CAPACITY: Cryptographically-Enforced In-Process Capabilities for Modern ARM Architectures

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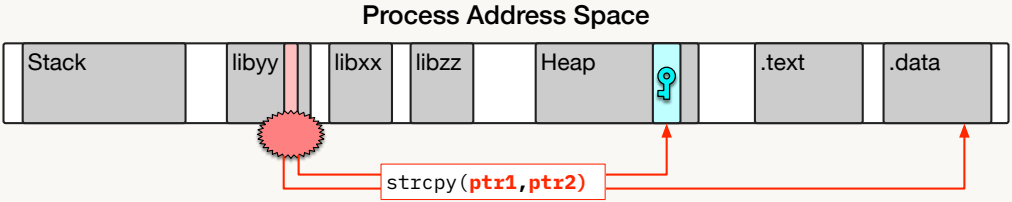
Perils of Monolithic Programs Designs



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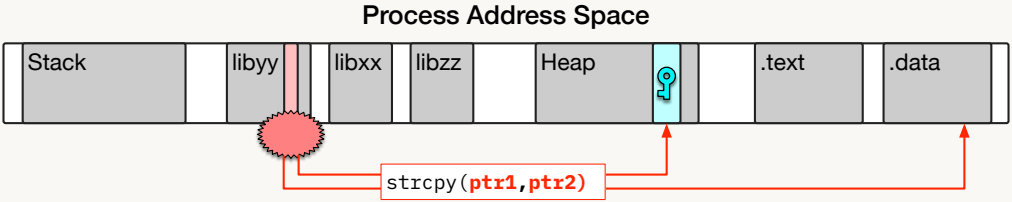

- A single vulnerability *anywhere* may be enough for adversary to compromise program

Process-based Isolation

Real-world examples: modern web browsers (Chrome, Safari, etc..) and OpenSSH

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Limitations

- Must be incorporated from design
- High engineering costs
- High performance overhead due to IPC

In-Process Isolation

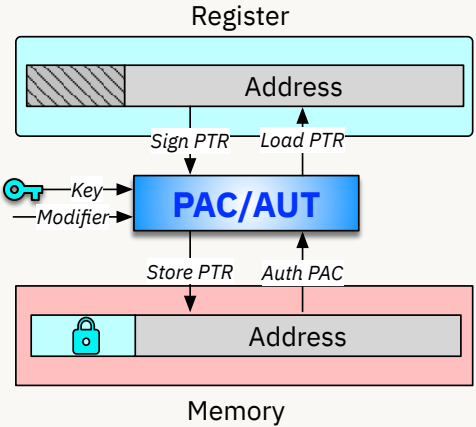
- **PKU-based Isolation in x86.** Isolates memory pages into multiple domains in page-granularity
  - ERIM (SEC ’19), Hodor (ATC ’19),
- **Reference monitor.** Supplements PKU memory isolation through syscall filtering
  - Jenny (SEC ’22), Cerberus (EuroSys ’22)

CAPACITY Research Statement

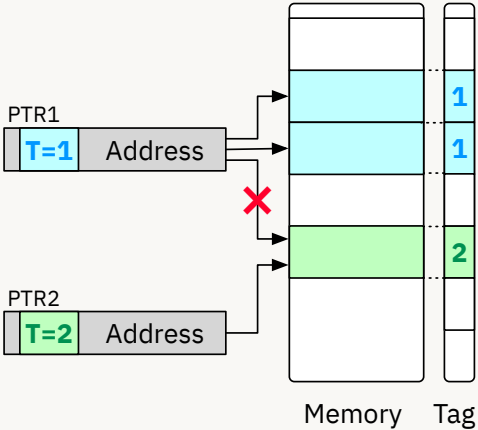
CAPACITY explores *capability*-based in-process isolation design inspired by the direction of new hardware security in modern ARM architecture.

