Cryptographic Algorithms with C

Design, Implementation, and Integration of Core Crypto Modules

Secure, Efficient, High-Performance Cryptographic Software Modules

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Chapter 1

Project Overview

I have developed a cryptographic software module in the C language, with an emphasis on high performance and efficiency. This document provides a comprehensive guide to the design, implementation, and integration of cryptographic modules written in C (sometimes assembly).

Key Objectives:

- Describing the cryptographic primitives and algorithms
  (block ciphers, hash functions, MACs, signature algorithms, etc.).
- Explaining the structure of the source files and headers.
- Providing guidelines for building, testing, and integrating these modules into larger software systems.

1.1 Directory Structure

```
CryptoModule/
├── bin
├── build
│   ├── *.o
│   └── *.d
├── include
│   ├── block_cipher
│   │   ├── block_cipher_api.h
│   │   ├── block_cipher_aes.h
│   │   └── ...
│   ├── mode
│   │   ├── mode_api.h
│   │   └── ...
│   ├── ...
│   └── api.h
├── src/
│   ├── block_cipher
│   │   ├── block_cipher_factory.c
│   │   ├── block_cipher_aes.c
│   │   └── ...
│   ├── mode
│   │   ├── mode_factory.c
│   │   └── ...
│   ├── ...
│   ├── cryptomodule_core.c
│   └── main.c
├── tests/
└── Makefile
```

1.2 My Development Environment

- **Operating System:**

```
@>$ cat /etc/os-release
NAME="Linux Mint"
VERSION="21.3 (Virginia)"
ID=linuxmint
ID_LIKE="ubuntu debian"
PRETTY_NAME="Linux Mint 21.3"
VERSION_ID="21.3"
HOME_URL="https://www.linuxmint.com/"
SUPPORT_URL="https://forums.linuxmint.com/"
BUG_REPORT_URL="http://linuxmint-troubleshooting-guide.readthedocs.io/en/latest/"
PRIVACY_POLICY_URL="https://www.linuxmint.com/"
VERSION_CODENAME=virginia
UBUNTU_CODENAME=jammy
```

- **Compiler:**

```
@>$ gcc --version
gcc (Ubuntu 11.4.0-1ubuntu1~22.04) 11.4.0
Copyright (C) 2021 Free Software Foundation, Inc.
This is free software; see the source for copying conditions.  There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
```

- **Hardware:**

```
@>$ lscpu
Architecture:            x86_64
  CPU op-mode(s):        32-bit, 64-bit
  Address sizes:         48 bits physical, 48 bits virtual
  Byte Order:            Little Endian
CPU(s):                  16
  On-line CPU(s) list:   0-15
Vendor ID:               AuthenticAMD
  Model name:            AMD Ryzen 7 5800X3D 8-Core Processor
    CPU family:          25
    Model:               33
    Thread(s) per core:  2
    CPU max MHz:         3400.0000
    CPU min MHz:         2200.0000
```

- **Additional Tools:**
  - valgrind for memory checks,
  - gdb for debugging,
  - and TBA

Chapter 2

Cryptographic Software Module

2.1 Block Cipher

A **block cipher** is a keyed family of permutations over a fixed-size data block.

- Let k be a fixed key size and n be a fixed block size.
- Let $\mathcal{K} = \{0,1\}^k$ be the set of possible k-bit keys (each key is chosen from this set).
- Let $\mathcal{M} = \{0,1\}^n$ be the set of all n-bit messages (plaintext blocks).
- Let $\mathcal{C} = \{0,1\}^n$ be the set of all n-bit ciphertext blocks.

