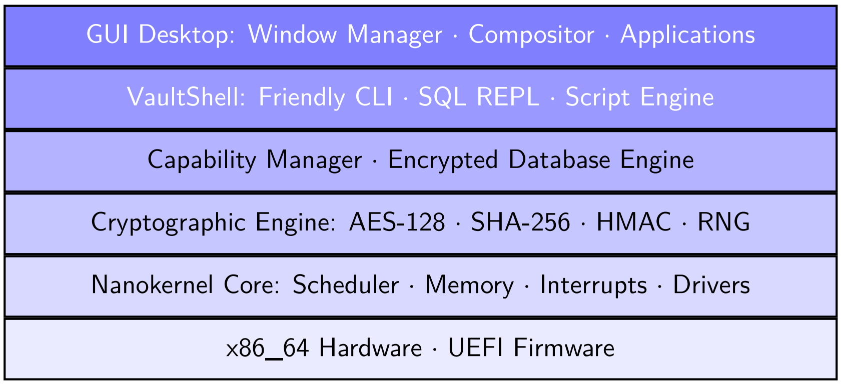
VaultOS

A Capability-Secured Nanokernel with Database-Centric Architecture

Design, Algorithms, and Implementation



GUI Desktop: Window Manager · Compositor · Applications
VaultShell: Friendly CLI · SQL REPL · Script Engine
Capability Manager · Encrypted Database Engine
Cryptographic Engine: AES-128 · SHA-256 · HMAC · RNG
Nanokernel Core: Scheduler · Memory · Interrupts · Drivers
x86_64 Hardware · UEFI Firmware

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Preface

VaultOS is a nanokernel operating system built on two radical premises:

1. **Everything is a database.** There is no file system, no `/proc`, no device files. Every system resource—processes, capabilities, messages, user data—is a row in an encrypted relational table, accessible only through a SQL-subset query language.

2. **All data is confidential.** Every database record is encrypted with AES-128-CBC using per-table keys derived from a master secret via HMAC-SHA256. Every access requires a cryptographically sealed capability token that proves authorization.

VaultOS deliberately rejects POSIX. There are no file descriptors, no `fork()`, no signals, no pipes, and no user/group permission bits. Instead, the system provides a small, formally analyzable interface: database queries mediated by unforgeable capability tokens.

Conventions. Algorithms are presented in the pseudocode style of Cormen, Leiserson, Rivest, and Stein (CLRS). We use $\mathcal{O}$-notation for asymptotic analysis. Diagrams use TikZ. Source code excerpts are in C or x86-64 assembly.

Part I

Foundations

Chapter 1

Introduction and Design Philosophy

1.1 The Database-as-OS Paradigm

Traditional operating systems expose heterogeneous interfaces: a file system for persistent storage, `/proc` for process metadata, signals for asynchronous notification, and sockets for communication. Each subsystem has its own access-control model, its own naming scheme, and its own failure modes.

VaultOS replaces this patchwork with a single abstraction: the *encrypted relational table*. Six system tables (Table 1.1) store all kernel state. User interaction proceeds entirely through a SQL-subset query language executed by the VaultShell REPL.

Table 1.1: VaultOS system tables.

ID	Table	Encrypted	Purpose
0	`SystemTable`	Yes	Boot metadata (OS name, version)
1	`ProcessTable`	Yes	Active processes (PID, state, capabilities)
2	`CapabilityTable`	Yes	HMAC-sealed access tokens
3	`ObjectTable`	Yes	User-defined objects (data blobs)
4	`MessageTable`	Yes	IPC message queue
5	`AuditTable`	Yes	Security audit log

Definition 1.1 (Database-as-OS)**.** An operating system in which every named resource r has a canonical representation as a tuple $\langle \mathrm{id}, \mathrm{col}_1, \ldots, \mathrm{col}_k \rangle$ in a table T, and every operation on r is expressed as a query $Q \in \{\textsc{Select}, \textsc{Insert}, \textsc{Update}, \textsc{Delete}\}$ over T.

1.2 Capability-Based Security Model

Access control in VaultOS is based on *capabilities*: unforgeable tokens that encode a subject's rights over an object.

Definition 1.2 (Capability)**.** A capability is a tuple

$$c = (\text{cap\_id},\ \text{obj\_id},\ \text{type},\ \text{owner},\ \text{rights},\ \text{parent},\ \sigma)$$

where $\sigma = \text{HMAC-SHA256}(K_{\text{master}},\ \text{cap\_id}\|\text{obj\_id}\|\text{owner}\|\text{rights}\|\text{type}\|\text{parent})$ is a 256-bit cryptographic seal.

Rights are encoded as a 6-bit mask:

Bit	**Right**	**Value**
0	Read	2^0
1	Write	2^1
2	Execute	2^2
3	Delete	2^3
4	Grant	2^4
5	Revoke	2^5

Theorem 1.3 (Capability Unforgeability)**.** *An adversary who does not know the master key K_{master} cannot produce a valid capability c' (one whose HMAC verifies) except with probability negligible in $|K_{\text{master}}|$, assuming HMAC-SHA256 is a secure PRF.*

Proof. If an adversary could forge a capability c' with non-negligible probability, they could construct a distinguisher for HMAC-SHA256 as a PRF, contradicting the assumed security of the construction (RFC 2104). The 40-byte input domain is fixed, so no length-extension attacks apply. □

1.3 Threat Model

VaultOS protects against:

- **Unauthorized data access:** All records encrypted; queries require valid capabilities.
- **Capability forgery:** HMAC-SHA256 seal prevents fabrication.
- **Timing side-channels:** Constant-time HMAC comparison prevents timing attacks.
- **Privilege escalation:** Delegated capabilities are strict subsets of parent rights.

Out of scope (MVP): cold-boot attacks, hardware Trojans, DMA attacks, Spectre/Meltdown.

Cryptographic RNG dependency. The security of all encryption and capability operations depends on the availability of hardware `RDRAND` (Intel Ivy Bridge and later). When `RDRAND` is unavailable, VaultOS falls back to a `RDTSC`-seeded `xorshift128+` generator, which provides statistical but *not* cryptographic randomness. In virtualised environments where TSC values are predictable, this fallback weakens all security guarantees—IVs become predictable and capability tokens lose unforgeability. The system logs a warning at boot when operating in fallback mode.

1.4 System Architecture Overview

Figure 1.1 shows the layered architecture.

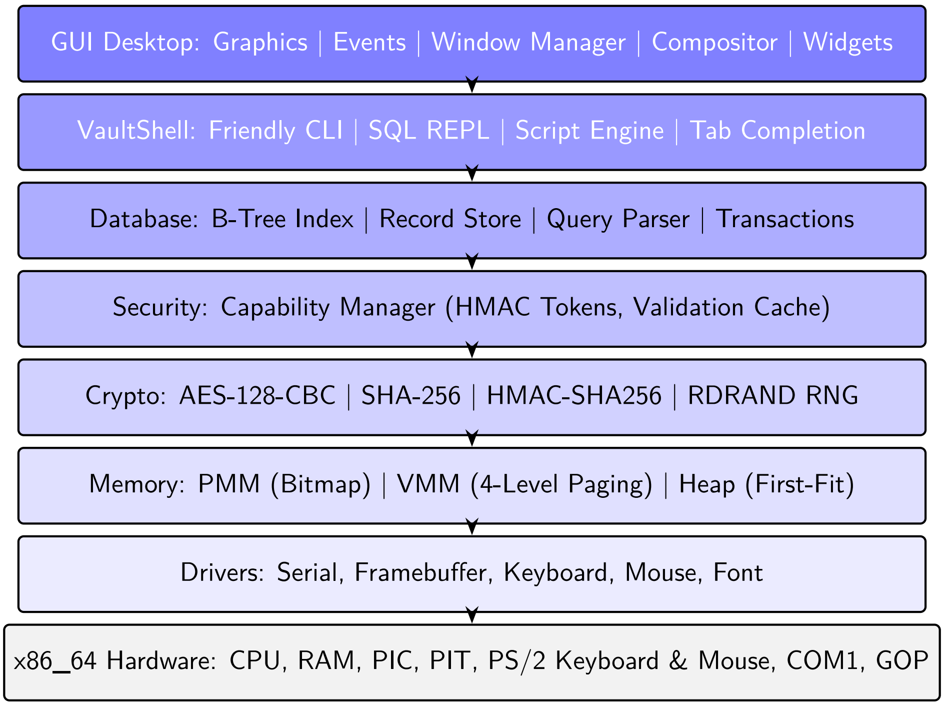
GUI Desktop: Graphics | Events | Window Manager | Compositor | Widgets
VaultShell: Friendly CLI | SQL REPL | Script Engine | Tab Completion
Database: B-Tree Index | Record Store | Query Parser | Transactions
Security: Capability Manager (HMAC Tokens, Validation Cache)
Crypto: AES-128-CBC | SHA-256 | HMAC-SHA256 | RDRAND RNG
Memory: PMM (Bitmap) | VMM (4-Level Paging) | Heap (First-Fit)
Drivers: Serial, Framebuffer, Keyboard, Mouse, Font
x86_64 Hardware: CPU, RAM, PIC, PIT, PS/2 Keyboard & Mouse, COM1, GOP

Figure 1.1: VaultOS layered architecture. Each layer depends only on the layers below it.

1.5 Comparison with Traditional OS Designs

Table 1.2: VaultOS vs. POSIX-based operating systems.

Aspect	**POSIX**	**VaultOS**
Resource abstraction	Files, sockets, pipes	Database rows
Access control	uid/gid, rwx bits	HMAC-sealed capabilities
Naming	Hierarchical paths	Table + row ID
IPC	Pipes, signals, shmem	Message table + queries
Process interface	`fork/exec/wait`	`proc_create/exit`
Encryption	Optional (dm-crypt, etc.)	Mandatory, per-table
Audit	Syslog (optional)	Built-in AuditTable
User interface	Shell + utilities	Friendly CLI + SQL REPL + GUI Deskto

Chapter 2

System Bootstrap

2.1 UEFI Boot Protocol

The bootloader is a PE32+ EFI application compiled against GNU-EFI. It executes the following steps:

1. Initialize the Graphics Output Protocol (GOP) at 1024 × 768 resolution.
2. Open the FAT32 system partition and load `VAULTOS.BIN` at physical address `0x100000` (1 MiB).
3. Acquire the UEFI memory map (with retry around `ExitBootServices`).
4. Locate the ACPI RSDP from the EFI configuration tables.
5. Transfer control to `kernel_main(BootInfo *)` at the kernel physical base.

2.2 BootInfo Structure

The bootloader passes a packed structure containing framebuffer parameters, the UEFI memory map, kernel location, and runtime service pointers:

Listing 2.1: BootInfo structure (simplified).

```c
typedef struct __attribute__((packed)) {
    uint64_t fb_base, fb_width, fb_height, fb_pitch;
    uint32_t fb_bpp, fb_pixel_format;
    uint64_t mmap_base, mmap_size, mmap_desc_size;
    uint32_t mmap_entry_count;
    uint64_t kernel_phys_base, kernel_size;
    uint64_t rsdp_address;
} BootInfo;
```

2.3 Kernel Initialization Sequence

The kernel initializes ten subsystems in strict dependency order (Figure 2.1).

