上海理工大学光电信息与计算机工程学院

《信息安全》实验报告

专　　业　计算机科学与技术

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成　　绩：

教师签字：

报告格式要求

1、 正文字体中文为宋体，五号，行距为固定值 18 磅，西文为 Times New Rome, 五号，行距为固定值 18 磅。

2、 章节标题为加粗宋体，小四号，段前段后各 0.5 行，行距为固定值 18 磅。

3、 打印时需双面打印。

实验一　AES 密码

一、 实验目的

实现 AES 的加密(Encryption)和解密(Decryption)

二、AES 基础

(1)AES 的所有操作都是针对于一个二维数组 state

一个 state 数组由 4 行 Nb 列组成

(2)AES 基于下列 5 个基本操作

1.异或(Exclusive Disjunction/XOR):当两个 digit 不同时输出为真

2.SubByte/InverseSubByte : 一个 byte 被另一个 byte 替代

加密时根据 S_Box 查表，解密时根据 Si_Box 查表

(每个 byte 都可以表示为两个十六进制的 digit，

其中第一个代表 S_Box 的行，第二个代表 S_Box 的列)

3.Shift Rows(Rotation)/Inverse Shift Rows:

重排 bytes，以不同的偏移量循环左移后三行

Row 0 不移动

Row 1 移动一个 byte

Row 2 移动两个 byte

Row3 移动三个 byte

解密时循环右移相对应的 byte

4.MixColumns/InverseMixColumns:

二维数组 state 的每一列上的每一个 byte 映射为一个新的值

a.将 state 的每一列左乘一个 4 * Nb 的矩阵,所得结果逐个异或而产生一个 byte

b. a 的乘法操作可以用两个查找表 L_Table 和 E_Table 来实现

step1 :一个 byte，其表示为两个十六进制的 digit，

而第一个 digit 用作 L_Table 的行数，第二个 digit 用作 L_Table 的列数

step2 : 将两个从 L_Table 获得的值相加，得到一个新的 byte

step3： 在 E_Table 查看这个相加的结果(按 digit 来查)

Note:任何数与 1 相乘的结果都是它本身

5.AddRoundKey:state 数组的每个 byte 都和 round key 的每个 byte 相异或(XOR)

(3) 对于 128 比特的 key,执行 10 rounds(轮)

对于 192 比特的 key,执行 12 rounds(轮)

对于 256 比特的 key,执行 14 rounds(轮)

(4) AES 的框架

从第一轮到倒数第二轮，均执行:

a.SubBytes/InverseSubBytes

b.ShiftRows/InverseShiftRows

c.MixColumns/InverseMixColumns

d.AddRoundKey

最后一轮 不执行 MixColumns/InverseMixColumns

(6) Key Expansion

将一个长度为 Nk 的输入 key 生成一个长度为 Nb * (Nr + 1)的线性 key

Nb : state 数组的列数

Nr: 轮的个数

Nk: key 的长度

记 W[i]为 expanded key 的第 i 个 word

三、程序的数据结构设计和算法描述

(1) Key Expansion

```
Begin
    word temp;
    for i <- 0 to (Nk - 1)
        w[i] <- ((unsigned char) key [ 4 * i ] << 24)
             | ((unsigned char) key [ 4 * i + 1 ] << 16)
             | ((unsigned char) key [ 4 * i + 2 ] << 8)
             | ((unsigned char) key [ 4 * i + 3 ] );
    end for

    for i <- (Nk - 1) to Nb * Nr
        temp = w[i - 1];
        if (i mod Nk == 0)
            temp = SubWord ( RotWord (temp))
             XOR (Rcon [ i / Nk ] << 24) ;
        else if ( Nk > 6 and ( i mod Nk ) == 4 )
            temp = SubWord(temp);
        end if
        w[i] = w[i - Nk] XOR temp;
    end for
End
```

(2) Encryption

```
Begin
    state = plaintext
    1.KeyExpansion
    2.AddRoundkey(state,Expandedkey[0])
```

```
        3.for r <- 1 to (Nr - 1)
            a. SubBytes (state , S-Box)
            b. ShiftRows (state)
            c. MixColumns(state)
            d. AddRoundKey(state,ExpandedKey[r])
        4. SubBytes (state , S-Box)
           ShiftRows (state)
           AddRoundKey(state,ExpandedKey[Nr])
        Out = cipherText
End
```