A **block cipher** is have two efficient induced functions:

$$E : \mathcal{K} \times \mathcal{M} \to \mathcal{C} \quad \text{and} \quad D : \mathcal{K} \times \mathcal{C} \to \mathcal{M},$$

referred to as the **encryption** and **decryption** functions, respectively. These must satisfy:

1. *Invertibility (permutation property)*: For each fixed key $k \in \mathcal{K}$, the encryption function

   $$E_k(\cdot) = E(k, \cdot) : \mathcal{M} \to \mathcal{C} \quad \text{is a bijection (i.e., permutation) on } \{0,1\}^n.$$

   In other words, for every key k, there is a unique inverse $D_k(\cdot) = D(k, \cdot) : \mathcal{C} \to \mathcal{M}$ s.t.

   $$D_k\big(E_k(m)\big) = m \quad \text{and} \quad E_k\big(D_k(c)\big) = c \quad \text{for every } m \in \mathcal{M} \text{ and } c \in \mathcal{C}.$$

2. *Keyed operation*: The cipher's behavior depends on the choice of key k. Changing k results in a different permutation over the n-bit block space.

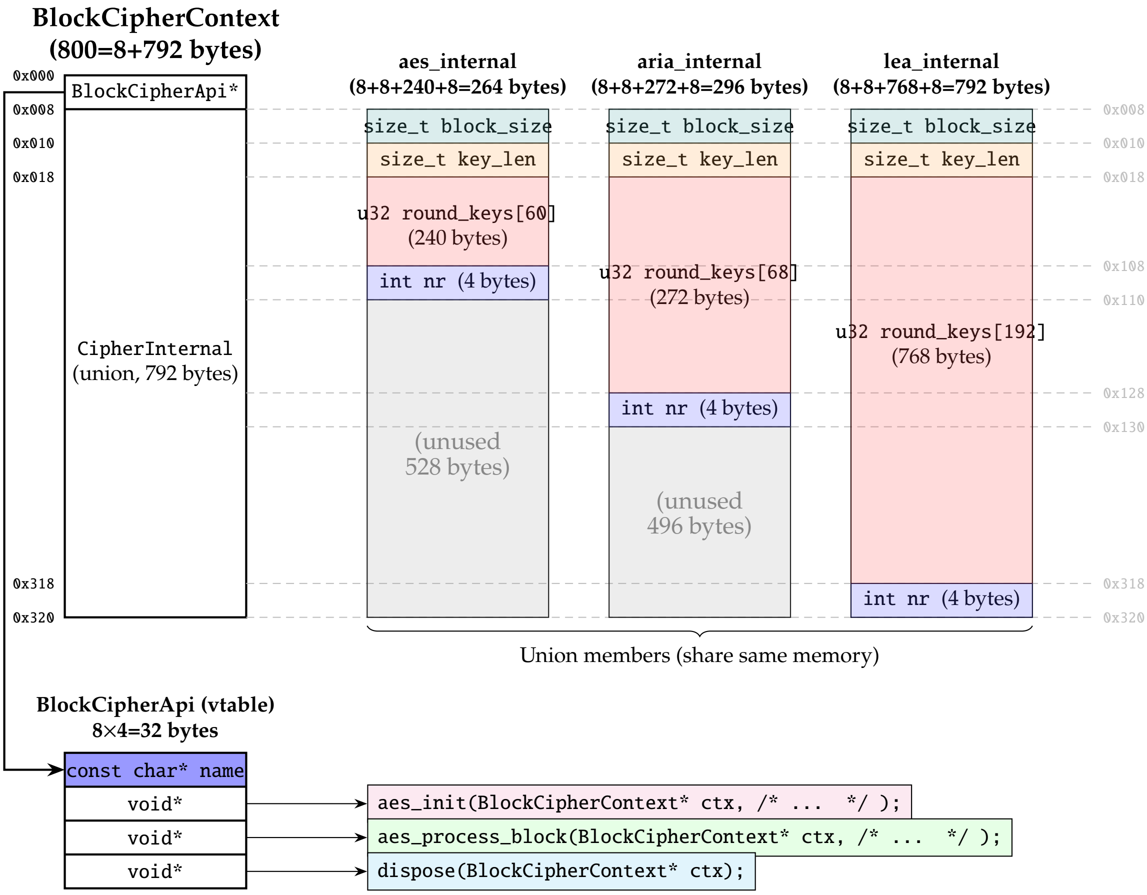
Alg.	$\boldsymbol{n}$ (bit)	$\boldsymbol{k}$ (bit)	**# of Rounds**	**RK Size** (bit)	**# of RKs**	**Total RK Size** (bit)
AES–128	128	128	10	128 (4-word)	11	1408 (44-word)
AES–192	128	192	12	128 (4-word)	13	1664 (52-word)
AES–256	128	256	14	128 (4-word)	15	1920 (60-word)
ARIA-128	128	128	12	128 (4-word)	13	1664 (52-word)
ARIA-192	128	192	14	128 (4-word)	15	1920 (60-word)
ARIA-256	128	256	16	128 (4-word)	17	2176 (68-word)
LEA-128	128	128	24	192 (6-word)	24	4608 (144-word)
LEA-192	128	192	28	192 (6-word)	28	5376 (168-word)
LEA-256	128	256	32	192 (6-word)	32	6144 (192-word)

