ABSTRACT
The use of unsafe programming languages still remains one of the major root causes of software vulnerabilities. Although well-known defenses that detect and mitigate memory-safety related issues exist, they don’t address the challenge of software resilience, i.e., whether a system under attack can continue to carry out its function when subjected to malicious input. We propose secure rollback of isolated domains as an efficient and secure method of improving the resilience of software targeted by run-time attacks. We show the practicability of our methodology by realizing a software library for Secure Domain Rollback (SDRoB) and demonstrate how SDRoB can be applied to real-world software.

1 INTRODUCTION
Software written in unsafe programming languages can suffer from various memory-related vulnerabilities [37] that allow run-time attacks, such as control-flow attacks and non-control-data attacks [14], to compromise program behavior. Attackers use such run-time attacks to gain access to vulnerable software and systems. According to the Google Project Zero “0day In the Wild” dataset over 70% of the zero-day vulnerabilities between July 2014 and June 2022 can be attributed to memory-safety issues [123]. Research into run-time attacks has, during the past 30 years, led to an ongoing arms race between increasingly sophisticated attacks and run-time defenses to mitigate such attacks [102]. Today, major operating systems (OSs) provide such mitigations by default. This includes non-executable stack and heap areas, address-space-layout randomization (ASLR) [68], toolchain hardening options such as stack canaries [112], and hardware-enforced control-flow integrity (CFI) [30]. However, virtually all currently known defenses mitigate attacks by terminating the victim application [2, 7–13, 17–19, 25, 26, 29, 32–36, 38, 40, 41, 43, 47, 52, 56, 59–61, 63–65, 70, 72, 77, 79, 82, 83, 86, 87, 90, 93, 95–97, 99, 102, 105, 106, 109, 113, 115, 118, 120, 124]. Thus, even though applications are hardened against run-time attacks, the response can still be leveraged by attackers to create temporary denial-of-service conditions while the application is restarted, or to bypass security controls by resetting volatile system state, e.g., counts of failed login attempts.

Service-oriented applications are at particular risk as even a temporary failure in a critical component can affect a large number of clients. An example for such an application is Memcached, a general-purpose distributed memory-caching system, which is commonly used to speed up database-driven applications by caching database content.

Contributions. To address the limitation of current defenses and improve the resilience of software that is being targeted by run-time attacks we propose secure rollback of isolated domains. Secure rollback allows the state of a victim application under attack to be restored to a prior state, known to be unaffected by an ongoing run-time attack. This is possible by leveraging hardware-assisted software fault isolation (SFI) to compartmentalize the application into distinct domains that limit the effects of run-time attacks to isolated memory compartments. An application can be instrumented to isolate, e.g., “high-risk” code that operates with untrusted input in a secure in-process sandbox and roll back the application state if an attack is detected against sandboxed code. Domains can be nested to allow for efficient and secure rollback in different software architectures and use cases.

We show the practicability of our methodology by realizing a software library for secure domain rollback (SDRoB) for commodity 64-bit x86 processors with protection keys for userspace (PKU) [4, 51] and demonstrate how SDRoB can be applied to real-world software in case studies on Memcached, a popular distributed memory-cache system (Section 5.1), the NGINX web server (Section 5.2), and OpenSSL (Section 5.3). In summary, the contributions of this paper are:

- Secure Rollback of Isolated Domains is a novel scheme to improve software resilience against run-time attacks by rolling back the state of a victim application (Section 3).
- We explore different design patterns for compartmentalization and rollback and discuss their applicability to retrofit existing software with secure rollback (Section 3.4-3.6).
- We provide SDRoB, a realization of secure rollback for commodity 64-bit x86 processors with PKU (Section 4).
- We apply SDRoB in three case studies (Memcached, NGINX, and OpenSSL, Section 5) and show that it can be used with minor changes to application code, exhibiting in benchmarks on Memcached and NGINX a worst case performance overhead <7.2%, negligible overhead (2%-4%) in realistic multi-processing scenarios, and negligible memory overhead (0.4%-3%) . We assess the security and applicability of our approach in Section 6 and Section 7.
2 BACKGROUND

Memory-safety issues cause vulnerabilities such as buffer overflows, use-after-free, and format string vulnerabilities [102]. Today, countermeasures such as WnX [93], ASLR [61], stack canaries [25] and CFI [2] that mitigate memory vulnerabilities are widely deployed by all major OSs.

However, the current state-of-practice in run-time defenses focuses on detecting attacks and terminating the offending processes. This effectively prevents attackers from leveraging memory vulnerabilities as stepping stones for privilege escalation, remote code execution, or data exfiltration, but disregards availability concerns in favor of disrupting the attack’s kill chain. This is acceptable for protecting end users from threats, e.g., restarting a browser is a minor inconvenience. However, in high-availability applications any measure which may cause service disruption necessitates overall system resilience to be provided through redundancy and load balancing.

It may also be desirable to collect diagnostics data from the application when an attack is detected to aid in root-cause analysis. Instant termination of an application hinders the collection of diagnostics data, except perhaps a core dump, but collecting data from a process which is under the attacker’s control poses yet another challenge.

2.1 Software Fault Isolation

Software fault isolation (SFI) [103] is a technique for establishing logical protection domains within a process through program transformations. SFI instruments the program to intermediate memory accesses to ensure they do not violate domain boundaries. Since transitioning from one domain to another stays within the same process SFI solutions can offer better run-time efficiency compared to traditional process isolation, especially in use cases where domain transitions are frequent. SFI has been successfully deployed for sandboxing plug-ins in the Chrome browser [121], isolating OS kernel [89] and modules [13, 36, 70], as well as code accessed through foreign function interfaces in managed language runtimes [100].

SFI enforcement can be realized in different ways. The principal method to realize SFI for native code binaries is the use of an inline reference monitor through binary- [36] or compiler-based rewriting [13, 66, 70, 113] of the application binary. Recent SFI approaches leverage hardware-assistance (Section 2.3) to further improve enforcement efficiency [15, 44, 54, 57, 58, 62, 74, 88, 92, 101, 107, 111, 114]. Existing approaches to SFI share the drawback of memory vulnerability countermeasures as they respond to detected domain violations by terminating the offending process.

2.2 Checkpoint & Restore

Application checkpoint & restore [45] is a technique for increasing system resilience against failure. It involves saving the state of a running process periodically or before a critical operation, so that a failed process can later be restarted from the checkpoint. The cost of this depends on the amount of data that is needed to capture the system’s state and the checkpointing interval.

Several studies have focused on optimizing checkpointing [67, 122, 125]. Checkpoints can be created at system level or application level. At system level, checkpointing needs to capture a complete reproduction of the application’s memory as well as other attributes, such as sockets, open files, and pipes. At application level, checkpointing requires additional functionality inserted into the application itself to facilitate checkpoint & restore.

Secure checkpointing schemes [78] generally leverage cryptography to protect the integrity and confidentiality of checkpoint data at rest. However they generally do not consider attacks that may tamper with checkpointing code at the application level. Furthermore, the cost of bulk encryption of checkpoint data is too high for latency-sensitive applications, e.g., network traffic processing or distributed caches unless the system provides load balancing and redundancy.

In this work, we avoid the pitfalls of checkpoints that reproduce process memory by leveraging hardware-assisted fault isolation to partition an application process into distinct, isolated domains. This compartmentalization facilitates secure rollback of application state by isolating the effects of memory errors. This enables rollback to application states that precede the point of failure in the application’s call graph and are unaffected by a caught and contained error.

2.3 Memory Protection Keys

Memory protection keys (MPK) provide an access control mechanism that augments page-based memory permissions. MPK allows memory access permissions to be controlled without the overhead of kernel-level modification of page table entries (PTEs). On 64-bit x86 processors, protection keys for userspace code (PKU) are supported since Intel’s Skylake [51] and AMD’s Zen 3 [4] microarchitectures. Future Intel processors will add support for memory protection keys for supervisor mode (PKS) [51]. Similar hardware mechanisms are also available in ARMv8-A [5], IBM Power [48], HP PA-RISC [46] and Itanium [50] processor architectures.

Figure 1 illustrates the component of PKU on 64-bit x86 processors. Each memory page is associated with a 4-bit protection key stored in the page’s PTE. The access rights to memory associated with each protection key are kept in a protection key rights register (PKRU). The PKRU allows write-disable (WD) and access-disable (AD) policies to be configured for protection keys. These policies are enforced by hardware on each memory access.

Unlike MPK mechanisms for architectures such as ARMv8-A and IBM Power, which limit access to the PKRU to privileged code, the PKRU in 64-bit x86 is configurable from userspace. This allows domain transitions to occur efficiently without involving the OS kernel. However, it also means that PKU on its own cannot effectively enforce secure in-process isolation, but has to be combined with mechanisms such as WnX and CFI that can limit PKRU access to code which is trusted to manage isolation. Existing work has shown that compiler-based code rewriting [58] or binary inspection [107] when combined with system call filtering [111], or non-invasive hardware extensions [92], provide sufficient security for PKRU access to preclude bypassing PKU policies.

3 SECURE DOMAIN ROLLBACK

We propose secure rollback of isolated domains, a novel approach for improving the resilience of userspace software against run-time attacks that augments existing, widely deployed run-time defenses. First, we present our threat model and system requirements (Section 3.1). Then we introduce a motivating example (Section 3.2) and
use it to explain the high-level idea behind the solution (Section 3.3). Sections 3.4 to 3.6 delve deeper into specific aspects of the design.

3.1 Threat Model and Requirements

Assumptions. In this work, we assume that the attacker has arbitrary access to process memory, but is restricted by the following assumptions about the system:

A1 A Windows policy restricts the adversary from modifying code pages and performing code-injection.

A2 The application is hardened against run-time attacks and can detect an attack in progress, but not necessarily prevent the attacker from corrupting process memory. The general Linux protections (cf. Section 2) are in place.

We limit the scope of A2 to software-level attacks. Transient execution [119] and hardware-level attacks, e.g., fault injection [98], rowhammer [76] etc., which are generally mitigated at hardware, firmware, or kernel level, are out of scope.

Requirements. Our goal is to improve the resilience of an application against active run-time attack that may compromise the integrity of the application’s memory. We introduce a mechanism for secure rollback with requirements as follows:

R1 The mechanism must allow the application to continue operation after system defenses (A2) detect an attack.

R2 The mechanism must ensure that the integrity of memory after recovering from the detected attack is maintained.

To facilitate R1 and R2 the application is compartmentalized into isolated domains with the following requirements:

R3 Run-time attacks that affect one domain must not affect the integrity of memory in other domains.

R4 The attacker must not be able to tamper with components responsible for isolation or transitions between domains, or data used as part of the rollback process.

3.2 A Vulnerable C Program

Latent memory vulnerabilities may exist undiscovered within applications until they are set off by input that triggers the software defect. When a defect is triggered, it is highly likely that it causes the application’s memory to become corrupt in unexpected ways. As a motivating example, consider the program in Listing 1 that contains a "classic" buffer overflow vulnerability. The memory vulnerability is triggered by input that exceeds the size of the input buffer buf. As the input overflows the buffer it will corrupt the surrounding stack frame, and eventually overflow into the main function’s stack frame where it will corrupt the local variable sum.