- Fully exploits new ARM features that inherently exhibit characteristics of *capability*

New Hardware Security Features on ARM



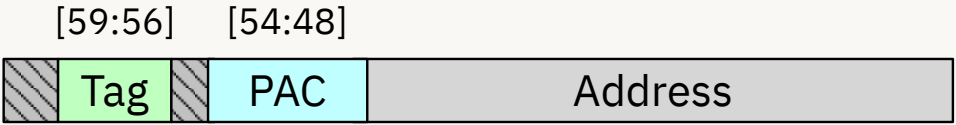
Pointer Authentication (PA)



Memory Tagging Extension (MTE)

PA+MTE

- PA and MTE can be **simultaneously enabled** to make pointer *authenticated* and *tagged*



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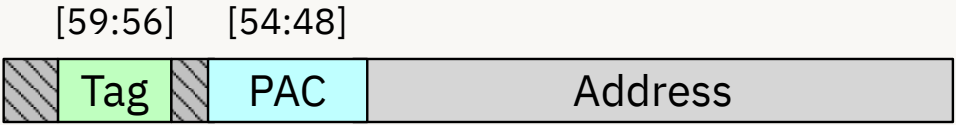
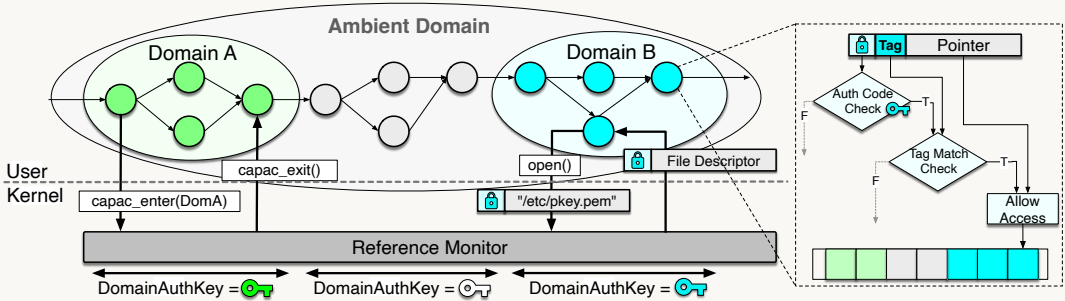
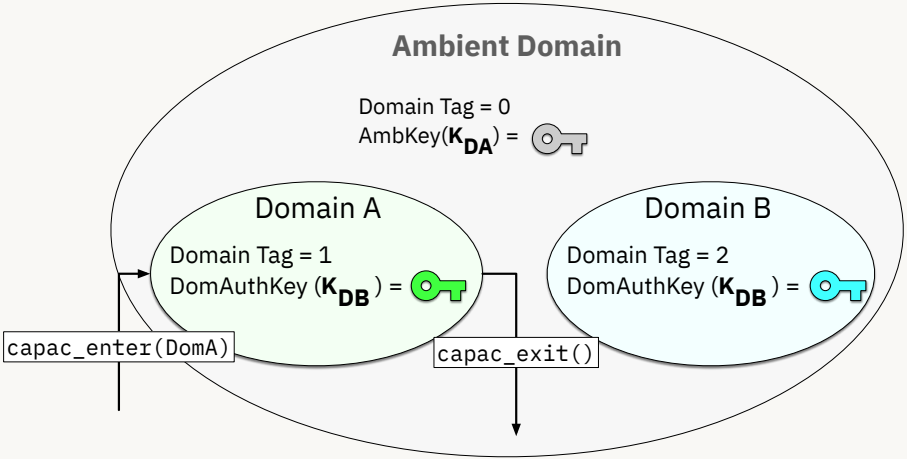


