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AES Algorithm

Theory:

The Advanced Encryption Standard (AES) is a symmetric-key block cipher algorithm that was established as a standard by the U.S. National Institute of Standards and Technology (NIST) in 2001. AES is widely used for securing data and communications because of its speed, security, and efficiency. It replaced the older Data Encryption Standard (DES) due to its limited key length and vulnerability to modern cryptographic attacks. Here's an overview of the AES algorithm:

1. Key Lengths:

AES supports key lengths of 128, 192, and 256 bits, making it significantly more secure than DES due to the longer key options.

2. Block Size:

AES operates on data in fixed-size blocks, with a block size of 128 bits (16 bytes). This means that data to be encrypted must be divided into 128-bit blocks, and encryption is performed on each block individually.

3. Substitution-Permutation Network:

AES uses a substitution-permutation network (SPN) structure, which is a series of mathematical operations applied iteratively to the data.

4. Key Expansion:

Before encryption, the AES key is expanded to generate a set of round keys for each round of encryption. The number of rounds depends on the key length: 10 rounds for 128-bit keys, 12 rounds for 192-bit keys, and 14 rounds for 256-bit keys.

5. Round Operations:

Each round of AES consists of four main operations:

- SubBytes: A byte-wise substitution operation where each byte of the block is replaced using a predefined substitution table (S-box).

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- ShiftRows: Bytes within the block are shifted to provide diffusion.

- MixColumns: Column-wise mixing operation that provides additional diffusion.

- AddRoundKey: Round key material is XORed with the block's state.

6. Final Round:

In the final round, the MixColumns operation is omitted, but the AddRoundKey operation is applied.

7. Encryption:

To encrypt a message, it is divided into 128-bit blocks. Each block undergoes the series of round operations for a total number of rounds corresponding to the key size. The last block may require padding to reach 128 bits.

8. Decryption:

Decryption in AES is the reverse process of encryption. Each round operation is reversed in order, using the round keys in reverse order.

9. Security:

AES is considered highly secure and has withstood extensive cryptanalysis. The security of AES relies on the key length and the strength of the substitution-permutation operations.

10. Applications:

AES is used in a wide range of applications, including secure data storage, secure communication protocols (e.g., HTTPS for web browsing), file encryption, and more. It is one of the most widely used encryption algorithms in the world.

Code:

```
// ./aes encrypt -p shreeshail -p aeskey

#include <iostream>
#include <iomanip>
#include <stdio.h>
#include <string.h>
```

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```
static const uint8_t sbox[256] = {
        //0     1     2      3     4     5     6     7      8     9     A      B
   C     D     E     F
        0x63, 0x7c, 0x77, 0x7b, 0xf2, 0x6b, 0x6f, 0xc5, 0x30, 0x01, 0x67,
0x2b, 0xfe, 0xd7, 0xab, 0x76,
        0xca, 0x82, 0xc9, 0x7d, 0xfa, 0x59, 0x47, 0xf0, 0xad, 0xd4, 0xa2,
0xaf, 0x9c, 0xa4, 0x72, 0xc0,
        0xb7, 0xfd, 0x93, 0x26, 0x36, 0x3f, 0xf7, 0xcc, 0x34, 0xa5, 0xe5,
0xf1, 0x71, 0xd8, 0x31, 0x15,
        0x04, 0xc7, 0x23, 0xc3, 0x18, 0x96, 0x05, 0x9a, 0x07, 0x12, 0x80,
0xe2, 0xeb, 0x27, 0xb2, 0x75,
        0x09, 0x83, 0x2c, 0x1a, 0x1b, 0x6e, 0x5a, 0xa0, 0x52, 0x3b, 0xd6,
0xb3, 0x29, 0xe3, 0x2f, 0x84,
        0x53, 0xd1, 0x00, 0xed, 0x20, 0xfc, 0xb1, 0x5b, 0x6a, 0xcb, 0xbe,
0x39, 0x4a, 0x4c, 0x58, 0xcf,
        0xd0, 0xef, 0xaa, 0xfb, 0x43, 0x4d, 0x33, 0x85, 0x45, 0xf9, 0x02,
0x7f, 0x50, 0x3c, 0x9f, 0xa8,
        0x51, 0xa3, 0x40, 0x8f, 0x92, 0x9d, 0x38, 0xf5, 0xbc, 0xb6, 0xda,
0x21, 0x10, 0xff, 0xf3, 0xd2,
        0xcd, 0x0c, 0x13, 0xec, 0x5f, 0x97, 0x44, 0x17, 0xc4, 0xa7, 0x7e,
0x3d, 0x64, 0x5d, 0x19, 0x73,
        0x60, 0x81, 0x4f, 0xdc, 0x22, 0x2a, 0x90, 0x88, 0x46, 0xee, 0xb8,
0x14, 0xde, 0x5e, 0x0b, 0xdb,
        0xe0, 0x32, 0x3a, 0x0a, 0x49, 0x06, 0x24, 0x5c, 0xc2, 0xd3, 0xac,
0x62, 0x91, 0x95, 0xe4, 0x79,
        0xe7, 0xc8, 0x37, 0x6d, 0x8d, 0xd5, 0x4e, 0xa9, 0x6c, 0x56, 0xf4,
0xea, 0x65, 0x7a, 0xae, 0x08,
        0xba, 0x78, 0x25, 0x2e, 0x1c, 0xa6, 0xb4, 0xc6, 0xe8, 0xdd, 0x74,
0x1f, 0x4b, 0xbd, 0x8b, 0x8a,
        0x70, 0x3e, 0xb5, 0x66, 0x48, 0x03, 0xf6, 0x0e, 0x61, 0x35, 0x57,
0xb9, 0x86, 0xc1, 0x1d, 0x9e,
        0xe1, 0xf8, 0x98, 0x11, 0x69, 0xd9, 0x8e, 0x94, 0x9b, 0x1e, 0x87,
0xe9, 0xce, 0x55, 0x28, 0xdf,
        0x8c, 0xa1, 0x89, 0x0d, 0xbf, 0xe6, 0x42, 0x68, 0x41, 0x99, 0x2d,
0x0f, 0xb0, 0x54, 0xbb, 0x16 };