Modern C compilers guard against this particular vulnerability in two ways: 1) by deprecating the gets() function in favor of fgets() with explicit array bounds checks, 2) by emitting stack canaries at stack frame boundaries which indicate if a buffer overflow corrupts a function’s stack frame. Listing 2 shows how the hardened application is terminated at run-time when the overflow is detected. However, by the time the overflow is detected the application’s memory has already been corrupted, rendering the application process unrecoverable.

3.3 High-level Idea

The objective of the secure rollback mechanism is to recover the application’s execution state, after a memory defect has triggered, to a prior state before the application’s memory has been corrupted (R2). Thus, the application can resume its execution and continue to provide its services without interruption (R1). To facilitate this, the application is compartmentalized into separate, isolated domains that each execute in distinct memory compartments allocated from the process’s memory space. Should the execution of code inside a domain fail due to a memory defect, the memory that belongs to the domain may be corrupt. However, since the effects of the memory defect are isolated to the memory belonging to the failing domain (R3, R4) the application’s execution can now be recovered by: 1) discarding any affected memory compartments, 2) unwinding the application’s stack to a state prior to the offending domain began its execution, and 3) performing an application-specific error handling procedure that avoids triggering the same defect again, e.g., by discarding the potentially malicious input that caused it.

Listing 3 shows how the program from Listing 1 is modified to benefit from secure rollback. The call to get_number() has been wrapped by a call to the enter_domain() function θ. This wrapper function is part of secure rollback instrumentation, here shown with simplified arguments. It performs the following actions:

- Save information about the calling environment such as register values, including the stack and instruction pointers, and signal mask (in a manner similar to C setjmp() [84]) for later use by the rollback mechanism
- Reserve a portion of application memory to store the new domain’s stack and heap, persisting for the duration the domain remains active (see Section 3.4).
- Update the hardware-enforced memory access policy, granting access to the new domain’s memory areas and protecting all other memory. Global data is set to read-only.
- Finally, invoke the function inside the new domain.

The newly spawned domain can end its execution in one of two ways: 1) normal domain exit, or 2) abnormal domain exit. A normal domain exit θ occurs when the application’s execution flow returns naturally from the code invoked inside the domain to the call site. This means that the isolated code has completed successfully and application execution is resumed outside the domain. An abnormal domain exit occurs θ if the isolated code tries to access memory past the confines of the domain’s memory area, or a possible run-time attack is detected. In an abnormal domain exit, the execution of the
domain is halted, the domain’s memory is discarded, and the application execution is resumed by restoring the calling environment from the information stored prior to invoking the offending domain, effectively rolling back application state to the point before the domain started executing. In Listing 3, the effects of a buffer overflow inside get_number() are limited to the newly created domain; the main function’s stack is unaffected by the overflow, and the rollback mechanism can thus transfer control back to main().

The caller learns a domain’s exit status from enter_domain()’s return value. On abnormal domain exit the application is expected to take an alternate action to avoid the conditions that lead to the previous abnormal exit before reretrying the operation. For example, a service-oriented application can close the connection to a potentially malicious client. The rollback of application state is limited to the state of the application’s memory. Operations that have side-effects on the application’s environment, e.g., reading from a socket, are still visible to the application after rollback.

In the following we explain design patterns for secure rollback that apply to different software architectures.

### 3.4 Domain Life Cycle

As part of process initialization, all application memory, including stack, heap, and global data, are assigned to the root domain, which forms the initial isolated domain where an application executes. Application subroutines are compartmentalized into nested domains to create multiple recovery points from which rollbacks can be performed at any point during execution. As the names suggests, domains can be nested in the sense that several domains can be entered subsequently starting from the root domain, each with a dedicated rollback procedure (cf. Section 3.5). While read-only access from any nested domain to data in the parent domain may be allowed, writable access is forbidden in order to contain any memory safety violations to the nested domain. By default, nested domains have read access to the root domain to enable reading global variables. We envision two flavors of isolation with rollback for application subroutines:

- **Protecting the application from a subroutine**: Code that may have undetected memory vulnerabilities, e.g., third-party software libraries, can be executed in a nested domain by instrumenting calls to the functionality so that they execute in their own domain and may be rolled back in case memory safety violations are detected.

- **Protecting a subroutine from its caller**: parts of the application that operate on sensitive data such as cryptographic keys can be isolated from vulnerabilities in its callers, preventing the leak and loss of such data. For example, functions for encryption, decryption, or key derivation from the OpenSSL library can be isolated in their own nested domain to protect the application’s cryptographic keys if a fault occurs in a calling nested domain. Listing 6 in Section 4.1 and the calling nested domain in Appendix B show a concrete example of isolating OpenSSL.

When the application’s execution flow enters any isolated subroutine, a nested domain is created and assigned a substack and subheap area. To support the two application scenarios described above, we identify two design patterns for nested domains. The type of a domain determines how it continues its life cycle, in particular what happens upon domain exit.

**Persistent Domains.** A persistent domain retains all assigned memory areas even after the application’s execution flow returns from the persistent nested domain to the parent domain. Another code path may enter the persistent domain again, at which point access is granted to memory areas that belong to the persistent domain. Modules that maintain state information across invocations should be isolated in a persistent domain so that their state is not lost after a normal domain exit. For instance, some software libraries may encapsulate such state by creating a "context" object that decouples domain-specific data from business logic. One strategy for compartmentalizing such libraries is to ensure each distinct context is allocated in different persistent domains. A good example of this pattern is OpenSSL which can be instantiated multiple times within an application using different contexts. Assigning one persistent domain per concurrent context therefore ensures cryptographic keys associated in memory with one context remain isolated from other domains.

On abnormal exits from any domain, the rollback mechanism is triggered and all state of the domain is discarded. Note that for persistent domains this may have serious repercussions for an application, if the program state depends on the persistent state of the isolated library. When, for example, the abnormal exit leads to the loss of session keys for a TLS connection, the application may need to recover by re-initializing the affected context and close connections that were handled in the lost context.

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Listing 1: A vulnerable C application.

```c
int get_number() { 
  char buf[BUFSIZE]; // BUFSIZE = 8
  gets(buf); // read input to buf 
  return atoi(buf); // return number as integer, or zero
} 

void main(void) { 
  int sum = 0; // sum of all inputs 
  for (;;) { 
    sum += get_number(); 
    printf("The sum so far: %d\n", sum);
  } 
}
```

Listing 2: A stack overflow is detected at run-time.

```c
int ret; // to store return value on normal domain exit
for(;;) { 
  // run get_number in isolated domain 
  if(enter_domain(&get_number, &ret) == OK) { 
    sum += ret; // normal domain exit 
    printf("The sum so far: %d\n", sum);
  } else { // abnormal domain exit 
    printf("ERROR! Bad Input");
  } 
}
```

Listing 3: The loop from Listing 1 equipped for rollback.

```c
int get_number() { 
  char buf[BUFSIZE]; // BUFSIZE = 8
  gets(buf); // read input to buf 
  return atoi(buf); // return number as integer, or zero
} 

void main(void) { 
  int sum = 0; // sum of all inputs 
  for (;;) { 
    sum += get_number(); 
    printf("The sum so far: %d\n", sum);
  } 
}
```
Depending on the application, the parent domain may or may not be given access to a persistent nested domain’s memory. For instance, in the case of cryptographic libraries, access to the persistent domain’s memory from any other domain should be blocked to protect sensitive data stored by the library. In such cases data cannot be directly passed between the caller and callee in distinct domains and shared data, e.g., call arguments and results need to be copied between the nested domain and its callee via a designated shared memory area. This is similar to how data is passed between different protection domains in, e.g., Intel SGX enclaves [53].

**Transient Domains.** Memory areas assigned to transient nested domains persist until the application’s execution flow returns from such a domain to the parent domain at which point the stack as well as unused heap memory areas assigned to the transient nested domain are discarded. For this the rollback mechanism needs to keep track of memory allocations in a nested domain. Any allocated memory in a transient nested domain’s heap area can be merged back to the parent domain’s heap area or discarded upon a normal domain exit, depending on the specific application scenario. In the example in Listing 4, execution enters a nested domain ❶ where get_name() ❷ dynamically allocates a buffer in heap memory ❸ and returns it as a result to main(). In a normal domain exit ❹, the active allocation of the transient domain is merged to the root domain where main() lives. This means that control of the buffer allocated in the transient domain and pointed to by ret is transferred. The developer can free this memory later ❺. Unused heap area of the nested domain and the stack are discarded automatically by the secure rollback mechanism. On an abnormal domain exit ❻ substack area and subheap area assigned to the transient nested domain are discarded by the rollback mechanism already and no further clean-up by the developer is necessary.

```
1 void get_name() { ❶
2     void *buf;
3     buf = malloc(BUFSIZE); ❷ // BUFSIZE = 8
4     gets(buf);
5     return buf;
6 }
7 void main(void) { ❹
8     void *ret;  // holds the return value
9     for (;;) {
10         if(enter_domain(&get_name, ret) == OK){ ❸
11             printf("%s", ret);  // normal domain exit
12             free(ret); ❸
13         } else {  // abnormal domain exit
14             printf("ERROR! Bad Input");
15         }
16     }
```

**Listing 4: Domain Merging Area Example**

The overall life cycle of a nested domain in the transient style is depicted in Figure 2, highlighting the different steps the rollback mechanism performs to isolate execution in a nested domain from its parent. As an example, we consider a call to a function or library *F* that takes one in-memory argument and returns a value. The call ❶ is wrapped by enter_domain(), which creates a new domain ❷, allocates separate stack and heap memory ❸, saves the caller context ❹, and copies the input argument onto the new heap ❺. The domain transition step ❸ performs mainly two actions: 1) reconfiguring the memory protection mechanism to restrict or grant memory access policies for the entered domain, 2) switch between the stacks of the two domains. If a fault is caught in the nested domain ❹, the abnormal domain exit is triggered ❻, discarding the contents of the faulty domain, and executing the custom error handling code ❼. The normal domain exit ❹ stores the result and deletes the domain including freeing its memory. In the “Handle Result” step ❼, control is transferred to the developer-provided handler code for normal exits. In both exit cases, after the handler code is executed, regular program execution resumes in the parent domain. For persistent domains, creation ❽ is only needed for the first invocation and deletion steps ❹ are omitted.

### 3.5 Domain Nesting and Rollback

Domain nesting enables creating new isolated domains within others. Each nested domain has exactly one parent domain, which is responsible for creating the nested domain. All domains may have zero or more nested child domains, i.e., nested domains may be created by already nested domains.

Transient and persistent-style domains can be nested with each other. One example of a domain nesting configuration is illustrated in Figure 3. Here, the first level of domains is transient and its subsequent nested domain can be persistent. This setup allows developers to simplify error handling by directing rollbacks from the more deeply nested persistent domain to also return to the recovery point established for the transient domain. At the event of an abnormal domain exit, the rollback can occur from any nesting level to a lower nesting level according to application requirement, i.e., the rollback can be configured to occur from nesting level 2 to 1, or from 2 to 0 as seen in Figure 3. Rollbacks may occur from any nested domain, but not from the root domain.