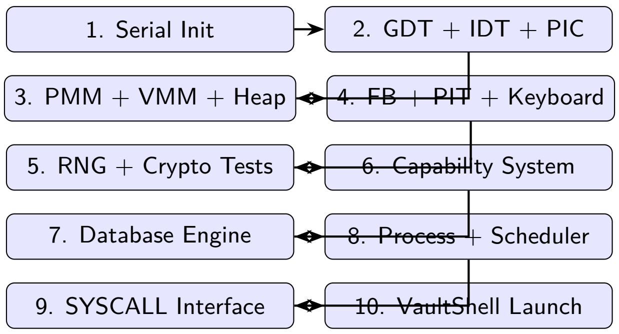

Figure 2.1: Kernel initialization sequence. Each phase depends on all preceding phases.

2.4 Higher-Half Kernel Design

The kernel is linked at virtual address `0xFFFFFFFF80000000` but loaded at physical address `0x100000`. This *higher-half* design reserves the lower 128 TiB of virtual space for user processes.

Definition 2.1 (Virtual Address Space Layout)**.** The 48-bit canonical virtual address space is partitioned as follows:

`0x0000000000000000`–`0x00007FFFFFFFFFFF`	User space (128 TiB)
`0xFFFFFFFF80000000`–`0xFFFFFFFF81FFFFFF`	Kernel code/data (2 MiB)
`0xFFFFFFFF82000000`–`0xFFFFFFFF91FFFFFF`	Kernel heap (256 MiB)
`0xFFFFFFFF92000000`–`0xFFFFFFFFBFFFFFFF`	Physical direct map (up to 1 GiB)
`0xFFFFFFFFC0000000`–`0xFFFFFFFFCFFFFFFF`	Framebuffer

Part II

Memory Management

Chapter 3

Physical Memory Manager

The physical memory manager (PMM) tracks the availability of 4 KiB physical pages using a bitmap data structure.

3.1 Bitmap Allocator Design

Definition 3.1 (Page Bitmap)**.** Let $N = \lfloor M/4096 \rfloor$ be the number of physical pages, where M is the total physical memory in bytes. The bitmap $B[0 \ldots \lceil N/64 \rceil - 1]$ is an array of 64-bit words where bit i of word $B[\lfloor i/64 \rfloor]$ is 1 if page i is allocated, and 0 if free.

For 4 GiB of RAM, $N = 2^{20}$ pages and the bitmap occupies $2^{20}/8 = 128$ KiB—a fixed overhead of 0.003%.

3.2 Algorithm: Pmm-Alloc

Algorithm 1: Pmm-Alloc(): Allocate one physical page.

```
1 for $w \leftarrow 0$ to $\lceil N/64 \rceil - 1$ do
2     if $B[w] \neq$ 0xFFFFFFFFFFFFFFFF then
3         $b \leftarrow$ index of lowest clear bit in $B[w]$
           // __builtin_ctzll(~B[w])
4         page $\leftarrow 64w + b$
5         if $page < N$ then
6             set bit $b$ in $B[w]$
7             used_pages $\leftarrow$ used_pages $+ 1$
8             return page $\times$ 4096                    // physical address
9 return 0                                                   // out of memory
```

3.3 Algorithm: Pmm-Free

Algorithm 2: PMM-FREE(phys_addr): Free one physical page.

```
1 page ← phys_addr/4096
2 if $page \geq N$ or $bit$ ($page \bmod 64$) $of$ $B[\lfloor page/64 \rfloor]$ $is$ $clear$ then
3     error "double free or invalid page"
4 clear bit (page mod 64) in $B[\lfloor \text{page}/64 \rfloor]$
5 used_pages ← used_pages − 1
```

3.4 Complexity Analysis

Theorem 3.2 (PMM Allocation Complexity)**.** *PMM-ALLOC runs in $\mathcal{O}(N/64)$ worst-case time and $\mathcal{O}(1)$ best-case time, where N is the number of physical pages.*

Proof. The outer loop iterates over at most $\lceil N/64 \rceil$ words. Each iteration performs a constant-time comparison and bit scan. In the best case, the first word contains a free bit. In the worst case, all words must be scanned. The per-word bit scan (`ctzll`) executes in $\mathcal{O}(1)$ on x86-64 via the `BSF`/`TZCNT` instruction. □

Chapter 4

Virtual Memory and Paging

4.1 x86-64 Four-Level Page Tables

The x86-64 architecture uses a four-level radix tree to translate 48-bit virtual addresses to physical addresses.

Definition 4.1 (Page Table Entry)**.** A 64-bit page table entry (PTE) encodes:

$$\text{PTE} = \underbrace{\text{phys\_addr}[51:12]}_{\text{40 bits}} \parallel \underbrace{\text{flags}[11:0]}_{\text{12 bits}}$$

where flags include Present (P), Writable (W), User (U), and No-Execute (NX, bit 63).

Definition 4.2 (Virtual Address Decomposition)**.** A 48-bit virtual address v is decomposed as:

$$\begin{aligned}
\text{PML4 index} &= (v \gg 39) \mathbin{\&} \texttt{0x1FF} \\
\text{PDPT index} &= (v \gg 30) \mathbin{\&} \texttt{0x1FF} \\
\text{PD index} &= (v \gg 21) \mathbin{\&} \texttt{0x1FF} \\
\text{PT index} &= (v \gg 12) \mathbin{\&} \texttt{0x1FF} \\
\text{Offset} &= v \mathbin{\&} \texttt{0xFFF}
\end{aligned}$$

4.2 Virtual Address Space Layout

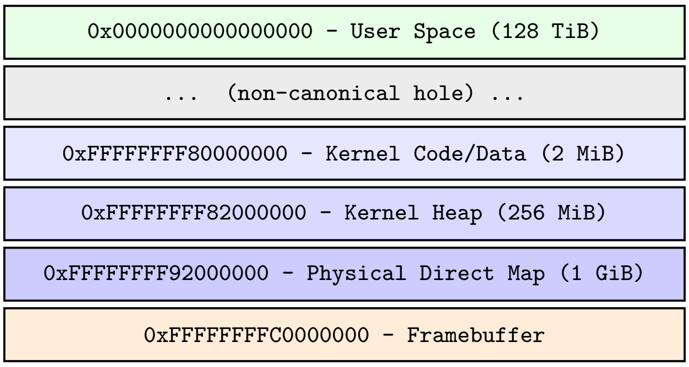
0x0000000000000000 - User Space (128 TiB)
... (non-canonical hole) ...
0xFFFFFFFF80000000 - Kernel Code/Data (2 MiB)
0xFFFFFFFF82000000 - Kernel Heap (256 MiB)
0xFFFFFFFF92000000 - Physical Direct Map (1 GiB)
0xFFFFFFFFC0000000 - Framebuffer

Figure 4.1: Virtual address space layout of the VaultOS kernel.

4.3 Algorithm: Page-Map

Algorithm 3: PAGE-MAP(pml4, virt, phys, flags): Map a virtual page to a physical frame.

```
pml4e ← pml4[PML4_INDEX(virt)]
if pml4e is not present then
    allocate a zeroed page for PDPT
    pml4[PML4_INDEX(virt)] ← pdpt_phys | P | W
pdpt ← extract address from pml4e
// Repeat for PDPT → PD → PT
// (Each level: check present, allocate if needed, descend)
pt[PT_INDEX(virt)] ← phys | flags
```

4.4 Algorithm: Virt-To-Phys

Algorithm 4: VIRT-TO-PHYS(pml4, virt): Translate virtual to physical address.

```
Walk PML4 → PDPT → PD → PT using index functions
if any level is not present then
    return 0                                   // page not mapped
if PD entry has Huge flag (2 MiB page) then
    return pd_phys | (virt & 0x1FFFFF)
return pt_phys | (virt & 0xFFF)
```

Theorem 4.3 (Translation Correctness). *For any virtual address v mapped via* PAGE-MAP *to physical address p with flags f, a subsequent call to* VIRT-TO-PHYS *returns p, provided no intervening unmap or CR3 reload invalidates the* *mapping.*

Proof sketch. PAGE-MAP(v, p, f) writes the entry (base $= p$, flags $= f$) into the page-table entry (PTE) selected by the level-1 index of v. The four-level walk in VIRT-TO-PHYS extracts exactly the same indices from v (bits 47–39, 38–30, 29–21, 20–12) and follows the same PML4→PDP→PD→PT chain. At the final level it reads the PTE base address, which is p. Since x86-64 address translation is deterministic for a given CR3 and page-table contents, the result follows. The "no intervening unmap" proviso ensures the PTE has not been cleared between the two calls. $\square$

Chapter 5

Kernel Heap Allocator

5.1 First-Fit with Coalescing

The kernel heap is a doubly-linked list of blocks, each preceded by a header:

Listing 5.1: Heap block header.

```c
typedef struct heap_block {
    uint64_t     magic;     /* 0xDEADBEEF */
    size_t       size;      /* usable data bytes */
    bool         free;
    heap_block_t *next, *prev;
} heap_block_t;
```

5.2 Algorithm: Kmalloc

Algorithm 5: KMALLOC(n): Allocate n bytes from the kernel heap.

```
1  $n \leftarrow$ ALIGN-UP($n, 16$)
2  $b \leftarrow$ head of block list
3  while $b \neq$ nil do
4      if $b.free$ and $b.size \geq n$ then
5          if $b.size - n > sizeof(header) + 32$ then
6              SPLIT($b$, $n$)          // create free block from remainder
7          $b.free \leftarrow$ false
8          return pointer to $b$'s data area
9      $b \leftarrow b.next$
10 return nil                                   // out of memory
```

5.3 Algorithm: Kfree with Coalescing

Algorithm 6: KFREE(p): Free a previously allocated block and coalesce neighbors.

```
1  $b \leftarrow$ block header preceding $p$
2  assert $b.magic = \texttt{0xDEADBEEF}$
3  $b.free \leftarrow$ true
   // Forward coalescing
4  if $b.next \neq$ nil and $b.next.free$ then
5      $b.size \leftarrow b.size + \text{sizeof(header)} + b.next.size$
6      $b.next \leftarrow b.next.next$
7      if $b.next \neq$ nil then
8          $b.next.prev \leftarrow b$
   // Backward coalescing
9  if $b.prev \neq$ nil and $b.prev.free$ then
10     $b.prev.size \leftarrow b.prev.size + \text{sizeof(header)} + b.size$
11     $b.prev.next \leftarrow b.next$
12     if $b.next \neq$ nil then
13         $b.next.prev \leftarrow b.prev$
```

Theorem 5.1 (Heap Invariant)**.** *After any sequence of* KMALLOC *and* KFREE *operations, no two adjacent blocks in the free list are both free.*

Proof. KFREE explicitly coalesces with both the predecessor and successor blocks. If either neighbor is free, the blocks are merged. Therefore, upon return from KFREE, the freed block has no free neighbor, maintaining the invariant. KMALLOC can only split a free block into (allocated, free), which cannot create adjacent free blocks. □

Part III

Cryptographic Primitives

Chapter 6

SHA-256

SHA-256 is the foundation of VaultOS's integrity guarantees. It is used in HMAC for capability sealing and in key derivation for per-table encryption.

