(const char* name)
{
    FILE* fp = fopen(name, "wb");
    if (fp == NULL) {
        return false;
    }

    int width_image_input = width_image_input_CNN;
    int height_image_input = height_image_input_CNN;
    int width_image_C1 = width_image_C1_CNN;
    int height_image_C1 = height_image_C1_CNN;
    int width_image_S2 = width_image_S2_CNN;
    int height_image_S2 = height_image_S2_CNN;
    int width_image_C3 = width_image_C3_CNN;
    int height_image_C3 = height_image_C3_CNN;
    int width_image_S4 = width_image_S4_CNN;
    int height_image_S4 = height_image_S4_CNN;
    int width_image_C5 = width_image_C5_CNN;
    int height_image_C5 = height_image_C5_CNN;
    int width_image_output = width_image_output_CNN;
    int height_image_output = height_image_output_CNN;

    int width_kernel_conv = width_kernel_conv_CNN;
    int height_kernel_conv = height_kernel_conv_CNN;
    int width_kernel_pooling = width_kernel_pooling_CNN;
    int height_kernel_pooling = height_kernel_pooling_CNN;

    int num_map_input = num_map_input_CNN;
    int num_map_C1 = num_map_C1_CNN;
    int num_map_S2 = num_map_S2_CNN;
    int num_map_C3 = num_map_C3_CNN;
    int num_map_S4 = num_map_S4_CNN;
    int num_map_C5 = num_map_C5_CNN;
    int num_map_output = num_map_output_CNN;

    int len_weight_C1 = len_weight_C1_CNN;
    int len_bias_C1 = len_bias_C1_CNN;
    int len_weight_S2 = len_weight_S2_CNN;
    int len_bias_S2 = len_bias_S2_CNN;
    int len_weight_C3 = len_weight_C3_CNN;
    int len_bias_C3 = len_bias_C3_CNN;
    int len_weight_S4 = len_weight_S4_CNN;
    int len_bias_S4 = len_bias_S4_CNN;
    int len_weight_C5 = len_weight_C5_CNN;
    int len_bias_C5 = len_bias_C5_CNN;
    int len_weight_output = len_weight_output_CNN;
    int len_bias_output = len_bias_output_CNN;

    int num_neuron_input = num_neuron_input_CNN;
    int num_neuron_C1 = num_neuron_C1_CNN;
```

关闭

```
    int num_neuron_S2 = num_neuron_S2_CNN;
    int num_neuron_C3 = num_neuron_C3_CNN;
    int num_neuron_S4 = num_neuron_S4_CNN;
    int num_neuron_C5 = num_neuron_C5_CNN;
    int num_neuron_output = num_neuron_output_CNN;

    fwrite(&width_image_input, sizeof(int), 1, fp);
    fwrite(&height_image_input, sizeof(int), 1, fp);
    fwrite(&width_image_C1, sizeof(int), 1, fp);
    fwrite(&height_image_C1, sizeof(int), 1, fp);
    fwrite(&width_image_S2, sizeof(int), 1, fp);
    fwrite(&height_image_S2, sizeof(int), 1, fp);
    fwrite(&width_image_C3, sizeof(int), 1, fp);
    fwrite(&height_image_C3, sizeof(int), 1, fp);
    fwrite(&width_image_S4, sizeof(int), 1, fp);
    fwrite(&height_image_S4, sizeof(int), 1, fp);
    fwrite(&width_image_C5, sizeof(int), 1, fp);
    fwrite(&height_image_C5, sizeof(int), 1, fp);
    fwrite(&width_image_output, sizeof(int), 1, fp);
    fwrite(&height_image_output, sizeof(int), 1, fp);

    fwrite(&width_kernel_conv, sizeof(int), 1, fp);
    fwrite(&height_kernel_conv, sizeof(int), 1, fp);
    fwrite(&width_kernel_pooling, sizeof(int), 1, fp);
    fwrite(&height_kernel_pooling, sizeof(int), 1, fp);