static const uint8_t rsbox[256] = {
      0x52, 0x09, 0x6a, 0xd5, 0x30, 0x36, 0xa5, 0x38, 0xbf, 0x40, 0xa3, 0x9e,
0x81, 0xf3, 0xd7, 0xfb,
      0x7c, 0xe3, 0x39, 0x82, 0x9b, 0x2f, 0xff, 0x87, 0x34, 0x8e, 0x43, 0x44,
0xc4, 0xde, 0xe9, 0xcb,
      0x54, 0x7b, 0x94, 0x32, 0xa6, 0xc2, 0x23, 0x3d, 0xee, 0x4c, 0x95, 0x0b,
0x42, 0xfa, 0xc3, 0x4e,
      0x08, 0x2e, 0xa1, 0x66, 0x28, 0xd9, 0x24, 0xb2, 0x76, 0x5b, 0xa2, 0x49,
0x6d, 0x8b, 0xd1, 0x25,
      0x72, 0xf8, 0xf6, 0x64, 0x86, 0x68, 0x98, 0x16, 0xd4, 0xa4, 0x5c, 0xcc,
0x5d, 0x65, 0xb6, 0x92,
```

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```
        0x6c, 0x70, 0x48, 0x50, 0xfd, 0xed, 0xb9, 0xda, 0x5e, 0x15, 0x46, 0x57,
0xa7, 0x8d, 0x9d, 0x84,
        0x90, 0xd8, 0xab, 0x00, 0x8c, 0xbc, 0xd3, 0x0a, 0xf7, 0xe4, 0x58, 0x05,
0xb8, 0xb3, 0x45, 0x06,
        0xd0, 0x2c, 0x1e, 0x8f, 0xca, 0x3f, 0x0f, 0x02, 0xc1, 0xaf, 0xbd, 0x03,
0x01, 0x13, 0x8a, 0x6b,
        0x3a, 0x91, 0x11, 0x41, 0x4f, 0x67, 0xdc, 0xea, 0x97, 0xf2, 0xcf, 0xce,
0xf0, 0xb4, 0xe6, 0x73,
        0x96, 0xac, 0x74, 0x22, 0xe7, 0xad, 0x35, 0x85, 0xe2, 0xf9, 0x37, 0xe8,
0x1c, 0x75, 0xdf, 0x6e,
        0x47, 0xf1, 0x1a, 0x71, 0x1d, 0x29, 0xc5, 0x89, 0x6f, 0xb7, 0x62, 0x0e,
0xaa, 0x18, 0xbe, 0x1b,
        0xfc, 0x56, 0x3e, 0x4b, 0xc6, 0xd2, 0x79, 0x20, 0x9a, 0xdb, 0xc0, 0xfe,
0x78, 0xcd, 0x5a, 0xf4,
        0x1f, 0xdd, 0xa8, 0x33, 0x88, 0x07, 0xc7, 0x31, 0xb1, 0x12, 0x10, 0x59,
0x27, 0x80, 0xec, 0x5f,
        0x60, 0x51, 0x7f, 0xa9, 0x19, 0xb5, 0x4a, 0x0d, 0x2d, 0xe5, 0x7a, 0x9f,
0x93, 0xc9, 0x9c, 0xef,
        0xa0, 0xe0, 0x3b, 0x4d, 0xae, 0x2a, 0xf5, 0xb0, 0xc8, 0xeb, 0xbb, 0x3c,
0x83, 0x53, 0x99, 0x61,
        0x17, 0x2b, 0x04, 0x7e, 0xba, 0x77, 0xd6, 0x26, 0xe1, 0x69, 0x14, 0x63,
0x55, 0x21, 0x0c, 0x7d };

void fillString(std::string &a, bool isPlaintext)
{
    if (isPlaintext)
    {
        for (int i = a.length(); i < 16; i++)
        {
            a += " ";
        }
    }
    else
    {
        for (int i = a.length(); i < 32; (i++*2))
        {
            a += 0x20;
        }
    }

}

void fillArr(uint8_t arr[4][4], std::string str)
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
```