Table 2.1: Comparison of AES, ARIA, and LEA parameters for 128-, 192-, and 256-bit keys.

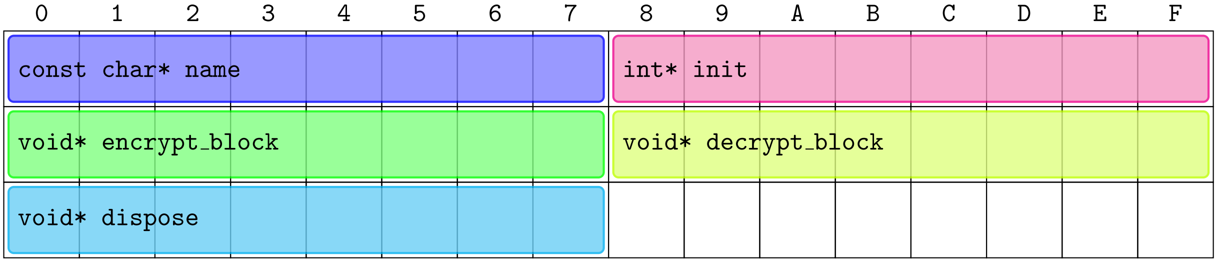
```c
typedef struct __BlockCipherApi__ {
        const char *name;
        void (*init)(BlockCipherContext* ctx, /* ... */);
        void (*process_block)(BlockCipherContext* ctx, /* ... */);
        void (*dispose)(BlockCipherContext* ctx);
} BlockCipherApi;

typedef union __CipherInternal__ {
        struct __aes_internal__ {
                /* ... */
        } aes_internal;
        struct __aria_internal__ {
                /* ... */
        } aria_internal;
        struct __lea_internal__ {
                /* ... */
        } lea_internal;
} CipherInternal;

typedef struct __BlockCipherContext__ {
        const BlockCipherApi *api;
        CipherInternal internal_data; /* Generic internal state for any cipher */
} BlockCipherContext;
```



BlockCipherApi (vtable, 40 bytes)



2.1.1 AES (Advanced Encryption Standard)

Table 2.2: Parameters of the Block Cipher AES (1-word = 32-bit)

Algorithms	Block Size (N_b-word)	Key Length (N_k-word)	Number of Rounds (N_r)	Round-Key Length (word)	Number of Round-Keys ($N_r + 1$)	Total Size of Round-Keys ($N_b(N_r + 1)$)
AES-128	4	4	10	4	11	44 (176-byte)
AES-192	4	6	12	4	13	52 (208-byte)
AES-256	4	8	14	4	15	60 (240-byte)

