# Extending Applications Safely and Efficiently

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## Intro & Background

**Motivation for Extension Frameworks**

- Many modern applications (e.g., web servers, databases, browsers) support plugin-style extensions for:
  - **Performance optimization** (e.g., custom query optimizers [1, 38])
  - **New functionality** (e.g., domain-specific logic [46, 48])
  - **Security hardening** (e.g., dynamic taint analysis [44, 59])
  - **Observability and debugging** (e.g., performance tracing, failure analysis [37, 43, 58, 74])
- A typical extension model provides:
  1. **Extension Entrypoints**—predetermined "hooks" in the host application where the extension can run.
  2. **Runtime Loading**—when a thread reaches a hook, execution jumps into the extension and returns afterwards.

**Key Challenges**

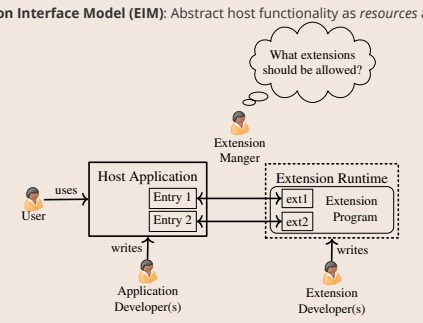
1. **Interconnectedness vs. Safety**
   - Extensions need access to application state (interconnectedness), but that must be limited to avoid buggy or malicious behavior that could crash or compromise the app (safety).
   - Existing frameworks rarely give fine-grained control over exactly which parts of the application an extension may read or write.
2. **Isolation vs. Efficiency**
   - Process- or container-level isolation is heavy: frequent context switches impose large performance penalties.
   - Software fault isolation (SFI) can be lighter weight but still incurs significant overhead.
   - The ideal is **in-process**, low-overhead isolation with minimal runtime cost.

**Shortcomings of Existing Approaches**

- **Native execution** (e.g., LD_PRELOAD, dynamic binary rewriting) is fast but offers no real isolation or safety.
- **Software Fault Isolation (SFI)** (e.g., Native Client, WebAssembly, Lua, RLBox, XFI) enforces isolation but either lacks fine-grained permission controls or still incurs nontrivial overhead.
- **Subprocess or micro-VM** (e.g., lwC, Shreds, Orbit, Wedge) can isolate, but often require application modifications and incur high IPC/context-switch costs.
- **eBPF uprobes** isolate extensions reasonably well but cannot enforce per-hookpoint permissions in user space, and each user-side hook requires a kernel trap, hurting performance.

**Our Solution at a Glance**

- **Extension Interface Model (EIM)**: Abstract host functionality as *resources* and *capabilities*.



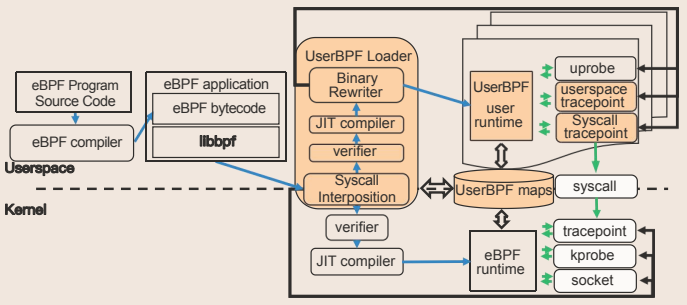

- **Extension Entry Declarations**
  - Annotate the host functions that become hookpoints for extensions, including name and signature.
  - Example:

```
Extension_Entry(
  name           = "processBegin",
  extension_hook = "ngx_http_process_request",
  prototype      = (Request *r) -> int
);
Extension_Entry(
  name           = "updateResponseContent",
  extension_hook = "ngx_http_content_phase",
  prototype      = (Request *r) -> int*
);
```

  - These annotations are extracted at compile time to build the *development-time EIM specification*.
2. **Deployment-Time EIM Configuration**
   - For each declared Extension Entry, an **Extension Class** specifies:
     1. A capability set (subset of the declared state/function capabilities).
     2. Optional resource limits (e.g., "instructions < ∞," "memory < 8 MB").
   - Example YAML for two Nginx hooks:

```
Extension_Class(
  name           = "observeProcessBegin",
  extension_hook = "processBegin",
  allowed_caps   = { instructions < inf, nginxTime, readPid, read(r) }
)
Extension_Class(
  name           = "updateResponse",
  extension_hook = "updateResponseContent",
  allowed_caps   = { instructions < inf, read(r), write(r) }
)
```

   - An extension manager (person or script) writes this deployment-time policy to enforce "least privilege" at runtime.