PA+MTE inherently exhibit characteristics of **capability-based access control**

CAPACITY Overview

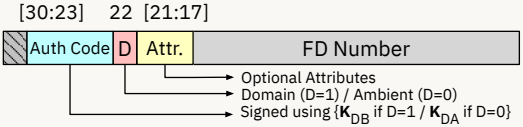


CAPACITY Domains

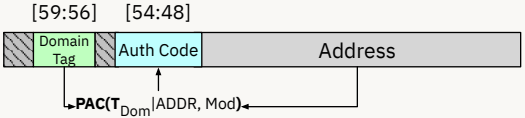


Non-forgeable References

- **Domain-private references**: Signed/Authenticated with DomAuthKey ($\mathbf{K}_{DB}$), exclusive to owner domain
- **Ambient references**: Signed/Authenticated with Ambient Key ($\mathbf{K}_{DA}$), valid in all domain (e.g., `stdin`)

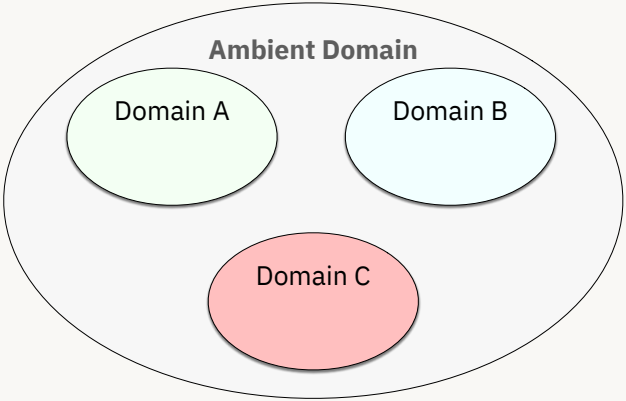


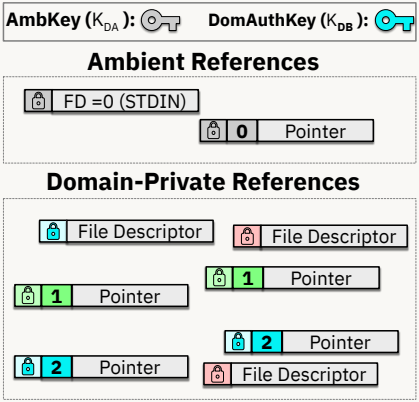
CAPACITY signed file descriptor



CAPACITY tagged & signed pointer

Domains Switching and Reference Validity





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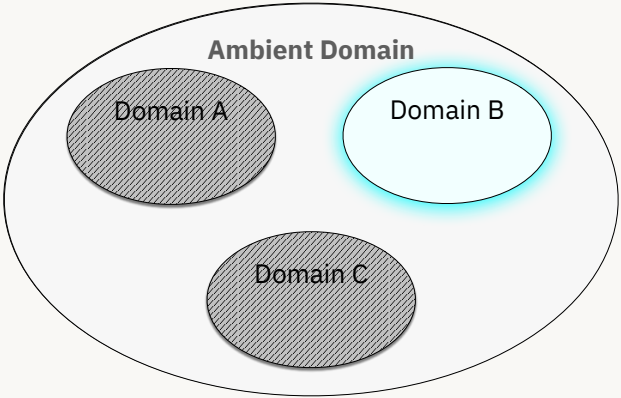