6.1 Merkle-Damgård Construction

SHA-256 follows the Merkle-Damgård paradigm: the message is padded to a multiple of 512 bits, then processed in 512-bit (64-byte) blocks. Each block is compressed into the running 256-bit state.

Definition 6.1 (SHA-256 State)**.** The state consists of eight 32-bit words $H_0, \ldots, H_7$ initialized to the fractional parts of the square roots of the first eight primes:

$$H_0 = \texttt{6a09e667}, \quad H_1 = \texttt{bb67ae85}, \quad \ldots, \quad H_7 = \texttt{5be0cd19}$$

6.2 Compression Function

Algorithm 7: SHA256-Transform($H[0..7]$, block[0..63]): Process one 512-bit block.

```
   // Message schedule
1  for $i \leftarrow 0$ to 15 do
2      $W[i] \leftarrow$ big-endian 32-bit word from block[$4i \ldots 4i{+}3$]
3  for $i \leftarrow 16$ to 63 do
4      $W[i] \leftarrow \sigma_1(W[i-2]) + W[i-7] + \sigma_0(W[i-15]) + W[i-16]$
   // Initialize working variables
5  $a, b, c, d, e, f, g, h \leftarrow H[0], H[1], \ldots, H[7]$
   // Compression rounds
6  for $i \leftarrow 0$ to 63 do
7      $T_1 \leftarrow h + \Sigma_1(e) + \mathrm{Ch}(e, f, g) + K_i + W[i]$
8      $T_2 \leftarrow \Sigma_0(a) + \mathrm{Maj}(a, b, c)$
9      $h \leftarrow g;\ g \leftarrow f;\ f \leftarrow e;\ e \leftarrow d + T_1$
10     $d \leftarrow c;\ c \leftarrow b;\ b \leftarrow a;\ a \leftarrow T_1 + T_2$
   // Update state
11 $H[i] \leftarrow H[i] + \{a, b, c, d, e, f, g, h\}_i$ for $i = 0, \ldots, 7$
```

The mixing functions are defined as:

$$
\begin{aligned}
\mathrm{Ch}(x, y, z) &= (x \wedge y) \oplus (\neg x \wedge z) \\
\mathrm{Maj}(x, y, z) &= (x \wedge y) \oplus (x \wedge z) \oplus (y \wedge z) \\
\Sigma_0(x) &= \mathrm{ROTR}^2(x) \oplus \mathrm{ROTR}^{13}(x) \oplus \mathrm{ROTR}^{22}(x) \\
\Sigma_1(x) &= \mathrm{ROTR}^6(x) \oplus \mathrm{ROTR}^{11}(x) \oplus \mathrm{ROTR}^{25}(x) \\
\sigma_0(x) &= \mathrm{ROTR}^7(x) \oplus \mathrm{ROTR}^{18}(x) \oplus (x \gg 3) \\
\sigma_1(x) &= \mathrm{ROTR}^{17}(x) \oplus \mathrm{ROTR}^{19}(x) \oplus (x \gg 10)
\end{aligned}
$$

6.3 Block-Based Update

Algorithm 8: SHA256-Update(ctx, data, len): Incrementally feed data to the hash function.

```
buffered ← ctx.count mod 64
ctx.count ← ctx.count + len
if $buffered > 0$ then
    need ← 64 − buffered
    if $len < need$ then
        copy data to buffer at offset buffered
        return
    copy need bytes to complete buffer
    SHA256-Transform(ctx.state, ctx.buffer)
    advance data by need;
    len ← len − need
while $len \geq 64$ do
    SHA256-Transform(ctx.state, data)        // process directly
    advance data by 64;
    len ← len − 64
if $len > 0$ then
    copy remaining len bytes to ctx.buffer
```

Observation 6.2. The block-based update processes aligned 64-byte blocks directly from the input buffer, avoiding 64× per-byte overhead compared to a naïve byte-at-a-time approach. For HMAC computation of a 64-byte ipad, this processes the entire block in a single call to SHA256-Transform.

Chapter 7

AES-128

AES-128 provides confidentiality for all database records. VaultOS implements both a software path with precomputed lookup tables and a hardware-accelerated path using AES-NI instructions.

7.1 Rijndael Cipher Structure

AES-128 operates on 128-bit (16-byte) blocks using a 128-bit key, performing 10 rounds of transformations on a 4×4 byte matrix called the *state*.

Definition 7.1 (AES Round)**.** Each round (except the last) applies four transformations:

$$\text{Round}(s, k_r) = \textsc{AddRoundKey}(\textsc{MixColumns}(\textsc{ShiftRows}(\textsc{SubBytes}(s))), k_r)$$

The final round omits MixColumns.

7.2 GF(2^8) Arithmetic and Precomputed Tables

The MixColumns step requires multiplication in GF(2^8) with the irreducible polynomial $x^8 + x^4 + x^3 + x + 1$ (= `0x11B`).

Rather than computing these multiplications at runtime (8 iterations per byte), VaultOS uses six precomputed 256-byte lookup tables:

Table	Usage
mul2[256]	MixColumns: $\{2\} \cdot x$
mul3[256]	MixColumns: $\{3\} \cdot x$
mul9[256]	InvMixColumns: $\{9\} \cdot x$
mul11[256]	InvMixColumns: $\{b\} \cdot x$
mul13[256]	InvMixColumns: $\{d\} \cdot x$
mul14[256]	InvMixColumns: $\{e\} \cdot x$

This replaces $48 \times 8 = 384$ loop iterations per block with 48 table lookups.

7.3 Algorithm: AES-Key-Expand

Algorithm 9: AES-KEY-EXPAND(key[0..15]): Expand 128-bit key to 11 round keys.

```
w[0..3] ← 32-bit words from key
for $i ← 4$ to 43 do
    temp ← $w[i-1]$
    if $i \bmod 4 = 0$ then
        temp ← SubWord(RotWord(temp)) ⊕ Rcon[$i/4$]
    $w[i] ← w[i-4]$ ⊕ temp
```

7.4 Algorithm: AES-Encrypt-Block

Algorithm 10: AES-ENCRYPT-BLOCK(ctx, block[0..15]): Encrypt one 128-bit block.

```
AddRoundKey(block, ctx.rk[0])
for $r ← 1$ to 9 do
    SubBytes(block)                        // S-box lookup, 16 bytes
    ShiftRows(block)                       // cyclic row rotations
    MixColumns(block)                      // GF($2^8$) via lookup tables
    AddRoundKey(block, ctx.rk[$r$])
SubBytes(block)
ShiftRows(block)
AddRoundKey(block, ctx.rk[10])
```

7.5 CBC Mode

Algorithm 11: AES-CBC-ENCRYPT(ctx, iv, pt, ct, len)

```
prev ← iv
for $off ← 0$ to $len - 16$ step 16 do
    for $i ← 0$ to 15 do
        ct[off + $i$] ← pt[off + $i$] ⊕ prev[$i$]
    AES-Encrypt-Block(ctx, ct + off)
    prev ← ct + off                        // pointer, no copy
```

Observation 7.2. The CBC encrypt implementation avoids redundant `memcpy` by maintaining a pointer to the previous ciphertext block rather than copying it to a temporary buffer. This eliminates 2 of 3 `memcpy` calls per block.

7.6 AES-NI Hardware Acceleration

When the CPU supports AES-NI (detected via `CPUID.01H:ECX[25]`), VaultOS dispatches to a hardware-accelerated path:

Listing 7.1: AES-NI encrypt (inline assembly sketch).

```
movdqu   (%block), %xmm0        ; Load plaintext block
pxor     0(%rk),   %xmm0        ; AddRoundKey 0
aesenc   16(%rk),  %xmm0        ; Rounds 1-9 (9 instructions
    )
aesenc   32(%rk),  %xmm0
; ... (rounds 3-9) ...
aesenclast 160(%rk), %xmm0      ; Final round
movdqu   %xmm0,    (%block)     ; Store ciphertext
```

For decryption, each intermediate round key must be transformed via `AESIMC` (InvMixColumns) before use with `AESDEC`.

Table 7.1: AES-128-CBC performance: 1 KiB × 100 iterations.

Operation	**AES-NI (Haswell)**	**Software (Nehalem)**	**Speedup**
Encrypt	29,388 cycles/op	217,929 cycles/op	7.4×
Decrypt	39,023 cycles/op	284,357 cycles/op	7.3×

Theorem 7.3 (CBC IND-CPA Security). *AES-128-CBC with random IVs is IND-CPA secure (indistinguishable under chosen-plaintext attack) assuming AES is a pseudorandom permutation (PRP), up to 2^{64} blocks (the birthday bound on 128-bit blocks).*

Chapter 8

HMAC-SHA256 and Random Number Generation

8.1 HMAC Construction

HMAC-SHA256 (RFC 2104) provides message authentication:

$$\mathrm{HMAC}(K, m) = \mathrm{SHA256}((K \oplus \mathrm{opad}) \parallel \mathrm{SHA256}((K \oplus \mathrm{ipad}) \parallel m))$$

where ipad = $\texttt{0x36}^{64}$ and opad = $\texttt{0x5C}^{64}$.

8.2 Pre-computed Context

Since the master key K is fixed at boot, VaultOS pre-computes the SHA-256 state after processing the ipad and opad blocks:

Algorithm 12: HMAC-Init(ctx, K, klen): Pre-compute HMAC state for key K.

```
1 if $klen > 64$ then
2     $K' \leftarrow \mathrm{SHA256}(K)$;   pad to 64 bytes with zeros
3 else
4     $K' \leftarrow K$ padded to 64 bytes with zeros
5 $\mathrm{ipad}[i] \leftarrow K'[i] \oplus \texttt{0x36}$ for $i = 0, \ldots, 63$
6 $\mathrm{opad}[i] \leftarrow K'[i] \oplus \texttt{0x5C}$ for $i = 0, \ldots, 63$
7 $\mathrm{ctx.inner\_base} \leftarrow \mathrm{SHA256\text{-}Update}(\mathrm{SHA256\text{-}Init}(), \mathrm{ipad}, 64)$
8 $\mathrm{ctx.outer\_base} \leftarrow \mathrm{SHA256\text{-}Update}(\mathrm{SHA256\text{-}Init}(), \mathrm{opad}, 64)$
```

Algorithm 13: HMAC-Compute(ctx, data, len, mac): Compute HMAC using pre-computed context.

```
1 inner ← clone(ctx.inner_base)
2 SHA256-Update(inner, data, len)
3 SHA256-Final(inner, inner_hash)
4 outer ← clone(ctx.outer_base)
5 SHA256-Update(outer, inner_hash, 32)
6 SHA256-Final(outer, mac)
```

Observation 8.1. Pre-computing the HMAC context eliminates re-hashing the 128 bytes of ipad and opad for every HMAC computation. For capability validation (40-byte payload), this reduces SHA-256 block processing from 4 blocks to 2 blocks per HMAC—a $\sim 3\times$ speedup.

8.3 Constant-Time Verification

Algorithm 14: HMAC-Verify($a[0..n-1]$, $b[0..n-1]$): Constant-time comparison.

```
1 diff ← 0
2 for $i \leftarrow 0$ to $n-1$ do
3     diff ← diff | $(a[i] \oplus b[i])$
4 return diff = 0
```

The OR-accumulation ensures the loop runs in exactly n iterations regardless of where mismatches occur, preventing timing side-channel attacks.