### 3.6 Multithreading

The secure rollback mechanism supports POSIX threads. In most cases, threads need to communicate with each other using shared memory, hence they need to access root domain memory. Consequently, it would not be possible to isolate two threads completely from each other or from the main process.

Nevertheless, it is still possible to isolate partial code paths within the thread to separate domains, i.e., each thread can still create nested domains with stacks and heaps that are isolated from the root domain and other nested domains. Hence, each thread may recover via rollback from errors in such nested domains. If one of the threads suffers an abnormal exit from the root domain, the rollback mechanism cannot recover other threads and the application must be terminated.

Threads have shared access to global and root domain heap memory, to per-thread stack areas and thread-local storage. It is possible to strengthen the isolation by configuring exclusive memory access to each thread’s stack. However, the security benefits are arguably marginal when heap access is still shared. A shared root domain allows a higher number of parallel threads to be supported, if the available domains provided by the underlying memory protection mechanism is limited, as only threads that instantiate nested domains consume domain slots. However, one could allow the developer to configure stricter, non-uniform access privileges to other threads.
Figure 2: Domain life cycle for calling an internal or library function \( F \) in a nested domain from a parent domain. Dotted arrows represent execution of user space instructions. Steps ① to ④ initialize the domain. An argument \( \text{arg} \) of size \( \text{size} \) is copied into the nested domain in step ① and the result is returned in variable \( \text{ret} \) in step ⑥. Deleting the domain in steps ⑦ and ⑧ reverses the initialization and frees all of the nested domain’s memory. Code for steps ① and ④ is provided by the programmer.

![Domain life cycle diagram](image)

Figure 3: Deeply nested domains. Arrows indicate: ← entering domain, → normal domain exit, → abnormal domain exit. Normal exits ②, ➀ occur in reverse domain entering order. Abnormal exits ③, ④ may deviate from that: both persistent and transient domain roll back to the root domain.

![Deeply nested domains diagram](image)

Table 1: SDRoB API. \( udi \): user domain index.

| API Name          | Arguments         | Description                                                                 |
|-------------------|-------------------|-----------------------------------------------------------------------------|
| sdrob_init()      | \( udi, \text{options} \) | Initialize Domain \( udi \)                                                  |
| sdrob_malloc()    | \( udi, \text{size} \) | Allocate \( \text{size} \) memory in domain \( udi \)                       |
| sdrob_free()      | \( udi, \text{adr} \) | Free memory at \( \text{adr} \) in domain \( udi \)                          |
| sdrob_dprotect()  | \( udi, \text{iddi}, \text{PROT} \) | Set domain \( udi \) ’s access permissions to \( \text{PROT} \) on target data domain \( \text{iddi} \) |
| sdrob_enter()     | \( udi \)          | Enter Domain \( udi \)                                                       |
| sdrob_exit()      | —                  | Exit Domain \( udi \)                                                        |
| sdrob_destroy()   | \( udi, \text{options} \) | Destroy Domain \( udi \)                                                     |
| sdrob_deinit()    | \( udi \)          | Delete return context of Domain \( udi \)                                    |
| sdrob_call()      | \( udi, \text{fun}, \text{arg}, \text{size, ret} \) | Convenience wrapper for single function calls with one argument |

4 PROTOTYPE IMPLEMENTATION

We implement the concept of secure domain rollback as SDRoB – a C-language Linux library for the 64-bit x86 architecture using PKU as the underlying isolation primitive. The library provides an API to control the life cycle of domains.

4.1 SDRoB API

Developers use the SDRoB API calls shown in Table 1 to flexibly enhance their application with a secure rollback mechanism, accounting for the design patterns described above.

Domains are initialized by \( \text{sdrob_init()} \) where the developer chooses a unique index to reference the domain in future API calls. \( \text{Execution} \) and \( \text{data} \) domains may be created, where the latter may hold shareable data pages but cannot execute code. For execution domains we further distinguish domains that are accessible or inaccessible to their parent, and whether an abnormal domain exit should be handled in the parent or grandparent domain. A domain can only be initialized once per thread (unless it is deinitialized or destroyed before by the programmer) and the point of initialization for execution domains marks the execution context to which control flow returns in case of an abnormal domain exit.

The API call’s return value fulfills two roles. When the domain is first initialized, it returns \( \text{OK} \) on success or an error message, e.g., if the domain was already initialized in the current thread. On abnormal domain exit, control flow returns another time from the init function and the return value signifies the index of the nested domain that failed and was configured to return to this point. This means that error handling for abnormal domain exits needs to be defined in a case split on the return value of the \( \text{sdrob_init()} \) function.

After initialization, memory in an execution or data domain can be managed using \( \text{sdrob_malloc()} \) and \( \text{sdrob_free()} \), e.g., to be able to pass arguments into the domain. For inaccessible domains, a shared data domain needs to be used to exchange data. Using \( \text{sdrob_dprotect()} \) access permissions to a data domain can be configured for child domains.

An execution domain initialized in the current domain can be entered and exited using \( \text{sdrob_enter()} \) and \( \text{sdrob_exit()} \). This switches the stack and heap to the selected domain and back, and changes the memory access permissions accordingly. Currently, the SDRoB prototype does not copy local variables on such domain
Listing 5: Using other API calls (orange) to implement sdrob_call(udi_F,F,arg,size,ret) (pseudocode).

transitions. Such variables need to be passed via registers or heap memory.

Supporting the transient domain design pattern, child domains can be deleted using sdrob_destroy() \(②\), with the option to either discard the domain’s heap memory or, if accessible, merge it to the current domain. The persistent domain pattern can then be implemented by simply not destroying the domain after exiting it, so that it can be entered again.

An important requirement is that a nested execution domain needs to be destroyed before the function that initialized that domain returns. Otherwise, the stored execution context to which to return would become invalid as it would point to a stack frame that no longer exists. To provide more flexibility, sdrob_deinit() \(⑤\) allows to just discard a child domain’s execution context but leave its memory intact. Before entering the domain again, it needs to be re-initialized, setting a new return context for abnormal exits.

Finally, we provide sdrob_call() \(⑤\) which implements the life cycle of enter_domain() shown in Figure 2 for a function \(F\) that receives a pointer to an object in memory as input and returns an integer-sized value. To illustrate the API, Listing 5 shows how sdrob_call() can be implemented.

In the example, we first initialize a new accessible execution domain for function \(F\). If an abnormal exit occurs in that domain, control returns here, so we save the error code in err. If initialization succeeded, we allocate a local variable \(r\) in a register to retrieve the return value later. We also allocate memory for the input argument at adr in the new domain. Since that domain is accessible, we can copy the argument directly from the parent domain. Afterwards, we enter the nested domain and invoke \(F\) on the copy of the argument, saving the return value. After exiting, we are back in the parent domain and can copy the return value to the desired location (which is inaccessible to the nested domain). We free all temporary memory and destroy the nested domain, freeing its remaining memory.\(^1\)

Finally, we return OK in case of normal domain exit, or the error code otherwise. Users of sdrob_call() can then define their own error handling depending on this return value as shown earlier.

\(^1\)Calling sdrob_free() is actually redundant here; sdrob_destroy() would free this memory as well with the NO_HEAP_MERGE option.

OpenSSL. Listing 6 shows an EVP_EncryptUpdate() wrapper for OpenSSL that implements the persistent domain pattern introduced in Section 3.4. Here, OpenSSL allocates its data, such as the context (ctx) \(①\) from a domain which is inaccessible from its parent. While the caller can hold a pointer to ctx, the object itself is inaccessible to the parent domain. Arguments are copied in via a data domain \(①\). The wrapped function must read buffered input and write its output to its parent domain. There are three possible design choices for passing buffer data between the respective domains: 1) the OpenSSL domain has read-only access to the parent, i.e., it’s called from the root domain; input can be read directly, but output must be copied through the data domain used for argument passing \(①\), \(②\) the parent domain is inaccessible to the OpenSSL and it must copy both input and output via the data domain used for argument passing \(①\), \(②\), \(③\) the parent domain is responsible for setting up a shared data domain between the respective domains and the wrapper can access the shared area directly via the argument pointers.

This persistent domain can be combined with a transient domain as shown in Figure 3 to 1) encapsulate the pointer to ctx within an outer domain, 2) protect the root domain from errors in the caller, e.g., an out buffer of insufficient size, and 3) simplify error handling for the OpenSSL domain. Appendix B shows a concrete usage example.

4.2 Implementation Overview

In a nutshell, SDRoB is implemented using four components: 1) a hardware mechanism for enforcing in-process memory protection, 2) an isolated monitor data domain that houses control data for managing execution and data domains, 3) initialization code that is run at the beginning of each application that is linked to the SDRoB library, setting up the monitor domain and memory protection, as well as 4) trusted reference monitor code that realizes the SDRoB API calls, having exclusive access to the monitor data domain. Below we provide more details about these components.

Memory Protection. SDRoB uses PKU protection keys (cf. Section 2.3) as a hardware-assisted SFI mechanism to create different isolated domains within an application governed by different memory access policies. When a domain is created, a unique protection key is assigned for it. At each domain transition, PKRU is updated to grant access to memory areas as permitted for the newly entered domain, and to prevent access to other memory areas. Our evaluation platform supports Intel PKU, hence it allows us to manage up to 15 isolated domains at a time for each process. Software abstractions for MPK, like libmpk [86], increase the number of available domains.

SDRoB Control Data. SDRoB stores global control data in the monitor data domain for keeping track of, e.g., the registered domain identifiers and the protection key usage. It also stores per-thread information for domains such as stack size, heap size, parent domain, and memory access permissions. To support abnormal domain exits, the currently executing domain and the saved execution contexts are stored too.

\(^2\)Pointer args is kept in a callee-saved register (r12) to remain accessible after sdrob_enter(OPENSSL_UDI) (line 17) changes the domain stack.