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```
            arr[i][j] = str[(4*i) + j];
        }
    }
}

void printArray(uint8_t arr[4][4])
{
    std::cout << "----------------" << std::endl;
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            std::cout << arr[j][i] << " ";
        }
        std::cout << std::endl;
    }
    std::cout << "----------------" << std::endl;
}

void printArrayHex(uint8_t arr[4][4])
{
    std::cout << "----------------" << std::endl;
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            std::cout << std::hex << (int)arr[j][i] << " ";
        }
        std::cout << std::endl;
    }
    //std::cout << std::endl;
    std::cout << "----------------" << std::endl;
}

void printOneLine(uint8_t arr[4][4])
{
    std::cout << "hex: ";
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            if ((int)arr[i][j] - 10 < 0)
            {
                std::cout << "0";
            }
            std::cout << std::hex << (int)arr[i][j];
        }
    }
    std::cout << std::endl;
}

void printOneLinePlain(uint8_t arr[4][4])
{
    std::cout << "plaintext: ";
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            if ((int)arr[i][j] - 10 < 0)
            {
                std::cout << "0";
            }
            std::cout << (char)arr[i][j];
        }
    }
    std::cout << std::endl;
}

void subBytes(uint8_t a[4][4])
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            std::stringstream stream;
            stream << std::hex << (int)a[i][j];
            std::string result(stream.str());

            int left, right;
            std::stringstream().swap(stream);

            if (result.length() < 2)
            {
                left = 0;
            }
            else
            {
                stream << std::hex << result[0];
                stream >> std::hex >> left;
            }

            std::stringstream().swap(stream);
            stream << std::hex << result.back();
            stream >> std::hex >> right;
            a[i][j] = sbox[right + (16 * left)];
        }
```

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```
    }
}

void invSubBytes(uint8_t a[4][4])
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            std::stringstream stream;
            stream << std::hex << (int)a[i][j];
            std::string result(stream.str());

            int left, right;

            std::stringstream().swap(stream);

            if (result.length() < 2)
            {
                left = 0;
            }
            else
            {
                stream << std::hex << result[0];
                stream >> std::hex >> left;
            }

            std::stringstream().swap(stream);

            stream << std::hex << result.back();
            stream >> std::hex >> right;
            a[i][j] = rsbox[right + (16 * left)];
        }
    }
}

void shiftRows(uint8_t a[4][4])
{
    uint8_t b[4][4];
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            b[j][i] = a[(j + i) % 4][i];
        }
    }
    std::copy(&b[0][0], &b[0][0]+4*4,&a[0][0]);
}
```