8.4 Random Number Generation

VaultOS seeds its entropy pool from the `RDRAND` instruction (when available) and falls back to `RDTSC`-based seeding with an xorshift128+ PRNG.

Theorem 8.2 (HMAC Unforgeability)**.** *Under the assumption that SHA-256 is a pseudorandom function (PRF) when keyed, HMAC-SHA256 is* (t, q, ϵ)*-unforgeable: no adversary running in time* t *and making* q *queries can forge a valid MAC with probability greater than* $\epsilon + q \cdot 2^{-256}$.

Part IV

Data Structures

Chapter 9

B-Tree Index

The database engine indexes every table with a B-tree of order $b = 64$, providing $\mathcal{O}(\log_b n)$ search, insert, and delete operations.

9.1 B-Tree Properties

Definition 9.1 (B-Tree of Order b)**.** A B-tree of order b (maximum branching factor) satisfies:

1. Every node has at most b children and $b - 1$ keys ($= 63$ for $b = 64$).
2. Every non-root internal node has at least $\lceil b/2 \rceil$ children ($= 32$) and $\lceil b/2 \rceil - 1$ keys ($= 31$).
3. The root has at least 2 children (if non-leaf) or 0 keys (if empty tree).
4. A node with k keys has $k + 1$ children (if internal).
5. All leaves appear at the same depth.

In VaultOS, `BTREE_ORDER` $= 64$, so nodes store up to 63 keys and 64 child pointers. Each node occupies approximately $63 \times 8 + 63 \times 8 + 64 \times 8 + 8 = 1{,}520$ bytes, fitting comfortably in L1 cache.

Remark 9.2. Our order b corresponds to CLRS *minimum degree* $t = b/2 = 32$: CLRS requires $t - 1 \leq k \leq 2t - 1$ keys per non-root node, giving $31 \leq k \leq 63$, which matches our $\lceil b/2 \rceil - 1 \leq k \leq b - 1$. Some references (Knuth) define order as the maximum number of keys; ours defines it as the maximum number of children.

9.2 Node Structure

Listing 9.1: B-tree node structure.

```c
typedef struct btree_node {
    uint64_t    keys[63];         /* sorted key array */
    void       *values[63];       /* associated record
        pointers */
    btree_node *children[64];    /* child pointers */
    uint32_t    num_keys;
    bool        is_leaf;
} btree_node_t;
```

9.3 Algorithm: B-Tree-Search

Algorithm 15: B-TREE-SEARCH(x, k): Search for key k in subtree rooted at x.

```
1 $i \leftarrow 0$
2 while $i < x.num\_keys$ and $k > x.keys[i]$ do
3     $i \leftarrow i + 1$
4 if $i < x.num\_keys$ and $k = x.keys[i]$ then
5     return $x.values[i]$
6 if $x.is\_leaf$ then
7     return nil
8 return B-TREE-SEARCH($x.children[i]$, $k$)
```

9.4 Algorithm: B-Tree-Insert

Algorithm 16: B-TREE-INSERT(T, k, v): Insert key k with value v into B-tree T.

```
1 $r \leftarrow T.root$
2 if $r.num\_keys = 63$ then
3     $s \leftarrow$ new node (leaf $=$ false)
4     $s.children[0] \leftarrow r$
5     $T.root \leftarrow s$
6     B-TREE-SPLIT-CHILD($s$, 0)
7     B-TREE-INSERT-NONFULL($s$, $k$, $v$)
8 else
9     B-TREE-INSERT-NONFULL($r$, $k$, $v$)
```

9.5 Algorithm: B-Tree-Split-Child

Algorithm 17: B-TREE-SPLIT-CHILD(x, i): Split full child $x.children[i]$.

```
y ← x.children[i]                        // full child ($y.num\_keys = 63$)
z ← new node ($z.is\_leaf ← y.is\_leaf$)
mid ← 31                                   // median index
// Copy upper half of y to z
for $j ← 0$ to 30 do
    $z.keys[j] ← y.keys[\mathrm{mid}+1+j]$
    $z.values[j] ← y.values[\mathrm{mid}+1+j]$
if not $y.is\_leaf$ then
    for $j ← 0$ to 31 do
        $z.children[j] ← y.children[\mathrm{mid}+1+j]$
$z.num\_keys ← 31$
$y.num\_keys ← 31$
// Promote median key to parent
shift $x.keys[i..], x.children[i{+}1..]$ right by 1
$x.keys[i] ← y.keys[\mathrm{mid}]$
$x.values[i] ← y.values[\mathrm{mid}]$
$x.children[i+1] ← z$
$x.num\_keys ← x.num\_keys + 1$
```

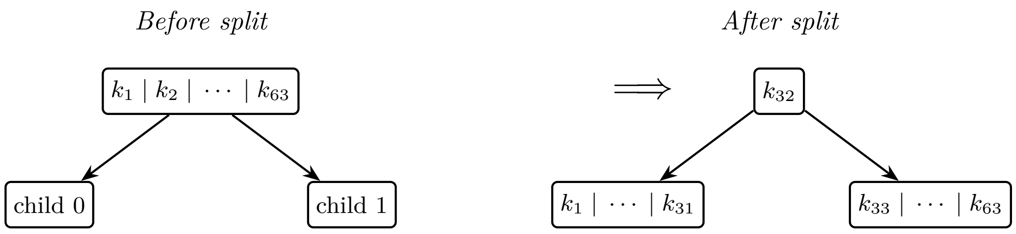
Before split
$k_1 \mid k_2 \mid \cdots \mid k_{63}$
child 0
child 1
$\Longrightarrow$
After split
k_{32}
$k_1 \mid \cdots \mid k_{31}$
$k_{33} \mid \cdots \mid k_{63}$

Figure 9.1: B-tree node split: the median key is promoted to the parent.

Theorem 9.3 (B-Tree Height Bound). *A B-tree of order $b = 64$ (CLRS minimum degree $t = b/2 = 32$) containing n keys has height $h \le \log_t(\frac{n+1}{2}) = \log_{32}(\frac{n+1}{2})$.*

Proof. The root has at least 1 key and 2 children. Every other internal node has at least $t = 32$ children and $t-1 = 31$ keys. At depth $d \ge 1$ there are at least $2t^{d-1}$ nodes, each with at least $t-1$ keys. Summing: $n \ge 1+2(t-1)\sum_{i=0}^{h-1} t^i = 2t^h - 1$, yielding $h \le \log_t(\frac{n+1}{2})$. □

Corollary 9.4. *For $n = 10^6$ keys, $h \le 1 + \log_{32}(500{,}000) \approx 4.8$, so the tree has at most 5 levels. For $n = 10^3$ (typical VaultOS workload), $h \le 3$.*

9.6 Algorithm: B-Tree-Delete (Lazy)

Algorithm 18: B-TREE-DELETE(T, k): Delete key k from B-tree T (lazy MVP).

```
1  $x \leftarrow T.root$
2  while $x \neq NULL$ do
3      $i \leftarrow 0$
4      while $i < x.num\_keys$ and $k > x.keys[i]$ do
5          $i \leftarrow i + 1$
6      if $i < x.num\_keys$ and $k = x.keys[i]$ then
           // Key found at position $i$
7          if $x.is\_leaf$ then
               // Case 1: Leaf node -- shift remaining keys left
8              for $j \leftarrow i$ to $x.num\_keys - 2$ do
9                  $x.keys[j] \leftarrow x.keys[j + 1]$
10                 $x.values[j] \leftarrow x.values[j + 1]$
11             $x.num\_keys \leftarrow x.num\_keys - 1$
12             return TRUE
13         else
               // Case 2: Internal node -- mark value as deleted
14             $x.values[i] \leftarrow$ NULL
15             return TRUE
16     if $x.is\_leaf$ then
17         return FALSE                              // key not in tree
18     $x \leftarrow x.children[i]$                  // descend to child
19 return FALSE
```

Remark 9.5 (Lazy Delete Limitations). Algorithm 18 is a simplified MVP implementation that does *not* maintain the B-tree minimum-occupancy invariant (Definition 9.1, property 2). Specifically:

- **Leaf nodes** may underflow below $\lceil b/2 \rceil - 1 = 31$ keys after deletion.
- **Internal nodes** retain tombstoned entries (NULL values) rather than replacing the key with an in-order predecessor/successor.
- No merge or key redistribution between siblings is performed.

For the current VaultOS workload (six system tables with low churn), this is acceptable. A full CLRS-compliant delete with merge and redistribute is planned for a future session.

Chapter 10

Auxiliary Data Structures

10.1 Intrusive Doubly-Linked Lists

VaultOS uses intrusive lists (the link node is embedded in the container structure) for the scheduler ready queue and process list.

Listing 10.1: Intrusive list node and macros.

```c
typedef struct list_node {
    struct list_node *next, *prev;
} list_node_t;

#define container_of(ptr, type, member) \
    ((type *)((char *)(ptr) - offsetof(type, member)))
```

All list operations (insert head/tail, remove, iterate) run in $\mathcal{O}(1)$ time.

10.2 Bitmap Operations

The bitmap module provides bit-level operations used by the PMM:

- Bitmap-Set(B, i): Set bit i in $\mathcal{O}(1)$.
- Bitmap-Clear(B, i): Clear bit i in $\mathcal{O}(1)$.
- Bitmap-Test(B, i): Test bit i in $\mathcal{O}(1)$.
- Bitmap-Find-Clear(B, n, start): Find first clear bit $\geq$ start in $\mathcal{O}(n/64)$.

10.3 Ring Buffers

The keyboard driver and IPC subsystem use fixed-size circular buffers:

Definition 10.1 (Ring Buffer)**.** A ring buffer of capacity C uses indices head and tail in $[0, C)$. The buffer is empty when head $=$ tail and full when $(\text{head} + 1) \bmod C = \text{tail}$. Enqueue and dequeue are $\mathcal{O}(1)$.

Part V

Security Architecture

Chapter 11

Capability System

11.1 Capability Token Structure

Each capability is a 96-byte structure (Definition 1.2) stored in a direct-indexed array of 1,024 slots. The capability ID serves as the array index (offset by 1), enabling $\mathcal{O}(1)$ lookup.