\(^3\)Buffer args.out requires room to store int + cipher_block_size bytes of data. The cipher_block_size is known from ctx [6].
Listing 6: Wrapper function for \texttt{EVP\_EncryptUpdate()} that executes OpenSSL in a persistent nested domain (excerpt). Data is passed between parent and nested domain via shared data domain \texttt{OPENSSL\_DATA\_UDI}. Error handling is omitted for brevity.

\begin{verbatim}
int __wrap_EVP_EncryptUpdate(EVP_CIPHER_CTX *ctx, unsigned char *out, int *outl, const unsigned char *in, int inl) {
  register evp_encrypt_update_args_t *args asm ("r12"); // holds copied function arguments and return value
...

  args = sdrob_malloc(OPENVSSL\_DATA\_UDI, sizeof(evp_encrypt_update_args_t));
  args->ctx = ctx;
  args->inl = inl;
  // copy ctx from current domain to shared data domain

  if (out != NULL && inl == 0) {
    // inl + cipher_block_size is upper bound for yet unknown output size
    args->out = sdrob_malloc(OPENVSSL\_DATA\_UDI, inl + cipher_block_size);
  } else {
    // copy out encrypted data from shared data domain
    args->out = out;
  }

  if (in != NULL && inl == 0) {
    // copy in from current domain to shared data domain
    args->in = sdrob_malloc(OPENVSSL\_DATA\_UDI, (size_t)inl);
  } else {
    // copy in from current domain to shared data domain
    memcpys(args->in, in, inl);
  }

  sdrob_enter(OPENVSSL\_UDI);
  // execute real EVP\_EncryptUpdate in inaccessible domain
  args->ret = __real_EVP_EncryptUpdate(args->ctx, args->out, &(args->outl), args->in, args->inl);
  sdrob_exit();

  *outl = args->outl;
  // copy out outl value from shared data domain
  memcpys(out, args->out, (size_t)*outl);
  if (out != NULL) {
    // copy out encrypted data from shared data domain
  }
...
}
\end{verbatim}

Initialization. An application is compiled with the SDRoB library to use the rollback mechanism. The library provides a constructor function that is executed before \texttt{main()} to assign all application memory to the initial isolated domain as a root domain associated with one of the PKU protection keys. It then initializes SDRoB global control data where the default stack and heap size for domains is configurable through environment variables. Furthermore, it sets the root domain as active domain, to be updated at domain transitions by the reference monitor, and finally initializes a signal handler. For the multithreading scenario, SDRoB has a thread constructor function as well, that is executed before the thread start routine function to assign a thread memory area to a domain and associate it with one of the protection keys.

Reference Monitor. The reference monitor is responsible for bookkeeping of domain information in SDRoB control data. It performs domain initialization, domain memory management, and secure domain transitions, including updating the memory access policy, and saving and restoring the execution state of the calling domain. Only the reference monitor has access to the monitor data domain by updating the PKRU register accordingly. The monitor code is executed using the stack of the nested domain that invoked it.

Error Detection. Memory access violations are generally reported to userspace software either via 1) a SEGFAULT signal, e.g., when a domain tries to write past the confines of its memory area, or 2) calls to runtime functions inserted by instrumentation, e.g., GCC’s stack protector calls \_\_stack\_chk\_fail() if a stack guard check fails. That function is typically provided by glibc and terminates the application. During process initialization, SDRoB sets up its own signal handler for the SEGFAULT signal, where the cause for a segmentation fault is given by a signal code (\texttt{si\_code}) available in a \texttt{siginfo\_t} structure [85] provided by the runtime to the signal handler. For instance, violations of PKU access rules are reported by \texttt{SEGV\_PKUERR} signal code. In Linux the SEGFAULT signal is always delivered to the thread that generated it. If the SDRoB signal handler detects a violation that occurred in a nested domain, it triggers an abnormal domain exit. For faults occurring in the root domain or being attributed to a cause the SDRoB signal handler is not prepared to handle, the process is still terminated. SDRoB also provides its own implementation of \_\_stack\_chk\_fail() that replaces the glibc implementation to respond to stack guard violations.

SDRoB can be extended to incorporate other run-time error detection mechanisms, such as Clang CFI [1] or heap-based overflow protections (e.g., heap red zones [95]), improving the recovery capabilities. Probabilistic and passive protections such as ASLR hinder the exploitation of memory safety violations but cannot detect them. Yet, our rollback mechanism is compatible with ASLR, as domains are created at run-time.

Rollback. The secure rollback from a domain is achieved by the reference monitor saving the execution context of the parent domain into SDRoB control data when that domain is initialized. SDRoB uses a \texttt{setjmp()}-like functionality to store the stack pointer, the instruction pointer, the values of other registers, and the signal mask for the context to which the call to \texttt{sdrob\_init()} returns. Note that we cannot simply call \texttt{setjmp()} within \texttt{sdrob\_init()} because that execution context would become invalid as soon as the initialization routine terminates. On an abnormal domain exit, the saved parent execution state is used to restore the application’s state to the initialization point prior to entering the nested domain by
using longjmp(). This rollback lets the application continue from that last secure point of execution that is now redirected to the developer-specified error handling code. To simplify programming under these non-local goto semantics [84], we only allow to set the return point once per domain and thread. Moreover, the convention that a domain needs to be destroyed or deinitialized before the function that initialized it returns, ensures that the saved execution context is always valid.

4.3 Memory Management and Isolation

The secure rollback mechanism is achieved by creating different domains within an application and ensuring that a memory defect within a domain only affects that domain’s memory, not the memory of others. Using the underlying SFI mechanism based on PKU, each domain is isolated from other domains.

Global Variables. We modify the linker script to ensure that global variables are allocated in a page-aligned memory region that can be protected by PKU. At application initialization, all global variables are assigned to the root domain; consequently they are not accessible to nested domains. As a pragmatic solution to the problem, we make the root domain by default read-only for all nested domains. Write access to global data may then be achieved by allocating it on the heap of a shared data domain, referenced by a global pointer. Note that this approach breaks the confidentiality of the root domain towards nested domains. As our main goal is integrity, and confidential data can still be stored and processed in separate domains, we find it a reasonable trade-off for our prototype.

Stack Management. SDRoB creates a disjoint stack for each execution domain to ensure that the code running in a nested domain cannot affect the stacks of other domains. The stack area is allocated when first initializing a domain and protected using the protection key assigned to that domain. As an optimization, we never unmap the stack area, even when the domain is destroyed, but keep it for reuse, i.e., when a new domain is initialized. At each domain entry, we change the stack pointer to the nested domain stack pointer and push the return address of the sdrob_enter() call, so that the API call returns to the call site using the new stack. Then we update the PKRU register according to memory access policy for that domain. A similar maneuver is performed when switching back to the parent domain’s stack via sdrob_exit().

Heap Management. In order to manage a domain’s heap allocations as described in Section 3.4 the underlying allocator must have the ability to differentiate between allocations that occur in different domains and ensure that the underlying memory is chosen from an address range in a particular domain’s reserved heap area. Traditionally the heap is set up to be one large continuous memory area. Modern malloc() implementations, including the GNU Allocator in glibc [69] have the ability to maintain multiple disjoint heap areas, typically for the purpose of optimizing memory access patterns in multi-threaded applications. For example, the GNU Allocator internally maintains one or more memory areas, referred to as arenas, that are reserved via mmap() to provide the backing memory for the application’s initial heap and subsequently allocated thread heaps. Concurrent allocations require threads to obtain a lock on the arena structure that malloc() operates on. Consequently, by assigning different arenas to different threads the GNU Allocator enables memory allocations in different threads to occur concurrently without interfering with each other. Unfortunately the GNU Allocator’s design does not guarantee thread-isolation between arenas; if a thread fails to allocate memory from the arena attached to it, the malloc() implementation continues the search for a suitable large block of memory to satisfy the allocation from the application’s other arenas [42]. Because heap isolation in SDRoB requires memory management with strict guarantees that allocations within a domain are satisfied only from memory reserved for that domain, we opted to use an allocator that natively supports fully disjoint heap areas instead of the default glibc GNU Allocator. For our implementation, we chose the Two-Level Segregated Fit (TLSF) [73] allocator [21]. TLSF is a "good-fit", constant-time allocator that allocates memory blocks from one or more pools of memory. Each free block in a pool is linked in two different doubly linked lists: 1) a free list of blocks belonging to the same size class, and 2) a list ordered by physical address. The TLSF control structure contains a free list bitmap that describes the availability of free memory blocks in different size ranges. TLSF uses processor bit instructions and the bitmap to locate a corresponding linked list of suitable-sized free blocks.

Each SDRoB domain is assigned its own TLSF control structure and memory pool that correspond to the domain’s subheap. The size of the initial pool assigned to domains is configurable via an environmental variable. Each individual TLSF pool is limited to 4GB in size [73]. Beyond that, a domain’s memory is increased by reserving additional pools for the domain’s TLSF allocator.

Lazy Heap Initialization. In order to reduce the memory footprint when domains don’t make heap allocations, the control structure and initial memory pool are not initialized when the domain is created. Instead, the reference monitor initializes the domain’s TLSF instance the first time the domain allocates heap memory with the malloc() family of functions. We interpose such functions with wrappers by placing the SDRoB library before libc in the library load order. Upon initialization the associated memory pool is protected by associating it with the domain’s protection key.

Subheap Merging. Recall from Section 4.1 that a domain’s subheap is either discarded or merged with the parent domain’s subheap when sdrob_destroy() is called, depending on the option parameter provided. To enable subheap merging we extended the TLSF implementation to associate a partially consumed pool to a pre-existing TLSF control structure. When a subheap is merged, its associated protection key is updated to match the parent domain’s protection key. The parent’s TLSF control structure is then updated as follows: 1) detect used and unused blocks in the memory pool being merged, 2) link all these blocks to the pre-existing block lists in the parent domain, 3) update the parent domain’s TLSF free list bitmap for unused blocks, and 4) delete the child domain’s TLSF control structure. If the heap is not be merged when the domain is destroyed any allocations are freed and the underlying memory pools can be reused by new domains.
5 CASE STUDIES

We evaluate the performance of SDRoB with three different real-world case studies: Memcached, NGINX, and OpenSSL. Two aspects are evaluated: 1) rollback latency on an abnormal exit, 2) performance impact of the isolation mechanism. We run our experiments on Dell PowerEdge R540 machines with 24-core MPK-enabled Intel(R) Xeon(R) Silver 4116 CPU (2.10GHz) having 128 GB RAM and using Ubuntu 18.04, Linux Kernel 4.15.0. We compiled Memcached and NGINX with -O2 optimizations, -pie (for ASLR), -fstack-protector-strong, and -fcf-protection.

5.1 Memcached

Memcached [75] is a general-purpose distributed memory caching system, which is used to speed up database-driven applications by caching database content. To do so efficiently, Memcached stores its state in non-persistent memory; after termination and restart, clients must start over and resend a large amount of requests to return to the situation prior to the restart. Even in real-world deployments with built-in redundancy and automatic remediation, small outages can take up to a few minutes to re-route requests to an unaffected cluster [81]. Several studies propose to use low latency persistent storage for Memcached [71, 126] but these solutions come with a non-negligible performance overhead. As availability and resilience of Memcached to unforeseen failures is of high importance, it is a worthwhile target for hardening with secure domain rollback. The main thread in Memcached accepts connections and dispatches them among worker threads to handle related requests. Memcached uses a hash table to map keys to an index and slab allocation to manage the in-memory database. Memcached has an event-driven architecture, handling each client request as an event. The clients can send get, set, and update commands with key and value arguments. To handle a request, command parser subroutines in Memcached classify the client request, then the key-value pairs are fetched from, inserted in, or updated in the database, according to the client’s command. If a client event contains a malicious request leading to memory corruption, the database and hash table, as well as the complete application memory area, are corrupted and Memcached must be restarted. As a result, one malicious request affects the availability of the caching service to all clients.