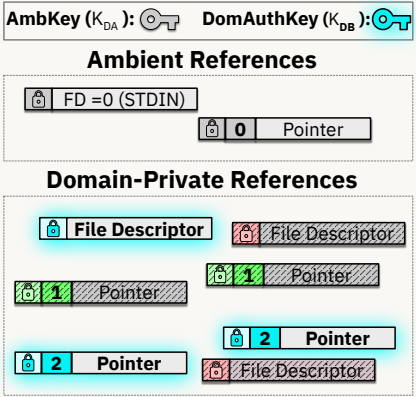

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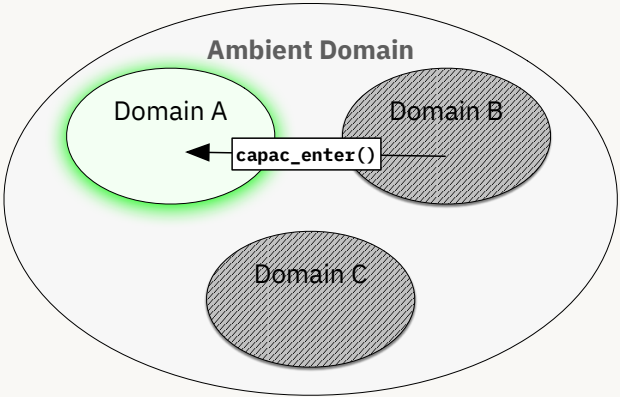

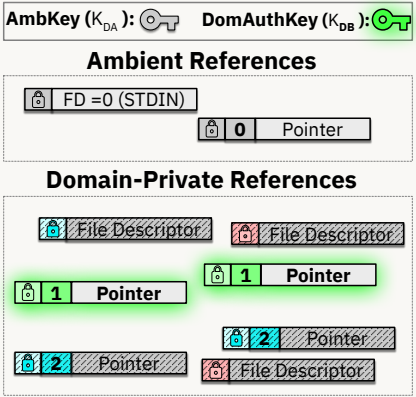

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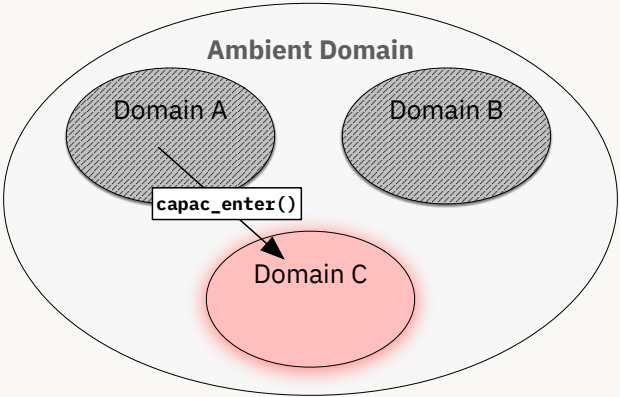
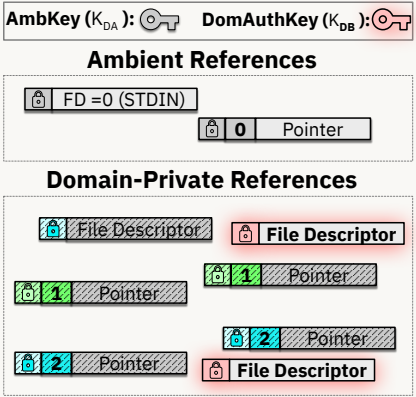
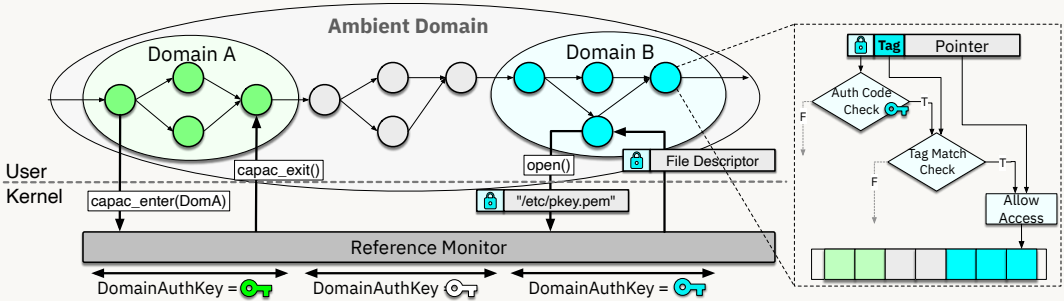