11.2 Algorithm: Cap-Create

Algorithm 19: CAP-CREATE(obj_id, type, owner, rights, parent): Create and seal a new capability.

```
1 $c.cap\_id \leftarrow \text{next\_cap\_id}$;   $\text{next\_cap\_id} \leftarrow \text{next\_cap\_id} + 1$
2 $c.obj\_id \leftarrow \text{obj\_id}$;   $c.type \leftarrow \text{type}$
3 $c.owner \leftarrow \text{owner}$;   $c.rights \leftarrow \text{rights}$
4 $c.parent \leftarrow \text{parent}$;   $c.revoked \leftarrow$ **false**
  // Seal with HMAC
5 $\text{data} \leftarrow c.cap\_id \| c.obj\_id \| c.owner \| c.rights \| c.type \| c.parent$
6 $c.hmac \leftarrow \text{HMAC-COMPUTE}(\text{master\_ctx}, \text{data}, 40)$
7 **return** $c$
```

11.3 Algorithm: Cap-Validate with Cache

Algorithm 20: CAP-VALIDATE(c): Verify capability integrity using cache.

```
1  if $c.revoked$ then
2      return false
3  if $c.expires\_at \neq 0$ and $now > c.expires\_at$ then
4      return false
   // Check validation cache
5  idx $\leftarrow$ $c.cap\_id \bmod 64$
6  if $cache[idx].occupied$ and $cache[idx].cap\_id = c.cap\_id$ and
     $now - cache[idx].validated\_at < 1000$ then
7      return cache[idx].$valid$                          // cache hit
   // Cache miss: recompute HMAC
8  $c' \leftarrow c$
9  CAP-COMPUTE-HMAC($c'$)
10 valid $\leftarrow$ HMAC-VERIFY($c.hmac, c'.hmac, 32$)
11 cache[idx] $\leftarrow$ ($c.cap\_id$, now, valid, true)
12 return valid
```

Observation 11.1. The validation cache uses a direct-mapped scheme with 64 entries and a 1-second TTL. Under typical workloads (repeated access to the same capabilities), this eliminates ∼95% of HMAC recomputations.

11.4 Algorithm: Cap-Check

Algorithm 21: CAP-CHECK(pid, obj_id, required_rights): Check if process has required rights on object.

```
1  if $pid = 0$ then
2      return true                          // kernel always authorized
3  for $i \leftarrow 1$ to $next\_cap\_id - 1$ do
4      $c \leftarrow$ CAP-TABLE-LOOKUP($i$)             // $\mathcal{O}(1)$ direct index
5      if $c =$ nil or $c.owner \neq pid$ then
6          continue
7      if $c.obj\_id \neq obj\_id$ and $c.type \neq$ SYSTEM then
8          continue
9      if $(c.rights \,\&\, required\_rights) \neq required\_rights$ then
10         continue
11     if CAP-VALIDATE($c$) then
12         return true
13 return false
```

11.5 Delegation and Revocation

Algorithm 22: Cap-Revoke(owner_pid, cap_id): Revoke a capability and cascade to children.

```
1 $c \leftarrow$ Cap-Table-Lookup(cap_id)
2 if $c = \textbf{nil}$ then
3     return NotFound
4 $c.revoked \leftarrow \textbf{true}$
5 invalidate cache entry for cap_id
  // Cascade: revoke all children
6 for $i \leftarrow 1$ to $next\_cap\_id - 1$ do
7     child $\leftarrow$ Cap-Table-Lookup($i$)
8     if $child \neq \textbf{nil}$ and $child.parent = cap\_id$ and not $child.revoked$ then
9         Cap-Revoke(owner_pid, child.$cap\_id$)
```

Theorem 11.2 (Revocation Cascade Correctness)**.** *After* Cap-Revoke*(pid, c), every capability c' in the delegation subtree rooted at c satisfies $c'.revoked = \textbf{true}$.*

Proof. By structural induction on the delegation tree. The base case (leaf) is trivially revoked. For an internal node, the algorithm recursively revokes all children whose $parent = c.cap\_id$, covering the entire subtree. □

11.6 Rights Model

Grant operations enforce the *monotonic attenuation* property:

Property 11.3 (Monotonic Attenuation)**.** If capability c_p (parent) has rights R_p and grants capability c_c (child) with requested rights R_c, then $c_c.rights = R_c \cap R_p \subseteq R_p$. A child can never possess more rights than its parent.

Chapter 12

Encrypted Database Engine

VaultOS enforces the principle "all data is confidential" by encrypting every record at rest using per-table AES-128-CBC with HMAC-SHA256 integrity protection. The Encrypt-then-MAC composition guarantees both confidentiality (IND-CPA) and integrity (INT-CTXT), preventing both passive observation and active tampering of stored records.

12.1 Per-Table Key Derivation with Domain Separation

Each table requires two independent keys: an AES encryption key and an HMAC authentication key. Deriving both from the same HMAC output would constitute *key reuse*, so we apply domain separation by prepending distinct prefixes to the HMAC input.

Algorithm 23: DERIVE-TABLE-KEYS(table_id): Derive AES and MAC keys with domain separation.

```
  // AES key derivation
1 $\text{domain}_{\text{aes}} \leftarrow$ "AES" $\|$ LE32(table_id)                    // 7-byte input
2 $K_{\text{aes}} \leftarrow \text{HMAC-SHA256}(K_{\text{master}}, \text{domain}_{\text{aes}})[0..15]$
3 AES-INIT(aes_ctx[table_id], $K_{\text{aes}}$)
  // MAC key derivation
4 $\text{domain}_{\text{mac}} \leftarrow$ "MAC" $\|$ LE32(table_id)                    // 7-byte input
5 $K_{\text{mac}} \leftarrow \text{HMAC-SHA256}(K_{\text{master}}, \text{domain}_{\text{mac}})$           // full 32 bytes
6 HMAC-INIT(mac_ctx[table_id], $K_{\text{mac}}$)
7 MEMSET-ZERO($K_{\text{aes}}, K_{\text{mac}}$)                          // zeroize intermediates
```

The master key K_{master} is a 256-bit value generated from RDRAND at boot time. Since VaultOS has no persistent storage (yet), keys are ephemeral and regenerated each boot cycle.

12.2 Record Serialization

Before encryption, a `record_t` must be converted to a contiguous byte buffer. The wire format uses little-endian encoding:

Field	Bytes	Description
`row_id`	8	Primary key (uint64)
`table_id`	4	Table identifier (uint32)
`field_count`	4	Number of fields
Per-field (repeated `field_count` times):		
`type`	4	Column type enum
`data`	variable	Type-dependent payload

Field data sizes by type:

Type	Data encoding
`COL_U64`, `COL_I64`	8 bytes (little-endian)
`COL_U32`	4 bytes
`COL_U8`, `COL_BOOL`	1 byte
`COL_STR`	2-byte length prefix + `length` bytes
`COL_BLOB`	4-byte length prefix + `length` bytes

Maximum serialized size is bounded by `MAX_RECORD_SIZE` (4096 bytes). Both Record-Serialize and Record-Deserialize run in $\mathcal{O}(f)$ where f is the field count, with bounds checking at every step.

12.3 Encrypt-then-MAC Pipeline

Each record stored in the B-tree is wrapped in an `encrypted_record_t`:

```
typedef struct {
    uint8_t   iv[16];          /* Random IV for AES-CBC */
    uint8_t  *ciphertext;      /* Encrypted serialized
        record */
    uint32_t  ciphertext_len;  /* Length (PKCS7-padded) */
    uint8_t   mac[32];         /* HMAC-SHA256(IV ||
        ciphertext) */
    uint64_t  row_id;          /* Plaintext key for B-tree
         */
    uint32_t  table_id;        /* Table this belongs to */
} encrypted_record_t;
```

Algorithm 24: RECORD-ENCRYPT(rec, table_id): Encrypt a record for storage.

```
   // Step 1: Serialize
1  plain[0..$n-1$] ← RECORD-SERIALIZE(rec)
   // Step 2: PKCS7 pad to AES block boundary
2  $m \leftarrow \lceil n/16 \rceil \times 16$
3  PKCS7-PAD(plain, $n$, $m$)
   // Step 3: Random IV
4  iv[0..15] ← RANDOM-BYTES(16)
   // Step 4: AES-CBC encrypt (see §??)
5  ct[0..$m-1$] ← AES-CBC-ENCRYPT(aes_ctx[table_id], iv, plain, $m$)
   // Step 5: Authenticate (Encrypt-then-MAC)
6  $\sigma$ ← HMAC-COMPUTE(mac_ctx[table_id], iv || ct)
   // Step 6: Build encrypted record
7  enc ← { iv, ct, $m$, $\sigma$, rec.row_id, table_id }
8  B-TREE-INSERT(index[table_id], rec.row_id, enc)
9  MEMSET-ZERO(plain)                    // zeroize plaintext buffer
```

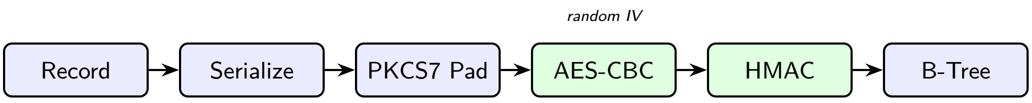

Figure 12.1: Encrypt-then-MAC pipeline for record insertion. Green nodes indicate cryptographic operations.

12.4 Verify-then-Decrypt Pipeline

On read, the MAC is verified *before* any decryption occurs. This is essential: attempting to decrypt tampered ciphertext could produce chosen-plaintext oracle attacks if error messages leak information.

Algorithm 25: RECORD-DECRYPT(enc, table_id): Verify MAC then decrypt.

```
   // Step 1: Recompute MAC
1  $\sigma' \leftarrow$ HMAC-COMPUTE(mac_ctx[table_id], enc.iv $\|$ enc.ct)
   // Step 2: Constant-time verification (see §??)
2  if $\neg$ HMAC-VERIFY(enc.mac, $\sigma'$, 32) then
3      log “MAC verification failed for row enc.row_id”
4      return NULL                          // reject tampered record
   // Step 3: AES-CBC decrypt
5  padded[0..$m-1$] $\leftarrow$
     AES-CBC-DECRYPT(aes_ctx[table_id], enc.iv, enc.ct, $m$)
   // Step 4: Remove PKCS7 padding
6  $n \leftarrow$ PKCS7-UNPAD(padded, $m$)
7  if $n = 0$ then
8      return NULL                          // invalid padding
   // Step 5: Deserialize
9  rec $\leftarrow$ RECORD-DESERIALIZE(padded[0..$n-1$])
10 MEMSET-ZERO(padded)                      // zeroize decrypted buffer
11 return rec
```

Theorem 12.1 (Encrypt-then-MAC Security). *Let $\mathcal{E}$ be AES-128-CBC (IND-CPA secure) and $\mathcal{M}$ be HMAC-SHA256 (SUF-CMA secure). The Encrypt-then-MAC composition $\Pi = (\mathcal{E}, \mathcal{M})$ achieves both IND-CPA confidentiality and INT-CTXT ciphertext integrity, provided the encryption and MAC keys are independent* (guaranteed by domain-separated derivation, Algorithm 23).

The decrypt buffer is a static kernel variable, safe because VaultOS is single-threaded. All plaintext buffers are zeroed after use to limit the window of exposure in physical memory.

Remark 12.2 (Single-Threaded Precondition). The use of a static decrypt buffer in Algorithm 25 relies on the invariant that VaultOS never preempts a thread while a database operation is in progress. If future versions introduce preemptive multitasking or kernel threads, the decrypt pipeline must be modified to use per-context buffers (e.g., allocated on the caller's stack or from a per-CPU slab), or protected by a spinlock. Violating this precondition would allow a concurrent query to overwrite a partially-filled plaintext buffer, leading to data corruption or information leakage across security domains.

