AES SYSTEM REPORT

The AES system is a widely used symmetric key encryption algorithm that is used to secure sensitive data in various applications. It is a block cipher which operates on 128-bit blocks of data at a time, and can use keys of length 128, 192, or 256 bits. The number of rounds performed by the algo depends on the key length, it can perform 10, 12 or 14 rounds.

The AES system we have implemented uses keys of size 128 bit, and 10 rounds.

To use the system we need a plain_text and a master key, these are hexadecimal strings of length 32, and are equal to 128 bits. In the system you either enter these strings on your own, or randomly generate plain_text and master key for convenience.

In the report we use,

```
plain_text = "dd06309f04da87df644726e304234012"
master_key = "ddee540d70661c716d12c764c450ecee"
```

Okay now we have the plain_text and the master key. We can use the **encrypt_128** function which takes in a hex string of 128 bits as plain_text, and a master key of 128 bits, to generate a cipher_text of 128 bits.

```
cipher_text = encrypt_128(plain_text, master_key)
```

Similarly to decrypt the cipher_text we use **decrypt_128** which requires the cipher_text and the key as parameters.

```
decrypted_text = decrypt_128(cipher_text, master_key)
```

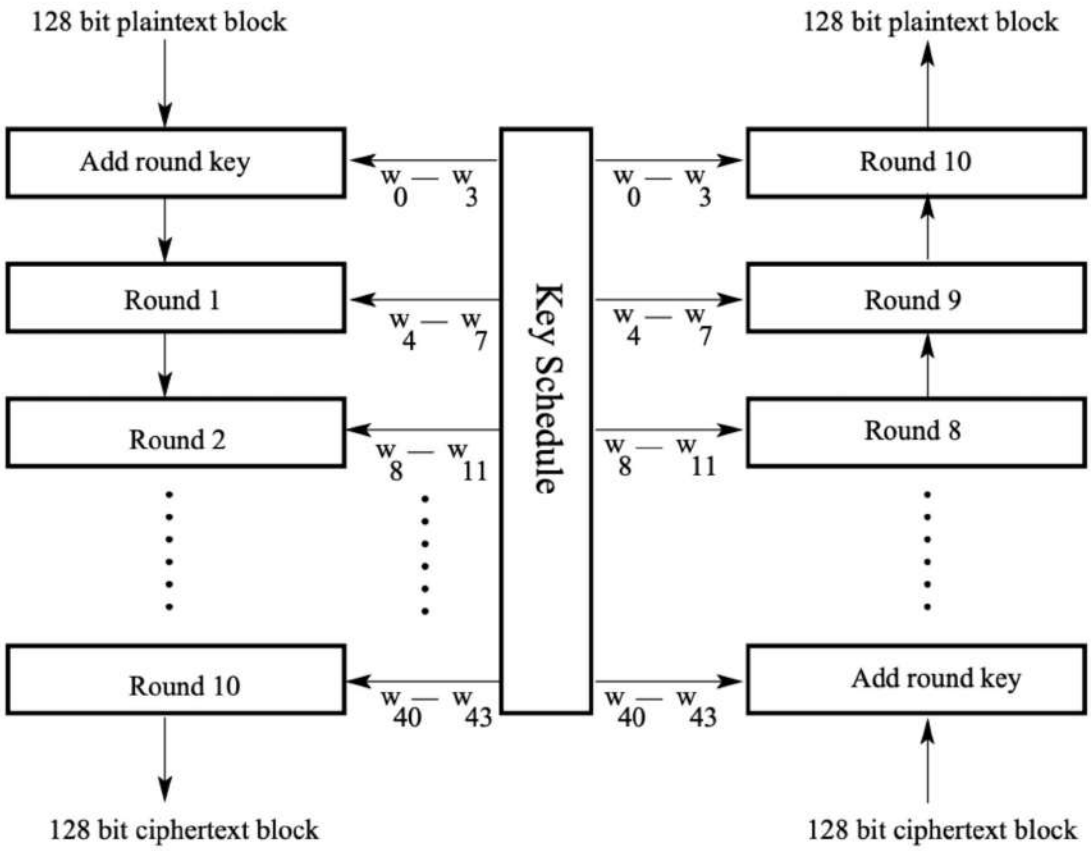
Finally after generating the decrypted text from the cipher text we can check if it comes out to be equal to original plain_text.

```
print("\nplain_text: ", plain_text)
print("cipher_text: ", cipher_text)
print("decrypted_text: ", decrypted_text)
print(plain_text == decrypted_text)
```

```
plain_text:  dd06309f04da87df644726e304234012
cipher_text:  6530edf3d3e4987fa4d9a15bc65e4c61
decrypted_text:  dd06309f04da87df644726e304234012
True
```