CAPACITY Design and Implementation



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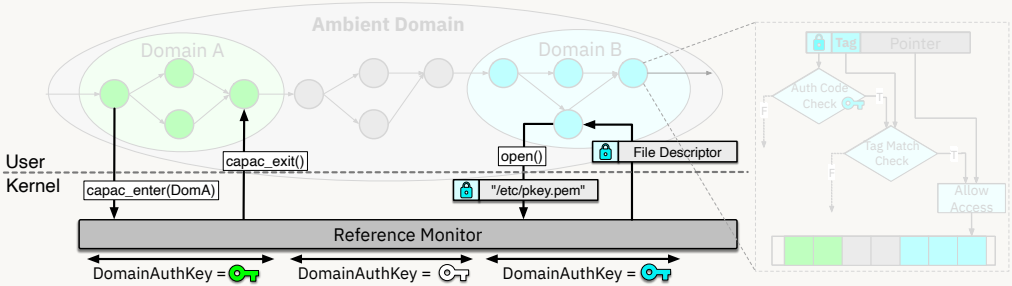
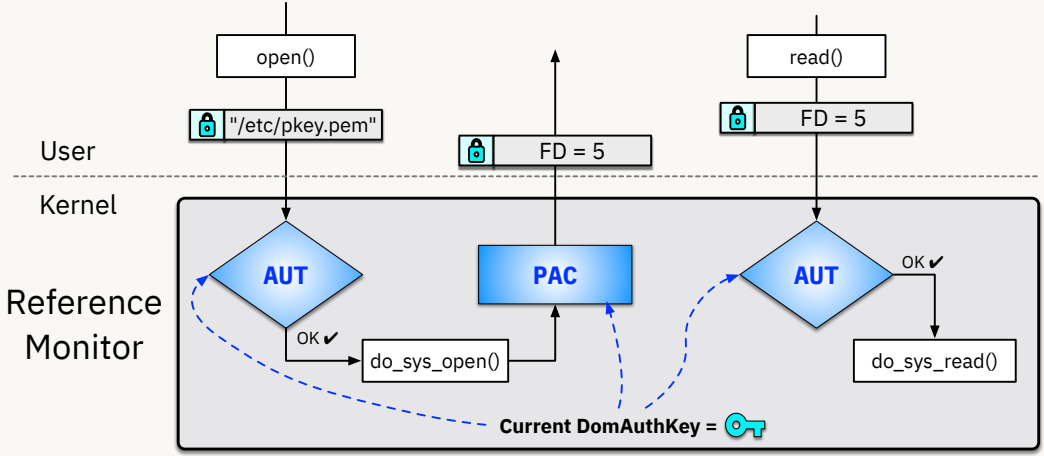
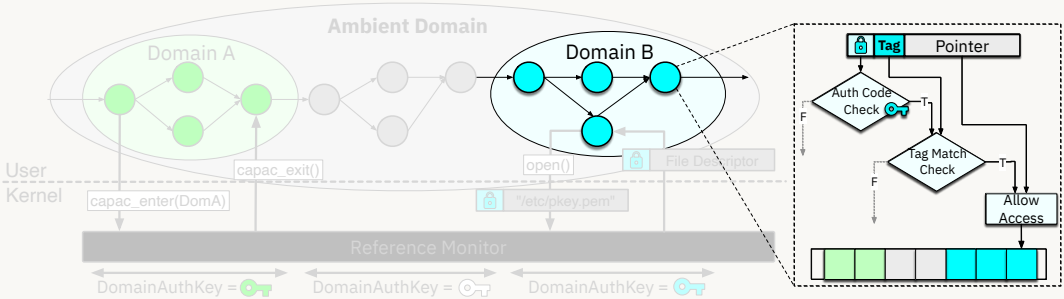