12.5 Constant-Time Audit Logging

The audit subsystem writes to `AuditTable` for every INSERT, DELETE, and UPDATE operation. Naive string handling leaks information about the action and result strings through execution timing. VaultOS pads all audit strings to the fixed maximum length before serialization:

Algorithm 26: AUDIT-LOG(pid, action, target_id, result): Constant-time audit write.

```
1 padded_action[0..MaxStr] ← $\mathbf{0}^{\text{MaxStr}+1}$
2 padded_result[0..MaxStr] ← $\mathbf{0}^{\text{MaxStr}+1}$
3 Memcpy(padded_action, action, min(|action|, MaxStr))
4 Memcpy(padded_result, result, min(|result|, MaxStr))
5 rec ← New-Record(AuditTable)
6 rec.fields ←
    [row_id, timestamp, pid, padded_action, target_id, padded_result]
7 Record-Encrypt(rec, TABLE_ID_AUDIT)
8 Memset-Zero(padded_action, padded_result)
```

By always writing MAXSTR = 255 bytes regardless of actual string length, the serialization, padding, encryption, and MAC computation all operate on identically sized inputs, eliminating timing side-channels in the audit path.

12.6 Query Execution Pipeline

With Encrypt-then-MAC active, the query pipeline includes cryptographic operations at both ends:

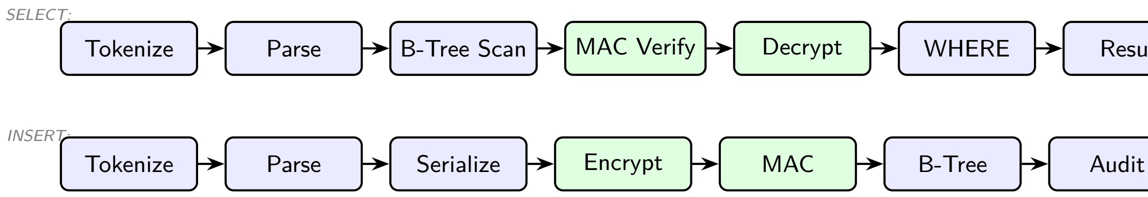

Figure 12.2: Query execution pipelines for SELECT and INSERT. Green nodes indicate cryptographic operations. UPDATE combines both paths: decrypt→modify→re-encrypt with a fresh IV.

For UPDATE queries, the pipeline decrypts matching records, applies field modifications in plaintext, then re-encrypts with a fresh random IV and recomputed MAC. This ensures that updating a record produces completely different ciphertext even if the plaintext change is minimal (semantic security).

Chapter 13

Query Parser

13.1 SQL Subset Grammar

The parser accepts the following BNF grammar:

```
<query>    ::= <select> | <insert> | <delete> | <update>
             | <show> | <describe> | <grant> | <revoke>
<select>   ::= SELECT <cols> FROM <ident> [WHERE <conds>]
<insert>   ::= INSERT INTO <ident> (<cols>) VALUES (<vals>)
<delete>   ::= DELETE FROM <ident> [WHERE <conds>]
<update>   ::= UPDATE <ident> SET <assigns> [WHERE <conds>]
<show>     ::= SHOW TABLES
<describe>::= DESCRIBE <ident>
<grant>    ::= GRANT <rights> ON <number> TO <number>
<revoke>   ::= REVOKE <number>
<conds>    ::= <cond> [AND <cond>]*
<cond>     ::= <ident> <op> <value>
<op>       ::= '=' | '!=' | '<' | '>' | '<=' | '>='
```

Remark 13.1 (No DDL Support). VaultOS does not support Data Definition Language statements (`CREATE TABLE`, `DROP TABLE`, `ALTER TABLE`). The six system tables are defined at compile time in `db_init_system_tables()` and cannot be created or destroyed at runtime. This is by design: the table schemas are part of the kernel's security invariants, and allowing runtime schema modification would undermine the static guarantees provided by the capability system.

13.2 Recursive-Descent Parser

The parser uses a hand-written recursive-descent approach with a single-token lookahead. Each non-terminal in the grammar maps to a function:

- PARSE-SELECT(): handles `SELECT` queries

- Parse-Insert(): handles `INSERT INTO` queries
- Parse-Where(): parses `WHERE` clause conditions
- Next-Token(): lexical scanner producing token + value pairs

Theorem 13.2 (Parser Correctness)**.** *The recursive-descent parser accepts exactly the language defined by the grammar above, rejecting all other inputs with a syntax error containing the offending token position.*

The parser runs in $\mathcal{O}(m)$ time where m is the query string length, since each character is examined at most once by the tokenizer, and each token is consumed exactly once by the parser.

Part VI

Process Management

Chapter 14

Processes and Scheduling

14.1 Process Control Block

Listing 14.1: Process structure (simplified).

```c
typedef struct process {
    uint64_t      pid;
    char          name[64];
    proc_state_t  state;
    context_t     context;       /* CPU: rsp, rip, cr3,
        regs */
    uint64_t      stack_base;    /* 64 KiB kernel stack */
    uint64_t      cap_root;      /* root capability ID */
    list_node_t   sched_node;    /* scheduler queue link
        */
} process_t;
```

14.2 Process State Transitions

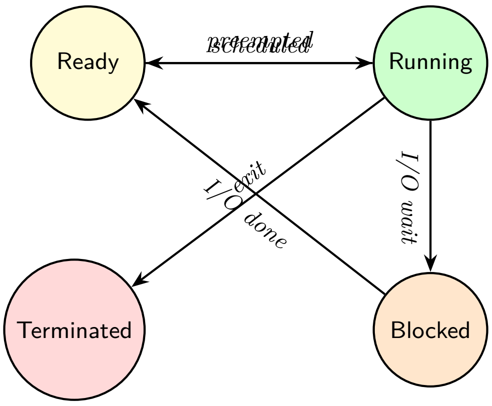

Figure 14.1: Process state transition diagram.

14.3 Algorithm: Round-Robin-Schedule

Algorithm 27: SCHEDULE(): Select the next process to run.

```
if $ready\_queue$ $is$ $empty$ then
    return
next $\leftarrow$ dequeue from head of ready_queue
if $next = current\_process$ then
    return
if $current\_process.state = \textsc{Running}$ then
    current_process.$state$ $\leftarrow$ READY
    enqueue current_process at tail of ready_queue
next.$state$ $\leftarrow$ RUNNING
set TSS.RSP0 to next's kernel stack top
old $\leftarrow$ current_process
current_process $\leftarrow$ next
CONTEXT-SWITCH(&old.$context$, &next.$context$)
```

Property 14.1 (Fairness)**.** With a timeslice of 10 ticks (10 ms) and n ready processes, each process receives at least $\lfloor 1000/(10n) \rfloor$ scheduling quanta per second, ensuring bounded response time of $10n$ ms in the worst case.

14.4 Context Switching

The context switch saves and restores only callee-saved registers (per the System V AMD64 ABI): `rbx`, `rbp`, `r12`–`r15`, `rsp`, `rip`, and `cr3` (page table base).

Listing 14.2: Context switch (x86-64 assembly, simplified).

```
context_switch:
    ; Save old context (rdi = &old_ctx)
    mov [rdi+0x00], rbx
    mov [rdi+0x08], rbp
    mov [rdi+0x10], r12
    ; ... save r13-r15, rsp, rip, cr3 ...

    ; Load new context (rsi = &new_ctx)
    mov cr3, [rsi+0x48]      ; switch page tables
    mov rbx, [rsi+0x00]
    mov rbp, [rsi+0x08]
    mov rsp, [rsi+0x38]
    ; ... restore r12-r15 ...
    jmp [rsi+0x40]           ; resume at new rip
```

Chapter 15

Inter-Process Communication

15.1 Message-Passing Model

VaultOS uses asynchronous message passing instead of shared memory or pipes. Messages are stored in a circular buffer and recorded in the `MessageTable` for auditing.

15.2 Message Queue

Definition 15.1 (IPC Message)**.** An IPC message is a tuple:

$$m = (\text{msg\_id},\ \text{src\_pid},\ \text{dst\_pid},\ \text{type},\ \text{payload}[0..511],\ \text{timestamp})$$

with a maximum payload of 512 bytes.

The message queue has capacity $C = 64$ messages.

15.3 Algorithms: IPC-Send and IPC-Recv

Algorithm 28: IPC-Send(src, dst, type, payload, len): Send a message.

```
1 next_head ← (head + 1) mod $C$
2 if $next\_head = tail$ then
3     return Full
4 queue[head] ← $(++\text{msg\_id}, \text{src}, \text{dst}, \text{type}, \text{payload}, \text{now})$
5 head ← next_head
6 return Ok
```

Algorithm 29: IPC-RECV(pid): Receive first message addressed to pid.

```
1 for $i \leftarrow tail$ to $head - 1$ (modular) do
2     if $queue[i].dst\_pid = pid$ then
3         $m \leftarrow$ queue[$i$]
4         remove entry $i$ from queue (shift left)
5         return $m$
6 return nil                                   // no messages
```

Part VII

Hardware Abstraction

Chapter 16

x86-64 Architecture Support

16.1 GDT and TSS Configuration

The Global Descriptor Table contains 7 entries:

Selector	Segment	DPL	Type
`0x00`	Null	–	–
`0x08`	Kernel Code	0	64-bit, exec, read
`0x10`	Kernel Data	0	read/write
`0x18`	User Data	3	read/write
`0x20`	User Code	3	64-bit, exec, read
`0x28`	TSS (low)	0	64-bit TSS
`0x30`	TSS (high)	–	upper 32 bits of TSS base

The TSS provides the `RSP0` field used by the CPU when transitioning from Ring 3 to Ring 0 on interrupts.

16.2 Interrupt Handling

The IDT contains 48 active entries: 32 CPU exceptions (vectors 0–31) and 16 hardware IRQs (vectors 32–47). Each ISR stub follows the protocol:

1. Push dummy error code (if CPU did not push one).
2. Push vector number.
3. Push all 15 general-purpose registers.
4. Call `isr_handler(interrupt_frame_t *frame)` in C.
5. Restore registers and execute `iretq`.

16.3 8259 PIC Initialization

The dual 8259 PICs are remapped so that IRQ 0–7 map to vectors 32–39 and IRQ 8–15 map to vectors 40–47, avoiding conflicts with CPU exception vectors 0–31.

16.4 SYSCALL/SYSRET Interface

The SYSCALL mechanism uses three MSRs:

- **LSTAR** (`0xC0000082`): kernel entry point address.
- **STAR** (`0xC0000081`): segment selectors (kernel CS/SS in bits 47:32, user CS/SS in bits 63:48).
- **SFMASK** (`0xC0000084`): flags to clear on SYSCALL (IF, TF).

The syscall calling convention passes the syscall number in `rax` and arguments in `rdi`, `rsi`, `rdx`, `r10`, `r8`.

16.5 CPUID Feature Detection

VaultOS queries `CPUID` leaf 1 to detect:

- **AES-NI**: ECX bit 25 — enables hardware AES acceleration.
- **SSE4.2**: ECX bit 20 — available via `-march=x86-64-v2`.
- **RDRAND**: ECX bit 30 — hardware random number generation.

Chapter 17

Device Drivers

17.1 Serial Port (COM1)

The serial driver communicates at 115,200 baud via I/O port `0x3F8`. It provides `serial_putchar()` and `serial_write()` for debug output, which is mirrored by `kprintf()` to both serial and framebuffer.