### 2.1 EIM Model

1. **Development-Time EIM Specification**
   - **State Capabilities**
     - Written as `read(var)` or `write(var)` to specify allowed global variables or struct-field accesses.
     - Example:

```
State_Capability(
  name      = "readPid",
  operation = read(ngx_pid)
);
```

   - **Function Capabilities**
     - Specify which host functions an extension may call, including their prototypes and optional pre/post-conditions.
     - Example:

```
Function_Capability(
  name        = "nginxTime",
  prototype   = (void) -> time_t,
  constraints = { return_value > 0 }
);
```

   - At development time, the application author declares which global variables or functions an extension may access (e.g., `read(pid)`, `write(r->headers)`, `call get_time()`).
   - At deployment time, the extension manager chooses a minimal set of capabilities for each hook (adhering to "least privilege").
- **bpftime Extension Runtime**: A lightweight, in-process framework that:
  - Uses a **verifier** similar to eBPF's to guarantee extension bytecode matches the declared EIM constraints—zero runtime cost in user space.
  - Leverages Intel Memory Protection Keys (MPK) via an ERIM-style approach to enforce in-process isolation without context switches.
  - Applies **binary rewriting** to "conceal" hookpoints so that, if no extension is loaded, there is literally no added cost at that hook.
  - Maintains compatibility with existing eBPF tools (bcc, libbpf, bpftrace) by intercepting and rewriting eBPF loading and Map operations (bpftime Maps).

### 2.2 bpftime Loader

1. **eBPF Syscall Interception**
   - bpftime intercepts standard eBPF loading syscalls (`bpf()`, map-related calls) in user space.
   - It implements a user-space shim that translates those requests into calls to the real kernel eBPF API via UNIX-domain sockets or file descriptors.
   - This maintains full compatibility with bcc, libbpf, bpftrace, etc., requiring no kernel code changes.
2. **Verifier**
   - Accepts raw eBPF bytecode and the selected Extension Class's capability constraints.
   - Translates each declared capability (e.g., "can call get_time," "can read pointer r->headers") into a set of clauses or predicates that the eBPF verifier understands.
   - Ensures the loaded bytecode obeys these constraints—no out-of-bounds pointer use, no disallowed calls—purely at load time, so there is zero runtime-execution overhead.
3. **Binary Rewriter**
   - Uses `ptrace` to pause the target process and injects the bpftime runtime library into its address space.
   - Relies on Frida + Capstone to rewrite machine instructions at each declared hookpoint:
     1. At every `uprobe/uretprobe` hook, replace the original instruction(s) with a jump (trampoline) into the extension's entry stub, then execute the original instructions upon return from the extension.
     2. For arbitrary syscall hooks (e.g., `sysenter`), use a "z-poline" instructionation technique to insert jumps with minimal instruction-overhead.
   - **Concealed Hookpoints**: If no extension is currently loaded for a given hook, the code at that hookpoint remains exactly as before—no added branches or jumps—so the cost is literally zero when unused.