CAPACITY reference monitor

CAPACITY Reference monitor and File References

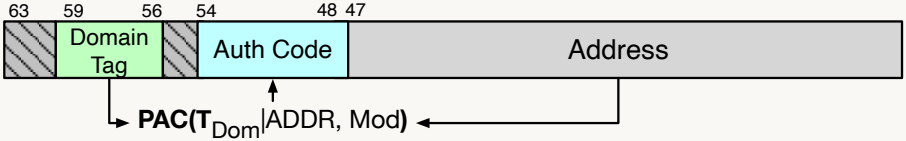


Instrumentation Framework and Domain Memory Isolation



CAPACITY instrumentation framework and Runtime library

Instrumentation Framework and Domain Memory Isolation



- **Tagged domain-private stack:** Instrumentation of domain functions to provide tagged stacks
- **Tagged domain-private heap:** Extended heap allocator to tag memory and provide tagged pointers

Domain-aware Pointer Load/Store Instrumentation

Annotated program

```
1  void sensitive_func(
2      DOM_PRIV void* sensitive_ptr,
3               void* ambient_ptr
4  )
5      ...
```

```
1  // Domain-Private PTR
2  pacdb   ptr, mod          PTR-Sign
3  str     ptr, [mem]
4  ...
5  ldr     ptr, [mem]
6  autdb   ptr, mod          PTR-Auth
```

```
1  // Ambient PTR
2  pacda   ptr, mod          PTR-Sign
3  str     ptr, [mem]
4  ...
5  ldr     ptr, [mem]
6  autda   ptr, mod          PTR-Auth
```

Programming Model

```
1     ...
2   void load_secret(DOM_PRIV crypto_ctx_t* ctx,
3                    const char * key_path){
4
5
6
7
8
9   ...
10 }
```

: Domain-private references : Ambient references

Action : CAPACITY actions ANNOT: CAPACITY annotations

Programming Model

```
1     ...
2   void load_secret(DOM_PRIV crypto_ctx_t* ctx,
3                    const char * key_path){
4     // Import the secret key from the filesystem
5     int fd                                                  FD-Sign
6         = open(key_path, O_RDONLY);                         PATH-Auth
7
8
9   ...
10 }
```

: Domain-private references : Ambient references

Action : CAPACITY actions ANNOT: CAPACITY annotations

Programming Model

```
1     ...
2   void load_secret(DOM_PRIV crypto_ctx_t* ctx,
3                    const char * key_path){
4     // Import the secret key from the filesystem
5     int fd                                                    FD-Sign
6         = open(key_path, O_RDONLY);                           PATH-Auth
7     ctx->secret_key = capac_malloc(KEY_LEN + 1);              PTR-Sign
8
9   ...
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: Domain-private references : Ambient references

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Programming Model