**Memcached with SDRoB.** We propose that each client event should be handled in a nested domain. In case of memory corruption, the abnormal domain exit occurs in the nested domain, we discard the related nested domain contents and come back to the root domain securely. Memcached closes the related connection, and it can continue its execution, handling another client request without restarting.

Figure 4 shows a sequence diagram of Memcached with SDRoB. We configure SDRoB with a partially isolated multithreading configuration (see in Section 3.6), because the main thread needs to communicate with the worker threads. Each event is handled using the `drive_machine()` function with a corresponding connection buffer. We isolate this function using the SDRoB API, along the lines of Listing 5. Recall from Section 3.4 that nested domains only have read access to data that belongs to the parent domain. Nevertheless, certain subroutines, such as `drive_machine()`, need to update shared state residing in a parent domain, e.g., the connection buffer. As a solution, the event handler that calls `drive_machine()` initializes an accessible, nested domain D (3) and makes a deep copy of the connection buffer that is made available to `drive_machine()` (4). It then enters D (5) and calls `drive_machine()` (6) to handle the client request, working on a copy of the connection buffer. After successfully handling the request, it exits from D (7), the original connection buffer in the parent domain is updated with any changes present in the shared copy (8). On abnormal domain exit, the copied connection buffer is discarded. Since the event handler returns after handling the request, we need to invalidate the saved execution context of D. As `drive_machine()` does not allocate any persistent state in D, we could use the transient domain pattern and destroy D. However, as an optimization, we retain the copy of the connection buffer used by the domain, hence `sdrob_deinit()` (10) is used.

The `drive_machine()` function also needs to read and write the hash table and database to perform look-ups, insertions, and updates. We allocate it in a dedicated data domain, accessible by the nested domain of each thread. To allow inserts and updates, we wrap the `slabs_alloc()` function, that normally returns a pointer to a memory area in the database, to return a copy of that area to insert the key-value pair. Similarly, we wrap `store_item()` which stores new data and updates the hash table. Each event handler first performs its operation on a copy of the corresponding item. On normal domain exits from D, we insert the key-value pair to the database, and update the hash table (9). On an abnormal domain exit (11-12), the corrupt key-value pair is discarded along with all other memory of the domain. Note that this solution delays updates to the database. However, due to the atomic nature of the Memcached requests, consistency is not affected. Our changes were limited to two source files in Memcached and 484 new lines of wrapper code. In total, the changes amounted to ~550 LoC of the 29K SLoC code base (~2%).

Memcached uses a shared mutex to synchronize worker threads. Here, our copying mechanism for shared data does not work, because it would hide concurrent accesses to the mutex and break the synchronization. We opted to create a separate data domain for the mutex that every worker can access. See Section 7 for a security discussion of this scheme.
Performance Impact. We used the Yahoo! Cloud Service Benchmark (YCSB) [22] to test the impact of SDROB on Memcached performance. YCSB has two phases: a loading phase that populates the database with key-value pairs, and a running phase which perform read and update operations on this data. We used workloads with sizes of 1KiB, with a read/write distributions of 95/5. For our measurements, we stored $1 \times 10^7$ key-value pairs (1KiB each) and performed $1 \times 10^8$ operations on those pairs. Operations were performed with a Zipfian distribution over the keys. We compiled Memcached v1.6.13 and evaluated the performance with the TLSF allocator and with SDROB as described in Section 5.1. We compare the results against YCSB on unmodified Memcached. Figure 5 shows the load and running phase throughput (operations/second) of the three versions for 1, 2, 4, and 8 workers over 5 benchmark runs. Each thread was pinned to separate CPU cores. We used 32 YCSB clients with 16 threads pinned to separate cores for each test. We fully saturated Memcached cores for 1, 2, and 4 threads but were unable to reach saturation for 8 threads. We concluded that TLSF has negligible impact on throughput in all our tests (<1%). For Memcached augmented with SDROB the load and running phase overhead is 2.9% / 4.1%, respectively, for 4 threads, and 4.5% / 5.5% for 2 threads. SDROB introduced a worst-case overhead of 7.0% / 7.1% for a single thread. We measured a performance degradation of < 4.1% for 8 threads but lack confidence in the soundness of that result as the CPU was not saturated (cf. Table 6 in Appendix A for all figures). We measured the memory overhead of SDROB from the maximum resident set size (RSS) after the YCSB load phase and comparing the RSS of Memcached with SDROB to the baseline. The mean RSS increase is 0.4% ($\sigma = 171$KiB).

5.2 NGINX

NGINX [80] is an open-source web server implemented as a multiproccessing application with a master process and one or more worker processes. The master process is responsible for maintaining the worker processes that handle client HTTP requests for several connections at a time. If a malicious client request leads to memory corruption, the worker process may crash and the master process restarts it, however all active connections of that worker are lost. Due to its complexity and exposure to untrusted inputs, the HTTP parser is a vulnerable component of NGINX. Similar to [49], we propose that each client HTTP request is parsed in a nested domain. Thus, if a memory corruption is detected in the parser, an abnormal domain exits occurs and we discard the related nested domain content to come back to the root domain securely without restarting the worker process. The related connection is closed, but all other connections are unaffected.

We sandboxed the HTTP parser (ngx_http_parser.c) to execute in an accessible permanent nested domain, by instrumenting all NGINX parser functions using the SDROB API. NGINX creates a temporary memory pool for each client request to hold a request buffer. We direct the allocation of these pools to a separate data domain that is accessible by the nested domain. The request buffer data structure links back to header data and URI data in the connection buffers. To protect this root domain data and make it accessible to the parser, it is copied into the nested domain and the results are copied back on domain exit. The NGINX Parser executes multiple phases, e.g., parsing request lines or headers. Thus, domain transitions occur repeatedly in one request. On an abnormal domain exit, it is not important which parser phase has corrupted the memory: we always close the corresponding connection. Hence we save as execution context first entry point of the NGINX parser to come back to at an abnormal domain exit. Our changes were limited to one file in NGINX and 195 new lines of wrapper code. In total, the changes amount to ~220 LoC of the 150K LoC code base (0.15%).

Rollback Latency. We reproduced CVE-2009-2629 [27] to verify the rollback mechanism and compiled NGINX v0.6.39 with SDROB. The CVE causes a buffer underflow in the linked connection buffer data. By having the parser operate on copies of that data in the nested domain, the underflow triggers a domain violation and thus an abnormal domain exit. We measured the latency of the abnormal domain exit starting from catching SEGFAULT to accepting a new connection. The mean latency is 3.4µs ($\sigma = 0.67$µs). We compared it with restarting the worker process by the master process for reference. The mean latency is 996µs ($\sigma = 44$µs).
With respect to attack detection, we assume that an attack or fault with one worker for different file sizes. Figure 5 shows mean throughput (requests/second) of the three versions of NGINX with one worker process for different file sizes over 5 benchmark runs. We compiled NGINX v.1.23.1 and compared it to NGINX with TLSF allocator and SDRoB. The latter introduced overheads between 1.6% (128KiB) and 6.5% (1KiB). We scaled up the number of workers for NGINX with SDRoB and observed that the overhead is independent of that number as expected. (cf. Table 8 in Appendix A for all figures). We measured the memory overhead of SDRoB from the maximum resident set size (RSS) after benchmarking the 128-KiB file size with four worker processes, and comparing the RSS of NGINX with SDRoB to the baseline. The mean RSS increase is 3.06% ($\sigma=50$KiB). We profiled the cost of domain switching for NGINX and observed that 30% – 50% of that cost comes from writing to the PKRU register, which flushes the processor pipeline [86, 107].

5.3 OpenSSl
SDRoB allows isolating a library without changing it, enabling later integration into applications. We evaluated the performance impact on OpenSSL 1.1.0 for all three design choices explained in Section 4.1 by adapting the built-in OpenSSL speed benchmark and running the aes-256-gcm cipher via the EVP_EncryptUpdate function (cf. Listing 6) for 3s, measuring the number of encryptions. As expected, memcpy operations cause notable performance overhead and the third option, a parent-managed shared domain, performed best. Even without copy operations, SDRoB substantially degraded the performance of cryptographic operations for small input sizes (4% to 80%). For more realistic input sizes $\geq$32KiB we did not measure any statistically significant overhead (< 2%, cf. Table 7 in Appendix A for all figures).

6 SECURITY EVALUATION
The primary security requirement for our work is defined with

**R1** The mechanism must allow the application to continue operation after system defenses (A2) detect an attack.

Our proposal satisfies this requirements by compartmentalizing applications into isolated domains where an attack against a child domain can be detected, which leads to the termination of that domain, while the parent domain is informed and can continue operation. With respect to attack detection, we assume that an attack or fault will exhibit an illegal memory access that triggers a SEGFAULT signal. We then use signal handlers to detect and handle the failure, leading to a termination of the crashed child domain and a rollback of the parent domain to a well-defined state. Compartmentalization is achieved by implementing the following two requirements:

**R2** The mechanism must ensure that the integrity of memory after recovering from the detected attack is maintained.

**R3** Run-time attacks that affect one domain must not affect the integrity of memory in other domains.

In our implementation of SDRoB, we use PKU as a mechanism to enforce in-process isolation while facilitating efficient domain switches. The security of this mechanism critically relies on protecting potential gadgets in the SDRoB implementation that allow an attacker to manipulate the PKRU register.

To guarantee the security of SDRoB, the following orthogonal defenses need to be in place: 1) PKU crucially relies on untrusted domains to not contain unsafe WRPKRU or XRSTOR instructions that manipulate the PKRU register [20]. This can be guaranteed through WiX and binary inspection [107]. For programs that do not rely on dynamic code generation, this policy can be implemented with very low run-time overhead. Alternative proposals of hardware designs for PKU-like security features restrict access to userspace configuration registers [92]. 2) Since the SDRoB library necessarily contains WRPKRU instructions, we must employ a CFI mechanism to protect the API implementation of our Reference Monitor and statically ensure that the Reference Monitor API does not contain abusable WRPKRU or XRSTOR gadgets. 3) An alternative way to modify PKRU is by utilizing sigreturn is described in [20]: An untrusted domain may exploit sigreturn gadgets and a fabricated sigframe crafted on the stack to make the kernel write an arbitrary value to the PKRU. This can happen without using a WRPKRU or XRSTOR gadget in userspace. sigreturn attacks are mitigated by ASLR [23] but precluding them requires kernel-level authentication of sigframe data [64]. 4) As highlighted in [20, 91], existing PKU sandboxes do not sufficiently safeguard the syscall interface. Attackers can use a number of unsafe system calls that do not honor PKRU to erase or manipulate protected memory pages. Previous work [91, 111] proposes efficient syscall filtering mechanisms to prevent untrusted domains from invoking unsafe syscalls. With the above security mechanisms in place, SDRoB satisfies our fourth requirement:

**R4** The attacker must not be able to tamper with components responsible for isolation or transitions between domains, or data used as part of the rollback process.