(3) Decryption

```
    Begin
        State = cipherText
        1.Key Expansion
        2.AddRoundKey(state,ExpandedKey[0])
        3.for r <- (Nr - 1) to 1
            a. InverseShiftRows(state)
            b. InverseSubBytes(state,S-Box)
            c. AddRoundKey(State,ExpandedKey[r])
        4. InverseSubBytes(state,S-Box)
           InverseShiftRows(state)
           AddRoundKey(state,ExpandedKey[Nr])
        Out = plaintext
    End
```

四、程序代码

```
//AES.h
#define word unsigned int
#define byte unsigned char

#include<iostream>
#include<vector>
#include<fstream>
#include<string>
#include<sstream>
using namespace std;

class AES
{
    vector<word> ExpandedKey;
    int Nk; //width of key block
    int Nr; //number of round
    int Nb; //block size
    static const byte S_Box[256];
    static const byte Si_Box[256];
    static const byte Rcon[30];
    static const byte ColMixMatrix[4][4];
    static const byte InvColMixMatrix[4][4];
    static const byte AlogTable[256];
    static const byte LogTable[256];
    string cipherText;
    byte state[4][4];

    byte Mul(byte a,byte b);
    void MixColumns();
    void ShiftRows();
    void SubBytes();
    byte SubByte(byte oneByte);
    word SubWord(word val);
    word RotWord(word val);

    void InvMixColumns();
    void InvShiftRows();
    byte InvSubByte(byte oneByte);
    void InvSubBytes();

    void AddRoundKey(int roundNo);
    void KeyExpansion(string key);
```

```
   public:
    enum KeySize {AES128 = 128,AES192 = 192,AES256 = 256};

    AES(string key,int bitSize);
    ~AES();
    void Encrypt(string plainText);
    string GetCipherText();
    void Decrypt(string cipherText);
    string ToString();
};

//AES.cpp
#include "AES.h"

byte AES::Mul(byte a,byte b){
    if(a && b){
        return AlogTable[((unsigned char)LogTable[a] + (unsigned char)LogTable[b]) % 255];
    }
    return 0;
}

//Encrypt
void AES::MixColumns(){
    byte temp[4];
    for(int c = 0;c < Nb;c++){
        //4 rows and Nb columns to store temp mix col value
        for(int r = 0;r < 4;r++){
            temp[r] = Mul(ColMixMatrix[r][0],(state[0][c]))
                    ^Mul(ColMixMatrix[r][1],(state[1][c]))
                    ^Mul(ColMixMatrix[r][2],(state[2][c]))
                    ^Mul(ColMixMatrix[r][3],(state[3][c]));

        }
        state[0][c] = temp[0];
        state[1][c] = temp[1];
        state[2][c] = temp[2];
        state[3][c] = temp[3];
    }
}

void AES::ShiftRows(){
    //row    always 4
    for(int r = 0;r < 4;r++){
```

```
		byte temp[4];
		for(int c = 0;c < Nb;c++){
			temp[c] = state[r][(r + c) % Nb];
		}
		state[r][0] = temp[0];
		state[r][1] = temp[1];
		state[r][2] = temp[2];
		state[r][3] = temp[3];
	}

}

byte AES::SubByte(byte oneByte){
	//one byte represent in hex (xy)
	//x is row index AND y is column index
	return S_Box[oneByte];
}

void AES::SubBytes(){
	for(int i = 0;i < 4;i++){
		for(int j = 0;j < Nb;j++){
			state[i][j] = SubByte(state[i][j]);
		}
	}
}

void AES::AddRoundKey(int roundNo){
	for(int col = 0;col < Nb;col++){
		word roundKeyVal = ExpandedKey[(roundNo * Nb) + col];
		for(int row = 3;row >= 0;row--){
			state[row][col] ^= (roundKeyVal & 0xFF);
			roundKeyVal = roundKeyVal >> 8;
		}
	}
}

//destructor
AES::~AES(){}

//constructor
AES::AES(string key,int bitSize){
	Nr = bitSize / 32 + 6;
	Nk = bitSize / 32;
	Nb = 4; //always 4
```

```
    ExpandedKey.resize(Nk * (Nr + 1));

    KeyExpansion(key);
}

word AES::SubWord(word val){
    byte oneByte;
    word res = 0;

    for(int i = 0;i < 4;i++){
        res = res << 8;
        oneByte = (val >> 24) & 0xFF;
        res = res | SubByte(oneByte);
        val = val << 8;
    }

    return res;
}

word AES::RotWord(word val){
    word res = val << 8;
    res = res | (val >> 24);
    return res;
}

void AES::KeyExpansion(string key){
    word temp;

    for(int i = 0;i < Nk;i++){
        ExpandedKey[i] = ((unsigned char) key[4 * i] << 24) |
                 ((unsigned char) key[4 * i + 1] << 16) |
                 ((unsigned char) key[4 * i + 2] << 8) |
                 ((unsigned char) key[4 * i + 3]);
    }

    for(int i = Nk - 1;i < Nb * Nr + 1;i++){
        temp = ExpandedKey[i - 1];
        if(i % Nk == 0){
            temp = (SubWord(RotWord(temp)))
                  ^(Rcon[i / Nk] << 24);
        }else if(Nk > 6 && (i % Nk == 4)){
            temp = SubWord(temp);
        }
```

```
            ExpandedKey[i] = ExpandedKey[i - Nk] ^ temp;
        }
}

void AES::Encrypt(string plainText){
        if((plainText.length() % (4 * Nb)) != 0)
            plainText.append((4 * Nb) - (plainText.length() % (4 * Nb)),'\0');
        int count = 0;
        while(count < (plainText.length())){
            //copy one block into state
            for(int c = 0;c < Nb;c++){
                for(int r = 0;r < 4;r++){
                    state[r][c] = plainText[count + (c * Nb) + r];
                }
            }
            AddRoundKey(0);

            int i;
            for(i = 1;i < Nr;i++){
                SubBytes();

                ShiftRows();

                MixColumns();

                AddRoundKey(i);
            }

            //finally
            SubBytes();
            ShiftRows();
            AddRoundKey(Nr);

            cipherText = cipherText + ToString();
            count += 4 * Nb;

        }
}

string AES::GetCipherText(){
        return cipherText;
}
```