### 2.3 bpftime Runtime

1. **In-Process Isolation via MPK**
   - Follows an ERIM-style approach using Intel Memory Protection Keys (MPK):
     1. Each extension is assigned a distinct MPK indices; extension code/data pages are tagged with that key.
     2. On entry into the extension, `WRPKRU` flips the PKRU so that pages tagged for that extension become writable/exec-readable.
     3. On exit, `WRPKRU` flips PKRU back so that extension pages become non-writable at user level.
     4. The host application cannot tamper with extension code or data, ensuring strong isolation, all without expensive context switches or syscalls.
   - Fully implemented on x86-64; ARM support can be added via similar ARM PK mechanisms (AMPK).
2. **bpftime Maps (Efficient Data Structures)**
   - Unlike native eBPF Maps (which require syscalls), bpftime Maps operate entirely in user space, providing zero-syscall access:
     - **Local (Non-shared) Mode**: Single-process, per-extension local hash tables.
     - **Inter-process Shared Mode**: Shared memory segments for multiple processes to share state.
     - **Kernel-Backed Mode**: Hybrid mode where the map is kernel-visible for use by both kernel probes and user-space extensions.
   - Supported data structures: Hash Map, Array, LPM Trie, Ring Buffer, Perf Event Array, per-CPU variants, etc.
   - Internally optimized with lock-free or per-CPU data structures so that typical operations (lookup, update, delete) are an order of magnitude faster than native eBPF Maps.

## Implementation

## Use Cases

We implemented and evaluated six representative scenarios to demonstrate bpftime's security, customizability, observability, and performance advantages.

1. **Nginx Plugin (Web Server Security Extension)**
   - **Goal**: Deploy a firewall extension in Nginx's forward-proxy mode to block SQL-injection and XSS attacks.
   - **Implementation**:
     - At the `processBegin` hook, define an Extension Class that only allows reading/writing the current `Request` object (`read(r)`, `write(r)`).
     - The extension inspects the URL; if malicious, return a 404 immediately.
   - **Result**: When the extension is loaded, bpftime adds only ~2% overhead—much lower than Lua, WebAssembly, ERIM, or RLBox.
2. **sslsniff (Distributed HTTPS Tracing)**
   - **Goal**: Observe encrypted TLS/SSL traffic end-to-end for distributed tracing/observability.
   - **Conventional eBPF Approach**: Uprobes on OpenSSL's `SSL_read`/`SSL_write` cause up to ~30% throughput drop.
   - **bpftime Implementation**:
     - Automatically place hookpoints at each uprobe site.
     - Create an "Observability" Extension Class that permits reading pointers needed to record metadata.
     - Write trace records into a shared bpftime Map only if constraints are met.
   - **Measured Results (Figure 8)**:
     - eBPF uprobes: up to 28.06% throughput reduction.
     - bpftime: up to 7.41% throughput reduction.
3. **Syscount (Per-Process Syscall Counting)**
   - **Goal**: Count system calls *only* from a target process rather than all processes.
   - **Conventional Approach (bcc)**: Place kprobes on every process; filter in user space—incurs system-wide overhead.
   - **bpftime Implementation**:
     - Hook only `sysenter`/`sysexit` for the target process using an "Observability" Extension Class.
   - **Measured Results (Figure 9)**:

| Scenario | Throughput (RPS) |
|---|---|
| Native (no hooking) | 19,705 |
| Kernel uprobe (unfiltered) | 17,676 (−10.24%) |
| bpftime for target process (filtered) | 19,042 (−3.36%) |
| Kernel uprobe (with user-side filter) | 17,817 (−9.57%) |
| bpftime (unmonitored processes) | ~19,800 (≈ native) |

   - bpftime introduces ~3.36% overhead to the monitored process and zero overhead to others; native eBPF imposes ~10% everywhere.
4. **DeepFlow (Microservices Observability Platform)**
   - **Goal**: Provide end-to-end tracing across kernel and user space for Go-based microservices.
   - **Conventional eBPF Implementation**: Uprobes on many Go runtime functions cause up to 50% drop in throughput.
   - **bpftime Implementation**:
     - Modify ~10 lines of extension code to reuse automatic hook injection.
     - Use an Observability Class to limit capabilities to safe reads of call stacks/IDs.
   - **Measured Results (Figure 6)**:

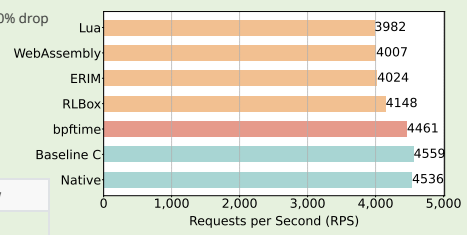
| Workload | Native Throughput | eBPF DeepFlow | bpftime DeepFlow |
|---|---|---|---|
| Small Replies | 250 k RPS | 115 k RPS (−54%) | 170 k RPS (−32%) |
| Large Replies | 47 k RPS | 21 k RPS (−55%) | 31 k RPS (−34%) |