It is possible to implement secure rollback of isolated domains on top of other isolation mechanisms e.g., within Intel SGX to equip enclaves with rollback or by using capability-based enforcement of isolation, e.g., CHERI or ARM Morello. Such uses will incur different low-level security requirements and exhibit different performance characteristics. Furthermore, SDRoB is not limited to rely on SEGFALT handling but could employ different attack oracles that, e.g., trigger when a domain invokes an unexpected system call.

7 DISCUSSION

**Applicability.** As highlighted earlier, secure rollback of isolated domains is particularly suited for service-oriented applications that need strong availability guarantees and may hold volatile state like
client sessions, TLS connections, or object caches. Redundancy and load balancing can minimize the impact of DoS attacks, but loss of volatile state can still degrade service quality for clients, which our approach mitigates.

Of course, different applications will benefit from secure rollback in different ways. A prime target for this mechanism are subroutines and libraries that handle sequences of external, untrusted data, e.g., functions that perform input validation, JavaScript engines in web browsers, database front-ends, or video, image, and document renderers. Such components exhibit a heightened degree of exposure towards potential attacks since they operate directly on unsanitized input. Thus, an application should isolate them in their own domain so that any memory corruption is contained and execution can continue on a different path after recovery via the rollback mechanism.

In practice, the specific setup of domains and protections will depend highly on the architecture of individual applications. We expect retrofitting existing applications written in unsafe programming languages in lieu of a complete re-write in a memory-safe language, to be a compelling use case. As such, the design of secure rollback incorporates different options to compartmentalization.

Furthermore, rollbacks that occur in long-running services may serve as early warning signals of an attack campaign. The incident may be reported to a Security Information and Event Management (SIEM) system and appropriate action, such as blocking malicious clients in firewall rules can be taken to shield the overall system from repeated attacks, minimizing the impact on legitimate clients.

Limitations. It is clear that all applications can be easily compartmentalized and refactored to make use of SDRoB. For example, applications that rely on global mutexes might suffer from availability issues when a child domain that holds a lock crashes and the lock is not released prior to continuation of the parent domain. Options for resolving this are, e.g., to provide an SDRoB-aware locking mechanism as part of our SDRoB library, or to prefer local locks with well-defined scope instead of global locks. This aids serializing access, e.g., when domains operate on copies of protected objects.

Another potential issue comes with complex data structures used by target applications. Similar to other strong isolation mechanisms such as Intel SGX, data needs to be copied into the address space of the protection domain [24], which is done by entry wrappers. Both, manual as well as automated generation of these wrappers can be error prone and may hamper security [108]. Generally, domain transitions and domain termination bear subtle risks. Currently, confidentiality of child domain data is not guaranteed after destroying it and we leave it to the developer to realize such requirements, e.g., scrub sensitive allocations from memory before leaving the domain.

The use of SDRoB as a mechanism that increases the availability of long-running services may open up a side-channel attack surface. As observing errors might give an attacker insights into an application’s execution, the observable effects of a rollback (e.g., delayed execution) might also give such insights. Coupled with the absence of re-randomization of the application’s memory layout, an attacker could potentially use this to break probabilistic defenses such as ASLR. A potential protection against such attacks could be achieved by making the rollback behavior of SDRoB configurable and force an application restart after a certain number of rollbacks, similarly to probabilistic defenses for pre-forking applications [65].

Ultimately the security of SDRoB depends on the correctness of our library implementation and further exploration of the attack surface and potentially formal verification of our code are envisaged to harden our approach.

Additionally, we further envision the following possible extensions to SDRoB:

Global variables. Currently, global variables are stored in the root domain that is read-only by default to allow access to all nested domains. A more comprehensive solution would place these variables in their own dedicated data domain(s) with a reserved identifier.

Accessing local variables. As discussed in Section 4.1, having dedicated stacks per domain precludes accessing local variables across domain transitions. Beyond the use of registers for passing arguments and heap memory in shared domains for passing data, SDRoB could also incorporate existing compiler support for disjoint stacks present in GCC [117] to facilitate accesses to objects across stack boundaries, e.g., arguments passed on the stack.

Access control. At the moment, a very simple policy governs access to domains: in principle only parent domains can perform API calls targeting a nested domain. Still, more flexible policies may be desirable, i.e., inheriting access to data domains from a parent. However, such features need to be designed carefully, not to over-complicate the programming model, or to compromise security.

Strongly Isolated Multithreading Design. SDRoB currently employs the partially isolated multithreading design discussed in Section 3.6. However, if an application employs threads that do not need to synchronize on shared data, e.g., worker threads processing local data, then each thread can have a separate isolated root domain containing each thread’s stack and heap area. This strongly isolated setup prevents that a compromised thread can access any data owned by other threads. Furthermore, in case of abnormal domain exit from a thread root domain, the rollback mechanism can be configured to discard all the compromised thread’s domains and recreate the thread from scratch without aborting the application. It would be possible to allow the setup and initialization of thread root domains to the configurable by the programmer, to allow for hybrid configurations where a subset of threads may fail without affecting the main process. To this end we would add thread creation to the SDRoB API to let the programmer specify thread root domain identifiers, instead of wrapping pthread_create() as is done now. This would allow allocating threads to the same root domains explicitly and also to share data domains with otherwise strongly isolated threads.

Thread safety. Different threads can initialize the same domain individually. However, our current implementation of domains is not thread-safe apart from shared root domains, i.e., it is undefined what happens if two threads enter a given nested domain at the same time. The programmer needs to ensure that entry to shared nested domains (e.g., an isolated crypto library) is synchronized. While our internal data structures can support concurrent domain entry, more work is needed to manage abnormal domain exits. If such an exit is triggered by one thread, it should be propagated automatically to all other threads that might be running in that domain.
8 RELATED WORK

Hardware-assisted compartmentalization. The idea of using MPK for compartmentalizing applications is not new; PKU in 64-bit x86 is used to augment SFI approaches that generally suffer from high enforcement overheads [94, 113]. Such work generally falls into two broad categories: 1) in-process isolation [15, 44, 54, 57, 58, 88, 92, 107, 111, 114], and 2) isolation for unikernels and library operating systems [62, 74, 101]. In-process isolation using PKU has been scrutinized for the lack of controls on PKRU access which may leave schemes vulnerable to attacks that bypass established isolation domains [20, 91, 111]. Countermeasures proposed against such attacks, include code rewriting [58], binary inspection [107], system call filtering [91, 111] and variations on the PKU hardware design [31, 39, 92]. Secure multi-threading has also been considered [16, 57, 104]. However, in-process SFI, similar to the defenses discussed in Section 2, does not consider how to recover from attacks regardless of whether enforced via software or hardware. This work addresses this gap by introducing capabilities for secure rollback.

Capability hardware, such as a CHERI [115, 118] also enables compartmentalized fault isolation. CompartmentOS [3] provides recovery capabilities for CHERI faults in compartments, but unlike SDRoB, it is geared toward safety-critical embedded systems, not commercial off-the-shelf processors.

Checkpoint & restore. Existing approaches to checkpoint & restore, such as CRIU [55] provide support for process snapshots that can enable rollback-like functionality. However, checkpoint & restore generally suffers from high overheads due to relying on reproducing process memory and do not consider in-memory attacks in their threat models [67, 78, 116, 122, 125]. SDRoB avoids these drawbacks by combining in-process isolation to limit the scope of attacks and to ensure the integrity of memory after rollback.

N-variant Execution. N-variant Execution (NVX) [110] provides resilience against invasive attacks by introducing redundancy through running multiple, artificially diversified variants of the same application in tandem and monitor each distinct copy for divergent behavior. If any inconsistencies between the instances are detected NVX terminates the offending instances’ execution while unaffected instances can continue. While SDRoB shares the goal of improving software resilience with NVX we consider use cases for which the high cost of replicating compute instances and I/O across each instance is impractical. Safety-critical applications for which the high deployment cost of NVX may be justified are outside the scope of this work.

9 CONCLUSION & FUTURE WORK

We presented the novel concept of secure rollback of isolated domains which complements protection mechanisms against memory safety vulnerabilities. It provides a hardening mechanism to recover from detected violations, thus improving the availability and resilience of software applications. At its core, secure rollback uses hardware-assisted in-process memory isolation to isolate exposed functionality in separate domains, so that a compromise in one domain cannot spread to other parts of a program’s memory. When a compromise is detected by selected defense mechanisms, a rollback to a previously defined consistent state of the application occurs, enabling error handling and resuming the application.

We explored various design patterns for domains and presented SDRoB, our prototype library implementation of secure rollback. We demonstrated its applicability to real software by adding it to the multi-threaded Memcached system, multiprocessing NGINX and the OpenSSL library.

Besides alleviating current limitations discussed above, we aim to improve usability for the programmer, e.g., by providing a domain specific language and compiler support for the definition of domains and the exchange of data between them, similar to the edger8t tool used for Intel SGX enclaves. Providing an amenable, secure, and efficient implementation of the secure rollback mechanism will fill an important gap in the current software security architecture.

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A SUPPLEMENTARY MEASUREMENTS

Table 2 shows the detailed results for our rollback latency measurements for Memcached. The Rollback latency column gives the mean latency in μs over 1000 rollback iterations and the σ column the standard deviation. We measured both the rollback that destroys the offending domain but leaves the contents of its memory intact and a version of the rollback that "scrubs" (zeros) the full contents of domain memory before it can be re-allocated, as indicated in the Zerosing of domain data column. The latter estimates the upper bound for maintaining confidentiality guarantees for nested domains using a 4GB heap pool and 4MB domain stack that store sensitive information as discussed in Section 7. As rollbacks are exceptional events, we deem the 0.2s latency reasonable for use cases with confidentiality requirements. The latency could be reduced by tracking and scrubbing only allocations that contain sensitive data, or reducing the reserved memory for confidential domains.

Table 4 shows the detailed results of our memory consumption measurements for Memcached. The Maximum resident set size column reports the mean maximum resident size (RSS) reported by the Bash shell built-in time command over five iterations of the YCSB benchmark loading phase for the unmodified baseline (Baseline) and Memcached equipped with SDRoB (SDRoB). The columns marked σ give the relative standard deviation of the RSS. We used used four worker threads for this experiment as indicated in the #Wkr column. Table 6 shows the detailed result of our throughput measurements of the YCSB benchmark for Memcached using different numbers of threads (#Thr) that were summarized in Section 5. The Throughput column gives the throughput in operations / seconds of three versions of Memcached: 1) The unmodified baseline (Baseline), 2) Memcached using the TLSF allocator (TLSF), and 3) Memcached equipped with SDRoB (SDRoB). The columns marked σ give the relative standard deviation of the throughput over ten benchmark runs as percentage for the aforementioned versions. The Throughput degradation column gives the degradation of throughput in percentage of (a) Memcached using the TLSF allocator compared to the baseline (TLSF/Baseline), (b) Memcached equipped with SDRoB compared to Memcached using the TLSF allocator (SDRoB/TLSF), and (c) Memcached equipped with SDRoB compared to baseline (SDRoB/Baseline).