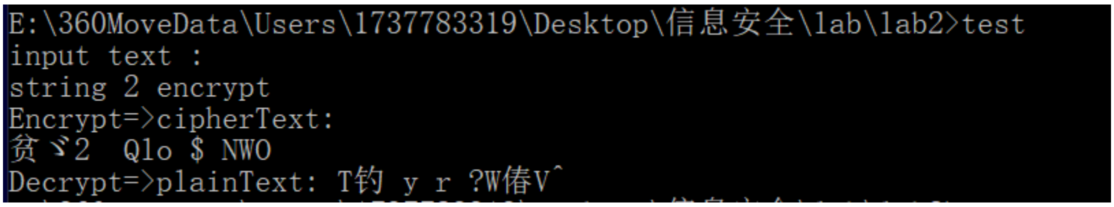
```
string AES::ToString(){
    string str;
    for(int c = 0;c < Nb;c++){
        for(int r = 0;r < Nb;r++){
            str.push_back(state[r][c]);
        }
    }
    return str;
}

//Decrypt
void AES::InvMixColumns(){
    byte temp[4];

    for(int c = 0;c < Nb;c++){
        //4 rows and Nb columns to store temp mix col value;
        for(int r = 0;r < 4;r++){
            temp[r] = Mul(InvColMixMatrix[r][0],(state[0][c]))
                    ^ Mul(InvColMixMatrix[r][1],(state[1][c]))
                    ^ Mul(InvColMixMatrix[r][2],(state[2][c]))
                    ^ Mul(InvColMixMatrix[r][3],(state[3][c]));
        }
        state[0][c] = temp[0];
        state[1][c] = temp[1];
        state[2][c] = temp[2];
        state[3][c] = temp[3];
    }
}

void AES::InvShiftRows(){
    //row is always 4
    for(int r = 0;r < 4;r++){
        byte temp[4];

        temp[0] = state[r][0];
        temp[1] = state[r][1];
        temp[2] = state[r][2];
        temp[3] = state[r][3];

        for(int c = 0;c < Nb;c++){
            state[r][(r + c) % Nb] = temp[c];
        }
    }
}
```

```
byte AES::InvSubByte(byte oneByte){
        //one byte representation in hex(xy)
        //x is row index and y is column index
        return Si_Box[oneByte];
}

void AES::InvSubBytes(){
        for(int i = 0;i < 4;i++){
                for(int j = 0;j < Nb;j++){
                        state[i][j] = InvSubByte(state[i][j]);
                }

        }
}

void AES::Decrypt(string cipherText){
        if((cipherText.length() % (4 * Nb)) != 0)
                cipherText.append((4 * Nb) - (cipherText.length() % (4 * Nb)),'\0');
        int count = 0;

        while(count < (cipherText.length())){
                //copy one block into state
                for(int c = 0;c < Nb;c++){
                        for(int r = 0;r < 4;r++){
                                state[r][c]=cipherText[count + (c * Nb) + r];
                        }
                }
                AddRoundKey(Nr);

                int i;
                for(i = Nr - 1;i > 0;i--){
                        InvShiftRows();
                        InvSubBytes();
                        AddRoundKey(i);
                        InvMixColumns();
                }

                //finally
                InvSubBytes();
                InvShiftRows();
                AddRoundKey(0);
                count += 4 * Nb;
```

```
    }
}

//data
const byte AES::Rcon[30] =
{
    0,1,2,4,8,16,32,
    64,128,27,54,108,40,
    85,77,102,47,94,68,
    99,58,105,53,106,44,
    77,125,6,17,59
};

const byte AES::ColMixMatrix[4][4] =
{
    2,3,1,1,