Code 2.1: include/block_cipher/block_cipher.h

```c
/* Forward declaration for the context. */
typedef struct BlockCipherContext BlockCipherContext;

/* The vtable or function pointer set describing any block cipher. */
typedef struct BlockCipherApi {
	const char *name; /* e.g. "AES" or "MyCipher" */

	/* Initialize the cipher with the chosen block size and key. */
	int (*init)(
		BlockCipherContext* ctx,
		size_t block_size,
		const u8* key,
		size_t key_len
	);
	/* Encrypt exactly one block. */
	void (*encrypt_block)(
		BlockCipherContext* ctx,
		const u8* plaintext,
		u8* ciphertext
	);
	/* Decrypt exactly one block. */
		void (*decrypt_block)(
		BlockCipherContext* ctx,
		const u8* ciphertext,
		u8* plaintext
	);
	/* Clean up resources, if needed. */
	void (*dispose)(
```

```c
                     BlockCipherContext* ctx
        );

} BlockCipherApi;

/* The context structure storing state. */
struct BlockCipherContext {
        const BlockCipherApi *api;
        u8 internal_data[256]; /* Example placeholder for key schedule, etc. */
};
```

Code 2.2: include/block_cipher/block_cipher_aes.h

```c
const BlockCipherApi* get_aes_api(void);
```