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```
void invShiftRows(uint8_t a[4][4])
{
    uint8_t b[4][4];
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            b[j][i] = a[(((j - i) % 4) + 4) % 4][i];
        }
    }
    std::copy(&b[0][0], &b[0][0]+4*4,&a[0][0]);
}


void mixColumns(uint8_t a[4][4])
{
    for (int i = 0; i < 4; i++)
    {
        uint8_t tmp[4];
        uint8_t multi[4];
        for (int j = 0; j < 4; j++)
        {
            tmp[j] = a[i][j];
            uint8_t h = (unsigned char)((signed char)a[i][j] >> 7);
            multi[j] = a[i][j] << 1;
            multi[j] ^= 0x1B & h;
        }

        a[i][0] = multi[0] ^ tmp[3] ^ tmp[2] ^ multi[1] ^ tmp[1];
        a[i][1] = multi[1] ^ tmp[0] ^ tmp[3] ^ multi[2] ^ tmp[2];
        a[i][2] = multi[2] ^ tmp[1] ^ tmp[0] ^ multi[3] ^ tmp[3];
        a[i][3] = multi[3] ^ tmp[2] ^ tmp[1] ^ multi[0] ^ tmp[0];
    }
}

uint8_t wasd(uint8_t a)
{
    uint8_t h = (unsigned char)((signed char)a >> 7);
    return ((a << 1) ^ 0x1b & h);
}

void invMixColumns(uint8_t a[4][4])
{
    uint8_t x[4] = {0x9f, 0xdc, 0x58, 0x9d};
    uint8_t y[4];
    uint8_t a9[4];
    uint8_t a11[4];
```

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```
    uint8_t a13[4];
    uint8_t a14[4];
    for (int i = 0; i < 4; i++)
    {
        uint8_t tmp[4][4];

        for (int j = 0; j < 4; j++)
        {
            tmp[0][j] = wasd(wasd(wasd(a[i][(0 + j) % 4]) ^ a[i][(0 + j) % 4])
^ a[i][(0 + j) % 4]);
            tmp[1][j] = wasd(wasd(wasd(a[i][(1 + j) % 4])) ^ a[i][(1 + j) %
4]) ^ a[i][(1 + j) % 4];
            tmp[2][j] = wasd(wasd(wasd(a[i][(2 + j) % 4]) ^ a[i][(2 + j) %
4])) ^ a[i][(2 + j) % 4];
            tmp[3][j] = wasd(wasd(wasd(a[i][(3 + j) % 4]))) ^ a[i][(3 + j) %
4];
        }
        for (int k = 0; k < 4; k++)
        {
            a[i][k] = tmp[(((0 - k) % 4) + 4) % 4][k] ^ tmp[(((1 - k) % 4) +
4) % 4][k] ^ tmp[(((2 - k) % 4) + 4) % 4][k] ^ tmp[(((3 - k) % 4) + 4) %
4][k];
        }
    }

}

void addRoundKey(uint8_t a[4][4], uint8_t b[4][4])
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            a[i][j] ^= b[i][j];
        }
    }
}

void rotWord(uint8_t a[4])
{
    uint8_t b[4];
    for (int i = 0; i < 4; i++)
    {
        b[i] = a[(i + 1) % 4];
    }
    std::copy(&b[0], &b[0]+4,&a[0]);
}
```

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```
void printKeySchedule(uint8_t a[44][4])
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 44; j++)
        {
            std::cout << std::hex << (int)a[j][i] << " ";
        }
        std::cout << std::endl;
    }
}

void copyColumn(uint8_t a[4], uint8_t b[4])
{
    for (int i = 0; i < 4; i++)
    {
        b[i] = a[i];
    }
}

void subBytesRow(uint8_t a[4])
{
    for (int i = 0; i < 4; i++)
    {
        std::stringstream stream;
        stream << std::hex << (int)a[i];
        std::string result(stream.str());

        int left, right;

        std::stringstream().swap(stream);

        if (result.length() < 2)
        {
            left = 0;
        }
        else
        {
            stream << std::hex << result[0];
            stream >> std::hex >> left;
        }

        std::stringstream().swap(stream);