    1,2,3,1,
    1,1,2,3,
    3,1,1,2
};

const byte AES::InvColMixMatrix[4][4] =
{
    0x0E,0x0B,0x0D,0x09,
    0x09,0x0E,0x0B,0x0D,
    0x0D,0x09,0x0E,0x0B,
    0x0B,0x0D,0x09,0x0E
};

//L-table
const byte AES::LogTable[256] =
{
    0,0,25,1,50,2,26,198,75,199,27,104,51,238,223,3,
    100,4,224,14,52,141,129,239,76,113,8,200,248,105,28,193,
    125,194,29,181,249,185,39,106,77,228,166,114,154,201,9,120,
    101,47,138,5,33,15,225,36,18,240,130,69,53,147,218,142,
    150,143,219,189,54,208,206,148,19,92,210,241,64,70,131,56,
    102,221,253,48,191,6,139,98,179,37,226,152,34,136,145,16,
    126,110,72,195,163,182,30,66,58,107,40,84,250,133,61,186,
    43,121,10,21,155,159,94,202,78,212,172,229,243,115,167,87,
    175,88,168,80,244,234,214,116,79,174,233,213,231,230,173,232,
    44,215,117,122,235,22,11,245,89,203,95,176,156,169,81,160,
    127,12,246,111,23,196,73,236,216,67,31,45,164,118,123,183,
    204,187,62,90,251,96,177,134,59,82,161,108,170,85,41,157,
    151,178,135,144,97,190,220,252,188,149,207,205,55,63,91,209,
    83,57,132,60,65,162,109,71,20,42,158,93,86,242,211,171,
    68,17,146,217,35,32,46,137,180,124,184,38,119,153,227,165,
    103,74,237,222,197,49,254,24,13,99,140,128,192,247,112,7
};

const byte AES::S_Box[256] =
{
    99,124,119,123,14,107,111,59,48,1,103,43,2,41,85,118,
    54,126,55,125,6,89,71,16,83,44,94,81,100,92,114,64,
    73,3,109,38,54,63,9,52,52,91,27,15,113,40,49,21,
    4,57,35,61,24,106,5,102,7,18,128,30,21,39,78,117,
    9,125,44,26,27,110,90,96,82,59,42,77,41,29,47,124,
    83,47,0,19,32,4,79,91,106,53,66,57,74,76,88,49,
    48,17,86,5,67,77,51,123,69,7,2,127,80,60,97,88,
    81,93,64,113,110,99,56,11,68,74,38,33,16,1,13,46,
    51,12,19,20,95,105,68,23,60,89,126,61,100,93,25,115,
    96,127,79,36,34,42,112,120,70,18,72,20,34,94,11,37,
    32,50,58,10,73,6,36,92,62,45,84,98,111,107,28,121,
    25,56,55,109,115,43,78,87,108,86,12,22,101,122,82,8,
    70,120,37,46,28,90,76,58,24,35,116,31,75,67,117,118,
    112,62,75,102,72,3,10,14,97,53,87,71,122,63,29,98,
    31,8,104,17,105,39,114,108,101,30,121,23,50,85,40,33,
    116,95,119,13,65,26,66,104,65,103,45,15,80,84,69,22
};

const byte AES::Si_Box[256] =
{
    82,9,106,43,48,54,91,56,65,64,93,98,127,13,41,5,
    124,29,57,126,101,47,1,121,52,114,67,68,60,34,23,53,
    84,123,108,50,90,62,35,61,18,76,107,11,66,6,61,78,
    8,46,95,102,40,39,36,78,118,91,94,73,109,117,47,37,
    114,8,10,100,122,104,104,22,44,92,92,52,93,101,74,110,
    108,112,72,80,3,19,71,38,94,21,70,87,89,115,99,124,
    112,40,85,0,116,68,45,10,9,28,88,5,72,77,69,6,
    48,44,30,113,54,63,15,2,63,81,67,3,1,19,118,107,
    58,111,17,65,79,103,36,22,105,14,49,50,16,76,26,115,