Code 2.3: src/block_cipher/block_cipher_aes.c

```c
typedef struct AesInternal {
        size_t block_size; /* Typically must be 16 for AES */
        size_t key_len; /* 16, 24, or 32 for AES-128/192/256 */
        u32 round_keys[60];
        int nr; /* e.g., 10 for AES-128, 12, or 14... */
} AesInternal;
```

2.1.2 ARIA (Academy, Research Institute, and Agency)

2.1.3 LEA (Lightweight Encryption Algorithm)

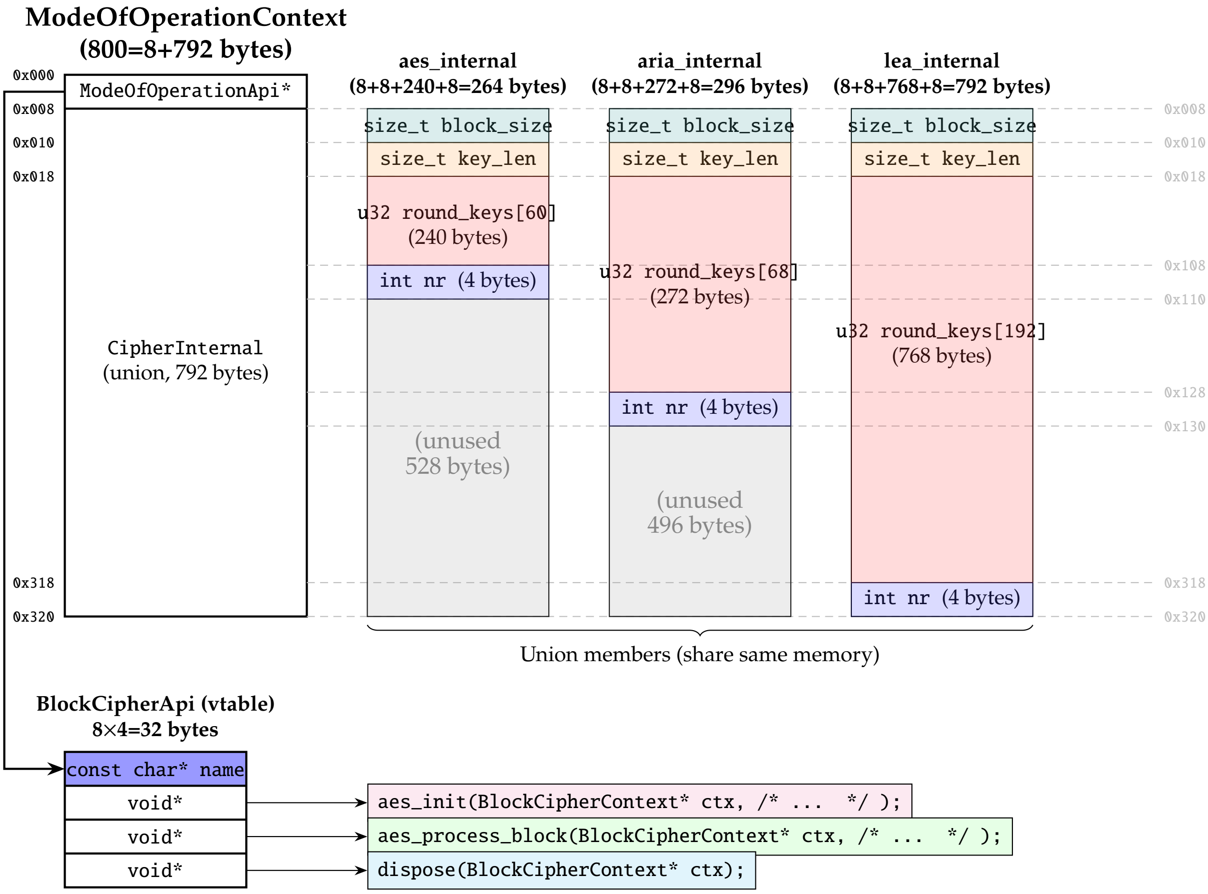
2.2 Modes of Operation

```c
typedef struct __ModeOfOperationApi__ {
	const char *name;
	void (*init)( /* ... */ );
	void (*process)( /* ... */ );
	void (*dispose)( /* ... */ );
} ModeOfOperationApi;

typedef union __ModeInternal__ {
	struct __cbc_internal__ {
		/* ... */
	} cbc_internal;
	struct __ctr_internal__ {
		/* ... */
	} ctr_internal;
	struct __gcm_internal__ {
		/* ... */
	} gcm_internal;
	struct __ecb_internal__ {
		/* ... */
	} ecb_internal;

} ModeInternal;

typedef struct __ModeOfOperationContext__ {
	const ModeOfOperationApi *api; // Pointer to the mode API
	BlockCipherContext cipher_ctx; // Block cipher context
	ModeInternal internal_data; // Internal state for the mode
} ModeOfOperationContext;
```