    fwrite(&num_map_input, sizeof(int), 1, fp);
    fwrite(&num_map_C1, sizeof(int), 1, fp);
    fwrite(&num_map_S2, sizeof(int), 1, fp);
    fwrite(&num_map_C3, sizeof(int), 1, fp);
    fwrite(&num_map_S4, sizeof(int), 1, fp);
    fwrite(&num_map_C5, sizeof(int), 1, fp);
    fwrite(&num_map_output, sizeof(int), 1, fp);

    fwrite(&len_weight_C1, sizeof(int), 1, fp);
    fwrite(&len_bias_C1, sizeof(int), 1, fp);
    fwrite(&len_weight_S2, sizeof(int), 1, fp);
    fwrite(&len_bias_S2, sizeof(int), 1, fp);
    fwrite(&len_weight_C3, sizeof(int), 1, fp);
    fwrite(&len_bias_C3, sizeof(int), 1, fp);
    fwrite(&len_weight_S4, sizeof(int), 1, fp);
    fwrite(&len_bias_S4, sizeof(int), 1, fp);
    fwrite(&len_weight_C5, sizeof(int), 1, fp);
    fwrite(&len_bias_C5, sizeof(int), 1, fp);
    fwrite(&len_weight_output, sizeof(int), 1, fp);
    fwrite(&len_bias_output, sizeof(int), 1, fp);

    fwrite(&num_neuron_input, sizeof(int), 1, fp);
    fwrite(&num_neuron_C1, sizeof(int), 1, fp);
    fwrite(&num_neuron_S2, sizeof(int), 1, fp);
    fwrite(&num_neuron_C3, sizeof(int), 1, fp);
    fwrite(&num_neuron_S4, sizeof(int), 1, fp);
    fwrite(&num_neuron_C5, sizeof(int), 1, fp);
    fwrite(&num_neuron_output, sizeof(int), 1, fp);

    fwrite(weight_C1, sizeof(weight_C1), 1, fp);
    fwrite(bias_C1, sizeof(bias_C1), 1, fp);
    fwrite(weight_S2, sizeof(weight_S2), 1, fp);
    fwrite(bias_S2, sizeof(bias_S2), 1, fp);
    fwrite(weight_C3, sizeof(weight_C3), 1, fp);
    fwrite(bias_C3, sizeof(bias_C3), 1, fp);
    fwrite(weight_S4, sizeof(weight_S4), 1, fp);
    fwrite(bias_S4, sizeof(bias_S4), 1, fp);
    fwrite(weight_C5, sizeof(weight_C5), 1, fp);
    fwrite(bias_C5, sizeof(bias_C5), 1, fp);
    fwrite(weight_output, sizeof(weight_output), 1, f|
    fwrite(bias_output, sizeof(bias_output), 1, fp);

    fflush(fp);
    fclose(fp);

    return true;
}

double CNN::test()
{
    int count_accuracy = 0;

    for (int num = 0; num < num_patterns_test_CNN; num++) {
```

关闭

```
            data_single_image = data_input_test + num * num_neuron_input_CNN;
            data_single_label = data_output_test + num * num_neuron_output_CNN;

            Forward_C1();
            Forward_S2();
            Forward_C3();
            Forward_S4();
            Forward_C5();
            Forward_output();

            int pos_t = -1;
            int pos_y = -2;
            double max_value_t = -9999.0;
            double max_value_y = -9999.0;

            for (int i = 0; i < num_neuron_output_CNN; i++) {
                if (neuron_output[i] > max_value_y) {
                    max_value_y = neuron_output[i];
                    pos_y = i;
                }

                if (data_single_label[i] > max_value_t) {
                    max_value_t = data_single_label[i];
                    pos_t = i;
                }
            }