Table 3 shows the detailed results for our rollback latency measurements for NGINX. The columns are similar to those in Table 2. Table 5 shows the detailed results of our memory consumption measurements for NGINX. We report the mean maximum RSS over 10 iterations of the NGINX benchmark for the unmodified baseline (Baseline) and NGINX equipped with SDRoB (SDRoB). The columns marked σ give the relative standard deviation of the RSS. We used 4 workers processes for this experiment as indicated in the #Wkr column.

Table 8 shows the detailed result of our throughput measurements of the ab tool for NGINX using different file sizes starting from 0KiB to 128KiB with different worker processes that were summarized in Section 5. The Throughput column gives the throughput in requests / seconds of three versions of NGINX: 1) The unmodified baseline (Baseline), 2) NGINX using the TLSF allocator (TLSF), and 3) NGINX equipped with SDRoB (SDRoB). The columns marked σ give the relative standard deviation of the throughput over five benchmark runs as percentage for the aforementioned versions. The Throughput degradation column gives the degradation of throughput in percentage of (a) NGINX using the TLSF allocator compared to the baseline (TLSF/Baseline), (b) NGINX equipped with SDRoB compared to NGINX using the TLSF allocator (SDRoB/TLSF), and (c) NGINX equipped with SDRoB compared to baseline (SDRoB/Baseline).

Table 7 the detailed result of our throughput measurements of the OpenSSL benchmark tool for different input sizes from 16 to 262144 bytes that were summarized in Section 5. The Throughput column gives the throughput in 1000s of bytes / seconds of three versions of OpenSSL: SDRoB 1. – 3. correspond to the three different design choices for the EVP_EncryptUpdate() wrapper described in Section 4.1: SDRoB 1. – OpenSSL domain has read-only access to parent, SDRoB 2. – the wrapper is responsible for copying input/output via an intermediate data domain, SDRoB 3. – the parent domain sets up a shared data domain which the OpenSSL domain in the wrapper can access directly.
### Table 2: Memcached: Rollback latency

| Zeroing of domain data | Rollback latency (µs) | SDRoB | σ |
|------------------------|------------------------|-------|---|
| No (default)           | 3.46 ± 0.9µs           |       |   |
| Yes                    | 228376.99 (0.2s)       | ±2500µs |   |

### Table 3: NGINX: Rollback latency

| Zeroing of domain data | Rollback latency (µs) | SDRoB | σ |
|------------------------|------------------------|-------|---|
| No (default)           | 3.41 ± 0.7µs           |       |   |
| Yes                    | 232632,4168 (0.2s)     | ±2400µs |   |

### Table 4: Memcached: Memory consumption

| #Thr | Maximum resident set size (KiB) | SDRoB | σ |
|------|---------------------------------|-------|---|
| 4    | 14535444.8 ± 1.19%              |       |   |
|      | 14598972.8 ± 1.18%              |       |   |

### Table 5: NGINX: Memory consumption

| #Wkr | Maximum resident set size (KiB) | SDRoB | σ |
|------|---------------------------------|-------|---|
| 4    | 3135.6 ± 1.59%                  |       |   |
|      | 3234.8 ± 1.71%                  |       |   |

### Table 6: Memcached: Detailed table of throughput measurements.

| #Thr | Throughput (ops/sec) | Throughput degradation (%) |
|------|-----------------------|----------------------------|
|      | Baseline | σ | TLSF | σ | SDRoB | σ | TLSF/Baseline | SDRoB/TLSF | SDRoB/Baseline |
|------|----------|---|------|---|-------|---|---------------|-------------|---------------|
| Loading Phase |
| 1    | 83913    | ±0.69% | 84191 | ±0.46% | 78047 | ±0.89% | +0.33% | -7.30% | -6.99% |
| 2    | 117194   | ±1.05% | 117275 | ±0.18% | 111838 | ±0.40% | +0.07% | -4.64% | -4.57% |
| 4    | 157920   | ±1.24% | 157982 | ±0.43% | 153328 | ±0.63% | +0.04% | -2.95% | -2.91% |
| 8    | 161161   | ±0.80% | 161448 | ±0.75% | 160910 | ±1.13% | +0.18% | -0.33% | -0.16% |
| Running Phase |
| 1    | 99722    | ±0.46% | 99829 | ±0.52% | 92645 | ±0.23% | +0.11% | -7.20% | -7.10% |
| 2    | 155247   | ±0.54% | 155015 | ±0.51% | 146715 | ±0.17% | -0.15% | -5.35% | -5.50% |
| 4    | 223958   | ±0.20% | 223886 | ±0.41% | 214671 | ±0.54% | -0.03% | -4.12% | -4.15% |
| 8    | 234823   | ±0.76% | 235007 | ±0.62% | 225277 | ±0.62% | +0.08% | -4.14% | -4.07% |

### Table 7: OpenSSL: Detailed table of throughput measurements.

| Input bytes | Throughput (1000s of bytes/sec) | Throughput degradation (%) |
|-------------|----------------------------------|-----------------------------|
|             | Baseline | σ | SDRoB 1. | σ | SDRoB 2. | σ | SDRoB 3. | σ | 1/Baseline | 2/Baseline | 3/Baseline |
| 2^a         | 267879   | ±1.04% | 53570 | ±2.08% | 33995 | ±1.41% | 53851 | ±3.02% | -80.00% | -87.31% | -79.90% |
| 2^b         | 724060   | ±1.47% | 196647 | ±1.84% | 127678 | ±1.02% | 201048 | ±2.88% | -72.84% | -82.37% | -72.23% |
| 2^a         | 1508889  | ±2.11% | 616788 | ±1.79% | 1192933 | ±1.32% | 639910 | ±2.07% | -59.12% | -71.59% | -57.59% |
| 2^a         | 2515179  | ±1.85% | 1551532 | ±1.66% | 428704 | ±1.74% | 1610508 | ±1.76% | -38.31% | -52.57% | -35.97% |
| 2^a         | 3073966  | ±1.96% | 2744814 | ±1.17% | 2503868 | ±1.51% | 2842073 | ±1.10% | -10.71% | -18.55% | -7.54% |
| 2^a         | 3139433  | ±1.78% | 2856443 | ±1.11% | 2567001 | ±1.18% | 3025082 | ±1.52% | -9.01% | -18.23% | -3.64% |
| 2^a         | 3167069  | ±1.16% | 2855263 | ±1.13% | 2577581 | ±1.48% | 3111608 | ±1.35% | -9.85% | -18.61% | -1.75% |
| 2^a         | 3184860  | ±1.18% | 2904903 | ±0.71% | 1532381 | ±1.60% | 3169666 | ±1.23% | -8.79% | -51.89% | +0.28% |
| 2^a         | 3198742  | ±1.14% | 2941696 | ±0.83% | 2637291 | ±1.54% | 3207550 | ±1.05% | -8.04% | -17.55% | +0.38% |
### Table 8: NGINX: Detailed table of throughput measurements.

| File size (KiB) | Baseline | Throughput (reqs./sec.) | Throughput degradation (%) |
|----------------|----------|-------------------------|-----------------------------|
|                | 1 worker |                         |                            |
| 0              | 69386    | ±1.40%                  | 66953 ±2.21%               | -2.96%                      | -2.75%                      | -5.63%                      |
| 1              | 55454    | ±1.01%                  | 55484 ±0.74%               | -0.31%                      | -6.17%                      | -6.46%                      |
| 2              | 55184    | ±0.81%                  | 55273 ±0.26%               | -0.21%                      | -4.93%                      | -5.13%                      |
| 4              | 55506    | ±0.70%                  | 54753 ±1.28%               | -1.33%                      | -4.88%                      | -6.14%                      |
| 8              | 53413    | ±2.33%                  | 53574 ±1.20%               | -0.14%                      | -4.51%                      | -4.37%                      |
| 16             | 51302    | ±1.13%                  | 50841 ±0.26%               | -0.78%                      | -3.61%                      | -4.36%                      |
| 32             | 47702    | ±0.83%                  | 47498 ±1.46%               | -0.02%                      | -5.39%                      | -5.42%                      |
| 64             | 37049    | ±0.83%                  | 36687 ±1.16%               | -0.83%                      | -2.51%                      | -3.31%                      |
| 128            | 25852    | ±0.55%                  | 25808 ±0.69%               | -0.06%                      | -1.54%                      | -1.60%                      |
| 2 workers      |          |                         |                            |
| 0              | 132013   | ±1.80%                  | 131029 ±1.97%              | -0.68%                      | -5.09%                      | -5.73%                      |
| 1              | 106254   | ±0.61%                  | 105192 ±1.40%              | -1.36%                      | -4.95%                      | -6.24%                      |
| 2              | 104029   | ±0.68%                  | 104104 ±1.35%              | -0.18%                      | -4.57%                      | -4.74%                      |
| 4              | 104776   | ±1.21%                  | 105309 ±0.73%              | +0.30%                      | -5.37%                      | -5.09%                      |
| 8              | 101995   | ±1.30%                  | 101960 ±0.56%              | +0.24%                      | -5.78%                      | -5.55%                      |
| 16             | 98139    | ±0.44%                  | 96381 ±1.16%               | -1.74%                      | -4.32%                      | -5.99%                      |
| 32             | 89601    | ±0.43%                  | 89253 ±1.62%               | -0.16%                      | -5.01%                      | -5.17%                      |
| 64             | 67910    | ±1.31%                  | 67249 ±1.10%               | -0.95%                      | -4.40%                      | -5.31%                      |
| 128            | 46904    | ±1.36%                  | 46821 ±0.49%               | -0.12%                      | -2.68%                      | -2.80%                      |
| 4 workers      |          |                         |                            |
| 0              | 258531   | ±3.90%                  | 257575 ±3.03%              | -0.37%                      | -5.37%                      | -5.72%                      |
| 1              | 203020   | ±2.92%                  | 202384 ±2.45%              | -0.31%                      | -4.68%                      | -4.98%                      |
| 2              | 202407   | ±2.61%                  | 202701 ±2.88%              | +0.15%                      | -5.79%                      | -5.65%                      |
| 4              | 203555   | ±2.69%                  | 204389 ±3.70%              | +0.21%                      | -4.71%                      | -4.51%                      |
| 8              | 198404   | ±3.43%                  | 197599 ±2.38%              | -0.41%                      | -5.02%                      | -5.41%                      |
| 16             | 188374   | ±4.20%                  | 188913 ±2.48%              | +0.29%                      | -4.84%                      | -4.57%                      |
| 32             | 172736   | ±2.38%                  | 169735 ±2.61%              | -1.74%                      | -5.06%                      | -6.71%                      |
| 64             | 135227   | ±3.61%                  | 132880 ±1.76%              | -1.74%                      | -3.87%                      | -5.54%                      |
| 128            | 93900    | ±2.62%                  | 93940 ±3.21%               | +0.04%                      | -2.43%                      | -2.38%                      |
B OPENSSL EXAMPLE

The excerpts of code in Listing 7 and Listing 8 show an example usage of SDRoB with deeply nested domains as explained in Section 3.5. The excerpts show a simple file encryption server in an event-driven architecture that encrypts client data using OpenSSL and stores the ciphertext on the server.