```
1     ...
2   void load_secret(DOM_PRIV crypto_ctx_t* ctx,
3                    const char * key_path){
4     // Import the secret key from the filesystem
5     int fd                                                    FD-Sign
6         = open(key_path, O_RDONLY);                           PATH-Auth
7     ctx->secret_key = capac_malloc(KEY_LEN + 1);              PTR-Sign
8     read(fd, ctx->secret_key, KEY_LEN);                       FD-Auth / PTR-Auth
9   ...
10 }
```

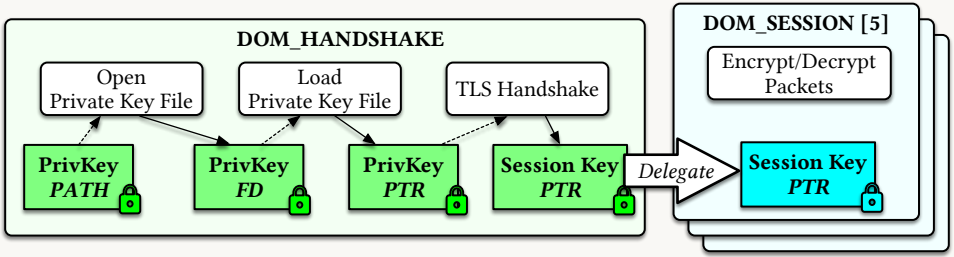
: Domain-private references : Ambient references

Action : CAPACITY actions ANNOT: CAPACITY annotations

Evaluation method

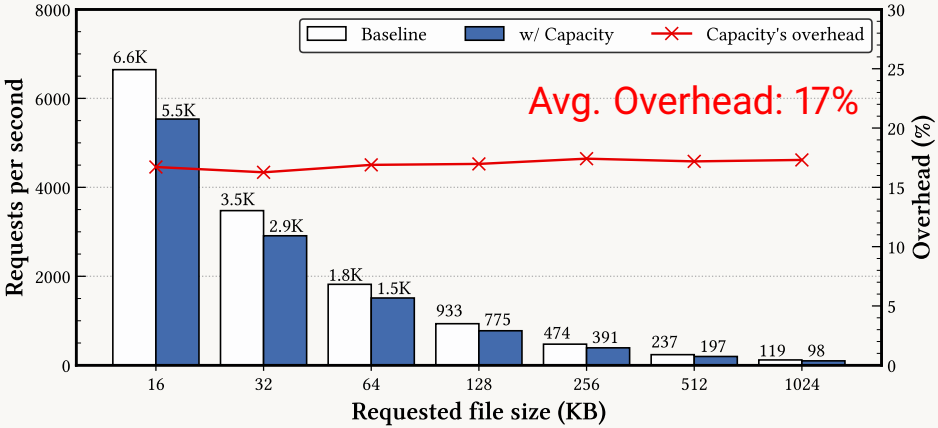
- **Microbenchmarks** on runtime library, reference monitor and instrumented code
  - Reference monitor incurs **2.65% slowdown** on average
- **Three real-world programs**: Nginx+LibreSSL, OpenSSH, and wget
- All experiments were conducted on M1 Mac Mini with Asahi Linux
  - PA is supported natively
  - MTE was *not* available in real hardware
    $\rightarrow$ functional evaluation (QEMU) + emulated overheads

NGINX Webserver prototype



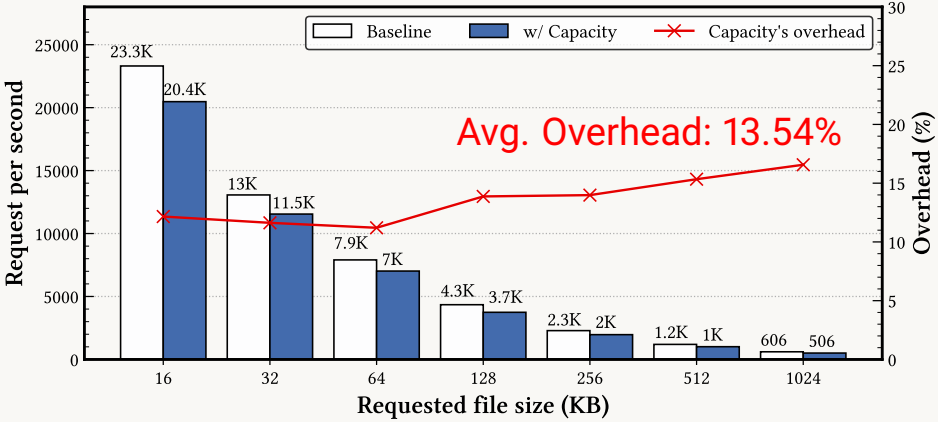
Lifecycle protection of server private key

Webserver prototype benchmark



Webserver throughput on single-threaded experiment

Webserver prototype benchmark



Webserver throughput on multi-threaded experiment

More details

- **Implementation details**
  - Maturing instrumentation framework to be compatible with real-world programs
  - Supporting capability token delegation among domains
- **Thorough security analysis**
  - How does CAPACITY prevent domain impersonation?
  - How difficult is it to forge the signed pointers?
  - etc...

👉 For more details, please check out our paper!

Thank you

Q&A time!!