   - bpftime delivers ≥1.5× throughput of eBPF DeepFlow in all cases.
5. **FUSE Caching (User-Space File System Cache)**
   - **Goal**: Speed up FUSE-based user-space file systems (Passthrough, LoggedFS).
   - **Conventional FUSE**: Each I/O involves a user↔kernel↔FS transition, incurring high latency.
   - **bpftime Implementation**:
     - Hook `open`, `close`, `getdents`, `stat` syscalls to maintain an in-user-space cache (bpftime Map).
     - Kernel kprobes watch `unlink` to keep cache coherent.
   - **Measured Latency (Table 2)**:

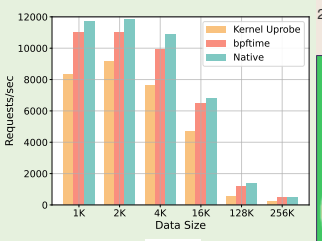
| Scenario | Native FUSE Latency (ms) | bpftime Cache Latency (ms) | Speedup |
|---|---|---|---|
| Passthrough, `fstat` | 3.65 | 0.176 | ≈ 20.8× |
| LoggedFS, `fstat` | 7.40 | 0.184 | ≈ 40.2× |
| LoggedFS, `openat` | 17.0 | 0.074 | ≈ 229.7× |
| Passthrough, `find` | 5.1 | 1.6 | ≈ 3.19× |

6. **Redis Durability Tuning (Custom Persistence Strategies)**
   - **Background**: Redis default persistence policies:
     1. **no AOF**: No durability—crashes lose all data.
     2. **everysec**: fsync every second—can lose ≈ $10^4$ updates on crash.
     3. **alwayson**: fsync on every write—≈ 6× performance penalty.
   - **Goal**: Provide user-space extensions that batch I/O and delay fsyncs for a better performance-durability tradeoff.
   - **Implementation Steps**:
     1. Add three new functions in Redis (for batching writes and deferred fsync).
     2. Annotate relevant write/fsync callsites with bpftime hooks.
     3. Define three Extension Classes:
        - **Batch I/O**: Buffer up to *b* writes before invoking `fsync`, losing at most *b* updates on crash.
        - **Delayed-fsync**: Only invoke `fsync` if a previous `fsync` is still in flight—losing at most 2 updates.
          - **Fast-notify Optimization**: Use a shared counter between user and kernel to skip redundant syscalls when no new fsync is required.
   - **Measured Performance (Figure 7)**:

| Configuration | Throughput (req/s) | Notes |
|---|---|---|
| no AOF | 87 k | (no durability) |
| everysec | 72 k | Might lose ≈ $7.2\times10^4$ updates on crash |
| alwayson | 13 k | (fsync on every write) |
| Batch 1 | ≈ 19 k | Loss ≤ 1 update |
| Batch 3 | ≈ 43 k | +1.7× vs. everysec, loss ≤ 3 updates |
| Batch 12 | ≈ 48 k | +1.9× vs. everysec, loss ≤ 12 updates |
| Batch 24 | ≈ 50 k | +2.1× vs. everysec, loss ≤ 24 updates |
| Batch 48 | ≈ 53 k | +2.3× vs. everysec, loss ≤ 48 updates |
| Delayed-fsync | 40 k | ≤ 2 updates lost; ≈ 4.15× faster than alwayson |
| Delayed-fsync + Fast-notify | 65 k | ≤ 2 updates lost; ≈ 10% slower than everysec, but 5 orders of magnitude fewer losses (2 vs. $7.2\times10^4$) |




bpftime-nginx-module




ssl-nginx




jit_execution_times

## Citation

Anjo Vahldiek-Oberwagner, Eslam Elnikety, Nuno O. Duarte, Michael Sammler, Peter Druschel, and Deepak Garg.
"ERIM: Secure, Efficient In-Process Isolation with Protection Keys (MPK)."
In Proceedings of the 28th USENIX Security Symposium (USENIX Security '19), pp. 1221–1238, 2019.

Yuzhuo Jing and Peng Huang.
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