Our AES system uses 11 keys, one key is used in the initial round (round 0) and the other 10 are used in the 10 rounds, these keys are generated from the master key using key expansion.

AES system is based on this:



AES Encryption AES Decryption

[Img Source]: This Figure is from Lecture 8 of "Computer and Network Security" by Avi.

Key Expansion: The Key Expansion process is used to generate a set of round keys from the original master key. The key schedule operates by performing a series of operations on the original encryption key, including substitution, permutation, and XOR operations, to generate a set of round keys that are used in the encryption process.

The key expansion process involves several steps(Complex g function):

Key Generation: The original encryption key is used as the first round key. This key is then used to generate subsequent round keys using a key schedule.

```
w = [()]*44

for i in range(4):
    w[i] = (key[4*i], key[4*i+1], key[4*i+2], key[4*i+3])

for i in range(4, 44):
    temp = w[i-1]
    word = w[i-4]
```

- The key is copied into the first four words of the expanded key.
- The remain- der of the expanded key is filled in four words at a time. Each added word w[i] depends on the immediately preceding word, w[i - 1], and the word four positions back,w[i - 4].

Substitution: The round key is passed through the AES S-Box, which substitutes each byte of the key with a corresponding byte from the S-Box.

```
def SubstitutionOfWord(word):
    ...
```

Rotation: The bytes of the round key are rotated by one or more positions to the left.

```
def RotationOfWord(word):
    '''
    Takes from 1 to the end, adds on from the start to 1
    '''
    result = word[1:] + word[:1]
    return result
```

XOR: The round key is XORed with a fixed constant value that depends on the round number.

```
def HexandXor(hex1, hex2):
    '''
    Convert to binary and xor it and  cut the prefix value return hex value.
    '''
    binvalue1 = bin(int(str(hex1), 16))
    binvalue2 = bin(int(str(hex2), 16))

    xord = int(binvalue1, 2) ^ int(binvalue2, 2)

    hexed = hex(xord)[2:]

    if len(hexed) != 8:
        hexed = '0' + hexed

    return hexed
```

The HexandXor function will do the xor of Substitute word and value of Rconstant computed value from the table and the result will be stored in ‘temp’ string and further it will be xor with the

first word w0 and the output will be stored in w4, and this result will be xor with w5 and so on to generate 11 keys for 10 rounds.

Encryption:

The AES algorithm consists of several key components that are used to **encrypt** the input data. These components include:

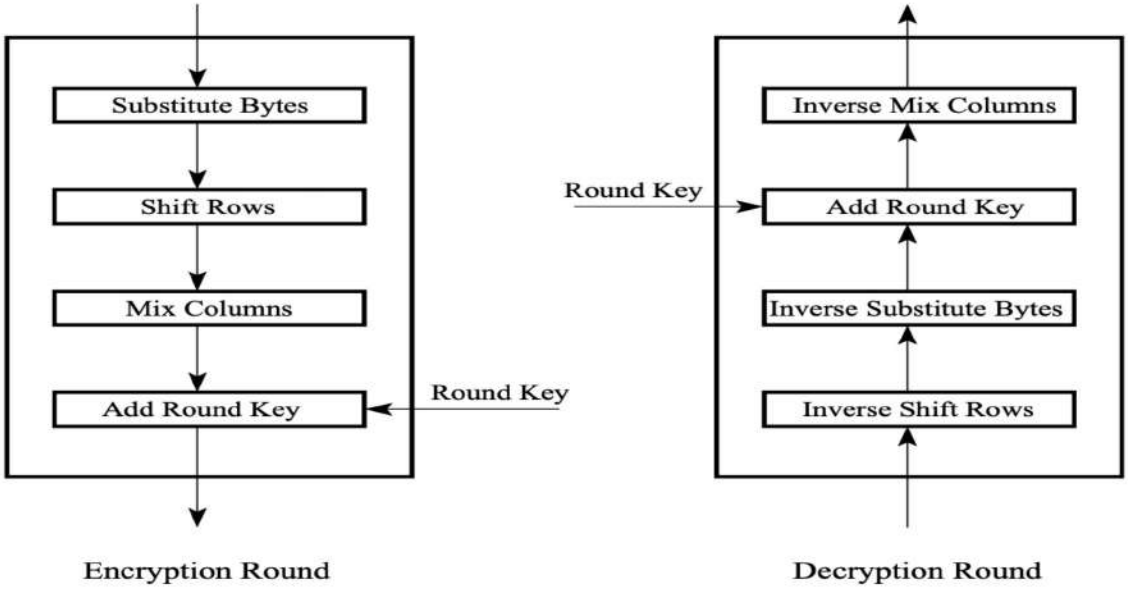
SubBytes Function
ShiftRows Function
MixColumns Function
AddRoundKey Function