Upon receiving a client request the event_handler function (Listing 7) performs the following tasks:

1. Reads the encryption key from a file chosen by user and generates a random initialization vector (IV).
2. Calls gcm_encrypt_user_data (Listing 8), which:
   1. Reads a plaintext message from the user via a file descriptor that corresponds to a communication socket.
   2. Encrypts said plaintext with AES GCM using the OpenSSL's “Envelope” (EVP) API.
3. Finally (Listing 7), the even_handler stores the ciphertext (and Galois/counter mode tag) for later retrieval.

The objective to introducing rollback capability to the event handler is to achieve the properties described in Section 4.1, namely to (1) protect the event handler running in the root domain from errors in gcm_encrypt_user_data, e.g., the possible overflow to the plaintext buffer (Listing 8, ➀), (2) encapsulate the pointer to the OpenSSL context (ctx) within an outer, nested domain in such a way that OpenSSL's key objects remain inaccessible to gcm_encrypt_user_data should it malfunction, and (3) simplify error handling for the domain in which the OpenSSL code is run.

To this end, the event handler (running in the root domain) creates a persistent domain for OpenSSL execution that is inaccessible from both the root domain and any nested domain (Listing 7, ➀). This execution domain is immediately deinitialized to invalidate its saved execution context to avoid unintended rollbacks to the beginning of event_handler. The actual execution context for rollback (within another nested domain) is established later.

The event handler (still running in the root domain) creates two additional data domains (Listing 7, ➀ and ➁). The first data domain (➀) is used to store the encryption key after it has been read from the file, and the random initialization vector (❼). Both the root domain and the OpenSSL domain can access this domain area.

The second data domain (❼) is used for data that is shared between the OpenSSL domain and the domain gcm_encrypt_user_data will run in. This corresponds to the third design option in Section 4.1 with respect to how the OpenSSL wrapper (Listing 6) is expected to operate. The OpenSSL domain is granted access to the data domain as the data domain is created (❼). The nested domain used to run the gcm_encrypt_user_data() function is then initialized, then granted access to the data domain (Listing 7, ➁). The event handler (still running in the root domain) uses this shared data domain to allocate buffers that hold the plaintext, ciphertext, and the Galois/Counter Mode (GCM) tag which are either used to communicate data to the nested domains, or data back from them (Listing 7, ❼).

The gcm_encrypt_user_data() function is then invoked inside the nested domain (Listing 7, ➁). It then re-initializes the OpenSSL domain to set it to use the nested domain’s saved execution context upon an abnormal domain exit (Listing 8, ❼). This avoids the need to establish individual rollback points for each individual OpenSSL invocation that execute in the dedicated persistent domain.

In case of an abnormal domain exit from either domain the execution of the gcm_encrypt_user_data() or OpenSSL is rolled back to the point of the second sdrob_init() in event_handler (Listing 7, ➀). The return value of that call (if other than SUCCESSFUL_RETURNED) indicated the UDI of the domain that initiated the abnormal exit. When this occurs, the SDRoB library has already destroyed the offending execution domain, but the caller uses the returned UDI to determine any remaining cleanup operations, such as destroying any remaining domains (Listing 7, ➀ and ❼). Note that in ❼, if the nested domain running Listing 8 experienced and abnormal domain exit, the persistent OpenSSL domain still remains, but cannot be entered again until a new execution context for rollback is established. In principle the event handler could leave the domain intact (but deinitialized) at ❼ and reuse it the next time the event handler is called. For clarity, we show each domain explicitly destroyed in Listing 7. In ❼, the persistent OpenSSL domain experienced an abnormal exit. As it was initialized by gcm_encrypt_user_data() to use the calling domains execution context for rollback (Listing 8, ➀) SDRoB has automatically destroyed both the offending OpenSSL domain and the nested domain where gcm_encrypt_user_data() executed. Data domain are always left intact after rollback and must be explicitly destroyed.

On normal domain exit it is the responsibility of the event handler to deinitialize or destroy any domains before it exits, as explained in Section 4.2. Similar to above, the event handler could choose to leave any of the domains intact (but deinitialize) to reuse them the next time it is entered.
int event_handler(struct event_handler_args *args)
{

gcm_encrypt_user_data_args_t gcc_args; // holds read-only arguments for gcm_encrypt_user_data()

register gcm_encrypt_user_data_args_t *gcm_args_p asm("r12") = &gcc_args; // pointer passed across callee-saved registers

register int ciphertext_len asm("r13"); // return value from nested domain held in callee-saved registers

if(sdrob_init(OPENSSL_UDI, EXECUTION_DOMAIN | INACCESSIBLE_DOMAIN | RETURN_HERE) != SUCCESSFUL_RETURNED) {
    handleErrors(); /* If the OpenSSL domain initialization fails, don’t continue*/
}
sdrob_deinit(OPENSSL_UDI);

if(sdrob_init(OPENSSL_PRIVATE_DATA_UDI, DATA_DOMAIN) != SUCCESSFUL_RETURNED) {
    sdrob_destroy(OPENSSL_UDI, NO_HEAP_MERGE);
    handleErrors();
    sdrob_dprotect(OPENSSL_UDI, OPENSSL_PRIVATE_DATA_UDI, READ_ENABLE | WRITE_ENABLE);
}

if(sdrob_init(OPENSSL_SHARED_DATA_UDI, DATA_DOMAIN) != SUCCESSFUL_RETURNED) {
    sdrob_destroy(OPENSSL_PRIVATE_DATA_UDI, NO_HEAP_MERGE);
    sdrob_destroy(OPENSSL_UDI, NO_HEAP_MERGE);
    handleErrors();
}
sdrob_dprotect(OPENSSL_UDI, OPENSSL_SHARED_DATA_UDI, READ_ENABLE | WRITE_ENABLE);

gcm_args.key = sdrob_malloc(OPENSSL_PRIVATE_DATA_UDI, AES_GCM_KEY_LEN);
if (read_key_from_file(key_p, AES_GCM_KEY_LEN, args->pathname) != 1){
    handleErrors();
}
gcm_args.iv = sdrob_malloc(OPENSSL_PRIVATE_DATA_UDI, AES_GCM_IV_LEN);
if (RAND_bytes(gcm_args->iv, sizeof(AES_GCM_IV_LEN)) != 1){
    handlerErrors();
}

udi_t ret = sdrob_init(NESSED_DOMAIN_UDI, EXECUTION_DOMAIN| ACCESSIBLE_DOMAIN| RETURN_TO_CURRENT);
if(ret == SUCCESSFUL_RETURNED) {
    sdrob_dprotect(NESSED_DOMAIN_UDI, OPENSSL_SHARED_DATA_UDI, READ_ENABLE | WRITE_ENABLE);

gcm_args.ciphertext = sdrob_malloc(OPENSSL_SHARED_DATA_UDI, CIPHER_TEXT_LEN);
gcm_args.plaintext = sdrob_malloc(OPENSSL_SHARED_DATA_UDI, args->plaintext_len);
gcm_args.tag = sdrob_malloc(OPENSSL_SHARED_DATA_UDI, TAG_SIZE);

    sdrob_enter(NESSED_DOMAIN_UDI);
ciphertext_len = gcm_encrypt_user_data(gcm_args.p);  ②
    sdrob_exit();
    sdrob_destroy(NESSED_DOMAIN_UDI, NO_HEAP_MERGE);
} else {
    switch (ret) {
    case NESSED_DOMAIN_UDI:
        sdrob_destroy(OPENSSL_UDI, NO_HEAP_MERGE);
        sdrob_destroy(OPENSSL_PRIVATE_DATA_UDI, NO_HEAP_MERGE);
        break;
    case OPENSSL_UDI:
        sdrob_destroy(OPENSSL_SHARED_DATA_UDI, NO_HEAP_MERGE);
        sdrob_destroy(OPENSSL_PRIVATE_DATA_UDI, NO_HEAP_MERGE);
        break;
    default:
        abort();
    }
    return OPERATION_FAILED;
}

// store ciphertext and tag for later retrieval  ④
sdrob_destroy(OPENSSL_UDI, NO_HEAP_MERGE);
    sdrob_destroy(NESSED_DOMAIN_UDI, NO_HEAP_MERGE);
    sdrob_destroy(OPENSSL_SHARED_DATA_UDI, NO_HEAP_MERGE);
    sdrob_destroy(OPENSSL_PRIVATE_DATA_UDI, NO_HEAP_MERGE);
}

Listing 7: An excerpt from an example file encryption server. The excerpt shows the event handler code that has been augmented to perform the SDRoB domain management, executing in the root domain. Some error handling has been omitted for brevity.
int gcm_encrypt_user_data(const gcm_encrypt_user_data_args_t *args) {
    size_t len = 0;
    size_t num_bytes_read = 0;
    size_t ciphertext_len = 0;
    EVP_CIPHER_CTX *ctx;

    if(sdrob_init(OPENSSL_UDI, EXECUTION_DOMAIN, INACCESSIBLE_DOMAIN, RETURN_TO_PARENT) != SUCCESSFUL_RETURNED) {
        return GCM_ENCRYPT_FAILED;
    }

    if((ctx = EVP_CIPHER_CTX_new()) == NULL) { // create and initialize the OpenSSL context
        sdrob_deinit(OPENSSL_UDI); // deinitialize domain before returning
        return GCM_ENCRYPT_FAILED;
    }

    if(EVP_EncryptInit_ex(ctx, EVP_aes_256_gcm(), NULL, NULL, NULL) != 1) // initialize cipher for encryption
        goto err_out;

    if(EVP_CIPHER_CTX_ctrl(ctx, EVP_CTRL_GCM_SET_IVLEN, args->iv_len, NULL) != 1) // set length of IV
        goto err_out;

    if(EVP_EncryptInit_ex(ctx, NULL, NULL, args->key, args->iv) != 1) // load key and iv from private data domain
        goto err_out;

    while(num_bytes_read < plaintext_len) {
        num_bytes_read += read(fd, plaintext, 1024);
    }

    if(EVP_EncryptUpdate(ctx, NULL, &len, args->aad, args->aad_len) != 1) // provide any additional authentication data
        goto err_out;

    if(EVP_EncryptUpdate(ctx, args->ciphertext, &len, args->plaintext, args->plaintext_len) != 1)
        ciphertext_len = len;

    if(EVP_EncryptFinal_ex(ctx, args->ciphertext + len, &len) != 1) // finalize the encryption
        goto err_out;

    if(EVP_CIPHER_CTX_ctrl(ctx, EVP_CTRL_GCM_GET_TAG, TAG_SIZE, args->tag) != 1) // read the tag to the shared domain
        goto err_out;

    sdrob_deinit(OPENSSL_UDI); // deinitialize domain before returning
    EVP_CIPHER_CTX_free(ctx); // success, cleanup and return
    return ciphertext_len;
}

Listing 8: The gcm_encrypt_user_data function reads a plaintext message from a descriptor provided as argument and encrypts the plaintext with AES GCM using OpenSSL’s high-level, envelope (EVP) API. The call to the EVP API functions have been wrapped to execute in domain OPENSSL_UDI as shown in Listing 6 in Section 4.1.