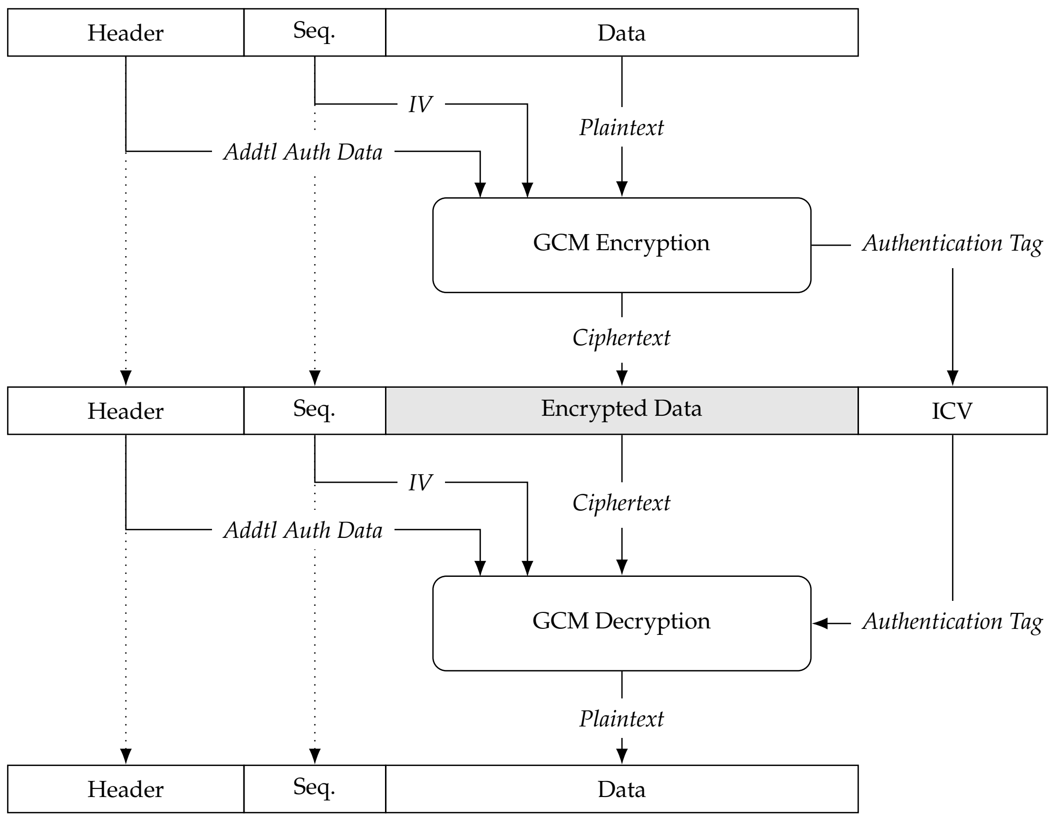


2.2.1 ECB

2.2.2 CBC

2.2.3 CTR

2.3 Galois Counter Mode (GCM)



2.3.1 Multiplication in GF(2^{128})

Definition 2.1. Let $\mathbb{F}_2 = \{0, 1\}$ be the field with two elements. Fix an irreducible polynomial

$$f(x) \;=\; x^{128} + x^7 + x^2 + x + 1 \quad \in \mathbb{F}_2[x].$$

Then

$$\mathrm{GF}(2^{128}) \;=\; \mathbb{F}_2[x] \,/\, \big(f(x)\big)$$

is the degree-128 extension field.

Remark 2.1. Every element $\alpha \in \mathrm{GF}(2^{128})$ can be written uniquely as

$$\alpha \;=\; a_{127}x^{127} + a_{126}x^{126} + \cdots + a_1 x + a_0 \quad (a_i \in \{0, 1\}).$$

We identify α with the 128-bit vector $(a_0, \ldots, a_{127}) \in \mathbb{F}_2$.

Polynomial Representation and Reduction Multiplication in $\mathbb{F}_2[x]$ is carry-less:

$$\left(\sum_i a_i x^i\right) \cdot \left(\sum_j b_j x^j\right) = \sum_{i,j} \left(a_i b_j\right) \, x^{i+j},$$

with all additions mod 2. To get the product in GF(2^{128}), we then reduce the degree-$\leq$ 254 result modulo $f(x)$.

Bit-Level Algorithm We implement multiplication by a simple "shift-and-add" method with reduction on each shift, often called `xtime`.

Definition 2.2 (`xtime` map). For $v \in \mathrm{GF}(2^{128})$ represented as a 128-bit word, define

$$\texttt{xtime}(v) = \begin{cases} v \ll 1, & \text{if the MSB of } v \text{ is } 0, \\ (v \ll 1) \oplus R, & \text{if the MSB of } v \text{ is } 1, \end{cases}$$

where R is the bit-vector corresponding to the reduction polynomial $x^7 + x^2 + x + 1$.

Pseudocode

Algorithm 1 Multiply two field elements $a, b \in \mathrm{GF}(2^{128})$

Require: $a, b \in \{0,1\}^{128}$ as 128-bit words
Ensure: $c = a \cdot b \bmod f(x)$

$c \leftarrow 0$
$v \leftarrow a$
for $i = 0$ to 127 **do**
  if bit i of b is 1 **then**
    $c \leftarrow c \oplus v$
  end if
  $v \leftarrow \texttt{xtime}(v)$
end for
return c

References: [oST], [MV04]

2.4 Random Number Generator

2.5 Hash Functions

2.6 Message Authentication Codes

2.7 Key Derivation Functions

2.8 Key Exchange

2.9 Signature Algorithms

Chapter 3

Build and Integration

Chapter 4

Testing

Bibliography

[MV04] David A. McGrew and John Viega. The galois/counter mode of operation (gcm). Technical report, Submission to NIST Modes of Operation Process, Cisco Systems, Inc. and Secure Software, January 2004. Initial version posted January 15, 2004.

[oST] National Institute of Standards and Technology. Galois/counter mode (gcm) and gmac.

Appendices