Each and every element of each of the 10 rounds of AES is programmed and no library is used. In encrypt_128, the original plain_text is first converted to a state matrix, and is stored in [4]x[4] bytes (displayed in int) matrix. Where each column represents one word, this is done by the function get_state(). So the original plain_text gets converted to a 4 x 4 matrix.

221	4	100	4
6	218	71	35
48	135	38	64
159	223	227	18

Now this matrix is further worked upon, and is passed to **Round 0 (Initial Round):**
During the initial round, the input plaintext matrix is XORed with the initial round key (this is the first key of the 11 keys generated by key expansion).

Round 1 to Round 9:



The rounds 1 to 9 of the AES encryption algorithm consist of four steps that are applied in sequence given in the image. Each round uses a different key, round 1 uses the 2nd key generated by key expansion and so on.

Round 10 (Final Round):

This differs from other rounds as it does not have the mixcolumns step, the output of this round gives the cipher text.

Image shows the output of each round in hex string, round 10 gives the cipher text and round 0 is the initial round. This was done using encrypt_128(plain_text, master_key)
plain_text: dd06309f04da87df644726e304234012
master key: ddee540d70661c716d12c764c450ecee

```
==== ENCRYPTION BEGINS ====

0 00e8649274bc9bae0955e187c073acfc
1 ae2a5a5201d0e63ebd7198188cb87b9e
2 7156feb7a79706c65e4880e79b141da8
3 3d403d9f2f15ec20d4e7656521ffc640
4 ac8fb454c34d9ef265ffa5631c19c92f
5 c0ab95116ed137cf5331a14e89a43b8d
6 b17d8f9f118a5c4a167e8a432534b0f0
7 f57b044725e855e9a7bfa0dbf35829aa
8 f9f08ac8bfa9d9bb92c2d78283f6700b
9 6d192af2158fe962672cad257e33291f
10 6530edf3d3e4987fa4d9a15bc65e4c61
```

cipher_text = 6530edf3d3e4987fa4d9a15bc65e4c61

Decryption:

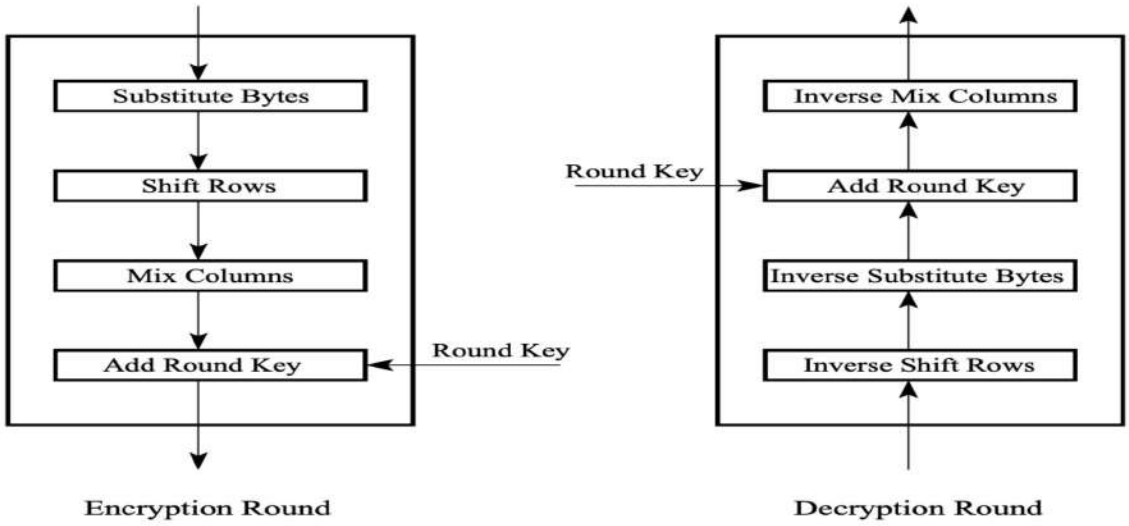
This is done using the function decrypt_128(cipher_text, master_key).
The AES algorithm consists of several key components that are used to **decrypt** the input data. These components include:

Inverse Shift Rows
Inverse Substitute Bytes
Add Round Key
Inverse Mix Columns

Similar to encrypt_128, the original cipher_text is first converted to a state matrix, and is stored in [4]x[4] bytes (displayed in int) matrix. Where each column represents one word, this is done by the function get_state(). So the original cipher_text gets converted to a 4 x 4 matrix.
Now this matrix is further worked upon, and is passed to **Round 0 (Initial Round):**

During the initial round, the input cipher_text matrix is XORed with the last round key (this is the 11th key of the 11 keys generated by key expansion).

Round 1 to Round 9:



The rounds 1 to 9 of the AES decryption algorithm consist of four steps that are applied in sequence given in the image. The steps used here are different in order and are inverse of the functions used in encryption. Each of these rounds use a different key (in reverse order of what was used in encrypt_128). Round 9 uses the 2nd key generated by key expansion and so on.

Round 10 (Final Round):
This differs from other rounds as it does not have the mixcolumns step but the order of the functions is the same, the output of this round gives the decrypted text.

Image shows the output of each round in hex string, round 10 gives the decrypted text and round 0 is the initial round. This was done using decrypt_128(cipher_text, master_key)
cipher_text: 6530edf3d3e4987fa4d9a15bc65e4c61
master key: ddee540d70661c716d12c764c450ecee

```
==== DECRYPTION BEGINS ====

0 3c7395c05971a58985c3e5aaf3d41e3f
1 99d30e2b082551e84f427eeaec8c3513
2 e69be0ac3f08a5a05c6af21e0d21fcb9
3 c87e7e8c82f3e7db471873d63fff4a1a
4 ba3e325d9fc7e282ed492a8aa7629a2f
5 91e306152e16dd204dd48d899c730bfb
6 27594d091594b4db481627b7fd09ce4d
7 a388cdc25c52a4a958fabbb414b16f94
8 e470460b7ca321007a6cbeb264e58ead
9 6365f8b092fc914f018f43e4ba9b1417
10 dd06309f04da87df644726e304234012
```

decrypted_text: dd06309f04da87df644726e304234012

a)

decrypted_text matches the original **plain_text** which is dd06309f04da87df644726e304234012. the ciphertext when decrypted yields the original plaintext.

b) Verify that the output of the 1st encryption round is same as the output of the 9th decryption round.

c) Verify that the output of the 9th encryption round is same as the output of the 1st decryption round.

These screenshots are taken from the aes system we implemented, through them we can interpret that

The output of the 1st encryption round is same as the output of the 9th decryption round.