    106,84,116,34,25,83,53,123,30,7,55,24,28,117,33,110,
    71,15,26,113,29,41,59,119,111,73,98,14,86,24,66,27,
    4,86,62,75,58,46,121,32,102,37,64,2,120,51,90,12,
    31,35,88,51,120,7,57,49,79,18,16,89,39,128,20,95,
    96,81,127,87,25,75,74,13,45,27,122,97,109,55,100,17,
    96,32,59,77,82,42,11,80,56,21,69,60,125,83,103,97,
    23,43,4,126,70,119,42,38,31,105,20,99,85,33,12,125
```

```
};


//E-table
const byte AES::AlogTable[256] =
{
        1,3,15,17,51,85,255,26,46,114,150,161,248,19,53,
        95,225,56,72,216,115,149,164,247,2,6,10,30,34,102,170,
        229,52,92,228,55,89,235,38,106,190,217,112,144,171,230,49,
        83,245,4,12,20,60,68,204,79,209,104,184,211,110,178,205,
        76,212,103,169,224,59,77,215,98,166,241,8,24,40,120,136,
        131,158,185,208,107,189,220,127,129,152,179,206,73,219,118,154,
        181,196,87,249,16,48,80,240,11,29,39,105,187,214,97,163,
        254,25,43,125,135,146,173,236,47,113,147,174,233,32,96,160,
        251,22,58,78,210,109,183,194,93,231,50,86,250,21,63,65,
        195,94,226,61,71,201,64,192,91,237,44,116,156,191,218,117,
        159,186,213,100,172,239,42,126,130,157,188,223,122,142,137,128,
        155,182,193,88,232,35,101,175,234,37,111,177,200,67,197,84,
        252,31,33,99,165,244,7,9,27,45,119,153,176,203,70,202,
        69,207,74,222,121,139,134,145,168,227,62,66,198,81,243,14,
        18,54,90,238,41,123,141,140,143,138,133,148,167,242,13,23,
        57,75,221,124,132,151,162,253,28,36,108,180,199,82,246,1
};


//test.cpp
#include "AES.cpp"

int main(){
        unsigned char a[] =
        {
                0x1a,0x91,0xf7,0x20,
                0x5e,0x45,0x67,0x06,
                0xa2,0x5b,0x66,0xde,
                0x5f,0x14,0x59,0x88,
                '\0'
        };

        char b[] =
        {
                0x73,0x74,0x72,0x69,
                0x6e,0x67,0x20,0x32,
                0x20,0x65,0x6e,0x63,
                0x72,0x79,0x70,0x74,
        '\0'
    };

    string key;
    string text;

    for(int i = 0;i < 16;i++){
        key.push_back(a[i]);

        text.push_back(b[i]);
    }

    cout << "input text : " << endl<< text << endl;

    AES obj (key,AES::KeySize::AES128);

    obj.Encrypt(text);
    string cipherText = obj.GetCipherText();
    cout << "Encrypt=>cipherText: "<< endl << cipherText << endl;

    obj.Decrypt(cipherText);
    string plainText = obj.ToString();
    cout << "Decrypt=>plainText: "<< plainText << endl;

    return 0;
}
```

五、运行截图



```
E:\360MoveData\Users\1737783319\Desktop\信息安全\lab\lab2>test
input text :
string 2 encrypt
Encrypt=>cipherText:
贫ヾ2  Q1o $ NWO
Decrypt=>plainText: T钧 y r ?W倖V^
```