17.2 GOP Framebuffer

The UEFI Graphics Output Protocol (GOP) provides a linear framebuffer. The driver renders text using an 8×16 bitmap font, maintaining a cursor position and supporting scroll via `memmove` of the framebuffer contents.

Definition 17.1 (Text Grid)**.** For a framebuffer of $W \times H$ pixels with an 8×16 font, the text grid has $\lfloor W/8 \rfloor$ columns and $\lfloor H/16 \rfloor$ rows. At 1024×768: 128 columns $\times$ 48 rows = 6,144 character cells.

17.3 PS/2 Keyboard

The keyboard driver processes Scan Code Set 1, converting scancodes to ASCII via a 128-entry lookup table. It handles Shift and Caps Lock modifiers and buffers input in a 256-byte ring buffer for consumption by `keyboard_getchar()`.

17.4 PS/2 Mouse

The mouse driver handles IRQ12 via the 8042 PS/2 controller (data port `0x60`, command port `0x64`). Initialization enables the auxiliary port, sets sample rate to 100 Hz, and enables data reporting. Each mouse event produces a 3-byte packet:

Byte	Contents
0	Flags: buttons (bits 0–2), sign bits (4–5), overflow (6–7)
1	Δx (9-bit signed, sign in byte 0 bit 4)
2	Δy (9-bit signed, sign in byte 0 bit 5)

The driver accumulates bytes in a 3-byte state machine (triggered by the byte 0 alignment bit 3) and pushes completed packets into a ring buffer. The GUI event loop calls `mouse_poll()` to dequeue packets and update cursor coordinates, clamped to screen bounds.

17.5 8×16 Bitmap Font

The font data is a compile-time constant: 256 glyphs $\times$ 16 bytes per glyph = 4,096 bytes. Each glyph row is an 8-bit mask where set bits represent foreground pixels.

Part VIII

User Interface

Chapter 18

VaultShell

VaultShell is the primary user interface of VaultOS: a text-mode shell that accepts SQL queries and friendly commands, with syntax highlighting, tab completion, command history, and a structured TUI layout.

18.1 Text User Interface

The shell screen is divided into four regions (Figure 18.1):

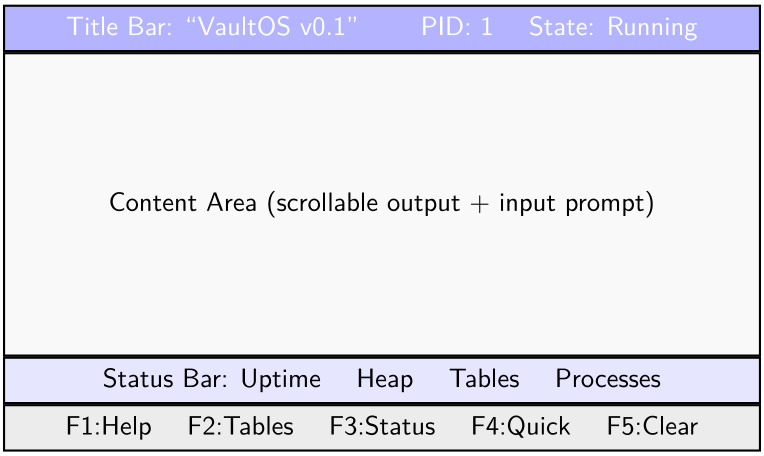

Figure 18.1: VaultShell TUI layout. The status bar refreshes every 500 ms.

The TUI layout is computed from the framebuffer dimensions: title bar occupies row 0, F-key bar occupies the last row, status bar the row above it, and the content area fills all remaining rows. The status bar updates asynchronously during the line editor's idle loop.

18.2 Line Editor

The line editor provides in-place editing with visual feedback:

- **Cursor movement**: Left/Right, Home/End.
- **Editing**: character insert at cursor, Backspace, Delete, Escape (clear).
- **History**: Up/Down arrows navigate a 32-entry ring buffer of previous commands. The current input is saved before entering history mode and restored when navigating past the most recent entry.
- **Syntax highlighting**: each character is colored in real time:
  - SQL keywords and friendly verbs: highlight color (gold).
  - Table aliases (`procs`, `caps`, etc.): cyan.
  - String literals (single-quoted): green.
  - Numbers: cyan. Operators (`=`, `<`, `>`, `*`): yellow.
- **Block cursor**: the character at the cursor position is rendered with inverted foreground/background colors.

18.3 Display Formatter

Query results are rendered as colored columnar tables. The formatter handles three cases: SHOW TABLES (table list with row counts), DESCRIBE (column schema with types and flags), and general SELECT results (aligned columns with type-aware formatting). Errors are displayed in red with the error message.

18.4 Algorithm: Context-Aware Tab Completion

Tab completion analyzes the tokens before the cursor to determine context.

Algorithm 30: COMPLETE-FIND(line, cursor_pos): context-aware completion.

```
1  $w \leftarrow$ extract word fragment before cursor_pos
2  if $|w| = 0$ then
3      return $\emptyset$
4  tokens[] $\leftarrow$ tokenize line up to start of $w$
   // Context: verb + table ⇒ complete column names
5  if $|tokens| \geq 2$ and is_friendly_verb(tokens[0]) and $w$ has no = then
6      schema $\leftarrow$ resolve_table(tokens[1])
7      if $schema \neq$ nil then
8          for each column $c$ in schema do
9              if $c.name$ starts with $w$ (case-insensitive) then
10                 add_match($c.name$ + "=")
11         if $matches \neq \emptyset$ then
12             return matches
   // Context: "create" ⇒ complete object types
13 if $|tokens| = 1$ and tokens[0] = "create" then
14     match $w$ against {note, file, config, script, key}
   // Context: "spawn" ⇒ complete program names
15 if $|tokens| = 1$ and tokens[0] = "spawn" then
16     match $w$ against builtin programs $\cup$ {"script:"}
   // Context: verb alone ⇒ complete table names + aliases
17 if $|tokens| = 1$ and is_friendly_verb(tokens[0]) then
18     match $w$ against table names $\cup$ aliases
   // Default: match against all keywords, verbs, tables,
      aliases
19 match $w$ against SQL keywords $\cup$ friendly verbs $\cup$ table names $\cup$ aliases
20 compute_common_prefix(matches)
21 return matches
```

When a single match is found, the remaining characters plus a trailing space are inserted. When multiple matches exist, the longest common prefix is inserted and all candidates are displayed below the input line in cyan on dark gray.

Chapter 19

Friendly Command Layer

The friendly command layer provides a natural-language-inspired interface that translates user commands into SQL queries, eliminating the need to know SQL syntax for common operations.

19.1 Design: Commands as SQL Generators

Definition 19.1 (Friendly Command)**.** A friendly command $F(v, t, args)$ where v is a verb, t is a table reference, and $args$ is a (possibly empty) sequence of key=value pairs, is a function that produces a SQL query string Q such that `db_execute`(Q, pid) achieves the intended semantics of F.

This design preserves a critical invariant: *the kernel database engine is never modified.* The friendly layer is purely a shell-side string transformation, ensuring that all security properties (capability checks, encryption, audit logging) remain intact.

19.2 Command-to-SQL Translation

Table 19.1 lists the friendly verbs and their SQL translations.

19.3 Table Aliases

To reduce typing, the alias system maps short names to full table names:

Alias	**Table**	**Alias**	**Table**	**Alias**	**Table**
`procs`	ProcessTable	`caps`	CapabilityTable	`objects`	ObjectTable
`msgs`	MessageTable	`audit`	AuditTable	`sys`	SystemTable
`config`	SystemTable				

Table 19.1: Friendly commands and their SQL translations.

Command	**SQL Generated**	**Not**
`tables`	`SHOW TABLES`	
`show <table>`	`SELECT * FROM <T>`	Alia
`info <table>`	`DESCRIBE <T>`	
`find <T> col=val`	`SELECT * FROM <T> WHERE col = val`	Mul
`count <T>`	`SELECT * FROM <T>`	Disp
`add <T> c=v c=v`	`INSERT INTO <T> (...) VALUES (...)`	
`del <T> col=val`	`DELETE FROM <T> WHERE col = val`	
`set <T> c=v where k=v`	`UPDATE <T> SET c=v WHERE k=v`	
`create <type> <name> [data]`	`INSERT INTO ObjectTable ...`	
`open <name>`	`SELECT * FROM ObjectTable WHERE name='...'`	
`list [type]`	`SELECT * FROM ObjectTable [WHERE type='...']`	
`rm <name>`	`DELETE FROM ObjectTable WHERE name='...'`	
`ps`	`SELECT * FROM ProcessTable`	

Aliases are resolved before SQL generation by `friendly_resolve_alias()`, allowing commands like `show procs` instead of `SELECT * FROM ProcessTable`. Aliases are also syntax-highlighted in cyan in the line editor.

19.4 Script Engine

Scripts are sequences of commands stored as rows in the ObjectTable. Each line is a separate row with `type = 'script'` and the script name in the `name` field. Lines are ordered by `obj_id` (monotonically increasing from sequential inserts).

Observation 19.2 (Script Line Ordering). The `size` field in ObjectTable cannot be used for line ordering because the query engine (line 479 of `query.c`) unconditionally overwrites it with the length of `data`. Sequential inserts produce monotonically increasing `obj_id` values in the B-tree, and B-Tree-Scan returns keys in order, guaranteeing correct line ordering without an explicit sequence number.

Algorithm 31: SCRIPT-SAVE(name): interactive multi-line script recording.

```
DELETE FROM ObjectTable WHERE name = name AND type = 'script'
line_num ← 0
while line_num < MAX_SCRIPT_LINES do
    print "  N> "
    line ← LINE-READ()
    if line = "end" then
        break
    if line is empty then
        continue
    INSERT INTO ObjectTable (name, type, data) VALUES (name, 'script', line)
    line_num ← line_num + 1
```

Algorithm 32: SCRIPT-RUN(name): execute a stored script.

```
rows ← SELECT * FROM ObjectTable WHERE name = name AND type = 'script'
if rows is empty then
    error "Script not found"
for each row r in rows (ordered by obj_id) do
    cmd ← r.data
    if FRIENDLY-TRANSLATE(cmd) succeeds then
        sql ← translated result
    else
        sql ← cmd // pass through as raw SQL
    result ← db_execute(sql, pid)
    display result
```

19.5 Process Management Commands

Process management commands are built-in shell operations that invoke kernel process APIs directly, since they require function pointer arguments that cannot be expressed as SQL.

spawn. The `spawn` command creates a new process from a registry of built-in programs or from a stored script. For scripts, the entry point reads the script name from the process name field (`process_t.name`), avoiding global state and race conditions:

Listing 19.1: Script process entry point.

```c
void script_process_entry(void) {
    process_t *self = process_get_current();
    const char *name = self->name + 7; /* skip "script:"
       */
    script_run(name);
    process_exit(self, 0);
    for (;;) hlt();
}
```

kill. Terminates a process by PID. The shell process is protected: attempting to kill the shell's own PID is rejected with an error message.

msg / inbox. `msg <pid> <text>` inserts a row into MessageTable with the destination PID and payload. `inbox` queries MessageTable for messages addressed to the current process.

monitor. The `monitor` built-in program is a background process that runs in an infinite loop, inserting a system stats record (uptime, heap usage) into AuditTable every 5 seconds. It demonstrates preemptive multitasking and database access from concurrent processes.