            if (pos_y == pos_t) {
                ++count_accuracy;
            }

            Sleep(1);
        }

        return (count_accuracy * 1.0 / num_patterns_test_CNN);
    }

}
```

测试代码如下：

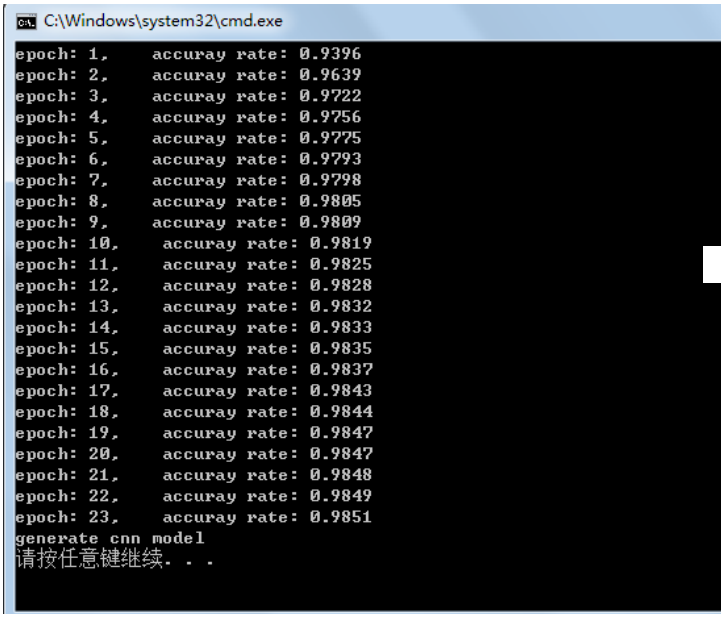
[cpp]

```
int test_CNN_train()
{
    ANN::CNN cnn1;
    cnn1.init();
    cnn1.train();

    return 0;
}

int test_CNN_predict()
{
    ANN::CNN cnn2;
    bool flag = cnn2.readModelFile("E:/GitCode/NN_Test/data/cnn.model");
    if (!flag) {
        std::cout << "read cnn model error" << std::endl;
        return -1;
    }

    int width{ 32 }, height{ 32 };
    std::vector<int> target{ 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 };
    std::string image_path{ "E:/GitCode/NN_Test/data/images/" };

    for (auto i : target) {
        std::string str = std::to_string(i);
        str += ".png";
        str = image_path + str;

        cv::Mat src = cv::imread(str, 0);
        if (src.data == nullptr) {
            fprintf(stderr, "read image error: %s\n", str.c_str());
            return -1;
        }

        cv::Mat tmp(src.rows, src.cols, CV_8UC1, cv::Scalar::all(255));
        cv::subtract(tmp, src, tmp);

```

关闭

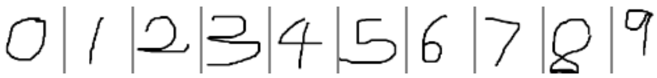
```
            cv::resize(tmp, tmp, cv::Size(width, height));

            auto ret = cnn2.predict(tmp.data, width, height);

            fprintf(stdout, "the actual digit is: %d, correct digit is: %d\n", ret, i);
        }

        return 0;
}
```

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

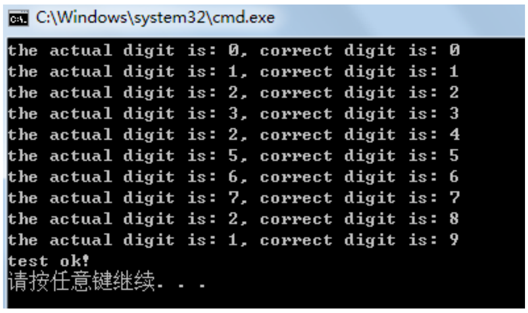


```
C:\Windows\system32\cmd.exe
epoch: 1,    accuray rate: 0.9396
epoch: 2,    accuray rate: 0.9639
epoch: 3,    accuray rate: 0.9722
epoch: 4,    accuray rate: 0.9756
epoch: 5,    accuray rate: 0.9775
epoch: 6,    accuray rate: 0.9793
epoch: 7,    accuray rate: 0.9798
epoch: 8,    accuray rate: 0.9805
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：



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

顶 3

踩 0

下一篇 [illegible]

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查看评论

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>J

关闭

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}
```

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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

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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