        stream << std::hex << result.back();
        stream >> std::hex >> right;
        a[i] = sbox[right + (16 * left)];
    }
```

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```
}



void keySchedule(uint8_t cipherKey[4][4], uint8_t ok[44][4])
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            ok[i][j] = cipherKey[i][j];
        }
    }

    static const uint8_t rcon[10] = { 0x01, 0x02, 0x04, 0x08, 0x10, 0x20,
0x40, 0x80, 0x1b, 0x36};

    for (int i = 4; i < 44; i++)
    {
        uint8_t tmpRcon[4] = {0, 0, 0, 0};
        uint8_t tmp[4];
        copyColumn(ok[i - 1], tmp);


        if (i % 4 == 0)
        {
            tmpRcon[0] = rcon[(i/4) - 1];
            rotWord(tmp);
            subBytesRow(tmp);
        }

        for (int j = 0; j < 4; j++)
        {
            ok[i][j] = (i % 4 == 0) ? (ok[i - 4][j] ^ tmp[j] ^ tmpRcon[j]) :
(ok[i - 4][j] ^ tmp[j]);
        }
    }
}

void updateRoundKey(uint8_t a[44][4], uint8_t b[4][4], unsigned int round)
{
    if (round > 10)
    {
        std::cout << "The round cannot be larger than 10" << std::endl;
        exit(1);
    }
    for (int i = 0; i < 4; i++)
    {
```

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```
        for (int j = 0; j <4; j++)
        {
            b[i][j] = a[i + (4*round)][j];
        }
    }
}

void fromHex(std::string str, uint8_t ret[4][4])
{
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 4; j++)
        {
            ret[i][j] = std::stoi(str.substr((2*j)+(8*i), 2), 0, 16);
        }
    }
}

void printUsage()
{
    std::cout << "Usage: ./aes encrypt/decrypt -p/-h <text> -p/-h <key>" <<
std::endl;
}

int main(int argc, char** argv)
{
    bool encrypt = -1;
    bool textIsPlaintext = -1;
    bool keyIsPlaintext = -1;

    if (argc != 6)
    {
        printUsage();
        return 0;
    }

    const std::string needsAName = argv[1];
    if (needsAName == "encrypt")
    {
        encrypt = 1;
    }
    else if (needsAName == "decrypt")
    {
        encrypt = 0;
    }
    else
    {
        printUsage();
```

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```
        return 0;
    }

    const std::string textFormat = argv[2];
    if (textFormat == "-p")
    {
        textIsPlaintext = 1;
    }
    else if (textFormat == "-h")
    {
        textIsPlaintext = 0;
    }
    else
    {
        printUsage();
        return 0;
    }

    std::string text = argv[3];
    if (text.size() > 16 && textIsPlaintext)
    {
        std::cout << "The text in plaintext cannot be more than 16
characters." << std::endl;
        return 0;
    }
    else if (text.size() > 32 && !textIsPlaintext)
    {
        std::cout << "The text in hex format cannot be more than 32
characters." << std::endl;
        return 0;
    }

    const std::string keyFormat = argv[4];
    if (keyFormat == "-p")
    {
        keyIsPlaintext = 1;
    }
    else if (keyFormat == "-h")
    {
        keyIsPlaintext = 0;
    }
    else
    {
        printUsage();
        return 0;
    }

    std::string key = argv[5];
```

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```
    if (key.size() > 16 && keyIsPlaintext)
    {
        std::cout << "The key in plaintext cannot be more than 16 characters."
<< std::endl;
        return 0;
    }
    else if (key.size() > 32 && !keyIsPlaintext)
    {
        std::cout << "The key in hex format cannot be more than 32
characters." << std::endl;
        return 0;
    }

    if (text.size() < 16 && textIsPlaintext)
    {
        fillString(text, textIsPlaintext);
    }
    else if (text.size() < 32 && !textIsPlaintext)
    {
        fillString(text, textIsPlaintext);
    }

    std::cout << "Text: " << text << std::endl;
    std::cout << "Key:  " << key << std::endl;

    uint8_t fullKey[44][4];
    uint8_t state[4][4];
    uint8_t roundKey[4][4];

    if (textIsPlaintext)
    {
        fillArr(state, text);
    }
    else
    {
        fromHex(text, state);
    }

    if (keyIsPlaintext)
    {
        fillArr(roundKey, key);
    }
    else
    {
        fromHex(key, roundKey);
    }