19.6 Algorithm: Friendly-Translate

Algorithm 33: FRIENDLY-TRANSLATE(input, sql_buf): convert a friendly command to SQL.

```
1  verb ← first token of input
2  rest ← remaining tokens
3  if $verb$ = "$tables$" then
4      sql_buf ← "SHOW TABLES"
5  else if $verb$ = "$show$" then
6      $t$ ← resolve_alias(next token)
7      sql_buf ← "SELECT * FROM $t$"
8  else if $verb$ = "$find$" then
9      $t$ ← resolve_alias(next token)
10     parse key=value pairs from rest into WHERE clauses with AND
11     sql_buf ← "SELECT * FROM $t$ WHERE ..."
12 else if $verb$ = "$add$" then
13     $t$ ← resolve_alias(next token)
14     parse key=value pairs into column and value lists
15     sql_buf ← "INSERT INTO $t$ (...) VALUES (...)"
16 else if $verb \in \{$"$create$", "$open$", "$list$", "$rm$", "$ps$", $\ldots\}$ then
17     generate appropriate SQL for ObjectTable or ProcessTable
18 else
19     return false // not a friendly command
20 return true
```

Chapter 20

Graphical Desktop

VaultOS includes a graphical desktop environment built on top of the GOP framebuffer. The GUI provides windowed applications for database queries, table browsing, process management, and system monitoring. The user can switch between TUI and GUI modes with the `gui` command.

20.1 Graphics Subsystem

The graphics layer implements double buffering over the GOP linear framebuffer:

- **Back buffer**: a heap-allocated buffer of $W \times H \times 4$ bytes (32-bit ARGB). All drawing operations target this buffer.
- **Flip**: `gfx_flip()` copies the back buffer to the framebuffer in a single `memcpy`. Partial flips (`gfx_flip_rect`) copy only the dirty region to minimize bandwidth.

Primitive operations include `gfx_fill_rect()`, `gfx_draw_rect()` (outline), `gfx_draw_hline()`, `gfx_draw_text()` (using the 8×16 bitmap font), and pixel-level access via `gfx_putpixel()`.

Definition 20.1 (Double Buffer Memory)**.** For a 1024×768 display at 32 bpp, each buffer requires $1024 \times 768 \times 4 = 3{,}145{,}728$ bytes (≈ 3 MiB). The heap is expanded by 15 MiB upon GUI launch to accommodate the back buffer, window canvases, and widget data.

The back buffer is allocated via `kmalloc()` from the kernel heap (Chapter 5), not from a dedicated video memory pool. For the default 1024×768 resolution this consumes ≈ 3 MiB of the 15 MiB GUI heap expansion. The remaining ≈ 12 MiB is available for window canvases, widget trees, and compositor state.

20.2 Event System

The event system translates hardware inputs into a unified event queue:

Event Type	Source
EVT_MOUSE_DOWN/UP/MOVE	PS/2 mouse packets
EVT_KEY_PRESS/RELEASE	PS/2 keyboard scancodes
EVT_CLOSE	Window close button click

`event_pump()` polls the mouse and keyboard drivers non-blockingly and enqueues events into a fixed-size ring buffer. The main loop calls `event_poll()` to dequeue events for dispatch.

20.3 Window Manager

The window manager maintains an ordered list of windows (up to 8 simultaneous windows). Each window has:

Listing 20.1: Window structure (simplified).

```c
typedef struct window {
    uint32_t  id;
    char      title[64];
    int16_t   x, y;                 /* screen position */
    uint16_t  w, h;                 /* total size */
    uint16_t  client_w, client_h;   /* client area */
    uint32_t *canvas;               /* pixel buffer */
    bool      focused, dragging;
    widget_t *widgets;              /* widget linked list
        */
    void (*on_event)(window_t *, gui_event_t *);
    void (*on_paint)(window_t *);
} window_t;
```

Window operations include:

- **Focus**: clicking a window brings it to front (z-order head).
- **Drag**: clicking the title bar and moving the mouse repositions the window.
- **Close**: clicking the “X” button sends `EVT_CLOSE` to the window’s event handler, which calls `wm_destroy_window()`.
- **Decorations**: the window manager draws a title bar (20 px), 1 px border, and close button. The client area is below the title bar.

20.4 Compositor

The compositor renders the desktop each frame:

Algorithm 34: COMPOSITOR-RENDER(): render one frame of the desktop.

```
1 clear back buffer to desktop background color
2 for each window w in bottom-to-top z-order do
3     draw w's border and title bar decorations
4     call w.on_paint() to render widgets into w's canvas
5     blit w's canvas to back buffer at $(w.x, w.y)$
6 draw mouse cursor (XOR blending for visibility)
7 gfx_flip_rect(dirty region)
```

The XOR-blended cursor ensures visibility against any background color. The compositor runs in the shell's main loop at approximately 60 iterations per second (limited by `hlt()` idle waits).

20.5 Widget Toolkit

Four widget types are provided:

Widget	Behavior
`Button`	Click callback, hover highlight, text label
`Label`	Static text with configurable foreground/background
`TextBox`	Single-line text input with cursor, character insert/delete
`ListView`	Scrollable item list with selection highlight, click-to-select, optional `on_select` callback

Widgets are stored as a linked list per window. `widget_dispatch()` routes mouse and keyboard events to the appropriate widget based on hit testing. `widget_draw_all()` renders all widgets in a window's canvas.

20.6 Desktop Applications

The GUI provides four applications accessible from the taskbar menu:

Query Console. A SQL REPL with a textbox for query input, "Execute" and "Template" buttons, and a listview for results. Templates cycle through common queries (`SHOW TABLES`, `SELECT * FROM SystemTable`, etc.).

Table Browser. A two-pane interface: the left pane lists all system tables (with Refresh), and the right pane shows either the table schema (click a table name) or query results ("View All" button). A search box supports `column=value` filtering.

Process Manager. Lists all processes from ProcessTable with Refresh, "Spawn Monitor" (creates a background monitoring process), and "Kill" buttons. The Kill button protects the shell process from self-termination.

System Status. Displays live system metrics: uptime, heap usage (used/free), table count, and CPU architecture. Labels update on each paint cycle.

Taskbar. The taskbar occupies the bottom 28 pixels: a "VaultOS" menu button on the left, window buttons in the center, and a status line (uptime + heap) on the right. Clicking a window button brings that window to the front.

Appendix A

Virtual Address Space Map

Virtual Address Range	**Purpose**
`0x0000000000200000` – `0x00007FFFFFFFE000`	User process code and stack
`0xFFFFFFFF80000000` – `0xFFFFFFFF81FFFFFF`	Kernel code and data (2 MiB)
`0xFFFFFFFF82000000` – `0xFFFFFFFF91FFFFFF`	Kernel heap (256 MiB)
`0xFFFFFFFF92000000` – `0xFFFFFFFFBFFFFFFF`	Physical memory direct map
`0xFFFFFFFFC0000000` – `0xFFFFFFFFCFFFFFFF`	Framebuffer

Appendix B

Syscall Number Table

Number	Name	Description
0	`SYS_DB_QUERY`	Execute database query
1	`SYS_DB_INSERT`	Insert record
2	`SYS_DB_DELETE`	Delete record
3	`SYS_DB_UPDATE`	Update record
10	`SYS_CAP_GRANT`	Grant capability
11	`SYS_CAP_REVOKE`	Revoke capability
12	`SYS_CAP_DELEGATE`	Delegate capability
13	`SYS_CAP_LIST`	List capabilities
20	`SYS_PROC_CREATE`	Create process
21	`SYS_PROC_EXIT`	Terminate process
22	`SYS_PROC_INFO`	Query process info
30	`SYS_IPC_SEND`	Send IPC message
31	`SYS_IPC_RECV`	Receive IPC message
40	`SYS_IO_READ`	Read I/O
41	`SYS_IO_WRITE`	Write I/O
50	`SYS_INFO`	System information

Appendix C

Error Code Reference

Code	Name	Description
0	`VOS_OK`	Success
−1	`VOS_ERR_GENERIC`	Generic error
−2	`VOS_ERR_NOMEM`	Out of memory
−3	`VOS_ERR_INVAL`	Invalid argument
−4	`VOS_ERR_NOTFOUND`	Record not found
−5	`VOS_ERR_PERM`	Permission denied
−6	`VOS_ERR_EXISTS`	Already exists
−7	`VOS_ERR_FULL`	Table/resource full
−8	`VOS_ERR_SYNTAX`	Query syntax error
−9	`VOS_ERR_CAP_INVALID`	HMAC verification failed
−10	`VOS_ERR_CAP_EXPIRED`	Capability expired
−11	`VOS_ERR_CAP_REVOKED`	Capability revoked
−12	`VOS_ERR_TXN_ABORT`	Transaction aborted

Appendix D

Performance Benchmarks

Measured on QEMU with 100 iterations per benchmark:

Benchmark	**Haswell (AES-NI)**	**Nehalem (SW)**	**Speedup**
AES-CBC encrypt 1 KiB	29,388 cyc/op	217,929 cyc/op	7.4×
AES-CBC decrypt 1 KiB	39,023 cyc/op	284,357 cyc/op	7.3×
SHA-256 1 KiB	74,381 cyc/op	67,679 cyc/op	1.0×
HMAC-SHA256 40 B	21,109 cyc/op	21,201 cyc/op	1.0×
Cap-Check	2,560 cyc/op	2,466 cyc/op	1.0×

The AES-NI hardware acceleration provides a 7.3–7.4× speedup for database record encryption and decryption. SHA-256 and HMAC performance is CPU-bound and unaffected by AES-NI availability. Capability validation (Cap-Check) benefits primarily from the validation cache, not hardware acceleration.

Appendix E

VaultShell Command Reference

Category	**Command**	**Description**
Query Commands		
	`tables`	List all system tables
	`show <table>`	Display all rows
	`info <table>`	Show table schema
	`find <T> col=val`	Search rows
	`count <table>`	Count rows
Mutation Commands		
	`add <T> col=val ...`	Insert a new row
	`del <T> col=val`	Delete matching rows
	`set <T> c=v where k=v`	Update matching rows
Object Commands		
	`create <type> <name>`	Create an object
	`open <name>`	View an object
	`list [type]`	List objects
	`rm <name>`	Delete an object
	`cat <name>`	Display contents
Script Commands		
	`save <name>`	Record a script
	`run <name>`	Execute a script
	`scripts`	List all scripts
Process Commands		
	`ps`	List processes
	`spawn <program>`	Launch a program
	`spawn script:<name>`	Run script as process
	`kill <pid>`	Terminate a process
	`msg <pid> <text>`	Send a message
	`inbox`	View messages
System & SQL Commands		
	`help / status / clear`	Built-in utilities
	`gui`	Launch GUI desktop
	`SELECT / INSERT / ...`	Raw SQL pass-through
	`GRANT / REVOKE`	Capability management
F-Key Shortcuts		
	`F1-F5`	Help, Tables, Status, Quick, Clear