The output of the 9th encryption round is same as the output of the 1st decryption round.

```
output of the 1st encryption round:  ae2a5a5201d0e63ebd7198188cb87b9e
output of the 9th encryption round:  6d192af2158fe962672cad257e33291f
```

```
output of the 1st decryption round:  6d192af2158fe962672cad257e33291f
output of the 9th decryption round:  ae2a5a5201d0e63ebd7198188cb87b9e
```

Testing AES with two pairs of 128 bit <plaintext, ciphertext>

1)

```
plain_text 1afe096fa27385cc1d851b64f9e4263b
master key f960c3b4faef4eb7593853b1e8ba742e

==== ENCRYPTION BEGINS ====

0 e39ecadb589ccb7b44bd48d5115e5215
1 5ceb7222153a7c352433276a59292988
2 d23c298ef958eea7c2efd6b67471fb82
3 788338ee343fddd5b005f96849fdce72
4 5dc0c826270d408ad9fd34cc1fc938c1
5 83993a5b9fc7cb4b642c729f2a36df5c
6 7cc3fe7a6dd6130eaaeb95d10a9b2fa6
7 91dfdfe6dd1d5eb0357ee14693464f03
8 4f76d520f5e4ea9d923a494e46cb3276
9 81de64ff9a1317189250d1707a6f4d75
10 513353e6a7217b9220a0be289bed46ae

output of the 1st encryption round:  5ceb7222153a7c352433276a59292988
output of the 9th encryption round:  81de64ff9a1317189250d1707a6f4d75

==== DECRYPTION BEGINS ====

0 0c7d3e9db853e3164fa843adda1df051
1 84693b38e68023b74f1f035e5a38872f
2 81a4f87bc1f3848e965a9ee7dc9e585a
3 10f62a243ce915daac14bbab672e7d3e
4 ecc6404adb719e39430580b3e5ee1fdb
5 4cd71878cc5407f735dde87ec0ba094b
6 bc759940186b8b28e75407033becc145
7 b56af61399df0f1925a3a55c92eb284e
8 4a80ccc459c3a59336a54096cbe91002
9 11de52596a7a00b91b587421820b1f03
10 1afe096fa27385cc1d851b64f9e4263b

output of the 1st decryption round:  81de64ff9a1317189250d1707a6f4d75
output of the 9th decryption round:  5ceb7222153a7c352433276a59292988

plain_text:  1afe096fa27385cc1d851b64f9e4263b
cipher_text:  513353e6a7217b9220a0be289bed46ae
decrypted_text:  1afe096fa27385cc1d851b64f9e4263b
True
```

2)

```
plain_text 45eb6e86d07505516e41eae34dc54217
master key cd3189ab009c0df2ed1022b0d8f68a1c

==== ENCRYPTION BEGINS ====

0 88dae72dd0e908a38351c8539533c80b
1 fcbf793d36e1013a601f38e4cb0c814c
2 5cd30a46eed69b9563ced7a87f6ff183
3 34ed4aecfa52fef7635e1c0caf009b05
4 6ddcd43b15aaacf4ab9cd0ba79b345ce
5 84d08d0bd2dfa5524c06c1f97a6c9776
6 0e92ef70bfe8f9a4eb9c12b84dca5eb7
7 696791af4e3508bff9e3af542e1335e0
8 955e1d7ae90ca7db76fb8cce60ead9e4
9 eace332e039abf706f74e45792a20375
10 8eab0dc2b39eaea9f021ce9c013db081

output of the 1st encryption round:  fcbf793d36e1013a601f38e4cb0c814c
output of the 9th encryption round:  eace332e039abf706f74e45792a20375

==== DECRYPTION BEGINS ====

0 87b8699d7b927b31a83ac3514f8b085b
1 2afe64691e0f35da3887a4b9d0585c8b
2 f99679e12f119679997d810831853020
3 ab9bc9a908de5851e974df49e34f996c
4 5f9e7838b56f882b29505d00da700699
5 3cac708b59de6ee2626d48bfb68691f4
6 18009c6b2d5814cefb63d6687955bbfe
7 4af60eec288ba15afba8672ad26614c2
8 b0f8072905c00c27d0feb6801f087c69
9 c41ee82b70d1e8d8ecc3940a2a5730ed
10 45eb6e86d07505516e41eae34dc54217

output of the 1st decryption round:  eace332e039abf706f74e45792a20375
output of the 9th decryption round:  fcbf793d36e1013a601f38e4cb0c814c

plain_text:  45eb6e86d07505516e41eae34dc54217
cipher_text:  8eab0dc2b39eaea9f021ce9c013db081
decrypted_text:  45eb6e86d07505516e41eae34dc54217
True
```