    if (encrypt)
```

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```
    {
        std::cout << "-------- Encrypting --------" << std::endl;
        keySchedule(roundKey, fullKey);
        updateRoundKey(fullKey, roundKey, 0);
        addRoundKey(state, roundKey);
        for (int i = 1; i <= 9; i++)
        {
            subBytes(state);
            shiftRows(state);
            //printArrayHex(state);
            mixColumns(state);
            //printArrayHex(state);
            updateRoundKey(fullKey, roundKey, i);
            addRoundKey(state, roundKey);
        }

        subBytes(state);
        shiftRows(state);
        updateRoundKey(fullKey, roundKey, 10);
        addRoundKey(state, roundKey);

        //printArrayHex(state);
        printOneLine(state);
    }
    else
    {
        std::cout << "-------- Decrypting --------" << std::endl;
        keySchedule(roundKey, fullKey);
        updateRoundKey(fullKey, roundKey, 10);
        addRoundKey(state, roundKey);
        invShiftRows(state);
        invSubBytes(state);

        for (int i = 9; i >= 1; i--)
        {
            updateRoundKey(fullKey, roundKey, i);
            addRoundKey(state, roundKey);
            invMixColumns(state);
            invShiftRows(state);
            invSubBytes(state);
        }

        updateRoundKey(fullKey, roundKey, 0);
        addRoundKey(state, roundKey);
        printOneLine(state);
        printOneLinePlain(state);
    }
```

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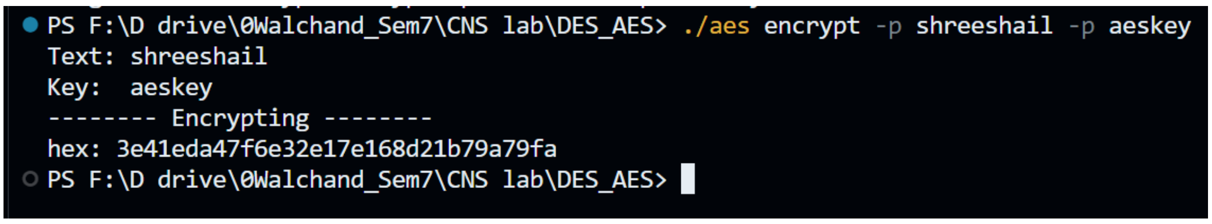
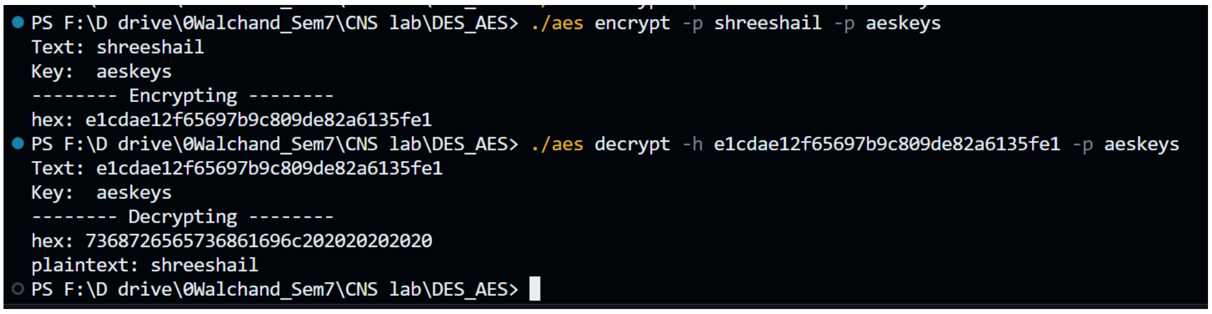
Batch: B4

```
    return 0;
}
```

Screenshot:



```
● PS F:\D drive\0Walchand_Sem7\CNS lab\DES_AES> ./aes encrypt -p shreeshail -p aeskey
  Text: shreeshail
  Key:  aeskey
  -------- Encrypting --------
  hex: 3e41eda47f6e32e17e168d21b79a79fa
○ PS F:\D drive\0Walchand_Sem7\CNS lab\DES_AES>
```



```
● PS F:\D drive\0Walchand_Sem7\CNS lab\DES_AES> ./aes encrypt -p shreeshail -p aeskeys
  Text: shreeshail
  Key:  aeskeys
  -------- Encrypting --------
  hex: e1cdae12f65697b9c809de82a6135fe1
● PS F:\D drive\0Walchand_Sem7\CNS lab\DES_AES> ./aes decrypt -h e1cdae12f65697b9c809de82a6135fe1 -p aeskeys
  Text: e1cdae12f65697b9c809de82a6135fe1
  Key:  aeskeys
  -------- Decrypting --------
  hex: 736872656573686169c202020202020
  plaintext: shreeshail
○ PS F:\D drive\0Walchand_Sem7\CNS lab\DES_AES>
```